

Imperial College London  
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# **Turbulent Explosions in Hydrogen Enriched Fuel Blends**

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and the Diploma of Imperial College London

To my parents

# **Declaration of Originality**

I, Tao Li, declare that the present thesis is the outcome of my own original research, with the work of others appropriately cited and a list of the references can be found in the Bibliography.

Tao Li, September 2017

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# Abstract

This thesis presents an experimental investigation of turbulent explosions resulting from hydrogen enriched fuel blends in an obstructed flame tube facility. The influence of mixture reactivity and thermal radiation induced ignition in turbulent explosions were studied followed by a quantification of the flow field development.

Fuel lean binary  $\text{H}_2/\text{CO}$ ,  $\text{H}_2/\text{CH}_4$  and ternary  $\text{H}_2/\text{CH}_4/\text{CO}$  mixtures were first studied in a two-obstacle configuration to assess the impact of mixture reactivity on explosion overpressures and flame speeds. The mixture reactivity was varied by introducing different  $\text{H}_2$  substitutions at equivalence ratios of 0.80, 0.60 and 0.40. The results highlight significant differences in explosion behaviour between the two blending components, with CO mixtures providing substantially higher overpressures than the corresponding  $\text{CH}_4$  blends. The results suggest that methane has a mitigating effect up to comparatively high hydrogen blending fractions and that synergistic effects between fuel components need to be taken into account. A new scaling parameter ( $\beta$ ) is proposed that successfully linearises the peak explosion overpressure between different fuel blends in response to the hydrogen concentration. A scaling based on acoustic theory shows good agreement with experimental data and a simple method for estimating the overpressure change caused by variations in the mixture reactivity in a fixed geometry is also evaluated.

The impact of thermal radiation induced ignition was explored in fuel lean  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures with a continuous wave laser operating in the near infrared as the radiation source and acetylene black particles as the radiation target due to their relationship with soot emissions. Influences of ignition location and ignition delay time were studied. The results show that the ignition kernels caused by irradiated particles can be successfully entrained into the main flow and/or recirculation zones formed around obstacles and cause multipoint explosions. The resulting relationship between fuel consumption ahead of the advancing flame and the evolution of the strength of the explosion was shown to be complex and typically lead to increased explosion durations with reduced peak pressures. The complex effect of forward radiation induced ignition on the pressure development

stems from the interactions of the two explosion kernels resulting in two sharp pressure rises separated by a quasi-stable stage with a duration depending on the radiation induced ignition time. The total impulse was estimated by integrating the instantaneous pressure over time and the results show different characteristics for different configurations.

The mixture reactivity also affects turbulent explosions indirectly via turbulence-chemistry interactions in the critical recirculation zones behind the obstacles. The flow field development was therefore quantified in a two obstacle configuration using high-speed (10 kHz) particle image velocimetry (PIV), time-series PIV and Mie scattering in  $\text{H}_2/\text{CO}/\text{Air}$  and  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures with  $\text{H}_2$  substitution levels of 50%, 80% and 100% for a fixed stoichiometry of 0.60. The time-resolved evolution of the recirculation zone behind the second obstacle was successfully captured with the explosion over-pressure and flame propagation speed also measured. Data is presented for the mean horizontal ( $\bar{u}$ ) and vertical ( $\bar{v}$ ) velocity components at 24 spatial locations for each mixture along with the translational velocities of the shear driven recirculating eddies. It is shown that, despite large differences in flow velocities and over-pressures, the impact of the mixture reactivity on the temporal evolution of the flow field evolution can be approximately normalised using a dimensionless time scale.

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# Nomenclature

## Abbreviations

|        |                                                              |
|--------|--------------------------------------------------------------|
| BR     | Blockage Ratio (= Obstacle area / cross sectional tube area) |
| C-J    | Chapman-Jouguet                                              |
| CFD    | Computer Fluid Dynamics                                      |
| CLICHE | Confined LInked CHamber Explosion                            |
| CW     | Continuous Wave                                              |
| DDT    | Deflagration Detonation Transition                           |
| FA     | Flame Acceleration                                           |
| HS-PIV | High-Speed Particle Image Velocimetry                        |
| TS-PIV | Time-Series Particle Image Velocimetry                       |
| L/d    | Length to diameter ratio                                     |
| LDA    | Laser Doppler Anemometry                                     |
| NIR    | Near InfraRed                                                |
| L-D    | Landau-Darrieus                                              |
| K-H    | Kelvin-Helmholtz                                             |
| PLIF   | Planar Laser Induced Fluorescence                            |
| R-T    | Rayleigh-Taylor                                              |
| R      | Radiation induced ignition                                   |
| S      | Spark ignition                                               |



|       |                                                          |
|-------|----------------------------------------------------------|
| SCOPE | Shell Code for Overpressure Prediction in gas Explosions |
| TTL   | Transistor–Transistor Logic                              |
| VCEs  | Vapor Cloud Explosions                                   |

#### **Chemical Species**

|                                    |                      |
|------------------------------------|----------------------|
| CH <sub>4</sub>                    | Methane              |
| CO                                 | Carbon monoxide      |
| CO <sub>2</sub>                    | Carbon dioxide       |
| H <sub>2</sub>                     | Hydrogen             |
| He                                 | Helium               |
| N <sub>2</sub>                     | Nitrogen             |
| NO <sub>x</sub>                    | Nitrogen oxides      |
| O <sub>2</sub>                     | Oxygen               |
| OH                                 | Hydroxyl             |
| CH <sub>2</sub> O                  | Formaldehyde         |
| (FeMn) <sub>2</sub> O <sub>3</sub> | Iron manganese oxide |

#### **Greek Symbols**

|              |                                                                     |
|--------------|---------------------------------------------------------------------|
| $\alpha$     | Conventional composition parameter for H <sub>2</sub> content [–]   |
| $\beta$      | Newly proposed composition parameter for H <sub>2</sub> content [–] |
| $\epsilon$   | Linear prediction uncertainty [–]                                   |
| $\epsilon_b$ | Velocity uncertainties associated with bias [–]                     |
| $\epsilon_r$ | Velocity uncertainties associated with relaxation time [–]          |
| $\epsilon_t$ | Turbulence dissipation rate [m <sup>2</sup> s <sup>–3</sup> ]       |
| $\gamma$     | Specific heat capacity ratio [–]                                    |
| $\lambda$    | Wavelength [ $\mu$ m]                                               |

|                 |                                                                                           |
|-----------------|-------------------------------------------------------------------------------------------|
| $\lambda_{max}$ | Wavelength of the maximum irradiance [ $\mu\text{m}$ ]                                    |
| $\mu$           | Dynamic viscosity [ $\text{kg s}^{-1} \text{m}^{-1}$ ]                                    |
| $\nu$           | Kinematic viscosity [ $\text{m}^2 \text{s}^{-1}$ ]                                        |
| $\Phi$          | Equivalence ratio [–]                                                                     |
| $\pi$           | Pressure ratio across the shock wave [–]                                                  |
| $\rho_b$        | Density of the burned gas mixture [ $\text{kg m}^{-3}$ ]                                  |
| $\rho_p$        | Density of the seeding particles [ $\text{kg m}^{-3}$ ]                                   |
| $\rho_u$        | Density of the unburned gas mixture [ $\text{kg m}^{-3}$ ]                                |
| $\sigma$        | Stefan-Boltzmann constant ( $= 5.67 \times 10^{-8}$ ) [ $\text{W m}^{-2} \text{K}^{-4}$ ] |
| $\tau$          | Expansion ratio [–]                                                                       |
| $\tau_A, t_A$   | Flame arrival time [ms]                                                                   |
| $\tau_{ig}$     | Ignition time [ms]                                                                        |
| $\tau_{mf}$     | Main flame arrival time [ms]                                                              |
| $\tau_s$        | Relaxation time of the seeding particles [ms]                                             |

#### **Latin Symbols, uppercase**

|           |                                                                                             |
|-----------|---------------------------------------------------------------------------------------------|
| $A_F$     | Flame surface area [ $\text{m}^2$ ]                                                         |
| $A$       | Flame tube cross sectional area [ $\text{m}^2$ ]                                            |
| $C$       | Characteristic frequency of the particle motion [ $\text{s}^{-1}$ ]                         |
| $C_A$     | Mole fraction of air in gas mixture [–]                                                     |
| $C_F$     | Mole fraction of fuel (CO and/or $\text{CH}_4$ ) in gas mixture [–]                         |
| $C_H$     | Mole fraction of hydrogen in gas mixture [–]                                                |
| $C_p$     | Specific heat capacity at constant pressure [ $\text{kg m}^2 \text{K}^{-1} \text{s}^{-2}$ ] |
| $C_v$     | Specific heat capacity at constant volume [ $\text{kg m}^2 \text{K}^{-1} \text{s}^{-2}$ ]   |
| $C_k, C'$ | Constant numbers [–]                                                                        |

|                        |                                                            |
|------------------------|------------------------------------------------------------|
| $Da$                   | Damköhler number ( $= t_I/t_F$ ) [–]                       |
| $D_h$                  | Hydraulic diameter [m]                                     |
| $E$                    | Irradiance [ $\text{MW m}^{-2}$ ]                          |
| $Ka$                   | Karlovitz stretch factor ( $= t_F/t_K$ ) [–]               |
| $Ma$                   | Flame speed Mach number ( $= S_F/c_0$ ) [–]                |
| $Ma^*, Ma_1^*, Ma_2^*$ | Normalised mixture reactivity based Mach number [–]        |
| $\Delta P$             | Overpressure [kPa]                                         |
| $P_0$                  | Initial pressure [kPa]                                     |
| $P^*$                  | Measured normalised peak overpressure [–]                  |
| $\bar{P}^*$            | Average of measured normalised peak overpressure [–]       |
| $\hat{P}^*$            | Predicted normalised peak overpressure [–]                 |
| $R_H$                  | Hydrogen composition parameter used by Yu et al. [123] [–] |
| $Re$                   | Reynolds number [–]                                        |
| $Re_t$                 | Turbulent Reynolds number [–]                              |
| $R^2$                  | Coefficient of determination [–]                           |
| $S_F$                  | Flame speed [ $\text{m s}^{-1}$ ]                          |
| $S_L$                  | Laminar burning velocity [ $\text{m s}^{-1}$ ]             |
| $S_T$                  | Turbulent burning velocity [ $\text{m s}^{-1}$ ]           |
| $S_p$                  | Displacement of the seeding particle [m]                   |
| $T$                    | Temperature [K]                                            |
| $T_{ad}$               | Adiabatic flame temperature [K]                            |
| $U$                    | Gas velocity behind shock wave [ $\text{m s}^{-1}$ ]       |
| $U_f$                  | Velocity of the main flow [ $\text{m s}^{-1}$ ]            |
| $U_p$                  | Velocity of the seeding particle [ $\text{m s}^{-1}$ ]     |

|        |                                                                 |
|--------|-----------------------------------------------------------------|
| $U'_p$ | Measured velocity of the seeding particle [ $\text{m s}^{-1}$ ] |
|--------|-----------------------------------------------------------------|

#### Latin Symbols, lowercase

|                    |                                                                           |
|--------------------|---------------------------------------------------------------------------|
| $b$                | Wien's displacement constant ( $= 2.90 \times 10^{-3}$ ) [ $\text{m K}$ ] |
| $c_0$              | Speed of sound [ $\text{m s}^{-1}$ ]                                      |
| $d_p$              | Diameter of the seeding particle [ $\text{m}$ ]                           |
| $l_F$              | Flame thickness [ $\text{m}$ ]                                            |
| $l_I$              | Integral length scale [ $\text{m}$ ]                                      |
| $t_F$              | Chemical time scale [ $\text{s}$ ]                                        |
| $t_I$              | Integral turbulence time scale [ $\text{s}$ ]                             |
| $t_K$              | Kolmogorov turbulence time scale [ $\text{s}$ ]                           |
| $v'$               | Turbulent fluctuation [ $\text{m s}^{-1}$ ]                               |
| $u_u$              | Velocity of the unburned gas mixture [ $\text{m s}^{-1}$ ]                |
| $u_b$              | Velocity of the burned gas mixture [ $\text{m s}^{-1}$ ]                  |
| $x$                | Horizontal distance from the second obstacle [ $\text{mm}$ ]              |
| $y$                | Height from the bottom of the tube [ $\text{mm}$ ]                        |
| $\bar{u}, \bar{v}$ | Mean horizontal and vertical velocity components [ $\text{m s}^{-1}$ ]    |

#### Superscripts

|   |                      |
|---|----------------------|
| * | Normalised parameter |
|---|----------------------|

#### Subscripts

|       |                 |
|-------|-----------------|
| $max$ | Maximum         |
| $ref$ | Reference point |
| $st$  | Stoichiometric  |

# 1. Introduction

Energy is essential for economic development and human civilisation. With the development of knowledge and technology, renewable energy such as solar energy and wind energy is being increasingly used, but still the majority of the energy consumption comes from fossil fuel. Due to the unbalanced distribution of fossil fuel on the earth and, practically, the need for large energy supply in a short time, transport over long distances and the subsequent storage on a large scale becomes a necessity. Such storage sites feature a high energy density and are capable of maintaining a stable energy supply. However, it also creates huge risks to the surrounding facilities, properties and human lives in case some unexpected accidents happen. Vapour cloud explosions (VCEs) are an associated hazard that receives more and more attention. In this chapter, a general description of VCEs is given followed by the methods to estimate the possible damage. The flame propagation speed and the resulting overpressure time history are critical parameters in estimating the resulting damage, and are discussed in the context of the flame acceleration process. Studies on radiation induced ignition are reviewed due to the possible augmentation effect in VCEs. This chapter ends with an outline of this thesis.

## 1.1. Vapour cloud explosions

In large fuel storage sites, a vapour cloud can form when a leakage presents. Leakage may occur because of a facility defect, failure of a container resulting from erosion, improper or careless operation or some other unexpected reason. When a leakage occurs, flammable gases or liquids will blend with the air, forming a highly explosive cloud typically covering a large area. The amount of flammable mixture relates to the leak time. An accidental ignition source such as a spark, accumulated static electricity, or even a high temperature object can ignite the cloud, leading to a serious explosion.

Vapour cloud explosions draw increasing attention due to the devastating impact

and the frequency of such explosions. Understanding the mechanisms behind such explosions is paramount in explaining, mitigating and, ultimately, avoiding such accidents. The choice of the storage site, the design of the facilities, the materials used, etc. could all be affected by considering the impact of such explosions. Additional sensors might need to be installed to monitor the related parameters and extra safety measures might be required need to be taken in case of accidents. A risk assessment cannot be comprehensive without considering the possibility of such explosions and the related safety measures taken. A number of such explosions have occurred in the past. Strehlow [1] and Lewis [2] presented a detailed and comprehensive review, including the time, location, fuel type, leaking duration, the amount of fuel leaked, size of the vapour cloud, possible reasons, as well as injuries and casualties. These accidents happened both onshore and offshore and the leaked fuels cover a large range from very reactive fuels such as hydrogen and ethylene to less reactive fuels like propane and methane, and to mixed hydrocarbons. The damage of a vapour cloud explosion not only comes from the overpressure generated, but also from the fires that follow.

While VCEs cause tremendous losses, they also provide myriads of valuable data, which is of great help in setting light upon the mechanisms and estimating the potential damage.

## **1.2. Estimating the damage from VCEs**

Most of the vapour cloud explosions produce blast waves of various magnitude, which together with the fires that (may) follow, are the main cause of damage. The extent of the damage depends on many factors, some of the important ones are the fuel type, the amount of the substance escaped, the equivalence ratio, obstacles in the flame propagation direction and the ignition source. A qualitative description is far from enough in activities such as designing a fuel storage or carrying out a thorough risk assessment. Therefore, building models to estimate the damage quantitatively becomes a necessity.

Vapour cloud explosions are essentially very complex physical-chemical processes. The fuel type, the equivalence ratio affect the chemical reactions. The shape and size of the cloud, the ignition location and the obstacles influence the fluid dynamics. The interactions between the flame and obstacle, between the chemistry and turbulence, between flame and shock waves make it much more complex. The difficulties also lie in the wide range of time and length scales. The

actual size of the cloud is on the scale of metres or kilometres while the smallest turbulent eddy falls on the sub millimetre scale. Significant differences exist in the time scale of mixture formation and the fast chemical reactions. Further more, the cloud cannot be totally homogeneous in reality. Stratification will occur resulting from the differences in the density of the fuel and air. The state of the gas mixture might be premixed, non-premixed or partially premixed. When liquid fuel exists, evaporation has to be considered as well as multi-phase fluid dynamics.

Despite the seemingly unconquerable difficulties, a number of models are available to date to estimate the damage from gaseous explosions and they are well reviewed by several researchers [3–7]. These models can be formed into three categories, namely empirical models, phenomenological models and computational fluid dynamic (CFD) models.

Empirical models are based on experimental data and contain little or no physics. These models are usually very simple, straightforward, time efficient and do not need accurate input, but the results can be very inaccurate, or even misleading [4]. However, they are still widely used in industry because of their simplicity. The TNT-equivalency method was among the first prediction models and has been used for many years. It depicts the explosive potential of the vapour cloud by converting it to an equivalent charge weight of TNT whose blast data is known from experiments [4]. In order to calculate the equivalent weight of TNT, an empirically determined efficiency factor is used which can introduce vast discrepancies in the resulting overpressure. There also exist fundamental differences between the blast wave from a vapour cloud explosion and a TNT explosion, especially in the near field [8]. Typically, a vapour cloud explosion generates a smaller explosion overpressure with a longer duration and higher impulse than a blast wave from TNT explosions [4]. In far field, however, the TNT-equivalency method can be used to estimate the possible damage. Later, it was realised that the overpressures in VCEs are generated only by part of the cloud which is confined or partially confined and this gives a good reason for the advance of TNO Multi-Energy Method [9]. The part of the cloud that is confined or congested is modelled separately using a 1-D explosion model, in which a hemispherical cloud of stoichiometric concentration and a constant flame speed is assumed. If there are more than one part of the cloud that is confined or congested, then they should be modelled separately. The difficulty in this method lies in the estimation of the initial blast wave. Apart from these two commonly used methods, there are many other models available such as the Baker-Strehlow Method, the Congestion Assessment Method and the Sedg-

wick Loss Assessment Method as summarised in the Health & Safety Laboratory report by Lea and Ledin [7].

Phenomenological models are simplified models which include only the essence of the physics of an explosion. Detailed conservative equations are not solved, but rather empirical correlations are used. The geometry is generally quite simple, usually a rectangular chamber with turbulence generating grids to represent the obstacles. In terms of both the cost of the simulation results, it falls somewhere between empirical correlations and CFD simulations. The SCOPE (Shell Code for Overpressure Prediction in gas Explosions) model is one such model developed by Shell Global Solutions [10]. Explosions in venting conditions can be modelled with the external explosion considered. The turbulent burning velocity is calculated based on experimental correlations while the flame surface area enhancement after passing the grid is based on CFD results. Further details of this method, the basic differential equations, empirical correlations and the hierarchical structure of the model are given by Puttock et al. [10,11]. Lowesmith et al. [12] used this model with slight modifications to predict the explosion overpressure and the flame speed in vented confined explosions involving methane/hydrogen mixtures and good agreement was found with the experimental results. One drawback linked with this model is that it can only calculate the scenario where ignition occurs at the rear end of the closed chamber opposite side of the vent. CLICHE (Confined LInked CHamber Explosion) code is another phenomenological model developed by Advantica Technologies Ltd. [7], which is capable of predicting the overpressure from explosions where a sequence of chambers are interlinked. Besides, there is no restriction on the ignition location, making it more closely related to a practical explosion scenario.

Computational fluid dynamics models simulate explosions by numerically solving all the conservative equations within a discretised domain. The advantage over the previous two is that it can give the largest amount of information on the flow field, the velocity, the temperature, density and, of course, the pressure. Such methods can in principle model the real geometry without simplification. The precision is also the highest among the three. However, it is very time consuming and needs powerful computing sources, which makes it infeasible for large scale plants or fuel storages. Furthermore, the physics and chemistry applied in such models remain conjectural.

The flame speed is an important parameter in all models. The explosion overpressure is generally accepted to be proportional to the heat release rate, which is



directly related to the flame speed. Therefore, the flame acceleration in an explosion scenario is extremely important for an accurate estimate of the damage and a detailed, comprehensive description of the flame acceleration is necessary.

### **1.3. Flame acceleration leading to explosions**

In a vapour cloud explosion, it is generally assumed that ignition occurs at a single point and is followed by coherent flame propagation through the rest of the cloud. The chemical energy stored in the fuel is released in the combustion process. The rate of energy release and the extent of potential damage is thus related to the consumption rate of the fuel, which is directly related to the burning velocity, the speed at which the flame front moves, normal to its surface relative to the unburned gas mixture [13].

Typically, the flame in an explosion propagates in two distinct modes, known as deflagration and detonation. In deflagrations, the flame propagates at subsonic speeds, and the propagation is governed by (turbulent) heat transfer and diffusion. No appreciable changes in pressure are observed in low speed deflagrations. In detonations, however, the flame propagation can reach speeds from 1000 to 3500 m/s depending on the mixture. The chemical reactions in a detonation are triggered by the fast compression of the flammable gases and the resulting temperature rise from the shock wave. The detonation wave is in turn sustained by the energy released from the chemical reactions. The detonation velocity for stoichiometric hydrocarbon mixtures is roughly 2000 m/s. The high overpressure associated with the high flame speed can cause devastating damage [13].

Detonations can be triggered indirectly via a weak ignition followed by flame acceleration and transition from deflagration to detonation (DDT) or directly by a strong ignition source. Most of the VCEs in history did not involve a detonation except two possible cases, Port Hudson and Bruailles incidents [4]. In the former one, a dense, stable and slowly dispersing cloud of propane of about 60 tonnes, covering an area of 10 acres, was formed [2]. It was ignited after around 24 min by a refrigerator spark in a concrete blockhouse and the venting of the explosion provided a strong and turbulent ignition source for the remaining cloud, which triggered the possible detonation, or quasi-detonation. In the Bruailles incident, ethylene, which is highly reactive and has a wide detonable limit, was leaked. The leak was from a high pressure pipeline, therefore the ignition probably occurred in highly turbulent conditions, which would favour the transition to detonation [4].

Starting from an initial flame kernel, where the flame propagates at the laminar burning velocity, typically less than 1 m/s, to the final fast deflagration or detonation, where the flame travels at a few thousand m/s, numerous factors can attribute to the flame acceleration process.

Considering a freely propagating flame in a laminar flow, the flame speed normal to its surface relative to the unburnt gas is called the laminar burning velocity [14]. It is a property of the mixture alone and mainly depends on the gas type, equivalence ratio, initial temperature and pressure as well as the stretch caused by the flow. For most hydrocarbons, the laminar burning velocity is in the range of 0.3 – 0.7 m/s. This is the velocity at which a fixed observer would see a flame travel through a stagnant mixture in a fully open-ended tube. The mass conservation across the flame front gives

$$\rho_u S_L = \rho_b(u_u + S_L - u_b) \quad (1.1)$$

in which,  $u_u$  and  $u_b$  are the velocities of the unburned and burned gas respectively,  $\rho_u$  and  $\rho_b$  the corresponding density and  $S_L$  the laminar burning velocity. The expansion ratio  $\tau$  is defined as

$$\tau = \frac{\rho_u}{\rho_b} - 1 \quad (1.2)$$

Substitute into Eq. (1.1) and we have

$$u_u = u_b + \tau S_L \quad (1.3)$$

In cases where the burned gas is prevented from moving, for instance, the centre-ignited VCEs and flame propagation from the closed end of a tube (the case in the current experiment),  $u_b = 0$ , thus

$$u_u = \tau S_L \quad (1.4)$$

A fixed observer would see the flame travel at the burning velocity augmented by the expansion ratio. A typical value for the expansion ratio would be 7 so that laminar flame speed is in the range of 2 – 5 m/s.

Turbulence plays an important role in the flame acceleration. Turbulent combustion, until today, remains one of the most intensively studied but least understood phenomenon in combustion research [15]. Turbulent flow is characterised by vor-

tices of various scales. The energy is transferred from large scale eddies to smaller ones down to the Kolmogorow scale where the energy is consumed by friction. These eddies can wrinkle, penetrate and even tear the flame front, enlarging the flame surface area and the burning velocity considerably. The interactions between the turbulent eddies and flame structure characterise turbulent combustion into several combustion regimes [16]. The eddies also enhance the mixing process and promote heat and mass transfer, which also results in an increase in the burning velocity.

The turbulent burning velocity, defined as the approach velocity of the turbulent flame brush relative to the unburned mixture, unlike the laminar burning velocity, largely depends on the flow condition, i.e. the turbulence intensity [14]. It is a fundamental and paramount parameter in turbulent combustion and considerable amount of effort has been devoted regarding to the definition, measurement, correlation and prediction of the turbulent burning velocity [17–20].

Obstacles in the propagation path can accelerate the flame considerably by introducing turbulence in the recirculation zone behind the obstacle. Turbulence will increase the rate of heat release due to interface wrinkling resulting in an increased flame front area. The result is an increase in the flow velocity, in turn, causing stronger turbulence, which further increases the rate of heat release. This positive flame acceleration feedback mechanism has been well established [21, 22]. Meanwhile, the geometrical increase of the flame surface also plays a role in obstructed channels [15]. In earlier work, Chapman and Wheeler [23] photographed the  $\text{CH}_4/\text{Air}$  flame propagation in a round tube with and without restrictions, finding that the flame accelerated significantly faster in the case with restrictions. Moen et al. [21] obtained flame speeds up to 130 m/s in stoichiometric methane-air mixtures – around  $\sim 24$  times the flame speed observed in the absence of obstacles. Wang et al. [24] studied the influence of blockage ratio in flame acceleration and reported that a larger blockage ratio benefits the flame acceleration accompanied by a stronger heat dissipation, so the final effect relies on competition between the two factors. Shchelkin spirals [25, 26] were used by Lindstedt and Michels [27], showing an improved performance in flame acceleration due to the reduced momentum losses. Na'inna et al. [28] and Gamezo et al. [29] reported that the separation distances of obstacles have a significant influence on the flame propagation speeds. Chan et al. [30] further investigated the effect of the confinement in an obstructed rectangular channel with a top perforated plate featuring different opening areas to provide different degrees of confinement. The results show that

flame acceleration in an obstructed tube was compromised by the venting. A quantitative description of the flame-obstacle interaction was given by Sakthitharan [31] and Lindstedt and Sakthitharan [32]. Time resolved velocity measurements were carried out using Laser Doppler Anemometry (LDA) in a rectangular tube with a baffle-type obstacle. Turbulence production and the dissipation rate of the turbulence were estimated. The turbulence within the recirculation zone behind the obstacle was found to be essentially isotropic while anisotropic turbulence was observed within the shear layer at the time of the flame arrival. The peak pressure observed coincides with the final burnout of the gas pocket behind the obstacle.

The enhancing effect of obstacles is significant, but the flame speed slows down immediately after the obstacle as pointed out by Moen et al. [21]. Lee et al. [33] studied the flame acceleration in a round tube consisting of a three-meter's obstacle section close to the ignition followed by an eight-meter smooth obstacle-free section. Hydrogen diluted with air was used with  $H_2$  concentrations from 10% to 45%. Different obstacles including Shchelkin spirals and orifice plates with various blockage ratios were used. Flame acceleration was observed for all cases in the obstacle section. Upon entering the obstacle-free section, a remarkable drop in the flame speed was observed for hydrogen concentrations up to 20% although the flame may re-accelerate later in the smooth tube or decay depending on the hydrogen concentration. For  $H_2$  concentrations larger than 25%, no deceleration was observed because a quasi-detonation (see next page for its definition) had already been achieved in the obstructed section.

Repeated obstacles, however, can accelerate the flame speed continuously and even trigger a transition from deflagration to detonation [27,34–36]. Lee et al. [37] studied this phenomenon thoroughly with a wide range of hydrocarbon-air mixtures in tubes of different diameter and different blockage ratio. A steady-state terminal flame speed was believed to be achievable in obstructed tubes, based on which, four regimes were determined, the choking, quasi-detonation, Chapman-Jouguet (C-J) detonation as well as the quenching regime [38]. Kuznetsov et al. [39] photographically visualised the turbulent flame propagation and different regimes in obstructed tubes. In the choking regime, the flame accelerated to a terminal velocity at the order of the sound speed in the combustion products, i.e. 600 – 1000 m/s. Ciccarelli and Dorofeev [15] pointed out that in a smooth tube, a flame accelerating to such a flame speed usually transits to a detonation, while in obstructed tubes, the turbulence can sustain such a flame velocity without DDT. The shock wave ahead of the flame front in this regime dispersed in all directions due

to the complex reflections from the obstacles. Chue et al. [40] proposed that this complex shock-flame structure can be modelled as a Chapman-Jouguet deflagration and argued that flame propagation in this regime was more governed by the mixture energy content rather than turbulent transport rates. This is supported by the experimental observations that the tube diameter and wall roughness does not affect the final steady flame velocity. Another regime is the quasi-detonation regime, where the flame propagates at close to the C-J velocity, but with a deficit and the larger the blockage ratio, the larger the velocity deficit. The deficit is expected to be caused by the enhanced heat and momentum loss associated with the obstacles since in a smooth tube, the velocity deficit is very small, about 1% – 2% due to the boundary layer effects [15]. Further acceleration leads to the normal C-J detonation regime where a shock wave is formed and coupled with the reaction zone immediately after it. The quenching regime, in the experiment of Lee et al. [37], refers to the case where the flame became fully quenched after travelling a short distance. This regime occurs for large blockage ratios and mixtures approaching the flammable limits. These regimes have also been observed by other researchers using different fuels and configurations (e.g. [22, 29, 33, 41–45]).

In the experiments carried out by Kuznetsov et al. [46,47], a slow subsonic flame propagation ( $\sim 100 - 200$  m/s) was observed besides the choked flame and detonation, therefore, they categorised the flame acceleration as weak or strong. A set of parameters were considered to be important in the flame acceleration behaviour, such as the expansion ratio, ratio of specific heats, Lewis number, Markstein number and Zeldovich number [15]. A categorisation based on the expansion ratio and Zeldovich number appeared promising [15].

Bradley et al. [48, 49] recently suggested that there is another feedback mechanism promoting the flame acceleration process and it is more profound at high flame speeds. The expansion of the combustion products builds up a shock wave ahead of the flame front and there will be a sharp temperature rise in the unburned mixtures when the shock wave passes. The mixture reactivity will increase due to the temperature rise and so the turbulent burning velocity. Besides, there will be a tendency for the Markstein number to decrease [50], which also increase the turbulent burning velocity. The increased flame speed will further increase the strength of the shock, which in turn increases the temperature rise. This mechanism becomes more important as the flame speed increases, because the pressure ratio associated with a slow flame is marginal.

Turbulence can increase the flame speed by increasing the flame surface area

and the transport of the local mass and energy, but cannot increase to infinity. When the turbulence intensity exceeds a certain level, quenching begins to have an impact, which will compromise the flame acceleration. The burning velocity can be enhanced by turbulence to a limited level of 10 – 20 times the laminar burning velocity [15]. Bradley et al. [48] theoretically calculated the maximum turbulent burning velocity a certain mixture can achieve and the findings agreed well with the experimental results. The likelihood of DDT has also been estimated by calculating the autoignition time of the mixture after the shock wave.

Flame instability also plays an important role in turbulence generation and flame acceleration [50,51]. A planar flame is intrinsically unstable because of the Landau-Darrieus (L-D) instability [52, 53]. The hydrodynamic effects associated with the expansion of the combustion products cause the initial slightly curved flame to become more curved. A linear analysis reveals that the flame front is unstable to perturbations of any wavelength, while the rate of growth is inversely proportional to their wavelength, which means that small flame wrinkles grow faster than the larger ones [54]. Another one is the diffusive instability which is caused by the unbalanced diffusion of heat and mass. For a mixture with  $Le < 1$ , such instabilities can increase the curvature of a slightly curved flame front and lead to unstable flames. While for mixtures with  $Le > 1$ , it has the effect of smoothing the flame wrinkles and stabilise the flame. In obstructed channels, the effects of L-D and diffusive instabilities are relatively weak compared to Kelvin-Helmholtz (K-H) and Rayleigh-Taylor (R-T) instabilities and the former might only play a role at the initial stage of the flame propagation [15]. The K-H instability is associated with shear flow featuring a large velocity difference across the interface [55]. The displacement flow due to the expansion of the combustion products can attain high Re numbers [32], under which the sheared interface evolves into well-defined concentrated vortices [56]. The R-T instability develops when a lighter fluid is accelerated towards a heavier fluid [57,58]. Keenan et al. [59] introduced R-T instability as an additional time-dependent combustion enhancing mechanism into the modelling of premixed deflagrations, which led to closer agreement with experimental results. In obstructed channels, both K-H and R-T instabilities are triggered when the flame is suddenly accelerated over an obstacle, leading to enhanced flame surface area and burning velocity.

## 1.4. Radiation induced ignition of explosions

Particles subjected to strong radiation can cause ignition of the surrounding explosive atmosphere and this could potentially augment the damage in large scale vapour cloud explosions via additional multi-point explosion kernels. It can also potentially increase the risk in mine industries since optical fibres have been increasingly used for monitoring and remote control. Should a defect occur on the fibre, the light emerged could cause serious explosions [60]. Radiation effects are also expected to be of potential importance in dust explosions [60, 61].

Moore and Weinberg [62] first proposed the radiation induced multi-point ignition mechanism, which tries to explain the unexpected high overpressures in the 1974 Flixborough explosion. They stated that the forward thermal radiation from hot combustion products in large vapour cloud explosions can cause multi-point ignition ahead of the flame front via suspended particles, and therefore increase the overall flame propagation speed considerably, leading to higher overpressures. Later in their experiments, ignition was successfully achieved in propane/air mixtures using a continuous wave (CW) CO<sub>2</sub> laser (operating at 10.6  $\mu\text{m}$ ) with a uniform radiation flux of up to 400 kW/m<sup>2</sup> over an area of 7.1 mm<sup>2</sup> [63, 64]. The lowest radiation flux that achieved ignition was 100 kW/m<sup>2</sup>. By contrast, the black body radiation from a stoichiometric flame was estimated [62] to be in the order of 1 MW/m<sup>2</sup> assuming a flame temperature of 2000 K and unit emissivity. Adler et al. [65] further extended the experiment using stoichiometric mixtures of a range of hydrocarbons as well as of diethyl ether, carbon disulphide and hydrogen. The results were presented in the form of the minimum flux as a function of the ignition time. The minimum radiation flux was surprisingly low at 22 kW/m<sup>2</sup> for carbon disulphide–air mixtures. Stamatov et al. [66] showed that the ignition delay was inversely proportional to the radiation flux in methane/air mixtures using a AR+ laser operating at 514.5 nm to ignite alumina particles. Beyrau et al. [60] and Hadjipanayis [67] used a CW laser diode operating at 808 nm  $\pm$  2 nm to investigate radiative ignition in the atmosphere of butane–air mixtures. Possible ignition was shown for a range of carbon based materials including different carbon blacks, graphite, the C<sub>60</sub> fullerene and diamond powder, as well as for non-reactive powders such as silicon carbide, iron-, copper- and silicon oxides. The ignition time decreased with an increase in the irradiance and the shortest ignition time was about 20 ms for acetylene black particles at an irradiance of 1.6 MW/m<sup>2</sup>. Comparatively, Hardee et al. [68] recorded a radiation flux of the order 450 kW/m<sup>2</sup>

in CH<sub>4</sub>-air LNG fireballs, while Roberts [69] reported values in the range 140 – 450 kW/m<sup>2</sup> in LPG fire balls. Direct measurements by Roberts et al. [70] showed a maximum surface emissive power up to 556 kW/m<sup>2</sup> in a 1708 kg LPG non-premixed fireball. Holbrow et al. [71] measured the thermal radiation from fireballs caused by dust explosions. Six types of dust were used and average surface emissive powers of 227 kW/m<sup>2</sup> and 2900 kW/m<sup>2</sup> were obtained for coal and aluminium dust, respectively. The radiance on particles suspended ahead of a flame front also strongly depends on the presence of soot, the flame temperature and, to a lesser extent, the burnt gas composition. The influence of soot, fuel type, fuel-air ratio as well as combustion pressure has been investigated by Lefebvre [72]. Hadjipanayis et al. [73] estimated flame radiation from the major combustion products (H<sub>2</sub>O and CO<sub>2</sub>) and a sensitivity analysis was performed to assess the impact of the equivalence ratio, mixture pressure, flame temperature and soot fraction. It was shown that the emissivity of gas-soot mixtures is mainly determined by the soot concentration and to a lesser extent by temperature.

The particle size was found to have a significant impact on the time to ignition. Specifically, finer particles led to shorter ignition times due to the higher surface area to volume ratio which was found to reduce both particle and gas heating times. Hadjipanayis found that finer particles feature an increased rate of temperature rise under radiation [67].

Flammable particles and non-flammable particles can behave differently. Moore and Weinberg [63,64], based on the ignition behaviour of cotton wool (flammable) and Kaowool (non-flammable), concluded that for lower radiation fluxes, flammable particles ignited first while for larger radiation fluxes, non-flammable particles ignited first. Further more, non-flammable particles can ignite propane/air mixtures almost throughout its flammable range while for flammable particles, ignition could not be achieved near the rich limit. The reason was attributed to the volatilisation of the particles, which forms a layer of gases beyond the rich limit around the particles. Hadjipanayis [67] found similar results that ignition could be achieved across the whole flammability range of butane/air using silicon carbide particles, while near the rich flammability no ignition could be obtained with carbon black. Beyrau et al. [74] suggested that for inert particles, this radiation induced ignition is intrinsically thermal ignition and thus the temperature plays a key role, while for reactive particles, it becomes complex because evaporation and surface chemistry could have an impact. Time-resolved temperature measurement under irradiance was carried out by Beyrau et al. [74] using emission spectroscopy



concerning that the rate of the temperature rise and the equilibrium temperature could directly relate to the ignition time. The ignition temperature was measured with two different ignition regimes observed by comparing the temperature history under radiation in both inert and explosive atmosphere. For non-reactive powders, the ignition temperature falls within the range  $1200 \pm 200$  K obtained from powders with different particle sizes while for reactive powders, temperature appears not to be the sole ignition criteria.

The above mentioned studies feature a relatively large radiation area compared to the quenching dimension. Concerns on ignition caused by optical fibres leads to other studies where particles are mounted onto the fibre tip directly, characterising a much smaller radiation area. Hills et al. [75] and Zhang et al. [76] experimentally ignited more than 300 gas/air mixtures using a CW Nd:YAG laser operating at  $1.06 \mu\text{m}$  as the radiation source. Both single-mode and multi-mode fibres were used to deliver the laser beam with particles of Appin coal at different sizes tested. No explosion was achieved in hydrogen/air mixtures using single-mode fibre because of the limited maximum power about 300 mW. When 100/140  $\mu\text{m}$  multi-mode optical fibre was used, ignitions were achieved typically within 100 ms of illumination. They also examined the minimum power needed to ignite coal particles of 38 – 45  $\mu\text{m}$  using a 50/125  $\mu\text{m}$  optical fibre and a minimum power of 100 mW was found for hydrogen/air mixtures with 10% – 15% hydrogen. The minimum power increased sharply near the lower flammable limit of 4%. A theoretical model was built to predict the ignition in hydrogen/air mixtures with the ignition marked by the occurrence of a positive temperature gradient near the particle surface [75]. This model predicted that the minimum optical power needed increased rapidly for particles less than 10  $\mu\text{m}$  and larger than 60  $\mu\text{m}$  which was not in good agreement with experimental data indicating no clear relationships. The predicted optimal hydrogen/air concentration of 13% for ignition with 40- $\mu\text{m}$  particles agreed well with the experimental results of 10% – 15%. Dubaniewicz et al. [77,78] studied the ignition in methane/air mixtures with the minimum energy and time delay compared. A mixed manganese oxide ((FeMn)<sub>2</sub>O<sub>3</sub>) with a particle size of 0.6  $\mu\text{m}$  and black iron oxide with an average particle size of 0.4  $\mu\text{m}$  were used. Coal dust with a volatility of 37% and ash content of 6% was also tested. It was found that using single-mode fibres, threshold ignition delay was approximately proportional to the inverse square of the igniting power. The smaller core fibres required lower incident power for ignition than larger core fibres, but larger power density.

## 1.5. Thesis outline

This thesis is divided into six chapters beginning with a general description of vapour cloud explosions. The flame acceleration process is discussed, focusing on the enhancing effect of obstacles as a result of the importance of turbulence. The augmentation of radiation induced ignition in large vapour cloud explosions cannot currently be ruled out and thus a review was also presented in Chapter 1.

Chapter 2 elaborates the experimental facilities used in this thesis. The basic facilities, a flame tube and the associated components, are introduced first. A different configuration, specifically for the radiation induced ignition experiments, is presented in the second section. A high-speed particle image velocimetry (HS-PIV) setup is given afterwards with the measurement uncertainties analysed. The chapter finishes with a description of the experimental procedure.

In Chapter 3, explosion overpressure and flame speed resulting from hydrogen enriched binary ( $\text{H}_2/\text{CO}$  and  $\text{H}_2/\text{CH}_4$ ) and ternary fuels ( $\text{H}_2/\text{CH}_4/\text{CO}$ ) are presented. The significantly different behaviours of CO and  $\text{CH}_4$  blended with hydrogen is highlighted. Scalings of the peak explosion overpressure are explored based on a newly proposed mixture composition parameter ( $\beta$ ) and acoustic theory.

Chapter 4 presents the results of radiation induced ignition experiments. The radiation ignition time scale was first explored under quiescent conditions using fuel lean  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures with different hydrogen concentrations. The influence of the secondary radiation induced ignition kernel on the overall explosion overpressure development is discussed thereafter, focusing on the impact of radiation induced ignition location and ignition delay time ( $\tau_{ig}$ ). The flame speed and pressure impulse are also included due to the relevance in assessing the explosion severity.

In Chapter 5, high speed particle image velocimetry (HS-PIV) measurements in the critical recirculation region behind an obstacle are presented. Both CO and  $\text{CH}_4$  blended with  $\text{H}_2$  were used considering the significantly different explosion behaviour presented in Chapter 3. Time-resolved velocity data was obtained with the influence of mixture reactivity studied. The comprehensive dataset obtained shows the links between the flow field, flame speeds and the resulting overpressure.

Finally, Chapter 6 concludes the present study and gives suggestions for future work.

## 2. Experimental configurations

Any experimental configuration is mainly determined by its purpose, the parameters to be measured and the corresponding measurement techniques. It is also restricted by the available space, safety considerations as well as cost. In this thesis, three main objectives to be achieved are (a) the quantitative of the explosion behaviour (overpressure and flame speed) of hydrogen enriched fuels, (b) the impact of radiation induced ignition in turbulent explosions, (c) the quantification of the flow field development in turbulent explosions. This chapter accordingly describes the corresponding experimental configurations in three sections, the basic facilities, the instruments for radiation induced ignition and the high-speed particle image velocimetry (HS-PIV) setup for flow field measurement. The last section in this chapter lists the experimental procedure.

### 2.1. Basic experimental facilities

The basic experimental facilities consist of the following components:

1. A flame tube facility capable of replicating laboratory scale explosions safely and reproducibly.
2. A gas mixing system to prepare homogeneous premixed flammable mixtures of given composition.
3. An ignition device to initiate the flame propagation.
4. Basic measurement instruments including pressure transducers and ionisation probe detectors.

The general layout out of the experimental system is shown in Figure 2.1.

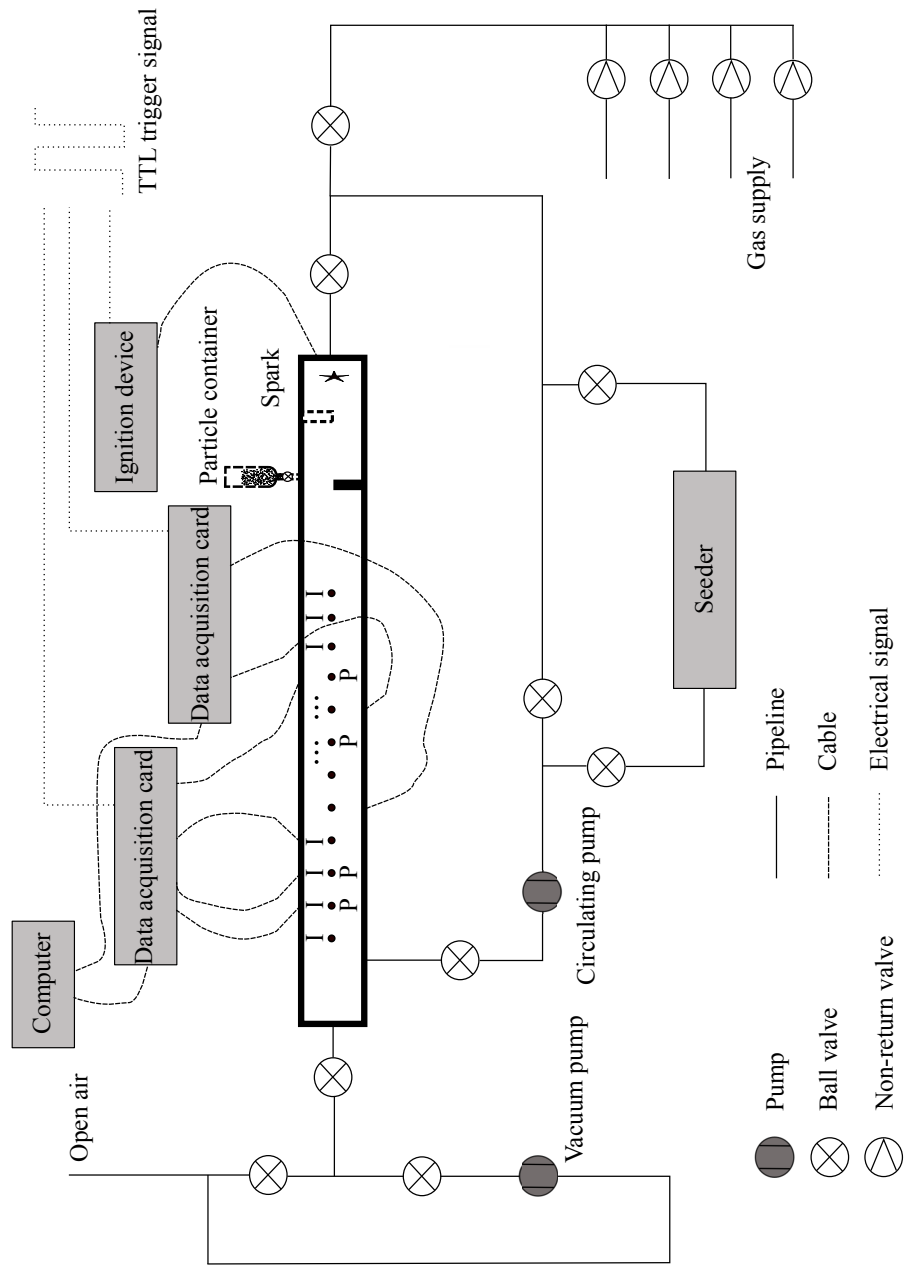


Figure 2.1.: General layout of the flame tube facility (P – Pressure transducer, I – Ionisation probe detector). The locations of the obstacles and particle container are indicated above. The seeder was used only in the HS-PIV experiments.

### 2.1.1. Flame tube

A flame tube with a rectangular cross-section area of  $72 \times 34$  mm and a total length of 4400 mm was used in this experiment. Figure 2.2 shows a picture of the flame tube fixed onto height-adjustable tables. The tube is made up of four parts: two interchangeable optical sections of length 400 mm and two longer driven sections of length 1800 mm. The optical section is made of copper and can be fitted with high-quality fused silicon glass windows on both sides if optical access is needed. The rectangular cross-section characteristic allows an optical access without introducing additional difficulties associated with the light refraction at the glass surface into the interpretation of the results. It also offers a (close to) two-dimensional flow field facilitating measurement and model simulation. There are three ports on both top and bottom of each optical section that can be used to accommodate pressure transducers, ionisation probe detectors, cross fractal grids [79] or obstacles. The two longer flame-driven sections are made of copper with aluminium shield outside and round ports located along the centreline of the side walls to install pressure transducers and ionisation probe detectors (see Figure 2.2).

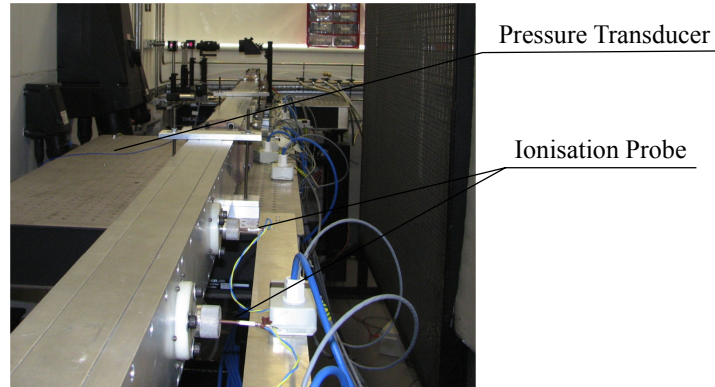


Figure 2.2.: Image of the flame tube facility.

The length to diameter ratio ( $L/d$ ) is an important parameter in flame propagation studies. The pressure back-reflection waves from the closed non-ignition end of the tube will interact with the forward propagation flame and lead to highly chaotic, non-reproducible results. Therefore, the  $L/d$  ratio must be large enough to allow measurement to be taken before the arrival of the pressure back-reflection. The current tube features a  $L/d$  ratio of 95, ensuring a long enough acoustic time scale to permit undisturbed and reproducible results within the region of measurement. In the configuration used for the radiation induced multi-point ignition

experiments, another section with a length of 2818 mm was added, enlarging the L/d ratio to 156 and providing a longer measurement time without being affected by the pressure wave reflected from the downstream closed end. Details of the modification are given in Section 2.2.1.

### **2.1.2. Gas mixing system**

In combustion experiments, the composition of the gas mixture is critical for reproducibility. Small variations in the equivalence ratio or for a specific gas component, e.g. hydrogen, may result in large uncertainties. In the current experiment, the flame tube not only serves as the flame propagation vessel, but also as the mixing chamber. The explosive atmosphere was created using bottled gases of CO (purity 99.999%), CH<sub>4</sub> (purity 99.5%) and H<sub>2</sub> (purity 99.99%) diluted with filtered air. A partial pressure method was adopted in the preparation due to the simplicity in implementation yet high accuracy [67, 80]. The fuel components were injected first to the required partial pressure and dry filtered air was added finally to the required initial pressure. The injection process was controlled via digital mass flow controllers (Bronkhorst UK LTD) [81]. The opening and closing of the flow controllers are automatically adjusted based on the real-time pressure inside the tube monitored by a static pressure transducer (UNIK 5000; GE Measurement & Control). Leak tests were performed on a regular basis to ensure identical conditions throughout the entire measurement and the leak rate was  $< 16$  Pa/s compared to a filling time less than 60 s.

After injecting the gas components, homogenisation was achieved by circulating the gas mixture via an ATEX rated circulating pump (MD 4C EX; Vacuubrand) for five minutes corresponding to 28 flame-tube-volumes. In the radiation induced ignition experiment, the flame tube was extended (see Section 2.2.1) and the circulation time was increased to ten minutes corresponding to 23 flame-tube-volumes.

### **2.1.3. Ignition device**

A standard electronic ignition device (Sparkrite SX1000; EDA Sparkrite, Ltd.) with an energy release of 5 mJ [80] was installed at one end of the tube as indicated in Figure 2.1. It consists of a spark plug and a power supply of 12 V. The spark plug protrudes the solid surface by 55 mm and all the subsequent measurement of the location, e.g. the location of the pressure transducer, is the distance to the spark plug rather than to this end of the tube. The spark was triggered by a standard

TTL signal of 5 V, which also triggered all the data acquisition cards to achieve synchronised measurement. When camera was used (radiation induced ignition experiment and HS-PIV measurement), the same TTL signal was also used to trigger the recording sequence.

#### **2.1.4. Pressure transducers**

The explosion overpressure was measured using four piezoelectric pressure transducers ( $1 \times$  PCB 113A21 and  $3 \times$  PCB 113B21; PCB Piezotronics, Inc.) installed along the flame tube. The transducers are made of acceleration-compensated rigid quartz elements, manufactured to eliminate resonance and are well suited to measure dynamic pressures in explosion scenarios. They provide virtually noise-free, clean and high resolution signals at a frequency of 1 MHz. Another major advantage of these transducers is that there are no ringing effects even with sudden appreciable changes in pressure, as may be expected in transient flame propagation [31]. The pressure transducers are accommodated in plastic plugs and then fixed to the flame tube. Silicone rubber coating was applied manually with a thickness of  $\sim 0.3$  mm to thermally insulate the diaphragm to minimise the change in offset voltage caused by the temperature variations since the pressure transducer surface is exposed to high temperatures when the flame travels past it. The coating lasts for approximately 400 runs (experiments) before starting to peel off the surface. The sudden pressure drop after the flame passed measured without the coating was eliminated after coating with silicone rubber as shown by Sakthitharan [31]. The transducer with the silicone rubber coating can also avoid the drift in the offset voltage caused by the thermal effects [31]. The signals from the transducers are amplified, digitised and then stored in a microcomputer for further analysis.

#### **2.1.5. Ionisation probes**

Ionisation probe detectors were mounted along the tube to measure the flame arrival times and the flame propagation speed can readily be obtained by dividing the distances between two consecutive probes by the corresponding differences in the flame arrival time. The ionisation probes are made of coaxial stainless steel cable with an outer diameter of 1.5 mm and the resistance  $> 10 \text{ M}\Omega$  between the core and the sheath [31]. The circuit was developed and successfully used by Lindstedt [80] and Lindstedt and Michels [82] with a positive electrode collector

and a bias of 125 V applied across the coaxial cable. The results of ionisation within a flame cause a current flow across the probe and a pulse is generated via the custom-built amplifier. The probes are mounted within PTFE plugs which are then fitted into the ports along the tube. The use of PTFE plugs ensures shielding of the probes from direct electrical interference transmitted via the flame tube.

## **2.2. Configuration for radiation induced multi-point explosions**

Based on the review on radiation induced ignition in Chapter 1, and considering the possible magnitude of radiation level as well as the likelihood of the appearance of suspended particles, the radiation induced ignition mechanism cannot currently be ruled out, which leads to the current experimental study. In the previous studies on radiatively ignition, both open and enclosed geometries have been used. Moore and Weinberg [63, 64] used a premixed propane-air burner with the particles suspended at the burner mouth via a fine quartz fibre. Later Adler et al. [65] employed a water cooled porous plug burner to provide the flammable atmosphere. A spherical explosion chamber with a volume of 0.5 L was used by Stamatov et al. [66] with the particles held in the centre. Enclosed chambers with volumes of 2 L, 8 L and 20 L were used by Hills et al. [75], Zhang et al. [76], Welzel et al. [83] and Dubaniewicz et al. [77, 78], respectively. Beyrau et al. [60] and Hadjipanayis [67] used an initially confined chamber sealed with a thin aluminium foil, which was ruptured upon ignitions, to study the radiatively ignition performance of a number types of particles in the atmosphere of butane and air.

In this experiment, the focus is on the possibility of radiation induced ignition via soot, as an example of dust particles, trapped in corners around obstacles and their subsequent entrainment into the adjacent recirculation zone as well as the pressure development. Such particles can potentially be present or transported by pressure waves propagating ahead of a flame front and then trapped in more stagnant regions. In order to achieve this, the following requirements on the experimental facility have to be met:

1. Reproducible preparation of homogeneous explosive mixtures of specified composition.
2. A closed chamber allowing laboratory scale explosions to happen.



3. A sufficient long test time free of the interference from the pressure back-reflections.
4. Capability of generating turbulence in the irradiated region.
5. Injecting the particles into an explosive atmosphere safely with high repeatability.
6. Optical access to allow the passing-through of laser beam and recording of the flame evolution.

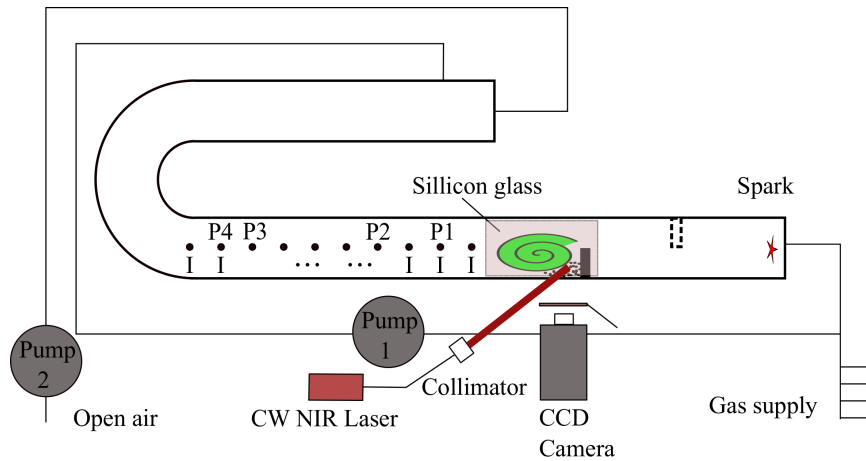


Figure 2.3.: Schematic of the experimental setup for radiation induced ignition (P – Pressure transducers, I – Ionisation probe detectors).

### 2.2.1. Modification of the flame tube

The original flame tube (see Section 2.1.1) was modified to fulfil the radiation induced ignition experiment according to the requirements mentioned above. An end-section with a total length of 2818 mm, featuring a round cross-section with an inner diameter of 89 mm was added to the original tube to provide a longer test time free of reflected pressure waves from the closed downstream end. One solid obstacle with a thickness of 5 mm and a height of 36 mm, offering a blockage ratio of 50%, was installed at a distance of 400 mm from the ignition end to generate turbulence. For one experimental series, an identical second obstacle was installed on the top wall at a distance of 80 mm from the ignition to enhance flame propagation. A silicon glass (268 (W)  $\times$  72 (H)  $\times$  25 (D) mm) was installed on one side of the optical section to allow recording and an infrared laser beam was directed

through this window upon the particles. The setup is schematically shown in Figure 2.3 with the dimensions of the modified flame tube shown in Figure 2.4. Ten ionisation probes were used to measure the flame arrival time and four pressure transducers were installed to record the pressure development with their locations specified in Table 2.1.

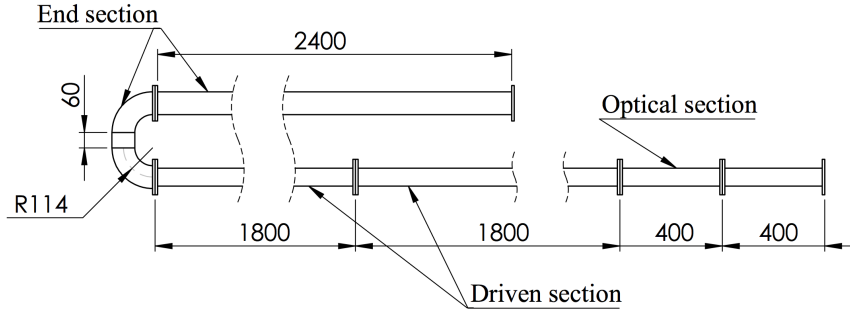


Figure 2.4.: Dimensions of the modified flame tube (unit: mm).

Table 2.1.: Locations (X) of pressure transducers (P) and ionisation probe (I) detectors from the ignition point.

| X [m]  | 0.600 | 0.845 | 1.075 | 1.305 | 1.535 | 1.765 | 2.000 | 2.225 | 3.145 | 3.450 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sensor | I     | P1+I  | I     | P2+I  | I     | I     | I     | P3+I  | P4+I  | I     |

### 2.2.2. Particle injector

In the experiment, the radiation induced ignition time scale plays a critical role. To remove any possible side effects associated with heat transfer at the boundary of the agglomerate, enough particles were irradiated, leaving the controlling factors to be the radiation power and mixture reactivity. The drawback associated is that not all the particles are consumed during the combustion and some particles will be dispersed by the pressure wave and stick onto the silicon glass window. Therefore, the glass window needs to be cleaned every run to prevent the laser power from being affected by contamination. The impact of radiatively ignition location was explored by igniting both downstream and upstream of the obstacle (see Chapter 4). When ignited downstream, the particles can be introduced before closing the window. However, in the case of upstream ignition, the particles will be blown away during the mixture preparation and thus a particle injector, schematically shown in Figure 2.5, was designed to inject the particles. An explosive-proof device is extremely important, because the particles are injected into highly explo-

sive atmosphere. A pneumatic valve was accordingly used to prevent any possible electric spark. The working gas of the valve was supplied using a N<sub>2</sub> cylinder at 8 bar. A Burkert solenoid controller, which is also ATEX rated, was used to control the pneumatic valve. The volume of the injector is around  $2.8 \times 10^{-3}$  L, which is negligible compared to a volume of 0.37 L in the critical recirculation region behind the obstacle (the total volume of the flame tube is 28.3 L), therefore, the (local) inhomogeneity introduced during the particle injection is inconsequential.

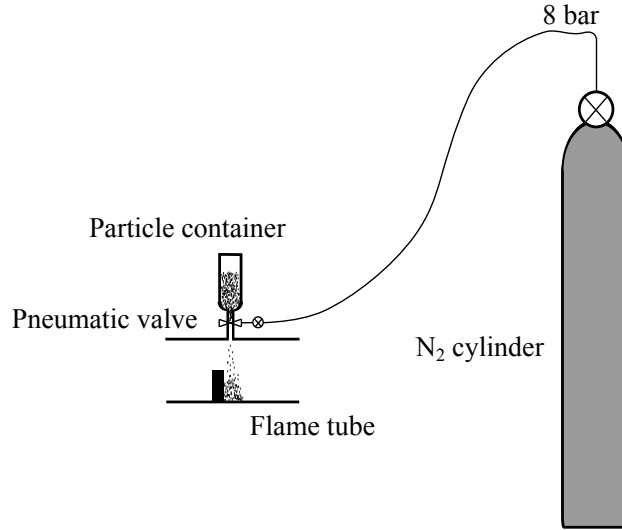


Figure 2.5.: Particle injector.

### 2.2.3. Radiation source

To assess the possibility of thermal radiation induced multi-point ignition in large vapour cloud explosions, a radiation source with similar characteristics to that from combustion products is favoured. The radiation in an explosion has a number of sources, excited molecules, radicals as well as the continuous radiation from solid particles such as soot and dust. In the absence of the latter, the main radiation comes from hot water vapour and CO<sub>2</sub>. Assuming a characteristic temperature of 2200 K [73] in the explosion products and a black body radiation, the maximum irradiance is approximately 1300 kW/m<sup>2</sup> according to the Stephan-Boltzman's law ( $E = \sigma T^4$ , where  $E$  is the irradiance,  $\sigma = 5.67 \times 10^{-8}$  W/(m<sup>2</sup>·K<sup>4</sup>) the Stefan-Boltzmann constant and  $T$  the absolute temperature). The spectral distribution lies in the range of  $\lambda = 1 - 5 \mu\text{m}$ , while the maximum irradiance is at  $\lambda_{max} = 1.3 \mu\text{m}$  given by Wien's law ( $\lambda_{max} = b/T$ , where  $b = 2.90 \times 10^{-3}$  m·K is the Wien's dis-

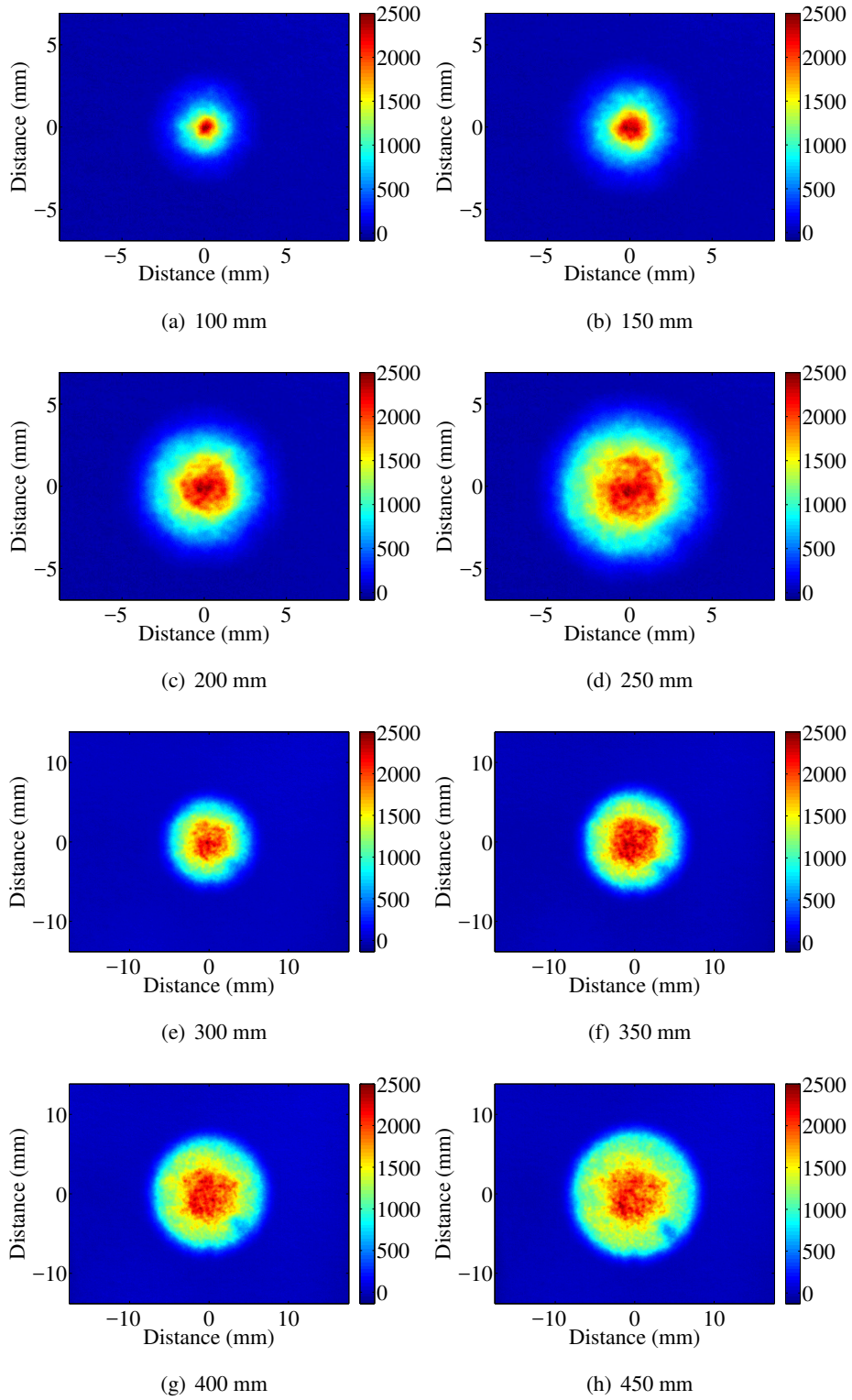


Figure 2.6.: Camera images of the laser spot with the target at different distances from collimator. Colour bar indicates laser light intensity.

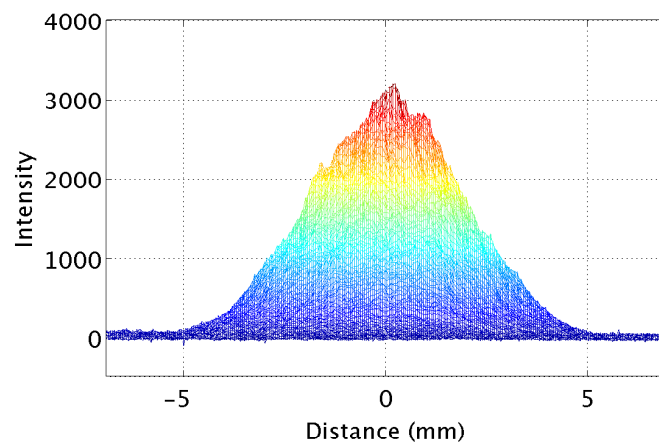
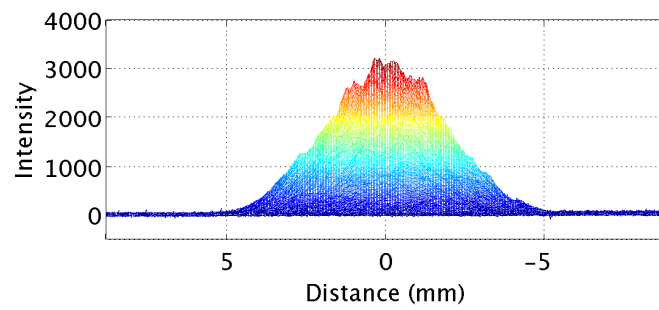
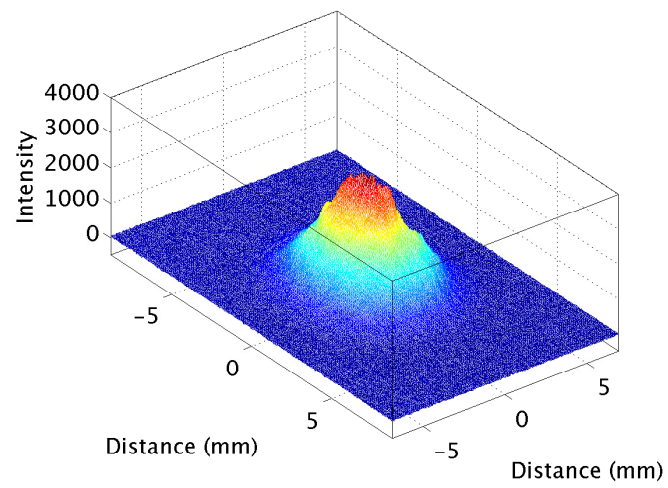


Figure 2.7.: Spatial distribution of the laser beam with the target located at a distance of 200 mm from the collimator. The intensity units in counts.

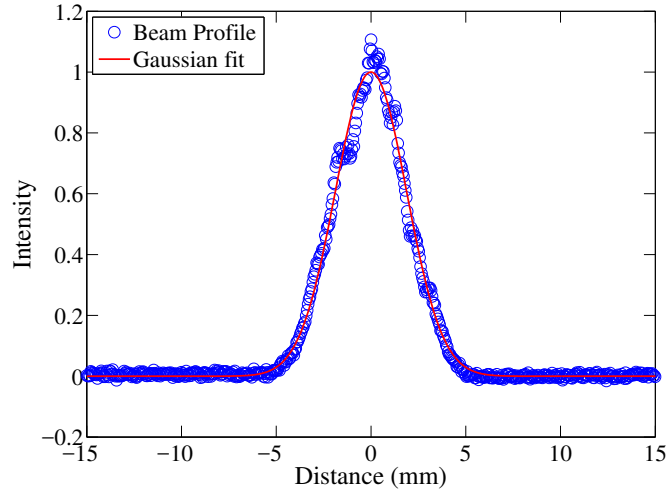


Figure 2.8.: Spatial distribution of the laser intensity (unit: counts) and Gaussian fit.

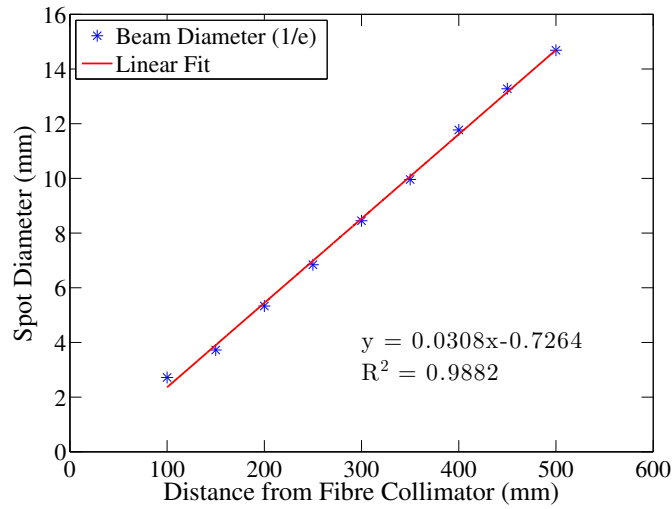


Figure 2.9.: Beam size as a function of the distance from the collimator.

placement constant). Accordingly a infrared light source capable of producing a radiation flux at the order of  $1000 \text{ kW/m}^2$  over an area larger than the quenching dimension of the investigated flammable mixtures is preferred. Laser light has the capability of producing highly intensified radiation and was used in previous research. Moore and Weinberg [63, 64] employed a  $\text{CO}_2$  laser operating at  $10.6 \mu\text{m}$ . Stamatov et al. [66] used a AR+ laser operating at  $514.5 \text{ nm}$  while Nd:YAG laser operating at  $1.06 \mu\text{m}$  was used by Hills et al. [75] and Zhang et al. [76].

In this research, a CW laser diode (LIMO50-FG400-WL808; LIMO GmbH) operating at  $808 \text{ nm} \pm 2 \text{ nm}$  was used as the radiation source to replicate the infrared radiation from combustion products. The maximum optical power was 50.9 W. The laser diode was coupled to a high-power laser fibre (multi-mode, LIMO-SMA905-F400-1.5) and a collimator (F220SMA-780, Thorlabs). The light after the collimator was not perfectly collimated and the divergence of the beam was characterised by projecting the laser beam onto a white paper target and imaging it with a CCD camera. A Gaussian spatial distribution of the beam intensity was determined and the radiation flux was calculated by dividing the laser power by laser spot area which was considered as 68% of the Gaussian beam profile ( $1/e$ ). Hadjipanayis [67] stated from experiment that the  $1/e$  criteria gives a more appropriate representative of the irradiated area for the ignition of the adjacent charge.

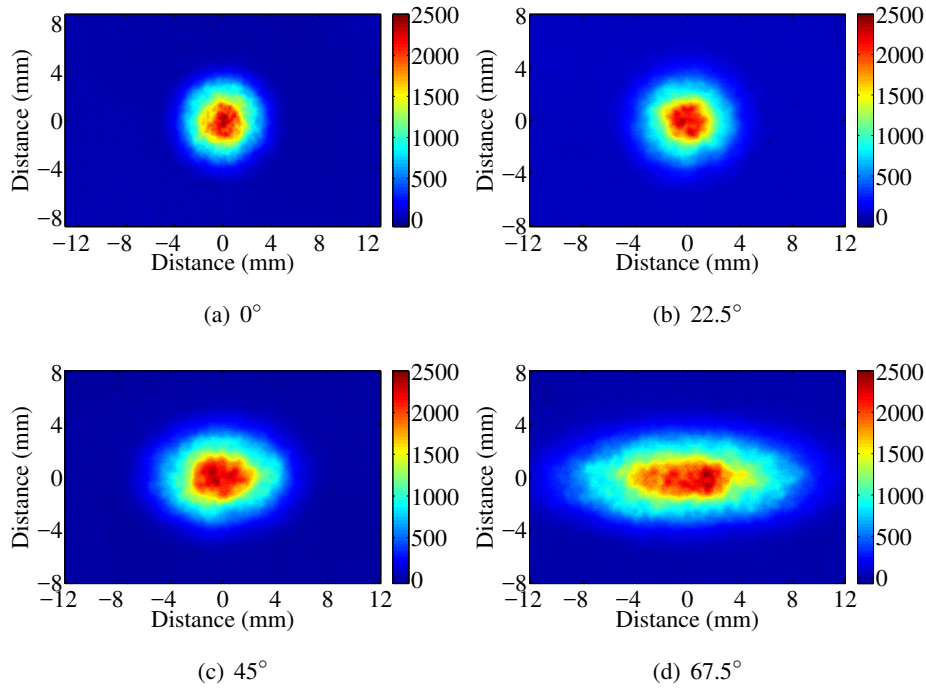


Figure 2.10.: Camera images of the laser beam at different angles. Colour bar indicates laser light intensity.

The camera images of the laser spot when the target was located at different distances from the collimator are shown in Figure 2.6. Figure 2.7 gives the spatial distribution of the laser energy when the target was located at a distance of 200 mm from the collimator, which is the distance between the particle agglomerates and

the collimator in this experiment. Figure 2.8 shows the laser beam intensity distribution along the line crossing the centre of the laser spot when the target is 200 mm away from the collimator together with its Gaussian fit. The diameter of the beam increases with the distance from the collimator, which is illustrated in Figure 2.9.

Restricted by the facility, the laser beam was projected onto the particles at an angle and the influence of the shooting laser beam angle on the beam area was also characterised. Figure 2.10 illustrates the camera images of the laser spot at different angles while keeping the distance fixed at 200 mm and Figure 2.11 shows the variation of actual beam area with the angle based on the 1/e rule. It can be seen that the influence is marginal at small angles and becomes stronger with the angle increasing. In this experiment, the angle was smaller than 30°.

The laser beam was directed through a silicon glass window (25 mm in thickness) as shown in Figure 2.3. The attenuation of the laser power was quantified by measuring the laser power both before and after the glass and a reduction of 10% was observed, as shown in Figure 2.12. In the calculations of radiation flux, the power after the glass was used, which was the actual power delivered onto the particles.

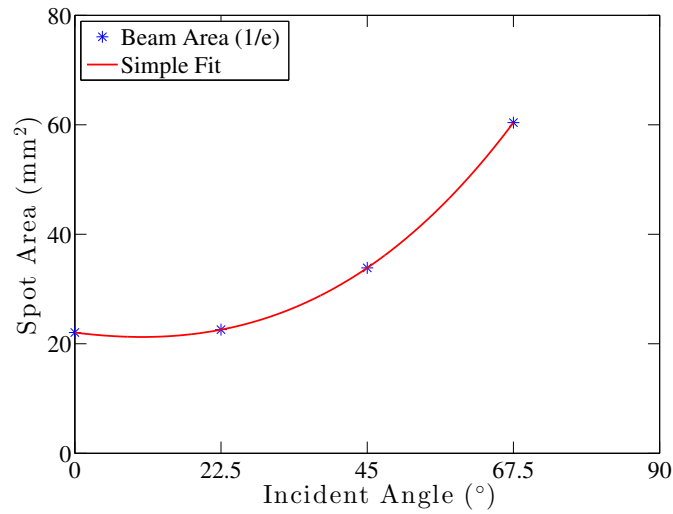


Figure 2.11.: Influence of the angle on the beam size.

#### 2.2.4. Ignition detection

The ignition event was recorded using a high speed CCD camera with a recording rate of 2000 Hz, providing an uncertainty of 0.5 ms. Combined filters with a band-



pass region of 335 – 500 nm were used to filter out the original laser light and its reflections in order to protect the camera chip and get a clear image of the ignition kernel. The recording started at the same time as the radiation synchronised by a TTL signal. The onset of the ignition was marked by the appearance of an outward propagating flame in the images and the ignition time was defined as the interval from target illumination to ignition. A sequence of the recorded images are shown in Figure 4.3, in which case the ignition time was 9 ms.

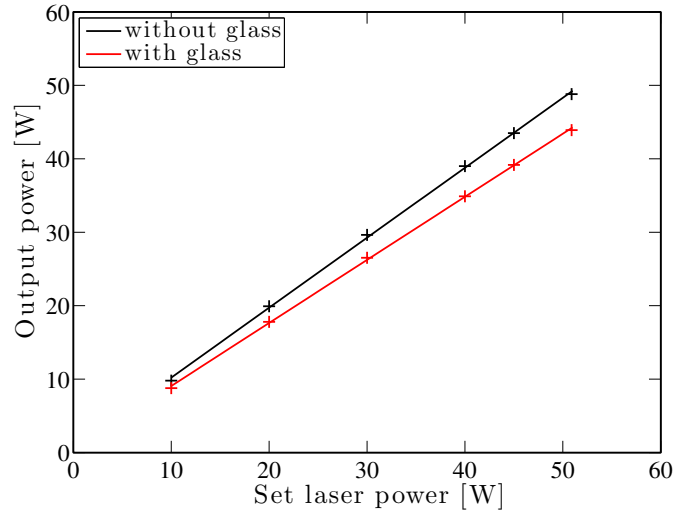


Figure 2.12.: Attenuation of the laser power through the silicon glass.

### 2.2.5. Irradiated particles

The properties of the irradiated particles can have significant influence on the ignition delay time as reviewed in Section 1.4. The micro structure of the particles affects the absorption efficiency of the laser energy and the heat loss to the surrounding atmosphere, which directly affects the ignition time. In this work, acetylene black particles were used as the radiation target due to their relationship with soot emissions. They feature an amorphous microstructure consisting of very fine particles typically of 35 nm in size but tend to agglomerate to much larger structures. The particles appear black, suggesting high absorptivity of the NIR laser light used. Hadjipanayis [67] compared the ignition delay times of a variety of different particles, finding that the acetylene black gives the shortest ignition delay time. In this experiment, it is also desirable to keep the time to ignition short given the modest distance (400 mm) between the irradiated area and the spark ignited

flame. The particles were kept and dried in an oven (120 C°) for at least 24 hours before each experiment.

### **2.3. Mie scattering and high-speed particle image velocimetry (HS-PIV)**

Particle image velocity (PIV) is a well established and widely used experimental technique in combustion research due to its attractive and advanced capability of measuring a 2-D planar flow field non-intrusively [84–86]. It allows the investigation of the turbulent flows over a broad range of length scales. Together with other laser based techniques, such as planar laser-induced fluorescence, great progress has been made in the understanding of turbulence-flame interactions. In order to achieve a deeper understanding of the relationships between the flow field, deflagration speed and the resulting overpressure, and to provide data relating to the scaling of explosion overpressures presented in Chapter 3, simultaneous Mie scattering and High-speed PIV at 10 kHz was performed to quantify the flow field evolution ahead of the advancing flame front.

#### **2.3.1. Mie scattering and HS-PIV configuration**

High-speed PIV at 10 kHz was performed to quantify the flow field evolution in order to tackle the transient nature of the current flame propagation featuring typically a time scale of millisecond. The HS-PIV system consists of an Edgeware Nd: YAG laser (IS6II-DE) operating at 532 nm and a high speed camera (Photron Fastcam SA6) synchronised by an external LaVision high speed controller. The camera was fitted with a Nikon 50 mm lens (f1.4) and a 3 nm narrow band filter for a wavelength of 532 nm. Silicone fluid (Polycraft Dow Corning 200/50; flash point 373 K) was introduced as seeding droplets (particles) within the last 30 seconds during the circulation process through the inlet pipe (see Figure 2.1). The seeding particles (droplets), with an average diameter of 0.5  $\mu\text{m}$ , were generated via a liquid nebuliser (PALAS, AGF 10.0). The droplets have an evaporation temperature of 373 K and therefore the flow field can only be measured in the unreacted mixtures ahead of the flame front.

The experimental configuration is shown schematically in Figure 2.13. Two solid obstacles with a thickness of 5 mm and a height of 36 mm (blockage ratio of 50%), were installed at distances of 80 mm and 400 mm from the ignition end

in a staggered arrangement. A similar configuration was previously investigated by Hampp and Lindstedt [79] performing 10 kHz PIV measurements in the recirculation region behind a single obstacle with a turbulence-generating cross fractal grid (CFG) installed upstream of the obstacle (between the obstacle and ignition spark). The flame passing through the CFG was also visualised using chemiluminescence based imaging at 2.5 kHz. The measurement window was located 50 mm downstream the obstacle (the height of the obstacle was 36 mm) in their work and it is essential to develop a better understanding of the flow field close to the obstacle. The current measurement window accordingly starts 3 mm downstream. The geometry was also simplified by the replacement of the cross-fractal grid with a solid obstacle to more readily facilitate theoretical studies. The laser light sheet was directed vertically from the top into the optical section with a thickness around 0.8 mm in the centre of the recirculation zone. A silicon glass window (268 (W)  $\times$  72 (H)  $\times$  25 (D) mm) was installed on one side of the optical section (facing the camera) to offer optical access and recording. Eight ionisation probe detectors and four pressure transducers were mounted along the tube to measure the flame arrival time and pressure development and the locations are specified in Table 2.2.

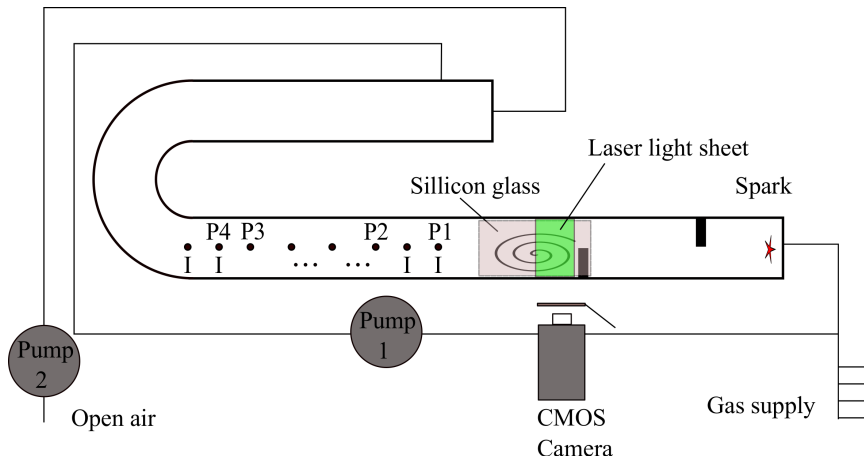


Figure 2.13.: Schematic of the experimental test facility.

Table 2.2.: Locations (X) of pressure transducers (P) and ionisation probe (I) detectors from the ignition point.

| X [m]  | 0.845 | 1.075 | 1.305 | 1.535 | 2.000 | 2.225 | 3.145 | 3.450 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sensor | P1+I  | I     | P2+I  | I     | I     | P3+I  | P4+I  | I     |

The Mie scattering images feature a resolution of  $352 \times 426$  pixels (corresponding to  $52 \times 63$  mm in physical space) and the measurement was controlled by LaVision DaVis 8.3. The optimal timing between the double laser pulses ( $\Delta t$ ) varies depending on the mixture reactivity (details can be found in Table 2.3 together with the estimated uncertainties). The maximum pressure at the outlet of the ATEX rated circulation pump is 1.2 bar and a pressure drop of 0.5 bar is necessary for the nebuliser (seeder) to work. Therefore, the initial pressure was 50 kPa in all the HS-PIV measurement. The leak rate was  $< 16$  Pa/s compared to a filling time of around 45 s.

Table 2.3.: Summary of the estimated uncertainties in the experiments where  $\Delta t$  is the time interval between the two laser pulses,  $\epsilon_r$  and  $\epsilon_b$  the error associated with relaxation time and velocity bias. The mixtures used were  $\text{H}_2/\text{CO}/\text{Air}$  and  $\text{H}_2/\text{CH}_4/\text{Air}$  at  $\Phi = 0.60$  with different  $\text{H}_2$  substitutions specified below and PIV denotes standard PIV and TS-PIV Time-Series PIV.

| Mixture                             | $\text{H}_2$<br>[%] | $\Delta t$ [ $\mu\text{s}$ ] |        | $\epsilon_r$ [%] |        | $\epsilon_b$ [%] |        |
|-------------------------------------|---------------------|------------------------------|--------|------------------|--------|------------------|--------|
|                                     |                     | PIV                          | TS-PIV | PIV              | TS-PIV | PIV              | TS-PIV |
| $\text{H}_2/\text{Air}$             | 100                 | 6                            | 100    | -5.2             | -0.75  | 0.03             | 0.07   |
| $\text{H}_2/\text{CO}/\text{Air}$   | 50                  | 15                           | 100    | -14.1            | -0.75  | 0.02             | 0.02   |
|                                     | 80                  | 10                           | 100    | -8.0             | -0.75  | 0.03             | 0.05   |
| $\text{H}_2/\text{CH}_4/\text{Air}$ | 50                  | 15                           | 100    | -14.1            | -0.75  | 0.01             | 0.02   |
|                                     | 80                  | 15                           | 100    | -14.1            | -0.75  | 0.02             | 0.02   |

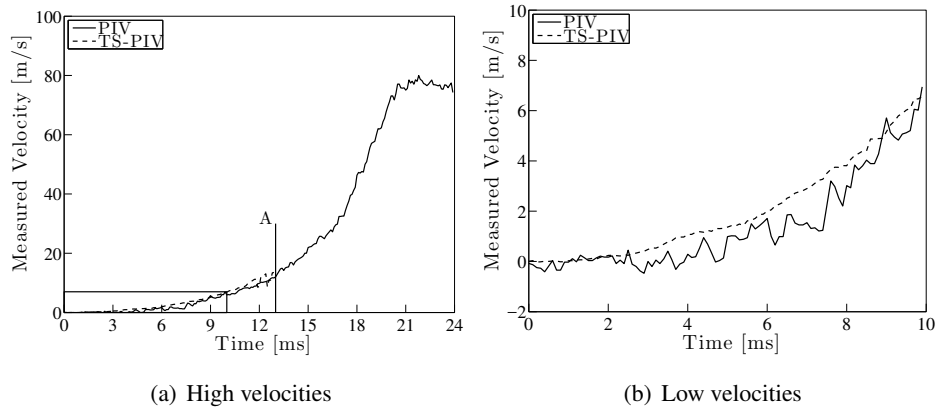


Figure 2.14.: Comparison of the standard PIV and time-series PIV calculation at a point  $x = 10$  mm,  $y = 50$  mm (see Figure 5.4(b) for its location) in  $\text{H}_2/\text{CO}/\text{Air}$  mixtures with  $\text{H}_2 = 50\%$  and  $\Phi = 0.60$ .

### 2.3.2. Measurement uncertainties

The particle image velocimetry calculations were carried out using DaVis 8.3 via a multi-pass method with a decreasing interrogation window size from  $128 \times 128$  pixels to  $32 \times 32$  pixels with a 75% overlap. The final pass of the smallest interrogation window was performed on a high accuracy mode with an adaptive PIV calculation warping the round weighted window to an elliptical (maximum aspect ratio of four) Gaussian bell to incorporate the local flow field acceleration [87]. Prior to the calculation of the velocity vectors, background subtractions were performed to enhance the signal to noise ratio for the Mie scattering images featuring  $352 \times 426$  pixels corresponding to  $52 \times 63$  mm in physical space and providing a spatial resolution of  $147 \mu\text{m}$ . A normalised cross-correlation function was used to compensate the varying background intensities and signal densities [88]. The standard PIV calculation was used for high velocities (after line A in Figure 2.14(a)). For low velocities, time-series PIV was used, which effectively removes the fluctuations in the measured velocity compared to standard PIV calculations. Figure 2.14 exemplifies the difference between PIV and time-series PIV at a point  $x = 10$  mm,  $y = 50$  mm (see Figure 5.4(b) for its location) in  $\text{H}_2/\text{CO}/\text{Air}$  mixtures with  $\text{H}_2 = 50\%$  and  $\Phi = 0.60$ . It is obvious that for low velocities, the standard PIV calculation is affected by noise. The resulting velocity field features  $45 \times 54$  vectors giving a vector spacing of 1.16 mm. The transient nature of the flame propagation makes it difficult to obtain statistically independent turbulence information. The mean flow velocities averaged from at least three experiments are shown along with the variability.

Table 2.4.: Physical properties of the gas mixtures where  $\rho_u$ ,  $\mu$ ,  $\gamma$  and  $S_L$  are the density of the unburned gas mixture, dynamic viscosity, expansion ratio and laminar burning velocity.

| Mixture                             | $\text{H}_2$ [%] | $\rho_u$ [ $\text{kg}/\text{m}^3$ ] | $\mu \times 10^5$ [ $\text{Pa} \cdot \text{s}$ ] | $\gamma$ | $S_L$ [m/s] |
|-------------------------------------|------------------|-------------------------------------|--------------------------------------------------|----------|-------------|
| $\text{H}_2/\text{Air}$             | 100              | 0.47                                | 1.84                                             | 4.54     | 0.82        |
| $\text{H}_2/\text{CO}/\text{Air}$   | 50               | 0.53                                | 1.84                                             | 4.72     | 0.43        |
|                                     | 80               | 0.49                                | 1.84                                             | 4.61     | 0.63        |
| $\text{H}_2/\text{CH}_4/\text{Air}$ | 50               | 0.55                                | 1.82                                             | 4.58     | 0.18        |
|                                     | 80               | 0.52                                | 1.83                                             | 4.57     | 0.34        |

The velocity lag between the seeding particles and the flow field is another source of uncertainties. Smaller seeding particles follow the flow better, but limit the intensity of the reflected light [86, 89]. The current average droplet size was

0.5  $\mu\text{m}$  and the relaxation time to a step change in the fluid velocity can therefore be estimated to 0.74  $\mu\text{s}$  using Eq. (2.1) [81, 90], where  $d_p$  is the average seeding particle size,  $\rho_p$  is the density of the seeding particles (971  $\text{kg/m}^3$ ) and  $\mu$  the viscosity of the reactants (see Table 2.4).

$$\tau_s = d_p^2 \frac{\rho_p}{18\mu} \quad (2.1)$$

The motion of the seeding particles under Stokes' resistance with a large density ratio between the particle and fluid (in the current scenario,  $\rho_p/\rho_u \approx 1867 \gg 1$  where  $\rho_u$  is the density of the unreacted gas mixture listed in Table 2.4) was analysed by Melling and is governed by Eq. (2.2) [90], where  $C$  is the characteristic frequency of the particle motion defined as the reciprocal of the relaxation time, and  $U_f$ ,  $U_p$  the velocity of the bedded flow and the seeding particles, respectively.

$$\frac{dU_p}{dt} = C(U_f - U_p) \quad (2.2)$$

$$C = \frac{1}{\tau_s} \quad (2.3)$$

Integrating Eq. (2.2) over time gives

$$U_p = U_f - C_k e^{-Ct} \quad (2.4)$$

where  $C_k$  is a constant to be determined. Assuming a worst case scenario where a seeding particle starts to accelerate from quiescence, the initial condition of  $U_p = 0$  at time zero gives  $C_k = U_f$ . Further assume  $U_f$  does not change over time (reasonable considering the short time interval between the two laser pulses in this study), the distance travelled by the seeding particle over a time period  $\Delta t$  can be calculated by integrating Eq. (2.4),

$$S_p = \int_0^{\Delta t} U_p dt = U_f \left( \Delta t - \frac{1}{C} (1 - e^{-C\Delta t}) \right) \quad (2.5)$$

The velocity calculated using PIV without noticing the velocity lag is

$$U'_p = S_p/\Delta t = U_f \left( 1 - \frac{1}{C\Delta t} (1 - e^{-C\Delta t}) \right) \quad (2.6)$$

Then the uncertainties associated with the relaxation time can be estimated using Eq. (2.7).

$$\epsilon_r = \frac{U'_p - U_f}{U'_p} = 1 - \frac{1}{1 - \frac{1}{C\Delta t}(1 - e^{-C\Delta t})} \quad (2.7)$$

In this experiment, the  $\Delta t$  used was  $6 \mu s$ ,  $10 \mu s$  and  $15 \mu s$ , giving estimated errors of -14.1%, -8.0% and -5.2%, respectively. For time-series PIV,  $\epsilon_r$  is -0.75%. The negative sign means that the measured velocity is smaller than the real flow field velocity, which is obviously a result of the drag effect. Considering that this is a worst-case-scenario estimate, the uncertainties associated with the measurements will be much smaller due to the fact that the seeding particles have already reached a certain magnitude of velocity at the first laser pulse.

$$\frac{\Delta x}{\Delta z} = \frac{x + \Delta x}{L} \quad (2.8)$$

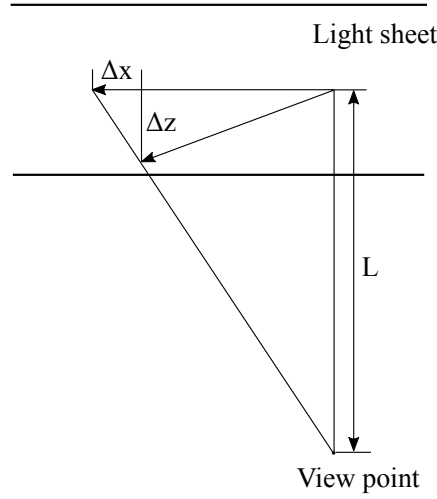


Figure 2.15.: Velocity bias due to out-of-plane velocity.

The out-of-plane velocity, which is the velocity perpendicular to the measurement plane, may also introduce errors in 2-D PIV via velocity bias and the disappearance of seeding particles [91, 92]. The velocity bias due to the out of plane velocity is illustrated in Figure 2.15, where  $\Delta x$  is the spurious displacement and  $\Delta z$  the out-of-plane displacement. The distance between the light sheet and the view point (camera) is 450 mm in the current setup and denoted by  $L$  in Figure 2.15. During the short time interval ( $\Delta t$ ) between the two laser pulses, the associated velocity bias error can be calculated as  $\epsilon_b = \frac{\Delta x/\Delta t}{(x+\Delta x)/\Delta t}$ . The maximum gas velocity attained in this experiment is  $< 200$  m/s at the time the flame

arrives at the measurement section. Assuming a 10% velocity fluctuation gives an out-of-plate velocity of 20 m/s and the velocity bias error can thus be estimated to be  $\epsilon_b = 0.02\%$ . For time-series PIV, although  $\Delta t$  increases, the flow speed decreases (time-series PIV was performed only for low flow speeds) and the resulted velocity bias is below 0.1%. If the out-of-plate velocity is too large, the seeding particles will disappear outside the thin laser light sheet, which is the other error associated with out-of-plate velocity. Again, assuming a 10% velocity fluctuation, the maximum out-of-plate displacement  $\Delta z$  is around 0.1 mm, which is much less than the thinnest light sheet size of 0.5 mm, so this error can be neglected in the current measurements.

The strong heat release in thin reaction layers and the corresponding temperature gradient can lead to uncertainties associated with thermophoresis [86, 93]. The impact was insignificant for the current diagnostic set up as the measurements were performed in the reactants ahead of the flame front and the silicone oil seeding particles evaporate at a temperature of 373 K. The temperature gradient can also result in an inhomogeneous field of refraction index, causing beam steering and image distortion. However, on a laboratory scale the deformation of the light sheet is negligible and the image distortion does not affect accuracy if the time interval between the cross-correlated images is sufficiently small as pointed out by Stella et al. [86].

## 2.4. Experimental procedure

To ensure good repeatability, the experimental procedure should be consistent between different experiments. The operational procedure for the current experiments is described as below:

1. Turn on the power supply and check carefully to make sure every component works properly, e.g. flow controllers, solenoid valves, ignition device. If high speed laser is used, wait for 20 – 30 minutes for the laser head to heat up.
2. Flush the flame tube with air for one minute to blow away the remaining combustion products from the previous experiment, providing repeatable initial conditions.
3. Empty the flame tube with the vacuum pump to a pressure below 5 kPa via



a rotary vane pump (RE 2.5; VACCUBRAND GmbH).

4. Prepare the target gas mixture using a partial pressure method. The fuel component is injected first. Air comes last. The filling process is less than one minute in total.
5. After filling, circulate the gas mixtures to achieve homogeneity via the ATEX rated pump (MD 4C EX; Vacuubrand). Before extending the tube, the gas mixture was circulated for five minutes corresponding to 28 flame-tube-volumes. With the extension to the flame tube, the circulation time was increased to ten minutes corresponding to 23 flame-tube-volumes. In the HS-PIV measurements, the seeding particles were introduced within the last 30 seconds of circulation.
6. Wait for two minutes to achieve quiescent conditions. Close the corresponding valves to isolate the flame tube completely.
7. Carry out synchronised measurement by triggering the spark and all the data acquisition cards using one TTL signal. In the radiation induced ignition experiments, acetylene black particles were injected before ignition.
8. Open the corresponding valves, empty the combustion products and restart the current sequence.

The whole process was controlled remotely via a purpose-written LabView program, in which the actual amount of fuel gas injected was checked before ignition to prevent any risks (e.g. over injection of a certain fuel component) from malfunction of the flow controllers. All the related experimental details were stored automatically. The whole process took around 30 minutes (45 minutes in the radiation induced ignition experiments where opening and closing of the glass window was necessary for cleaning).

### 3. Explosion overpressure and flame speed

Due to the depletion of fossil fuels and increasing environmental concerns, the need to find renewable and green energy sources is pressing. Hydrogen is seen as a promising future alternative fuel due to its zero-carbon emission characteristic. Direct use of hydrogen poses strong risks in safety consideration because of the very reactive nature. But used as an additive, hydrogen can enhance the reactivity of hydrocarbon fuels significantly, leading to improved combustion stability and widened flammable limits. Burning under lean or ultra-lean conditions is therefore possible, lowering the emissions of  $\text{CO}_2$  and  $\text{NO}_x$ . However, the explosion behaviour caused by hydrogen enrichment, has not been well established. In this chapter, the explosion overpressure and flame speed resulting from turbulent deflagrations of hydrogen enriched CO and/or  $\text{CH}_4$  are systematically studied in an obstructed flame tube facility. Scalings for the peak explosion overpressure are explored in the last section of this chapter.

#### 3.1. Introduction

Hydrogen has the potential as a zero-carbon emission energy carrier, provided that suitable (e.g. renewable) production methods are used. However, a safe and reliable hydrogen economy is challenging to achieve [94]. A potential way to use hydrogen in practical systems is as an additive that improves combustion characteristics. For example, the addition of hydrogen extends the lean operating limit and yields reduced CO and  $\text{NO}_x$  emissions [95, 96]. Moreover, the substitution of small amounts of kerosene with hydrogen can stabilise flames that may otherwise extinguish in gas turbine engines at the same operating point [97]. Wang et al. [98] have shown that the (initial) flame development is enhanced by hydrogen addition – especially under lean conditions. The recent progress in hydrogen enriched combustion has been reviewed by Tang et al. [99] with regard to aspects such as

minimum ignition energies, laminar burning velocities and flame instabilities.

While the addition of hydrogen benefits low emissions and flame stability, it also poses higher explosion risks due to the increased reactivity. This requires an assessment of related hazards in order to assure safe operation. In this context, Salzano et al. [100] used a 5 litre closed cylindrical vessel to study the combined impact of hydrogen substitution, initial pressure and turbulence on the explosion behaviour in  $H_2/CH_4/Air$  mixtures. It was concluded that a low hydrogen content (up to 10% by volume) has a negligible impact, while a hydrogen content in excess of 50% can result in a strong increase of the maximum rate of pressure rise (i.e.  $dP/dt$ ) regardless of the initial pressure. Similar results were observed by Ma et al. [101] using a 20 litre spherical vessel with hydrogen content varying from 0 to 100%. Lowesmith et al. [12] carried out a series of large scale explosion experiments in a 69300 litre enclosure with various hydrogen concentrations to assess the potential of using existing gas infrastructures to convey methane/hydrogen mixtures. A small increase in the flame speed and overpressure was observed when replacing  $CH_4$  with  $H_2$  up to 20% and a significant increase with a 50% substitution. Bauwens et al. [102] and Chao et al. [103] measured the explosion overpressure of hydrogen/hydrocarbon mixtures ( $H_2$ -air with  $\Phi = 0.5$ ,  $CH_4$ -air and  $C_3H_8$ -air with  $\Phi = 1$ ) under vented conditions. It was found that the  $H_2$ -air mixtures generated significantly higher overpressures than the hydrocarbon-air mixtures despite having similar laminar burning velocity. The enhancement of flame speed and overpressure associated with congestion was experimentally studied by Lowesmith et al. [104] in a series of large scale experiments. The flame speed entering the congestion region was found to be critical in terms of the subsequent turbulent explosion as well as the potential for deflagration to detonation transition (DDT).

The importance of the obstacles in flame propagation has been well established and reviewed in Chapter 1. For example, Ibrahim and Masri [105] stated that wall/plate type obstructions lead to the highest, and cylindrical obstructions yield the lowest, overpressure. In this experiment, wall type obstacles were used. Details of the configuration will be presented in the next section.

### 3.2. Experimental details

Experiments were performed in the flame tube facility (length  $\times$  width  $\times$  height of  $4420 \times 34 \times 36$  mm) with two obstacles installed at distances of 80 mm (top) and

360 mm (bottom) from the ignition in a staggered arrangement in order to enhance the flame propagation. A schematic is shown in Figure 3.1. The geometry is a development of a single obstacle configuration used by Lindstedt and Sakthitharan [32], in which a quantitative description of the interaction of the flame with a single obstacle was obtained by measuring the time-resolved velocities in a two-dimensional plane along the vertical tube axis. Eleven ionisation probe detectors were used to detect the flame arrival time, with the locations specified in Table 3.1, together with the four pressure transducers for pressure measurement. Details of the flame tube, pressure transducers, ionisation probe detectors and ignition device, as well as the experimental procedure, have been elaborated in Chapter 2 and will not be repeated here.

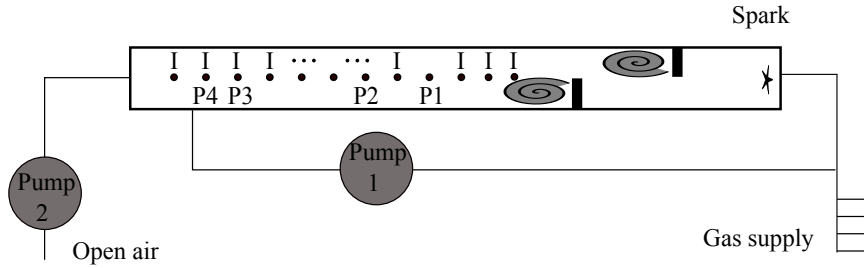


Figure 3.1.: Schematic of the experimental setup.

Table 3.1.: Locations (X) for pressure transducers (P) and ionisation probe (I) detectors from the ignition point.

| X [m]  | 0.400 | 0.480 | 0.600 | 0.845 | 1.075 | 1.305 | 1.535 | 1.765 | 2.000 | 2.225 | 3.145 | 3.450 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sensor | I     | I     | I     | P1    | I     | P2+I  | I     | I     | I     | P3+I  | P4+I  | I     |

The gas mixtures used cover both binary ( $H_2/CO$  and  $H_2/CH_4$ ) and ternary ( $H_2/CH_4/CO$ ) fuels with a wide range of hydrogen content from the lower ignition limit to that generating fast deflagrations. The preparation of the premixed gas mixtures has also been described in Chapter 2. The test matrices are given in Tables 3.2 and 3.3 for binary and ternary mixtures. The hydrogen content is defined in the customary manner,

$$\alpha = \frac{C_H}{C_H + C_F} \quad (3.1)$$

where  $C_H$  and  $C_F$  represent the mole fractions of  $H_2$  and  $CO$  or/and  $CH_4$ , respectively. A minimum of three repetitions were carried out for each mixture to provide an estimate of the repeatability.

Table 3.2.: Test matrix for binary fuel mixtures, where  $\alpha$  denotes the volumetric hydrogen content in the fuel blends (see Eq. (3.1)) and  $\Phi$  the equivalence ratio.

| $\Phi$        | $\alpha(H_2, CO)$                       | $\alpha(H_2, CH_4)$             |
|---------------|-----------------------------------------|---------------------------------|
| $\Phi = 0.80$ | 0.1 0.2 0.3 0.4 0.5                     | 0.0 0.2 0.4 0.5 0.6 0.7 0.8     |
| $\Phi = 0.60$ | 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 | 0.2 0.4 0.5 0.6 0.7 0.8 0.9 1.0 |
| $\Phi = 0.40$ | 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0         | 0.7 0.8 0.9 1.0                 |

Table 3.3.: Test matrix for ternary fuel blends at  $\Phi = 0.60$ , where  $\alpha$  denotes the volumetric hydrogen content in the fuel blends (see Eq. (3.1)).

| CO/CH <sub>4</sub> ratio | $\alpha(H_2, CO, CH_4)$                   |
|--------------------------|-------------------------------------------|
| 3 : 7                    | 0 0.2 0.4 0.6 0.7 0.8 0.9 1.0             |
| 5 : 5                    | 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 |
| 7 : 3                    | 0 0.2 0.4 0.6 0.8 0.9 1.0                 |

### 3.3. Pressure development

After ignition, the flame kernel propagates semi-spherically until it reaches the wall of the flame tube. Hampp and Lindstedt [79] visualised the initial laminar flame propagation via high-speed (2.5 kHz) chemiluminescence imaging in the same flame tube using a different obstacle configuration. The flame front propagates forward in a manner consistent with the velocity profile [32] with the thermal expansion of the hot combustion products causing flow ahead of the advancing flame. The resulting strong turbulence generation in the shear layers and recirculation zones in the wake of the obstacles leads to a turbulence driven explosion and results in a sharp pressure rise.

The pressure development in this experiment is exemplified in Figure 3.2 using a 60% H<sub>2</sub> / 40% CH<sub>4</sub> / Air mixture at  $\Phi = 0.80$ . The lines correspond to the four pressure transducers located at different distances from the ignition end. The error bars on the peak overpressure visualise the experimental uncertainty based on three repetitions. The two pressure rises resulting from turbulent explosions behind the two obstacles (see Figure 3.1) are marked in Figure 3.2. The amplitude of the pressure rise is closely related to the turbulence intensity behind each obstacle [32]. The modest initial pressure rise of approximately 25 kPa stems from the relatively weak turbulence behind the first obstacle. However, the resulting flame acceleration causes a faster flow ahead of the flame front, which coupled with the

longer flow development time and the subsequent interaction with the second obstacle results in higher turbulence levels. The highly fragmented flame front leads to an explosion behind the second obstacle causing a sharp second pressure rise of over 200 kPa. The timing and amplitude of the peak are strongly correlated with the mixture reactivity as discussed below. It should be noted that a moderate second peak in Zone A is recorded by each transducer and is caused by the pressure wave reflected from the ignition end. The signals in Zone B, which are somewhat chaotic, are affected by the pressure wave reflected from the closed far end of the flame tube and were not considered in the subsequent analysis.

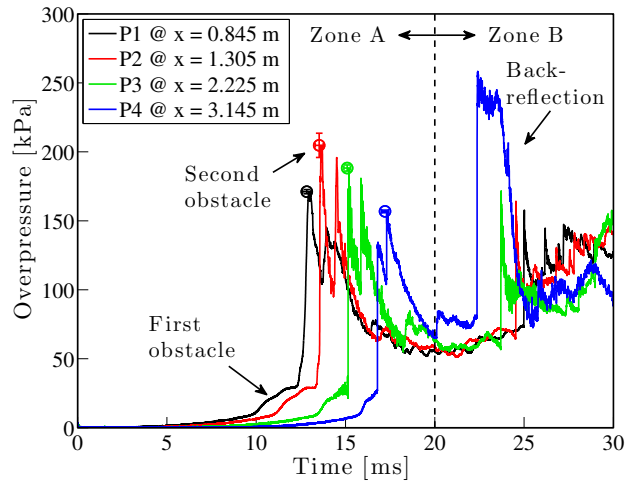


Figure 3.2.: Explosion overpressure development in a  $\text{H}_2/\text{CH}_4/\text{Air}$  mixture,  $\text{H}_2 = 60\%$ ,  $\Phi = 0.80$ . The errorbars are calculated based on three repetitions and the signals in Zone B are the pressure back-reflection waves from the downstream closed end.

Figures 3.3 – 3.5 show the time-resolved pressure build-up process in binary mixtures of  $\text{H}_2/\text{CO}/\text{Air}$  at equivalence ratios of 0.80, 0.60 and 0.40, respectively. The four lines correspond to the four pressure transducers at different locations. It is clear that the explosion overpressure increases with both hydrogen concentration and equivalence ratio. The small error bars (obtained based on at least three repetitions for each mixture) indicate good repeatability. Figures 3.6 – 3.8 show the pressure development in  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures. The hydrogen concentration was varied from the lower ignition limit to condition leading to strong turbulent deflagration in order to obtain a comprehensive assessment of the impact of  $\text{H}_2$  concentration. Further experiments using ternary mixtures ( $\text{H}_2/\text{CH}_4/\text{CO}$ ) with three different  $\text{CO}/\text{CH}_4$  ratios (3 : 7, 5 : 5 and 7 : 3) were also conducted at a fixed

stoichiometry of 0.60 and the results are shown in Figures 3.9 to 3.11.

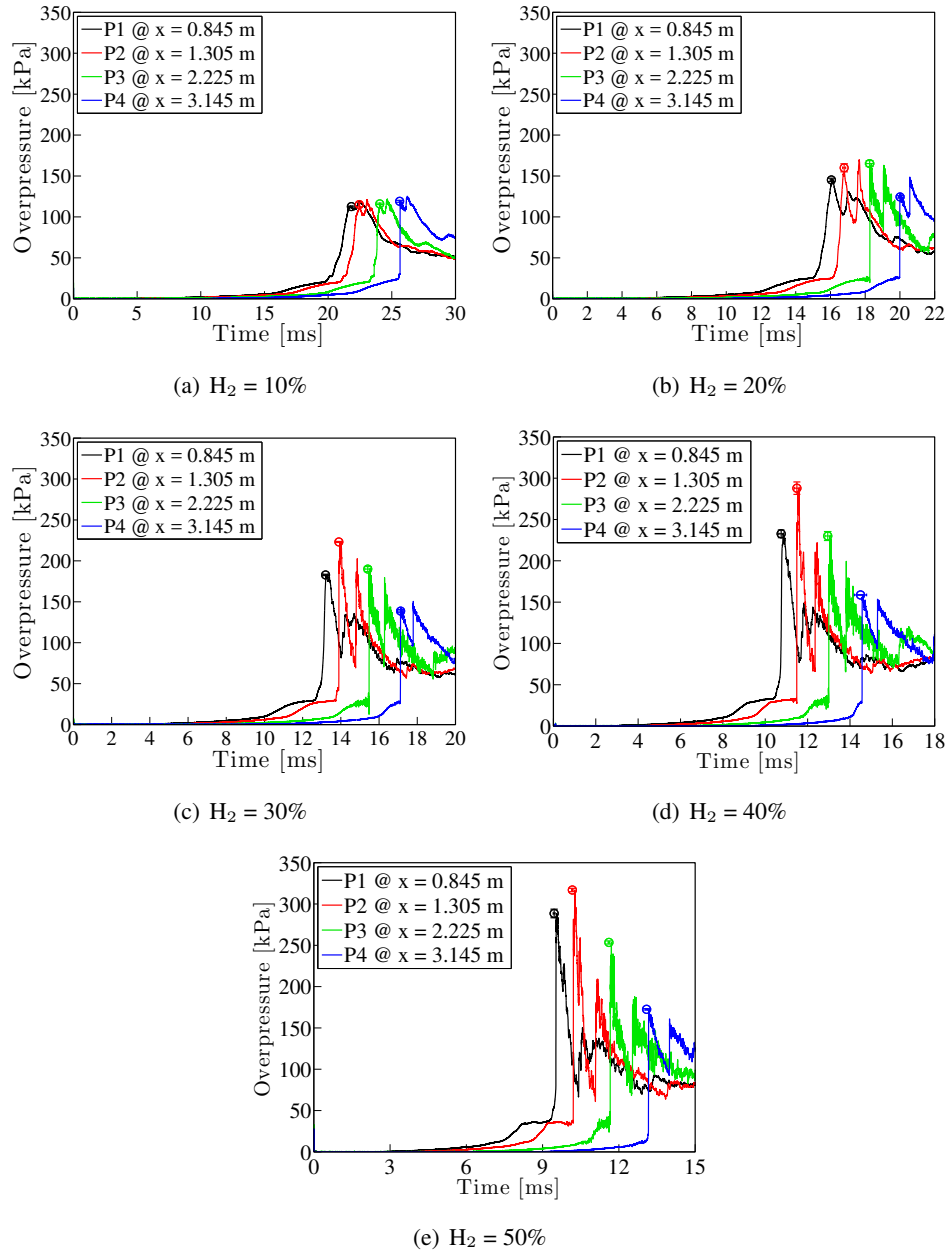


Figure 3.3.: Explosion overpressure development in  $H_2/CO/Air$  mixtures at  $\Phi = 0.80$ . The errorbars are calculated based on at least three repetitions.

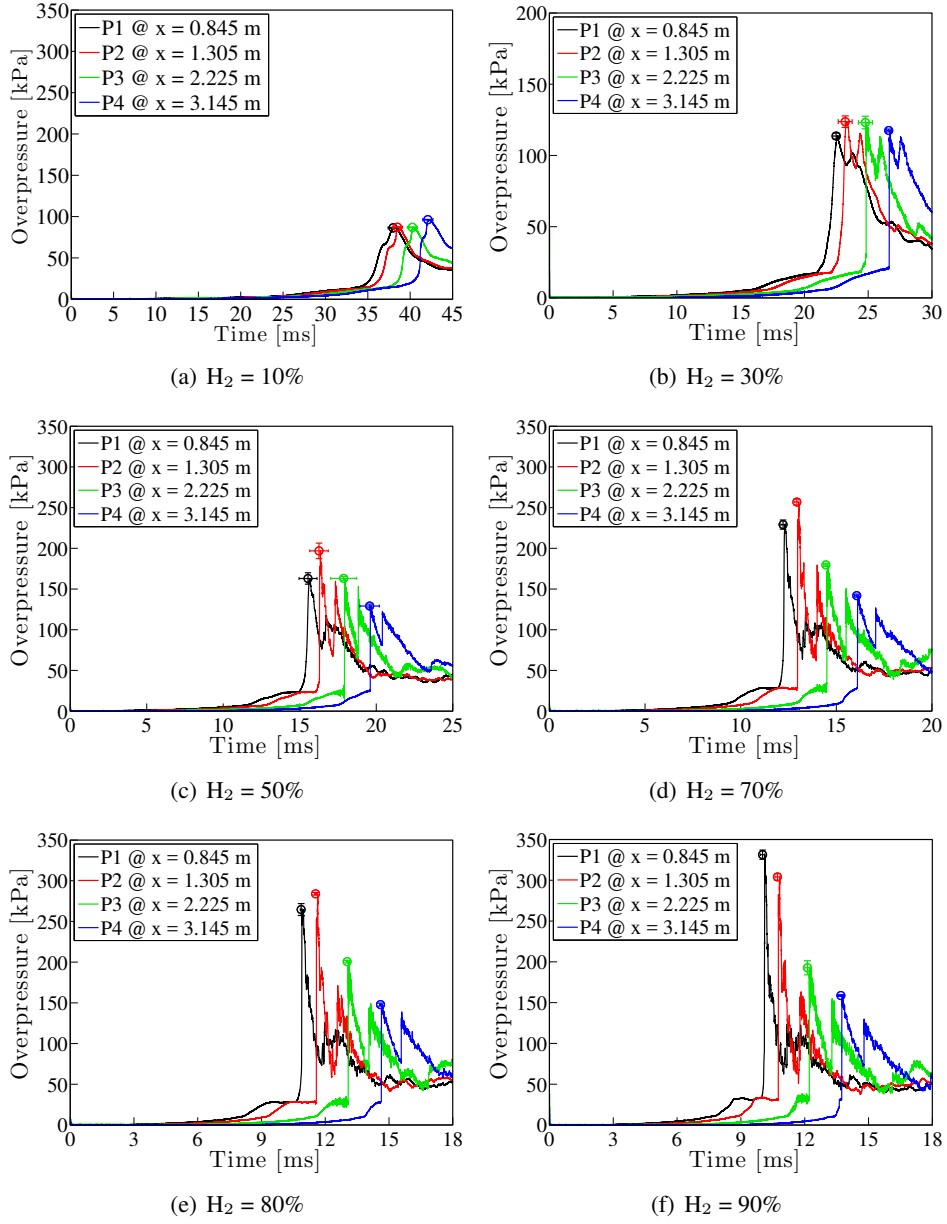


Figure 3.4.: Explosion overpressure development in  $\text{H}_2/\text{CO}/\text{Air}$  mixtures at  $\Phi = 0.60$ . The errorbars are calculated based on at least three repetitions.



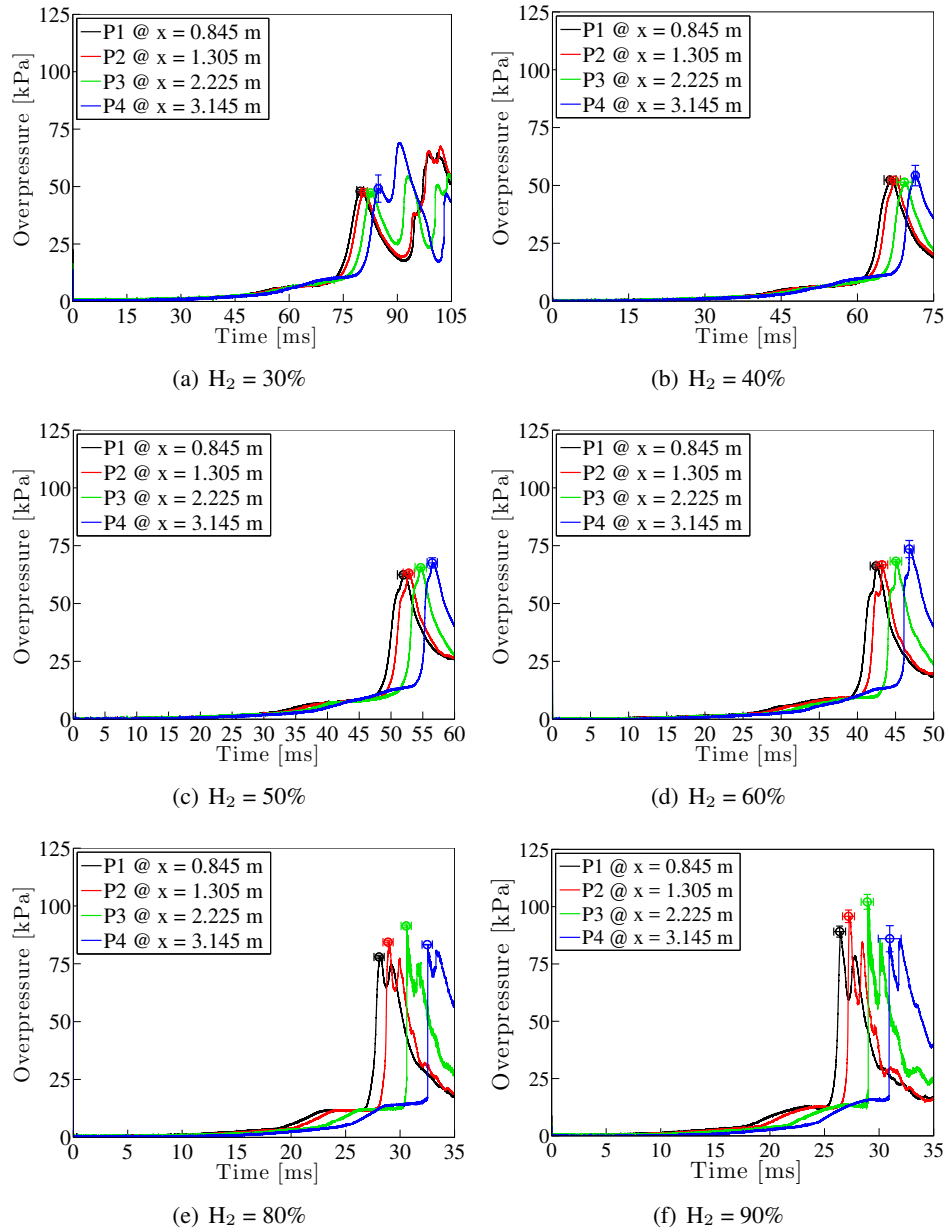


Figure 3.5.: Explosion overpressure development in  $\text{H}_2/\text{CO}/\text{Air}$  mixtures at  $\Phi = 0.40$ . The errorbars are calculated based on at least three repetitions.

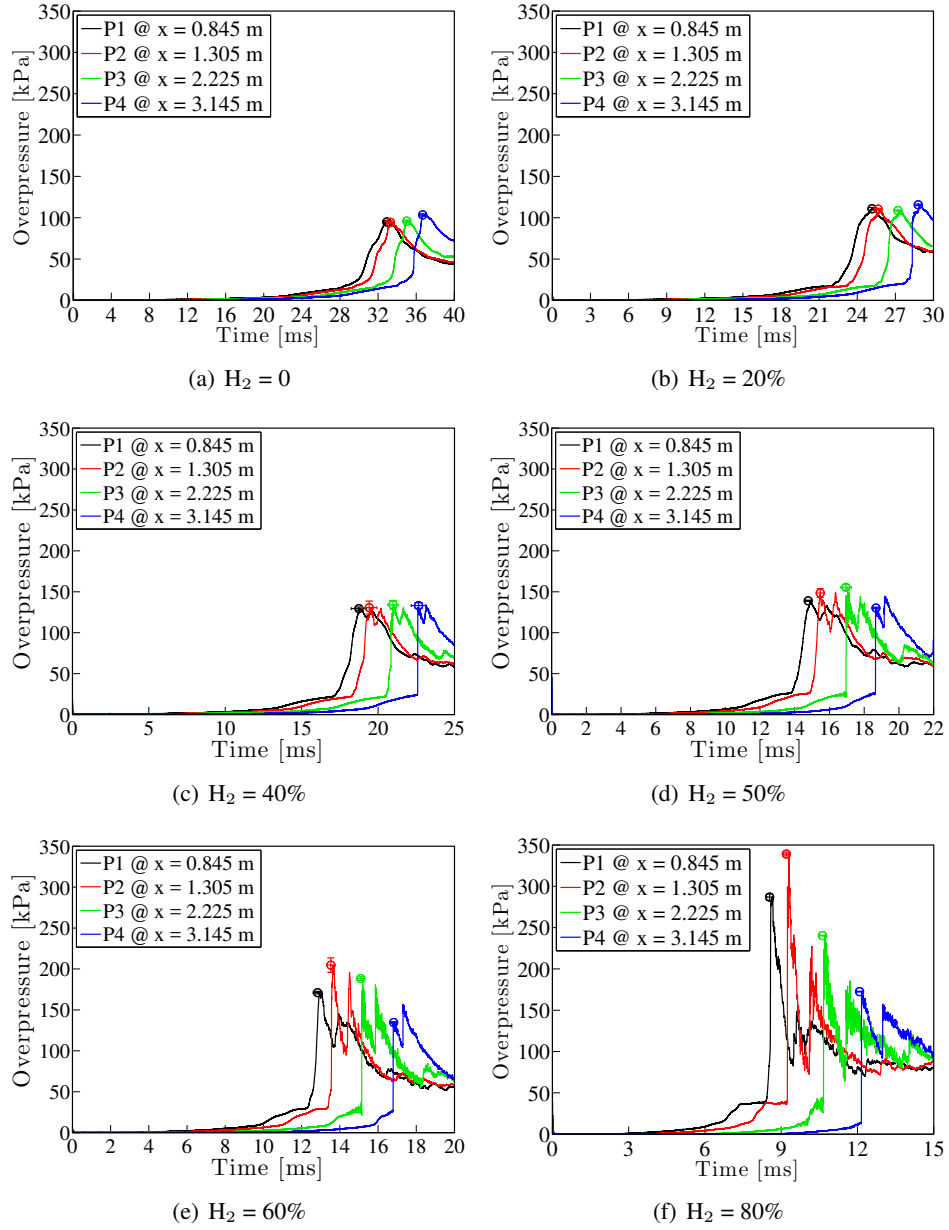


Figure 3.6.: Explosion overpressure development in  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures at  $\Phi = 0.80$ . The errorbars are calculated based on at least three repetitions.

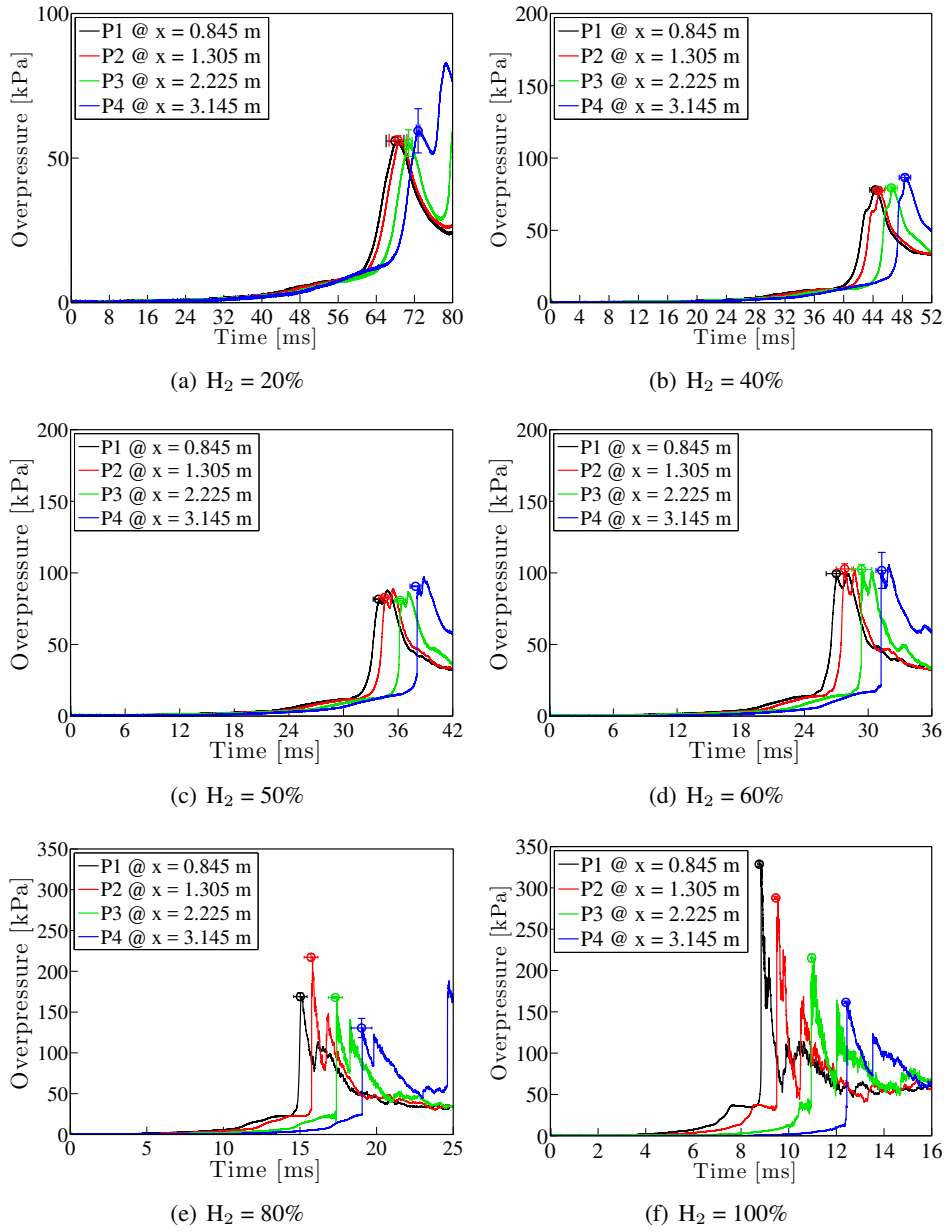


Figure 3.7.: Explosion overpressure development in  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures at  $\Phi = 0.60$ . The errorbars are calculated based on at least three repetitions.

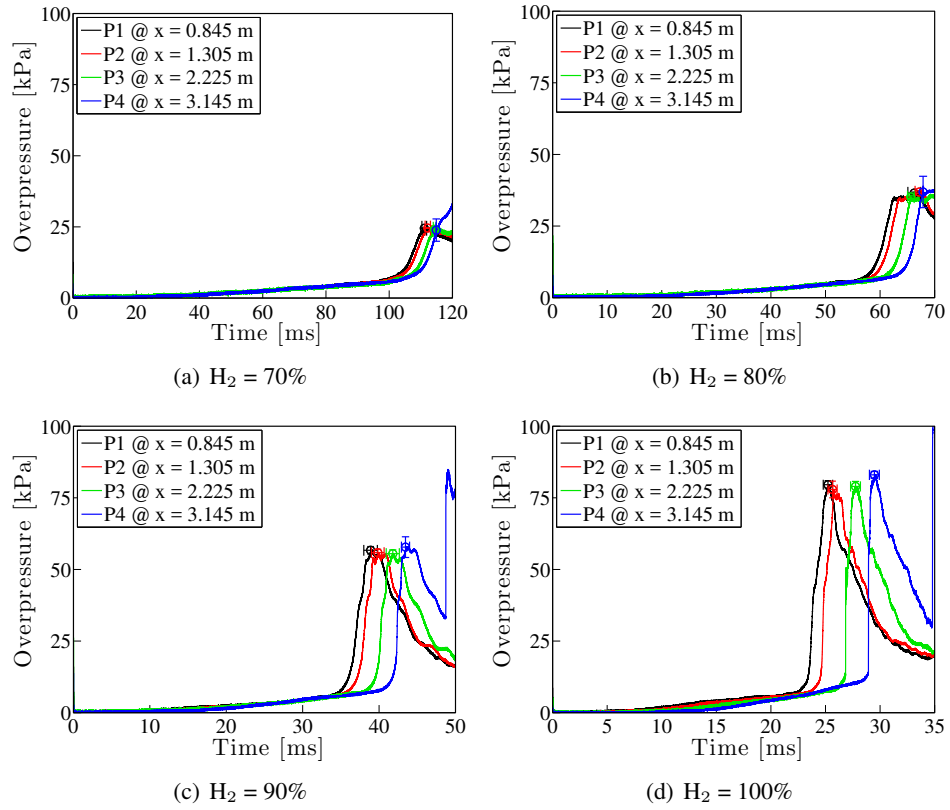


Figure 3.8.: Explosion overpressure development in  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures at  $\Phi = 0.40$ . The errorbars are calculated based on at least three repetitions.

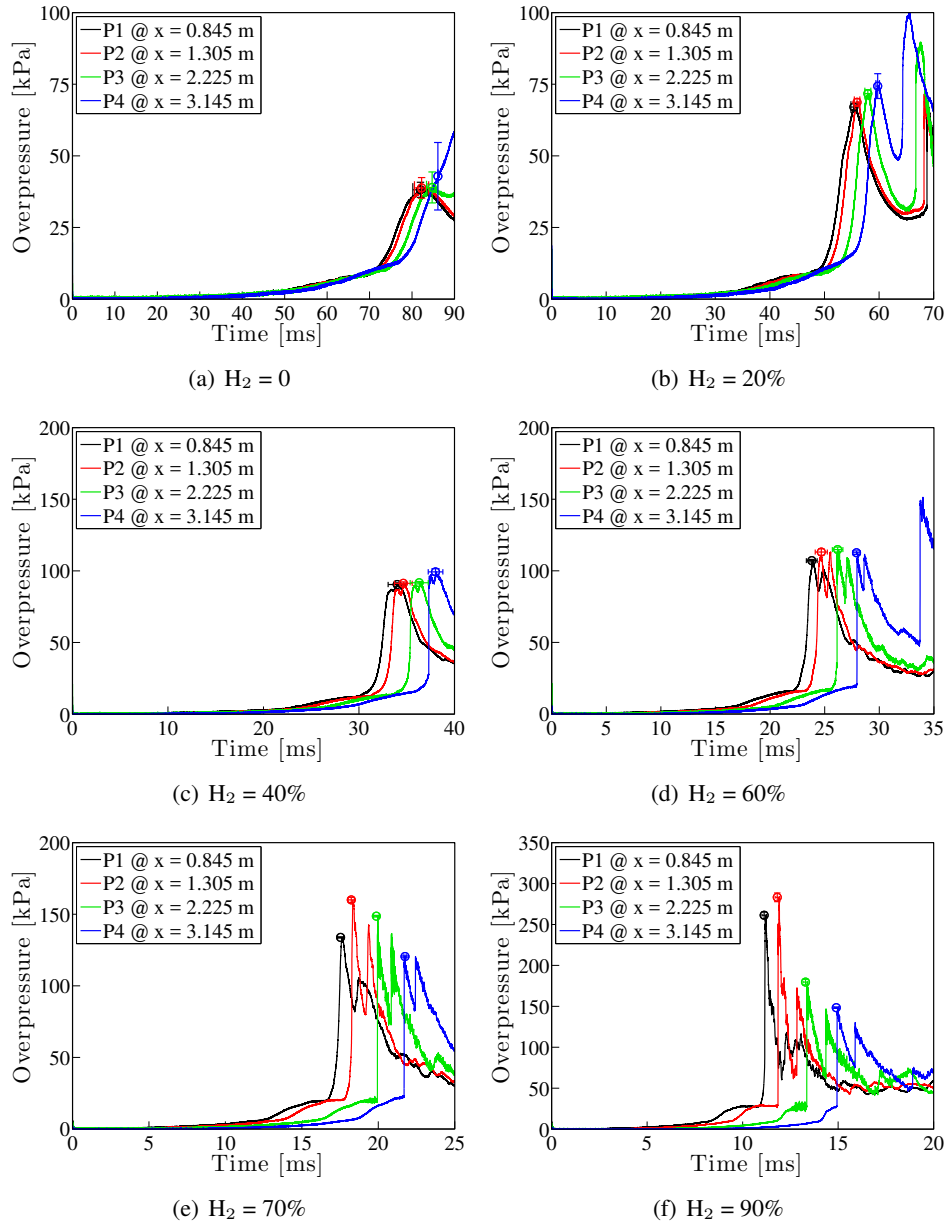


Figure 3.9.: Explosion overpressure development in ternary H<sub>2</sub>/CH<sub>4</sub>/CO mixtures with CO/CH<sub>4</sub> = 3/7 and  $\Phi = 0.60$ . The errorbars are calculated based on at least three repetitions.

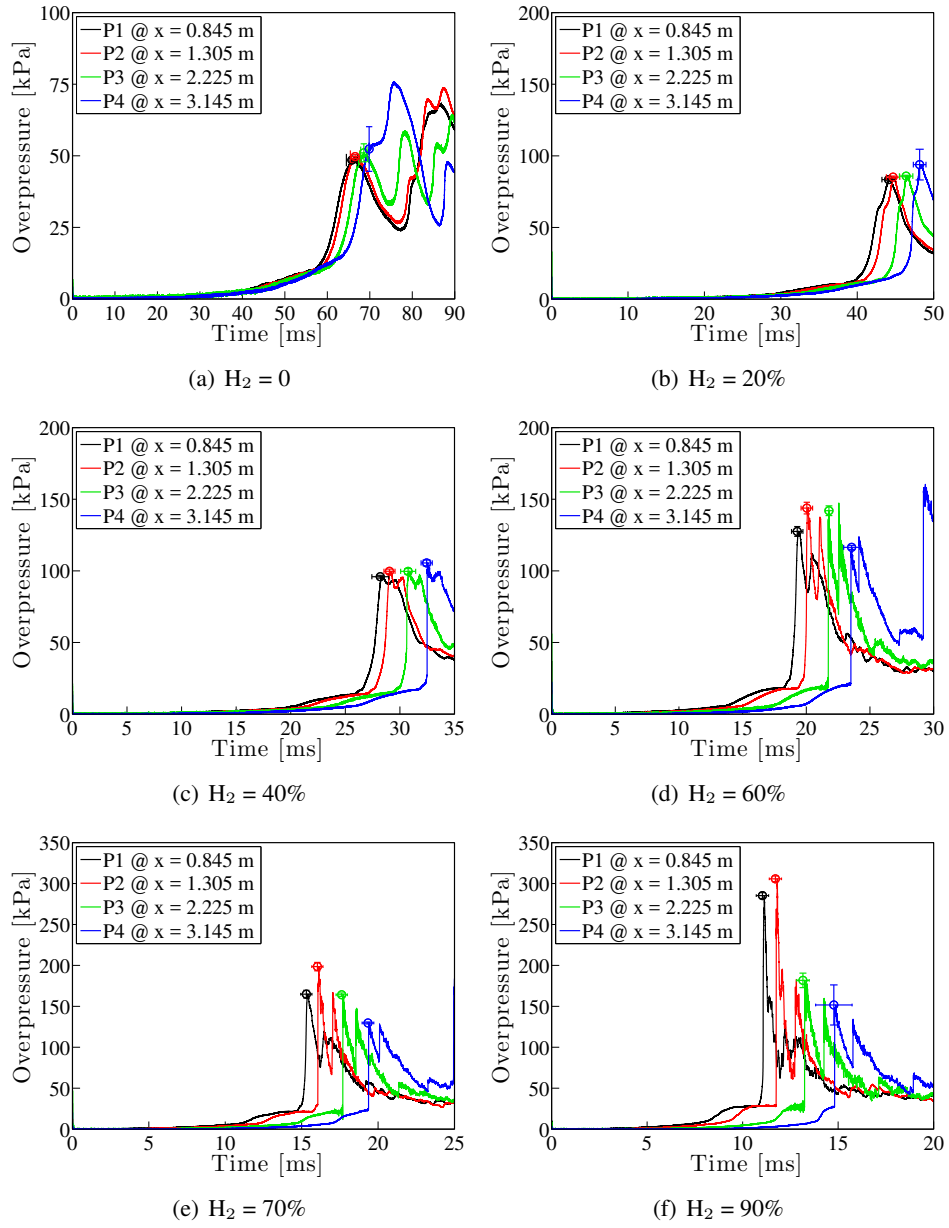


Figure 3.10.: Explosion overpressure development in ternary  $H_2/CH_4/CO$  mixtures with  $CO/CH_4 = 5/5$  and  $\Phi = 0.60$ . The errorbars are calculated based on at least three repetitions.

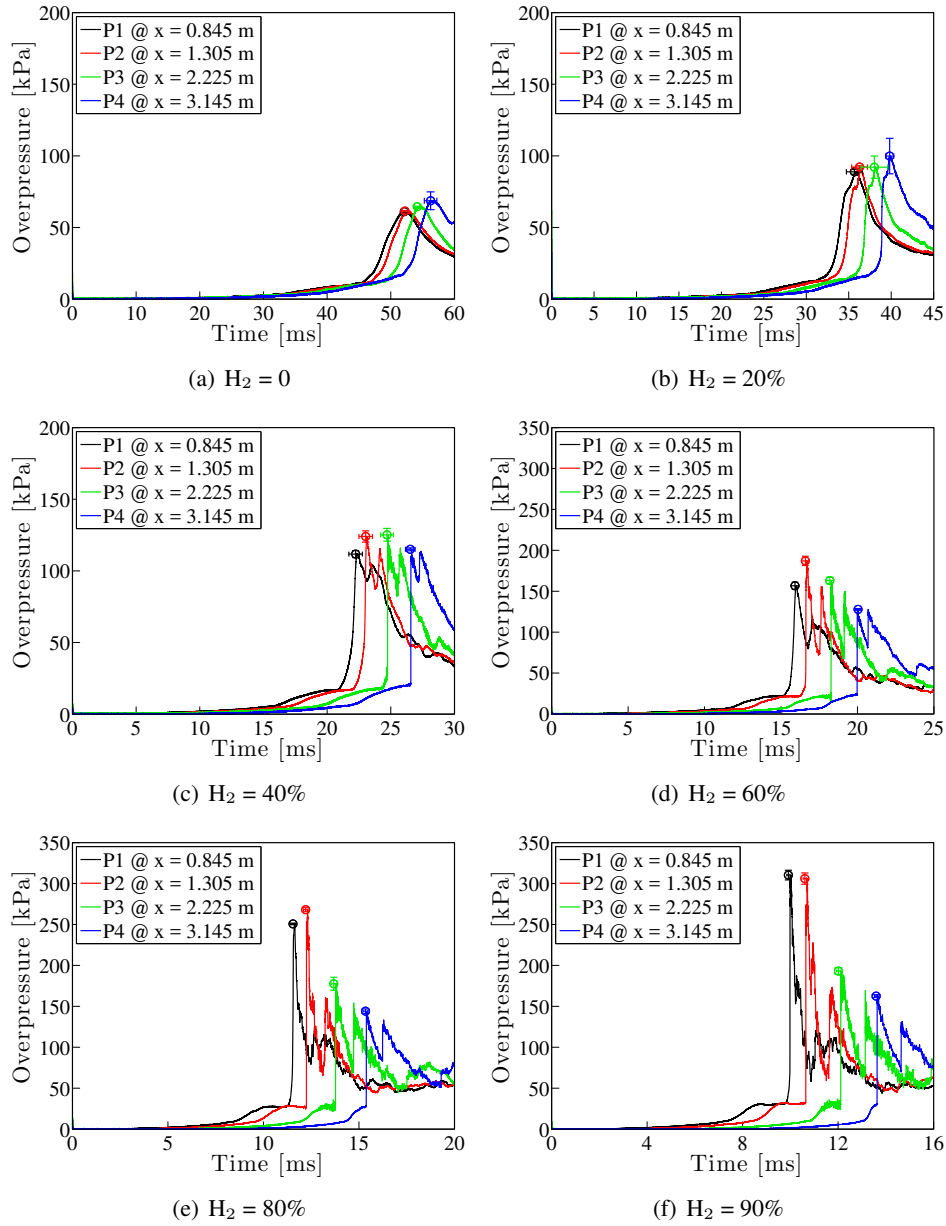


Figure 3.11.: Explosion overpressure development in ternary  $H_2/CH_4/CO$  mixtures with  $CO/CH_4 = 7/3$  and  $\Phi = 0.60$ . The errorbars are calculated based on at least three repetitions.

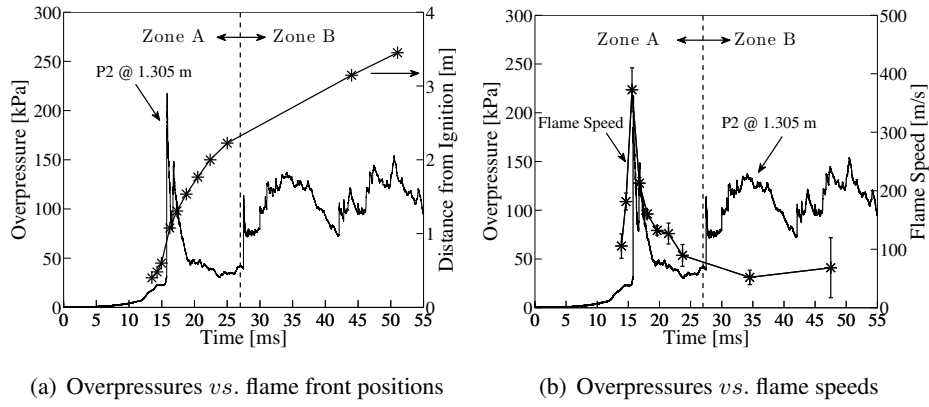


Figure 3.12.: Explosion overpressures, flame front positions and flame speeds in a  $\text{H}_2/\text{CH}_4/\text{Air}$  mixture with  $\Phi = 0.60$  and  $\text{H}_2 = 80\%$ . The pressure is from the second pressure transducer located 1.305 m from ignition and the signals in Zone B are affected by pressure waves reflected from the downstream end.

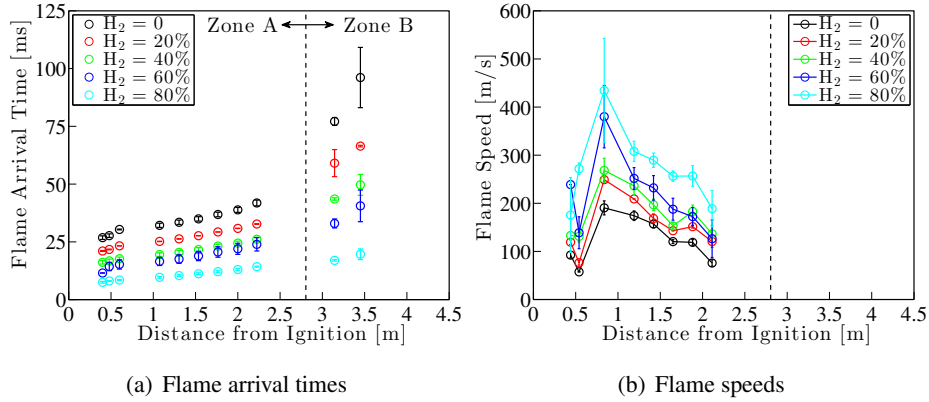


Figure 3.13.: Flame arrival times and flame speeds in  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures with  $\Phi = 0.80$  and different hydrogen content. The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

### 3.4. Flame arrival times and flame speeds

The ions carried with the flame can connect the initially open circuit in the ionisation probe detectors installed along the flame tube to register the flame arrival time. Figure 3.12 shows the overpressure trace recorded 1.035 m away from the ignition end along with flame front positions and flame speeds. The flame speed



was inferred from the probe positions and the measured arrival time differences. For this case, the flame front interacted with the pressure back-reflection at around 27 ms after ignition leading to large uncertainties in the measured flame speeds for the last two ionisation probes.

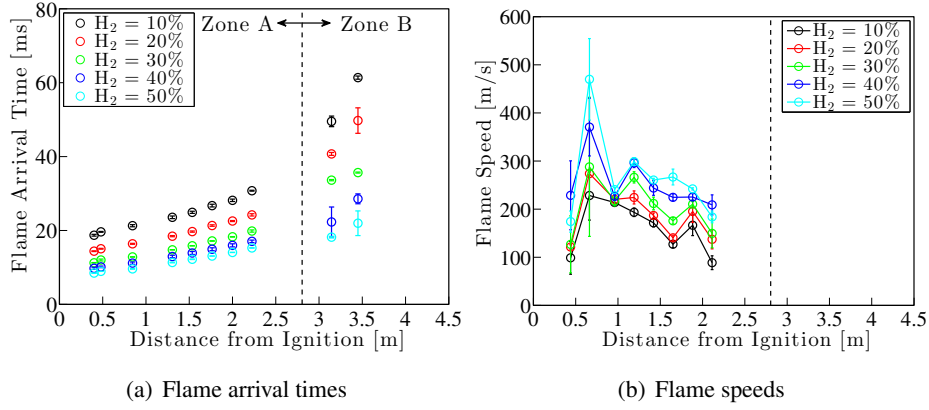


Figure 3.14.: Flame arrival times and flame speeds in  $H_2/CO/Air$  mixtures with  $\Phi = 0.80$  and different hydrogen contents. The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

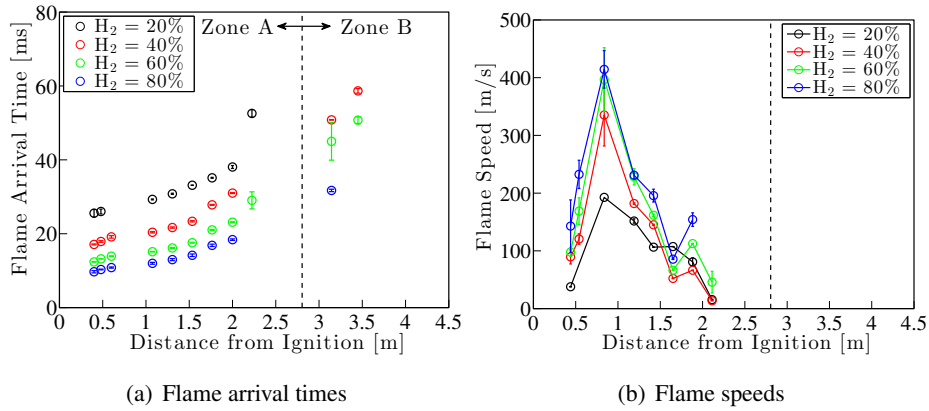


Figure 3.15.: Flame arrival times and flame speeds in  $H_2/CO/Air$  mixtures with  $\Phi = 0.60$  and different hydrogen contents. The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

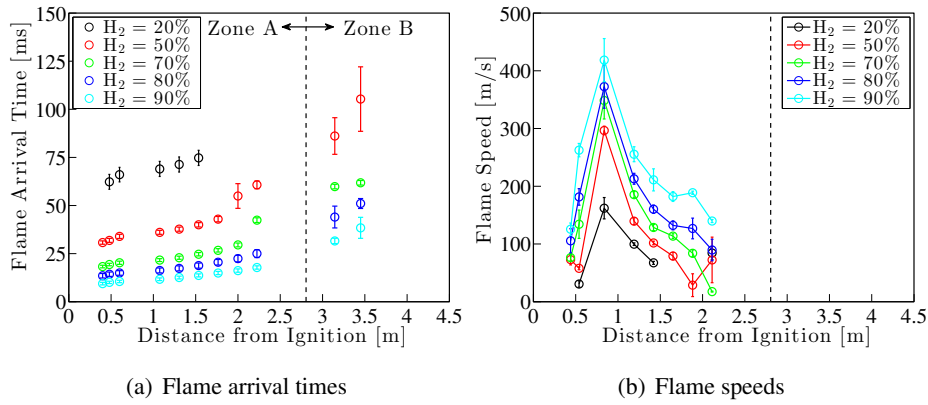


Figure 3.16.: Flame arrival times and flame speeds in  $H_2/CH_4/Air$  mixtures with  $\Phi = 0.60$  and different hydrogen contents. The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

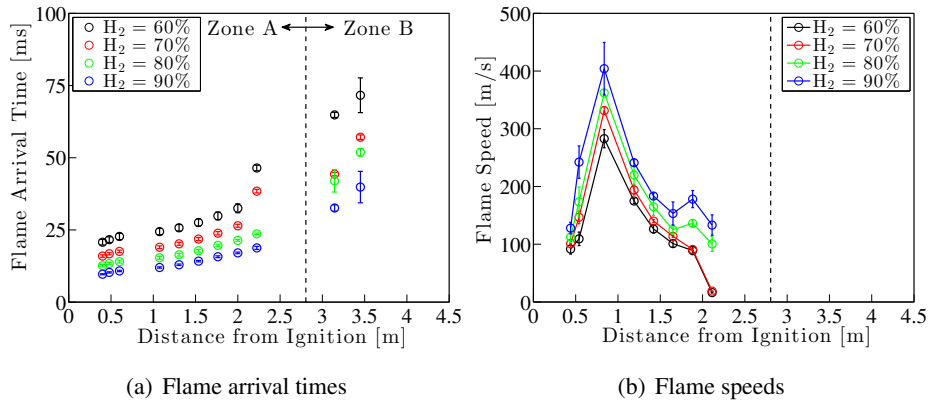


Figure 3.17.: Flame arrival times and flame speeds in ternary  $H_2/CH_4/CO$  mixtures with  $CO/CH_4 = 3/7$  and  $\Phi = 0.60$ . The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

The impact of increasing hydrogen blending on the flame arrival time and flame speed is exemplified in Figure 3.13 using  $H_2/CH_4/Air$  mixtures with  $\Phi = 0.80$ . The flame arrival time decreases and the flame speed increases with higher  $H_2$  concentration due to the elevated mixture reactivity. The flame speed experienced a sharp increase at a distance of 0.837 m from ignition, which is a direct result of the volumetric explosion behind the second obstacle seated 0.360 m from ignition.

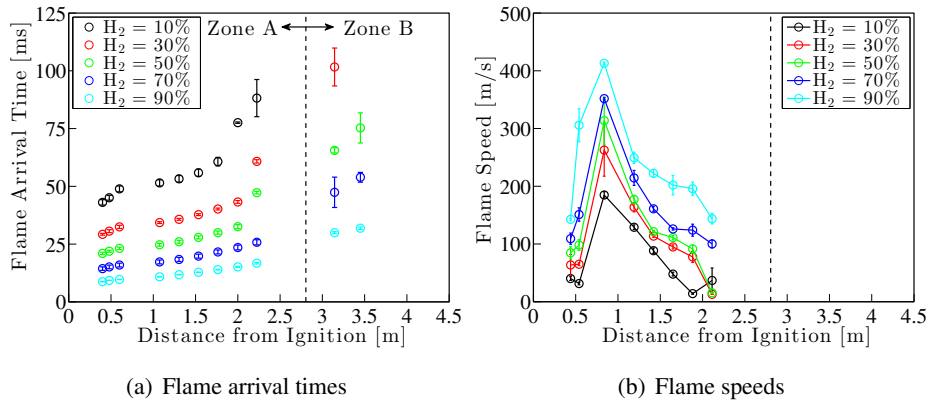


Figure 3.18.: Flame arrival times and flame speeds in ternary  $H_2/CH_4/CO$  mixtures with  $CO/CH_4 = 5/5$  and  $\Phi = 0.60$ . The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

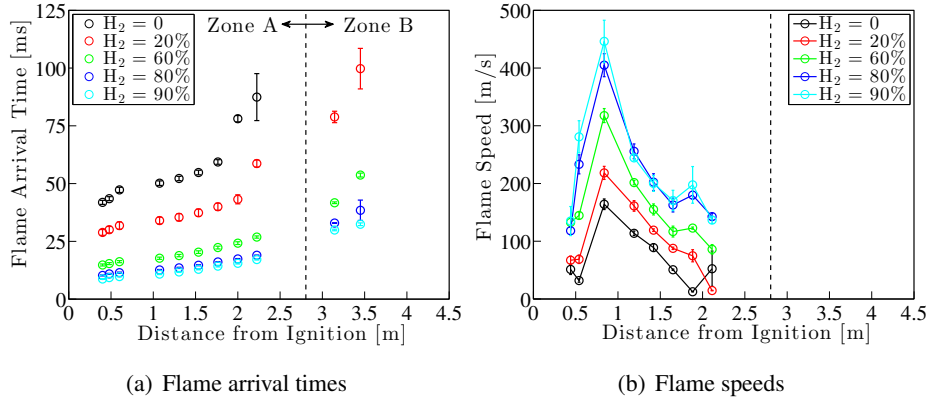


Figure 3.19.: Flame arrival times and flame speeds in ternary  $H_2/CH_4/CO$  mixtures with  $CO/CH_4 = 7/3$  and  $\Phi = 0.60$ . The errorbars are calculated based on at least three runs and the data in Zone B are affected by pressure waves reflected from the downstream end.

This can also be inferred from the coincidence of the arrival time of the maximum velocity and peak overpressure in Figure 3.13(b). Accordingly, the flame speeds measured at this point were used in scaling the peak explosion overpressure. Figures 3.14 – 3.16 give the flame arrival times and flame speeds for  $H_2/CO/Air$  mixtures at equivalence ratios of 0.80 and 0.60 and  $H_2/CH_4/Air$  mixtures at an equivalence ratio of 0.60, respectively. Figures 3.17 – 3.19 show that for ternary

mixtures. They share the same trend in that the flame arrival time decreases with increasing hydrogen concentration and the flame speed increases.

Comprehensive data sets on peak explosion overpressures (from the second pressure transducer located 1.305 m from ignition) and the maximum flame speeds are provided in Tables 3.4 and 3.5 for the binary mixtures and Table 3.6 for the ternary mixtures. For ultra-lean mixtures with an equivalence ratio of 0.40, the ionisation probe detectors were not triggered reliably so the flame speeds have been omitted.

Table 3.4.: Summary of the measurements for binary  $H_2/CO$  mixtures where  $\Delta P$  and FS denote the peak explosion overpressure (1.305 m from ignition) and the maximum flame speed. The Mach number ( $Ma$ ) was calculated based on the maximum flame speed and the calculated speed of sound ( $c_0$ ) in the unreacted mixture. The estimated mixture reactivity Mach numbers were denoted as  $Ma_1^*$ ,  $Ma_2^*$  and the superscript  $(^0)$  in the table indicates the reference value for estimation. For mixtures with an equivalence ratio of 0.40 the ionisation probe detectors were not triggered reliably and the corresponding data has been omitted.

|  | $H_2$ (%)        | 10   | 20                | 30                | 40   | 50   | –    | –    | –    |
|--|------------------|------|-------------------|-------------------|------|------|------|------|------|
|  | $\beta$          | 0.10 | 0.20              | 0.30              | 0.40 | 0.50 | –    | –    | –    |
|  | $\Delta P$ (kPa) | 125  | 178               | 223               | 283  | 323  | –    | –    | –    |
|  | FS (m/s)         | 228  | 274               | 288               | 370  | 470  | –    | –    | –    |
|  | $c_0$ (m/s)      | 351  | 355               | 360               | 364  | 369  | –    | –    | –    |
|  | $Ma$             | 0.65 | 0.77              | 0.80              | 1.02 | 1.27 | –    | –    | –    |
|  | $Ma_1^*$         | 0.54 | 0.79 <sup>0</sup> | 1.02              | 1.25 | 1.51 | –    | –    | –    |
|  | $Ma_2^*$         | 0.61 | 0.79 <sup>0</sup> | 0.95              | 1.09 | 1.25 | –    | –    | –    |
|  | $H_2$ (%)        | 10   | 20                | 30                | 40   | 50   | 60   | 70   | 80   |
|  | $\beta$          | 0.10 | 0.20              | 0.30              | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 |
|  | $\Delta P$ (kPa) | 86   | 103               | 123               | 149  | 200  | 233  | 258  | 286  |
|  | FS (m/s)         | –    | 193               | 252               | 335  | 369  | 397  | –    | 414  |
|  | $c_0$ (m/s)      | 350  | 353               | 357               | 360  | 364  | 367  | 371  | 375  |
|  | $Ma$             | –    | 0.55              | 0.71              | 0.93 | 1.01 | 1.08 | –    | 1.10 |
|  | $Ma_1^*$         | 0.37 | 0.53 <sup>0</sup> | 0.66              | 0.79 | 0.93 | 1.09 | 1.26 | 1.47 |
|  | $Ma_2^*$         | 0.42 | 0.53 <sup>0</sup> | 0.62              | 0.70 | 0.79 | 0.88 | 0.98 | 1.09 |
|  | $H_2$ (%)        | –    | –                 | 30                | 40   | 50   | 60   | 70   | 80   |
|  | $\beta$          | –    | –                 | 0.30              | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 |
|  | $\Delta P$ (kPa) | –    | –                 | 48                | 51   | 62   | 68   | 79   | 83   |
|  | $Ma_1^*$         | –    | –                 | 0.29 <sup>0</sup> | 0.32 | 0.36 | 0.40 | 0.44 | 0.48 |
|  | $Ma_2^*$         | –    | –                 | 0.29 <sup>0</sup> | 0.31 | 0.34 | 0.36 | 0.39 | 0.41 |

Table 3.5.: Summary of the measurements for binary  $\text{H}_2/\text{CH}_4$  mixtures where  $\Delta P$  and FS denote the peak explosion overpressure (1.305 m from ignition) and the maximum flame speed. The Mach number ( $Ma$ ) was calculated based on the maximum flame speed and the calculated speed of sound ( $c_0$ ) in the unreacted mixture. The estimated mixture reactivity Mach numbers were denoted as  $Ma_1^*$ ,  $Ma_2^*$  and the superscript ( $^0$ ) in the table indicates the reference value for estimation. For mixtures with an equivalence ratio of 0.40 the ionisation probe detectors were not triggered reliably and the corresponding data has been omitted.

|                                           | $\text{H}_2$ (%) | 0    | 20                | 40   | 50   | 60   | 70                | 80   | 90   | 100  |
|-------------------------------------------|------------------|------|-------------------|------|------|------|-------------------|------|------|------|
|                                           |                  |      |                   |      |      |      |                   |      |      |      |
| $\text{H}_2/\text{CH}_4$<br>$\Phi = 0.80$ | $\beta$          | 0    | 0.06              | 0.14 | 0.20 | 0.27 | 0.37              | 0.50 | –    | –    |
|                                           | $\Delta P$ (kPa) | 94   | 109               | 137  | 163  | 192  | 257               | 336  | –    | –    |
|                                           | FS (m/s)         | 190  | 249               | 268  | 314  | 380  | 411               | 434  | –    | –    |
|                                           | $c_0$ (m/s)      | 351  | 353               | 357  | 363  | 363  | 367               | 373  | –    | –    |
|                                           | $Ma$             | 0.54 | 0.70              | 0.75 | 0.87 | 1.05 | 1.12              | 1.16 | –    | –    |
|                                           | $Ma_1^*$         | 0.48 | 0.56 <sup>0</sup> | 0.70 | 0.82 | 0.99 | 1.27              | 1.74 | –    | –    |
|                                           | $Ma_2^*$         | 0.50 | 0.56 <sup>0</sup> | 0.66 | 0.73 | 0.84 | 0.99              | 1.24 | –    | –    |
| $\text{H}_2/\text{CH}_4$<br>$\Phi = 0.60$ | $\text{H}_2$ (%) | –    | 20                | 40   | 50   | 60   | 70                | 80   | 90   | 100  |
|                                           | $\beta$          | –    | 0.06              | 0.14 | 0.20 | 0.27 | 0.37              | 0.50 | 0.69 | 1.00 |
|                                           | $\Delta P$ (kPa) | –    | 56                | 77   | 92   | 104  | 138               | 212  | 282  | 342  |
|                                           | FS (m/s)         | –    | 162               | 230  | 297  | 309  | 349               | 373  | 418  | –    |
|                                           | $c_0$ (m/s)      | –    | 351               | 354  | 356  | 359  | 362               | 367  | 373  | 383  |
|                                           | $Ma$             | –    | 0.46              | 0.65 | 0.83 | 0.86 | 0.96              | 1.02 | 1.12 | –    |
|                                           | $Ma_1^*$         | –    | 0.31 <sup>0</sup> | 0.40 | 0.48 | 0.60 | 0.79              | 1.12 | 1.81 | 3.65 |
| $\text{H}_2/\text{CH}_4$<br>$\Phi = 0.40$ | $Ma_2^*$         | –    | 0.31 <sup>0</sup> | 0.37 | 0.42 | 0.49 | 0.59              | 0.76 | 1.07 | 1.74 |
|                                           | $\text{H}_2$ (%) | –    | –                 | –    | –    | –    | 70                | 80   | 90   | 100  |
|                                           | $\beta$          | –    | –                 | –    | –    | –    | 0.37              | 0.50 | 0.69 | 1.00 |
|                                           | P (kPa)          | –    | –                 | –    | –    | –    | 25                | 37   | 58   | 112  |
|                                           | $Ma_1^*$         | –    | –                 | –    | –    | –    | 0.16 <sup>0</sup> | 0.26 | 0.51 | 1.30 |
|                                           | $Ma_2^*$         | –    | –                 | –    | –    | –    | 0.16 <sup>0</sup> | 0.22 | 0.36 | 0.69 |
|                                           |                  | –    | –                 | –    | –    | –    | –                 | –    | –    | –    |

Table 3.6.: Summary of the measurement for ternary  $H_2/CH_4/CO$  mixtures at an equivalence ratio of 0.60, where  $\Delta P$  and FS denote the peak explosion overpressure (1.305 m from ignition) and the maximum flame speed. The Mach number ( $Ma$ ) was calculated based on the maximum flame speed and the calculated speed of sound ( $c_0$ ) in the unreacted mixture. The estimated mixture reactivity Mach numbers were denoted as  $Ma_1^*$ ,  $Ma_2^*$  and the superscript  $(^0)$  in the table indicates the reference value for estimation.

| CO/CH <sub>4</sub> = 3:7 |      |                   |                   |      |      |      |      |      |      |      |
|--------------------------|------|-------------------|-------------------|------|------|------|------|------|------|------|
| H <sub>2</sub> (%)       | 0    | 20                | 40                | 60   | 70   | 80   | 90   | –    | –    | –    |
| $\beta$                  | 0    | 0.07              | 0.18              | 0.33 | 0.43 | 0.56 | 0.74 | –    | –    | –    |
| $\Delta P$ (kPa)         | 40   | 68                | 93                | 115  | 161  | 221  | 290  | –    | –    | –    |
| FS (m/s)                 | 118  | 167               | –                 | 283  | 332  | 362  | 404  | –    | –    | –    |
| $c_0$ (m/s)              | 349  | 352               | 355               | 361  | 364  | 369  | 375  | –    | –    | –    |
| $Ma$                     | 0.34 | 0.48              | –                 | 0.78 | 0.91 | 0.98 | 1.08 | –    | –    | –    |
| $Ma_1^*$                 | 0.31 | 0.38 <sup>0</sup> | 0.51              | 0.76 | 0.98 | 1.36 | 2.05 | –    | –    | –    |
| $Ma_2^*$                 | 0.33 | 0.38 <sup>0</sup> | 0.47              | 0.62 | 0.74 | 0.93 | 1.24 | –    | –    | –    |
| CO/CH <sub>4</sub> = 5:5 |      |                   |                   |      |      |      |      |      |      |      |
| H <sub>2</sub> (%)       | 0    | 10                | 20                | 30   | 40   | 50   | 60   | 70   | 80   | 90   |
| $\beta$                  | 0    | 0.04              | 0.09              | 0.15 | 0.21 | 0.29 | 0.37 | 0.48 | 0.62 | 0.78 |
| $\Delta P$ (kPa)         | 49   | 68                | 85                | 96   | 100  | 116  | 142  | 199  | 257  | 296  |
| FS (m/s)                 | –    | 185               | 222               | 263  | 300  | 314  | 320  | 352  | 384  | 413  |
| $c_0$ (m/s)              | 349  | 350               | 352               | 354  | 356  | 359  | 362  | 366  | 370  | 376  |
| $Ma$                     | –    | 0.53              | 0.63              | 0.74 | 0.84 | 0.87 | 0.88 | 0.96 | 1.04 | 1.10 |
| $Ma_1^*$                 | 0.37 | 0.41              | 0.46 <sup>0</sup> | 0.53 | 0.62 | 0.74 | 0.91 | 1.16 | 1.55 | 2.23 |
| $Ma_2^*$                 | 0.39 | 0.42              | 0.46 <sup>0</sup> | 0.51 | 0.57 | 0.64 | 0.74 | 0.88 | 1.08 | 1.40 |
| CO/CH <sub>4</sub> = 7:3 |      |                   |                   |      |      |      |      |      |      |      |
| H <sub>2</sub> (%)       | 0    | 20                | 40                | 60   | 80   | 90   | –    | –    | –    | –    |
| $\beta$                  | 0    | 0.12              | 0.26              | 0.44 | 0.68 | 0.83 | –    | –    | –    | –    |
| $\Delta P$ (kPa)         | 62   | 92                | 122               | 180  | 274  | 305  | –    | –    | –    | –    |
| FS (m/s)                 | 164  | 218               | –                 | 318  | 405  | 446  | –    | –    | –    | –    |
| $c_0$ (m/s)              | 348  | 352               | 357               | 364  | 372  | 377  | –    | –    | –    | –    |
| $Ma$                     | 0.47 | 0.62              | –                 | 0.87 | 1.09 | 1.18 | –    | –    | –    | –    |
| $Ma_1^*$                 | 0.38 | 0.49 <sup>0</sup> | 0.66              | 0.94 | 1.51 | 2.03 | –    | –    | –    | –    |
| $Ma_2^*$                 | 0.41 | 0.49 <sup>0</sup> | 0.60              | 0.77 | 1.08 | 1.33 | –    | –    | –    | –    |

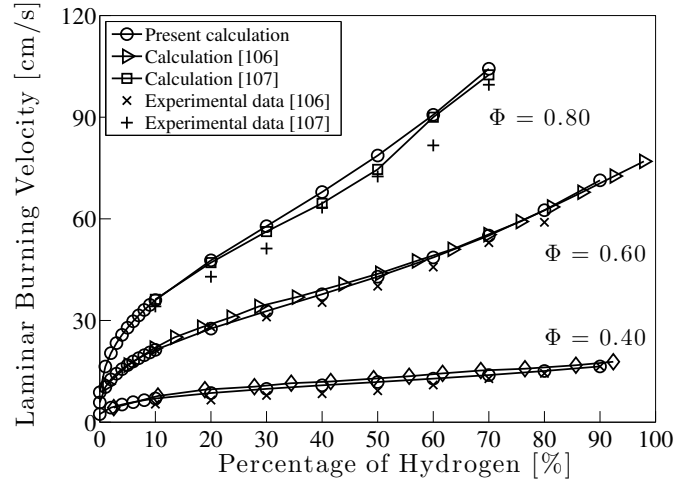
### 3.5. Scaling of the peak explosion overpressure

The wide range of mixtures included in the current study supports the evaluation of scaling laws describing the impact of mixture reactivity for methane and carbon monoxide blends with hydrogen on the explosion overpressure. In this section, the laminar burning properties of the investigated hydrogen enriched fuel mixtures are discussed first. Subsequently, a scaling based on a newly proposed mixture composition parameter ( $\beta$ ) is elaborated and the link between the measured explosion overpressure and flow Mach numbers is explored thereafter.

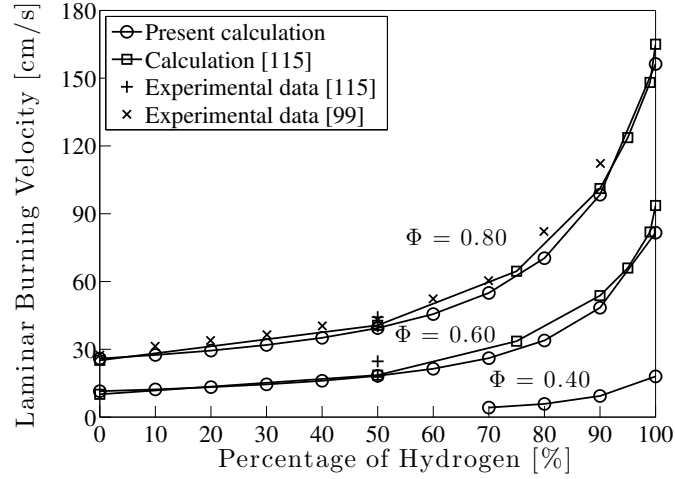
#### 3.5.1. Laminar burning properties

The laminar burning velocity is the speed at which the flame front propagates relative to the unburned mixture in a laminar mode and it represents a physical property of the mixture itself. In hydrogen enriched fuels, the laminar burning velocity is strongly related to the hydrogen substitution levels due to the related mixture reactivity. Zhang et al. [106] measured the laminar flame speeds of lean premixed  $H_2/CO/Air$  mixtures over a wide range of  $H_2$  content using particle image velocimetry. Simulations were also performed and the results show that the laminar burning velocity increased significantly with  $H_2$  content when it was less than 15% and gradually above 15%. Similar results were found by Bouvet et al. [107], reporting that the laminar flame speeds, obtained using chemiluminescence and schlieren techniques, of  $CO/Air$  mixtures were very sensitive to small hydrogen additions at an equivalence ratio of 0.6. Vagelopoulos et al. [108] measured the laminar flame speeds and strain rates in mixtures of  $CO$  with  $H_2$ ,  $CH_4$  and air using the counterflow twin-flame technique. The laminar flame speed was found to be very sensitive to the stretch rate in ultra-lean mixtures [109]. Fu et al. [110] studied the laminar flame speed and flame structure of a Bunsen burner using OH Planar Laser Induced Fluorescence (PLIF) with the enhancement effect of  $H_2$  analysed in terms of chemical kinetics. The difference in the colour of hydrogen enriched  $CO$  flames was attributed to the radiation spectrum of intermediate radicals produced in combustion. Natarajan et al. [111,112] measured the laminar flame speed of lean  $H_2/CO/CO_2/O_2/He$  mixtures with  $H_2$  levels from 20% – 90% and the influence of pressure and preheat was investigated. Numerical simulations based on a  $CO/H_2$  mechanism from Davis et al. [113] and a  $C1$  mechanism from Li et al. [114] were also performed. It turned out that the simulation over-predicted the temperature dependence for mixtures with medium to high levels of  $H_2$ .





(a)  $H_2/CO$



(b)  $H_2/CH_4$

Figure 3.20.: Calculated laminar burning velocities of  $H_2/CO$  and  $H_2/CH_4$  mixtures at an initial temperature of 298 K and pressure of 101.325 kPa.

Laminar burning velocities of  $H_2/CH_4$  mixtures have also been well studied [99, 115–119]. Donohoe et al. [115] obtained the laminar flame speeds at 1 and 5 atm for initial temperatures of either 300 or 450 K with the hydrogen content varied between 50% and 90% of the fuel mixture by volume. A constant-volume combustion chamber was used with a quartz window installed to allow optical access. The initial flame propagation was discussed by Wang et al. [98], focusing on the impact of hydrogen addition and concluded that the enhancement effect of hydro-

gen addition was more pronounced under lean conditions. The impact of initial pressure and hydrogen concentration on laminar burning characteristics in natural gas/hydrogen mixtures was also studied by Miao et al. [117] and Zheng et al. [118]. It was found that hydrogen increased the laminar burning velocity and flame instability and that elevated initial pressures lead to decreased flame stability. Tang et al. [99] gave a comprehensive review of the recent progress in hydrogen enriched combustion covering a broad range of topics such as the minimum ignition energy, laminar burning velocity and flame instability.

The laminar flame properties were determined for all the gas mixtures studied using an in-house Fortran code [120] with the chemistry adopted from Kraus and Lindstedt [121] featuring 33 species and 168 elementary reactions. The calculation domain of 7 mm was resolved using 330 control volumes and integrated to steady state using a time step of  $1 \times 10^{-5}$  s. The calculated laminar burning velocities ( $S_L$ ) of binary mixtures show good agreement with experimental and numerical results from literature [99, 106, 107, 115] as depicted in Figure 3.20. The laminar burning velocity increases with hydrogen blending fraction and equivalence ratio for both fuel blends. The influence of hydrogen content is more significant at higher equivalence ratios, which is reflected by the steeper slope. For  $H_2/CO$  mixtures, the laminar burning velocity increases rapidly at low hydrogen content, i.e.  $H_2 < 10\%$ , followed by a linear increase at higher  $H_2$  fractions with an  $\Phi$  dependent slope. This phenomenon was also observed by Zhang et al. [106]. By contrast,  $CH_4$  exhibits a characteristically different impact on the hydrogen combustion chemistry as illustrated in Figure 3.20(b). This suggest a stronger inhibiting impact of  $CH_4$  on the  $H_2$  chemistry than  $CO$ , in particular at low blending fractions. The laminar burning velocity of the ternary mixtures ( $H_2/CH_4/CO$ ), shown in Figure 3.21, increases with the  $CO$  substitutions for  $CH_4$ . However, the slopes are governed by the  $CH_4$  chemistry.

The transient flame acceleration in the current experimental configuration is dependent upon the mixture reactivity (e.g.  $S_L$ ) and turbulence intensity ahead of the flame front due to the flame surface area enhancement via wrinkling. The flow acceleration ahead of the flame front is affected by the expansion ratio ( $\tau$ ) of the hot products as defined in Eq. (3.2), where  $\rho_u$  and  $\rho_b$  are the initial and burned gas density, respectively.

$$\tau = \frac{\rho_u - \rho_b}{\rho_b} \quad (3.2)$$

The related physical properties, namely laminar burning velocity ( $S_L$ ), adiabatic flame temperature ( $T_{ad}$ ), expansion ratio ( $\tau$ ) and density of the unburned gas mixtures ( $\rho_u$ ) are listed in Tables 3.7 and 3.8 for binary mixtures and Table 3.9 for ternary mixtures. The thermal expansion ratio increases with the equivalence ratio as a result of the increased heat release for all fuel blends. Increasing  $H_2$  addition to CO results in a decreasing  $\tau$  due to a modest reduction in the adiabatic flame temperature. By contrast,  $H_2$  additions to  $CH_4$  increase  $T_{ad}$  due to the reduced thermal nitrogen ballast effect in the mixture. However, with increasing hydrogen concentrations the number of moles in the products reduces, which dampens the thermal expansion. The combined effect leads to a decreasing  $\tau$  for higher equivalence ratios (0.80 and 0.60) and a slightly increasing trend for lower equivalence ratios (0.40) with  $H_2$  blending fraction. In ternary mixtures,  $T_{ad}$  increases as a result of a more dominant effect of  $CH_4$  than CO and  $\tau$  decreases marginally with hydrogen blending fractions.

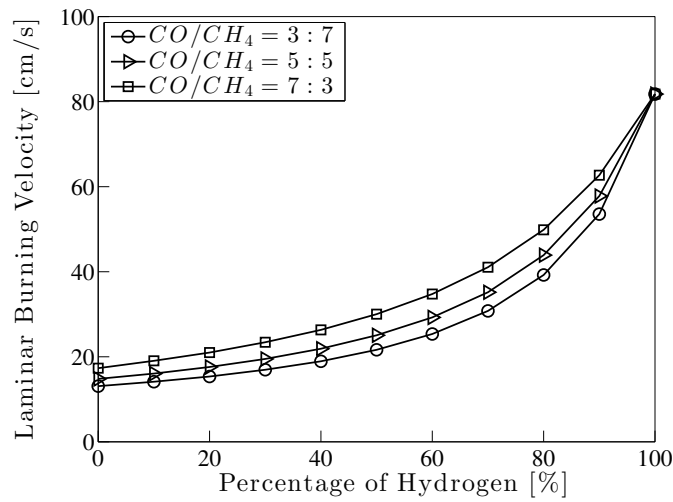


Figure 3.21.: Calculated laminar burning velocities of  $H_2/CH_4/CO$  mixtures at an initial temperature of 298 K and a pressure of 101.325 kPa.

Table 3.7.: Physical properties of H<sub>2</sub>/CO mixtures, where  $\rho_0$  is the density of the unburned gas mixtures,  $\nu$  the kinematic viscosity,  $T_{ad}$  the adiabatic flame temperature,  $\tau$  the expansion ratio,  $S_L$  the laminar burning velocity and  $Re$  the Reynolds number calculated using Eq. (3.20)

| $\Phi = 0.80$      |                               |                                       |              |        |             |       |
|--------------------|-------------------------------|---------------------------------------|--------------|--------|-------------|-------|
| H <sub>2</sub> [%] | $\rho_0$ [kg/m <sup>3</sup> ] | $\nu \times 10^5$ [m <sup>2</sup> /s] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$  |
| 10                 | 1.14                          | 1.60                                  | 2217         | 5.57   | 0.36        | 6778  |
| 20                 | 1.12                          | 1.64                                  | 2211         | 5.56   | 0.48        | 8865  |
| 30                 | 1.09                          | 1.68                                  | 2204         | 5.54   | 0.58        | 10393 |
| 40                 | 1.06                          | 1.72                                  | 2197         | 5.51   | 0.68        | 11795 |
| 50                 | 1.04                          | 1.77                                  | 2190         | 5.49   | 0.79        | 13403 |
| $\Phi = 0.60$      |                               |                                       |              |        |             |       |
| H <sub>2</sub> [%] | $\rho_0$ [kg/m <sup>3</sup> ] | $\nu \times 10^5$ [m <sup>2</sup> /s] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$  |
| 10                 | 1.15                          | 1.60                                  | 1931         | 4.85   | 0.21        | 3532  |
| 20                 | 1.13                          | 1.63                                  | 1920         | 4.82   | 0.28        | 4604  |
| 30                 | 1.11                          | 1.66                                  | 1908         | 4.79   | 0.33        | 5302  |
| 40                 | 1.09                          | 1.69                                  | 1896         | 4.75   | 0.38        | 5954  |
| 50                 | 1.07                          | 1.72                                  | 1884         | 4.72   | 0.43        | 6579  |
| 60                 | 1.05                          | 1.76                                  | 1872         | 4.69   | 0.49        | 7319  |
| 70                 | 1.02                          | 1.80                                  | 1860         | 4.65   | 0.55        | 7924  |
| 80                 | 1.00                          | 1.83                                  | 1848         | 4.61   | 0.63        | 8836  |
| 90                 | 0.98                          | 1.87                                  | 1837         | 4.58   | 0.72        | 9843  |
| $\Phi = 0.40$      |                               |                                       |              |        |             |       |
| H <sub>2</sub> [%] | $\rho_0$ [kg/m <sup>3</sup> ] | $\nu \times 10^5$ [m <sup>2</sup> /s] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$  |
| 30                 | 1.13                          | 1.63                                  | 1503         | 3.69   | 0.10        | 1325  |
| 40                 | 1.11                          | 1.65                                  | 1492         | 3.66   | 0.11        | 1422  |
| 50                 | 1.10                          | 1.68                                  | 1481         | 3.63   | 0.12        | 1528  |
| 60                 | 1.08                          | 1.70                                  | 1470         | 3.60   | 0.13        | 1615  |
| 70                 | 1.07                          | 1.73                                  | 1458         | 3.57   | 0.14        | 1711  |
| 80                 | 1.05                          | 1.75                                  | 1447         | 3.53   | 0.15        | 1784  |
| 90                 | 1.04                          | 1.78                                  | 1435         | 3.50   | 0.17        | 1989  |

Table 3.8.: Physical properties of  $\text{H}_2/\text{CH}_4$  mixtures, where  $\rho_0$  is the density of the unburned gas mixtures,  $\nu$  the kinematic viscosity,  $T_{ad}$  the adiabatic flame temperature,  $\tau$  the expansion ratio,  $S_L$  the laminar burning velocity and  $Re$  the Reynolds number calculated using Eq. (3.20)

| $\Phi = 0.80$    |                                     |                                             |              |        |             |       |
|------------------|-------------------------------------|---------------------------------------------|--------------|--------|-------------|-------|
| $\text{H}_2$ [%] | $\rho_0$ [ $\text{kg}/\text{m}^3$ ] | $\nu \times 10^5$ [ $\text{m}^2/\text{s}$ ] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$  |
| 0                | 1.14                                | 1.58                                        | 1994         | 5.70   | 0.26        | 5047  |
| 20               | 1.12                                | 1.61                                        | 1996         | 5.65   | 0.29        | 5489  |
| 40               | 1.10                                | 1.65                                        | 2011         | 5.63   | 0.35        | 6487  |
| 50               | 1.08                                | 1.67                                        | 2021         | 5.61   | 0.39        | 7076  |
| 60               | 1.07                                | 1.70                                        | 2033         | 5.58   | 0.45        | 8052  |
| 70               | 1.04                                | 1.75                                        | 2048         | 5.55   | 0.55        | 9469  |
| 80               | 1.01                                | 1.80                                        | 2070         | 5.50   | 0.70        | 11615 |
| $\Phi = 0.60$    |                                     |                                             |              |        |             |       |
| $\text{H}_2$ [%] | $\rho_0$ [ $\text{kg}/\text{m}^3$ ] | $\nu \times 10^5$ [ $\text{m}^2/\text{s}$ ] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$  |
| 20               | 1.14                                | 1.60                                        | 1674         | 4.58   | 0.13        | 2090  |
| 40               | 1.12                                | 1.63                                        | 1689         | 4.58   | 0.16        | 2527  |
| 50               | 1.11                                | 1.65                                        | 1699         | 4.58   | 0.18        | 2818  |
| 60               | 1.09                                | 1.67                                        | 1712         | 4.58   | 0.21        | 3228  |
| 70               | 1.07                                | 1.70                                        | 1728         | 4.58   | 0.26        | 3902  |
| 80               | 1.05                                | 1.75                                        | 1749         | 4.57   | 0.34        | 4998  |
| 90               | 1.01                                | 1.81                                        | 1780         | 4.56   | 0.49        | 6917  |
| 100              | 0.96                                | 1.92                                        | 1827         | 4.54   | 0.82        | 10903 |
| $\Phi = 0.40$    |                                     |                                             |              |        |             |       |
| $\text{H}_2$ [%] | $\rho_0$ [ $\text{kg}/\text{m}^3$ ] | $\nu \times 10^5$ [ $\text{m}^2/\text{s}$ ] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$  |
| 70               | 1.11                                | 1.66                                        | 1343         | 3.39   | 0.04        | 487   |
| 80               | 1.09                                | 1.69                                        | 1357         | 3.40   | 0.06        | 719   |
| 90               | 1.06                                | 1.73                                        | 1382         | 3.42   | 0.09        | 1054  |
| 100              | 1.02                                | 1.80                                        | 1424         | 3.47   | 0.18        | 2052  |

Table 3.9.: Physical properties of  $\text{H}_2/\text{CH}_4/\text{CO}$  mixtures with  $\Phi = 0.60$ , where  $\rho_0$  is the density of the unburned gas mixtures,  $\nu$  the kinematic viscosity,  $T_{ad}$  the adiabatic flame temperature,  $\tau$  the expansion ratio,  $S_L$  the laminar burning velocity and  $Re$  the Reynolds number calculated using Eq. (3.20)

| CO/CH <sub>4</sub> = 3 : 7 |                               |                                       |              |        |             |      |
|----------------------------|-------------------------------|---------------------------------------|--------------|--------|-------------|------|
| H <sub>2</sub> [%]         | $\rho_0$ [kg/m <sup>3</sup> ] | $\nu \times 10^5$ [m <sup>2</sup> /s] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$ |
| 0                          | 1.15                          | 1.58                                  | 1690         | 4.61   | 0.13        | 2120 |
| 20                         | 1.14                          | 1.61                                  | 1700         | 4.60   | 0.15        | 2420 |
| 40                         | 1.11                          | 1.64                                  | 1714         | 4.60   | 0.19        | 2985 |
| 60                         | 1.09                          | 1.68                                  | 1733         | 4.59   | 0.25        | 3829 |
| 70                         | 1.07                          | 1.72                                  | 1747         | 4.58   | 0.31        | 4653 |
| 80                         | 1.04                          | 1.76                                  | 1764         | 4.57   | 0.39        | 5679 |
| 90                         | 1.01                          | 1.82                                  | 1782         | 4.53   | 0.54        | 7540 |
| CO/CH <sub>4</sub> = 5 : 5 |                               |                                       |              |        |             |      |
| H <sub>2</sub> [%]         | $\rho_0$ [kg/m <sup>3</sup> ] | $\nu \times 10^5$ [m <sup>2</sup> /s] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$ |
| 0                          | 1.15                          | 1.58                                  | 1721         | 4.64   | 0.15        | 2459 |
| 10                         | 1.14                          | 1.59                                  | 1725         | 4.64   | 0.16        | 2600 |
| 20                         | 1.13                          | 1.61                                  | 1730         | 4.63   | 0.18        | 2894 |
| 30                         | 1.12                          | 1.62                                  | 1735         | 4.63   | 0.19        | 3012 |
| 40                         | 1.11                          | 1.64                                  | 1742         | 4.62   | 0.22        | 3450 |
| 50                         | 1.10                          | 1.67                                  | 1749         | 4.61   | 0.25        | 3878 |
| 60                         | 1.08                          | 1.70                                  | 1757         | 4.60   | 0.29        | 4409 |
| 70                         | 1.06                          | 1.73                                  | 1768         | 4.59   | 0.35        | 5213 |
| 80                         | 1.03                          | 1.78                                  | 1781         | 4.57   | 0.44        | 6345 |
| 90                         | 1.00                          | 1.84                                  | 1799         | 4.55   | 0.58        | 8048 |
| CO/CH <sub>4</sub> = 7 : 3 |                               |                                       |              |        |             |      |
| H <sub>2</sub> [%]         | $\rho_0$ [kg/m <sup>3</sup> ] | $\nu \times 10^5$ [m <sup>2</sup> /s] | $T_{ad}$ [K] | $\tau$ | $S_L$ [m/s] | $Re$ |
| 0                          | 1.16                          | 1.58                                  | 1769         | 4.70   | 0.17        | 2825 |
| 20                         | 1.13                          | 1.61                                  | 1774         | 4.68   | 0.21        | 3388 |
| 40                         | 1.11                          | 1.66                                  | 1780         | 4.65   | 0.26        | 4099 |
| 60                         | 1.07                          | 1.71                                  | 1789         | 4.62   | 0.35        | 5290 |
| 80                         | 1.02                          | 1.80                                  | 1802         | 4.58   | 0.50        | 7115 |
| 90                         | 0.99                          | 1.85                                  | 1811         | 4.55   | 0.63        | 8654 |

### 3.5.2. Scaling with a new $\beta$ parameter

The mixture reactivity is strongly dependent on hydrogen concentration as shown in the previous section in terms of the laminar burning velocity. The hydrogen content of the fuel blend can be described via Eq. (3.3), where  $C_H$  and  $C_F$  represent the mole fractions of  $H_2$  and  $CH_4/CO$ , respectively.

$$\alpha = \frac{C_H}{C_H + C_F} \quad (3.3)$$

Wu et al. [122] pointed out that the conventional composition parameter, defined in Eq. (3.3), imposes a disproportionately larger impact of the hydrogen concentration on the response of hydrocarbon flames. This can be attributed to the fact that hydrocarbons require more oxygen compared to  $H_2$  for a complete oxidation. The combustion in air accordingly results in a reduced heat release effect due to the thermal ballast of nitrogen. The non-linear behaviour with increasing  $H_2$  content in methane is also evident in the laminar burning properties as discussed in Section 3.5.1. Yu et al. [123] accordingly proposed an alternative scaling parameter ( $R_H$ ) to better represent the relative amount of hydrogen addition as shown in Eq. (3.4).

$$R_H = \frac{C_H + C_H/(C_H/C_A)_{st}}{C_F + [C_A - C_H/(C_H/C_A)_{st}]} \quad (3.4)$$

The above expression relates the amount of hydrogen and the amount of air required for full oxidation to the amount of the hydrocarbons and the residual amount of air. The  $R_H$  parameter has been shown to correlate the laminar burning velocity well for low  $H_2$  blending fractions [122–124]. An alternative scaling relationship may readily be formed as shown in Eq. (3.5), where the  $\beta$  parameter describes the mixture composition based on the amount of air required to fully oxidise the fuel.

$$\beta = \left[ \frac{C_H}{(C_H/C_A)_{st}} \right] / \left[ \frac{C_H}{(C_H/C_A)_{st}} + \sum_{k=1}^n \frac{C_{F,k}}{(C_F/C_A)_{st,k}} \right] \quad (3.5)$$

In Eq. (3.5),  $n$  is the number of fuel components,  $C_H$  the  $H_2$  mole fraction,  $C_{F,k}$  the mole fraction of fuel component  $k$  ( $CO$  and/or  $CH_4$ ) and  $(C_F/C_A)_{st,k}$  the stoichiometric fuel to air volumetric ratio for the pure fuel component  $k$  (e.g.  $(C_F/C_A)_{st,CH_4} = 0.105$ ,  $(C_F/C_A)_{st,CO} = 0.420$  and  $(C_H/C_A)_{st,H_2} = 0.420$ ). It is worth noting that the  $\beta$  parameter is bounded between 0 and 1, while  $R_H$  can exceed unity for high  $H_2$  concentrations.

The peak overpressure describes the severity of an explosion and is a key factor in hazard assessments. A direct comparison of the influence of hydrogen concentration and equivalence ratio on the peak overpressure in  $\text{H}_2/\text{CO}/\text{Air}$  and  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures is shown in Figure 3.22(a). The explosion overpressure (normalised by the initial pressure) increases linearly with hydrogen mole fraction for  $\text{H}_2/\text{CO}/\text{Air}$  mixtures. By contrast, increasing hydrogen addition for  $\text{CH}_4$  mixtures yields a delayed, but subsequently sharp increase in the overpressure. The enhancement for  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures becomes significant for hydrogen levels higher than 50%, which is consistent with previously reported results covering a wide range of scales [12, 100, 101]. The current results further show that  $\text{CH}_4$  has a stronger inhibiting effect on the  $\text{H}_2$  chemistry compared to CO. It can be noted that the  $\alpha$  parameter cannot be used to correlate the peak overpressures for the current  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures linearly. The non-linear impact of  $\text{H}_2$  content in  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures in terms of the explosion overpressure has been well established [12, 100, 101] and is readily evident in the laminar burning properties (i.e.  $S_L$ ).

$$R^2 = 1 - \frac{\sum_{i=1}^N (P_i^* - \hat{P}_i^*)^2}{\sum_{i=1}^N (P_i^* - \bar{P}^*)^2} \quad (3.6)$$

$$\epsilon = \sqrt{\frac{\sum_{i=1}^N (\frac{\hat{P}_i^* - P_i^*}{\bar{P}_i^*})^2}{N}} \quad (3.7)$$

The scaling parameter  $R_H$  was originally proposed for correlating laminar burning velocities at low hydrogen concentrations [123] and it removes some of the non-linearity effects of hydrogen concentration on the peak explosion overpressure for  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures as shown in Figure 3.22(b). It further removes the discrepancy of the hydrogen influence on the overpressure between the two binary fuel mixtures to a certain degree. Linear regression models were fitted for different stoichiometries with the results shown in Table 3.10 and evaluated in terms of the  $R^2$  norm (see Eq. (3.6)) and the linear prediction uncertainty ( $\epsilon$ ) as defined in Eq. (3.7), where  $P^*$  is the measured normalised peak overpressure,  $\bar{P}^*$  the average of the measured pressure,  $\hat{P}^*$  the linear prediction and  $N$  the total number of data points. The  $R_H$  scaling yields a good  $R^2$  value for  $\Phi = 0.8$  with increased uncertainties for equivalence ratios of 0.60 and 0.40 as shown in Figure 3.22(b) and Table 3.10. As noted above, the formulation was originally derived to correlate laminar burning velocities at low hydrogen contents and the current deviations are



accordingly not unexpected.

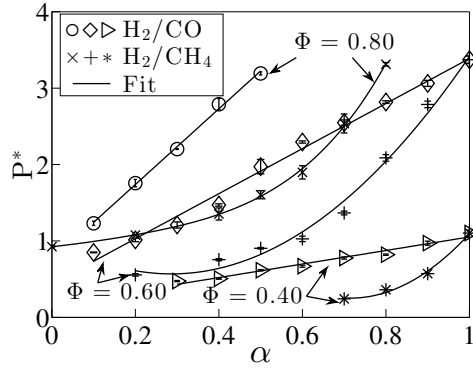
The new  $\beta$  parameter (see Eq. (3.5)) was found successful in correlating the current extended conditions with much higher  $H_2$  content and provides similar or improved  $R^2$  values and prediction uncertainties (see Table 3.10). The definition of the  $\beta$  scaling parameter removes the imbalance of the stoichiometric coefficients between the different fuels (i.e. 0.5 for  $H_2$  and CO and 2 for  $CH_4$ ) and provides a linear scaling of the peak overpressure with the hydrogen content for the current turbulence driven explosions in both  $H_2/CO/Air$  and  $H_2/CH_4/Air$  mixtures as shown in Figure 3.22(c). However, it should be noted that the scaling is only intended to reflect the impact of hydrogen content on mixtures with different syngas related fuel components and not the influence of the stoichiometry and the increase in the gradient with increasing equivalence ratio.

Furthermore, the  $\beta$  scaling does not improve matters for ultra lean mixtures ( $\Phi = 0.40$ ) and improvements aimed at removing the equivalence ratio dependent slope would likely require detailed flow field information. However, the current data suggests that in the absence of a deflagration to detonation transition (DDT), a linear approximation for  $\frac{dP^*}{d\beta}$  provides a good scaling for the impact of hydrogen enrichment on the explosion overpressure. The current values are given in Table 3.10.

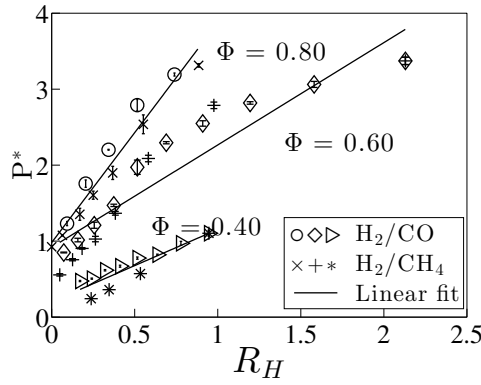
Table 3.10.: Scaling results of the peak explosion overpressure in  $H_2/CO/Air$  and  $H_2/CH_4/Air$  mixtures with  $R_H$  and  $\beta$  parameters. The  $R^2$  is the coefficient of determination assessed via Eq. (3.6) and  $\epsilon$  is the linear prediction uncertainty assessed via Eq. (3.7).

| $\Phi$ | $R_H$ scaling       |       |            | $\beta$ scaling       |       |            |
|--------|---------------------|-------|------------|-----------------------|-------|------------|
|        | $\frac{dP^*}{dR_H}$ | $R^2$ | $\epsilon$ | $\frac{dP^*}{d\beta}$ | $R^2$ | $\epsilon$ |
| 0.80   | 2.90                | 0.96  | 7.8%       | 4.89                  | 0.98  | 7.9%       |
| 0.60   | 1.35                | 0.88  | 20.3%      | 3.10                  | 0.98  | 9.3%       |
| 0.40   | 0.95                | 0.85  | 21.0%      | 1.06                  | 0.86  | 22.7%      |

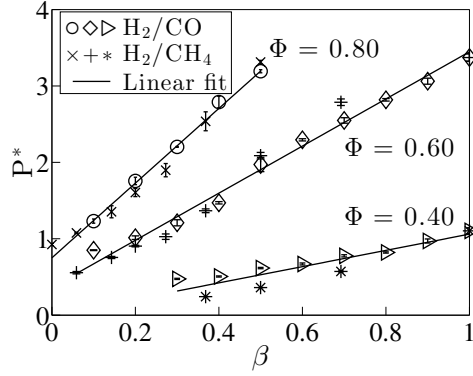
The significant differences in the explosion overpressures resulting from  $H_2/CO$  and  $H_2/CH_4$ , see Tables 3.4 and 3.5, can partly be attributed to the difference in nitrogen content, but also to the different interactions of CO and  $CH_4$  with the hydrogen chemistry. The stronger inhibiting effect of  $CH_4$  on the  $H_2$  chemistry has also been observed in the laminar burning properties. The distinct differences in behaviour encourage further investigation using ternary fuel blends (i.e.  $H_2/CH_4/CO$ ). The results are shown in Figure 3.23. The overall stoichiometry



(a) Scale with  $\alpha$

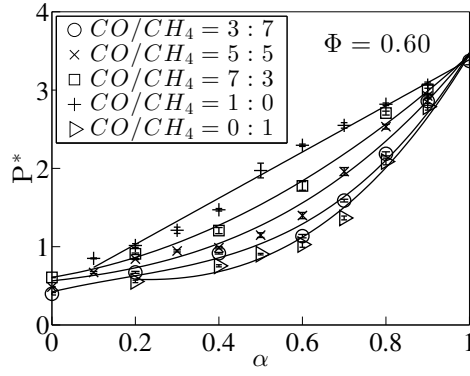


(b) Scale with  $R_H$

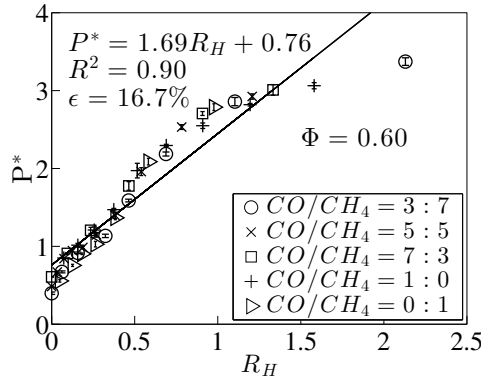


(c) Scale with  $\beta$

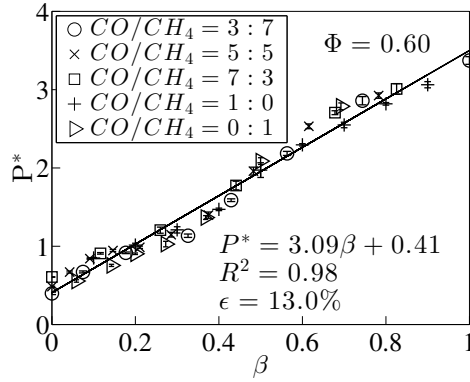
Figure 3.22.: Scaling of the peak explosion overpressure in binary mixtures with  $P^* = P/P_0$ , where  $P_0 = 101.325$  kPa is the initial pressure. The peak pressure was obtained from the second pressure transducer installed at a distance of 1.305 m from the ignition end. The symbols ( $\circ/\times - \Phi = 0.80$ ,  $\diamond/+ - \Phi = 0.60$  and  $\triangleright/* - \Phi = 0.40$ ) denote experimental data and the lines least square fits to the data.



(a) Scale with  $\alpha$



(b) Scale with  $R_H$



(c) Scale with  $\beta$

Figure 3.23.: Scaling of the peak explosion overpressure in ternary mixtures with  $P^* = P/P_0$ , where  $P_0 = 101.325$  kPa is the initial pressure. The peak pressure was obtained from the second pressure transducer installed at a distance of 1.305 m from the ignition end. The symbols denote experimental data and the lines least square fits with  $R^2$  indicating the coefficient of determination and  $\epsilon$  the prediction uncertainty.

was kept constant at 0.60, while the ratio between CO and CH<sub>4</sub> was varied (CH<sub>4</sub>/CO = 3:7, 5:5 and 7:3). Results for the binary fuel mixtures (H<sub>2</sub>/CO and H<sub>2</sub>/CH<sub>4</sub>) are also shown for comparison. The peak overpressures of the ternary mixtures are bounded by the binary mixture limits as shown in Figure 3.23(a). It further provides evidence that CH<sub>4</sub> has a stronger inhibiting effect than CO on the H<sub>2</sub> chemistry with pronounced differences between the CO and CO/CH<sub>4</sub> = 7:3. By contrast, the differences between the CH<sub>4</sub> and CO/CH<sub>4</sub> = 3:7 are comparatively modest. The  $R_H$  scaling collapses the data points relatively well, but does not remove the non-linearity. The  $\beta$  scaling removes the non-linearity and correlates the current peak overpressure of binary and ternary H<sub>2</sub>/CH<sub>4</sub>/CO mixtures for a given equivalence ratio. The  $\beta$  scaling in ternary mixtures at an equivalence ratio of 0.60 yields a  $\frac{dP^*}{d\beta}$  of 3.09 (see Figure 3.23(c)) while the counterpart in binary mixtures at  $\Phi = 0.60$  gives a value of 3.10 (see Table 3.10). This further suggests that, in the current configuration, a single correlation purely dependent on the equivalence ratio can be established for the explosion overpressure response to hydrogen content in syngas based fuels regardless of the CO/CH<sub>4</sub> ratio.

### 3.5.3. Scaling relations for flame propagation and peak overpressure

In vapour cloud explosions, the pressure wave induced by the expansion of the hot products culminates in a sharp pressure rise that is related to the fuel reactivity and the (turbulence generating) physical configuration. Gardner et al. [125], see Na'inna et al. [126], used the extensive MERGE programme data base of Mercx et al. [127] to propose an expression for the maximum pressure based on geometric parameters and the laminar burning velocity,

$$P = 4.8 \times 10^{-4} n^3 \text{BR}^2 D^{0.7} S_L^3 \quad (3.8)$$

where  $n$  is the number of obstacle rows (8 to 30), BR the blockage ratio (0.265 to 0.521) and  $D$  the obstacle tube diameter proportional to the obstacle length scale (19 to 168 mm). For a fixed geometry (e.g. the present study) the relative change in overpressure, measured from a reference point follows.

$$\frac{P}{P_{ref}} = \left[ \frac{S_L}{S_{L,ref}} \right]^3 \quad (3.9)$$

Taylor [128] studied the pressure wave caused by a uniformly expanding sphere surrounded by a uniformly expanding air wave. When the expansion velocity be-

comes large, a shock wave forms with a pressure ratio  $\pi = P/P_0$ , where  $P$  and  $P_0$  are the pressure immediately after and before the shock wave. Harrison and Eyre [129] and Gardner et al. [130] analysed their experimental data using a related simplified form shown in Eq. (3.10), where  $Ma_1$  is the flame speed Mach number and  $\gamma = C_p/C_v$  is the ratio of specific heat capacities.

$$\frac{\Delta P}{P_0} = (\pi - 1) = \frac{2\gamma Ma_1^2}{1 + Ma_1} \quad (3.10)$$

The specified  $Ma_1$  is based on the maximum flame speed ( $S_F$ ) and the speed of sound ( $c_0$ ) in the reactant gas mixture.

$$Ma_1 = \frac{S_F}{c_0} \quad (3.11)$$

The alternative expression in Eq. (3.12) follows directly from Taylor [128], where  $Ma = U/c_0$  and  $U$  is the gas velocity immediately behind the shock wave.

$$Ma^2 = \frac{2(\pi - 1)^2}{\gamma(\gamma - 1 + (\gamma + 1)\pi)} \quad (3.12)$$

Flame propagation speeds are typically measured using ionisation probe detectors. If the flame is primarily convected by the mean flow then the difference between  $Ma$  and  $Ma_1$  will not be excessive. For a closed end tube the flame speed can be written as Eq. (3.13), which accounts for the effects of expansion ratio and flame surface area enhancement,

$$S_F = S_L \cdot (\tau + 1) \cdot \frac{A_F}{A} \quad (3.13)$$

where  $A_F$  is the flame surface area and  $A$  the cross sectional tube area. For the initial laminar flame propagation,  $A_F$  is related to a (parabolic) pipe flow velocity profile. For the subsequent turbulent flame propagation, the flame area is related to turbulent fluctuations. Damköhler [131] applied mass conservation to equate  $A_F/A = S_T/S_L$ , where  $S_T$  is the turbulent burning velocity. A large number of correlations have been proposed [16, 132] and a common form is shown in Eq. (3.14), where  $C$  is expected to include a dependency on the ratio of the integral length scale ( $l_I$ ) of turbulence and the laminar flame thickness ( $l_F = \nu/S_L$ ) [16].

$$\frac{S_T}{S_L} = 1 + C \left( \frac{v'}{S_L} \right)^m \quad 0.5 \leq m \leq 1 \quad (3.14)$$

The value  $m \sim 0.7$  is often used [14, 16]. Bradley et al. [133, 134] have further shown that the Lewis ( $Le$ ) number and the Karlovitz stretch factor ( $Ka = t_F/t_K$ ), defined as the ratio of the chemical ( $t_F = l_F/S_L$ ) and Kolmogorov ( $t_K = (\nu/\epsilon_t)^{1/2}$ ) time scales ( $\epsilon_t$  is the rate of dissipation), can be expected to exert a significant influence. The following form was used to correlate a wide range of data,

$$\frac{S_T}{S_L} = \frac{0.88}{(Ka \cdot Le)^{0.3}} \left( \frac{v'}{S_L} \right) \quad (3.15)$$

Peters [16] showed that a number of relationships can be correlated as  $Re_t = Da^2 Ka^2$ , where the Damköhler number is defined as  $Da = t_I/t_F = l_I/(v't_F)$ . The scaling relationship given in Eq. (3.16) for  $S_T/S_L$ , which includes the length scale dependency, was also derived.

$$\frac{A_F}{A} = \frac{S_T}{S_L} \sim \left( \frac{v'}{S_L} \frac{l_I}{l_F} \right)^{1/2} \quad (3.16)$$

The definition of the laminar flame thickness and Eqs. (3.13) and (3.16) lead to,

$$S_F \simeq (\tau + 1) \cdot S_L \cdot Re_t^{1/2} \quad \text{where} \quad Re_t = \frac{v'l_I}{\nu} \quad (3.17)$$

where  $Re_t$  is the turbulent Reynolds number. Measurements of turbulence quantities in practical geometries are often very difficult to perform. Accordingly, estimates based on thermochemical parameters that reflect the mixture reactivity relative to a suitable reference value can potentially be useful. It follows from Eqs. (3.11) and (3.17) that the change in the  $Ma$  (or  $Ma_1$ ) can be estimated from Eq. (3.18) with the change in the overpressure estimated via Eq. (3.12).

$$Ma^* = Ma_{ref} \cdot \frac{(\tau + 1)}{(\tau_{ref} + 1)} \frac{S_L/c_0}{(S_L/c_0)_{ref}} \left( \frac{Re_t}{Re_{t,ref}} \right)^{1/2} \quad (3.18)$$

The above expression still requires the determination of turbulence properties. These are often exceptionally difficult to obtain in explosion related flows. The current configuration provides highly turbulent flows with Reynolds numbers  $Re > 100,000$  and  $2000 < Re_t < 4000$  reported by Lindstedt and Sakthitharan [32] for a similar configuration using stoichiometric methane-air mixtures. Abdel-Gayed and Bradley [135] derived (applied) the following correlation between the turbulent and flow Reynolds numbers based on pipe and parallel plate flow data.

$$Re_t = 13.45 \times 10^{-3} Re^{0.902} \quad \text{for} \quad 70 < Re_t < 3000 \quad (3520) \quad (3.19)$$

The turbulence levels will be significantly higher in obstructed channels. However, Eq. (3.19) was used by Alexiou et al. [136] to improve the agreement between predicted and measured rates of pressure rise in such configurations. The dependency of the flow Re number on the mixture reactivity can be estimated from,

$$Re = \frac{S_L(\tau + 1)D_h}{\nu} \quad (3.20)$$

where  $D_h$  is the hydraulic diameter (i.e.  $D_h = 4 \times \text{area} / \text{perimeter}$ ). The following results if only the scaling provided by Eq. (3.19), not the absolute value, is retained.

$$Ma^* = Ma_{ref} \cdot \frac{(\tau + 1)}{(\tau_{ref} + 1)} \frac{S_L/c_0}{(S_L/c_0)_{ref}} \left( \frac{Re}{Re_{ref}} \right)^{0.451}. \quad (3.21)$$

The particularly simple form of Eq. (3.22) follows and suggests a much weaker dependency on  $S_L$  than proposed by Gardner et al. [125].

$$Ma_1^* = Ma_{ref} \cdot \frac{c_{0,ref}}{c_0} \left[ \frac{(\tau + 1)}{(\tau_{ref} + 1)} \frac{S_L}{S_{L,ref}} \right]^{1.451} \quad (3.22)$$

The value of  $Ma_{ref}$  can be determined either from flame speed measurements or, via Eq. (3.12), from the peak pressure. The above analysis is only intended to reflect the increase in overpressure caused by changes in the mixture reactivity for a given stoichiometry and experimental configuration. The result cannot be expected to be general. Furthermore, a trivial form can be derived directly from Eq. (3.13) if it is assumed that the flame area in the initial laminar flow is self-similar and the relative scaling only depends on fluid properties.

$$Ma_2^* = Ma_{ref} \cdot \frac{c_{0,ref}}{c_0} \frac{(\tau + 1)}{(\tau_{ref} + 1)} \frac{S_L}{S_{L,ref}} \quad (3.23)$$

Figure 3.24 compares the measured peak explosion overpressures and the theoretical predictions using the measured flame speed  $Ma$  number. The scaling captures the mixture reactivity effect reasonably well. Some deviations exist and this can be expected as the flame speed measurements show scatter related to differences between the explosion events and emphasises the need for more detailed flow field measurements of explosion driven velocity fields.

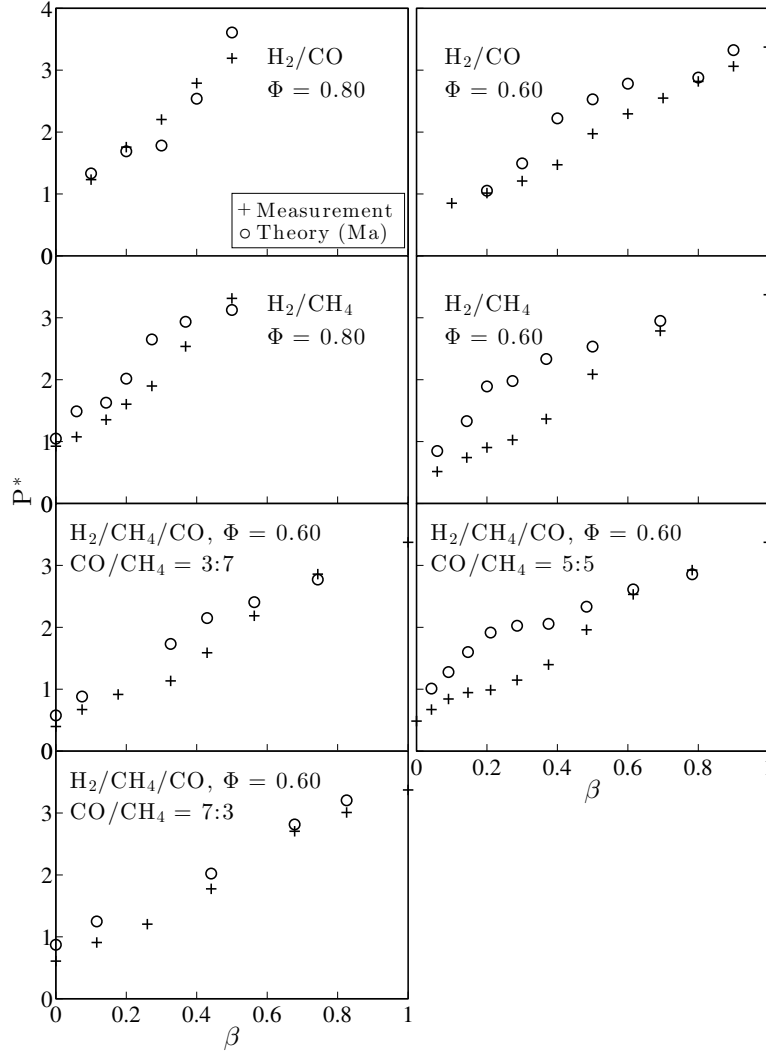


Figure 3.24.: Comparison of the measured peak overpressures and theoretical predictions using the scaling based on measured  $Ma$  numbers. The peak pressure was obtained from the second pressure transducer installed at a distance of 1.305 m from the ignition end and  $P^* = \Delta P/P_0$ , where  $P_0 = 101.325$  kPa is the initial pressure.

The estimated Mach numbers ( $Ma_1^*$  and  $Ma_2^*$ ) using Eqs. (3.22) and (3.23) reflect the mixture reactivity as associated with the laminar burning velocity and expansion ratio. Hence, the correlation does reflect the strength of the approach flow to the obstacles. It can clearly not be expected to reflect the characteristics of the resulting turbulent explosion. The results using the estimated mixture reactivity Mach numbers are illustrated in Figure 3.25. Predictions based on  $Ma_1^*$  show good



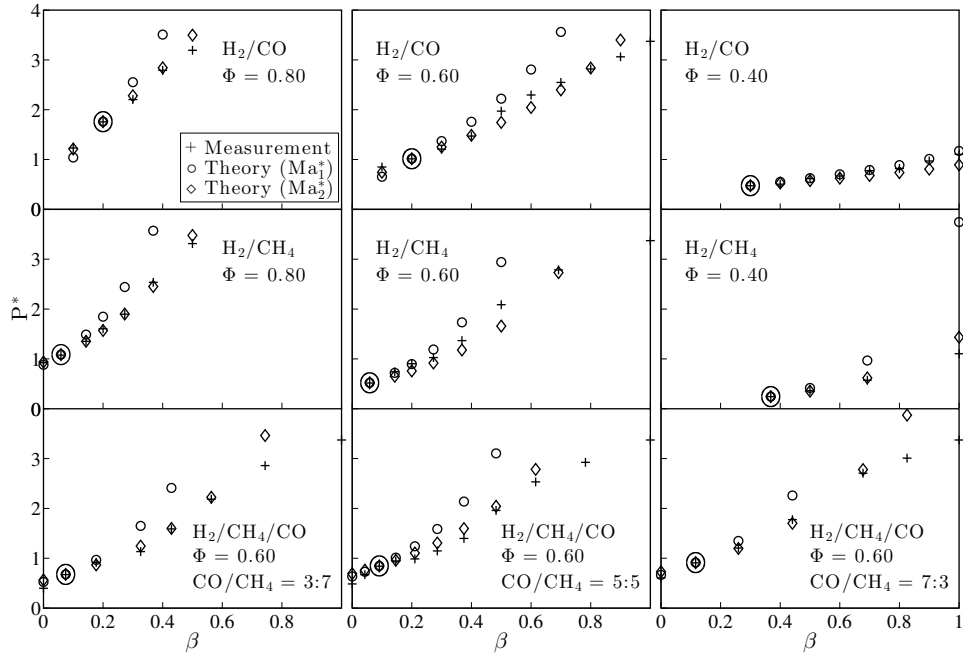


Figure 3.25.: Comparison of the measured peak overpressures and theoretical predictions using the scaling based on estimated  $Ma_1^*$  and  $Ma_2^*$  numbers. The peak pressure was obtained from the second pressure transducer installed at a distance of 1.305 m from the ignition point and  $P^* = \Delta P/P_0$ , where  $P_0 = 101.325$  kPa is the initial pressure.

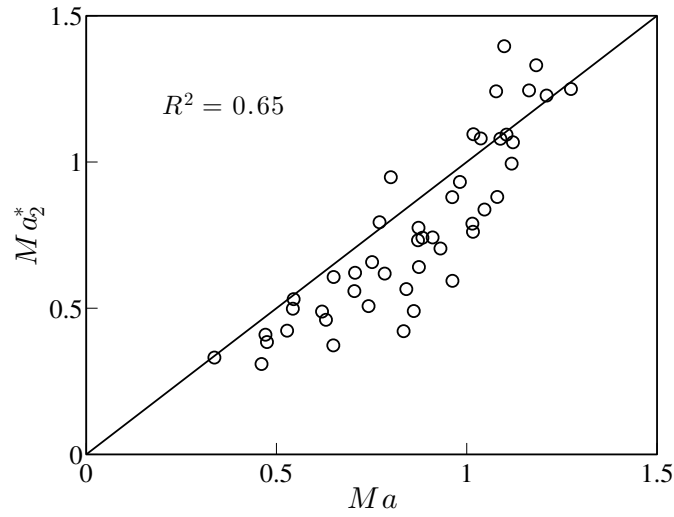


Figure 3.26.: Comparison of the measured Mach number ( $Ma$ ) and estimated Mach number ( $Ma_2^*$ ).

agreement for mixtures with lower mixture reactivity, yet overestimates the impact of mixture reactivity for more reactive mixtures. Improvements can be seen when scaling with the trivial expression  $Ma_2^*$ . Deviations prevail and this is not unexpected as the use of unstrained laminar burning velocities is only intended as a leading order approximation with further work required to quantify the influence of flame stretch, Lewis number and turbulence-chemistry interactions. Furthermore, it appears clear that scalings that are based on higher orders in the laminar burning velocity (e.g. Eqs. (3.8) and (3.9)) do not accurately reflect the current wide range of mixture reactivities. It should also be noted that the reference Mach numbers in the estimation (30% H<sub>2</sub> for H<sub>2</sub>/CO/Air with  $\Phi = 0.40$ , 70% H<sub>2</sub> for H<sub>2</sub>/CH<sub>4</sub>/Air with  $\Phi = 0.40$  and 20% H<sub>2</sub> for the rest) were calculated using the measured explosion overpressure and the reverse application of the scaling relation given by Eq. (3.12). The reference cases were illustrated in Figure 3.25. Figure 3.26 compares the estimated  $Ma_2^*$  and measured  $Ma$ . The data points are scattered around the diagonal line with a  $R^2$  norm of 0.65. The latter value suggests modest agreement with experimental data and caution is required when scaling the peak overpressure with the estimated flame speed Mach number ( $Ma_2^*$ ). The detailed data related are provided in Tables 3.4 and 3.5 for the binary mixtures and Table 3.6 for the ternary mixtures. For ultra-lean mixtures with  $\Phi = 0.40$ , the ionisation probe detectors did not trigger reliably and the flame speed data are accordingly omitted.

### 3.6. Conclusions

This chapter has investigated the turbulent explosions of H<sub>2</sub> enriched fuel blends (CO or/and CH<sub>4</sub>) in an obstructed channels, focusing on the influence of mixture reactivity, which was varied by introducing different H<sub>2</sub> substitution levels for three different equivalence ratios (0.80, 0.60 and 0.40). The results highlight an enhancing effect of mixture reactivity on explosion overpressure and flame propagation speed. The quantitative relationship between hydrogen mole fraction and peak overpressure depends on the blend type with a linear dependence in CO blends and an exponential relation in CH<sub>4</sub> blends. Methane was found to have a stronger inhibiting effect than CO on H<sub>2</sub> chemistry indicated by the lower overpressure at the same hydrogen concentration. Ternary fuel mixtures with an equivalence ratio of 0.60 and various CO/CH<sub>4</sub> ratios (3 : 7, 5 : 5 and 7 : 3) were also investigated to further show the synergistic effect.

A new scaling parameter  $\beta$  provides a linear correlation with a purely equiv-

alence ratio dependent gradient for the peak explosion overpressure in response to  $H_2$  content regardless of the fuel blend. The scaling based on a acoustic theory [128] and measured flame speed  $Ma$  number shows arguably good agreement with experimental data. The estimated Mach numbers ( $Ma_1^*$  and  $Ma_2^*$ ) incorporate the mixture reactivity effect via the laminar burning velocity and show some success in scaling the peak overpressure. The estimation method can be potentially used in circumstances where extensive flame speed data are not available but suitable reference points can be obtained in the same, or a very closely related, geometry.

The investigated gas mixtures and the scaling of peak overpressures together with the produced datasets provide novel insights into the risks associated with hydrogen enrichments of syngas, biogas and natural gas systems as well as providing data for model validation.

## 4. Radiation induced multipoint turbulent explosion

It has been discussed in previous chapters that possible secondary explosions via radiative ignition of dust particles ahead of the advancing flame front cannot currently be ruled out. Such particles may be trapped in corners around obstacles and can, following ignition, be entrained into the main flow and/or adjacent recirculation zones. The mechanism is illustrated in Figure 4.1 and related events may also play a role in dust explosions. This chapter explores the impact of secondary flame kernels on the explosions resulting from lean premixed  $\text{H}_2/\text{CH}_4/\text{Air}$  atmosphere. The total impulse was estimated by measuring the overpressure for the full duration of the explosion. The repeatability of the experiment is also presented.

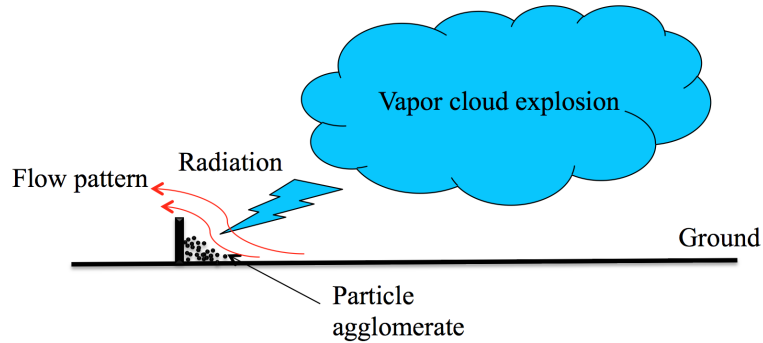


Figure 4.1.: Schematic of radiative ignition of dust particles around obstacles.

### 4.1. Influence of mixture reactivity on the radiative ignition time

Two time scales must be accommodated when exploring forward radiative ignition mechanisms. The first is the time for the main (primary) flame to arrive at the radiation induced ignition location ( $\tau_{mf}$ ) and the second is the time required for the suspended irradiated particles to cause ignition ( $\tau_{ig}$ ) at this location. The irradiated

particles ignition time must be smaller than the main flame arrival time ( $\tau_{ig} < \tau_{mf}$ ). The arrival time of the primary spark ignited (main) flame predominantly depends on the flame propagation mode, e.g. on turbulence generating obstacles and on the laminar burning velocity during the initial phase.

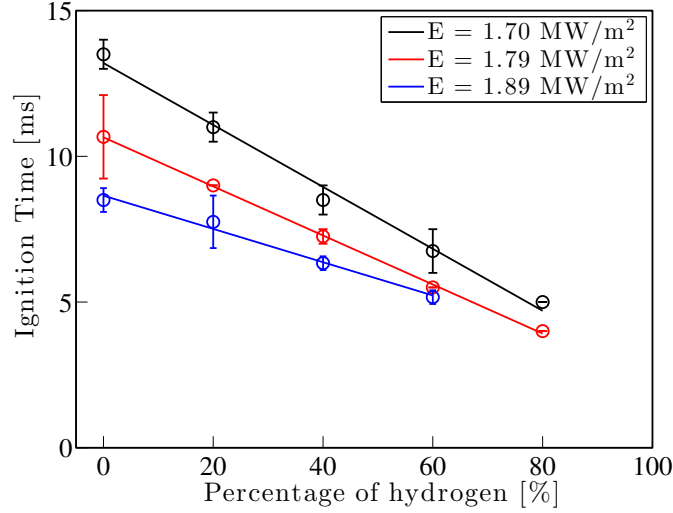


Figure 4.2.: Influence of hydrogen concentration on the radiation induced ignition time in quiescent condition. The explosive atmosphere is a  $H_2/CH_4$ /Air mixture with an equivalence ratio of 0.80.

The  $\tau_{ig}$  is less affected by the configuration, but strongly influenced by particle properties (e.g. size, surface to volume ratio, chemical composition and internal heat conductivity), the radiation intensity, the radiation area as well as the mixture reactivity. Beyrau et al. [74] measured the time-resolved temperature rise of uncoated silicon carbide particles with sizes in the range  $2.33 \leq \pi d_{50}/\lambda \leq 109$  and showed that the  $\tau_{ig}$  in stoichiometric butane–air mixtures increased from 37 ms to 152 ms at a constant irradiance of  $1.6 \text{ MW/m}^2$ . The comparative value for the current acetylene black ( $\pi d_p/\lambda = 0.14$ ) was 20 ms and the nanoscale structure, featuring interstitial spaces, was suggested as possible cause of the favourable ignition characteristics.

In the current case, the time-to-radiation induced ignition depends on the mixture reactivity, i.e. the  $H_2$  concentration. There are, comparatively, more studies on the properties of the particles, particle size and radiation intensity, but less on the mixture reactivity. Hence, the mixture reactivity was first characterised by studying quiescent (no primary flame)  $H_2/CH_4$ /Air mixtures with various  $H_2$  con-

centrations while keeping an overall equivalence ratio of 0.80 in the absence of spark ignition. A linear decrease in ignition time with an increasing amount of hydrogen in the reactant mixture was observed as shown in Figure 4.2. The time

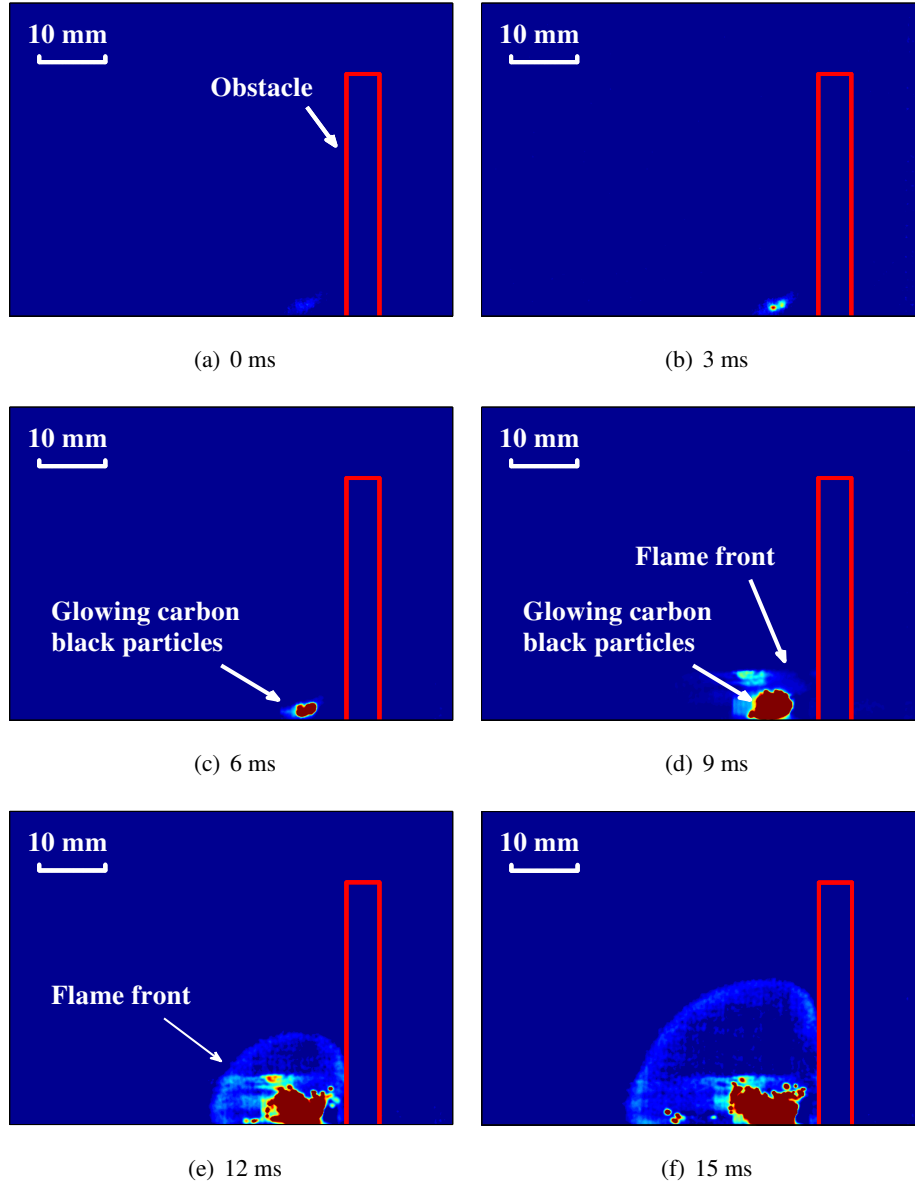


Figure 4.3.: The evolution of radiation induced ignition downstream of the obstacle in a quiescent (no primary spark ignited flame)  $\text{H}_2/\text{CH}_4/\text{Air}$  mixture with  $\text{H}_2 = 20\%$ ,  $\Phi = 0.80$  and  $E = 1.79 \text{ MW/m}^2$ . The figure shows selected slides from the experimentally recorded flame evolution.

to radiation induced ignition also decreases with an increase in irradiation. In a laboratory environment, it is desirable to keep the time to radiation induced ignition short, given the modest distance ( $\sim 400$  mm) between the irradiated area and the spark ignited primary flame. Figure 4.3 illustrates the ignition event in a  $\text{H}_2/\text{CH}_4/\text{Air}$  mixture in the absence of a primary flame using selected slides from the experimentally recorded flame evolution obtained using a CCD camera with a 2 kHz frame rate. The images have been enhanced for clarity. Ignition was achieved after 9 ms at an irradiance (E) of  $1.79 \text{ MW/m}^2$ . The particles glow for a few milliseconds before ignition and the flame then propagates outwards in a hemispherical mode given the restrictions of the obstacle and tube walls. The 2 kHz recording rate gives an uncertainty of 0.5 ms in the measured ignition time. Beyrau et al. [60] and Hadjipanayis [67] have shown that the ignition time becomes independent of the target orientation when the irradiated area is greater than  $17 \text{ mm}^2$  and the current value was set to  $23 \text{ mm}^2$  to remove the impact of buoyancy.

## 4.2. Pressure development in radiation induced multipoint explosions

The impact of radiative ignition is here studied for four cases. Case (a) is a reference case with only spark ignition, Case (b) features the addition of radiation induced ignition of particles downstream of the obstacle and Case (c) radiation induced ignition of particles upstream of the obstacle. Case (d) is identical to Case (c) apart from that a second obstacle is added closer to the spark source in order to increase flow and turbulence velocities.

### 4.2.1. Explosion evolution in the absence of radiative ignition

The pressure development for Case (a) is shown in Figure 4.4. The four lines correspond to the pressure transducer locations in Table 2.1. The dashed vertical line indicates the arrival of a pressure wave caused by back-reflection from the closed downstream end of the tube. The signal in Zone A exhibits a high reproducibility (the variability from three experiments is shown) in terms of the pressure evolution with the peak pressure around 65 kPa at 50 ms caused by the turbulence-driven explosion behind the obstacle. Zone B is affected by reflected pressure waves and can show a chaotic behaviour.

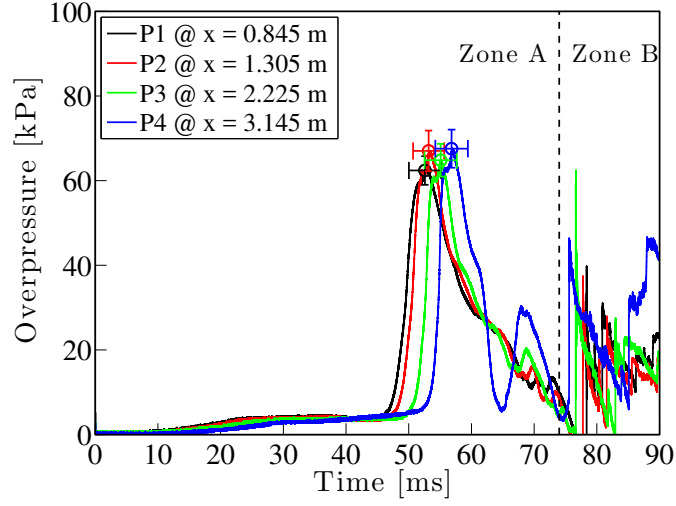


Figure 4.4.: Characteristic pressure traces resulting from a spark ignited flame only, Case (a), with the pressure transducer locations corresponding to Table 2.1. Zone A indicates the temporal domain free of pressure wave reflections from the closed far end of the tube. In zone B, such interactions cause a chaotic behaviour.

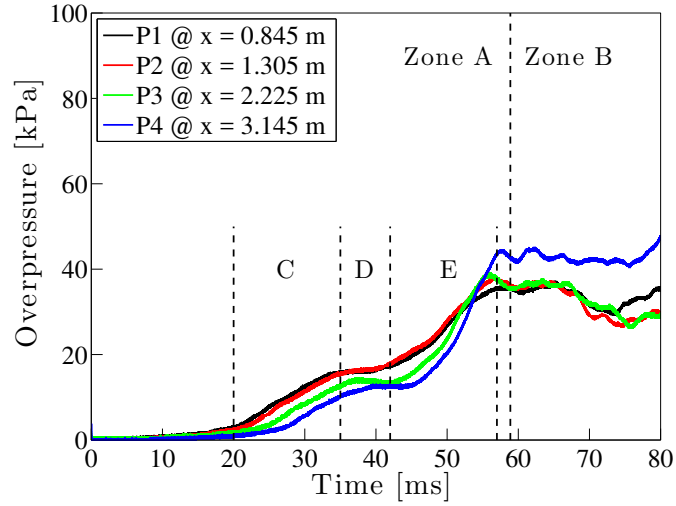


Figure 4.5.: Characteristic pressure traces resulting from spark ignition combined with radiation induced ignition downstream of the obstacle, Case (b), in a  $\text{H}_2/\text{CH}_4/\text{Air}$  mixture with  $\text{H}_2 = 20\%$ ,  $\Phi = 0.80$ ,  $E = 1.79 \text{ MW/m}^2$  and  $\tau_{ig} = 10 \text{ ms}$ .



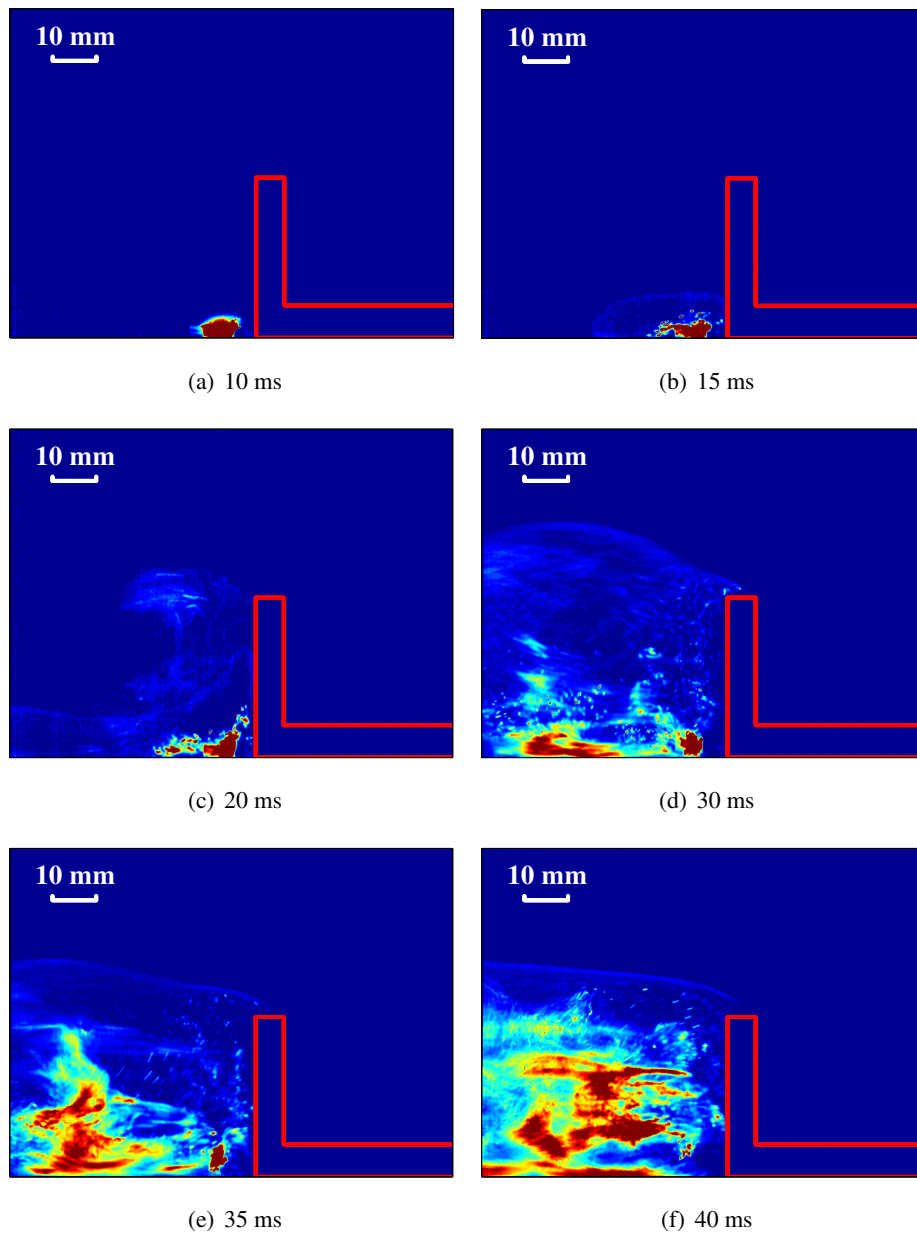


Figure 4.6.: Images of the early evolution of an explosion induced by spark ignition followed by radiation induced ignition downstream of the obstacle (Case b). Conditions as for Figure 4.5.

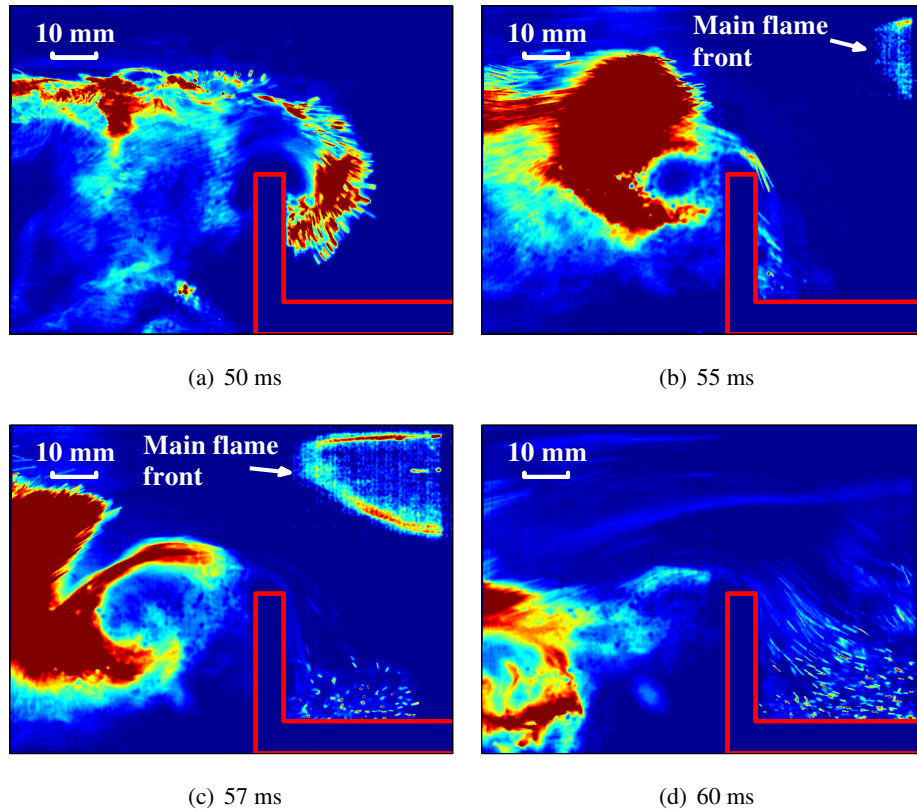


Figure 4.7.: Images of the final evolution of an explosion induced by spark ignition followed by radiation induced ignition downstream of the obstacle (Case b). Conditions as for Figure 4.5.

#### 4.2.2. Impact of radiative ignition of particles downstream of the obstacle

The pressure and early flame development for Case (b) with spark ignition augmented by radiation induced ignition of particles located downstream of the obstacle are shown in Figures 4.5 and 4.6. The long dashed line in Figure 4.5 indicates the arrival of the pressure wave caused by back-reflection. The three short dashed lines separate the pressure development into three stages, two sharper pressure rises, indicating two explosions in Stages C and E, bracketing a quasi-stable Stage D where the expansion caused by the primary flame supplies fresh reactants. The radiation induced ignition occurred around 10 ms as shown in Figure 4.6. The flame becomes squeezed during the propagation because of the combustion-driven flow caused by the primary flame. At around 20 ms, the recirculating flow behind

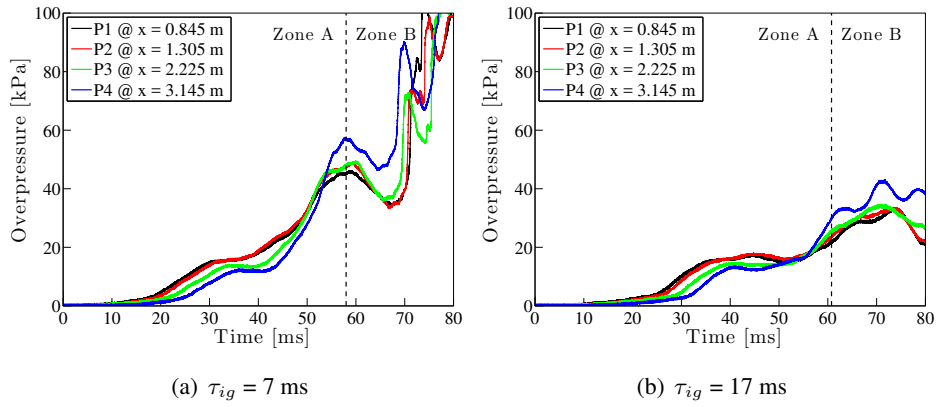


Figure 4.8.: Impact of different radiation induced ignition times downstream of the obstacle on the pressure evolution. Conditions as for Figure 4.5.

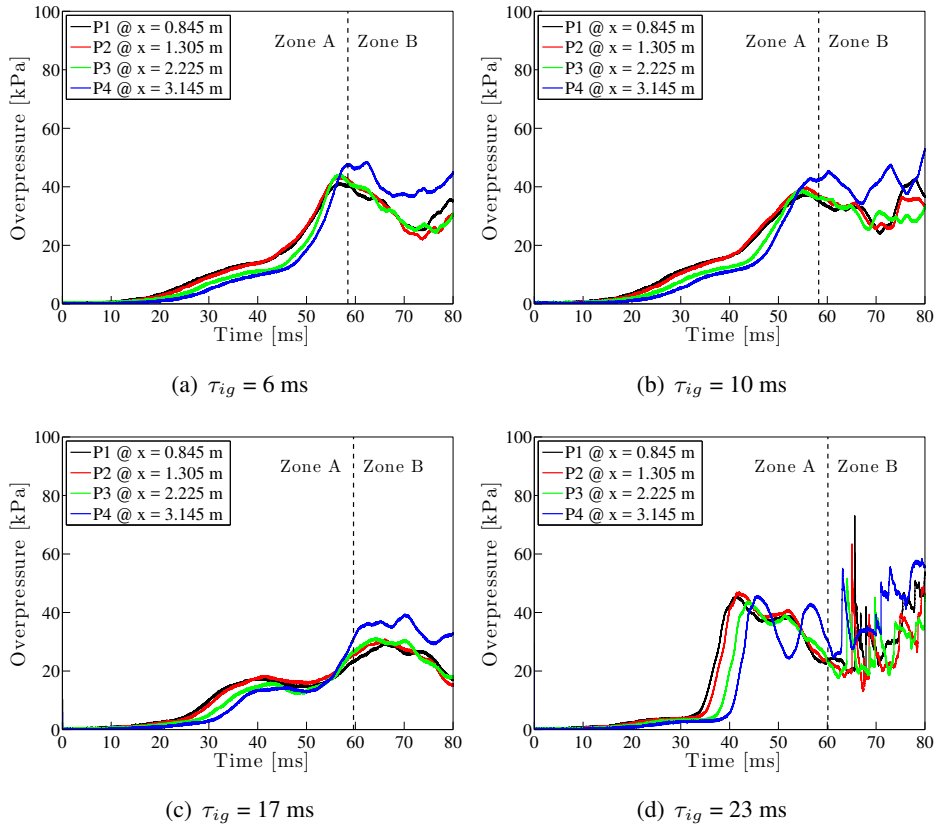


Figure 4.9.: Impact on the pressure evolution of different radiation induced ignition times upstream of the obstacle with other conditions as for Figure 4.5.

the obstacle begins to have an impact and the flame evolves into a local explosion leading to the pressure rise in Stage C. Later the flame exhibits a strong tendency to propagate upstream, as shown in Figure 4.7(a), before being pushed back by the approaching primary flame around 55 ms as shown in Figures 4.7(b) onwards. The combined effect leads to the second pressure rise in Stage E. The overall pressure development differs from the reference case and shows a strong coupling between the two flames. Accordingly, the impact of different ignition times was investigated and the results are shown in Figure 4.8. The relationship is quite complex. An earlier onset of radiation induced ignition leads to an earlier pressure rise and a shorter quasi-stable stage. The peak pressure ( $< 55$  kPa) is reduced compared to the reference case. However, the overpressure duration is substantially increased. The case where ignition is delayed until 17 ms, see Figure 4.8(b), shows a further reduction in the peak overpressure to 35 – 40 kPa coupled with the prolonged duration. The expansion of the radiation induced flame kernel can clearly cause a delay in the main flame arrival time and the combustion-driven flow of the primary flame affects the propagation of the secondary ignition kernel. Hence, the time to achieve radiation induced ignition has a major influence on the temporal evolution of the explosion.

#### **4.2.3. Impact of radiative ignition of particles upstream of the obstacle**

The pressure development for Case (c), featuring spark ignition combined with radiation induced ignition of particles located upstream of the obstacle, is shown in Figure 4.9. This case is arguably of greater practical relevance due to the similarity with the scenario shown in Figure 4.1. The pressure development is shown in Figure 4.9(b) with a time-to-radiation induced ignition of 10 ms. The early flame propagation is shown in Figure 4.10. The evolution is generally similar to Case (b), which featured radiation induced ignition of particles located downstream of the obstacle, and shows two pressure rise stages and a quasi-stable period. However, a major difference is that the ignition kernel is quickly transported downstream to the recirculation zone behind the obstacle and, potentially, beyond. From around 20 ms onwards, the secondary flame develops into a local explosion causing the first pressure rise. Between 30 ms and 40 ms, the flame burns in a quasi-stable mode as discussed above. An unsteady (e.g. flapping) motion of the shear layer above the obstacle can be inferred from Figures 4.10(e) and 4.10(f) as also obser-

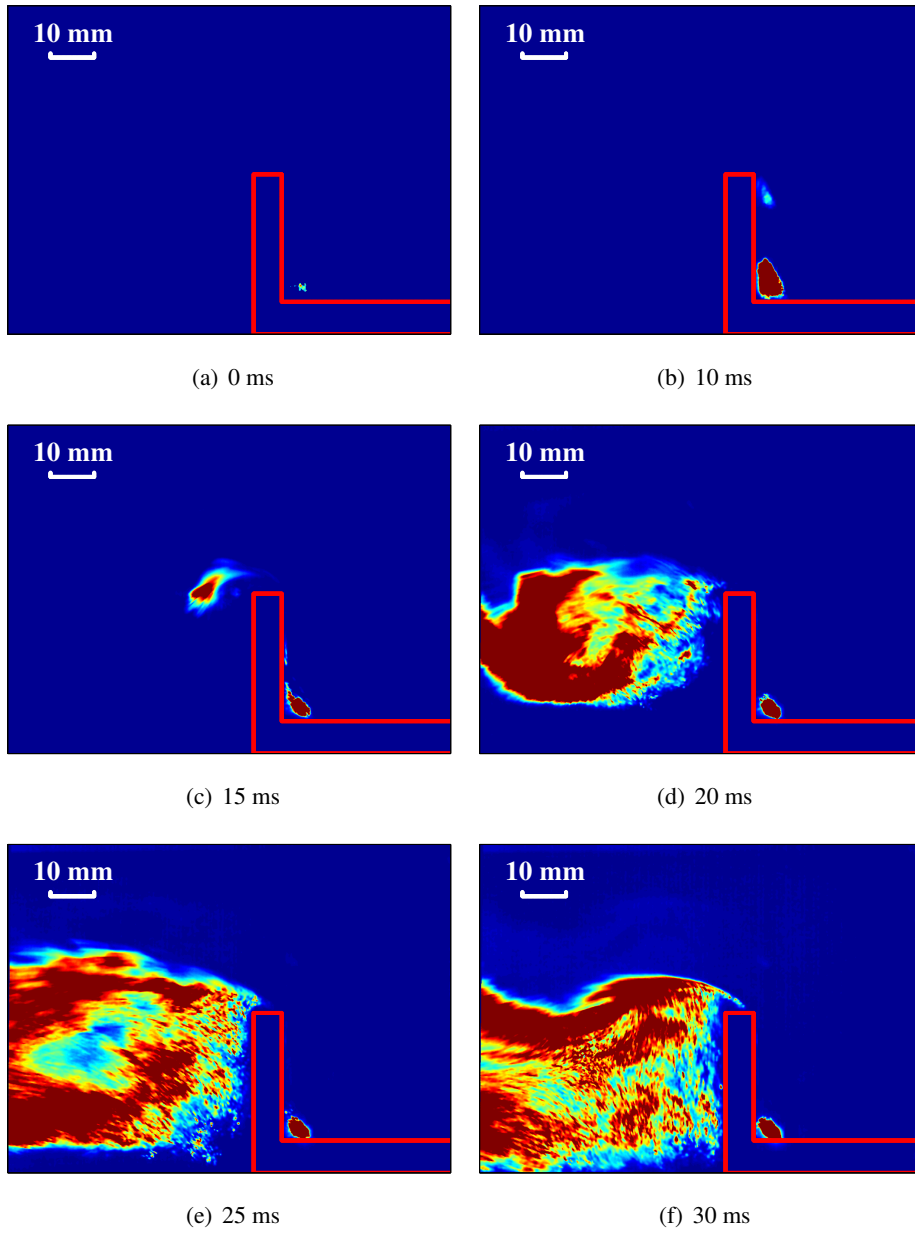


Figure 4.10.: Images of the early evolution of an explosion induced by spark ignition followed by a secondary radiation induced ignition upstream of the obstacle (Case c) with  $\tau_{ig} = 10$  ms. Conditions as for Figure 4.9.

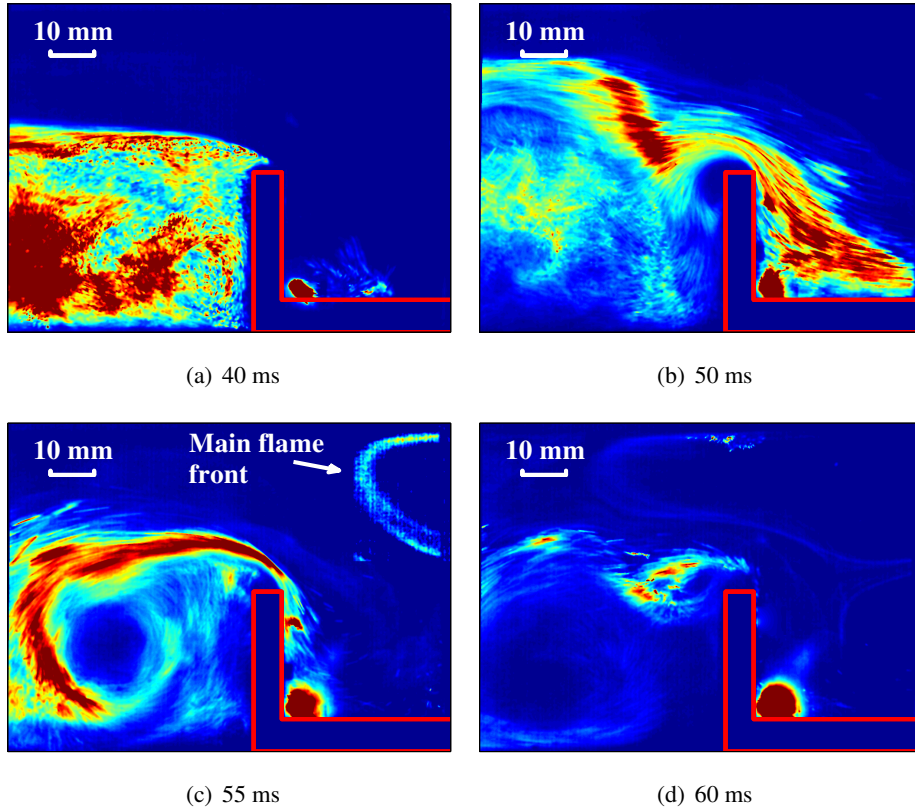


Figure 4.11.: Images of the final evolution of an explosion induced by spark ignition followed by a secondary radiation induced ignition upstream of the obstacle (Case c) with  $\tau_{ig} = 10$  ms. Conditions as for Figure 4.9.

ved by Lindstedt and Sakthitharan [32]. As the primary flame approaches, the combined effect of both flames contributes to the second pressure rise. The final burnout around the obstacle is shown in Figure 4.11, where the secondary explosion in the recirculation zone, caused by the supply of fresh reactants via the combustion induced flow from the primary flame, is readily evident at 55 ms as shown in Figure 4.11(c). The pattern serves to explain the increased duration of multi-point explosions as well as the reduced peak overpressure. The latter is caused by the earlier consumption of reactants in a flow field that has had less time to develop ahead of the primary flame.

An exception to the above behaviour occurs when the time-to-radiation induced ignition is increased to 23 ms in order to allow the flow field caused by the primary flame to develop further. The pressure evolution is shown in Figure 4.9(d) and the flame is visualised in Figures 4.12 and 4.13. The pressure build-up is distinctly di-

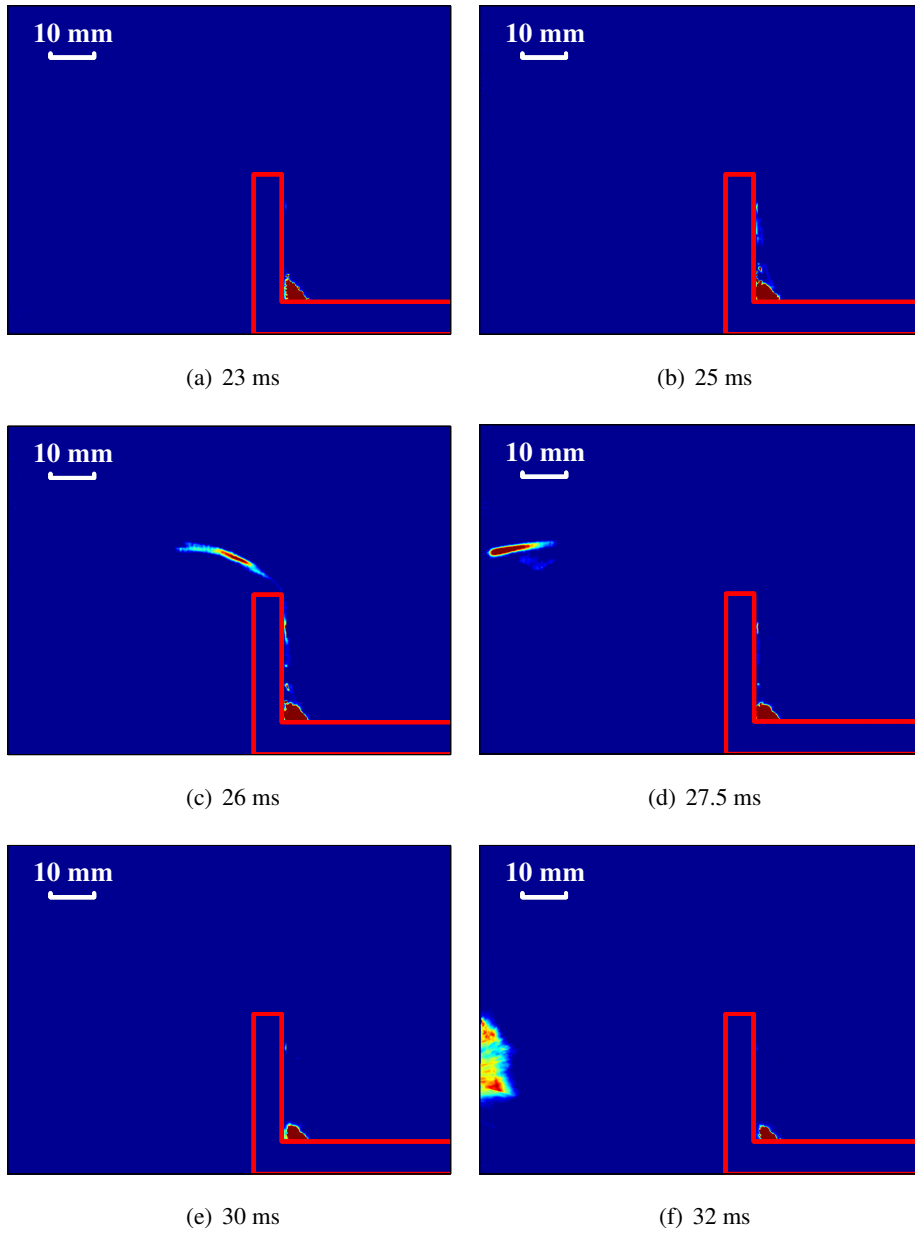


Figure 4.12.: Images of the early evolution of an explosion induced by spark ignition followed by a secondary radiation induced ignition upstream of the obstacle (Case c) with  $\tau_{ig} = 23$  ms. Conditions as for Figure 4.9.

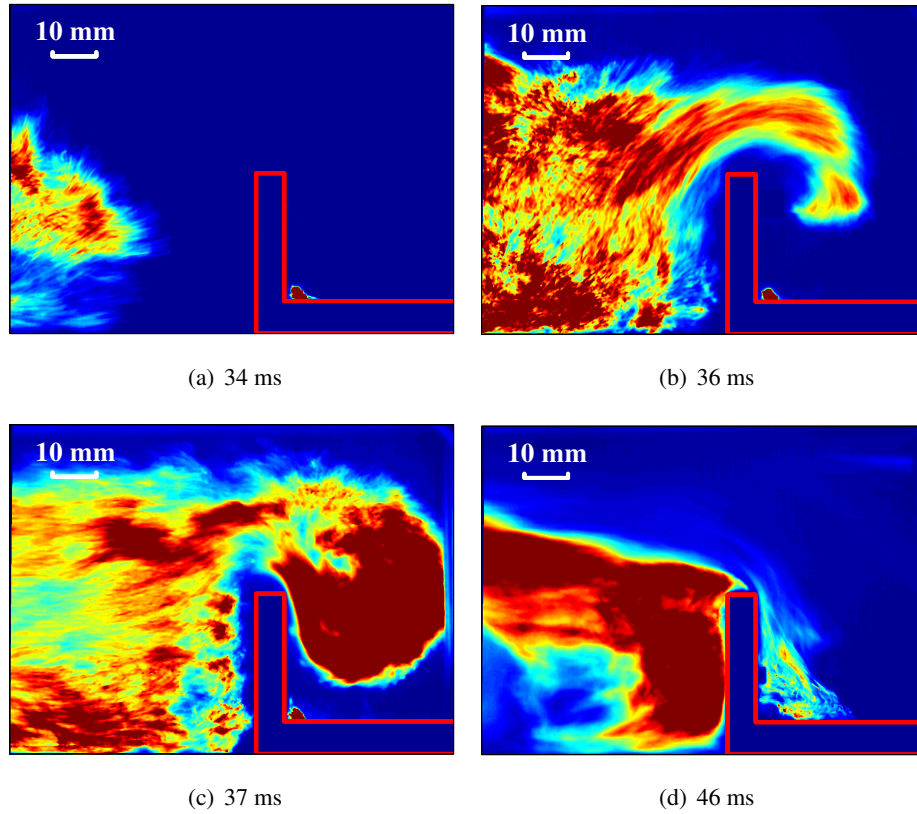


Figure 4.13.: Images of the final evolution of an explosion induced by spark ignition followed by a secondary radiation induced ignition upstream of the obstacle (Case c) with  $\tau_{ig} = 23$  ms. Conditions as for Figure 4.9.

fferent to the other three cases. The radiation induced ignition kernel is transported far downstream and out of the optical section as shown in Figures 4.12(a)–4.12(e). Once established, the resulting flame subsequently propagates in two directions. The backward-burning flame (propagating towards the primary flame) re-appears in the optical section at 32 ms as shown in Figure 4.12(f). The backward propagating flame moves sufficiently far upstream to reach the recirculation zone formed behind the obstacle towards the primary flame (the opposite side to what may be expected) as shown in Figures 4.13(b) and 4.13(c) and subsequently creates a local explosion at around 37 ms. The latter leads to the sharp pressure rise shown in Figure 4.9(d). The peak overpressure (around 45 kPa) is smaller than the case with spark ignition only, shown in Figure 4.4 (around 65 kPa), as the strength of the recirculation zone is likely affected by the opposing propagation directions of



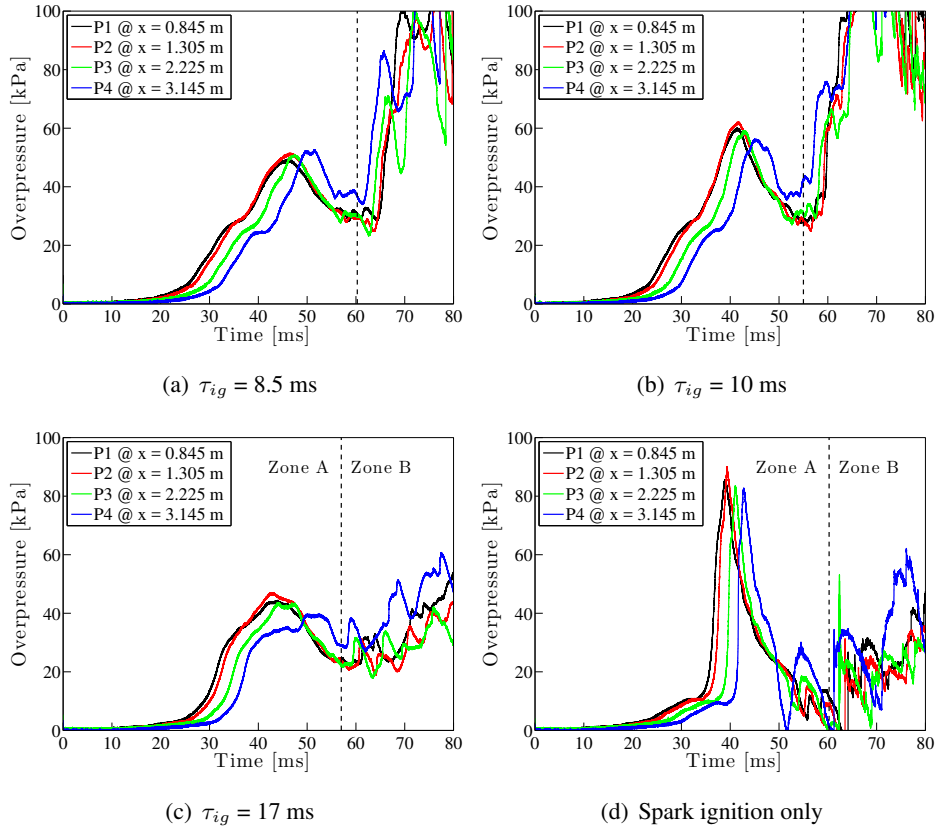


Figure 4.14.: Characteristic pressure traces for explosions induced by spark ignition followed by a secondary radiation induced ignition upstream of the second obstacle in the two obstacle configuration indicated by Figure 2.3. Conditions as for Figure 4.9 with  $\tau_{ig} = 8.5, 10$  and  $17$  ms. A reference case without a secondary flame is also shown in Figure 4.14(d).

the primary and secondary flames. In both cases the peak overpressure is caused by turbulence-driven explosions around the obstacle and the secondary ignition kernels may be quenched by high rates of strain. Overall, it is apparent that NIR laser induced radiation of particles can readily cause ignition leading to secondary explosions ahead of a propagating primary flame and that the resulting complex interactions impact the peak pressure and the overpressure duration. Typically the primary flame arrives relatively late after the consumption of the fuel around the obstacle by the secondary flame. The arrival time of the primary flame was therefore reduced by introducing a second obstacle with the same blockage ratio of 50% on the top of the tube at a distance of 80 mm from the ignition end (Case d). The results, shown in Figure 4.14, are similar to the case with one obstacle,

except that the peak overpressure arrives earlier and the quasi-stable stage becomes shorter. The peak pressures are also increased.

### 4.3. The impact of secondary flame kernels on flame speeds and arrival times

The pressure development can be correlated with flame speeds and flame arrival times, measured with ionisation probes along the tube, with Cases (a) (spark ignition only) and (b) shown in Figure 4.15. Consistent with the overpressure records, the early flame speed is strongly reduced by the secondary flame kernel compared to the case with only a primary spark ignited flame.

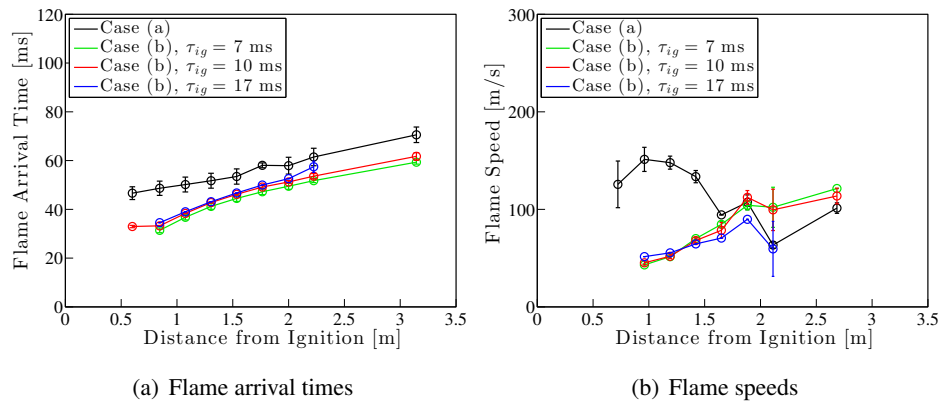


Figure 4.15.: Impact of radiation induced ignition on flame arrival times and flame speeds. Case (a) spark ignition only and Case (b) radiation induced ignition downstream of the obstacle.

### 4.4. The impact of secondary flame kernels on the pressure impulse

To estimate the severity of an explosion, it is not only the peak pressure that is important, but also the duration of the pressure load. The integral of the instantaneous pressure over time, defined as the total pressure impulse, can be used to quantify this effect. The pressure impulse was hence calculated using data obtained at the second pressure transducer before the arrival of the back-reflected wave (i.e. data only from Zone A as shown in Figure 4.4). The results are listed in Table 4.1, where Group I refers to the ignition of particles downstream of the single obsta-

cle, Group II to the ignition of particles upstream of the single obstacle and Group III the ignition of particles upstream of the second obstacle (same location as for Group II) in a two-obstacle configuration.

Table 4.1.: Pressure data where S indicates spark ignition and R radiation induced ignition downstream or upstream (towards the spark ignited flame kernel) of the obstacle and  $\tau_{ig}$  the timing of the ignition of the secondary flame kernel. The asterisk (\*) indicates limiting conditions where the experimental reproducibility is reduced and data from sample cases are presented.

| Group | Obstacles | Ignition method  | $\tau_{ig}$ [ms] | Pressure impulse [Pa·s] |
|-------|-----------|------------------|------------------|-------------------------|
| I     | 1         | S                | –                | $887 \pm 22$            |
|       |           | S + R downstream | 7                | $845 \pm 60$            |
|       |           | S + R downstream | 10               | $754 \pm 15$            |
|       |           | S + R downstream | 17               | $577 \pm 24$            |
| II    | 1         | S                | –                | $887 \pm 22$            |
|       |           | S + R upstream   | 6                | 688*                    |
|       |           | S + R upstream   | 10               | $693 \pm 62$            |
|       |           | S + R upstream   | 17               | $501 \pm 36$            |
|       |           | S + R upstream   | 23               | 902*                    |
| III   | 2         | S                | –                | $911 \pm 51$            |
|       |           | S + R upstream   | 8.5              | $1053 \pm 92$           |
|       |           | S + R upstream   | 10               | $1086 \pm 39$           |
|       |           | S + R upstream   | 17               | 958*                    |

It can be seen that although the introduction of radiation induced ignition lowered the peak overpressure, the pressure impulses are comparable with a dependency on the time-to-ignition also apparent.

Overall, the pressure impulse for Group III, where two obstacles are installed, is higher than for Groups I and II, and the pressure impulse with radiation induced secondary flame kernels actually exceeds that of the reference case featuring only the primary flame. For the limiting cases, at very short ignition times (i.e.  $\tau_{ig} = 6$  ms) the experiments were restricted by the selected laser power and particle properties, while for the two cases with the longest laser induced ignition time (i.e.  $\tau_{ig} = 23$  ms in Group II and  $\tau_{ig} = 17$  ms in Group III) the radiation induced ignition kernel was prone to quenching by the higher strain rates corresponding to a more developed turbulent flow. However, it should also be noted that in a practical scenario the irradiated area can be expected to be proportionally larger resulting in more substantial secondary flame kernels.

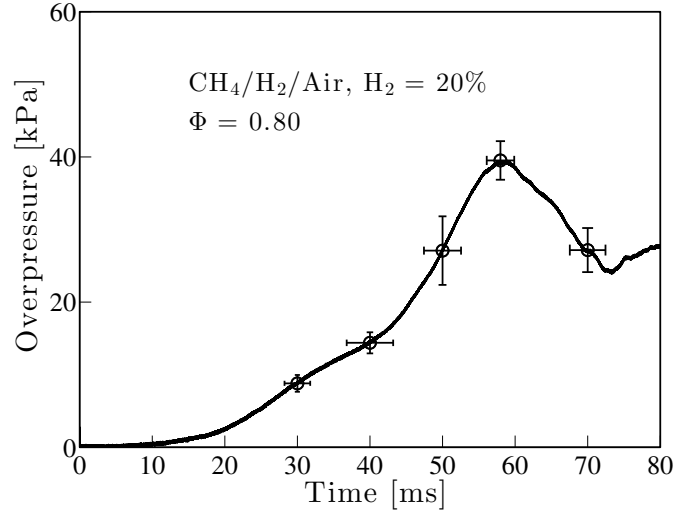


Figure 4.16.: Pressure registered at the second pressure transducer (1.305 m from the ignition), average of four runs, ignited upstream of the obstacle, H<sub>2</sub>/CH<sub>4</sub>/Air, H<sub>2</sub> = 20%,  $\Phi = 0.80$ ,  $\tau_{ig} = 10$  ms.

Table 4.2.: Detailed data for the four experiments corresponding to Figure 4.16. The flame arrival time ( $\tau_A$ ) was obtained at the first ionisation probe located 600 mm from the spark ignition end of the tube.

| Run | Mixture composition  |                     |          | $\Phi$ | $\tau_A$<br>[ms] | Peak pressure<br>[kPa] | Peak time<br>[ms] |
|-----|----------------------|---------------------|----------|--------|------------------|------------------------|-------------------|
|     | CH <sub>4</sub> [Pa] | H <sub>2</sub> [Pa] | Air [Pa] |        |                  |                        |                   |
| 1   | 7303                 | 1856                | 92231    | 0.802  | 55               | 40.2                   | 58.8              |
| 2   | 7384                 | 1837                | 92357    | 0.808  | 50               | 40.5                   | 55.1              |
| 3   | 7370                 | 1888                | 92436    | 0.808  | 53               | 39.9                   | 55.7              |
| 4   | 7303                 | 1848                | 92377    | 0.800  | 56               | 44.7                   | 57.8              |

## 4.5. Repeatability of results

The explosions studied in the current experiments are highly transient and variations in the initial flame kernel formation, unpredictable flame instabilities and flame obstacle interactions can all lead to significant variability in results even under very carefully controlled conditions. The repeatability in the absence of secondary flame kernels has been shown above (cf. Figure 4.4). The corresponding results for the pressure evolution resulting from radiation induced ignition are shown for Case (c) in Figure 4.16 for four repeated experiments. The pressure signals were taken from the second pressure transducer located at a distance of 1305 mm from the ignition end. The results suggest that repeatability is very good

with marginal variations in the peak pressure and the pressure wave arrival time. The overall equivalence ratio, critical in this experiment, was kept within  $0.804 \pm 0.004$  as shown in Table 4.2.

## 4.6. Conclusions

The impact of possible secondary ignitions caused by forward thermal radiation was explored using fuel lean  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures in a flame tube facility with obstacles installed to generate turbulence. A continuous wave laser operating in the near infrared was used as the radiation source and acetylene black particles were used as the radiation target due to their relationship with soot emissions, e.g. from Diesel engines. The influence of ignition location, ignition delay time and obstacle configuration were studied. It was shown that ignition kernels caused by irradiated particles can successfully be entrained into the main flow and/or recirculation zones formed around obstacles and cause multipoint explosions. The resulting relationship between fuel consumption ahead of the advancing flame and the evolution of the strength of an explosion is shown to be complex and typically lead to increased explosion durations with reduced peak pressures. The complex effect of forward radiation induced ignition on the pressure development stems from the interactions of the two explosion kernels resulting in two sharp pressure rises separated by a quasi-stable stage with the duration of the quasi-stable stage depending on the radiation induced ignition time. The main (spark ignited) flame arrival time was delayed by the secondary ignition kernel which can also be seen from the measured flame speeds. The total pressure impulse was calculated and found to be dependent on the configuration with a higher impulse in the two-obstacle configuration due to the enhanced turbulence intensity in the recirculation region.

Overall, the influence of thermal radiation induced ignition kernels can be expected to be complex in large vapour cloud explosions with a range of possible outcomes. The ignition kernels could be transported into the main flow region with reduced explosion overpressure and prolonged loading time. The ignition kernels could also be potentially transported further downstream, leading to a backward propagating flame impeding the main flame with different pressure development and impulse characteristics.

## 5. Flow field quantification using HS-PIV

In obstructed channels, the mixture reactivity has a direct impact on the flame propagation speed and the resulting overpressure as well as an indirect impact, e.g. through turbulence–chemistry interactions. The former has been described in the previous chapters, while the latter, the influence of mixture reactivity on flow field, remains to be quantified. In this chapter, the flow field in the critical recirculation region behind an obstacle in the previously described flame tube facility was quantified using high-speed particle image velocimetry (HS-PIV) and Mie scattering at 10 kHz. The impact of mixture reactivity was studied by introducing different H<sub>2</sub> substitutions (50%, 80% and 100%) in H<sub>2</sub>/CO/Air and H<sub>2</sub>/CH<sub>4</sub>/Air mixtures while keeping the equivalence ratio constant at  $0.60 \pm 0.02$ . Comprehensive datasets for the flow field evolution in the recirculation region were obtained.

### 5.1. Selection of conditions for flow field investigations

In obstructed channels, the rate of heat release is greatly enhanced by the turbulence in the developing recirculation zones behind the obstacles leading to fast deflagrations. The timing and magnitude of the resulting pressure peaks are strongly dependent on the mixture reactivity. In Chapter 3, explosion overpressures resulting from hydrogen enriched CO/Air and CH<sub>4</sub>/Air mixtures over a wide range of hydrogen concentrations and equivalence ratios were studied at an initial pressure of 101.325 kPa. Figure 5.1 shows the resulting normalised overpressures ( $P^* = P/P_0$ , where  $P_0 = 101.325$  kPa is the initial pressure) at an equivalence ratio of 0.60. For H<sub>2</sub>/CO/Air mixtures, the peak overpressure increases with hydrogen concentration linearly, while for H<sub>2</sub>/CH<sub>4</sub>/Air mixtures it increases gradually at low concentrations while becoming dramatic at higher concentrations. Two different regimes are noted for the H<sub>2</sub>/CH<sub>4</sub>/Air mixtures, a slow initial increase followed by a rapid increase beyond 60% H<sub>2</sub> substitution.

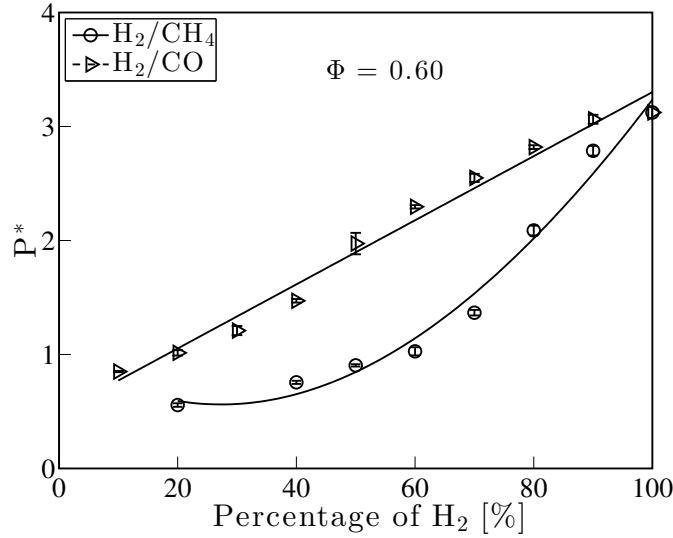


Figure 5.1.: Normalised peak explosion overpressures for H<sub>2</sub>/CO and H<sub>2</sub>/CH<sub>4</sub> mixtures at an equivalence ratio of 0.60. Pressure normalised by the initial pressure,  $P^* = P/P_0$ , where  $P_0 = 101.325$  kPa.

Following the above results, the H<sub>2</sub> substitution levels in the current study were chosen as 50% and 80%, covering the two regimes for CH<sub>4</sub> as outlined above, and the reference case of 100% H<sub>2</sub>. Figure 5.2 illustrates the pressure development in H<sub>2</sub>/CO/Air and H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with different hydrogen concentrations. The overpressures shown ( $P^* = P/P_0$ , where  $P_0 = 50$  kPa is the initial pressure) were obtained from the second pressure transducer located at a distance of 1.305 m from the ignition end and correspond approximately to the maximum recorded. A change in the hydrogen concentration impacts the peak overpressure differently for mixtures with CO and CH<sub>4</sub>. For H<sub>2</sub>/CH<sub>4</sub>/Air mixtures, the peak pressure increased by a factor of two with the change from 50% to 80% hydrogen substitution, but nearly tripled from 80% to 100%. The result shows a strongly non-linear impact of the hydrogen concentration on the explosion overpressure. For H<sub>2</sub>/CO/Air mixtures, the increase is close to a factor of two moving from 50% to 80% and then to 100% H<sub>2</sub> substitution. Furthermore, at a given hydrogen substitution level, the H<sub>2</sub>/CO/Air mixtures give higher peak overpressures and a faster time evolution suggesting a stronger inhibiting effect by CH<sub>4</sub> than CO. The results are consistent with data presented in Chapter 3.

The flame speeds, shown in Figure 5.3, decrease with a reduction in hydrogen content due to the reduced mixture reactivity and with distance due to the decay of

the explosion. The small error bars indicate good experimental repeatability. The stronger inhibiting effect of  $\text{CH}_4$  can also be seen from the reduced flame speed at the same hydrogen concentrations.

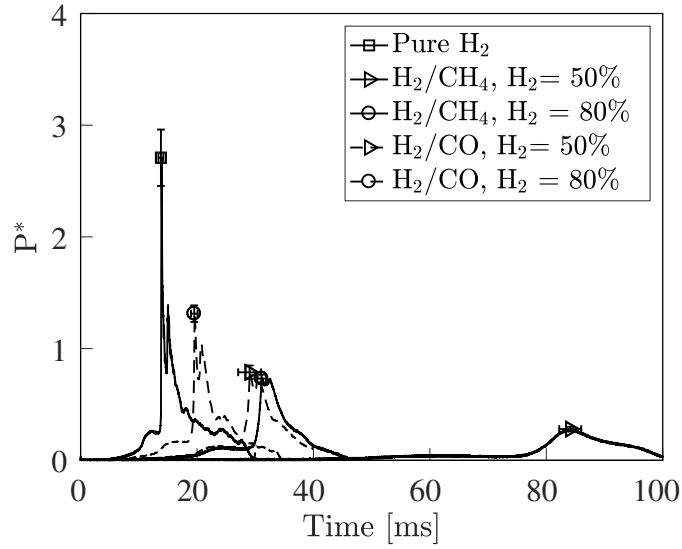


Figure 5.2.: Explosion overpressures registered at the second pressure transducer located 1.305 m from the ignition for  $\text{H}_2/\text{CO}$  and  $\text{H}_2/\text{CH}_4$  mixtures with  $\text{H}_2 = 50$ , 80 and 100% and  $\Phi = 0.60$ . Pressure normalised by the initial pressure,  $P^* = P/P_0$ , where  $P_0 = 50$  kPa.

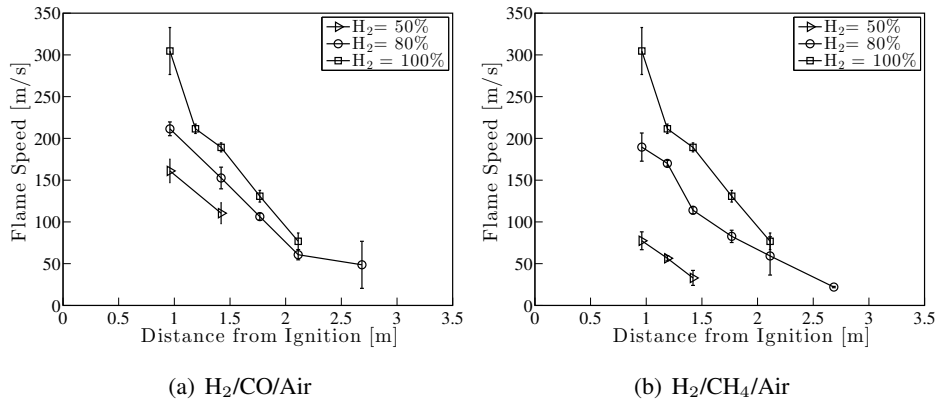


Figure 5.3.: Flame speeds in  $\text{H}_2/\text{CH}_4/\text{Air}$  and  $\text{H}_2/\text{CO}/\text{Air}$  mixtures with  $\text{H}_2 = 50$ , 80 and 100% and  $\Phi = 0.60$ .



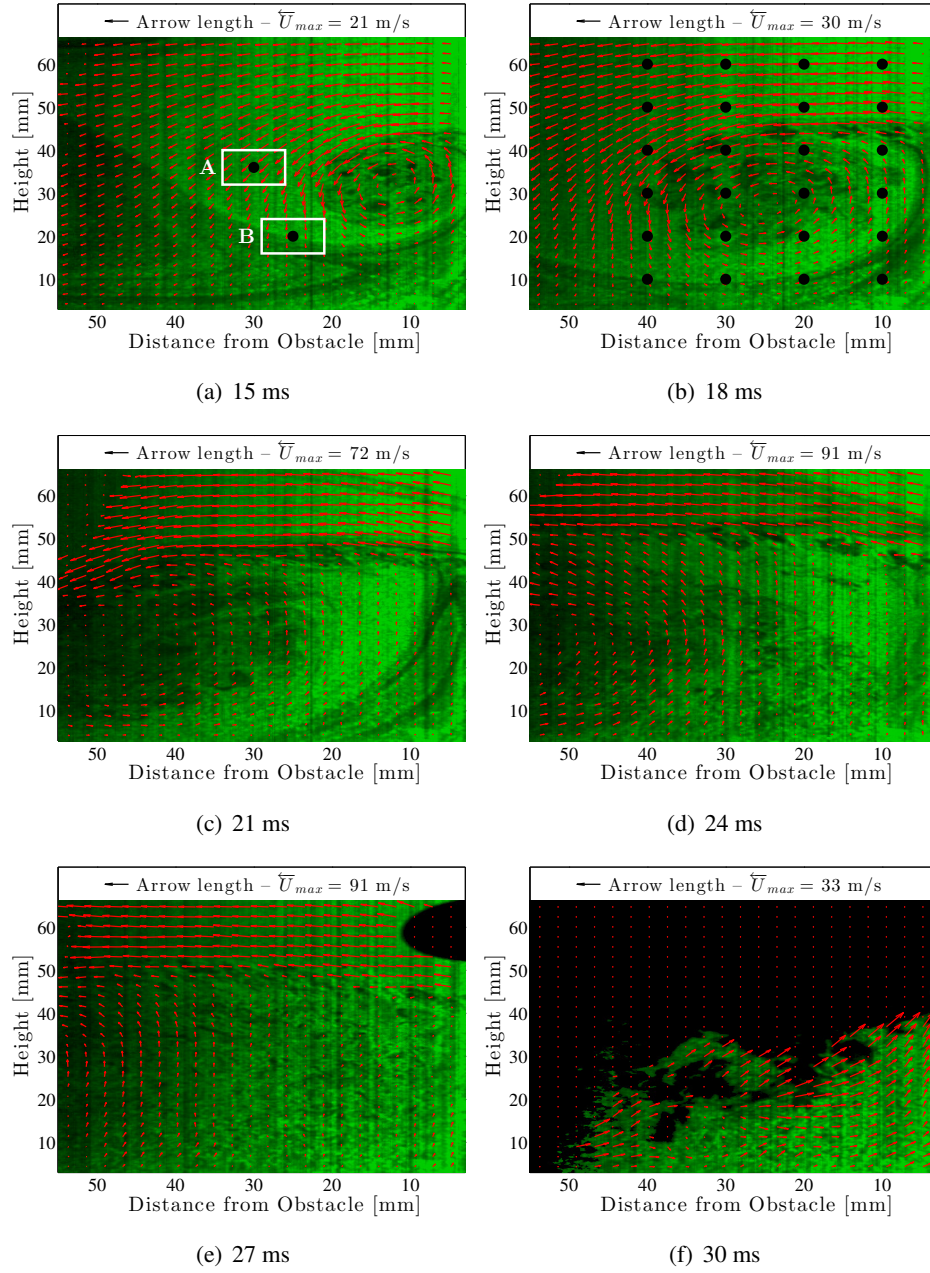


Figure 5.4.: High-speed (10 kHz) PIV and Mie scattering (green colour only; the flash temperature for the silicone oil droplets is 373 K) with superimposed velocity vectors in  $H_2/CH_4/Air$  mixtures,  $H_2 = 80\%$ ,  $\Phi = 0.60$ . The velocity vector length is scaled linearly with the velocity magnitude with the reference given at the top of each sub-graph. The dots in (a) indicate the location where a sensitivity analysis was performed and (b) shows the grid points where the time-resolved velocity was determined.

## 5.2. Flow visualisation and recirculation eddy tracking

High speed PIV at 10 kHz was performed to better understand the evolution of the flow in the recirculation zone behind the second obstacle where the dominant explosion occurs. Figure 5.4 shows the Mie scattering (green/light colour) images (the black parts of each image signify an absence of silicone oil droplets and hence temperatures above the evaporation temperature of 373 K) superimposed with velocity vectors for a  $\text{H}_2/\text{CH}_4/\text{Air}$  mixture with 80%  $\text{H}_2$ . The developing flow pattern ahead of the flame front is evident. In the time window from 15 to 24 ms after ignition, the eddy continues to grow with the centre gradually moving downstream away from the obstacle. The flame front, the black area in the top right hand corner of Figure 5.4(e), arrives at 27 ms. A maximum velocity of around 90 m/s is observed. The fuel in the recirculation zone is subsequently rapidly consumed via a highly fragmented flame front, as shown in Figure 5.4(f), with islands of combustion products surrounded by reactants. The peak pressure for this mixture also occurs at around this time (30 ms) and shows the correlation with the turbulent explosion in the recirculation zone behind the obstacle.

Before the flame front arrives, the eddies behind the second obstacle continue to grow with the centre moving downstream. The locations of the eddy centre at different times and the translation velocity in the horizontal direction ( $\bar{u}$ ) were calculated and the results are shown in Figure 5.5. The translation velocity of the eddy centre increases with time and hydrogen concentration. It can also be seen that the velocity increases faster in a more reactive mixture. The uncertainty (error bars) mainly stems from the tracking process. The detailed data can be found in Appendix A.

## 5.3. Quantification of the flow field

### 5.3.1. Sensitivity analysis on the interrogation window size

To gain more quantitative data on the flow field caused by the displacement effect of the combustion products, the mean velocity components in the horizontal ( $\bar{u}$ ) and vertical ( $\bar{v}$ ) directions were determined for interrogation windows of a suitable size at different locations. Averaging too many vectors may result in a loss of information, while too small a window size is not representative due to the limited number of vectors in the sample. Therefore, a sensitivity analysis on the window size was performed at two positions A and B, shown in Figure 5.4(a), with centres

(distance from the obstacle, distance from the lower wall) at (30, 36) mm and (25, 20) mm. Square windows of four different sizes (3×3 mm, 5×5 mm, 6×6 mm, 8×8 mm) were chosen with the number of vectors around 6, 20, 30 and 50 within the windows, respectively. Figure 5.6 shows the results for H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with 80% of H<sub>2</sub> and an equivalence ratio of 0.60. The mean velocity components show negligible differences for the four selected window sizes. For the subsequent data analysis, a window size of 5×5 mm containing around 20 vectors was used. At position A the horizontal velocity component ( $\bar{u}$ ) is positive, while at B it is predominantly negative.

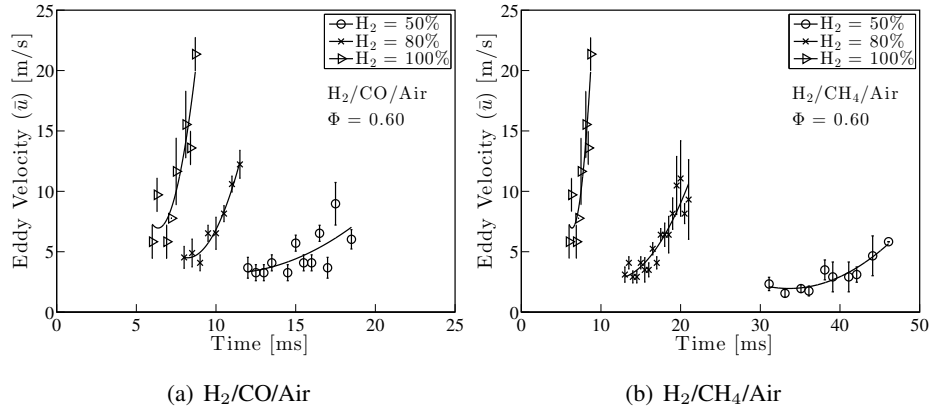


Figure 5.5.: The horizontal translation velocity ( $\bar{u}$ ) of the eddy centre for H<sub>2</sub>/CO and H<sub>2</sub>/CH<sub>4</sub> mixtures with H<sub>2</sub> = 50, 80 and 100% and a constant  $\Phi$  of 0.60.

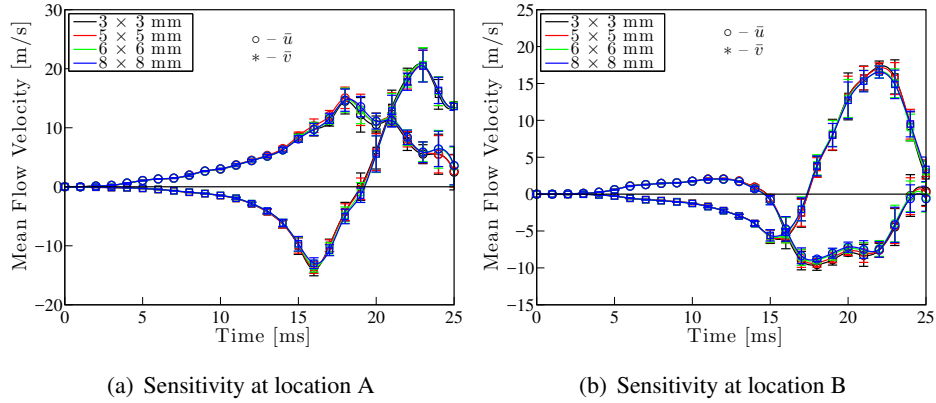


Figure 5.6.: Sensitivity of mean horizontal ( $\bar{u}$ ) and vertical ( $\bar{v}$ ) velocity components to window size (see Figure 5.4(a) for the locations of A and B).

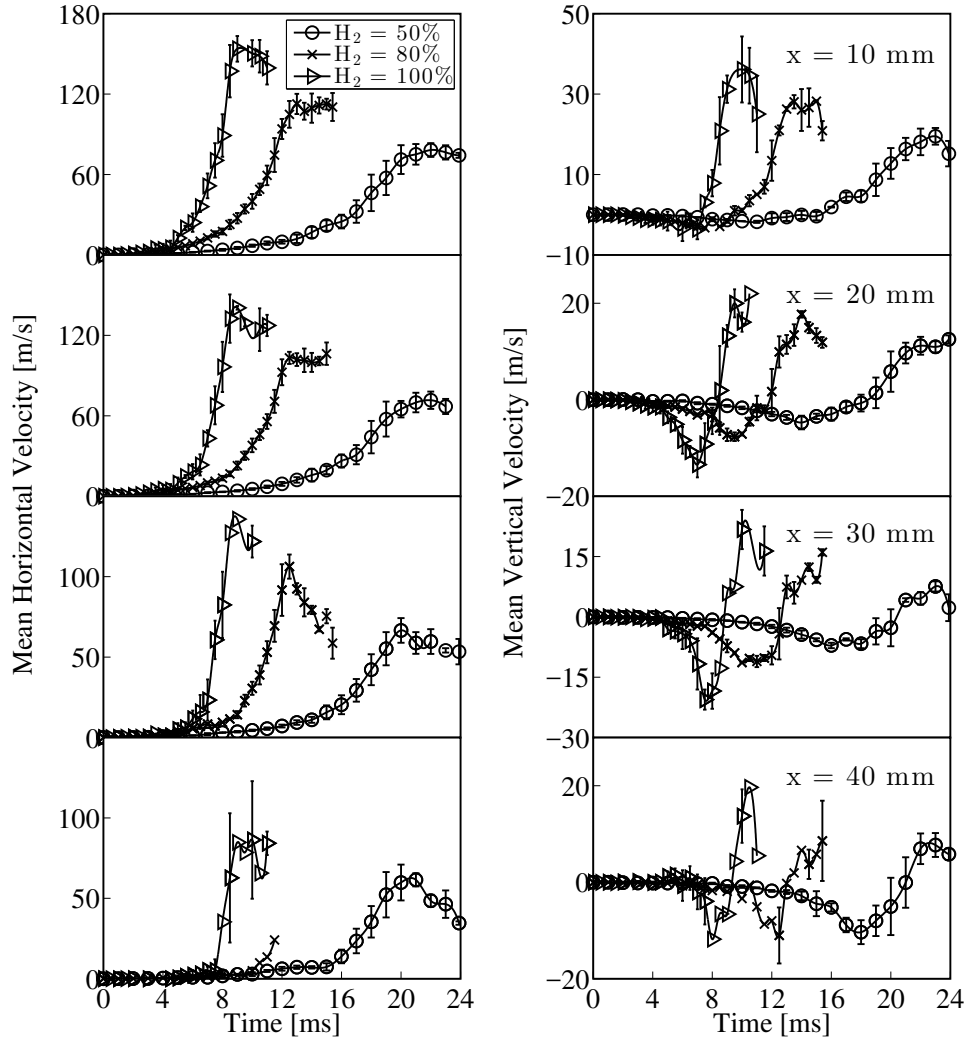


Figure 5.7.: Time-resolved velocities in  $H_2/CO/Air$  mixtures at  $x = 10$  mm downstream of the obstacle. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Selected characteristic error bars are shown for clarity. Locations of the points refer to Figure 5.4(b).

### 5.3.2. Evolution of the velocity field

The flow field behind the second obstacle was characterised by determining the time-resolved velocity development for an equally spaced matrix with 24 discrete points separated by 10 mm in both horizontal and vertical directions. The locations of the points are shown in Figure 5.4(b) with horizontal distances of 10, 20, 30, 40 mm from the obstacle and heights of 60, 50, 40, 30, 20, 10 mm. Figure 5.7 shows the time-resolved velocity development in  $H_2/CO/Air$  mixtures at four lo-

cations at the same height ( $y = 50$  mm), but at different distances from the obstacle ( $x = 10, 20, 30, 40$  mm). The flame propagation associated with the more reactive mixtures (higher hydrogen substitutions) is significantly faster and the velocity magnitude correspondingly higher in the horizontal and vertical directions. The same behaviour was observed for the  $H_2/CH_4/Air$  mixtures.

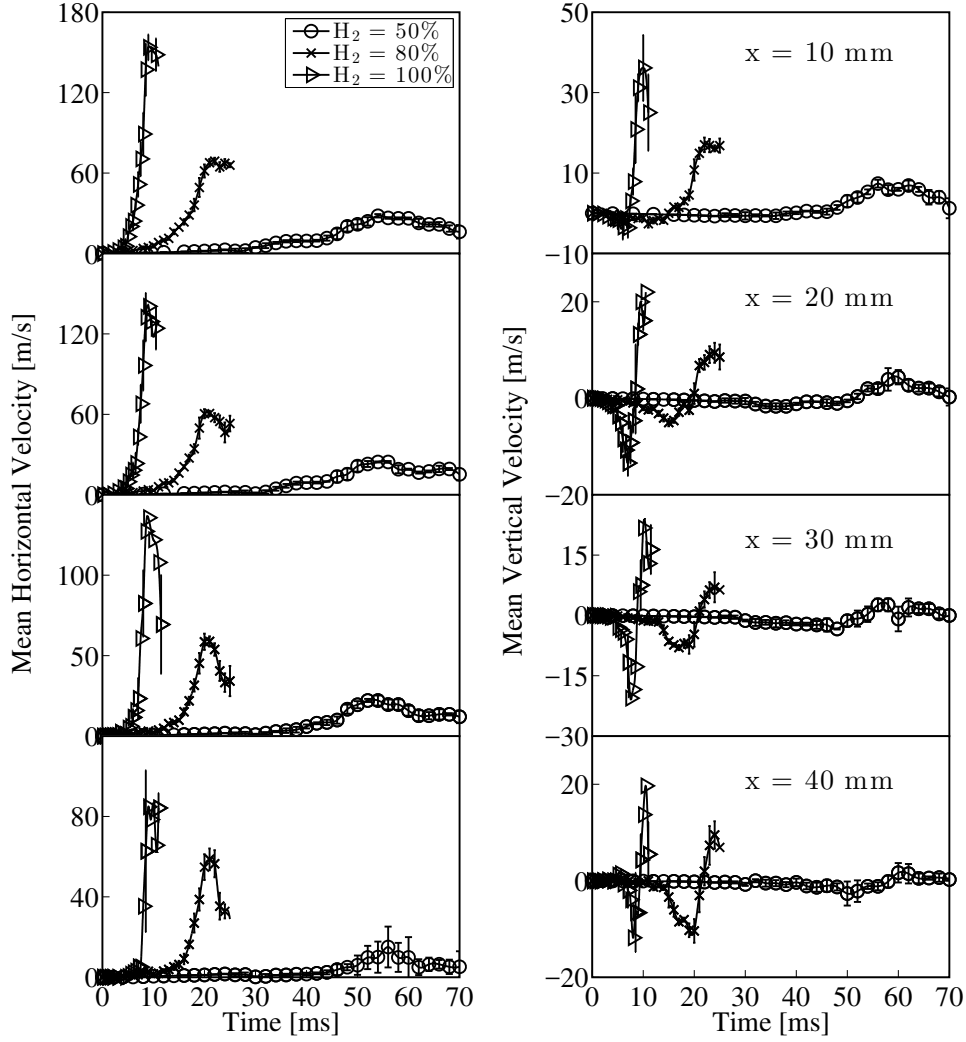


Figure 5.8.: Time-resolved velocities in  $H_2/CH_4/Air$  mixtures along a horizontal line at a height ( $y$ ) of 50 mm. Selected characteristic error bars are shown for clarity. Subplots correspond to distances from the obstacle ( $x$ ) at 10, 20, 30, 40 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

The introduction of a dimensionless time, normalised by the arrival time of the flame at the second obstacle ( $t^* = t/t_A$ , where  $t_A$  is the flame arrival time listed in

Table 5.1), makes it easier to compare the flow field development for mixtures with different reactivities. Figures 5.9 – 5.12 show the mean horizontal ( $\bar{u}$ ) and vertical ( $\bar{v}$ ) velocities for H<sub>2</sub>/CO/Air mixtures at points 10, 20, 30, 40 mm downstream the second obstacle in the normalised time domain and Figs. 5.13 – 5.16 show the same for H<sub>2</sub>/CH<sub>4</sub>/Air mixtures. The subplots in each figure correspond to the points at heights 60, 50, 40, 30, 20, 10 mm. In the normalised time domain, the velocity development shows a qualitatively similar behaviour with absolute value strongly depending on the mixture reactivity. The maximum velocity increases with the mixture reactivity and decreases slightly with the distance from the obstacle. For mixtures with the same hydrogen substitution level, the CO blends give higher maximum velocity which is consistent with the peak overpressure. A sharp velocity gradient exist in the vertical direction, notably at the height of the obstacle, indicating the existence of the shear layer with the associated strong turbulence generation. For instance, at 10 mm downstream for both H<sub>2</sub>/CO/Air and H<sub>2</sub>/CH<sub>4</sub>/Air mixtures (see Figs. 5.9 and 5.13),  $\bar{u}$  changes greatly from 150 m/s to -15 m/s above and below the obstacle height and the maximum  $\bar{v}$  component keeps at a similar magnitude of 20 – 30 m/s. The uncertainties associated with H<sub>2</sub>/Air mixtures at  $\Phi = 0.60$  tend to be larger as a result of the higher reactivity.

Table 5.1.: Summary of the characteristic results in the experiment where  $P_{max}$  is the peak overpressure,  $FS_{max}$  the maximum flame speed obtained from the ionisation probes,  $\bar{u}_{max}$  the maximum horizontal velocity along the vertical line located 10 mm downstream the obstacle and  $t_A$  the flame arrival time at the second obstacle.

| Mixture                              | $\Phi$ [-] | H <sub>2</sub> [%] | $P_{max}$ [kPa] | $FS_{max}$ [m/s] | $\bar{u}_{max}$ [m/s] | $t_A$ [ms] |
|--------------------------------------|------------|--------------------|-----------------|------------------|-----------------------|------------|
| H <sub>2</sub> /Air                  | 0.60       | 100                | 132             | 305              | 162                   | 11.5       |
| H <sub>2</sub> /CO/Air               | 0.60       | 50                 | 39              | 161              | 64                    | 24         |
|                                      |            | 80                 | 66              | 211              | 112                   | 16         |
| H <sub>2</sub> /CH <sub>4</sub> /Air | 0.60       | 50                 | 14              | 77               | 28                    | 70         |
|                                      |            | 80                 | 37              | 190              | 69                    | 25         |

The strength and downstream motion of the recirculation zone are strongly influenced by the mixture reactivity and lead to the strong quantitative differences for the velocity components. The horizontal ( $\bar{u}$ ) component reaches a maximum close to the top of the tube and becomes negative close to the bottom due to the flow reversal caused by recirculation. Specifically, at distances of 10 and 20 mm downstream,  $\bar{u}$  becomes negative below 30 mm in height, while at 30 and 40 mm

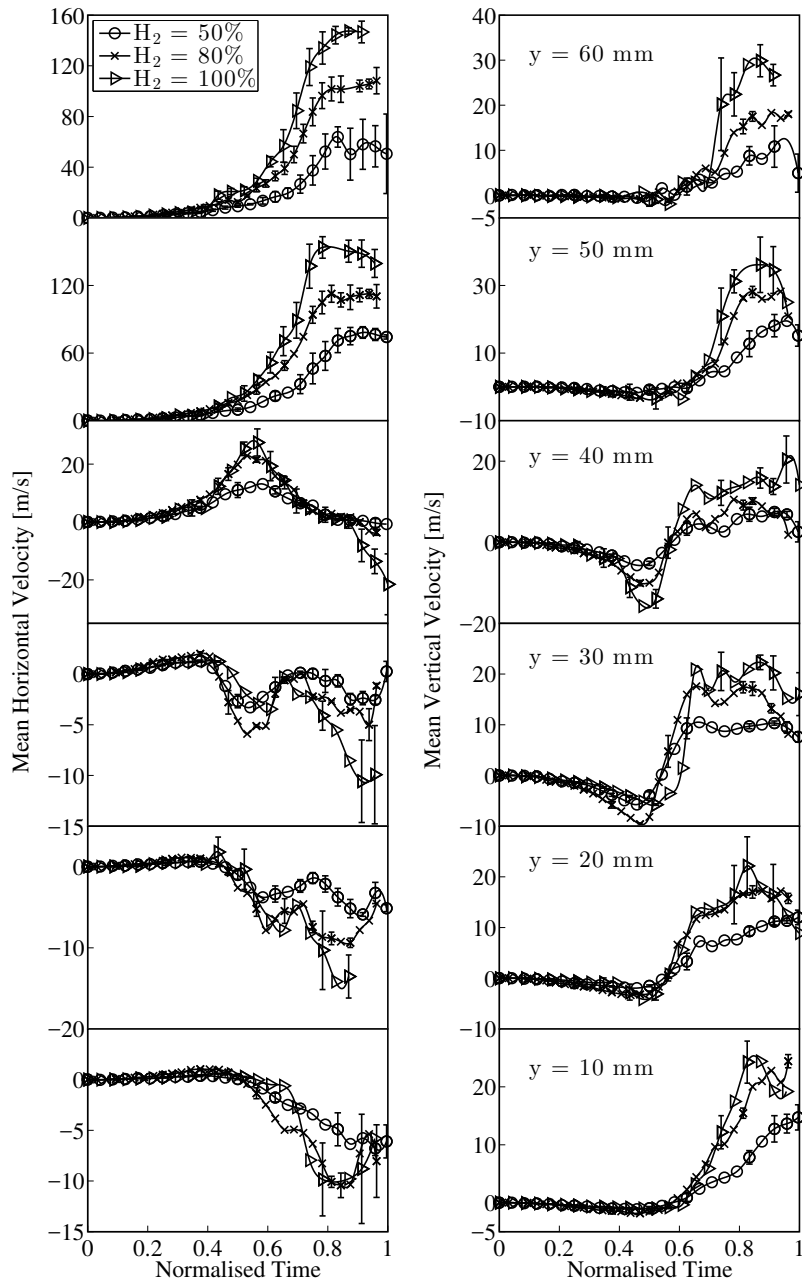


Figure 5.9.: Time-resolved velocities in  $H_2/CO/Air$  mixtures at  $x = 10$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

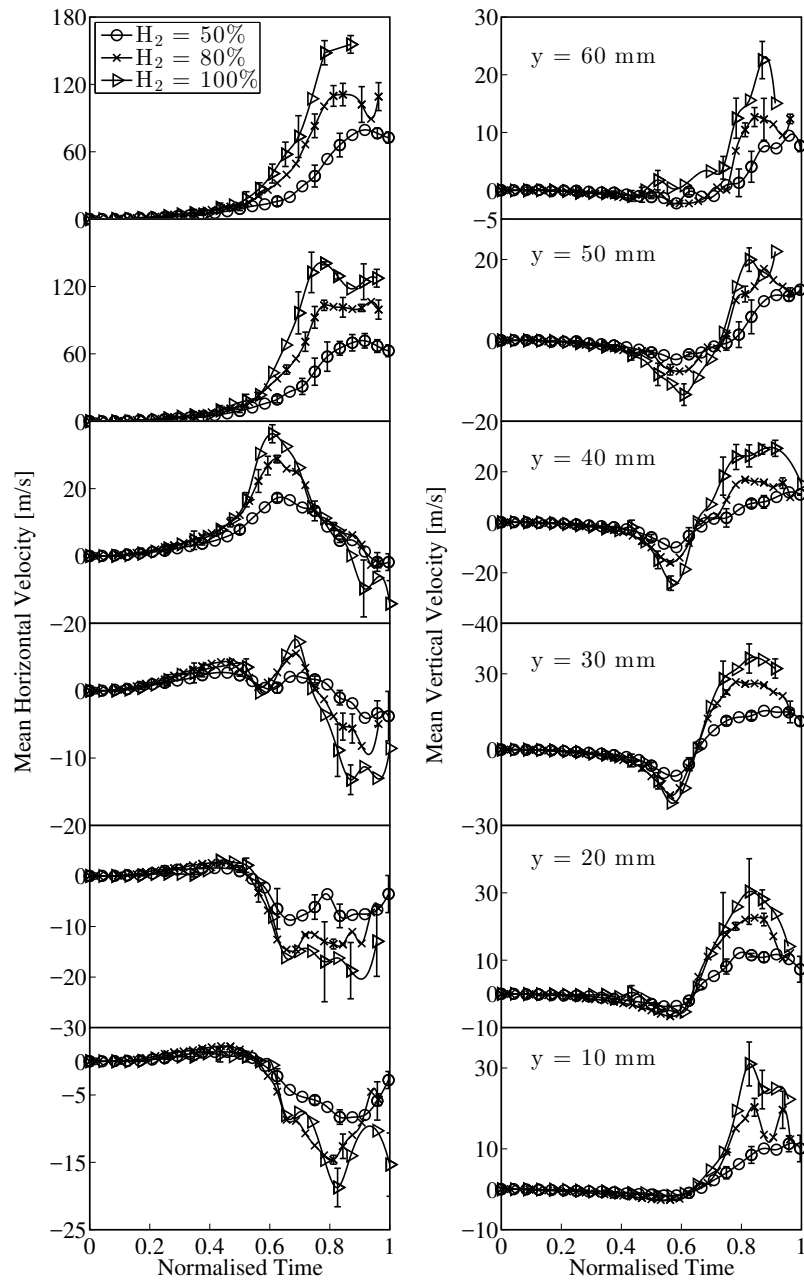


Figure 5.10.: Time-resolved velocities in  $H_2/CO/Air$  mixtures at  $x = 20$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).



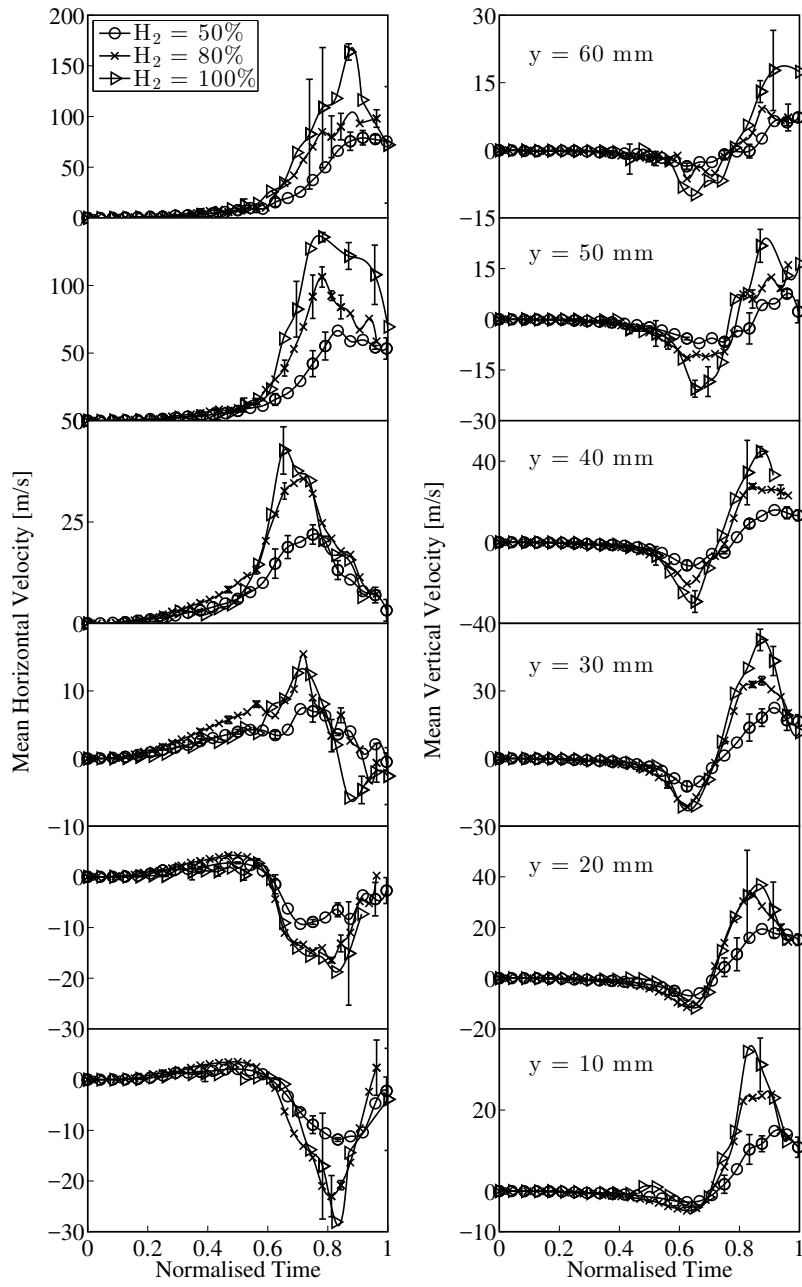


Figure 5.11.: Time-resolved velocities in  $H_2/CO/Air$  mixtures at  $x = 30$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

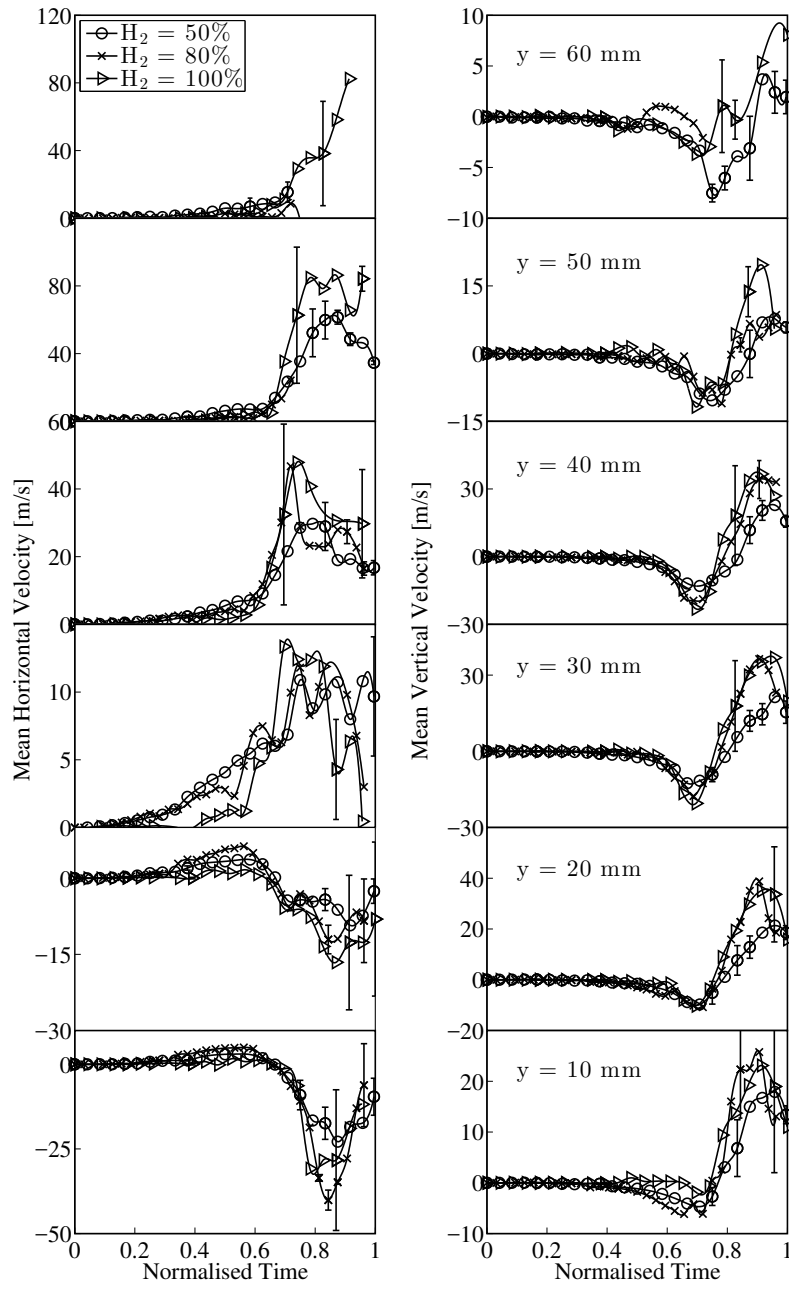


Figure 5.12.: Time-resolved velocities in  $H_2/CO/Air$  mixtures at  $x = 40$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

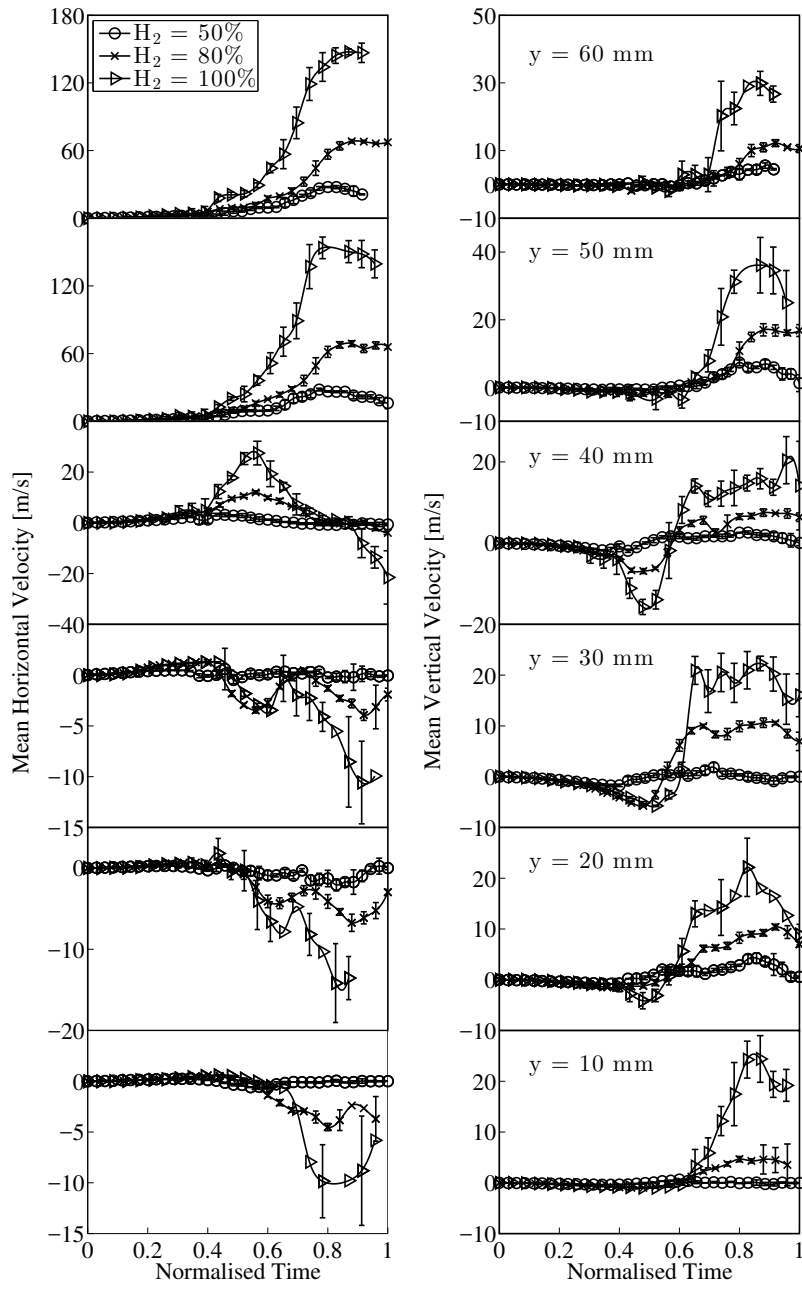


Figure 5.13.: Time-resolved velocities in  $H_2/CH_4/Air$  mixtures at  $x = 10$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

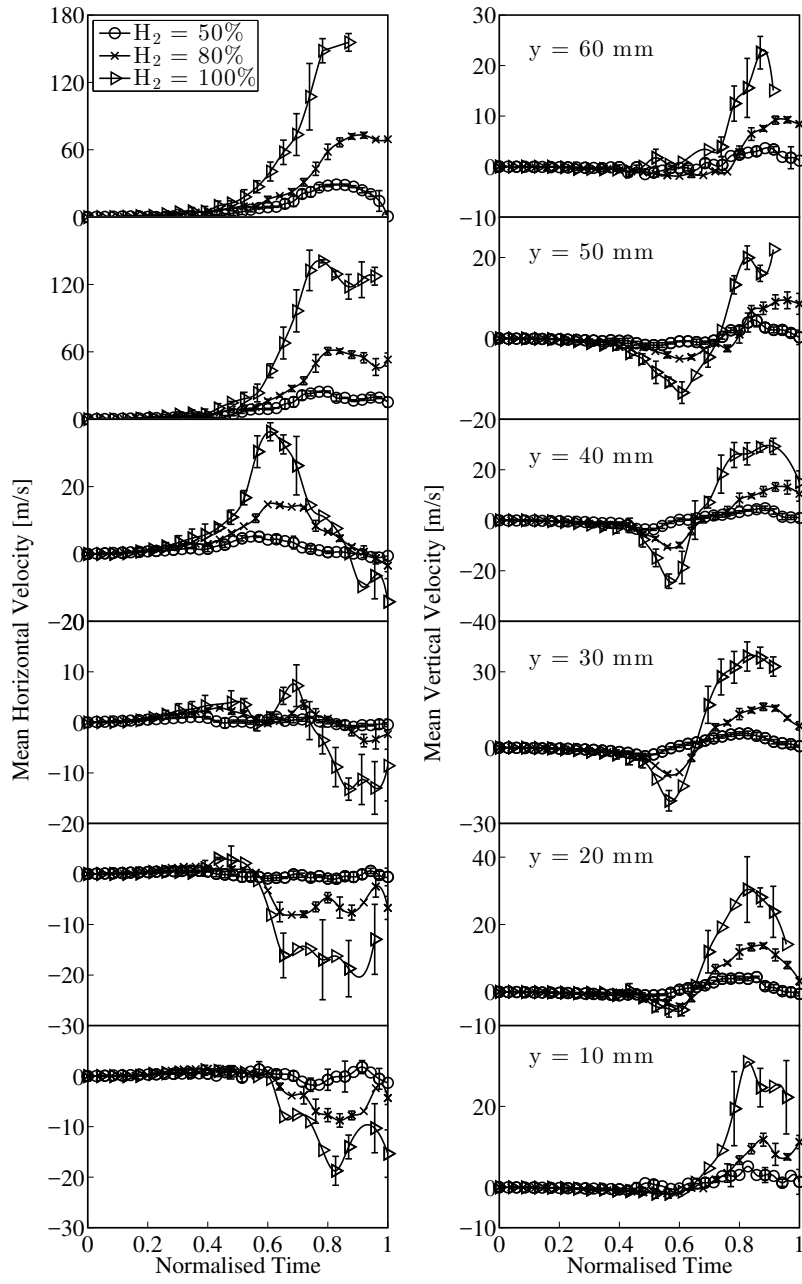


Figure 5.14.: Time-resolved velocities in  $H_2/CH_4/Air$  mixtures at  $x = 20$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

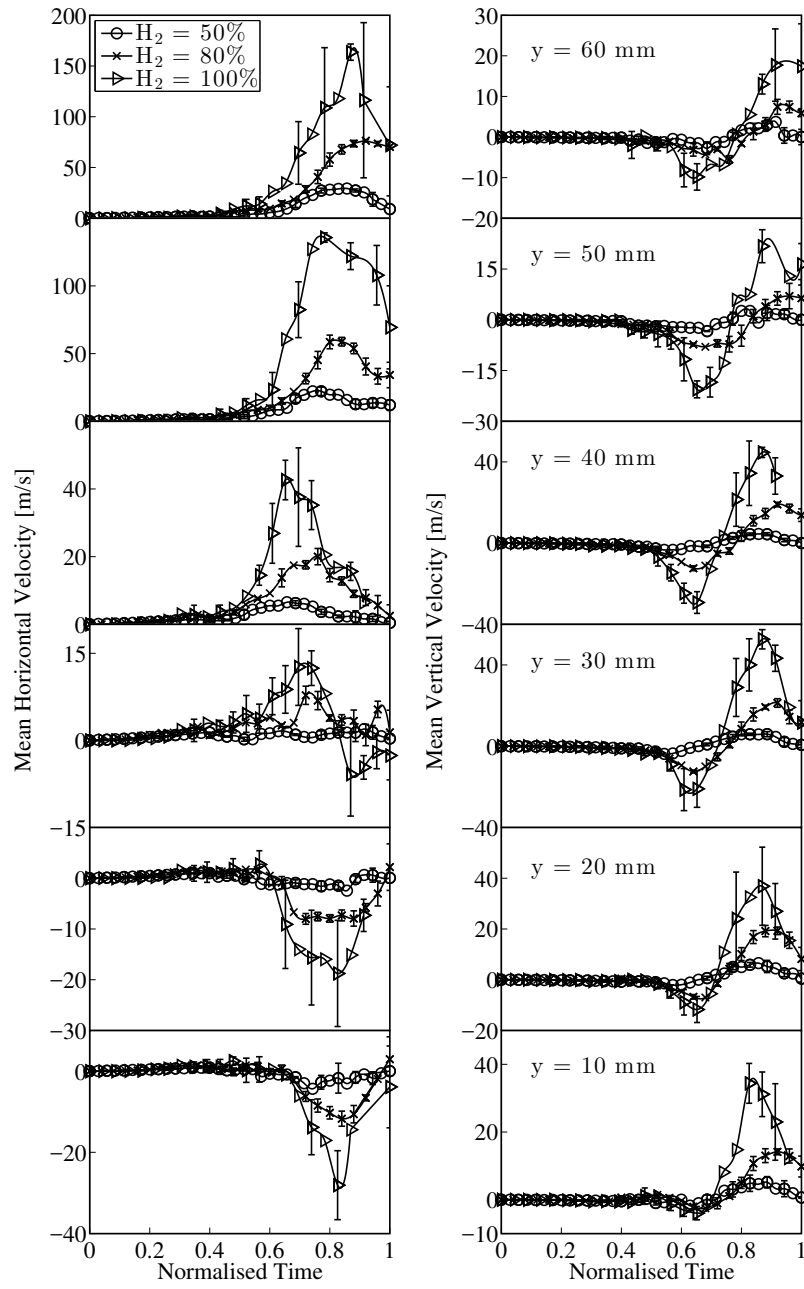


Figure 5.15.: Time-resolved velocities in  $H_2/CH_4/Air$  mixtures at  $x = 30$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

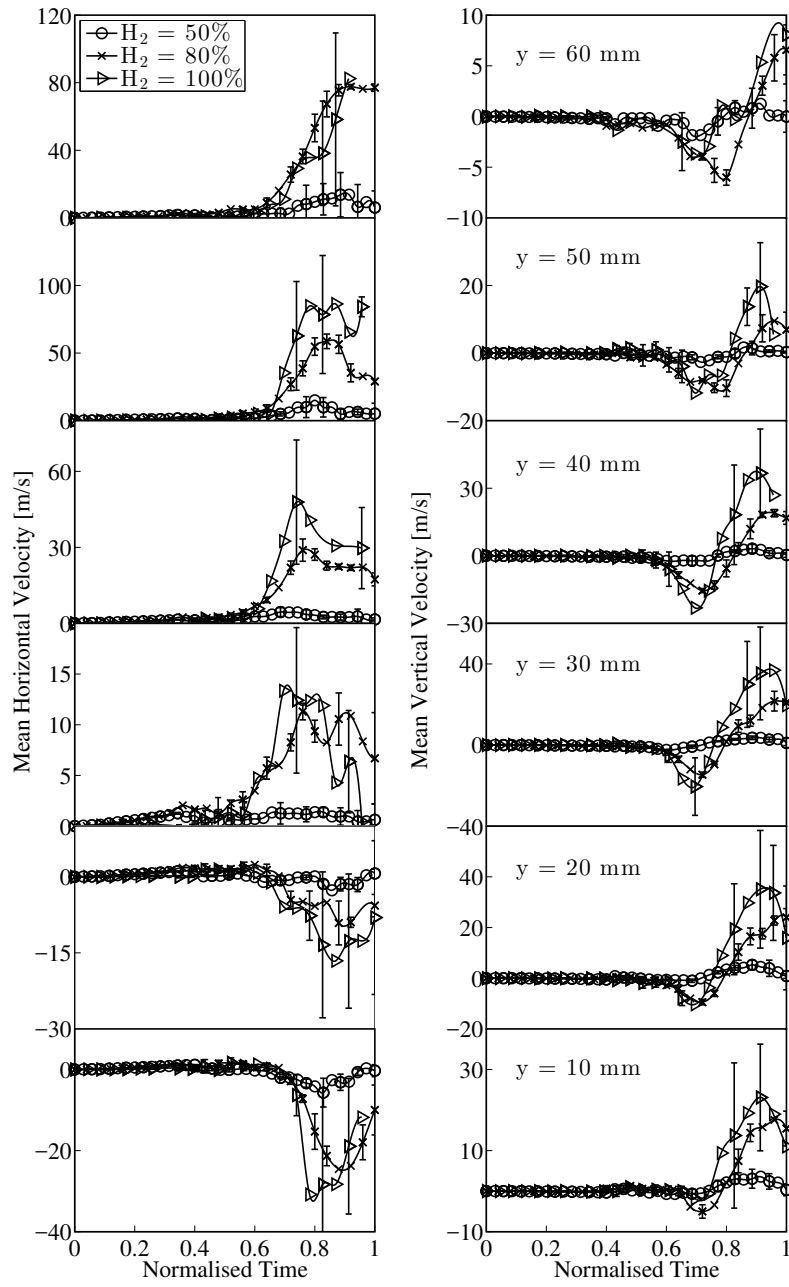


Figure 5.16.: Time-resolved velocities in  $H_2/CH_4/Air$  mixtures at  $x = 40$  mm downstream of the obstacle. Selected characteristic error bars are shown for clarity. Subplots correspond to heights ( $y$ ) at 60, 50, 40, 30, 20, 10 mm from top to bottom. Locations of the points refer to Figure 5.4(b).

downstream, it becomes negative only below 20 mm in height, indicating that while the recirculation eddy moves downstream, the centre of the eddy also moves slightly towards the bottom of the tube. The  $\bar{v}$  component is generally negative before turning positive and reaching the maximum, resulting from the opposite velocity directions at the front and tail of the recirculation eddy.

## 5.4. Conclusions

Turbulent explosions resulting from fuel lean  $H_2$  enriched CO/Air and  $CH_4$ /Air mixtures at an initial pressure of 50 kPa and room temperature were experimentally studied in an obstructed flame tube facility with the explosion overpressure and flame speed measured. High-speed PIV measurements at 10 kHz were performed in the critical recirculation zone to assess the impact of the mixture reactivity on the developing flow field. The mixture reactivity was modified by introducing different hydrogen substitutions (50, 80 and 100%) at a fixed stoichiometry of 0.60. The measured explosion overpressure and flame speed increase with the mixture reactivity. A stronger inhibiting effect of  $CH_4$  than CO on the chemistry of  $H_2$  was also observed as discussed in previous chapters. The flame morphology during the propagation was visualised with Mie scattering and the centre of the shear driven recirculation eddy was tracked with the horizontal translation velocity calculated. The flow field was further quantified by determining the mean horizontal ( $\bar{u}$ ) and vertical ( $\bar{v}$ ) velocity components via combined PIV and time-series PIV for an equally spaced matrix with 24 discrete points separated by 10 mm in both horizontal and vertical directions. It was found that the contribution of the ( $u$ ) and ( $v$ ) components to the overall velocity magnitude depends on the spatial locations and the development of the recirculation zone has been quantified. The flame propagation associated with a more reactive mixture is significantly faster and the velocity magnitude is also higher in both horizontal and vertical directions. The influence of the mixture reactivity on the flow field evolution in time can be approximated by normalising with the flame arrival time at the second obstacle where the dominant explosion occurs. In the normalised time domain, both  $\bar{u}$  and  $\bar{v}$  behave quantitatively similar regardless of the mixture reactivity and location. The horizontal component reaches the maximum close to the top of the tube and becomes negative at the bottom. The vertical component is generally negative before turning positive and reaching the maximum. The differences stem from the downstream motion of the recirculation eddy. The data produced forms part of a

comprehensive quantification of the time-resolved flow evolution in the recirculation zone ahead of the advancing flame front. It further shows the link between the flow field, flame acceleration and the resulting overpressure. The data are expected to support model development.



## 6. Conclusions

### 6.1. Summary of the present study

This thesis presents an experimental study of turbulent explosions resulting from hydrogen enriched lean CO and/or CH<sub>4</sub> blends and is motivated by the increased use of syngas/biogas for power generation. The experiments were carried out in a flame tube facility with the explosion overpressure and flame arrival time measured using pressure transducers and ionisation probe detectors. Obstacles were installed to enhance the flame propagation by introducing turbulence. The influence of mixture reactivity was first investigated with scaling laws explored. The impact of thermal radiation induced ignition in turbulent explosions was evaluated by analysing the pressure development and pressure impulse. The flow field evolution in the critical recirculation zone was further quantified using high-speed particle image velocimetry and Mie scattering to show the link between flow field, flame acceleration and the resulting explosion overpressure.

#### 6.1.1. Explosion overpressure and flame speed in hydrogen enriched fuels

The explosion behaviour (overpressure and flame speed) of hydrogen enriched binary fuels (H<sub>2</sub>/CO and H<sub>2</sub>/CH<sub>4</sub>) and ternary fuels (H<sub>2</sub>/CH<sub>4</sub>/CO) were comprehensively studied. Three different equivalence ratios ( $\Phi = 0.80, 0.60$  and  $0.40$ ) with a wide range of hydrogen substitutions from close to the lower ignition limit to mixtures producing strong turbulent explosions were chosen to assess the mixture reactivity effect. A flame tube facility featuring a rectangular cross-section area of  $34 \times 72$  mm and a length of 4400 mm ( $L/d = 96$  or  $156$ ) was used. Two obstacles with a thickness of 5 mm and a height of 36 mm, offering a blockage ratio of 50%, were installed at distances of 80 (top) and 360 mm (bottom) from ignition in a staggered arrangement to enhance the flame propagation. The explosion overpressure and flame arrival time were measured via pressure transducers and ionisation probe detectors installed along the tube.

The results highlight that both hydrogen content and equivalence ratio have significant influences on the explosion severity. The dependence of peak overpressure on  $H_2$  concentration shows a linear trend in  $H_2/CO/Air$  mixtures and exponential in  $H_2/CH_4/Air$  mixtures. For ternary fuels, namely  $H_2/CO/CH_4/Air$  mixtures, the trend tends to be more linear with increasing CO substitutions compared to  $CH_4$ . At the same equivalence ratio and hydrogen content,  $H_2/CO/Air$  mixtures give higher explosion overpressures than  $H_2/CH_4/Air$  mixtures, illustrating a stronger inhibiting effect of  $CH_4$  than CO on the chemistry of  $H_2$ . This effect is also present in ternary mixtures. The flame arrival time decreases and the flame speed increases with an increase in both equivalence ratio and hydrogen content.

The proposed mixture composition parameter  $\beta$  shows success in the linearisation of the data and the peak overpressure increases linearly with  $\beta$  regardless of the fuel blend type yet with equivalence ratio dependent slopes. The theoretical overpressure predictions based on acoustic theory [128] and measured flame speeds show good agreement with experimental data. The estimated Mach number ( $Ma_1^*$ ,  $Ma_2^*$ ) based on the Reynolds number and expansion ratio incorporates the mixture reactivity effect and give good predictions for mixtures with low mixture reactivity, yet with deviations for very reactive mixtures. The latter is not unexpected as the use of unstrained laminar burning velocities is only intended as a leading order approximation with further work required to quantify the influence of flame stretch, Lewis number and turbulence-chemistry interactions. The estimation method can, however, potentially be used in circumstances where extensive flame speed data are not available but suitable reference points can be obtained in the same, or a very closely related, geometry.

### 6.1.2. Impact of radiation induced multipoint ignition

The enhancing effect of thermal radiation based ignition in large vapour cloud explosions, proposed by Moore and Weinberg [62] and later used by Atkinson and Cusco [137] in trying to explain the Buncefield explosions, cannot currently be confirmed in view of uncertainty over the radiation intensity, ignition time scale, presence of the suspended particles, etc. To assess the impact of such radiation induced ignition kernels on the overall pressure development, a CW laser diode (LIMO50-FG400-WL808; LIMO GmbH) operating at  $808\text{ nm} \pm 2\text{ nm}$  was used as the radiation source to replicate the infrared radiation from hot combustion products and acetylene black particles were used as the radiation target due to their

relationship with smoke and soot emissions. The ignition event was recorded using a high speed CCD camera with a recording rate of 2 kHz, providing an uncertainty of 0.5 ms. The onset of ignition was marked by the appearance of an outward propagating flame in the images and the ignition time was defined as the interval from target illumination to ignition. The explosion overpressure and flame arrival time were measured in the experiment.

The influence of ignition time, ignition location and obstacle configuration was investigated. It was found that, once ignited, the resulting secondary flame kernels could be transported with the mean flow without experiencing extinction. Hence, ignition kernels caused by irradiated particles can successfully be entrained into recirculation zones formed around obstacles leading to explosions. The relationship between fuel consumption by the secondary explosion ahead of the advancing primary flame and the evolution of the strength of the overall explosion is complex and, typically, leads to an increased explosion duration with reduced peak pressures. The complex effect of forward radiation induced ignition on the pressure development stems from the interactions of the two explosion kernels resulting in two comparatively sharp pressure rises separated by a quasi-stable stage. The duration of the quasi-stable stage depends on the radiation induced ignition time. The introduction of a second obstacle shortened the main flame arrival time and led to a higher overpressure due to increased flow velocities. The total pressure impulse was calculated and found to be comparable regardless of the ignition location for a single obstacle case. For a two obstacle configuration, the pressure impulse obtained with a secondary explosion was found to be higher than for the single ignition point case irrespective of the timing of the secondary ignition. The results suggest that the load experienced during a vapour cloud explosion featuring secondary explosion kernels may be affected as the ratio between the peak overpressure and the total impulse differs.

Overall, the results have shown that the impact of thermal radiation in large vapour cloud and/or dust explosions can be expected to be complex with a range of possible outcomes. The latter include the convection of ignition kernels into the mean flow caused by the primary flame and the subsequent formation of secondary explosions. The latter may be sufficiently strong to cause a flow reversal that impedes the propagation of the primary event and may attenuate the peak pressure via complex secondary flow patterns. It is also evident that much longer duration explosions can be created resulting in different impulse characteristics.

### 6.1.3. Quantification of the flow field

The flow field evolution in turbulent explosions was determined using HS-PIV at 10 kHz and Mie scattering techniques in an obstructed channel to show the links between flow field, flame acceleration and the resulting explosion overpressure. Both fuel lean  $\text{H}_2/\text{CO}/\text{Air}$  and  $\text{H}_2/\text{CH}_4/\text{Air}$  mixtures at an equivalence ratio of 0.60 were investigated in view of the significantly different explosion behaviour. Three different hydrogen concentrations (50, 80, 100%) were selected to vary the mixture reactivity. The development of the recirculation eddy was successfully captured using Mie scattering and the horizontal translation velocity of the eddy was determined. The flow field was further quantified using a matrix of 24 discrete points with a distance of 10 mm in both horizontal and vertical directions. The velocity was determined by ensemble averaging over an interrogation window after a sensitivity analysis on the window size. The development of the velocity was shown to be highly location dependent. In the free flow region, the horizontal component is dominant while in the shear layer region, the horizontal and vertical components are comparable. The flame propagation associated with a more reactive mixture is significantly faster and the velocity magnitude is also higher in both horizontal and vertical directions. A normalisation with the flame arrival time at the second obstacle successfully approximates the influence of mixture reactivity on the flow field evolution. In the normalised time domain, both  $\bar{u}$  and  $\bar{v}$  behave in a qualitatively similar way regardless of the mixture reactivity and location. The horizontal component is primarily positive above the obstacle and negative below. The vertical component is generally negative before turning positive and reaching the maximum. The dominating factor is the downstream motion of the recirculation eddy. The data produced forms part of a comprehensive quantification of the time-resolved flow evolution in the recirculation zone ahead of the advancing flame front and is expected to support model development. The measurement will also facilitate the scaling of the peak explosion overpressures resulting from hydrogen enriched fuels.

## 6.2. Suggestions for the future work

Based on the results presented in this thesis, the following studies are suggested to fully understand the explosion behaviour of hydrogen enriched fuels and the impact of thermal radiation induced ignition.

1. The results highlight a significant difference in the explosion behaviour between CO and CH<sub>4</sub> when blended with H<sub>2</sub>. The explosion overpressure increases with hydrogen substitution linearly in the former while exponentially in the latter. At given equivalence ratios and hydrogen concentrations, H<sub>2</sub>/CO/Air mixtures also give higher overpressures than H<sub>2</sub>/CH<sub>4</sub>/Air mixtures. The results with ternary mixtures indicate the same trend that the explosion overpressure increases with more substitutions of CO for CH<sub>4</sub>. This distinct performance may stem from a complex catalytic effect of H<sub>2</sub> on the chemistry of CO and CH<sub>4</sub>. A detailed study on the chemical kinetics of H<sub>2</sub> enriched CO and CH<sub>4</sub> is therefore suggested.
2. The scaling based on acoustic theory and the measured  $Ma$  number as well as the estimated  $Ma_1^*$ ,  $Ma_2^*$  provide encouraging agreement with the experimental measurements and capture aspects of the mixture reactivity effect. However, the Lewis number effect associated with high hydrogen concentration and flame stretch associated with highly turbulent flame have not been incorporated in the scaling. It is likely that the future inclusion of such effects will provide improvements in the scaling.
3. The effect of thermal radiation induced ignition in turbulent explosions was studied on a laboratory scale. Acetylene black particles favouring a short ignition time were used due to the short distance between the spark and the irradiated particles in the current setup. A higher radiation flux (1.79 MW/m<sup>2</sup>) than that reported in previous literature was used for the same reason. Accordingly, intermedial-scale experiments are recommended to cover the current shortage of data and additional particles should be tested including those more reluctant to ignite.
4. The flow field was quantified using HS-PIV in the recirculation region due to the paramount importance in determining the generated overpressure. A comprehensive dataset of time-resolved velocities in both H<sub>2</sub>/CO and H<sub>2</sub>/CH<sub>4</sub> was obtained. In order to capture the whole recirculation region, the current measurement features  $45 \times 54$  vectors corresponding to a physical space of  $52 \times 63$  mm, giving a vector spacing of 1.16 mm. However, this space resolution is not enough to fully resolve the turbulent length scale. Measurements at higher resolutions are accordingly recommended for the future work.

5. The current obstacle-induced explosions highlight the critical role of turbulence in flame acceleration and pressure development. The time-resolved flow field evolution has been quantified using HS-PIV. To gain a deeper understanding of the flame-turbulence interactions, OH-PLIF and CH<sub>2</sub>O-PLIF are suggested to delineate the turbulent flame structure. The CH<sub>2</sub>O-PLIF measurement could also provide information on heat release rate as CH<sub>2</sub>O is commonly used as the flame marker for heat release rate [138] and this could be helpful in understanding the pressure development.

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## A. HS-PIV data sets

This appendix provides detailed velocity data sets of the HS-PIV measurements in the form of table. Locations of the measurement points refer to Figure A.1.

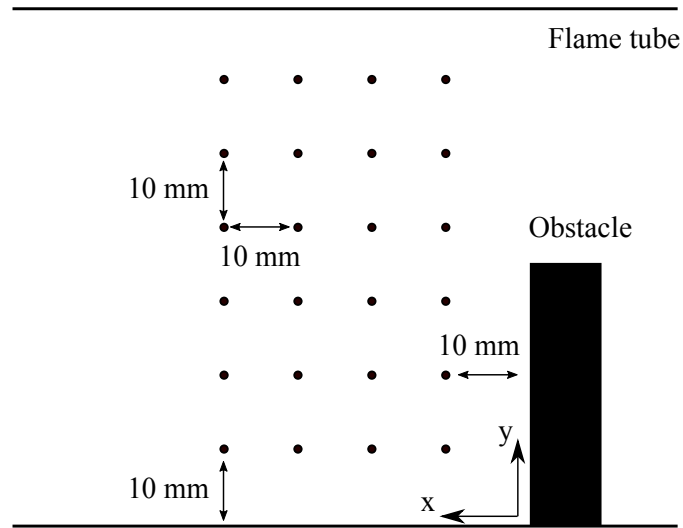


Figure A.1.: Grid of measurement points in HS-PIV.

Table A.1.: Early stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.04 | 0.09 | 0.13 | 0.17 | 0.22 | 0.26 | 0.3  | 0.35 | 0.39 | 0.43 | 0.48 |
| $u$       | (10, 60) | 0    | 0    | 0    | 0.4  | 0.8  | 1.9  | 2.8  | 3.8  | 4.1  | 5.3  | 18   |
|           | (10, 50) | 0    | 0    | 0    | 0.3  | 0.7  | 1.5  | 2.2  | 4.8  | 4.2  | 5.3  | 13   |
|           | (10, 40) | 0    | 0    | 0    | 0.3  | 0.7  | 1.4  | 1.8  | 4.3  | 4.9  | 4.8  | 12   |
|           | (10, 30) | 0    | 0    | 0    | 0.2  | 0.4  | 0.7  | 1    | 1.1  | 1.2  | 1.3  | 1.2  |
|           | (10, 20) | 0    | 0    | 0    | 0    | 0.1  | 0.3  | 0.5  | 0.5  | 0.6  | 0.3  | 1.8  |
| $u_{rms}$ | (10, 10) | 0    | 0    | 0    | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  |
|           | (10, 60) | 0    | 0    | 0.07 | 0.2  | 0.3  | 0.9  | 1.7  | 2.7  | 4.3  | 5.2  | 3.2  |
|           | (10, 50) | 0    | 0    | 0.03 | 0.2  | 0.3  | 0.9  | 1.9  | 2.8  | 4.1  | 5.3  | 2.3  |
|           | (10, 40) | 0    | 0    | 0.07 | 0.08 | 0.3  | 0.6  | 1.4  | 2.4  | 2.8  | 4.6  | 2.8  |
|           | (10, 30) | 0    | 0    | 0.02 | 0.06 | 0.07 | 0.08 | 0.02 | 0.04 | 0.04 | 0.05 | 0.07 |
| $v$       | (10, 20) | 0    | 0    | 0.07 | 0.04 | 0.09 | 0.2  | 0.3  | 0.5  | 0.6  | 0.6  | 1.8  |
|           | (10, 10) | 0    | 0    | 0.02 | 0.01 | 0.02 | 0.04 | 0.04 | 0.06 | 0.03 | 0.09 | 0.04 |
|           | (10, 60) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.3 | -0.2 | -0.1 | -0.4 | -    |
|           | (10, 50) | 0    | 0    | 0    | 0    | -0.1 | -0.5 | -0.7 | -1.2 | -1.2 | -1.4 | -1.6 |
|           | (10, 40) | 0    | 0    | 0    | -0.2 | -0.4 | -0.7 | -0.9 | -3.1 | -3.9 | -4   | -11  |
| $v_{rms}$ | (10, 30) | 0    | 0    | -0.2 | -0.3 | -0.6 | -1   | -1.3 | -1.7 | -2.4 | -3.2 | -4.1 |
|           | (10, 20) | 0    | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.6 | -0.9 | -0.9 | -1   | -2.7 |
|           | (10, 10) | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.8 | -0.9 |
|           | (10, 60) | 0    | 0    | 0.04 | 0.1  | 0.07 | 0.1  | 0.2  | 0.3  | 0.3  | 0.5  | -    |
|           | (10, 50) | 0    | 0    | 0.03 | 0.08 | 0.1  | 0.3  | 0.5  | 0.8  | 1.3  | 1.3  | 2.4  |
| $v_{rms}$ | (10, 40) | 0    | 0    | 0.04 | 0.08 | 0.2  | 0.5  | 1    | 1.9  | 2.3  | 3.7  | 2.5  |
|           | (10, 30) | 0    | 0    | 0.02 | 0.04 | 0.02 | 0.04 | 0.04 | 0.09 | 0.1  | 0.2  | 0.2  |
|           | (10, 20) | 0    | 0    | 0.04 | 0.07 | 0.1  | 0.2  | 0.3  | 0.6  | 0.9  | 1.2  | 1.6  |
|           | (10, 10) | 0    | 0    | 0.01 | 0.03 | 0.03 | 0.05 | 0.02 | 0.06 | 0.02 | 0.03 | 0.03 |
|           | (10, 60) | 0    | 0    | 0.01 | 0.03 | 0.03 | 0.05 | 0.02 | 0.06 | 0.02 | 0.03 | 0.05 |

Table A.2.: Late stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 6        | 6.5  | 7    | 7.5  | 8    | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.52     | 0.57 | 0.61 | 0.65 | 0.7  | 0.74 | 0.78 | 0.83 | 0.87 | 0.91 | 0.96 | 1    |
| $u$       | (10, 60) | 22   | 29   | 44   | 57   | 85   | 119  | 134  | 147  | 147  | —    | —    |
|           | (10, 50) | 24   | 36   | 52   | 71   | 89   | 137  | 154  | —    | 150  | 148  | —    |
|           | (10, 40) | 25   | 27   | 19   | 14   | 7.2  | 4.6  | 1.8  | 1.1  | 0.1  | -8.1 | -14  |
|           | (10, 30) | -1.8 | -2.9 | -3.5 | -0.3 | -2   | -2.3 | -4.1 | -5.5 | -8.5 | -11  | -9.9 |
|           | (10, 20) | -0.3 | -4   | -6.6 | -7.8 | -4.7 | -8.2 | -10  | -14  | —    | —    | —    |
|           | (10, 10) | 0.3  | 0    | -0.5 | -0.6 | -2.7 | -8   | -9.8 | —    | -9.8 | -8.8 | -5.8 |
|           | (10, 60) | 2.8  | 2.1  | 4    | 12.8 | 14   | 14.6 | 12.7 | 6.9  | 2.6  | 8.6  | —    |
|           | (10, 50) | 6.9  | 4.1  | 9.2  | 12.9 | 15.8 | 19.5 | 9.6  | —    | 9.8  | 12.1 | 12.4 |
| $u_{rms}$ | (10, 40) | 2.3  | 4.7  | 5    | 1.5  | 4.1  | 1.1  | 1    | 0.8  | 2.3  | 5.6  | 4.2  |
|           | (10, 30) | 0.3  | 0.2  | 0.3  | 2.3  | 2.1  | 2.2  | 1.4  | 2.8  | 4.5  | 4.1  | 4.8  |
|           | (10, 20) | 2.5  | 3.5  | 2.4  | 3.2  | 2.4  | 2.6  | 4.8  | 4.9  | —    | —    | —    |
|           | (10, 10) | 0.05 | 0.1  | 0.2  | 0.6  | 4.5  | 5.3  | 3.6  | —    | 10.4 | 5.4  | 3.9  |
|           | (10, 60) | -0.9 | -1.9 | 2.9  | 2.8  | 2.9  | 20   | 22   | 29   | 30   | 27   | —    |
|           | (10, 50) | -3.4 | -1.3 | -3.6 | 3.1  | 7.9  | 21   | 31   | —    | 36   | 35   | 25   |
|           | (10, 40) | -14  | -1.8 | 8.2  | 14   | 11   | 12   | 14   | 15   | 16   | 14   | 20   |
|           | (10, 30) | -5.8 | -3.6 | 1.5  | 21   | 17   | 21   | 18   | 21   | 22   | 20   | 15   |
| $v$       | (10, 20) | -3.1 | 0.7  | 5.6  | 13   | 14   | 14   | 16   | 22   | 18   | 16   | 13   |
|           | (10, 10) | -1   | -0.8 | -0.4 | 3.2  | 5.9  | 12   | 17   | 24   | 24   | 19   | 19   |
|           | (10, 60) | 0.9  | 1.7  | 4    | 2.8  | 5    | 10.3 | 4.8  | 12.8 | 3.6  | 2.4  | —    |
|           | (10, 50) | 3.2  | 1.6  | 2.5  | 1.2  | 3.3  | 8.4  | 3.4  | —    | 8.2  | 6.9  | 9.5  |
|           | (10, 40) | 2.3  | 6.9  | 3.3  | 1.7  | 1.9  | 3.1  | 4.4  | 1.9  | 2.5  | 2    | 5.8  |
|           | (10, 30) | 0.1  | 0.8  | 1.4  | 2.8  | 4.2  | 3.8  | 3.9  | 3.7  | 1.4  | 3.4  | 5    |
|           | (10, 20) | 1.2  | 1.7  | 2.5  | 2.6  | 4    | 5.5  | 5.8  | 5.7  | 9.1  | 6    | 6.8  |
|           | (10, 10) | 0.07 | 0.07 | 0.1  | 3.4  | 3    | 2.9  | 6.2  | 3.6  | 4.6  | 2.6  | 3.1  |
| $v_{rms}$ | (10, 60) | 0.9  | 1.7  | 4    | 2.8  | 5    | 10.3 | 4.8  | 12.8 | 3.6  | 2.4  | —    |
|           | (10, 50) | 3.2  | 1.6  | 2.5  | 1.2  | 3.3  | 8.4  | 3.4  | —    | 8.2  | 6.9  | 9.5  |
|           | (10, 40) | 2.3  | 6.9  | 3.3  | 1.7  | 1.9  | 3.1  | 4.4  | 1.9  | 2.5  | 2    | 5.8  |
|           | (10, 30) | 0.1  | 0.8  | 1.4  | 2.8  | 4.2  | 3.8  | 3.9  | 3.7  | 1.4  | 3.4  | 5    |
|           | (10, 20) | 1.2  | 1.7  | 2.5  | 2.6  | 4    | 5.5  | 5.8  | 5.7  | 9.1  | 6    | 6.8  |
|           | (10, 10) | 0.07 | 0.07 | 0.1  | 3.4  | 3    | 2.9  | 6.2  | 3.6  | 4.6  | 2.6  | 3.1  |
|           | (10, 60) | 0.9  | 1.7  | 4    | 2.8  | 5    | 10.3 | 4.8  | 12.8 | 3.6  | 2.4  | —    |
|           | (10, 50) | 3.2  | 1.6  | 2.5  | 1.2  | 3.3  | 8.4  | 3.4  | —    | 8.2  | 6.9  | 9.5  |

Table A.3.: Early stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [—] | 0        | 0.04 | 0.09 | 0.13 | 0.17 | 0.22 | 0.26 | 0.3  | 0.35 | 0.39 | 0.43 | 0.48 |
| $u$       | (20, 60) | 0    | 0    | 0    | 0.3  | 0.9  | 1.2  | 2.7  | 4.3  | 5.3  | 4.9  | 10   |
|           | (20, 50) | 0    | 0    | 0    | 0.1  | 0.7  | 1.3  | 2.6  | 4.1  | 5.3  | 4.6  | 9.7  |
|           | (20, 40) | 0    | 0    | 0    | 0.2  | 0.7  | 1.3  | 2.2  | 3.4  | 4.7  | 5.7  | 7.7  |
|           | (20, 30) | 0    | 0    | 0    | 0.1  | 0.4  | 0.9  | 1.5  | 2.4  | 2.6  | 3.2  | —    |
|           | (20, 20) | 0    | 0    | 0    | 0    | 0.1  | 0.4  | 0.5  | 0.4  | 0.3  | 1.1  | 3    |
| $u_{rms}$ | (20, 10) | 0    | 0    | 0    | 0    | 0    | 0.4  | 0.6  | 0.7  | 0.7  | 1.1  | 1    |
|           | (20, 60) | 0    | 0    | 0.06 | 0.2  | 0.4  | 0.7  | 1.6  | 2.5  | 3.2  | 4.6  | 4.3  |
|           | (20, 50) | 0    | 0    | 0.03 | 0.05 | 0.3  | 0.8  | 1.6  | 2.4  | 3.1  | 4.4  | 4.2  |
|           | (20, 40) | 0    | 0    | 0.02 | 0.07 | 0.3  | 0.6  | 1.2  | 2    | 2.7  | 3.2  | 1    |
|           | (20, 30) | 0    | 0    | 0.05 | 0.1  | 0.2  | 0.4  | 0.8  | 1.3  | 1.5  | 2.1  | —    |
| $v$       | (20, 20) | 0    | 0    | 0.02 | 0.06 | 0.08 | 0.2  | 0.3  | 0.2  | 0.4  | 1.6  | 0.2  |
|           | (20, 10) | 0    | 0    | 0.02 | 0.02 | 0.02 | 0.2  | 0.3  | 0.4  | 0.5  | 1    | 1.1  |
|           | (20, 60) | 0    | 0    | 0    | 0    | 0    | -0.1 | -0.4 | -0.5 | -0.5 | -0.6 | -1   |
|           | (20, 50) | 0    | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.7 | -1.1 | -1.5 | -1.5 | -3.6 |
|           | (20, 40) | 0    | 0    | 0    | -0.1 | -0.4 | -0.7 | -1.1 | -1.8 | -2.4 | -3.2 | -2   |
| $v_{rms}$ | (20, 30) | 0    | 0    | 0    | -0.2 | -0.3 | -0.6 | -1   | -1.6 | -2   | -2.7 | -4.3 |
|           | (20, 20) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.4 | -0.3 | -0.3 | -0.9 | 0.4  |
|           | (20, 10) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.4 | -0.6 | -0.5 | -0.8 | -1   |
|           | (20, 60) | 0    | 0    | 0.05 | 0.07 | 0.04 | 0.2  | 0.3  | 0.3  | 0.4  | 0.5  | 0.9  |
|           | (20, 50) | 0    | 0    | 0.07 | 0.1  | 0.1  | 0.2  | 0.4  | 0.8  | 0.9  | 1.3  | 1.2  |
| $u_{rms}$ | (20, 40) | 0    | 0    | 0.04 | 0.03 | 0.2  | 0.3  | 0.6  | 1    | 1.4  | 1.9  | 2.9  |
|           | (20, 30) | 0    | 0    | 0.03 | 0.09 | 0.2  | 0.3  | 0.5  | 1    | 1.2  | 1.8  | 2.5  |
|           | (20, 20) | 0    | 0    | 0.02 | 0.04 | 0.09 | 0.2  | 0.2  | 0.2  | 0.2  | 1.4  | 2.1  |
|           | (20, 10) | 0    | 0    | 0.03 | 0.01 | 0.03 | 0.1  | 0.2  | 0.3  | 0.3  | 0.6  | 0.6  |
|           | (20, 60) | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |



Table A.4.: Late stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 6        | 6.5  | 7    | 7.5  | 8    | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.52     | 0.57 | 0.61 | 0.65 | 0.7  | 0.74 | 0.78 | 0.83 | 0.87 | 0.91 | 0.96 | 1    |
| $u_{rms}$ | (20, 60) | 18   | 27   | 41   | 58   | 73   | 107  | 148  | —    | 156  | —    | —    |
|           | (20, 50) | 18   | 23   | 43   | 68   | 96   | 132  | 141  | 129  | 118  | 124  | —    |
|           | (20, 40) | 17   | 30   | 36   | 33   | 26   | 14   | 11   | 7.6  | 0.1  | -9.6 | -14  |
|           | (20, 30) | 3.5  | -0.3 | 0.9  | 5.2  | 7.3  | 0.3  | -3.6 | -8.8 | -13  | -11  | -13  |
|           | (20, 20) | 2.1  | -1.2 | -8.1 | -16  | -15  | -15  | -17  | -16  | -19  | —    | -8.6 |
|           | (20, 10) | 0.7  | 0    | -0.6 | -8   | -7.6 | -9   | -15  | -19  | -14  | -7.3 | -10  |
| $u_{rms}$ | (20, 60) | 6.4  | 5.3  | 8.5  | 10.9 | 18.6 | 29.6 | 10.8 | —    | 7.9  | —    | —    |
|           | (20, 50) | 5.7  | 7.9  | 6.1  | 14.2 | 18.7 | 18   | 1.3  | 2.6  | 11   | 15.9 | 7.9  |
|           | (20, 40) | 2.1  | 4.7  | 2.7  | 2.8  | 8.7  | 2.3  | 4.5  | 4.5  | 6.9  | 8.4  | 6.8  |
|           | (20, 30) | 1.2  | 1.4  | 1.1  | 1.7  | 4.1  | 3.8  | 2.7  | 3.9  | 2.2  | 5    | 5.2  |
|           | (20, 20) | 1.4  | 2    | 5.4  | 4.4  | 6.2  | 6.8  | 7.9  | 7    | 5.6  | —    | 6.9  |
|           | (20, 10) | 0.8  | 0.5  | 0.7  | 7.4  | 7    | 6.8  | 7.5  | 2.9  | 2.4  | 4.5  | 4.7  |
| $v$       | (20, 60) | 1.7  | 0.4  | 0.8  | —    | 3.3  | 3.9  | 12   | 16   | 23   | 15   | —    |
|           | (20, 50) | -8.4 | -11  | -13  | -9.2 | -4.6 | 1.9  | 13   | 20   | 16   | 22   | —    |
|           | (20, 40) | -15  | -24  | -19  | 0.1  | 7.1  | 18   | 26   | 26   | 29   | 29   | —    |
|           | (20, 30) | -12  | -21  | -15  | 0.4  | 17   | 28   | 32   | 36   | 36   | 32   | —    |
|           | (20, 20) | -4.3 | -5   | -5.4 | 1.9  | 12   | 19   | 26   | 30   | 28   | 24   | 14   |
|           | (20, 10) | -1.6 | -1.6 | -1.1 | 1.1  | 4.7  | 9.1  | 19   | 31   | 25   | 25   | 22   |
| $v_{rms}$ | (20, 60) | 1.7  | 0.6  | 1    | —    | 1.4  | 2    | 3.5  | 5.8  | 3.2  | 9.3  | —    |
|           | (20, 50) | 2.8  | 1.1  | 2.7  | 4.3  | 2.5  | 9.2  | 2.3  | 2.9  | 2    | 7.9  | —    |
|           | (20, 40) | 3.5  | 2.9  | 6.4  | 7.6  | 2.2  | 7.5  | 5    | 4.4  | 1.9  | 3.2  | —    |
|           | (20, 30) | 3.2  | 4.1  | 6.7  | 11   | 7.3  | 7.1  | 6.3  | 5.8  | 4.2  | 3.8  | —    |
|           | (20, 20) | 1.5  | 2.5  | 1.8  | 1.5  | 6.3  | 10.9 | 14.7 | 9.7  | 2.8  | 7.6  | 4.7  |
|           | (20, 10) | 1.1  | 1.1  | 1.4  | 1.8  | 4.3  | 7.2  | 9.2  | 5.4  | 4.8  | 7.4  | 9.1  |

Table A.5.: Early stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [—] | 0        | 0.04 | 0.09 | 0.13 | 0.17 | 0.22 | 0.26 | 0.3  | 0.35 | 0.39 | 0.43 | 0.48 |
| $u$       | (30, 60) | 0    | 0    | 0    | 0.1  | 0.3  | 0.2  | 0.4  | 1.8  | 1.6  | 1    | 4.4  |
|           | (30, 50) | 0    | 0    | 0    | 0.1  | 0.3  | 0.2  | 0.3  | 2.4  | 1    | 0.9  | 4.9  |
|           | (30, 40) | 0    | 0    | 0    | 0    | 0.2  | 0.5  | 1    | 3    | 2.8  | 2.1  | 3.7  |
|           | (30, 30) | 0    | 0    | 0    | 0    | 0.2  | 0.4  | 0.7  | 1.8  | 1.7  | 2.9  | 2.4  |
|           | (30, 20) | 0    | 0    | 0    | 0    | 0.1  | 0.2  | 0.2  | 1.5  | 1    | 1.2  | 1.1  |
| $u_{rms}$ | (30, 10) | 0    | 0    | 0    | 0    | 0.1  | 0.4  | 0.6  | 1.3  | 1.1  | 1.2  | 1    |
|           | (30, 60) | 0    | 0    | 0.04 | 0.08 | 0.2  | 0.2  | 0.6  | 1.8  | 2.4  | 1.6  | 3.4  |
|           | (30, 50) | 0    | 0    | 0.04 | 0.09 | 0.2  | 0.1  | 0.4  | 1.7  | 1.9  | 1.6  | 4    |
|           | (30, 40) | 0    | 0    | 0.1  | 0.1  | 0.2  | 0.5  | 1.1  | 1.8  | 2.9  | 1.9  | 2    |
|           | (30, 30) | 0    | 0    | 0.03 | 0.06 | 0.1  | 0.2  | 0.7  | 1.4  | 1.9  | 2.6  | 1    |
| $v$       | (30, 20) | 0    | 0    | 0.03 | 0.03 | 0.04 | 0.2  | 0.1  | 1.3  | 1.5  | 2    | 0.9  |
|           | (30, 10) | 0    | 0    | 0.03 | 0.04 | 0.07 | 0.2  | 0.4  | 1.1  | 1.2  | 1.6  | 1.8  |
|           | (30, 60) | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.4 | -2   | 0.2  |
|           | (30, 50) | 0    | 0    | 0    | -0.1 | -0.1 | 0    | -0.1 | -0.5 | -0.4 | -0.2 | -3   |
|           | (30, 40) | 0    | 0    | 0    | 0    | -0.1 | -0.3 | -0.4 | -1.1 | -1.3 | -1.1 | -2.4 |
| $u_{rms}$ | (30, 30) | 0    | 0    | 0    | 0    | 0    | -0.1 | -0.3 | -0.9 | -0.8 | -1.3 | -1.8 |
|           | (30, 20) | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.6 | -0.5 | -0.6 | 0    |
|           | (30, 10) | 0    | 0    | 0    | 0    | 0    | -0.2 | -0.2 | -0.5 | -0.4 | -0.5 | -0.6 |
|           | (30, 60) | 0    | 0    | 0.03 | 0.1  | 0.1  | 0.2  | 0.07 | 0.2  | 0.4  | 0.4  | 3.3  |
|           | (30, 50) | 0    | 0    | 0.06 | 0.04 | 0.1  | 0.1  | 0.2  | 0.4  | 0.4  | 0.3  | 1.3  |
| $u_{rms}$ | (30, 40) | 0    | 0    | 0.04 | 0.05 | 0.09 | 0.4  | 0.5  | 0.5  | 0.9  | 0.8  | 0.9  |
|           | (30, 30) | 0    | 0    | 0.04 | 0.03 | 0.07 | 0.1  | 0.5  | 0.5  | 0.8  | 1.3  | 0.7  |
|           | (30, 20) | 0    | 0    | 0.05 | 0.05 | 0.08 | 0.04 | 0.09 | 0.6  | 0.5  | 0.9  | 1.2  |
|           | (30, 10) | 0    | 0    | 0.02 | 0.02 | 0.04 | 0.07 | 0.1  | 0.4  | 0.4  | 0.5  | 0.7  |
|           | (30, 60) | 0    | 0    | 0.02 | 0.02 | 0.04 | 0.07 | 0.1  | 0.4  | 0.4  | 0.5  | 0.7  |

Table A.6.: Late stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 6        | 6.5  | 7    | 7.5  | 8    | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.52     | 0.57 | 0.61 | 0.65 | 0.7  | 0.74 | 0.78 | 0.83 | 0.87 | 0.91 | 0.96 | 1    |
| $u$       | (30, 60) | 12   | 14   | 26   | 34   | 64   | 83   | 109  | 118  | 164  | 116  | —    |
|           | (30, 50) | 12   | 16   | 23   | 61   | 82   | 127  | 136  | —    | 122  | —    | 108  |
|           | (30, 40) | 8.2  | 15   | 27   | 43   | 38   | 35   | 21   | 17   | 16   | 6.4  | —    |
|           | (30, 30) | 4.6  | 3.7  | 7.6  | 8.8  | 13   | 12   | 8.1  | 2    | -5.8 | -4.6 | -2   |
|           | (30, 20) | 0.4  | 2.7  | -0.4 | -9.1 | -14  | -16  | -16  | -19  | -15  | -7.3 | —    |
|           | (30, 10) | 0.2  | 0.4  | 0.4  | -0.9 | -6   | -14  | -17  | -28  | -14  | —    | -3.9 |
| $u_{rms}$ | (30, 60) | 6.6  | 7.1  | 7.9  | 14   | 30.8 | 54.2 | 59.2 | 70.1 | 8    | 76.4 | —    |
|           | (30, 50) | 5.1  | 10.6 | 12.8 | 12   | 20.6 | 24.9 | 3.5  | —    | 9.9  | —    | 22   |
|           | (30, 40) | 6.2  | 3    | 8.8  | 5.8  | 14.6 | 7.2  | 10.1 | 11   | 2.7  | 7.1  | —    |
|           | (30, 30) | 3.2  | 2.5  | 3.2  | 4.1  | 6.6  | 3    | 6.2  | 7.2  | 2    | 2.9  | 4.2  |
|           | (30, 20) | 1.1  | 2.7  | 2.5  | 8.7  | 6.7  | 9.3  | 10.6 | 10.5 | 10.2 | 3.2  | —    |
|           | (30, 10) | 3    | 3.1  | 0.5  | 4.6  | 2.6  | 6.8  | 10.4 | 8.5  | 10.9 | —    | 10.1 |
| $v$       | (30, 60) | -1.8 | -2.3 | -8.1 | -9.8 | -6.8 | -6.8 | 0.6  | 5.5  | 13   | 18   | —    |
|           | (30, 50) | -4.2 | -5.9 | -12  | -21  | -18  | -13  | 5.9  | 7.5  | 22   | —    | 13   |
|           | (30, 40) | -6.7 | -15  | -25  | -29  | -13  | 3.4  | 21   | 34   | 45   | 33   | —    |
|           | (30, 30) | -3.3 | -9   | -21  | -21  | -9.3 | 7.5  | 29   | 40   | 53   | 43   | 19   |
|           | (30, 20) | -1.6 | -4.7 | -8.9 | -12  | -5.5 | 11   | 24   | 32   | 37   | 27   | 15   |
|           | (30, 10) | 1    | -1.1 | -3.1 | -4   | -1.5 | 8.1  | 15   | 34   | 31   | 23   | 12   |
| $v_{rms}$ | (30, 60) | 1.6  | 3    | 4.1  | 3.3  | 6    | 4.5  | 6.1  | 5    | 2.4  | 8.9  | —    |
|           | (30, 50) | 3.8  | 2.7  | 6.4  | 2.5  | 4.4  | 7.5  | 7.6  | 6.2  | 4.9  | —    | 18   |
|           | (30, 40) | 4.6  | 4.1  | 4.9  | 5.4  | 7.8  | 12.1 | 13.2 | 15.9 | 2.5  | 9    | —    |
|           | (30, 30) | 1.7  | 3.2  | 10.3 | 9.1  | 8.7  | 9.4  | 14.3 | 12.9 | 4.8  | 6.5  | 17.2 |
|           | (30, 20) | 2    | 2.6  | 5    | 5.1  | 9    | 12.9 | 18.4 | 18   | 15.4 | 10.9 | 13.7 |
|           | (30, 10) | 0.7  | 2.1  | 1.8  | 2    | 5.8  | 7.4  | 12.4 | 5.9  | 6.6  | 11.3 | 7.5  |

Table A.7.: Early stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5 | 4    | 4.5  | 5    | 5.5  |
|-----------|-----------|---|------|------|------|------|------|------|-----|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.04 | 0.09 | 0.13 | 0.17 | 0.22 | 0.26 | 0.3 | 0.35 | 0.39 | 0.43 | 0.48 |
| $u$       | (40, 60)  | 0 | 0    | 0.1  | -0.1 | 0    | 0    | -0.1 | -   | 0    | 0.1  | 0.8  | -0.3 |
|           | (40, 50)  | 0 | 0    | 0    | 0.1  | 0    | -    | 0    | -   | -0.1 | 0    | 0.4  | 1.5  |
|           | (40, 40)  | 0 | 0    | 0    | 0.1  | 0.1  | -    | 0.1  | -   | -0.1 | 0.1  | 1.8  | 1.5  |
|           | (40, 30)  | 0 | 0    | 0    | 0.1  | 0.1  | 0.1  | 0.1  | -   | 0    | 0    | 0.6  | 0.9  |
|           | (40, 20)  | 0 | 0    | 0    | 0    | 0.1  | 0.1  | 0.2  | -   | 0    | 0    | 1.4  | 1.4  |
|           | (40, 10)  | 0 | 0    | 0    | 0    | 0    | 0.2  | 0.2  | -   | 0.3  | 0.1  | 0.8  | -0.1 |
| $u_{rms}$ | (40, 60)  | 0 | 0    | 0.1  | 0.06 | 0.2  | 0.1  | 0.1  | -   | 0.1  | 0.2  | 1    | 1.8  |
|           | (40, 50)  | 0 | 0    | 0.04 | 0.05 | 0.07 | -    | 0.1  | -   | 0.07 | 0.04 | 1.7  | 1.5  |
|           | (40, 40)  | 0 | 0    | 0.03 | 0.03 | 0.07 | -    | 0.1  | -   | 0.2  | 0.1  | 1    | 2.1  |
|           | (40, 30)  | 0 | 0    | 0.05 | 0.09 | 0.05 | 0.2  | 0.2  | -   | 0.2  | 0.2  | 1    | 1.9  |
|           | (40, 20)  | 0 | 0    | 0.01 | 0.04 | 0.08 | 0.1  | 0.1  | -   | 0.2  | 0.1  | 1.1  | 0.7  |
|           | (40, 10)  | 0 | 0    | 0.05 | 0.03 | 0.03 | 0.08 | 0.2  | -   | 0.3  | 0.3  | 1.7  | 0.6  |
| $v$       | (40, 60)  | 0 | 0    | 0    | 0    | 0.1  | -0.1 | 0    | -   | 0    | -0.1 | -1.3 | -0.5 |
|           | (40, 50)  | 0 | 0    | 0    | -0.1 | 0    | -    | 0.2  | -   | 0    | 0    | 1.2  | 1.5  |
|           | (40, 40)  | 0 | 0    | 0    | -0.1 | 0    | -    | 0.1  | -   | -0.1 | 0    | -0.9 | 0    |
|           | (40, 30)  | 0 | 0    | 0    | 0    | 0    | 0    | 0    | -   | -0.1 | -0.1 | 0.7  | -0.9 |
|           | (40, 20)  | 0 | 0    | 0    | 0    | 0    | 0    | 0    | -   | 0    | -0.1 | -0.8 | -0.5 |
|           | (40, 10)  | 0 | 0    | 0    | 0    | 0    | 0    | 0    | -   | -0.1 | -0.1 | 0    | 1    |
| $u_{rms}$ | (40, 60)  | 0 | 0    | 0.08 | 0.06 | 0.2  | 0.1  | 0.05 | -   | 0.2  | 0.1  | 2.5  | 1.5  |
|           | (40, 50)  | 0 | 0    | 0.07 | 0.1  | 0.03 | -    | 0.1  | -   | 0.2  | 0.2  | 1    | 1.4  |
|           | (40, 40)  | 0 | 0    | 0.06 | 0.07 | 0.04 | -    | 0.2  | -   | 0.2  | 0.2  | 0.8  | 1.1  |
|           | (40, 30)  | 0 | 0    | 0.03 | 0.04 | 0.08 | 0.1  | 0.07 | -   | 0.03 | 0.07 | 0.9  | 0.3  |
|           | (40, 20)  | 0 | 0    | 0.05 | 0.04 | 0.02 | 0.04 | 0.04 | -   | 0.02 | 0.1  | 1    | 1.4  |
|           | (40, 10)  | 0 | 0    | 0.02 | 0.02 | 0.05 | 0.06 | 0.08 | -   | 0.1  | 0.1  | 1.3  | 0.4  |

Table A.8.: Late stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/Air mixtures with  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 6        | 6.5  | 7    | 7.5  | 8    | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.52     | 0.57 | 0.61 | 0.65 | 0.7  | 0.74 | 0.78 | 0.83 | 0.87 | 0.91 | 0.96 | 1    |
| $u$       | (40, 60) | 0.1  | 2.9  | 3.1  | 7.8  | 11   | 29   | 36   | 58   | 82   | —    | —    |
|           | (40, 50) | 2.2  | 3    | 5.1  | 5    | 35   | 63   | 85   | 78   | 86   | 84   | —    |
|           | (40, 40) | 1.9  | 2.7  | 5.8  | 17   | 32   | 48   | 41   | —    | 31   | —    | 30   |
|           | (40, 30) | 1.3  | 1.2  | 4.7  | 5.9  | 13   | 12   | 12   | 12   | 4.3  | 6.4  | 0.4  |
|           | (40, 20) | 1    | 1.7  | 0.8  | -1.1 | -5.9 | -6.1 | -7.7 | -13  | -17  | -13  | -8   |
|           | (40, 10) | 1.6  | 0.8  | 1.2  | 0.2  | -1.3 | -6.3 | -31  | -28  | -28  | -19  | -12  |
|           | (40, 60) | 1.9  | 2.4  | 3.8  | 8.3  | 19.1 | 31   | 59.3 | 30.9 | 51.2 | 62   | —    |
|           | (40, 50) | 3.1  | 2.6  | 2.4  | 7    | 27   | 40.2 | 58.3 | 43.6 | 36.6 | 37.6 | 7.3  |
| $u_{rms}$ | (40, 40) | 2.2  | 2.2  | 5.5  | 17.1 | 26.7 | 24.5 | 23.1 | —    | 17.5 | —    | 16   |
|           | (40, 30) | 1.3  | 1.2  | 2.3  | 6.3  | 11.6 | 7.2  | 9.9  | 9.5  | 3.7  | 5    | 6.3  |
|           | (40, 20) | 1.1  | 1.2  | 1.1  | 1.6  | 5.7  | 1.9  | 4.9  | 14.4 | 14.7 | 13.2 | 10.8 |
|           | (40, 10) | 1.2  | 1.1  | 1.9  | 1    | 1.9  | 5.1  | 30.9 | 23.8 | 20.8 | 16.7 | 16.1 |
|           | (40, 60) | —    | -0.8 | —    | -2.5 | -3.7 | -2.9 | 1    | -0.3 | —    | 5.4  | —    |
|           | (40, 50) | -0.7 | 0.9  | -2   | -3.9 | -12  | -6.6 | -6.6 | 4.3  | 14   | 20   | 5.5  |
|           | (40, 40) | -0.1 | -1.9 | -5.9 | -15  | -23  | -15  | 7.6  | 18   | 34   | 37   | 27   |
|           | (40, 30) | -0.9 | -1.7 | -5.3 | -17  | -21  | -8.2 | 8.7  | 18   | 30   | 35   | 37   |
| $v$       | (40, 20) | -1.9 | -1.5 | -1.4 | -7.9 | -10  | -3.8 | 9    | 19   | 30   | 35   | 34   |
|           | (40, 10) | 0.3  | 0.3  | 0.3  | 0    | -1.9 | -0.7 | 9.4  | 14   | 19   | 23   | 19   |
|           | (40, 60) | —    | 1.4  | —    | 2.9  | 1.5  | 5.4  | 4.6  | 1.9  | —    | 8.1  | —    |
|           | (40, 50) | 3.2  | 2.5  | 3.6  | 4.8  | 9.1  | 8.2  | 13.5 | 5.3  | 5.5  | 13   | 6.7  |
|           | (40, 40) | 2.7  | 3.5  | 7.6  | 11.6 | 15.5 | 18.2 | 6.7  | 22.1 | 21.2 | 19.7 | 20.3 |
|           | (40, 30) | 1.5  | 1.2  | 3.2  | 20.1 | 14.2 | 10.1 | 12.6 | 17.8 | 21.2 | 22.8 | 25.1 |
|           | (40, 20) | 2    | 2    | 1.5  | 2.9  | 6.9  | 3.3  | 10   | 17.9 | 25.3 | 23.2 | 18.7 |
|           | (40, 10) | 0.9  | 1.2  | 1    | 1.2  | 4.6  | 2.3  | 13.6 | 17.9 | 14.3 | 13.1 | 17   |
| $v_{rms}$ | (40, 60) | —    | —    | —    | —    | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 50) | 3.2  | 2.5  | 3.6  | 4.8  | 9.1  | 8.2  | 13.5 | 5.3  | 5.5  | 13   | 6.7  |
|           | (40, 40) | 2.7  | 3.5  | 7.6  | 11.6 | 15.5 | 18.2 | 6.7  | 22.1 | 21.2 | 19.7 | 20.3 |
|           | (40, 30) | 1.5  | 1.2  | 3.2  | 20.1 | 14.2 | 10.1 | 12.6 | 17.8 | 21.2 | 22.8 | 25.1 |
|           | (40, 20) | 2    | 2    | 1.5  | 2.9  | 6.9  | 3.3  | 10   | 17.9 | 25.3 | 23.2 | 18.7 |
|           | (40, 10) | 0.9  | 1.2  | 1    | 1.2  | 4.6  | 2.3  | 13.6 | 17.9 | 14.3 | 13.1 | 17   |
|           | (40, 60) | —    | —    | —    | —    | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 50) | 3.2  | 2.5  | 3.6  | 4.8  | 9.1  | 8.2  | 13.5 | 5.3  | 5.5  | 13   | 6.7  |

Table A.9.: Early stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.04 | 0.08 | 0.13 | 0.17 | 0.21 | 0.25 | 0.29 | 0.33 | 0.38 | 0.42 | 0.46 | 0.5  |
| $u$       | (10, 60) | 0    | 0    | 0.2  | 0.4  | 1.1  | 1.4  | 2.1  | 2.8  | 3.7  | 4.7  | 6.1  | 8.1  |
|           | (10, 50) | 0    | 0    | 0.2  | 0.5  | 1.1  | 1.4  | 2    | 2.9  | 3.8  | 5.2  | 6.9  | 8.8  |
|           | (10, 40) | 0    | 0    | 0.2  | 0.4  | 0.9  | 1.4  | 2.1  | 2.7  | 3.9  | 4.9  | 6.8  | 9.6  |
|           | (10, 30) | 0    | 0    | 0.1  | 0.3  | 0.4  | 0.6  | 0.9  | 1.1  | 1.2  | 1.3  | 0.6  | -1.2 |
|           | (10, 20) | 0    | 0    | 0.1  | 0.1  | 0.3  | 0.3  | 0.4  | 0.5  | 0.6  | 0.6  | 0.4  | -0.1 |
|           | (10, 10) | 0    | 0    | 0    | 0.1  | 0.1  | 0.1  | 0.2  | 0.3  | 0.3  | 0.4  | 0.3  | 0.2  |
|           | (10, 60) | 0    | 0    | 0.06 | 0.1  | 0.05 | 0.1  | 0.4  | 0.3  | 0.6  | 0.5  | 0.9  | 1.2  |
|           | (10, 50) | 0    | 0    | 0.03 | 0.06 | 0.1  | 0.08 | 0.3  | 0.3  | 0.7  | 0.8  | 0.9  | 1.3  |
|           | (10, 40) | 0    | 0    | 0.08 | 0.06 | 0.08 | 0.1  | 0.2  | 0.2  | 0.5  | 0.5  | 1.1  | 1.7  |
|           | (10, 30) | 0    | 0    | 0.01 | 0.04 | 0.02 | 0.07 | 0.07 | 0.1  | 0.1  | 0.4  | 0.7  | 0.7  |
| $u_{rms}$ | (10, 20) | 0    | 0    | 0.01 | 0.01 | 0.02 | 0.05 | 0.07 | 0.07 | 0.1  | 0.03 | 0.06 | 0.2  |
|           | (10, 10) | 0    | 0    | 0.02 | 0.01 | 0.03 | 0.04 | 0.03 | 0.08 | 0.07 | 0.09 | 0.03 | 0.06 |
|           | (10, 60) | 0    | 0.1  | 0    | 0    | -0.1 | 0.1  | 0.1  | -0.2 | -0.1 | -0.3 | -0.6 | -1.1 |
|           | (10, 50) | 0    | 0    | 0.1  | 0    | -0.2 | -0.2 | -0.3 | -0.6 | -1.1 | -1.3 | -1.6 | -1.8 |
|           | (10, 40) | 0    | 0    | -0.1 | -0.1 | -0.4 | -1   | -1.4 | -1.8 | -2.5 | -3.3 | -4.7 | -5.2 |
|           | (10, 30) | 0    | 0    | -0.1 | -0.2 | -0.7 | -1.2 | -1.5 | -1.9 | -2.8 | -3.8 | -4.9 | -5.7 |
|           | (10, 20) | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.6 | -1   | -1.2 | -1.4 | -1.6 | -1.8 | -2   |
|           | (10, 10) | 0    | 0    | -0.1 | -0.2 | -0.2 | -0.4 | -0.5 | -0.7 | -0.9 | -1   | -1.1 | -1   |
|           | (10, 60) | 0    | 0    | 0.04 | 0.06 | 0.04 | 0.2  | 0.03 | 0.1  | 0.2  | 0.2  | 0.1  | 0.2  |
|           | (10, 50) | 0    | 0    | 0.03 | 0.03 | 0    | 0.08 | 0.1  | 0.03 | 0.09 | 0.2  | 0.02 | 0.3  |
| $v_{rms}$ | (10, 40) | 0    | 0    | 0.04 | 0.08 | 0.2  | 0.2  | 0.2  | 0.2  | 0.4  | 0.3  | 0.8  | 0.7  |
|           | (10, 30) | 0    | 0    | 0    | 0.02 | 0.2  | 0.05 | 0.04 | 0.2  | 0.3  | 0.3  | 0.5  | 0.6  |
|           | (10, 20) | 0    | 0    | 0.02 | 0.03 | 0.04 | 0.06 | 0.07 | 0.08 | 0.07 | 0.1  | 0.1  | 0.2  |
|           | (10, 10) | 0    | 0    | 0.03 | 0.01 | 0.05 | 0.01 | 0.09 | 0.1  | 0.2  | 0.1  | 0.3  | 0.3  |

Table A.10.: Late stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 23.9 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [–] | 0.54     | 0.58 | 0.62 | 0.67 | 0.71 | 0.75 | 0.79 | 0.83 | 0.88 | 0.92 | 0.96 | 1    |
| $u$       | (10, 60) | 11   | 13   | 17   | 19   | 27   | 37   | 52   | 64   | 50   | 58   | 51   |
|           | (10, 50) | 12   | 17   | 22   | 25   | 32   | 46   | 57   | 71   | 75   | 78   | 74   |
|           | (10, 40) | 12   | 13   | 11   | 8.2  | 6.5  | 5.7  | 2.5  | 0.7  | 0.6  | 0.4  | -0.3 |
|           | (10, 30) | -3.3 | -2.3 | -1.3 | -0.1 | 0.1  | 0    | -0.7 | -0.7 | -2.5 | -2.4 | -0.7 |
|           | (10, 20) | -2.6 | -3.8 | -3.4 | -3.1 | -2.4 | -1.4 | -2.1 | -3.8 | -5.2 | -5.9 | -3.2 |
|           | (10, 10) | -0.2 | -0.9 | -1.8 | -2.5 | -2.9 | -3.4 | -4.4 | -4.9 | -6.3 | -5.8 | -6.1 |
|           | (10, 60) | 0.5  | 2.6  | 4.1  | 4.1  | 7.2  | 11.6 | 13.9 | 8    | 20.5 | 19.8 | 16.3 |
|           | (10, 50) | 3.1  | 4.1  | 3.9  | 5.1  | 8.4  | 13.6 | 12.8 | 10.8 | 7.7  | 5.1  | 5.3  |
| $u_{rms}$ | (10, 40) | 1.6  | 0.2  | 0.9  | 1.5  | 0.9  | 3.1  | 2.6  | 0.5  | 0.8  | 0.3  | 1.5  |
|           | (10, 30) | 1.5  | 0.2  | 1    | 0.4  | 0.2  | 0.5  | 1.1  | 0.6  | 0.6  | 0.7  | 0.4  |
|           | (10, 20) | 1    | 0.4  | 1    | 0.4  | 0.8  | 0.7  | 1    | 1.1  | 1.1  | 0.2  | 1.3  |
|           | (10, 10) | 0.2  | 0.5  | 0.4  | 0.5  | 0.2  | 0.7  | 1.2  | 1.6  | 1.1  | 1.1  | 0.7  |
| $v$       | (10, 60) | 1.6  | 0.1  | 2    | 3.5  | 2.8  | 4.8  | 5.3  | 8.8  | 8.1  | 11   | –    |
|           | (10, 50) | -0.6 | 0    | -0.4 | 1.9  | 4.5  | 4.6  | 8.7  | 13   | 16   | 18   | 19   |
|           | (10, 40) | -2.6 | 0.6  | 3.4  | 4.5  | 3.5  | 2.7  | 5.7  | 6.9  | 6.4  | 7.5  | 6.9  |
|           | (10, 30) | 0.2  | 5.2  | 9.3  | 10   | 9.5  | 8.7  | 9.2  | 9.7  | 10   | 10   | 9.4  |
|           | (10, 20) | -0.3 | 2    | 3.3  | 7.3  | 6.3  | 7.5  | 7.6  | 9.3  | 10   | 11   | 12   |
|           | (10, 10) | -0.5 | 0.1  | 0.9  | 2.4  | 3.5  | 4.3  | 5.4  | 7.8  | 11   | 13   | 14   |
|           | (10, 60) | 1.7  | 1    | 1.9  | 2    | 1.4  | 2.4  | 4.1  | 2    | 6.5  | 4.6  | –    |
|           | (10, 50) | 1    | 1    | 1    | 0.09 | 1.1  | 1.4  | 4    | 3.8  | 2.8  | 3.3  | 2.1  |
| $v_{rms}$ | (10, 40) | 0.9  | 2    | 1.7  | 1.1  | 2.1  | 1.7  | 2.3  | 1.7  | 0.2  | 0.9  | 0.8  |
|           | (10, 30) | 2.4  | 2.9  | 2.1  | 0.6  | 0.7  | 1.2  | 1.1  | 0.5  | 0.1  | 0.4  | 1.1  |
|           | (10, 20) | 0.7  | 1.6  | 1.6  | 1.6  | 0.2  | 1.3  | 2.6  | 0.9  | 0.5  | 0.7  | 0.5  |
|           | (10, 10) | 0.4  | 0.3  | 0.7  | 0.8  | 0.6  | 0.9  | 1.4  | 1.2  | 1.8  | 2.3  | 1.6  |

Table A.11.: Early stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|-----------|---|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.04 | 0.08 | 0.13 | 0.17 | 0.21 | 0.25 | 0.29 | 0.33 | 0.38 | 0.42 | 0.46 | 0.5  |
| $u$       | (20, 60)  | 0 | 0    | 0.1  | 0.3  | 1.1  | 1.5  | 1.7  | 2.6  | 3.3  | 4.1  | 5.5  | 7.1  | 9.1  |
|           | (20, 50)  | 0 | 0    | 0.1  | 0.3  | 1    | 1.4  | 1.7  | 2.6  | 3.2  | 4.1  | 5.4  | 7.1  | 9.2  |
|           | (20, 40)  | 0 | 0    | 0.2  | 0.4  | 0.8  | 1.2  | 1.6  | 2.3  | 2.9  | 3.6  | 4.5  | 5.8  | 7.8  |
|           | (20, 30)  | 0 | 0    | 0.1  | 0.3  | 0.6  | 1    | 1.2  | 1.5  | 1.8  | 2.3  | 2.6  | 2.7  | 2.3  |
|           | (20, 20)  | 0 | 0    | 0    | 0.1  | 0.2  | 0.5  | 1    | 1.3  | 1.4  | 1.5  | 1.6  | 1.5  | 1    |
|           | (20, 10)  | 0 | 0    | 0    | 0    | 0.1  | 0.3  | 0.5  | 0.8  | 1.1  | 1.3  | 1.4  | 1.4  | 1.2  |
| $u_{rms}$ | (20, 60)  | 0 | 0    | 0.04 | 0.08 | 0.1  | 0.03 | 0.2  | 0.4  | 0.4  | 0.7  | 0.8  | 0.9  | 1.5  |
|           | (20, 50)  | 0 | 0    | 0.04 | 0.1  | 0.09 | 0.09 | 0.1  | 0.3  | 0.2  | 0.5  | 0.6  | 0.9  | 1.5  |
|           | (20, 40)  | 0 | 0    | 0.01 | 0.05 | 0.07 | 0.07 | 0.09 | 0.3  | 0.3  | 0.4  | 0.5  | 0.8  | 1.3  |
|           | (20, 30)  | 0 | 0    | 0.04 | 0.04 | 0.03 | 0.05 | 0.06 | 0.1  | 0.2  | 0.3  | 0.2  | 0.1  | 0.1  |
|           | (20, 20)  | 0 | 0    | 0.01 | 0.04 | 0.1  | 0.2  | 0.1  | 0.1  | 0.08 | 0.05 | 0.07 | 0.04 | 0.2  |
|           | (20, 10)  | 0 | 0    | 0.02 | 0.02 | 0.03 | 0.06 | 0.1  | 0.2  | 0.1  | 0.06 | 0.01 | 0.03 | 0.1  |
| $v$       | (20, 60)  | 0 | 0    | 0    | 0    | -0.2 | 0    | -0.1 | -0.3 | -0.4 | -0.4 | -0.8 | -1   | -1.2 |
|           | (20, 50)  | 0 | 0    | 0.1  | 0    | -0.3 | -0.3 | -0.3 | -0.7 | -0.9 | -1.3 | -1.7 | -2.3 | -3   |
|           | (20, 40)  | 0 | 0    | -0.1 | -0.2 | -0.3 | -0.5 | -0.9 | -1.2 | -1.5 | -2   | -2.8 | -4.1 | -6   |
|           | (20, 30)  | 0 | 0    | -0.1 | -0.1 | -0.3 | -0.6 | -0.9 | -1.2 | -1.6 | -2.2 | -2.9 | -4.1 | -6.3 |
|           | (20, 20)  | 0 | 0    | -0.1 | -0.2 | -0.4 | -0.5 | -0.5 | -0.8 | -1.1 | -1.5 | -1.9 | -2.4 | -3   |
|           | (20, 10)  | 0 | 0    | 0    | -0.1 | -0.2 | -0.3 | -0.4 | -0.5 | -0.6 | -0.8 | -1   | -1.2 | -1.3 |
| $v_{rms}$ | (20, 60)  | 0 | 0    | 0.09 | 0.03 | 0.2  | 0.1  | 0.1  | 0.04 | 0.3  | 0.3  | 0.1  | 0.1  | 0.3  |
|           | (20, 50)  | 0 | 0    | 0.04 | 0.1  | 0.09 | 0.1  | 0.2  | 0.2  | 0.1  | 0.2  | 0.3  | 0.3  | 0.4  |
|           | (20, 40)  | 0 | 0    | 0.02 | 0.01 | 0.09 | 0.1  | 0.1  | 0.1  | 0.1  | 0.3  | 0.4  | 0.8  | 1.1  |
|           | (20, 30)  | 0 | 0    | 0.01 | 0.08 | 0.05 | 0.08 | 0.1  | 0.1  | 0.2  | 0.2  | 0.3  | 0.7  | 1.2  |
|           | (20, 20)  | 0 | 0    | 0.03 | 0.03 | 0.04 | 0.06 | 0.1  | 0.1  | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  |
|           | (20, 10)  | 0 | 0    | 0.03 | 0.01 | 0.03 | 0.1  | 0.04 | 0.05 | 0.05 | 0.1  | 0.2  | 0.1  | 0.2  |



Table A.12.: Late stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 23.9 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [—] | 0.54     | 0.58 | 0.62 | 0.67 | 0.71 | 0.75 | 0.79 | 0.83 | 0.88 | 0.92 | 0.96 | 1    |
| $u$       | (20, 60) | 11   | 13   | 16   | 20   | 29   | 38   | 53   | 66   | 75   | 79   | 76   |
|           | (20, 50) | 12   | 16   | 19   | 26   | 31   | 44   | 58   | 65   | 70   | 72   | 63   |
|           | (20, 40) | 11   | 14   | 17   | 17   | 14   | 13   | 8.7  | 4.5  | 4.7  | 1.3  | -1.8 |
|           | (20, 30) | 1.4  | 0.4  | 0.4  | 2    | 1.9  | 1.7  | 0.9  | -1   | -1.9 | -4   | -3.3 |
|           | (20, 20) | -0.6 | -2.3 | -6.5 | -8.7 | -7.8 | -6.2 | -3.6 | -7.9 | -7.7 | -7.6 | -6.7 |
|           | (20, 10) | 0.5  | -0.7 | -2.2 | -4.3 | -5.3 | -5.8 | -6.8 | -8.3 | -8.3 | -8   | -5.9 |
| $u_{rms}$ | (20, 60) | 1.6  | 3.4  | 4.1  | 4.6  | 7.1  | 9.7  | 12.9 | 10.5 | 9    | 5.2  | 4.5  |
|           | (20, 50) | 2    | 4.7  | 3    | 4.8  | 7.2  | 12.1 | 13   | 6.1  | 7.3  | 6.4  | 5.6  |
|           | (20, 40) | 2.1  | 3.1  | 1.2  | 0.1  | 1.4  | 2.9  | 3.4  | 0.5  | 1.7  | 1.7  | 2.8  |
|           | (20, 30) | 0.4  | 0.2  | 0.8  | 1.6  | 0.4  | 0.5  | 0.9  | 1.1  | 1    | 0.8  | 1.8  |
|           | (20, 20) | 0.9  | 2.8  | 4    | 1    | 1.1  | 2.4  | 1.2  | 2.3  | 2    | 1.2  | 1.4  |
|           | (20, 10) | 0.3  | 0.6  | 1.1  | 1.2  | 0.7  | 0.6  | 1.3  | 1.1  | 1.9  | 3.5  | 2.8  |
| $v$       | (20, 60) | -1.4 | -2.3 | -0.3 | -1.1 | -1   | 0.9  | 1.3  | 4.1  | 7.6  | 7.3  | 9.4  |
|           | (20, 50) | -3.7 | -4.7 | -3.4 | -3   | -1.5 | -0.7 | 1.4  | 5.8  | 9.7  | 11   | 13   |
|           | (20, 40) | -8.5 | -9.9 | -5.4 | -1.7 | 1.4  | 1.7  | 5    | 7.4  | 8.1  | 10   | 12   |
|           | (20, 30) | -9.3 | -10  | -5.8 | 2.2  | 7.7  | 11   | 13   | 13   | 15   | 15   | 11   |
|           | (20, 20) | -3.7 | -3.6 | -2   | 2.8  | 5.3  | 8.1  | 12   | 11   | 11   | 12   | 10   |
|           | (20, 10) | -1.5 | -1.5 | -0.9 | 0.3  | 2.3  | 4.1  | 6.2  | 8.5  | 10   | 9.8  | 11   |
| $v_{rms}$ | (20, 60) | 0.1  | 0.7  | 0.6  | 1.8  | 0.8  | 0.2  | 2.4  | 2.7  | 1.1  | 3    | 0.8  |
|           | (20, 50) | 0.5  | 1.4  | 0.5  | 1.3  | 1.1  | 1.7  | 3.2  | 4.2  | 2.1  | 1.9  | 1.2  |
|           | (20, 40) | 1.6  | 0.3  | 3.2  | 3.1  | 1.6  | 3.6  | 4.4  | 1.5  | 2.5  | 2.1  | 1.9  |
|           | (20, 30) | 1.8  | 0.4  | 2.6  | 5.4  | 4.5  | 1.6  | 2.2  | 1.5  | 1.2  | 0.9  | 1.1  |
|           | (20, 20) | 0.5  | 0.4  | 0.6  | 2.3  | 3.2  | 2.2  | 1.5  | 0.5  | 1.5  | 1.6  | 2    |
|           | (20, 10) | 0.2  | 0.06 | 0.4  | 0.8  | 1.3  | 1.5  | 2.1  | 2.1  | 1.7  | 0.3  | 2    |

Table A.13.: Early stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.04 | 0.08 | 0.13 | 0.17 | 0.21 | 0.25 | 0.29 | 0.33 | 0.38 | 0.42 | 0.46 | 0.5  |
| $u$       | (30, 60) | 0    | 0    | 0.1  | 0.3  | 0.6  | 1.2  | 1.3  | 2.7  | 3.8  | 4.6  | 5.8  | 7.6  |
|           | (30, 50) | 0    | 0    | 0.1  | 0.2  | 0.6  | 1.2  | 1.3  | 3.1  | 3.6  | 4.5  | 5.5  | 7.1  |
|           | (30, 40) | 0    | 0    | 0.1  | 0.3  | 0.7  | 1    | 1.4  | 1.9  | 2.6  | 3.2  | 4    | 4.9  |
|           | (30, 30) | 0    | 0    | 0.1  | 0.3  | 0.5  | 0.9  | 1.3  | 1.6  | 2    | 2.6  | 3    | 3.5  |
|           | (30, 20) | 0    | 0    | 0    | 0.1  | 0.2  | 0.6  | 1.3  | 1.4  | 1.6  | 1.8  | 2.3  | 2.7  |
|           | (30, 10) | 0    | 0    | 0    | 0    | 0.1  | 0.3  | 0.8  | 1.3  | 1.4  | 1.6  | 1.7  | 2    |
| $u_{rms}$ | (30, 60) | 0    | 0    | 0.04 | 0.1  | 0.2  | 0.04 | 0.1  | 0.5  | 0.3  | 0.6  | 0.3  | 0.9  |
|           | (30, 50) | 0    | 0    | 0.05 | 0.1  | 0.2  | 0.2  | 0.05 | 0.6  | 0.01 | 0.5  | 0.5  | 0.8  |
|           | (30, 40) | 0    | 0    | 0.01 | 0.02 | 0.08 | 0.1  | 0.1  | 0.2  | 0.4  | 0.2  | 0.5  | 0.6  |
|           | (30, 30) | 0    | 0    | 0.01 | 0.03 | 0.07 | 0.06 | 0.05 | 0.08 | 0.2  | 0.3  | 0.2  | 0.3  |
|           | (30, 20) | 0    | 0    | 0.04 | 0.09 | 0.1  | 0.3  | 0.1  | 0.03 | 0.05 | 0.3  | 0.5  | 0.3  |
|           | (30, 10) | 0    | 0    | 0.01 | 0.03 | 0.05 | 0.1  | 0.2  | 0.09 | 0.1  | 0.05 | 0.2  | 0.3  |
| $v$       | (30, 60) | 0    | 0    | -0.2 | -0.2 | -0.1 | -0.1 | -0.2 | -0.2 | -0.4 | -0.5 | -0.7 | -1.3 |
|           | (30, 50) | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.3 | -0.6 | -0.7 | -0.9 | -1.3 | -1.7 |
|           | (30, 40) | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.3 | -0.5 | -0.8 | -1   | -1.3 | -1.7 | -2.5 |
|           | (30, 30) | 0    | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.5 | -0.8 | -1.1 | -1.4 | -1.8 | -2.5 |
|           | (30, 20) | 0    | 0    | 0    | 0    | -0.1 | -0.2 | -0.5 | -0.6 | -0.8 | -1.1 | -1.4 | -1.8 |
|           | (30, 10) | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.4 | -0.5 | -0.6 | -0.9 | -1.1 |
| $v_{rms}$ | (30, 60) | 0    | 0    | 0.09 | 0.05 | 0.04 | 0.09 | 0.07 | 0.1  | 0.03 | 0.06 | 0.2  | 0.2  |
|           | (30, 50) | 0    | 0    | 0.02 | 0.02 | 0.02 | 0.08 | 0.09 | 0.2  | 0.2  | 0.07 | 0.1  | 0.2  |
|           | (30, 40) | 0    | 0    | 0.02 | 0.02 | 0.03 | 0.02 | 0.07 | 0.2  | 0.2  | 0.1  | 0.3  | 0.4  |
|           | (30, 30) | 0    | 0    | 0    | 0.02 | 0.04 | 0.04 | 0.07 | 0.1  | 0.1  | 0.1  | 0.2  | 0.4  |
|           | (30, 20) | 0    | 0    | 0.03 | 0.01 | 0.06 | 0.1  | 0.04 | 0.03 | 0.07 | 0.2  | 0.2  | 0.3  |
|           | (30, 10) | 0    | 0    | 0.01 | 0.01 | 0.02 | 0.04 | 0.01 | 0.04 | 0.04 | 0.05 | 0.1  | 0.1  |

Table A.14.: Late stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 23.9 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.54     | 0.58 | 0.62 | 0.67 | 0.71 | 0.75 | 0.79 | 0.83 | 0.88 | 0.92 | 0.96 | 1    |
| $u$       | (30, 60) | 9.7  | 9    | 15   | 20   | 26   | 37   | 50   | 66   | 76   | 79   | 76   |
|           | (30, 50) | 9.3  | 11   | 16   | 20   | 29   | 42   | 55   | 67   | 59   | 60   | 53   |
|           | (30, 40) | 7.7  | 10   | 15   | 19   | 20   | 22   | 20   | 13   | 11   | 7.9  | 7    |
|           | (30, 30) | 4.2  | 4.2  | 3.5  | 4.3  | 7.3  | 7    | 6.3  | 3.6  | 4    | 0.7  | 2.1  |
|           | (30, 20) | 2.3  | 1.2  | -1.5 | -6.3 | -9.3 | -8.9 | -8   | -6.5 | -8.3 | -3.6 | -4.4 |
| $u_{rms}$ | (30, 10) | 1.8  | 1.1  | -0.7 | -3.3 | -6.4 | -8.9 | -11  | -12  | -11  | -10  | -4.7 |
|           | (30, 60) | 1.5  | 0.6  | 4.2  | 2.5  | 4.3  | 10.1 | 15.2 | 10.8 | 9    | 7.1  | 4    |
|           | (30, 50) | 1.4  | 1.8  | 4.3  | 5.9  | 7    | 9.6  | 10.3 | 7.7  | 6.7  | 7.7  | 1.4  |
|           | (30, 40) | 1.2  | 1.2  | 3.6  | 2.8  | 0.7  | 2.4  | 2    | 2.3  | 2.5  | 1.1  | 1.9  |
|           | (30, 30) | 0.3  | 0.03 | 0.5  | 0.9  | 2.9  | 1.6  | 2.1  | 0.2  | 1.8  | 1.5  | 2.9  |
|           | (30, 20) | 0.1  | 0.6  | 1.9  | 3.3  | 2.1  | 0.5  | 1    | 1.4  | 0.5  | 2.8  | 3.3  |
|           | (30, 10) | 0.03 | 0.5  | 1.2  | 1.9  | 2.2  | 1.7  | 1.1  | 0.4  | 1.4  | 3.2  | 2.3  |
|           | (30, 60) | -1.7 | -2.4 | -3.5 | -2.6 | -2.6 | -0.9 | -0.3 | -0.2 | 2.6  | 6.5  | 6.2  |
|           | (30, 50) | -3.3 | -4.4 | -5.7 | -7.1 | -5.6 | -6.7 | -3.6 | -2.7 | 4.2  | 4.6  | 7.6  |
|           | (30, 40) | -5.3 | -8.3 | -11  | -10  | -5.7 | -5.1 | 2.5  | 9.2  | 13   | 16   | 15   |
| $v$       | (30, 30) | -5.5 | -8.8 | -12  | -10  | -4.2 | 1.3  | 7.1  | 14   | 18   | 23   | 17   |
|           | (30, 20) | -3.5 | -5   | -6.8 | -5.9 | -0.9 | 4.3  | 9.4  | 16   | 19   | 18   | 17   |
|           | (30, 10) | -1.8 | -2.4 | -2.7 | -2.5 | -1   | 1.7  | 5.4  | 10   | 12   | 15   | 14   |
|           | (30, 60) | 0.3  | 1.1  | 0.7  | 0.9  | 0.5  | 0.9  | 1.2  | 1.5  | 2.3  | 1.9  | 0.7  |
|           | (30, 50) | 0.6  | 1    | 0.4  | 0.7  | 0.3  | 1.1  | 3.3  | 4.6  | 0.5  | 1.6  | 1.3  |
| $v_{rms}$ | (30, 40) | 1.1  | 1.7  | 2.4  | 0.4  | 3.5  | 0.6  | 5    | 2.2  | 2.3  | 1.4  | 2.9  |
|           | (30, 30) | 1.2  | 2.2  | 2.2  | 2    | 3.8  | 4.5  | 4.8  | 6    | 3.9  | 3.1  | 4.5  |
|           | (30, 20) | 0.6  | 1    | 1.2  | 0.8  | 3.8  | 3.7  | 6.5  | 6    | 1.8  | 0.8  | 3.1  |
|           | (30, 10) | 0.3  | 0.4  | 0.2  | 0.2  | 1.1  | 2.2  | 4.8  | 3.7  | 1.9  | 0.7  | 0.5  |
|           | (30, 60) | 0.3  | 0.4  | 0.2  | 0.2  | 1.1  | 2.2  | 4.8  | 3.7  | 1.9  | 0.7  | 0.5  |

Table A.15.: Early stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|-----------|---|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.04 | 0.08 | 0.13 | 0.17 | 0.21 | 0.25 | 0.29 | 0.33 | 0.38 | 0.42 | 0.46 | 0.5  |
| $u$       | (40, 60)  | 0 | 0    | 0.1  | 0.1  | 0.5  | 0.7  | 0.9  | 0.6  | 1.6  | 2.1  | 2.7  | 3.9  | 5.9  |
|           | (40, 50)  | 0 | 0    | 0.1  | 0.2  | 0.4  | 0.7  | 0.9  | 0.9  | 1.7  | 2.7  | 2.9  | 4.8  | 6.2  |
|           | (40, 40)  | 0 | 0    | 0.1  | 0.2  | 0.4  | 0.7  | 1.1  | 1.1  | 1.6  | 2.3  | 3.5  | 4.2  | 5.5  |
|           | (40, 30)  | 0 | 0    | 0.1  | 0.2  | 0.3  | 0.5  | 0.8  | 0.9  | 1.3  | 2.3  | 2.9  | 3.5  | 4.1  |
|           | (40, 20)  | 0 | 0    | 0    | 0.1  | 0.3  | 0.5  | 1    | 1.1  | 1.3  | 2    | 2.8  | 3.1  | 3.3  |
|           | (40, 10)  | 0 | 0    | 0    | 0    | 0.2  | 0.3  | 0.8  | 1    | 1.2  | 1.2  | 2.1  | 2.7  | 3    |
|           | (40, 60)  | 0 | 0    | 0.02 | 0.03 | 0.08 | 0.2  | 0.4  | 0.4  | 1.1  | 1.3  | 1.5  | 1.7  | 1.3  |
|           | (40, 50)  | 0 | 0    | 0.01 | 0.06 | 0.07 | 0.09 | 0.3  | 0.4  | 1.2  | 0.3  | 1.2  | 0.6  | 1.2  |
|           | (40, 40)  | 0 | 0    | 0.01 | 0.03 | 0.1  | 0.2  | 0.3  | 0.4  | 0.7  | 0.4  | 0.4  | 0.4  | 0.7  |
|           | (40, 30)  | 0 | 0    | 0.01 | 0.04 | 0.03 | 0.04 | 0.1  | 0.06 | 0.1  | 0.5  | 0.2  | 0.4  | 0.5  |
| $u_{rms}$ | (40, 20)  | 0 | 0    | 0.02 | 0.04 | 0.08 | 0.09 | 0.1  | 0.06 | 0.2  | 0.4  | 0.3  | 0.2  | 0.3  |
|           | (40, 10)  | 0 | 0    | 0.02 | 0.04 | 0.06 | 0.09 | 0.3  | 0.3  | 0.2  | 0.2  | 0.5  | 0.3  | 0.1  |
|           | (40, 60)  | 0 | 0    | -0.1 | -0.1 | -0.1 | 0    | -0.2 | -0.2 | -0.4 | -0.4 | -0.5 | -0.6 | -1   |
|           | (40, 50)  | 0 | 0    | -0.1 | -0.2 | -0.2 | -0.2 | -0.1 | -0.3 | -0.3 | -0.9 | -0.9 | -1.2 | -1.8 |
| $v$       | (40, 40)  | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.3 | -0.5 | -0.8 | -1.4 | -1.5 | -2.3 |
|           | (40, 30)  | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.5 | -1   | -1.4 | -1.6 | -2.3 |
|           | (40, 20)  | 0 | 0    | 0.1  | 0.1  | 0.1  | 0    | -0.3 | -0.3 | -0.2 | -0.6 | -1.1 | -1.4 | -1.6 |
|           | (40, 10)  | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.2 | -0.3 | -0.2 | -0.2 | -0.7 | -0.9 | -1.2 |
| $v_{rms}$ | (40, 60)  | 0 | 0    | 0.03 | 0.1  | 0.05 | 0.1  | 0.1  | 0.04 | 0.2  | 0.2  | 0.1  | 0.2  | 0.1  |
|           | (40, 50)  | 0 | 0    | 0.05 | 0.06 | 0.04 | 0.09 | 0.07 | 0.2  | 0.2  | 0.3  | 0.3  | 0.09 | 0.2  |
|           | (40, 40)  | 0 | 0    | 0.01 | 0.01 | 0.02 | 0.05 | 0.08 | 0.02 | 0.3  | 0.2  | 0.08 | 0.2  | 0.5  |
|           | (40, 30)  | 0 | 0    | 0.02 | 0.01 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 | 0.3  | 0.1  | 0.1  | 0.5  |
|           | (40, 20)  | 0 | 0    | 0.02 | 0.01 | 0.04 | 0.06 | 0.1  | 0.09 | 0.1  | 0.2  | 0.1  | 0.07 | 0.2  |
|           | (40, 10)  | 0 | 0    | 0.01 | 0    | 0.04 | 0.04 | 0.1  | 0.09 | 0.1  | 0.06 | 0.3  | 0.1  | 0.1  |

Table A.16.: Late stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 23.9 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.54     | 0.58 | 0.62 | 0.67 | 0.71 | 0.75 | 0.79 | 0.83 | 0.88 | 0.92 | 0.96 | 1    |
| $u$       | (40, 60) | 5.7  | 6.9  | 8.4  | 9.3  | 15   | —    | —    | —    | —    | —    | —    |
|           | (40, 50) | 7.2  | 7.1  | 7.4  | 14   | 23   | 35   | 52   | 60   | 62   | 49   | 46   |
|           | (40, 40) | 6.8  | 7.1  | 9.1  | 15   | 22   | 29   | 30   | 29   | 19   | 19   | 17   |
|           | (40, 30) | 4.9  | 5.5  | 6.2  | 6    | 6.9  | 11   | 8.8  | 9.8  | 11   | 8    | 11   |
|           | (40, 20) | 3.6  | 3.7  | 2.8  | 0.2  | 4.4  | 4.3  | 4.6  | 4.2  | 6.2  | 9.3  | 7.4  |
|           | (40, 10) | 3    | 2.9  | 1.8  | -0.1 | -3.9 | -9.1 | -17  | -17  | -23  | -18  | -17  |
|           | (40, 60) | 3.7  | 5    | 6.2  | 6.5  | 6    | —    | —    | —    | —    | —    | —    |
|           | (40, 50) | 1    | 0.7  | 2.2  | 4.2  | 7.6  | 9.8  | 14.1 | 11.2 | 4.1  | 3.7  | 8.5  |
| $u_{rms}$ | (40, 40) | 0.9  | 0.3  | 1.9  | 3.9  | 7.1  | 6.8  | 8.1  | 7.1  | 2.2  | 0.6  | 2.5  |
|           | (40, 30) | 0.6  | 0.4  | 0.3  | 1.3  | 1.6  | 3    | 3    | 1.1  | 1.7  | 0.8  | 5.1  |
|           | (40, 20) | 0.3  | 0.2  | 0.5  | 1.8  | 3.4  | 1.1  | 1.5  | 2.2  | 2.6  | 4.7  | 1.4  |
|           | (40, 10) | 0.08 | 0.09 | 0.6  | 1.3  | 2.8  | 4.4  | 6.7  | 4.8  | 4.3  | 1.2  | 5    |
|           | (40, 60) | -0.8 | -1.1 | -1.6 | -2.3 | -3.3 | -7.5 | -6   | -3.9 | -3.1 | 3.7  | 2.4  |
|           | (40, 50) | -2   | -2.8 | -4.4 | -5.2 | -8.9 | -10  | -8   | -5   | -0.1 | 6.9  | 7.7  |
|           | (40, 40) | -3.3 | -4.5 | -8   | -12  | -13  | -11  | -6.5 | -1.3 | 12   | 20   | 23   |
|           | (40, 30) | -3.5 | -5   | -7.2 | -13  | -12  | -9.2 | -2.2 | 5.6  | 12   | 15   | 21   |
| $v$       | (40, 20) | -2.4 | -3.7 | -5.6 | -8.8 | -9.7 | -5.1 | 1.1  | 7.6  | 13   | 19   | 21   |
|           | (40, 10) | -1.6 | -2.2 | -3   | -4.1 | -4.7 | -2.7 | 3.1  | 6.8  | 15   | 17   | 18   |
|           | (40, 60) | 0.6  | 1.1  | 1.1  | 1.4  | 0.9  | 0.9  | 1.2  | 2.1  | 3.2  | 3.3  | 2.1  |
|           | (40, 50) | 0.4  | 0.9  | 2.6  | 0.9  | 1.5  | 2.5  | 3.2  | 5.9  | 5.2  | 3.2  | 2.5  |
|           | (40, 40) | 0.7  | 2.4  | 1.4  | 2.6  | 2.2  | 3.3  | 6.4  | 9.6  | 5.9  | 4.4  | 3.8  |
|           | (40, 30) | 0.7  | 1.2  | 2.3  | 4    | 0.04 | 2.8  | 6.2  | 6.5  | 4.1  | 4.2  | 4.6  |
|           | (40, 20) | 0.6  | 0.8  | 1.3  | 2.2  | 1    | 4.5  | 4.5  | 5.8  | 4.4  | 5.2  | 3.3  |
|           | (40, 10) | 0.2  | 0.4  | 0.7  | 0.9  | 0.6  | 1.8  | 5.2  | 5.6  | 4.7  | 0.6  | 1    |
| $v_{rms}$ | (40, 60) | 0.6  | 1.1  | 1.1  | 1.4  | 0.9  | 0.9  | 1.2  | 2.1  | 3.2  | 3.3  | 2.1  |
|           | (40, 50) | 0.4  | 0.9  | 2.6  | 0.9  | 1.5  | 2.5  | 3.2  | 5.9  | 5.2  | 3.2  | 2.5  |
|           | (40, 40) | 0.7  | 2.4  | 1.4  | 2.6  | 2.2  | 3.3  | 6.4  | 9.6  | 5.9  | 4.4  | 3.8  |
|           | (40, 30) | 0.7  | 1.2  | 2.3  | 4    | 0.04 | 2.8  | 6.2  | 6.5  | 4.1  | 4.2  | 4.6  |
|           | (40, 20) | 0.6  | 0.8  | 1.3  | 2.2  | 1    | 4.5  | 4.5  | 5.8  | 4.4  | 5.2  | 3.3  |
|           | (40, 10) | 0.2  | 0.4  | 0.7  | 0.9  | 0.6  | 1.8  | 5.2  | 5.6  | 4.7  | 0.6  | 1    |
|           | (40, 60) | 0.6  | 1.1  | 1.1  | 1.4  | 0.9  | 0.9  | 1.2  | 2.1  | 3.2  | 3.3  | 2.1  |
|           | (40, 50) | 0.4  | 0.9  | 2.6  | 0.9  | 1.5  | 2.5  | 3.2  | 5.9  | 5.2  | 3.2  | 2.5  |

Table A.17.: Early stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  | 6    | 6.5  | 7    | 7.5  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.03 | 0.06 | 0.09 | 0.13 | 0.16 | 0.19 | 0.22 | 0.25 | 0.28 | 0.31 | 0.34 | 0.38 | 0.41 | 0.44 | 0.47 |
| $u$       | (10, 60) | 0    | 0    | 0.1  | 0.2  | 0.7  | 1.2  | 1.6  | 2.6  | 3.2  | 4.2  | 5.3  | 6.6  | 8    | 9.6  | 12   |
|           | (10, 50) | 0    | 0    | 0    | 0.2  | 0.7  | 1.2  | 1.6  | 2.7  | 3.5  | 4.6  | 5.8  | 6.9  | 8.4  | 10   | 13   |
|           | (10, 40) | 0    | 0    | 0.1  | 0.2  | 0.5  | 1.1  | 1.7  | 2.4  | 3.1  | 4.1  | 5.2  | 6.5  | 7.7  | 9.6  | 12   |
|           | (10, 30) | 0    | 0    | 0    | 0.2  | 0.4  | 0.5  | 0.8  | 1.2  | 1.4  | 1.4  | 1.7  | 1.8  | 2    | 1.7  | -0.3 |
|           | (10, 20) | 0    | 0    | 0    | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.7  | 1    | 1.1  | 1.1  | 1    | 0.7  | 0.4  |
|           | (10, 10) | 0    | 0    | 0    | 0.1  | 0.1  | 0.2  | 0.2  | 0.4  | 0.5  | 0.6  | 0.7  | 1    | 1    | 1    | 0.7  |
| $u_{rms}$ | (10, 60) | 0    | 0    | 0.04 | 0.06 | 0    | 0.1  | 0.08 | 0.09 | 0.2  | 0.3  | 0.5  | 0.6  | 0.6  | 0.8  | 1.1  |
|           | (10, 50) | 0    | 0    | 0.03 | 0.02 | 0.02 | 0.01 | 0.06 | 0.2  | 0.3  | 0.3  | 0.4  | 0.6  | 0.8  | 1    | 1.2  |
|           | (10, 40) | 0    | 0    | 0.03 | 0    | 0.04 | 0.06 | 0.04 | 0.2  | 0.3  | 0.3  | 0.4  | 0.4  | 0.6  | 0.9  | 1.4  |
|           | (10, 30) | 0    | 0    | 0.01 | 0.03 | 0.01 | 0.02 | 0.01 | 0.1  | 0.1  | 0.09 | 0.05 | 0.09 | 0.2  | 0.1  | 0.9  |
|           | (10, 20) | 0    | 0    | 0.01 | 0.02 | 0    | 0.06 | 0.02 | 0.03 | 0.09 | 0.1  | 0.03 | 0    | 0    | 0.05 | 0.1  |
|           | (10, 10) | 0    | 0    | 0    | 0.01 | 0.02 | 0    | 0.03 | 0.03 | 0    | 0.07 | 0    | 0.06 | 0.04 | 0.02 | 0.1  |
| $v$       | (10, 60) | 0    | 0    | 0    | 0.2  | -0.1 | -0.1 | 0.1  | -0.2 | -0.1 | -0.3 | -0.4 | -0.5 | -0.7 | -0.8 | -0.8 |
|           | (10, 50) | 0    | 0    | 0    | 0.1  | 0    | -0.2 | -0.2 | -0.6 | -0.8 | -1.1 | -1.4 | -1.7 | -2.1 | -2.5 | -3.3 |
|           | (10, 40) | 0    | 0    | 0    | -0.1 | -0.2 | -0.7 | -1.3 | -1.6 | -2   | -2.7 | -3.3 | -4.1 | -5.1 | -7   | -8.6 |
|           | (10, 30) | 0    | 0    | 0    | -0.1 | -0.3 | -0.9 | -1.2 | -1.6 | -2.1 | -2.8 | -3.6 | -4.7 | -5.8 | -7.1 | -8.4 |
|           | (10, 20) | 0    | 0    | 0    | -0.1 | -0.3 | -0.5 | -0.8 | -1.2 | -1.4 | -1.6 | -1.9 | -2.4 | -2.8 | -3.1 | -3.3 |
|           | (10, 10) | 0    | 0    | 0    | 0    | -0.2 | -0.3 | -0.4 | -0.6 | -0.8 | -0.8 | -1.1 | -1.3 | -1.4 | -1.5 | -1.8 |
| $v_{rms}$ | (10, 60) | 0    | 0    | 0    | 0.01 | 0.01 | 0.04 | 0.03 | 0.01 | 0.03 | 0.03 | 0.1  | 0.05 | 0.2  | 0.05 | 0.3  |
|           | (10, 50) | 0    | 0    | 0    | 0.01 | 0.07 | 0.01 | 0.02 | 0.04 | 0.2  | 0.03 | 0.06 | 0.2  | 0.2  | 0.2  | 0.2  |
|           | (10, 40) | 0    | 0    | 0    | 0    | 0    | 0.1  | 0.1  | 0.09 | 0.1  | 0.2  | 0.3  | 0.3  | 0.5  | 0.8  | 1    |
|           | (10, 30) | 0    | 0    | 0    | 0.03 | 0.02 | 0.1  | 0.08 | 0.07 | 0.2  | 0.2  | 0.3  | 0.4  | 0.6  | 0.7  | 0.7  |
|           | (10, 20) | 0    | 0    | 0    | 0.01 | 0.03 | 0.03 | 0.02 | 0.03 | 0.02 | 0.05 | 0.1  | 0.2  | 0.2  | 0.1  | 0.1  |
|           | (10, 10) | 0    | 0    | 0    | 0.01 | 0.01 | 0.02 | 0    | 0    | 0.04 | 0.07 | 0.03 | 0.02 | 0.02 | 0.07 | 0.06 |

Table A.18.: Late stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 8        | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 | 12   | 12.5 | 13   | 13.5 | 14   | 14.5 | 15   | 15.4 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.5      | 0.53 | 0.56 | 0.59 | 0.62 | 0.66 | 0.69 | 0.72 | 0.75 | 0.78 | 0.81 | 0.84 | 0.87 | 0.91 | 0.94 | 0.96 |
| $u$       | (10, 60) | 12   | 17   | 23   | 27   | 33   | 39   | 50   | 67   | 84   | 96   | 102  | 102  | 104  | 106  | 108  |
|           | (10, 50) | 18   | 23   | 27   | 34   | 40   | 49   | 59   | 75   | 94   | 105  | 113  | 107  | 110  | 112  | 110  |
|           | (10, 40) | 20   | 23   | 21   | 21   | 16   | 14   | 11   | 6.4  | 3.7  | 2.4  | 2.9  | 1.8  | 1.7  | 0    | -3.1 |
|           | (10, 30) | -4.6 | -5.9 | -5.1 | -5.1 | -1.9 | -0.6 | -0.5 | -0.1 | -2.2 | -2.3 | -2.7 | -3.8 | -3.5 | -3.7 | -5   |
|           | (10, 20) | -2.6 | -3.3 | -5.2 | -7.8 | -6.5 | -5.5 | -5.6 | -4.6 | -7.4 | -8.6 | -8.8 | -9.2 | -9.4 | -7.8 | -4.6 |
| $u_{rms}$ | (10, 10) | 0.2  | -0.4 | -1.3 | -2.5 | -3.8 | -5   | -4.9 | -5.3 | -6.3 | -8.3 | -10  | -10  | -7.3 | -5.4 | -8   |
|           | (10, 60) | 1.4  | 0.8  | 2.9  | 2.9  | 3.8  | 4.7  | 6.5  | 7.3  | 11   | 10.2 | 9.4  | 10.4 | —    | 4.6  | 3.9  |
|           | (10, 50) | 2.2  | 3.5  | 3.9  | 3.4  | 5.5  | 4.3  | 7.3  | 12.6 | 7.5  | 10   | 7.5  | 6.3  | 10.9 | 6    | 4    |
|           | (10, 40) | 1.9  | 1.6  | 0.8  | 1.4  | 2    | 2.1  | 1.2  | 1.1  | 1.3  | 0.6  | 0.08 | 1    | 1.2  | 0.7  | 1    |
|           | (10, 30) | 0.6  | 0.7  | 0.1  | 0.6  | 0.7  | 0.3  | 0.1  | 0.4  | 0.2  | 0.2  | 0.08 | 0.8  | 0.01 | 1.5  | 1.6  |
| $v$       | (10, 20) | 0.6  | 1.7  | 0.9  | 0.4  | 0.8  | 1.5  | 1.8  | 0.5  | 0.7  | 1.6  | 0.8  | 1    | 0.6  | 1.2  | 1.3  |
|           | (10, 10) | 0.2  | 0.3  | 0.5  | 0.7  | 0.7  | 0.5  | 0.02 | 0.3  | 0.8  | 0.3  | 0.5  | 1.2  | 1.1  | 0.3  | 3.6  |
|           | (10, 60) | -0.1 | 0.7  | -1.1 | 0.9  | 1.9  | 4.5  | 6    | 5.2  | 9.4  | 14   | 15   | 18   | 16   | 18   | 18   |
|           | (10, 50) | -1.1 | -2.9 | -1.5 | 1    | 1.1  | 3.5  | 5.1  | 6.9  | 13   | 21   | 26   | 28   | 26   | 27   | 28   |
|           | (10, 40) | -10  | -7.5 | -0.1 | 2.7  | 5.7  | 6.9  | 3.7  | 5.7  | 7.3  | 11   | 9.2  | 10   | 8.9  | 7    | 6.7  |
| $v_{rms}$ | (10, 30) | -8.2 | -1.3 | 4.7  | 11   | 16   | 18   | 17   | 14   | 15   | 16   | 17   | 17   | 16   | 13   | 12   |
|           | (10, 20) | -3   | -1.7 | 0.6  | 6.6  | 8.5  | 12   | 12   | 13   | 14   | 15   | 17   | 17   | 17   | 16   | 16   |
|           | (10, 10) | -1.6 | -1.2 | -0.5 | 0.8  | 2.3  | 4.4  | 6.6  | 9.6  | 10   | 13   | 15   | 20   | 21   | 23   | 21   |
|           | (10, 60) | 0.4  | 0.3  | 0.4  | 0.3  | 0.3  | 0.1  | 0.4  | 3.7  | 0.03 | 0.3  | 1.6  | 1.1  | 5.9  | 2    | 0.3  |
|           | (10, 50) | 0.5  | 0.01 | 0.5  | 1.2  | 0.4  | 1.4  | 0.01 | 1.7  | 5    | 1.2  | 0.5  | 1.7  | 5.2  | 4.8  | 0.2  |
| $v_{rms}$ | (10, 40) | 0.3  | 1.7  | 3.9  | 1.5  | 0.5  | 0.07 | 0.3  | 1.2  | 1.4  | 1.3  | 1.2  | 0.8  | 0.4  | 1.7  | 1.7  |
|           | (10, 30) | 1.3  | 2    | 3.1  | 1.6  | 0.5  | 0.6  | 2.2  | 0.5  | 0    | 0.7  | 1.1  | 1.3  | 0.5  | 0.9  | 0.5  |
|           | (10, 20) | 0.5  | 0.8  | 1.1  | 2.6  | 3.4  | 1.3  | 0.6  | 2.6  | 1.8  | 0.8  | 0.2  | 1.2  | 1.3  | 0.7  | 1.4  |
|           | (10, 10) | 0.09 | 0.2  | 0.5  | 0.8  | 1.3  | 0.9  | 0.9  | 1.5  | 1.1  | 0.8  | 0.9  | 4.2  | 0.9  | 0.3  | 0.1  |
|           | (10, 60) | 0.4  | 0.3  | 0.4  | 0.3  | 0.3  | 0.1  | 0.4  | 3.7  | 0.03 | 0.3  | 1.6  | 1.1  | 5.9  | 2    | 0.3  |

Table A.19.: Early stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  | 6    | 6.5  | 7    | 7.5  |
|-----------|-----------|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.03 | 0.06 | 0.09 | 0.13 | 0.16 | 0.19 | 0.22 | 0.25 | 0.28 | 0.31 | 0.34 | 0.38 | 0.41 | 0.44 | 0.47 |
| $u$       | (20, 60)  | 0 | 0    | 0    | 0.2  | 0.4  | 1    | 1.4  | 2.2  | 2.9  | 3.9  | 4.7  | 5.5  | 6.7  | 8.2  | 10   | 11   |
|           | (20, 50)  | 0 | 0    | 0    | 0.2  | 0.5  | 1.1  | 1.3  | 2.1  | 3    | 3.6  | 4.6  | 5.7  | 6.6  | 8    | 10   | 11   |
|           | (20, 40)  | 0 | 0    | 0    | 0.2  | 0.5  | 0.9  | 1.3  | 1.9  | 2.6  | 3.2  | 3.8  | 4.8  | 5.7  | 6.8  | 8.1  | 10   |
|           | (20, 30)  | 0 | 0    | 0    | 0.2  | 0.3  | 0.7  | 1    | 1.4  | 1.7  | 2.2  | 2.7  | 3.1  | 3.6  | 4    | 4.3  | 4.2  |
|           | (20, 20)  | 0 | 0    | 0    | 0.1  | 0.2  | 0.4  | 0.8  | 1.1  | 1.3  | 1.5  | 1.8  | 2.1  | 2.4  | 2.6  | 2.6  | 2.3  |
|           | (20, 10)  | 0 | 0    | 0    | 0.1  | 0.1  | 0.2  | 0.5  | 0.8  | 1.1  | 1.3  | 1.5  | 1.6  | 1.9  | 2.1  | 2.3  | 2.2  |
| $u_{rms}$ | (20, 60)  | 0 | 0    | 0.02 | 0.02 | 0.03 | 0.06 | 0.04 | 0.2  | 0.2  | 0.3  | 0.3  | 0.5  | 0.6  | 0.8  | 0.9  | 1.2  |
|           | (20, 50)  | 0 | 0    | 0    | 0.06 | 0.04 | 0.07 | 0.04 | 0.1  | 0.1  | 0.4  | 0.2  | 0.5  | 0.6  | 0.6  | 1    | 0.7  |
|           | (20, 40)  | 0 | 0    | 0.01 | 0    | 0.04 | 0.03 | 0.05 | 0.2  | 0.2  | 0.2  | 0.4  | 0.3  | 0.4  | 0.7  | 0.9  | 1.4  |
|           | (20, 30)  | 0 | 0    | 0    | 0.02 | 0    | 0.01 | 0.02 | 0.09 | 0.09 | 0.2  | 0.2  | 0.2  | 0.3  | 0.2  | 0.2  | 0.07 |
|           | (20, 20)  | 0 | 0    | 0.02 | 0.01 | 0.02 | 0.05 | 0.05 | 0    | 0.09 | 0.07 | 0.1  | 0.2  | 0.2  | 0.2  | 0.04 | 0.06 |
|           | (20, 10)  | 0 | 0    | 0    | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 | 0.06 | 0.1  | 0.2  | 0.1  | 0.02 |
| $v$       | (20, 60)  | 0 | 0    | 0    | 0    | 0.1  | -0.1 | 0    | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.9 | -1.2 | -1.4 | -0.8 |
|           | (20, 50)  | 0 | 0    | 0    | 0.1  | -0.1 | -0.3 | -0.2 | -0.5 | -0.8 | -1.1 | -1.2 | -1.5 | -1.9 | -2.4 | -3.1 | -2.7 |
|           | (20, 40)  | 0 | 0    | 0    | -0.1 | -0.2 | -0.3 | -0.5 | -1   | -1.4 | -1.6 | -2   | -2.5 | -3   | -4   | -5.3 | -7.4 |
|           | (20, 30)  | 0 | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.7 | -1   | -1.4 | -1.6 | -2.1 | -2.7 | -3.3 | -4.1 | -5.4 | -7.3 |
|           | (20, 20)  | 0 | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.5 | -0.7 | -0.9 | -1.3 | -1.6 | -1.9 | -2.3 | -2.8 | -3.3 | -4   |
|           | (20, 10)  | 0 | 0    | 0    | -0.1 | -0.2 | -0.3 | -0.4 | -0.5 | -0.5 | -0.8 | -1   | -1.2 | -1.4 | -1.6 | -1.8 | -2.2 |
| $v_{rms}$ | (20, 60)  | 0 | 0    | 0    | 0.1  | 0.03 | 0.07 | 0    | 0.1  | 0.2  | 0.2  | 0.01 | 0.1  | 0.1  | 0.2  | 0.1  | 1.3  |
|           | (20, 50)  | 0 | 0    | 0    | 0.01 | 0.07 | 0.05 | 0.04 | 0.03 | 0.01 | 0.1  | 0.06 | 0.2  | 0.2  | 0.2  | 0.3  | 0.02 |
|           | (20, 40)  | 0 | 0    | 0    | 0.01 | 0.02 | 0.06 | 0.02 | 0.1  | 0.03 | 0.09 | 0.2  | 0.2  | 0.3  | 0.5  | 0.7  | 1    |
|           | (20, 30)  | 0 | 0    | 0    | 0    | 0.01 | 0.04 | 0.05 | 0.06 | 0.08 | 0.1  | 0.2  | 0.2  | 0.3  | 0.4  | 0.7  | 1.1  |
|           | (20, 20)  | 0 | 0    | 0    | 0.03 | 0.02 | 0.03 | 0.05 | 0.02 | 0.1  | 0.2  | 0.1  | 0.2  | 0.2  | 0.2  | 0.3  | 0.5  |
|           | (20, 10)  | 0 | 0    | 0    | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0    | 0.1  | 0.1  | 0.1  | 0.08 | 0.06 | 0.2  | 0.2  |



Table A.20.: Late stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 8    | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 | 12   | 12.5 | 13   | 13.5 | 14   | 14.5 | 15   | 15.4 |
|-----------|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0.5  | 0.53 | 0.56 | 0.59 | 0.62 | 0.66 | 0.69 | 0.72 | 0.75 | 0.78 | 0.81 | 0.84 | 0.87 | 0.91 | 0.94 | 0.96 |
| $u$       | (20, 60)  | 12   | 15   | 21   | 26   | 32   | 40   | 49   | 67   | 83   | 100  | 110  | 111  | –    | 102  | 89   | 109  |
|           | (20, 50)  | 14   | 17   | 23   | 30   | 38   | 46   | 56   | 71   | 92   | 103  | 102  | 101  | 100  | 101  | 106  | 99   |
|           | (20, 40)  | 12   | 16   | 22   | 27   | 29   | 26   | 25   | 21   | 14   | 10   | 8.7  | 6.9  | 6.2  | 3.4  | -2.7 | -2   |
|           | (20, 30)  | 3.1  | 1.9  | 0.5  | 1.2  | 2.7  | 4.4  | 5.5  | 3.4  | 0.3  | -1.3 | -3.8 | -5.3 | -5.6 | -8.2 | –    | -4.9 |
|           | (20, 20)  | 1.5  | -0.2 | -3.3 | -6.8 | -13  | -15  | -15  | -12  | -12  | -13  | -13  | -14  | -11  | -13  | -7.2 | -6.4 |
|           | (20, 10)  | 1.7  | 1.1  | -0.1 | -2.2 | -4.5 | -8.7 | -8.9 | -11  | -12  | -14  | -15  | -13  | -11  | -9.1 | -4.5 | -5.7 |
| $u_{rms}$ | (20, 60)  | 0.1  | 0.3  | 1.2  | 4.9  | 3.1  | 4.9  | 7.2  | 9.5  | 10.6 | 10.1 | 9.2  | 10   | –    | 15.9 | 28.1 | 12.4 |
|           | (20, 50)  | 1.7  | 1.8  | 3.1  | 3.2  | 5.1  | 4.1  | 5.5  | 8.6  | 9.7  | 4.5  | 4.7  | 8.7  | 7.1  | 3.2  | 8.4  | 8.5  |
|           | (20, 40)  | 1.9  | 3.1  | 3.4  | 2.8  | 1.1  | 0.3  | 1.1  | 3.4  | 2.2  | 1.1  | 1.2  | 2.1  | 2.2  | 3.2  | 3.7  | 1.5  |
|           | (20, 30)  | 0.4  | 1    | 0.3  | 0.7  | 0.6  | 0.6  | 1.4  | 1.5  | 0.2  | 0.9  | 0.5  | 2    | 2.2  | 1.3  | –    | 3.3  |
|           | (20, 20)  | 0.4  | 1    | 1.9  | 2.1  | 2.7  | 1.1  | 0.9  | 0.1  | 1.8  | 2.5  | 1    | 0.2  | 1.6  | 2.9  | 2.7  | 1.9  |
|           | (20, 10)  | 0.2  | 0.3  | 0.6  | 1.2  | 0.6  | 0.8  | 1.7  | 0.2  | 0.6  | 1.4  | 0.7  | 1.8  | 0.5  | 0.4  | 1.5  | 0.9  |
| $v$       | (20, 60)  | -0.4 | -0.6 | -2.1 | -2.3 | -2.3 | -1.9 | -0.9 | 0.5  | 0.1  | 6.8  | 10   | 13   | 12   | 11   | 9.5  | 12   |
|           | (20, 50)  | -3.1 | -5.8 | -7.3 | -7.7 | -7.1 | -4.5 | -1.7 | -2   | 1.7  | 9.9  | 11   | 13   | 18   | 15   | 13   | 12   |
|           | (20, 40)  | -9.9 | -14  | -16  | -14  | -8.2 | -0.1 | 1.8  | 2.5  | 8.8  | 15   | 17   | 16   | 16   | 14   | 15   | 9.9  |
|           | (20, 30)  | -11  | -14  | -18  | -15  | -7.1 | 1.8  | 12   | 18   | 23   | 27   | 26   | 26   | 25   | 23   | 21   | 15   |
|           | (20, 20)  | -4.9 | -5.9 | -6.6 | -6   | -2.2 | 5.1  | 11   | 14   | 18   | 20   | 22   | 23   | 22   | 17   | 10   | 12   |
|           | (20, 10)  | -2.5 | -2.7 | -2.6 | -2.3 | -1.3 | 1.1  | 1.6  | 4.4  | 9.2  | 15   | 18   | 20   | 13   | 13   | 20   | 12   |
| $v_{rms}$ | (20, 60)  | 0.1  | 0.9  | 0.3  | 0.6  | 0.5  | 0.2  | 0.4  | 0.08 | 0.9  | 0.6  | 1.2  | 1.6  | 3.6  | 2.5  | 2.7  | 0.8  |
|           | (20, 50)  | 1.4  | 0.8  | 1.3  | 0.9  | 0.3  | 0.8  | 2.5  | 0.8  | 4.7  | 3.2  | 1.9  | 2.2  | 0.7  | 1.2  | 1.5  | 1.1  |
|           | (20, 40)  | 1.6  | 2.1  | 0.7  | 2.4  | 4.3  | 3.9  | 2.9  | 0.07 | 0.8  | 0.7  | 0.4  | 0.7  | 0.3  | 1.5  | 2.1  | 3.3  |
|           | (20, 30)  | 2.1  | 2.3  | 0.04 | 2.2  | 4.1  | 7    | 4.7  | 1.2  | 0.8  | 0.3  | 0.5  | 1.1  | 0.04 | 1.2  | 1.5  | 4.3  |
|           | (20, 20)  | 0.5  | 0.6  | 0.3  | 0.6  | 2.8  | 3.8  | 2.3  | 0.2  | 0.6  | 1.2  | 1    | 0.6  | 1.9  | 1.6  | 3.9  | 1    |
|           | (20, 10)  | 0.1  | 0.2  | 0    | 0.2  | 2.2  | 0.9  | 1.1  | 0.7  | 1.6  | 1.7  | 0.9  | 2.2  | 5.9  | 2.6  | 4.6  | 3.1  |

Table A.21.: Early stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  | 6    | 6.5  | 7    | 7.5  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.03 | 0.06 | 0.09 | 0.13 | 0.16 | 0.19 | 0.22 | 0.25 | 0.28 | 0.31 | 0.34 | 0.38 | 0.41 | 0.44 | 0.47 |
| $u$       | (30, 60) | 0    | 0    | 0    | 0.1  | 0.3  | 0.7  | 0.7  | 1.5  | 2.3  | 3.7  | 4.7  | 6.1  | 6.9  | 8.1  | 5.7  |
|           | (30, 50) | 0    | 0    | 0    | 0.1  | 0.3  | 0.7  | 0.9  | 1.1  | 1.9  | 3    | 3.9  | 4.7  | 5.6  | 6.9  | 7.2  |
|           | (30, 40) | 0    | 0    | 0    | 0.1  | 0.4  | 0.7  | 1.1  | 1.5  | 2.2  | 2.9  | 3.4  | 4.3  | 5    | 5.9  | 7    |
|           | (30, 30) | 0    | 0    | 0    | 0.1  | 0.3  | 0.6  | 1    | 1.3  | 1.8  | 2.3  | 2.9  | 3.4  | 4    | 4.6  | 5.2  |
|           | (30, 20) | 0    | 0    | 0    | 0.1  | 0.2  | 0.4  | 0.8  | 1.2  | 1.4  | 1.7  | 2.2  | 2.8  | 3.1  | 3.5  | 3.9  |
|           | (30, 10) | 0    | 0    | 0    | 0    | 0.1  | 0.3  | 0.6  | 1    | 1.3  | 1.5  | 1.8  | 2.3  | 2.8  | 3.1  | 3.3  |
| $u_{rms}$ | (30, 60) | 0    | 0    | 0    | 0.04 | 0.1  | 0.1  | 0.1  | 0.4  | 1    | 0.8  | 0.5  | 0.05 | 0.5  | 0.5  | 0.3  |
|           | (30, 50) | 0    | 0    | 0.01 | 0.03 | 0.05 | 0.1  | 0.2  | 0.4  | 0.1  | 0.01 | 0.6  | 0.3  | 0.6  | 0.7  | 0.8  |
|           | (30, 40) | 0    | 0    | 0.04 | 0.03 | 0.03 | 0    | 0.01 | 0.02 | 0.2  | 0.2  | 0.2  | 0.3  | 0.4  | 0.5  | 0.7  |
|           | (30, 30) | 0    | 0    | 0    | 0    | 0.02 | 0.01 | 0.01 | 0.06 | 0.1  | 0.2  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  |
|           | (30, 20) | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.04 | 0.05 | 0.3  | 0.1  | 0.1  | 0.3  | 0.2  |
|           | (30, 10) | 0    | 0    | 0.01 | 0.01 | 0.01 | 0    | 0.07 | 0.05 | 0    | 0.03 | 0.09 | 0.3  | 0.1  | 0.1  | 0.2  |
| $v$       | (30, 60) | 0    | 0    | 0.1  | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.3 | -0.3 | -0.7 | -0.9 | -1.2 | -1.2 | -1.6 |
|           | (30, 50) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.3 | -0.4 | -0.6 | -0.9 | -1   | -1.2 | -1.4 | -1.8 | -2.3 |
|           | (30, 40) | 0    | 0    | 0    | 0    | -0.2 | -0.2 | -0.4 | -0.6 | -0.8 | -1.1 | -1.3 | -1.6 | -2   | -2.5 | -3.3 |
|           | (30, 30) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.4 | -0.6 | -0.9 | -1.2 | -1.4 | -1.6 | -2   | -2.6 | -3.4 |
|           | (30, 20) | 0    | 0    | 0    | 0    | -0.1 | -0.2 | -0.2 | -0.5 | -0.6 | -0.8 | -1.2 | -1.4 | -1.7 | -1.9 | -2.5 |
|           | (30, 10) | 0    | 0    | 0    | 0    | 0    | 0    | -0.2 | -0.4 | -0.4 | -0.5 | -0.6 | -1   | -1.2 | -1.5 | -1.9 |
| $v_{rms}$ | (30, 60) | 0    | 0    | 0    | 0.03 | 0    | 0.08 | 0.07 | 0.1  | 0.1  | 0.1  | 0.05 | 0.1  | 0.04 | 0.06 | 0.01 |
|           | (30, 50) | 0    | 0    | 0    | 0.04 | 0.04 | 0    | 0.04 | 0.2  | 0.2  | 0.2  | 0.1  | 0.2  | 0.03 | 0.08 | 0.2  |
|           | (30, 40) | 0    | 0    | 0    | 0.01 | 0.03 | 0    | 0.03 | 0.07 | 0.04 | 0.1  | 0.04 | 0.05 | 0.2  | 0.3  | 0.4  |
|           | (30, 30) | 0    | 0    | 0    | 0.01 | 0    | 0.01 | 0.01 | 0.04 | 0.09 | 0.1  | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  |
|           | (30, 20) | 0    | 0    | 0    | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.05 | 0.05 | 0.06 | 0.01 | 0.09 | 0.2  | 0.3  |
|           | (30, 10) | 0    | 0    | 0    | 0.02 | 0.04 | 0.03 | 0.02 | 0.01 | 0.02 | 0.01 | 0.04 | 0.1  | 0.1  | 0.07 | 0.2  |

Table A.22.: Late stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 8        | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 | 12   | 12.5 | 13   | 13.5 | 14   | 14.5 | 15   | 15.4 |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.5      | 0.53 | 0.56 | 0.59 | 0.62 | 0.66 | 0.69 | 0.72 | 0.75 | 0.78 | 0.81 | 0.84 | 0.87 | 0.91 | 0.94 | 0.96 |
| $u$       | (30, 60) | 7.4  | 7    | 9.4  | 10   | 23   | 34   | 42   | 57   | 70   | 85   | 80   | 90   | —    | 93   | —    |
|           | (30, 50) | 9.4  | 12   | 14   | 23   | 31   | 39   | 53   | 69   | 92   | 106  | 92   | 84   | 79   | 67   | 75   |
|           | (30, 40) | 10   | 12   | 13   | 20   | 27   | 33   | 35   | 36   | 32   | 25   | 21   | 18   | 17   | 11   | 7.9  |
|           | (30, 30) | 6.4  | 6.9  | 8    | 6.8  | 6.4  | 8.6  | 10   | 15   | 9    | 7.1  | 3.4  | 6.4  | 2.6  | 1.4  | -3.3 |
|           | (30, 20) | 4.2  | 3.9  | 2.9  | 0.6  | -4.4 | -11  | -13  | -13  | -15  | -14  | -16  | -13  | -11  | -4.8 | -5.2 |
| $u_{rms}$ | (30, 10) | 3.5  | 3.2  | 2.5  | 0.8  | -1.7 | -6.3 | -11  | -13  | -15  | -21  | -23  | -21  | -16  | -9.6 | -2.4 |
|           | (30, 60) | 0.3  | 0.3  | 4.1  | 4.7  | 1.3  | 3.5  | 2.5  | 5.3  | 1.4  | 6.4  | 20.6 | 13.1 | —    | 7.6  | —    |
|           | (30, 50) | 0.1  | 0.03 | 2.2  | 3.7  | 4    | 5.9  | 6.9  | 9.9  | 16.1 | 7.5  | 3.5  | 8.8  | 2.6  | 1.3  | 4.4  |
|           | (30, 40) | 1.2  | 1.2  | 1    | 3.6  | 4.5  | 2    | 0.7  | 0.5  | 4.6  | 0.3  | 4.2  | 1.4  | 0.9  | 5.5  | 0.5  |
|           | (30, 30) | 0.4  | 0.3  | 0.5  | 0.5  | 0.2  | 2    | 2.5  | 2.7  | 3.7  | 0.2  | 2.4  | 1.1  | 4.8  | 0.6  | 0.3  |
| $v$       | (30, 20) | 0.09 | 0.2  | 0.7  | 1.5  | 4.2  | 3.7  | 0.3  | 0.7  | 0.3  | 0.8  | 0.5  | 1.7  | 4.5  | 8.6  | 0.4  |
|           | (30, 10) | 0.02 | 0.1  | 0.5  | 1.1  | 2.1  | 2.5  | 2.7  | 0.1  | 0.5  | 2    | 4.1  | 0.9  | 4.5  | 1.1  | 8.5  |
|           | (30, 60) | -2   | -0.9 | -2.4 | -1.2 | -6.3 | -3.9 | -4.7 | -5.1 | -1.4 | 0.7  | 2.1  | 3.9  | 9.2  | 7.7  | 6.7  |
|           | (30, 50) | -3.9 | -5.5 | -7.2 | -9   | -11  | -10  | -11  | -10  | -9.6 | -4.2 | 7.4  | 6    | 9.1  | 12   | 9.2  |
|           | (30, 40) | -6   | -7.7 | -11  | -15  | -20  | -18  | -11  | -6.8 | -0.8 | 12   | 23   | 28   | 26   | 26   | 25   |
| $v_{rms}$ | (30, 30) | -5.9 | -8.3 | -12  | -18  | -21  | -17  | -10  | -1.9 | 8    | 21   | 32   | 33   | 35   | 31   | 27   |
|           | (30, 20) | -4.1 | -5.4 | -7.2 | -9.5 | -11  | -10  | -5.1 | 4.8  | 14   | 23   | 30   | 33   | 28   | 24   | 20   |
|           | (30, 10) | -2.3 | -2.9 | -3.7 | -4.3 | -4.9 | -4.2 | -2.2 | 1.5  | 6    | 12   | 22   | 23   | 24   | 24   | 15   |
|           | (30, 60) | 0.09 | 0.6  | 0.7  | 0.4  | 1.3  | 2.3  | 0.03 | 0.3  | 2.1  | 3.4  | 1    | 5.5  | 3.2  | 0.3  | 3.8  |
|           | (30, 50) | 0.3  | 0.08 | 1.6  | 0.3  | 0.05 | 0.6  | 1.4  | 0.8  | 2.3  | 6.4  | 2.8  | 2.7  | 0.03 | 1    | 0.7  |
| $v_{rms}$ | (30, 40) | 1    | 1    | 0.8  | 3.1  | 2.7  | 3.7  | 5.9  | 3.2  | 7.4  | 5.8  | 3.5  | 1.2  | 0.3  | 2.6  | 3.3  |
|           | (30, 30) | 1    | 1.4  | 1.5  | 4.3  | 0.8  | 3.6  | 4.1  | 6.3  | 5.1  | 5.5  | 3.8  | 1.3  | 1.9  | 4.2  | 2.9  |
|           | (30, 20) | 0.5  | 0.7  | 1.2  | 1.2  | 0.1  | 2.7  | 3.8  | 4.3  | 3.7  | 4.5  | 1.5  | 0.2  | 1.2  | 5.5  | 1.1  |
|           | (30, 10) | 0.3  | 0.3  | 0.4  | 0.5  | 0.02 | 0.7  | 1.7  | 2.4  | 2.1  | 1.2  | 2.1  | 0.2  | 0.6  | 1.6  | 8.3  |
|           | (30, 60) | 0.3  | 0.3  | 0.4  | 0.5  | 0.02 | 0.7  | 1.7  | 2.4  | 2.1  | 1.2  | 2.1  | 0.2  | 0.6  | 1.6  | 8.3  |

Table A.23.: Early stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms] | 0 | 0.5  | 1    | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    | 4.5  | 5    | 5.5  | 6    | 6.5  | 7    | 7.5  |
|-----------|----------|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] |          | 0 | 0.03 | 0.06 | 0.09 | 0.13 | 0.16 | 0.19 | 0.22 | 0.25 | 0.28 | 0.31 | 0.34 | 0.38 | 0.41 | 0.44 | 0.47 |
| $u$       | (40, 60) | 0 | 0.1  | 0    | 0    | 0.1  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.1  | 0    | 0.6  | 1.3  | 1.2  | 1.8  |
|           | (40, 50) | 0 | 0    | 0    | 0.1  | 0.1  | 0.3  | 0.3  | 0.3  | 0.6  | 0.3  | 0.4  | 0.2  | 0.9  | 1.1  | 1.6  | 2    |
|           | (40, 40) | 0 | 0    | 0    | 0.1  | 0.2  | 0.4  | 0.7  | 0.9  | 1.1  | 1.7  | 2.3  | 2.6  | 2.5  | 2.4  | 2.7  | 3.5  |
|           | (40, 30) | 0 | 0    | 0    | 0.1  | 0.2  | 0.4  | 0.5  | 0.8  | 1    | 0.8  | 1.3  | 1.4  | 1.7  | 2.3  | 2.4  | 2.9  |
|           | (40, 20) | 0 | 0    | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.6  | 0.7  | 0.9  | 0.8  | 2.9  | 3.7  | 3.6  | 4.6  | 5    |
|           | (40, 10) | 0 | 0    | 0    | 0    | 0.1  | 0.2  | 0.3  | 0.7  | 1    | 1.1  | 1.2  | 2.8  | 3.1  | 3.6  | 4.2  | 4.5  |
| $u_{rms}$ | (40, 60) | 0 | 0    | 0.01 | 0    | 0.06 | 0.04 | 0.02 | 0.1  | 0.1  | 0.1  | 0.07 | 0.2  | 0.9  | 1.4  | 0.1  | 1.2  |
|           | (40, 50) | 0 | 0    | 0.03 | 0    | 0.06 | 0.1  | 0.08 | 0.2  | 0.5  | 0.2  | 0.3  | 0.3  | 0.9  | 0.6  | 0.2  | 0.9  |
|           | (40, 40) | 0 | 0    | 0.04 | 0.02 | 0.04 | 0.07 | 0.1  | 0.2  | 0.5  | 0.7  | 0.8  | 0.9  | 1.9  | 0.8  | 0.9  | 0.9  |
|           | (40, 30) | 0 | 0    | 0.01 | 0.01 | 0.04 | 0.03 | 0.1  | 0.2  | 0.4  | 0.09 | 0.3  | 0.2  | 0.1  | 0.2  | 0.9  | 1.2  |
|           | (40, 20) | 0 | 0    | 0.01 | 0    | 0.05 | 0.06 | 0.09 | 0.1  | 0.3  | 0.3  | 0.3  | 0.02 | 0.4  | 0.02 | 0.1  | 0.3  |
|           | (40, 10) | 0 | 0    | 0.02 | 0.01 | 0    | 0.02 | 0.05 | 0.3  | 0.3  | 0.3  | 0.4  | 0.3  | 0.1  | 0.4  | 0.4  | 0.2  |
| $v$       | (40, 60) | 0 | 0    | 0    | 0    | -0.1 | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.1 | -0.1 | -0.4 | -0.3 | -0.9 | -1.2 |
|           | (40, 50) | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.1 | -0.2 | -0.3 | -0.8 | -0.3 | -0.5 | -1.2 |
|           | (40, 40) | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.3 | -0.3 | -0.4 | -0.8 | -0.7 | -0.8 | -0.6 | -1.1 | -1.6 |
|           | (40, 30) | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.5 | -0.4 | -0.7 | -0.5 | -0.4 | -1.3 |
|           | (40, 20) | 0 | 0    | 0    | 0    | 0.1  | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.8 | -1   | -1.1 | -1.6 | -2.2 |
|           | (40, 10) | 0 | 0    | 0    | 0    | 0    | 0.1  | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.9 | -0.7 | -1   | -1.1 | -1.3 |
| $v_{rms}$ | (40, 60) | 0 | 0    | 0    | 0    | 0.01 | 0.06 | 0.04 | 0.02 | 0.06 | 0.08 | 0.2  | 0.05 | 0.03 | 0.08 | 0.1  | 0.6  |
|           | (40, 50) | 0 | 0    | 0    | 0.05 | 0.05 | 0.04 | 0    | 0.09 | 0.2  | 0.3  | 0.2  | 0.03 | 0.04 | 0.9  | 0.05 | 0.5  |
|           | (40, 40) | 0 | 0    | 0    | 0.03 | 0.01 | 0.04 | 0.01 | 0.02 | 0.3  | 0.1  | 0.1  | 0.2  | 0.5  | 0.2  | 0.06 | 0.03 |
|           | (40, 30) | 0 | 0    | 0    | 0.01 | 0.01 | 0.06 | 0.09 | 0.06 | 0.2  | 0.07 | 0.02 | 0.2  | 0.04 | 0.06 | 0.4  | 0.4  |
|           | (40, 20) | 0 | 0    | 0    | 0.01 | 0    | 0.03 | 0.01 | 0.09 | 0.1  | 0.07 | 0.2  | 0.06 | 0.03 | 0.06 | 0.05 | 0.3  |
|           | (40, 10) | 0 | 0    | 0    | 0    | 0.01 | 0.06 | 0.01 | 0.1  | 0.1  | 0.1  | 0.1  | 0.05 | 0.06 | 0.2  | 0.2  | 0.01 |

Table A.24.: Late stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/CO/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 8    | 8.5  | 9    | 9.5  | 10   | 10.5 | 11   | 11.5 | 12   | 12.5 | 13   | 13.5 | 14   | 14.5 | 15   | 15.4 |
|-----------|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0.5  | 0.53 | 0.56 | 0.59 | 0.62 | 0.66 | 0.69 | 0.72 | 0.75 | 0.78 | 0.81 | 0.84 | 0.87 | 0.91 | 0.94 | 0.96 |
| $u$       | (40, 60)  | 2.8  | 2.2  | 2.2  | 1    | 1    | 0.7  | 3.1  | 8.6  | -1.3 | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 50)  | 2.7  | 2.6  | 2.1  | 1.9  | 4.9  | 9.9  | 13   | 24   | —    | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 40)  | 3.8  | 4.4  | 4    | 8.4  | 12   | 21   | 30   | 47   | 29   | 23   | 23   | 24   | 28   | 27   | 23   | 17   |
|           | (40, 30)  | 2.8  | 2.3  | 4.5  | 7    | 7.5  | 6.4  | 6.3  | 10   | 12   | 8.3  | 10   | 18   | 17   | 9.8  | 6.8  | 3    |
|           | (40, 20)  | 5.7  | 5.9  | 6.3  | 5    | 2.6  | -0.6 | -3.2 | -5.9 | -3.1 | -4.4 | -8.5 | -12  | -12  | —    | -6.7 | -8.4 |
|           | (40, 10)  | 4.8  | 4.9  | 5    | 4.6  | 2.3  | -0.3 | -1.8 | -6.4 | -11  | -19  | -34  | -40  | -35  | -28  | -13  | -6.2 |
| $u_{rms}$ | (40, 60)  | 0.9  | 1.1  | 0.3  | 0.3  | 1.7  | 0.6  | 2.9  | 7.3  | 0.6  | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 50)  | 0.5  | 1.3  | 1.1  | 1.2  | 5.2  | 9.1  | 12   | 18.4 | —    | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 40)  | 0.8  | 1.2  | 1.5  | 0.4  | 3.5  | 0.3  | 0.1  | 2.9  | 26   | 21.2 | 16.1 | 13.2 | 5.5  | 3.5  | 5    | 2    |
|           | (40, 30)  | 0.1  | 1.1  | 1.3  | 3.1  | 1.1  | 3.8  | 4.9  | 5.6  | 9.3  | 7.6  | 3    | 2.3  | 2.3  | 5    | 5.7  | 1.2  |
|           | (40, 20)  | 0.4  | 0.3  | 0.1  | 1.1  | 2.4  | 2.5  | 1.6  | 4.7  | 2.8  | 2.1  | 4    | 2.8  | 1.3  | —    | 4.7  | 8.2  |
|           | (40, 10)  | 0.1  | 0.4  | 0.1  | 0.3  | 1.6  | 1.7  | 0.6  | 2.2  | 9.2  | 9.8  | 1    | 3    | 0.6  | 5.5  | 10.3 | 12.3 |
| $v$       | (40, 60)  | -0.9 | 0.4  | 1    | 1    | 0.7  | 0    | -0.6 | -2.1 | —    | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 50)  | -1.7 | -1   | -1.9 | -0.7 | -3.4 | -0.6 | -5.1 | -8.7 | -8   | -11  | -0.2 | 1.9  | 6.6  | 3.7  | 5.8  | 8.6  |
|           | (40, 40)  | -0.9 | -1.9 | -3.7 | -6.8 | -11  | -18  | -19  | -19  | -11  | -2.1 | 6.6  | 14   | 28   | 34   | 34   | 33   |
|           | (40, 30)  | -0.2 | -2   | -2.7 | -6.7 | -11  | -13  | -18  | -13  | -8.6 | 1.7  | 12   | 23   | 32   | 36   | 32   | 23   |
|           | (40, 20)  | -3   | -3.9 | -5.6 | -6.3 | -4.5 | -7.7 | -10  | -11  | -3.6 | 3.6  | 16   | 23   | 35   | 39   | 24   | 19   |
|           | (40, 10)  | -1.8 | -2.4 | -3.4 | -4.5 | -5.5 | -6.2 | -4.2 | -6.1 | 0.4  | 2.6  | 16   | 22   | 23   | 26   | 15   | 13   |
| $v_{rms}$ | (40, 60)  | 0.4  | 0.7  | 0.8  | 0.03 | 0    | 0.7  | 1.1  | 2.4  | —    | —    | —    | —    | —    | —    | —    | —    |
|           | (40, 50)  | 0.6  | 0.2  | 1.1  | 0.9  | 1.3  | 4.1  | 4.7  | 4.6  | 4.3  | 5.8  | 1.8  | 1.6  | 3    | 3    | 4.4  | 8.3  |
|           | (40, 40)  | 0.5  | 0.5  | 0.7  | 1.2  | 0.1  | 1.5  | 5.8  | 5.5  | 8.8  | 3.6  | 2.4  | 4.4  | 1.4  | 8.4  | 1.5  | 6.2  |
|           | (40, 30)  | 0.5  | 0.2  | 0.8  | 1.3  | 1    | 5.3  | 12.5 | 9.5  | 9    | 0.6  | 4.1  | 0.2  | 0.2  | 6.2  | 4.5  | 19.7 |
|           | (40, 20)  | 0.4  | 0.7  | 0.8  | 0.3  | 1    | 0.3  | 7.2  | 9.2  | 4.5  | 1    | 0.9  | 0.1  | 1    | 3.9  | 15.2 | 15.8 |
|           | (40, 10)  | 0.2  | 0.5  | 0.4  | 0.5  | 0.4  | 0.1  | 1.7  | 3.7  | 0.6  | 0.9  | 4.9  | 9.6  | 1.5  | 0.7  | 7.4  | 10.7 |

Table A.25.: Early stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms] | 0 | 2    | 4    | 6    | 8    | 10   | 12   | 14   | 16   | 18   | 20   | 22   | 24   | 26   | 28   | 30   | 32   | 34   |
|-----------|----------|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] |          | 0 | 0.03 | 0.06 | 0.09 | 0.11 | 0.14 | 0.17 | 0.2  | 0.23 | 0.26 | 0.29 | 0.31 | 0.34 | 0.37 | 0.4  | 0.43 | 0.46 | 0.49 |
| $u$       | (10, 60) | 0 | 0.1  | 0.3  | 0.4  | 0.5  | 0.7  | 0.9  | 1.1  | 1.3  | 1.5  | 1.8  | 2.1  | 2.5  | 2    | 2.2  | 2    | 4.5  | 6.2  |
|           | (10, 50) | 0 | 0.1  | 0.2  | 0.4  | 0.5  | 0.7  | 0.9  | 1.1  | 1.3  | 1.6  | 1.9  | 2.2  | 2.7  | 1.9  | 2.2  | 4.5  | 5.8  | 7.9  |
|           | (10, 40) | 0 | 0.1  | 0.2  | 0.3  | 0.4  | 0.6  | 0.7  | 0.9  | 1.1  | 1.3  | 1.6  | 1.9  | 2.3  | 1.2  | 1.3  | 3.2  | 3.1  | 2.8  |
|           | (10, 30) | 0 | 0.1  | 0.1  | 0.2  | 0.2  | 0.3  | 0.3  | 0.4  | 0.4  | 0.5  | 0.5  | 0.5  | 0.4  | -0.1 | -0.1 | 0    | 0.6  | -0.5 |
|           | (10, 20) | 0 | 0    | 0.1  | 0.1  | 0.1  | 0.2  | 0.2  | 0.2  | 0.3  | 0.3  | 0.3  | 0.2  | 0.1  | -0.1 | -0.3 | 0    | 0.3  | 0    |
|           | (10, 10) | 0 | 0    | 0    | 0.1  | 0.1  | 0.1  | 0.1  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.1  | 0.1  | -0.1 | -0.3 |
| $u_{rms}$ | (10, 60) | 0 | 0.01 | 0    | 0.05 | 0.06 | 0.04 | 0.06 | 0.08 | 0.1  | 0.09 | 0.1  | 0.2  | 0.2  | 1.1  | 1.6  | 1.8  | 1.8  | 1.8  |
|           | (10, 50) | 0 | 0    | 0.03 | 0.04 | 0.05 | 0.05 | 0.06 | 0.08 | 0.1  | 0.1  | 0.1  | 0.2  | 0.3  | 1.6  | 1.8  | 0.3  | 1.8  | 0.7  |
|           | (10, 40) | 0 | 0    | 0.03 | 0.03 | 0.04 | 0.05 | 0.06 | 0.08 | 0.09 | 0.1  | 0.1  | 0.2  | 0.1  | 1.7  | 1.5  | 0.5  | 0.7  | 0.3  |
|           | (10, 30) | 0 | 0    | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.06 | 0.2  | 0.1  | 0.4  | 2    | 0.4  |
|           | (10, 20) | 0 | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0    | 0.02 | 0.05 | 0.07 | 0.1  | 0.4  | 0.2  | 0.3  |
|           | (10, 10) | 0 | 0    | 0    | 0.01 | 0.01 | 0    | 0.01 | 0.01 | 0.01 | 0    | 0.01 | 0    | 0.01 | 0.02 | 0.04 | 0.08 | 0.07 | 0.1  |
| $v$       | (10, 60) | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | 0    | 0    | 0.3  | -0.4 | -0.2 |
|           | (10, 50) | 0 | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.4 | -0.4 | -0.5 | -0.6 | -0.7 | -0.5 | -0.6 | -0.6 | -0.5 | -0.6 |
|           | (10, 40) | 0 | -0.1 | -0.1 | -0.2 | -0.3 | -0.4 | -0.5 | -0.7 | -0.8 | -1   | -1.2 | -1.5 | -1.8 | -1.6 | -0.8 | -1.9 | -1   | 0    |
|           | (10, 30) | 0 | -0.1 | -0.1 | -0.2 | -0.3 | -0.4 | -0.5 | -0.6 | -0.8 | -1   | -1.2 | -1.5 | -1.6 | -1.7 | -1.7 | -0.8 | -0.5 | -0.2 |
|           | (10, 20) | 0 | -0.1 | -0.1 | -0.1 | -0.2 | -0.3 | -0.3 | -0.4 | -0.5 | -0.5 | -0.6 | -0.7 | -0.8 | -0.8 | -0.7 | 0.2  | 0.2  | 0.4  |
|           | (10, 10) | 0 | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.3 | -0.3 | -0.4 | -0.4 | -0.3 | -0.3 | -0.2 | 0    |
| $v_{rms}$ | (10, 60) | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0    | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.3  | 0.3  | 0.01 | 0.4  | 1.1  |
|           | (10, 50) | 0 | 0    | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 | 0.04 | 0.04 | 0.06 | 0.5  | 0.4  | 0.9  | 0.3  | 0.2  |
|           | (10, 40) | 0 | 0    | 0.01 | 0.02 | 0.03 | 0.03 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.2  | 0.1  | 0.5  | 0.6  | 0.4  | 0.4  | 0.3  |
|           | (10, 30) | 0 | 0    | 0.01 | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.07 | 0.09 | 0.1  | 0.2  | 0.2  | 0.2  | 0.2  | 0.8  | 0.5  | 0.6  |
|           | (10, 20) | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.01 | 0.04 | 0.05 | 1    | 0.4  |
|           | (10, 10) | 0 | 0    | 0    | 0    | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.05 | 0.09 |

Table A.26.: Late stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 36       | 38   | 40   | 42   | 44   | 46   | 48   | 50   | 52   | 54   | 56   | 58   | 60   | 62   | 64   | 66   | 68   | 70   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.51     | 0.54 | 0.57 | 0.6  | 0.63 | 0.66 | 0.69 | 0.71 | 0.74 | 0.77 | 0.8  | 0.83 | 0.86 | 0.89 | 0.91 | 0.94 | 0.97 | 1    |
| $u$       | (10, 60) | 6.2  | 8.2  | 9.4  | 9.4  | 10   | 14   | 16   | 20   | 22   | 26   | 28   | 26   | 24   | 21   | -    | -    | -    |
|           | (10, 50) | 9.1  | 9.4  | 9.3  | 9.5  | 11   | 15   | 20   | 22   | 24   | 28   | 26   | 26   | 23   | 22   | 22   | 19   | 16   |
|           | (10, 40) | 2.8  | 2    | 1.4  | 1.2  | 0.7  | 0.3  | 0.1  | -0.4 | -0.3 | -0.7 | -0.7 | -0.4 | -0.8 | -0.2 | -0.4 | -0.6 | -0.6 |
|           | (10, 30) | -0.2 | 0.1  | 0    | 0.1  | 0.3  | 0.3  | 0.2  | 0.2  | 0.3  | 0.3  | -0.2 | -0.2 | -0.2 | 0.1  | 0.1  | -0.1 | 0    |
|           | (10, 20) | -0.3 | -0.3 | -0.6 | -0.9 | -0.9 | -0.6 | -0.9 | -0.3 | -1.5 | -1.4 | -1.3 | -2.1 | -1.7 | -1   | -0.1 | 0.2  | 0    |
|           | (10, 10) | -0.4 | -0.6 | -0.6 | -0.6 | -0.3 | -0.2 | -0.1 | -0.1 | -0.1 | -0.1 | 0    | 0.1  | -0.1 | 0    | 0    | 0    | 0    |
|           | (10, 60) | 0.8  | 1.2  | 0.8  | 0.5  | 0.7  | 3.7  | 3.4  | 1.2  | 2.7  | 1.6  | 0.5  | 1.4  | 2    | 4.2  | 0.5  | -    | -    |
|           | (10, 50) | 0.8  | 0.9  | 0.4  | 0.6  | 1.9  | 4    | 3.9  | 3.7  | 3.2  | 1.2  | 0.6  | 0.8  | 0.7  | 3    | 1.5  | 1.7  | 2.4  |
|           | (10, 40) | 0.8  | 1    | 0.9  | 0.2  | 0.6  | 0.2  | 0.4  | 0.4  | 0.3  | 0.4  | 0.4  | 0.3  | 0.05 | 0.5  | 0.7  | 0.5  | 0.8  |
|           | (10, 30) | 0.2  | 0.3  | 0.2  | 0.3  | 0.2  | 0.01 | 0.09 | 0.1  | 0.07 | 0.2  | 0.1  | 0.3  | 0.6  | 1.3  | 0.8  | 0.2  | 0.1  |
| $u_{rms}$ | (10, 20) | 0.5  | 0.6  | 0.8  | 0.6  | 0.2  | 0.4  | 0.4  | 0.2  | 0.6  | 0.8  | 1    | 0.7  | 0.5  | 1.5  | 0.7  | 0.4  | 1    |
|           | (10, 10) | 0.1  | 0.03 | 0.2  | 0.1  | 0.2  | 0.1  | 0.01 | 0.04 | 0.05 | 0.07 | 0.05 | 0.1  | 0.05 | 0.1  | 0.2  | 0.07 | 0.05 |
|           | (10, 60) | 0.1  | 0.1  | -0.7 | -0.3 | 0.4  | 0.3  | 1.1  | 1.8  | 2.7  | 3.7  | 3    | 4.3  | 4.4  | 5.6  | 4.5  | -    | -    |
|           | (10, 50) | -0.6 | -0.1 | 0.1  | 0.5  | 0.4  | 0.4  | 1.4  | 3    | 3.9  | 5.3  | 7.4  | 5.9  | 5.9  | 6.9  | 5.9  | 4    | 1.3  |
|           | (10, 40) | 0.7  | 1.4  | 1.7  | 1.6  | 1.2  | 1.2  | 1.7  | 1.7  | 1.7  | 1.8  | 2.6  | 2.6  | 2    | 2    | 1.7  | 1.2  | 0.7  |
|           | (10, 30) | 0.3  | 0.4  | 0.3  | 0.9  | 0.2  | 0.7  | 1.2  | 1.9  | 0.6  | 0.6  | 0.3  | 0    | -0.2 | -0.4 | -0.9 | -0.3 | 0    |
|           | (10, 20) | 1    | 2    | 2    | 1.8  | 1.7  | 1.7  | 1.2  | 1.8  | 2    | 2.5  | 2.8  | 4.1  | 4.3  | 3.6  | 3    | 2    | 0.6  |
|           | (10, 10) | 0.1  | 0.3  | 0.4  | 0.6  | 0.4  | 0.1  | 0    | 0.1  | 0    | 0.2  | -0.1 | 0    | 0.1  | -0.2 | -0.3 | 0    | 0    |
|           | (10, 60) | 0.5  | 0.5  | 0.4  | 0.8  | 0.7  | 0.6  | 0.6  | 2.3  | 0.07 | 1.1  | 1.7  | 0.2  | 1.3  | 0.8  | 0.2  | -    | -    |
|           | (10, 50) | 0.8  | 0.5  | 0.3  | 0.09 | 0.2  | 0.7  | 0.6  | 1.4  | 1.3  | 0.6  | 1    | 1.1  | 0.4  | 1.2  | 0.6  | 1.8  | 1.5  |
| $v$       | (10, 40) | 0.6  | 0.4  | 0.8  | 0.5  | 0.3  | 0.5  | 0.3  | 0.2  | 0.5  | 0.3  | 0.1  | 0.4  | 0.6  | 0.4  | 0.9  | 1.2  | 1.7  |
|           | (10, 30) | 0.4  | 0.9  | 0.5  | 0.3  | 0.6  | 0.5  | 0.8  | 0.9  | 0.5  | 0.5  | 0.2  | 0.7  | 0.5  | 0.6  | 0.7  | 0.6  | 0.2  |
|           | (10, 20) | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 1.1  | 0.3  | 0.4  | 0.5  | 0.5  | 0.2  | 0.9  | 1    | 0.7  | 2.2  | 1.4  | 0.8  |
|           | (10, 10) | 0.03 | 0.06 | 0.1  | 0.04 | 0.3  | 0.2  | 0.01 | 0.1  | 0.05 | 0.1  | 0.08 | 0.1  | 0.5  | 0.3  | 0.4  | 0.1  | 0.1  |
|           | (10, 60) | 0.5  | 0.5  | 0.4  | 0.8  | 0.7  | 0.6  | 0.6  | 2.3  | 0.07 | 1.1  | 1.7  | 0.2  | 1.3  | 0.8  | 0.2  | -    | -    |
|           | (10, 50) | 0.8  | 0.5  | 0.3  | 0.09 | 0.2  | 0.7  | 0.6  | 1.4  | 1.3  | 0.6  | 1    | 1.1  | 0.4  | 1.2  | 0.6  | 1.8  | 1.5  |
|           | (10, 40) | 0.6  | 0.4  | 0.8  | 0.5  | 0.3  | 0.5  | 0.3  | 0.2  | 0.5  | 0.3  | 0.1  | 0.4  | 0.6  | 0.4  | 0.9  | 1.2  | 1.7  |
|           | (10, 30) | 0.4  | 0.9  | 0.5  | 0.3  | 0.6  | 0.5  | 0.8  | 0.9  | 0.5  | 0.5  | 0.2  | 0.7  | 0.5  | 0.6  | 0.7  | 0.6  | 0.2  |
|           | (10, 20) | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 1.1  | 0.3  | 0.4  | 0.5  | 0.5  | 0.2  | 0.9  | 1    | 0.7  | 2.2  | 1.4  | 0.8  |
|           | (10, 10) | 0.03 | 0.06 | 0.1  | 0.04 | 0.3  | 0.2  | 0.01 | 0.1  | 0.05 | 0.1  | 0.08 | 0.1  | 0.5  | 0.3  | 0.4  | 0.1  | 0.1  |

Table A.27.: Early stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 50\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 2    | 4    | 6    | 8    | 10   | 12   | 14   | 16   | 18   | 20   | 22   | 24   | 26   | 28   | 30   | 32   | 34   |
|-----------|-----------|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.03 | 0.06 | 0.09 | 0.11 | 0.14 | 0.17 | 0.2  | 0.23 | 0.26 | 0.29 | 0.31 | 0.34 | 0.37 | 0.4  | 0.43 | 0.46 | 0.49 |
| $u$       | (20, 60)  | 0 | 0.1  | 0.2  | 0.3  | 0.5  | 0.6  | 0.8  | 0.2  | 0.1  | 0.1  | 0.6  | -0.3 | 0.3  | 0.3  | 0.7  | 1.4  | 1.8  | 3.5  |
|           | (20, 50)  | 0 | 0.1  | 0.2  | 0.3  | 0.4  | 0.6  | 0.7  | 0.9  | 1.1  | 1.3  | 1.5  | 1.7  | 2.1  | 1.6  | 1.9  | 0.9  | 2.1  | 4.5  |
|           | (20, 40)  | 0 | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.9  | 1.1  | 1.2  | 1.4  | 1.7  | 1.4  | 1.5  | 2.3  | 2.7  | 3.8  |
|           | (20, 30)  | 0 | 0.1  | 0.1  | 0.2  | 0.3  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1    | 1.1  | 0.9  | 0.2  | -0.1 | 0.2  |
|           | (20, 20)  | 0 | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.3  | 0.4  | 0.5  | 0.5  | 0.6  | 0.6  | 0.6  | 0.6  | 0.5  | 0    | -0.1 | -0.2 |
|           | (20, 10)  | 0 | 0    | 0.1  | 0.1  | 0.1  | 0.2  | 0.3  | 0.3  | 0.4  | 0.4  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.1  | 0.8  | 0.9  |
| $u_{rms}$ | (20, 60)  | 0 | 0.01 | 0.04 | 0.05 | 0.05 | 0.05 | 0.07 | 0.4  | 0.4  | 0.4  | 0.5  | 0.3  | 0.5  | 0.8  | 0.6  | 1.1  | 1.3  | 2.1  |
|           | (20, 50)  | 0 | 0    | 0.04 | 0.02 | 0.02 | 0.03 | 0.05 | 0.06 | 0.08 | 0.09 | 0.1  | 0.1  | 0.2  | 1.1  | 1.3  | 0.7  | 1.2  | 1.4  |
|           | (20, 40)  | 0 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.06 | 0.08 | 0.1  | 0.1  | 0.1  | 0.7  | 0.9  | 0.5  | 0.8  | 0.7  |
|           | (20, 30)  | 0 | 0    | 0.01 | 0.02 | 0.02 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.04 | 0.01 | 0.2  | 0.2  | 1    | 0.3  |
|           | (20, 20)  | 0 | 0    | 0.01 | 0    | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.02 | 0.04 | 0.03 | 0.02 | 0.02 | 0.07 | 0.6  | 0.6  | 0.2  |
|           | (20, 10)  | 0 | 0    | 0.01 | 0.01 | 0    | 0.02 | 0.01 | 0.01 | 0.03 | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 1.5  | 0.6  | 0.4  |
| $v$       | (20, 60)  | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.3 | -0.1 | -0.1 | -1.2 | -0.1 | -1.5 |
|           | (20, 50)  | 0 | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.4 | -0.5 | -0.5 | -0.7 | -0.5 | -0.6 | -0.6 | -1.2 | -1.6 |
|           | (20, 40)  | 0 | 0    | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.9 | -1.1 | -1   | -1.3 | -1.9 | -3.4 | -3.6 |
|           | (20, 30)  | 0 | 0    | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.9 | -1.1 | -1.4 | -1.7 | -2.1 | -2.8 | -3.4 |
|           | (20, 20)  | 0 | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.8 | -1   | -0.8 | -0.7 | -1   |
|           | (20, 10)  | 0 | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.3 | -0.4 | -0.4 | -0.5 | -0.8 | -0.2 | 1    |
| $v_{rms}$ | (20, 60)  | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 | 0.03 | 0.3  | 0.4  | 1.2  | 0.4  | 0.7  |
|           | (20, 50)  | 0 | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.05 | 0.07 | 0.4  | 0.5  | 0.6  | 0.5  | 0.5  |
|           | (20, 40)  | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.05 | 0.06 | 0.09 | 0.1  | 0.4  | 0.6  | 0.9  | 0.5  | 0.2  |
|           | (20, 30)  | 0 | 0    | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.07 | 0.08 | 0.1  | 0.08 | 0.07 | 0.7  | 0.6  | 0.2  |
|           | (20, 20)  | 0 | 0    | 0    | 0.01 | 0    | 0.01 | 0.02 | 0.01 | 0.02 | 0.03 | 0.03 | 0.06 | 0.07 | 0.07 | 0.1  | 0.6  | 0.2  | 0.3  |
|           | (20, 10)  | 0 | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.02 | 0.03 | 1.6  | 1.4  | 0.3  |



Table A.28.: Late stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 36       | 38   | 40   | 42   | 44   | 46   | 48   | 50   | 52   | 54   | 56   | 58   | 60   | 62   | 64   | 66   | 68   | 70   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.51     | 0.54 | 0.57 | 0.6  | 0.63 | 0.66 | 0.69 | 0.71 | 0.74 | 0.77 | 0.8  | 0.83 | 0.86 | 0.89 | 0.91 | 0.94 | 0.97 | 1    |
| $u$       | (20, 60) | 4.8  | 6.6  | 8.1  | 8.8  | 9.2  | 12   | 14   | 21   | 22   | 26   | 28   | 29   | 27   | 24   | 20   | 14   | 0.6  |
|           | (20, 50) | 6.6  | 8.7  | 9.1  | 9.1  | 9.9  | 14   | 15   | 21   | 23   | 24   | 24   | 19   | 17   | 17   | 19   | 19   | 15   |
|           | (20, 40) | 4.6  | 5.1  | 5.1  | 4.2  | 4.4  | 3.8  | 3.4  | 1.9  | 1.5  | 1.1  | 0.5  | 0.6  | 0.5  | 0.1  | -0.1 | -0.9 | -1.1 |
|           | (20, 30) | 0.2  | 0    | 0.5  | 0.5  | 1.1  | 0.3  | 0.5  | 0.6  | 1    | 0.2  | 0.1  | -0.3 | -0.5 | -0.9 | -0.6 | -0.4 | -0.5 |
|           | (20, 20) | -0.6 | -0.6 | -0.6 | -0.9 | -0.8 | -0.7 | -0.1 | -0.2 | -0.7 | -0.4 | -0.9 | -0.9 | -0.4 | -0.6 | -0.1 | 0.6  | -0.2 |
|           | (20, 10) | -0.3 | 0.9  | 1.3  | 0.8  | 0.4  | 0.4  | 0.1  | -1.1 | -1.7 | -1.7 | -0.7 | -0.1 | -0.1 | 0.8  | 1.8  | 0.7  | -0.5 |
|           | (20, 60) | 2.5  | 1.9  | 0.7  | 0.7  | 0.5  | 4    | 4.7  | 3.9  | 4.3  | 2.6  | 1    | 0.2  | 0.8  | 0.9  | 2.3  | 2.2  | 9.2  |
|           | (20, 50) | 1.4  | 1.1  | 0.2  | 0.6  | 0.2  | 4.3  | 4.3  | 4.1  | 2.2  | 0.4  | 0.7  | 2.9  | 0.4  | 0.8  | 0.7  | 2.3  | 0.8  |
|           | (20, 40) | 0.8  | 0.7  | 0.2  | 0.6  | 1.2  | 1    | 1.9  | 1.1  | 0.9  | 0.4  | 0.4  | 1.2  | 0.5  | 0.3  | 0.4  | 1.1  | 0.8  |
|           | (20, 30) | 0.3  | 0.4  | 0.9  | 0.5  | 0.5  | 0.3  | 0.5  | 0.4  | 0.1  | 0.3  | 0.4  | 0.4  | 0.9  | 0.2  | 0.3  | 0.2  | 0.9  |
| $u_{rms}$ | (20, 20) | 1    | 0.8  | 0.04 | 0.5  | 0.5  | 0.2  | 0.6  | 0.4  | 0.7  | 0.2  | 0.5  | 0.7  | 0.8  | 1    | 0.9  | 0.5  | 0.7  |
|           | (20, 10) | 0.9  | 0.3  | 1.5  | 1.2  | 0.7  | 2    | 0.9  | 0.7  | 1.3  | 1.3  | 2.1  | 2.2  | 3.1  | 1    | 1.3  | 2.5  | 2.1  |
|           | (20, 60) | -1.2 | -0.8 | -0.3 | -0.3 | -0.3 | -0.6 | 0.7  | 0.3  | 0.3  | 2.1  | 2.4  | 2.8  | 3    | 3.6  | 3.4  | 1.9  | 1.8  |
|           | (20, 50) | -1.7 | -1.7 | -1.2 | -0.7 | -0.7 | -0.9 | -1.1 | -0.6 | 0.4  | 2    | 2    | 3.9  | 4.4  | 2.7  | 2.1  | 2.1  | 1.3  |
|           | (20, 40) | -3.6 | -2.2 | -0.8 | 0.2  | 0.2  | 0.8  | 1.3  | 1.9  | 2.2  | 2.6  | 3.3  | 3.9  | 4.4  | 4.8  | 3.5  | 1.4  | 1.2  |
|           | (20, 30) | -2.7 | -1.5 | -0.2 | 0.6  | 1.5  | 2.1  | 2.8  | 3.6  | 4.4  | 5.2  | 5.6  | 5.6  | 4.7  | 3.8  | 2.3  | 1.7  | 1.4  |
|           | (20, 20) | -1   | -0.8 | -0.3 | 0.6  | 1.1  | 1.4  | 2    | 2.9  | 3.9  | 3.9  | 4.1  | 3.9  | 4.4  | 1.7  | 1.3  | 0.3  | -0.1 |
|           | (20, 10) | 0.7  | 0.3  | -0.4 | -0.3 | 0.9  | 0.9  | 1.1  | 1.2  | 2.7  | 2.9  | 3    | 5.2  | 3    | 3    | 2.8  | 1.1  | 2.8  |
|           | (20, 60) | 0.9  | 0.6  | 0.4  | 0.3  | 0.6  | 1.3  | 0.9  | 0.8  | 1.7  | 0.5  | 0.6  | 0.9  | 1    | 1.4  | 0.6  | 2.1  | 2.2  |
|           | (20, 50) | 0.6  | 0.6  | 0.2  | 0.09 | 0.05 | 0.7  | 0.4  | 0.3  | 0.6  | 0.6  | 1    | 2.3  | 1.5  | 1.1  | 0.7  | 0.9  | 0.9  |
| $v$       | (20, 40) | 0.4  | 1    | 0.5  | 0.6  | 0.2  | 0.5  | 0.5  | 0.3  | 0.9  | 0.5  | 0.5  | 0.3  | 1.2  | 0.9  | 1    | 1.2  | 0.9  |
|           | (20, 30) | 0.08 | 0.6  | 0.5  | 0.6  | 0.6  | 0.4  | 0.4  | 1.2  | 0.6  | 0.7  | 0.7  | 0.9  | 1.3  | 0.8  | 0.8  | 0.6  | 1.2  |
|           | (20, 20) | 0.3  | 0.2  | 1.1  | 1.1  | 1    | 0.5  | 0.8  | 0.5  | 0.7  | 1    | 0.6  | 0.6  | 0.2  | 1.1  | 0.9  | 1.1  | 1.3  |
|           | (20, 10) | 1.1  | 0.7  | 0.3  | 0.6  | 1    | 0.8  | 1.2  | 1.8  | 2.2  | 2.7  | 3    | 1.6  | 1.7  | 1.8  | 1.4  | 0.9  | 1.1  |
|           | (20, 60) | 0.9  | 0.6  | 0.4  | 0.3  | 0.6  | 1.3  | 0.9  | 0.8  | 1.7  | 0.5  | 0.6  | 0.9  | 1    | 1.4  | 0.6  | 2.1  | 2.2  |
|           | (20, 50) | 0.6  | 0.6  | 0.2  | 0.09 | 0.05 | 0.7  | 0.4  | 0.3  | 0.6  | 0.6  | 1    | 2.3  | 1.5  | 1.1  | 0.7  | 0.9  | 0.9  |
|           | (20, 40) | 0.4  | 1    | 0.5  | 0.6  | 0.2  | 0.5  | 0.5  | 0.3  | 0.9  | 0.5  | 0.5  | 0.3  | 1.2  | 0.9  | 1    | 1.2  | 0.9  |
|           | (20, 30) | 0.08 | 0.6  | 0.5  | 0.6  | 0.6  | 0.4  | 0.4  | 1.2  | 0.6  | 0.7  | 0.7  | 0.9  | 1.3  | 0.8  | 0.8  | 0.6  | 1.2  |
|           | (20, 20) | 0.3  | 0.2  | 1.1  | 1.1  | 1    | 0.5  | 0.8  | 0.5  | 0.7  | 1    | 0.6  | 0.6  | 0.2  | 1.1  | 0.9  | 1.1  | 1.3  |
|           | (20, 10) | 1.1  | 0.7  | 0.3  | 0.6  | 1    | 0.8  | 1.2  | 1.8  | 2.2  | 2.7  | 3    | 1.6  | 1.7  | 1.8  | 1.4  | 0.9  | 1.1  |
| $u_{rms}$ | (20, 60) | -1.2 | -0.8 | -0.3 | -0.3 | -0.3 | -0.6 | 0.7  | 0.3  | 0.3  | 2.1  | 2.4  | 2.8  | 3    | 3.6  | 3.4  | 1.9  | 1.8  |
|           | (20, 50) | -1.7 | -1.7 | -1.2 | -0.7 | -0.7 | -0.9 | -1.1 | -0.6 | 0.4  | 2    | 2    | 3.9  | 4.4  | 2.7  | 2.1  | 2.1  | 1.3  |
|           | (20, 40) | -3.6 | -2.2 | -0.8 | 0.2  | 0.2  | 0.8  | 1.3  | 1.9  | 2.2  | 2.6  | 3.3  | 3.9  | 4.4  | 4.8  | 3.5  | 1.4  | 1.2  |
|           | (20, 30) | -2.7 | -1.5 | -0.2 | 0.6  | 1.5  | 2.1  | 2.8  | 3.6  | 4.4  | 5.2  | 5.6  | 5.6  | 4.7  | 3.8  | 2.3  | 1.7  | 1.4  |
|           | (20, 20) | -1   | -0.8 | -0.3 | 0.6  | 1.1  | 1.4  | 2    | 2.9  | 3.9  | 3.9  | 4.1  | 3.9  | 4.4  | 1.7  | 1.3  | 0.3  | -0.1 |
|           | (20, 10) | 0.7  | 0.3  | -0.4 | -0.3 | 0.9  | 0.9  | 1.1  | 1.2  | 2.7  | 2.9  | 3    | 5.2  | 3    | 3    | 2.8  | 1.1  | 2.8  |
|           | (20, 60) | 0.9  | 0.6  | 0.4  | 0.3  | 0.6  | 1.3  | 0.9  | 0.8  | 1.7  | 0.5  | 0.6  | 0.9  | 1    | 1.4  | 0.6  | 2.1  | 2.2  |
|           | (20, 50) | 0.6  | 0.6  | 0.2  | 0.09 | 0.05 | 0.7  | 0.4  | 0.3  | 0.6  | 0.6  | 1    | 2.3  | 1.5  | 1.1  | 0.7  | 0.9  | 0.9  |
|           | (20, 40) | 0.4  | 1    | 0.5  | 0.6  | 0.2  | 0.5  | 0.5  | 0.3  | 0.9  | 0.5  | 0.5  | 0.3  | 1.2  | 0.9  | 1    | 1.2  | 0.9  |
|           | (20, 30) | 0.08 | 0.6  | 0.5  | 0.6  | 0.6  | 0.4  | 0.4  | 1.2  | 0.6  | 0.7  | 0.7  | 0.9  | 1.3  | 0.8  | 0.8  | 0.6  | 1.2  |
|           | (20, 20) | 0.3  | 0.2  | 1.1  | 1.1  | 1    | 0.5  | 0.8  | 0.5  | 0.7  | 1    | 0.6  | 0.6  | 0.2  | 1.1  | 0.9  | 1.1  | 1.3  |
|           | (20, 10) | 1.1  | 0.7  | 0.3  | 0.6  | 1    | 0.8  | 1.2  | 1.8  | 2.2  | 2.7  | 3    | 1.6  | 1.7  | 1.8  | 1.4  | 0.9  | 1.1  |

Table A.29.: Early stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 50\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms] | 0 | 2    | 4    | 6    | 8    | 10   | 12   | 14   | 16   | 18   | 20   | 22   | 24   | 26   | 28   | 30   | 32   | 34   |
|-----------|----------|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] |          | 0 | 0.03 | 0.06 | 0.09 | 0.11 | 0.14 | 0.17 | 0.2  | 0.23 | 0.26 | 0.29 | 0.31 | 0.34 | 0.37 | 0.4  | 0.43 | 0.46 | 0.49 |
| $u$       | (30, 60) | 0 | 0.1  | 0.2  | 0.3  | 0.4  | 0.6  | 0.7  | 0.9  | 1    | 1.2  | 1.4  | 1.6  | 1.9  | 1.4  | 1.7  | 0.5  | 1.3  | 1.4  |
|           | (30, 50) | 0 | 0.1  | 0.1  | 0.3  | 0.4  | 0.5  | 0.6  | 0.8  | 0.9  | 1.1  | 1.3  | 1.5  | 1.8  | 1.3  | 1.5  | 0.9  | 1.8  | 2.8  |
|           | (30, 40) | 0 | 0.1  | 0.1  | 0.3  | 0.3  | 0.4  | 0.6  | 0.7  | 0.8  | 1    | 1.1  | 1.3  | 1.5  | 1.3  | 1.3  | 1.1  | 1.3  | 1.9  |
|           | (30, 30) | 0 | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1    | 1.2  | 1.3  | 1.4  | 0.9  | 0.7  | 0.8  |
|           | (30, 20) | 0 | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.6  | 0.7  | 0.8  | 0.9  | 1    | 1    | 0.3  | 0.5  | 0.5  |
| $u_{rms}$ | (30, 10) | 0 | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.3  | 0.4  | 0.5  | 0.6  | 0.6  | 0.7  | 0.8  | 0.8  | 0.9  | 0.5  | 0.2  | 0.4  |
|           | (30, 60) | 0 | 0.01 | 0.04 | 0.03 | 0.01 | 0.04 | 0.05 | 0.04 | 0.06 | 0.08 | 0.1  | 0.1  | 0.1  | 1    | 1.2  | 0.7  | 0.7  | 0.8  |
|           | (30, 50) | 0 | 0    | 0.01 | 0.01 | 0.03 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.1  | 0.1  | 0.1  | 0.9  | 1.1  | 0.5  | 0.7  | 0.4  |
|           | (30, 40) | 0 | 0.01 | 0.01 | 0.02 | 0.04 | 0.03 | 0.03 | 0.04 | 0.06 | 0.06 | 0.08 | 0.1  | 0.1  | 0.5  | 0.9  | 0.3  | 0.2  | 0.6  |
|           | (30, 30) | 0 | 0.01 | 0.01 | 0.03 | 0.01 | 0.04 | 0.04 | 0.03 | 0.05 | 0.07 | 0.06 | 0.06 | 0.07 | 0.05 | 0.03 | 0.5  | 0.1  | 0.1  |
| $v$       | (30, 20) | 0 | 0.01 | 0    | 0    | 0.02 | 0.02 | 0.04 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.03 | 0.02 | 0.6  | 0.5  | 0.5  |
|           | (30, 10) | 0 | 0    | 0.02 | 0    | 0.03 | 0.01 | 0.02 | 0.02 | 0.05 | 0.03 | 0.04 | 0.05 | 0.04 | 0.02 | 0.01 | 0.4  | 0.3  | 1.4  |
|           | (30, 60) | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.2 | -0.2 | -0.9 | -0.7 | -1.5 |
|           | (30, 50) | 0 | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.5 | -0.4 | -0.4 | -1.3 | -1.7 | -1.7 |
|           | (30, 40) | 0 | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.4 | -0.4 | -0.5 | -0.7 | -0.5 | -0.7 | -1.2 | -1.7 | -1.8 |
| $v_{rms}$ | (30, 30) | 0 | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.3 | -0.3 | -0.4 | -0.4 | -0.5 | -0.7 | -0.9 | -1.1 | -1.1 | -1.1 | -1.9 |
|           | (30, 20) | 0 | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.5 | -0.6 | -0.8 | -0.3 | -0.7 | -0.6 |
|           | (30, 10) | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.4 | 0.2  | 0    | 0.3  |
|           | (30, 60) | 0 | 0    | 0    | 0    | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.04 | 0.1  | 0.3  | 0.9  | 0.9  | 1    |
|           | (30, 50) | 0 | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.04 | 0.3  | 0.4  | 0.2  | 0.9  | 0.6  |
| $v_{rms}$ | (30, 40) | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.07 | 0.4  | 0.5  | 0.8  | 0.6  | 0.2  |
|           | (30, 30) | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.05 | 0.07 | 0.1  | 0.08 | 0.7  | 0.8  | 0.5  |
|           | (30, 20) | 0 | 0    | 0.01 | 0    | 0.02 | 0    | 0.02 | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.06 | 0.06 | 0.09 | 0.3  | 0.3  | 0.08 |
|           | (30, 10) | 0 | 0    | 0.01 | 0    | 0.02 | 0    | 0    | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.04 | 0.04 | 1    | 0.7  | 1.4  |
|           | (30, 60) | 0 | 0    | 0    | 0    | 0    | 0    | 0    | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.04 | 0.04 | 0.7  | 1.4  |

Table A.30.: Late stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 36       | 38   | 40   | 42   | 44   | 46   | 48   | 50   | 52   | 54   | 56   | 58   | 60   | 62   | 64   | 66   | 68   | 70   |     |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-----|
| $t^*$ [—] | 0.51     | 0.54 | 0.57 | 0.6  | 0.63 | 0.66 | 0.69 | 0.71 | 0.74 | 0.77 | 0.8  | 0.83 | 0.86 | 0.89 | 0.91 | 0.94 | 0.97 | 1    |     |
| $u$       | (30, 60) | 2.9  | 4.1  | 4.2  | 5.6  | 6.7  | 9.5  | 14   | 19   | 23   | 27   | 28   | 29   | 29   | 27   | 25   | 19   | 14   | 9   |
|           | (30, 50) | 3.4  | 4    | 5.9  | 8    | 8.5  | 9.9  | 17   | 19   | 22   | 22   | 20   | 20   | 16   | 13   | 13   | 13   | 12   | 12  |
|           | (30, 40) | 2.8  | 4.3  | 4.9  | 5.5  | 5.5  | 6.5  | 6.3  | 6.1  | 5.2  | 3.7  | 3.6  | 2.3  | 2.3  | 2.2  | 1.6  | 1.6  | 0.7  | 0.4 |
|           | (30, 30) | 0.2  | 0.2  | 1.1  | 1.2  | 1.6  | 1.5  | 1    | 0.6  | 0.5  | 1    | 1.2  | 1.4  | 1.3  | 1.3  | 2    | 1.4  | 0.7  | 0.3 |
|           | (30, 20) | -0.2 | 0.1  | -1.1 | -1.2 | -1.3 | -1   | -0.9 | -1.2 | -1.2 | -1.6 | -1.2 | -1.5 | -2.4 | -0.2 | 0.6  | 0.6  | 0.1  | 0.1 |
| $u_{rms}$ | (30, 10) | 0.5  | 0.5  | -1.3 | -0.6 | -0.8 | -0.8 | -1.5 | -3   | -4.4 | -2.8 | -2.4 | -1.7 | -3.1 | -1.5 | -0.8 | -1.7 | -0.5 | 0   |
|           | (30, 60) | 1.7  | 0.9  | 0.6  | 0.5  | 1.6  | 1.4  | 3.4  | 0.6  | 4.3  | 2.4  | 1.2  | 0.4  | 0.9  | 1.5  | 1.5  | 6.7  | 11.6 | 13  |
|           | (30, 50) | 1.4  | 1.8  | 1.2  | 0.6  | 1.6  | 2.2  | 2.8  | 2.2  | 0.9  | 3.1  | 3.1  | 3.2  | 3.1  | 3.4  | 2.3  | 3.2  | 0.7  | 3.9 |
|           | (30, 40) | 1.4  | 1.2  | 0.7  | 0.7  | 0.6  | 0.1  | 0.7  | 0.7  | 0.7  | 0.8  | 0.9  | 0.4  | 1.2  | 1.8  | 1.7  | 0.8  | 1    | 0.5 |
|           | (30, 30) | 0.3  | 0.8  | 0.5  | 0.8  | 0.3  | 0.4  | 0.2  | 0.2  | 0.3  | 0.7  | 0.6  | 0.5  | 1    | 1.5  | 0.9  | 1.2  | 1    | 0.2 |
| $v$       | (30, 20) | 0.3  | 1.1  | 0.7  | 0.2  | 0.2  | 0.5  | 0.6  | 0.2  | 0.4  | 1    | 1    | 0.7  | 1.5  | 0.6  | 1.1  | 1.4  | 0.5  | 1   |
|           | (30, 10) | 0.5  | 0.8  | 0.5  | 2.4  | 1.8  | 1.3  | 0.1  | 2.1  | 2.5  | 1.7  | 1    | 3.7  | 2.6  | 1.4  | 0.6  | 1.6  | 0.3  | 1   |
|           | (30, 60) | -1.3 | -1.3 | -0.5 | -0.7 | -1.4 | -1.5 | -2.8 | -1.2 | -1.2 | 0.5  | 1.7  | 2.2  | 2.2  | 3    | 3.7  | 0.4  | 0.4  | 0   |
|           | (30, 50) | -1.9 | -1.8 | -2.2 | -2.2 | -2.4 | -2.4 | -3.4 | -1.3 | -0.8 | 0.3  | 2.6  | 2.6  | -0.9 | 2    | 1.7  | 1.7  | 0.4  | 0   |
|           | (30, 40) | -2.6 | -3.3 | -3.3 | -3   | -1.4 | -1.6 | -1.6 | 0.3  | 1.6  | 2.5  | 3.7  | 4.4  | 4.5  | 4.4  | 3.1  | 1.5  | 1.3  | 0   |
| $v_{rms}$ | (30, 30) | -2.7 | -3.8 | -3.6 | -2.4 | -0.9 | 0    | 0.9  | 2.3  | 3.6  | 4.7  | 5.9  | 5.9  | 5.8  | 5.9  | 4.6  | 2.1  | 1.2  | 0.6 |
|           | (30, 20) | -1   | -1.4 | -2.1 | -1.9 | -1.1 | 0    | 0.6  | 2    | 2.5  | 5    | 5    | 5.9  | 6.5  | 5.2  | 4.5  | 2.5  | 2.4  | 0.5 |
|           | (30, 10) | -1   | -0.7 | -0.5 | 0    | -1.8 | -1   | 0    | 0    | 2.6  | 3.1  | 3.7  | 4.9  | 4.6  | 5.2  | 3.3  | 3.2  | 1.9  | 0.7 |
|           | (30, 60) | 0.7  | 1.1  | 0.8  | 0.6  | 0.4  | 1.6  | 1.6  | 0.6  | 2.1  | 0.7  | 0.7  | 0.7  | 1.4  | 1.1  | 2.3  | 1.9  | 3.1  | 1.9 |
|           | (30, 50) | 1    | 0.6  | 0.3  | 0.4  | 1    | 1.7  | 0.1  | 1.4  | 2    | 1.9  | 1.6  | 1.6  | 3.1  | 2.2  | 1.1  | 1.2  | 1.1  | 1.5 |
| $v_{rms}$ | (30, 40) | 1    | 0.6  | 0.5  | 0.8  | 0.1  | 2.1  | 0.6  | 1.8  | 0.7  | 0.7  | 0.8  | 0.6  | 1    | 0.7  | 0.7  | 0.8  | 1.2  | 1.6 |
|           | (30, 30) | 0.7  | 0.7  | 0.8  | 1    | 1.2  | 0.9  | 0.7  | 1.4  | 1.5  | 1.1  | 0.6  | 0.5  | 2.2  | 1.3  | 1.1  | 2.1  | 1.6  | 1.4 |
|           | (30, 20) | 0.3  | 0.5  | 0.8  | 0.5  | 1.5  | 0.7  | 0.7  | 1    | 0.8  | 1.1  | 2    | 0.9  | 2.1  | 2.4  | 2.2  | 1.3  | 1    | 1.4 |
|           | (30, 10) | 0.6  | 1.8  | 1.2  | 1    | 0.7  | 0.5  | 1.4  | 1.1  | 1.9  | 2.2  | 0.7  | 2.4  | 1.2  | 1.7  | 2    | 2.4  | 2.2  | 0.2 |

Table A.31.: Early stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 50\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 2    | 4    | 6    | 8    | 10   | 12   | 14   | 16   | 18   | 20   | 22   | 24   | 26   | 28   | 30   | 32   | 34   |
|-----------|-----------|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.03 | 0.06 | 0.09 | 0.11 | 0.14 | 0.17 | 0.2  | 0.23 | 0.26 | 0.29 | 0.31 | 0.34 | 0.37 | 0.4  | 0.43 | 0.46 | 0.49 |
| $u$       | (40, 60)  | 0 | 0.1  | 0.1  | 0.2  | 0.3  | 0.5  | 0.6  | 0.7  | 0.8  | 1    | 1.1  | 1.5  | 1.7  | 1.3  | 1.5  | 0.6  | 0.3  | 0.5  |
|           | (40, 50)  | 0 | 0.1  | 0.1  | 0.2  | 0.3  | 0.5  | 0.6  | 0.7  | 0.9  | 1    | 1.1  | 1.4  | 1.6  | 1.2  | 1.4  | 0.2  | 0.5  | 1.1  |
|           | (40, 40)  | 0 | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.7  | 0.8  | 0.9  | 1.1  | 1.2  | 1.5  | 1    | 1.2  | 0.5  | 0.3  | 1.1  |
|           | (40, 30)  | 0 | 0.1  | 0.1  | 0.1  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 1    | 1.1  | 1.3  | 0.9  | 1    | 0.3  | 0    | 0    |
|           | (40, 20)  | 0 | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1.1  | 1.2  | 1.2  | 0.1  | 0.2  | 0.2  |
| $u_{rms}$ | (40, 10)  | 0 | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.6  | 0.8  | 0.8  | 1    | 1.1  | 1.1  | 0.4  | 0.2  | -0.1 |
|           | (40, 60)  | 0 | 0.02 | 0.04 | 0.1  | 0.1  | 0.07 | 0.03 | 0.08 | 0.09 | 0.08 | 0.2  | 0.1  | 0.1  | 0.9  | 1    | 0.7  | 0.4  | 0.7  |
|           | (40, 50)  | 0 | 0.01 | 0.02 | 0.09 | 0.09 | 0.03 | 0.05 | 0.08 | 0.06 | 0.02 | 0.05 | 0.09 | 0.1  | 0.8  | 1    | 0.3  | 1.2  | 0.06 |
|           | (40, 40)  | 0 | 0.01 | 0.02 | 0.03 | 0.05 | 0.01 | 0.05 | 0.05 | 0.06 | 0.06 | 0.07 | 0.09 | 0.1  | 0.7  | 0.8  | 0.5  | 0.5  | 0.7  |
|           | (40, 30)  | 0 | 0.01 | 0.01 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.06 | 0.07 | 0.06 | 0.09 | 0.6  | 0.7  | 0.08 | 0.4  | 0.7  |
| $v$       | (40, 20)  | 0 | 0.02 | 0.02 | 0.04 | 0.06 | 0.01 | 0.02 | 0.04 | 0.05 | 0.04 | 0.06 | 0.09 | 0.06 | 0.04 | 0.1  | 0.9  | 0.1  | 0.9  |
|           | (40, 10)  | 0 | 0.01 | 0.01 | 0.01 | 0.04 | 0.02 | 0.04 | 0.03 | 0.02 | 0.06 | 0.04 | 0.06 | 0.06 | 0.07 | 0.05 | 0.6  | 0.5  | 0.8  |
|           | (40, 60)  | 0 | 0    | 0    | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.2 | -0.8 | -0.2 | -0.2 |
|           | (40, 50)  | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.3 | -0.3 | -0.7 | 0    | -0.5 |
|           | (40, 40)  | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.3 | -0.4 | -0.4 | -0.4 | -0.9 |
| $v_{rms}$ | (40, 30)  | 0 | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.3 | -0.4 | -0.7 | -0.4 | -0.7 |
|           | (40, 20)  | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.5 | 0.8  | 0.3  | 0.2  |
|           | (40, 10)  | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | 0.5  | 0.5  | 0.2  |
|           | (40, 60)  | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.1  | 0.2  | 0.5  | 0.6  | 1    |
|           | (40, 50)  | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0    | 0.01 | 0.02 | 0.02 | 0.01 | 0.03 | 0.03 | 0.2  | 0.2  | 0.3  | 0.3  | 0.7  |
| $v_{rms}$ | (40, 40)  | 0 | 0    | 0    | 0.01 | 0    | 0.02 | 0    | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.04 | 0.2  | 0.3  | 0.4  | 0.9  | 0.4  |
|           | (40, 30)  | 0 | 0    | 0    | 0.01 | 0.01 | 0    | 0.01 | 0    | 0.02 | 0.03 | 0.03 | 0.04 | 0.04 | 0.2  | 0.3  | 0.2  | 0.2  | 0.5  |
|           | (40, 20)  | 0 | 0    | 0.01 | 0.01 | 0.02 | 0    | 0.01 | 0    | 0.01 | 0.02 | 0.01 | 0.03 | 0.03 | 0.03 | 0.02 | 0.8  | 0.7  | 0.2  |
|           | (40, 10)  | 0 | 0    | 0.01 | 0    | 0.01 | 0.01 | 0.02 | 0    | 0.01 | 0.01 | 0.01 | 0.03 | 0.03 | 0.03 | 0.05 | 0.5  | 0.8  | 0.6  |
|           | (40, 60)  | 0 | 0    | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.1  | 0.2  | 0.5  | 0.6  | 1    |

Table A.32.: Late stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 50% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 36       | 38   | 40   | 42   | 44   | 46   | 48   | 50   | 52   | 54   | 56   | 58   | 60   | 62   | 64   | 66   | 68   | 70   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.51     | 0.54 | 0.57 | 0.6  | 0.63 | 0.66 | 0.69 | 0.71 | 0.74 | 0.77 | 0.8  | 0.83 | 0.86 | 0.89 | 0.91 | 0.94 | 0.97 | 1    |
| $u$       | (40, 60) | 0.3  | 0.9  | 0.9  | 2.4  | 2.4  | 2.5  | 2.5  | 7.2  | 8.1  | 9.5  | 11   | 11   | 14   | 14   | 6.5  | 9.3  | 6.1  |
|           | (40, 50) | 1.1  | 1.5  | 1.6  | 2    | 2.4  | 3.8  | 5    | 6    | 9.8  | 10   | 15   | 9.9  | 9.9  | 5    | 6.4  | 6.5  | 5.2  |
|           | (40, 40) | 1.2  | 1.2  | 1.9  | 2.7  | 2.7  | 3.5  | 4.5  | 4.3  | 4.3  | 3.5  | 3.2  | 2.5  | 2.5  | 2.5  | 2.7  | 1.5  | 1.5  |
|           | (40, 30) | 0.6  | 0.6  | 0.6  | 0.7  | 0.8  | 1.4  | 1.3  | 1.2  | 1.2  | 1.2  | 1.4  | 1.4  | 1    | 1    | 0.4  | 0.5  | 0.6  |
|           | (40, 20) | 0.4  | 0.6  | 0.2  | 0    | -1   | -0.8 | -0.7 | -0.6 | -0.1 | -0.1 | 0.1  | -1.4 | -2.7 | -1.4 | -1.5 | 0.3  | 0.7  |
|           | (40, 10) | -0.1 | 0.1  | 0.1  | -0.3 | -0.3 | -1   | -2.1 | -1.9 | -2.6 | -3.4 | -4.2 | -5.7 | -2.6 | -3.2 | -0.7 | 0.3  | -0.3 |
|           | (40, 60) | 0.8  | 0.9  | 1.2  | 1    | 1.2  | 1.5  | 3.2  | 3.3  | 5.4  | 11.2 | 10   | 9.3  | 10.3 | 13.1 | 13   | 13.2 | 11.7 |
|           | (40, 50) | 0.6  | 0.3  | 0.7  | 0.4  | 1    | 2.7  | 1.5  | 4.8  | 5.8  | 7.7  | 10.2 | 7.2  | 10.1 | 3.9  | 2.1  | 3.6  | 7.7  |
|           | (40, 40) | 0.4  | 0.8  | 0.9  | 0.5  | 1.4  | 0.4  | 1.7  | 3.1  | 2.1  | 1.9  | 0.9  | 0.7  | 0.4  | 1.2  | 2.9  | 1.3  | 0.6  |
|           | (40, 30) | 0.07 | 0.8  | 0.5  | 0.6  | 0.6  | 0.5  | 1    | 1    | 0.7  | 0.7  | 0.08 | 0.4  | 0.5  | 0.9  | 0.6  | 1.1  | 0.6  |
| $u_{rms}$ | (40, 20) | 0.6  | 1    | 0.5  | 0.2  | 0.2  | 0.7  | 0.9  | 0.5  | 0.5  | 0.5  | 0.8  | 0.9  | 0.9  | 1.3  | 1    | 1.4  | 1.5  |
|           | (40, 10) | 0.5  | 0.4  | 1.1  | 0.3  | 0.5  | 0.4  | 0.2  | 1.1  | 0.6  | 1    | 1.9  | 3.6  | 0.9  | 2    | 1.7  | 0.8  | 1.5  |
|           | (40, 60) | -0.2 | -0.2 | -0.9 | -0.4 | -0.3 | -0.7 | -1.8 | -1.8 | -1.3 | -0.5 | 0.2  | 0.9  | 0.5  | 0.8  | 1.2  | 0.1  | 0.1  |
|           | (40, 50) | -0.5 | -0.8 | -0.3 | -1.1 | -1.3 | -1   | -1.3 | -2.6 | -2.1 | -1.1 | -1.1 | -0.2 | 1.7  | 1.5  | 0.5  | 0.6  | 0.7  |
| $v$       | (40, 40) | -0.9 | -0.8 | -1.5 | -2.2 | -2.4 | -2.1 | -2.2 | -2.2 | -2.2 | 0.1  | 1.7  | 2.1  | 2.7  | 3.1  | 2.6  | 1.2  | 1.2  |
|           | (40, 30) | -0.7 | -1.1 | -1.9 | -2.4 | -2.2 | -1.3 | -0.8 | -0.1 | 1.2  | 1.8  | 2.2  | 2.8  | 3.1  | 3.6  | 3.6  | 2.7  | 2.9  |
|           | (40, 20) | -0.2 | -0.5 | -0.7 | -0.6 | -0.8 | -0.8 | -1   | -0.1 | 1.3  | 2.3  | 3.4  | 4.1  | 4.1  | 5.2  | 4.5  | 3.9  | 2.3  |
|           | (40, 10) | 0.2  | -0.4 | 0    | -0.7 | -0.7 | -0.4 | -0.6 | -0.5 | 0.1  | 1.3  | 2.1  | 3    | 2.8  | 3    | 3.6  | 2.4  | 2.1  |
|           | (40, 60) | 0.9  | 0.7  | 0.7  | 0.2  | 0.2  | 1    | 1.9  | 1.6  | 2.1  | 1.4  | 1.8  | 0.7  | 1.7  | 2    | 1.1  | 3.6  | 1.7  |
|           | (40, 50) | 0.6  | 0.5  | 0.8  | 0.7  | 0.9  | 1.3  | 0.7  | 2.5  | 2.2  | 0.6  | 0.8  | 1.2  | 2    | 2    | 1    | 0.3  | 0.9  |
| $u_{rms}$ | (40, 40) | 0.2  | 0.3  | 0.2  | 0.4  | 1.6  | 1    | 2.1  | 2.8  | 3.8  | 0.7  | 1    | 0.5  | 1.3  | 1.9  | 1.2  | 1.2  | 1.4  |
|           | (40, 30) | 1    | 0.4  | 0.2  | 0.5  | 0.7  | 0.4  | 0.8  | 0.8  | 0.4  | 0.2  | 0.1  | 0.4  | 0.6  | 0.8  | 2.3  | 1.2  | 2.3  |
|           | (40, 20) | 0.8  | 0.4  | 0.3  | 0.5  | 0.9  | 0.7  | 0.7  | 0.7  | 0.8  | 0.6  | 1.3  | 0.9  | 0.2  | 1.8  | 1.8  | 3.2  | 1.4  |
|           | (40, 10) | 0.6  | 0.4  | 0.8  | 0.7  | 0.6  | 0.2  | 1.1  | 1.1  | 0.4  | 1.4  | 2    | 1.2  | 0.4  | 2.3  | 0.7  | 1.9  | 1.1  |

Table A.33.: Early stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 80\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.04 | 0.08 | 0.12 | 0.16 | 0.2  | 0.24 | 0.28 | 0.32 | 0.36 | 0.4  | 0.44 | 0.48 |
| $u$       | (10, 60) | 0    | 0    | 0.2  | 0.7  | 1.4  | 1.5  | 2.2  | 2.9  | 3.4  | 4.4  | 5.8  | 8.2  |
|           | (10, 50) | 0    | 0    | 0.1  | 0.7  | 1.2  | 1.5  | 2.2  | 2.9  | 3.7  | 4.6  | 5.7  | 8.2  |
|           | (10, 40) | 0    | 0    | 0.2  | 0.5  | 1.1  | 1.4  | 1.8  | 2.5  | 3.2  | 4.1  | 4.6  | 7    |
|           | (10, 30) | 0    | 0    | 0.1  | 0.2  | 0.4  | 0.7  | 1    | 1.1  | 1.2  | 1.3  | 1.2  | 0.1  |
|           | (10, 20) | 0    | 0    | 0.1  | 0.1  | 0.3  | 0.3  | 0.5  | 0.6  | 0.7  | 0.7  | 0.3  | 0.5  |
|           | (10, 10) | 0    | 0    | 0    | 0    | 0.1  | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.5  |
| $u_{rms}$ | (10, 60) | 0    | 0    | 0.03 | 0.07 | 0.08 | 0.05 | 0.2  | 0.04 | 0.3  | 0.1  | 1.7  | 0.8  |
|           | (10, 50) | 0    | 0    | 0.05 | 0.1  | 0.06 | 0.04 | 0.3  | 0.07 | 0.3  | 0.2  | 1.2  | 0.4  |
|           | (10, 40) | 0    | 0    | 0.03 | 0.07 | 0.07 | 0.07 | 0.1  | 0.09 | 0.1  | 0.2  | 1.1  | 0.8  |
|           | (10, 30) | 0    | 0    | 0.02 | 0.06 | 0.07 | 0.08 | 0.02 | 0.04 | 0.04 | 0.05 | 0.07 | 0.4  |
|           | (10, 20) | 0    | 0    | 0.02 | 0.02 | 0.03 | 0.02 | 0.04 | 0.03 | 0.03 | 0.2  | 0.5  | 0.5  |
|           | (10, 10) | 0    | 0    | 0.02 | 0.01 | 0.02 | 0.04 | 0.04 | 0.06 | 0.03 | 0.09 | 0.04 | 0.05 |
| $v$       | (10, 60) | 0    | 0    | 0.1  | -0.1 | -0.1 | -0.3 | -0.2 | -0.3 | -0.4 | 0    | -1.9 | -0.5 |
|           | (10, 50) | 0    | 0    | 0    | -0.1 | -0.3 | -0.3 | -0.6 | -0.8 | -1.1 | -1.3 | -1.1 | -2.6 |
|           | (10, 40) | 0    | 0    | -0.1 | -0.3 | -0.7 | -1   | -1.4 | -1.8 | -2.4 | -3.1 | -3.8 | -6.7 |
|           | (10, 30) | 0    | 0    | -0.2 | -0.3 | -0.6 | -1   | -1.3 | -1.7 | -2.4 | -3.2 | -4.1 | -5.1 |
|           | (10, 20) | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.6 | -0.9 | -1.1 | -1.3 | -1.5 | -1.6 | -1.3 |
|           | (10, 10) | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.4 | -0.5 | -0.6 | -0.7 | -0.8 | -0.9 | -1   |
| $v_{rms}$ | (10, 60) | 0    | 0    | 0.04 | 0.04 | 0.09 | 0.03 | 0.06 | 0.06 | 0.03 | 0.03 | 0.7  | 0.5  |
|           | (10, 50) | 0    | 0    | 0.06 | 0.04 | 0.04 | 0.03 | 0.08 | 0.01 | 0.1  | 0.1  | 0.9  | 0.9  |
|           | (10, 40) | 0    | 0    | 0.01 | 0.03 | 0.06 | 0.04 | 0.08 | 0.09 | 0.1  | 0.2  | 0.5  | 0.5  |
|           | (10, 30) | 0    | 0    | 0.02 | 0.04 | 0.02 | 0.04 | 0.04 | 0.09 | 0.1  | 0.2  | 0.2  | 0.1  |
|           | (10, 20) | 0    | 0    | 0.02 | 0.02 | 0.02 | 0.04 | 0.03 | 0.05 | 0.05 | 0.07 | 0.8  | 0.5  |
|           | (10, 10) | 0    | 0    | 0.01 | 0.03 | 0.03 | 0.05 | 0.02 | 0.06 | 0.02 | 0.03 | 0.03 | 0.05 |

Table A.34.: Late stage flow field velocity data at a distance of 10 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   | 25   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.52     | 0.56 | 0.6  | 0.64 | 0.68 | 0.72 | 0.76 | 0.8  | 0.84 | 0.88 | 0.92 | 0.96 | 1    |
| $u$       | (10, 60) | 9.5  | 12   | 18   | 19   | 24   | 32   | 44   | 57   | 64   | 68   | 66   | 67   |
|           | (10, 50) | 11   | 16   | 20   | 24   | 29   | 36   | 49   | 62   | 68   | 69   | 65   | 66   |
|           | (10, 40) | 11   | 12   | 9.9  | 8.6  | 6.5  | 4.3  | 0.7  | 0.2  | -0.3 | -0.1 | 0.2  | -2   |
|           | (10, 30) | -2.9 | -3.5 | -2.7 | -1.1 | -0.2 | 0.5  | -0.5 | -1.3 | -2.3 | -2.8 | -3.9 | -3.1 |
|           | (10, 20) | -0.7 | -2.4 | -4.1 | -4.3 | -3.6 | -2.8 | -2.9 | -4.1 | -5.4 | -6.7 | -6.1 | -5.2 |
|           | (10, 10) | 0    | -0.5 | -1.4 | -2.1 | -2.8 | -3   | -3.5 | -4.5 | -3.8 | -2.4 | -2.7 | -3.7 |
|           | (10, 60) | 0.4  | 2.4  | 2.1  | 1.1  | 2.6  | 3.9  | 6.4  | 4.3  | 3.7  | 1.5  | 1.1  | 0.8  |
|           | (10, 50) | 1.1  | 1.7  | 0.5  | 2    | 1.9  | 4.6  | 7.1  | 4.9  | 2.8  | 2.5  | 3.6  | 3.2  |
| $u_{rms}$ | (10, 40) | 0.6  | 0.6  | 0.6  | 1    | 0.1  | 1.5  | 0.9  | 0.4  | 0.4  | 0.3  | 0.8  | 1    |
|           | (10, 30) | 0.2  | 0.3  | 0.4  | 0.2  | 0.3  | 0.1  | 0.6  | 0.2  | 0.3  | 0.4  | 0.5  | 2.1  |
|           | (10, 20) | 0.6  | 0.8  | 0.8  | 0.7  | 0.5  | 0.6  | 1    | 0.9  | 0.4  | 1.1  | 0.7  | 1    |
|           | (10, 10) | 0.1  | 0.2  | 0.2  | 0.3  | 0.2  | 0.09 | 0.6  | 0.4  | 1    | 1.7  | 1.5  | 2.2  |
|           | (10, 60) | -0.1 | -0.1 | -0.8 | 0.2  | 0.7  | 2.3  | 3.4  | 6    | 10   | 11   | 12   | 11   |
|           | (10, 50) | -1.3 | -1.7 | 0    | 1.6  | 1.5  | 3    | 4.5  | 11   | 15   | 17   | 17   | 16   |
|           | (10, 40) | -6.2 | -2.3 | 3.2  | 4.8  | 5.6  | 2.7  | 4.7  | 6.5  | 6.7  | 7.5  | 7.4  | 7.3  |
|           | (10, 30) | -3.6 | 1.5  | 6.2  | 9.1  | 10   | 8.3  | 8.4  | 9.9  | 10   | 11   | 11   | 8.5  |
| $v$       | (10, 20) | -0.6 | 0.4  | 1.9  | 3.4  | 6.1  | 6.3  | 6.7  | 8.3  | 9    | 9.2  | 10   | 9.4  |
|           | (10, 10) | -0.8 | -0.4 | 0.2  | 1.2  | 2.2  | 2.9  | 3.7  | 4.7  | 4.3  | 4.6  | 4.5  | 3.5  |
|           | (10, 60) | 0.3  | 0.6  | 0.9  | 0.7  | 1    | 0.7  | 1.6  | 1.6  | 1.8  | 1.3  | 1    | 0.3  |
|           | (10, 50) | 0.1  | 0.7  | 0.5  | 0.3  | 0.8  | 0.8  | 1.3  | 2.7  | 1.4  | 1.8  | 1.7  | 0.8  |
|           | (10, 40) | 0.3  | 1    | 0.8  | 0.7  | 1    | 0.8  | 2.3  | 0.7  | 0.6  | 0.9  | 0.2  | 1.2  |
|           | (10, 30) | 0.8  | 1.4  | 1.1  | 0.6  | 0.3  | 0.7  | 1.1  | 1.1  | 0.5  | 0.9  | 0.3  | 0.8  |
|           | (10, 20) | 0.6  | 0.5  | 0.6  | 0.6  | 0.7  | 0.5  | 0.7  | 1.1  | 0.5  | 0.6  | 0.5  | 1.3  |
|           | (10, 10) | 0.07 | 0.1  | 0.2  | 0.2  | 0.3  | 0.2  | 0.4  | 0.5  | 0.4  | 2.9  | 2.5  | 4.1  |
| $v_{rms}$ | (10, 60) | 0.3  | 0.6  | 0.9  | 0.7  | 1    | 0.7  | 1.6  | 1.6  | 1.8  | 1.3  | 1    | 0.3  |
|           | (10, 50) | 0.1  | 0.7  | 0.5  | 0.3  | 0.8  | 0.8  | 1.3  | 2.7  | 1.4  | 1.8  | 1.7  | 0.8  |
|           | (10, 40) | 0.3  | 1    | 0.8  | 0.7  | 1    | 0.8  | 2.3  | 0.7  | 0.6  | 0.9  | 0.2  | 1.2  |
|           | (10, 30) | 0.8  | 1.4  | 1.1  | 0.6  | 0.3  | 0.7  | 1.1  | 1.1  | 0.5  | 0.9  | 0.3  | 0.8  |
|           | (10, 20) | 0.6  | 0.5  | 0.6  | 0.6  | 0.7  | 0.5  | 0.7  | 1.1  | 0.5  | 0.6  | 0.5  | 1.3  |
|           | (10, 10) | 0.07 | 0.1  | 0.2  | 0.2  | 0.3  | 0.2  | 0.4  | 0.5  | 0.4  | 2.9  | 2.5  | 4.1  |
|           | (10, 60) | 0.3  | 0.6  | 0.9  | 0.7  | 1    | 0.7  | 1.6  | 1.6  | 1.8  | 1.3  | 1    | 0.3  |
|           | (10, 50) | 0.1  | 0.7  | 0.5  | 0.3  | 0.8  | 0.8  | 1.3  | 2.7  | 1.4  | 1.8  | 1.7  | 0.8  |

Table A.35.: Early stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 80\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.04 | 0.08 | 0.12 | 0.16 | 0.2  | 0.24 | 0.28 | 0.32 | 0.36 | 0.4  | 0.44 | 0.48 |
| $u$       | (20, 60) | 0    | 0    | 0.1  | 1.2  | 1.4  | 1.6  | 2.7  | 2.9  | 4.1  | 4.9  | 6.7  | 8    |
|           | (20, 50) | 0    | 0    | 0    | 1.2  | 1.4  | 1.5  | 2.5  | 2.8  | 3.8  | 3.3  | 6    | 8.5  |
|           | (20, 40) | 0    | 0    | 0.2  | 0.8  | 1.2  | 1.5  | 1.9  | 2.6  | 3    | 2.9  | 4.3  | 6.1  |
|           | (20, 30) | 0    | 0    | 0.2  | 0.3  | 0.6  | 0.9  | 1.2  | 1.5  | 1.7  | 2.1  | 2.5  | 2.9  |
|           | (20, 20) | 0    | 0    | 0    | 0.1  | 0.2  | 0.5  | 0.9  | 1.2  | 1.4  | 1    | 1    | 1    |
|           | (20, 10) | 0    | 0    | 0    | 0    | 0.1  | 0.2  | 0.6  | 1.1  | 1.3  | 1.4  | 1.4  | 1.4  |
| $u_{rms}$ | (20, 60) | 0    | 0    | 0.04 | 0.1  | 0.08 | 0.04 | 0.3  | 0.05 | 0.01 | 0.2  | 1.3  | 0.7  |
|           | (20, 50) | 0    | 0    | 0.01 | 0.03 | 0.03 | 0.02 | 0.06 | 0.1  | 0.04 | 0.3  | 0.3  | 0.8  |
|           | (20, 40) | 0    | 0    | 0.02 | 0.02 | 0.04 | 0.05 | 0.04 | 0.07 | 0.1  | 0.09 | 0.3  | 0.4  |
|           | (20, 30) | 0    | 0    | 0.02 | 0.01 | 0.04 | 0.03 | 0.03 | 0.06 | 0.1  | 0.4  | 0.2  | 0.3  |
|           | (20, 20) | 0    | 0    | 0.01 | 0.02 | 0.02 | 0.06 | 0.07 | 0.03 | 0.04 | 0.03 | 0.3  | 0.2  |
|           | (20, 10) | 0    | 0    | 0.02 | 0.01 | 0.03 | 0.01 | 0.07 | 0.07 | 0.06 | 0.03 | 0.03 | 0.03 |
| $v$       | (20, 60) | 0    | 0    | -0.1 | -0.1 | -0.1 | -0.2 | -0.3 | -0.5 | -0.5 | -0.8 | -1   | -1.1 |
|           | (20, 50) | 0    | 0    | -0.1 | -0.2 | -0.2 | -0.3 | -0.5 | -0.7 | -1   | -1.2 | -2.1 | -2.2 |
|           | (20, 40) | 0    | 0    | -0.1 | -0.2 | -0.3 | -0.5 | -0.8 | -1.1 | -1.3 | -1.7 | -3.1 | -5.3 |
|           | (20, 30) | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.6 | -0.8 | -1.1 | -1.4 | -1.7 | -2.2 | -3.9 |
|           | (20, 20) | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.4 | -0.6 | -0.8 | -1   | -1.2 | -0.2 | -1   |
|           | (20, 10) | 0    | 0    | 0    | -0.1 | -0.2 | -0.2 | -0.3 | -0.5 | -0.6 | -0.7 | -0.9 | -1.2 |
| $v_{rms}$ | (20, 60) | 0    | 0    | 0.01 | 0.06 | 0.03 | 0.03 | 0.05 | 0.04 | 0.1  | 0.04 | 0.09 | 0.1  |
|           | (20, 50) | 0    | 0    | 0.05 | 0.02 | 0.07 | 0.03 | 0.01 | 0.08 | 0.05 | 0.04 | 0.4  | 0.7  |
|           | (20, 40) | 0    | 0    | 0    | 0.03 | 0.01 | 0.07 | 0.06 | 0.04 | 0.06 | 0.08 | 0.4  | 0.3  |
|           | (20, 30) | 0    | 0    | 0.02 | 0.02 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.1  | 0.6  | 0.3  |
|           | (20, 20) | 0    | 0    | 0.03 | 0.02 | 0.04 | 0.08 | 0.05 | 0.06 | 0.06 | 0.05 | 0.3  | 0.3  |
|           | (20, 10) | 0    | 0    | 0.01 | 0.02 | 0.02 | 0.07 | 0.03 | 0.03 | 0.04 | 0.04 | 0.06 | 0.02 |



Table A.36.: Late stage flow field velocity data at a distance of 20 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   | 25   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0.52     | 0.56 | 0.6  | 0.64 | 0.68 | 0.72 | 0.76 | 0.8  | 0.84 | 0.88 | 0.92 | 0.96 | 1    |
| $u$       | (20, 60) | 9.6  | 9.6  | 16   | 19   | 23   | 31   | 43   | 58   | 67   | 72   | 73   | 69   |
|           | (20, 50) | 8.9  | 11   | 16   | 21   | 27   | 34   | 50   | 60   | 61   | 58   | 55   | 46   |
|           | (20, 40) | 8.2  | 11   | 15   | 14   | 14   | 14   | 8.3  | 6.6  | 4.6  | 2.1  | 0.6  | -1.3 |
|           | (20, 30) | 1.7  | 0.7  | -0.2 | 0.3  | 1.8  | 3.5  | 1.6  | 0.8  | -0.2 | -1.8 | -3.6 | -3.3 |
|           | (20, 20) | 0.9  | 0.2  | -3.2 | -7.5 | -8.1 | -8   | -6.5 | -4.7 | -6.6 | -7.6 | -5.6 | -2.5 |
|           | (20, 10) | 1    | 0.1  | 0.9  | -2.1 | -3.9 | -3.8 | -6.9 | -7.7 | -8.8 | -7.8 | -6.9 | -2.4 |
|           | (20, 60) | 0.5  | 0.3  | 2.9  | 0.6  | 2.7  | 3.4  | 5.9  | 6.8  | 4    | 2.4  | 2.5  | 1    |
|           | (20, 50) | 0.4  | 0.9  | 1.5  | 1.2  | 2.6  | 3.5  | 7.9  | 3.4  | 2    | 3.4  | 4.6  | 7.5  |
|           | (20, 40) | 0.9  | 1.3  | 0.4  | 0.4  | 0.6  | 0.4  | 1.6  | 0.2  | 0.9  | 0.5  | 1.7  | 1.8  |
|           | (20, 30) | 0.5  | 0.4  | 0.4  | 0.3  | 0.4  | 0.9  | 1.1  | 0.3  | 0.6  | 0.9  | 1.2  | 1.9  |
| $u_{rms}$ | (20, 20) | 0.5  | 0.2  | 1.9  | 1.9  | 0.9  | 0.6  | 1    | 1    | 2.1  | 1.5  | 3.2  | 2.1  |
|           | (20, 10) | 0.1  | 0.2  | 0.7  | 0.7  | 1.2  | 1.7  | 2.4  | 1.3  | 0.9  | 3.4  | 1.4  | 1.3  |
|           | (20, 60) | -1.4 | -1.7 | -1.9 | -1.5 | -1.7 | -0.9 | -1   | 2.9  | 6.4  | 7.5  | 9.2  | 8.4  |
|           | (20, 50) | -3.2 | -4.1 | -5   | -4.6 | -2.9 | -1.2 | -2.5 | 1    | 6.8  | 7.4  | 9    | 9.4  |
|           | (20, 40) | -7.2 | -11  | -9.8 | -4.2 | 0.3  | 1.7  | 3.5  | 8.1  | 9.7  | 11   | 13   | 13   |
|           | (20, 30) | -7.1 | -10  | -9.8 | -4.1 | 2.5  | 8.1  | 9.8  | 13   | 15   | 16   | 16   | 12   |
|           | (20, 20) | -2.3 | -3.2 | -4.2 | -1.9 | 1.6  | 6.7  | 8.6  | 12   | 13   | 14   | 11   | 8    |
|           | (20, 10) | -1.4 | -1.5 | -1.3 | -0.1 | -0.3 | 1.9  | 3.5  | 6.7  | 9.5  | 12   | 8.1  | 7.5  |
|           | (20, 60) | 0.06 | 0.08 | 0.9  | 0.7  | 1.3  | 0.2  | 1    | 1.2  | 1.2  | 0.5  | 0.8  | 0.6  |
|           | (20, 50) | 0.5  | 0.7  | 0.8  | 0.5  | 0.8  | 0.6  | 0.8  | 2.1  | 1.4  | 1.5  | 1.7  | 2.1  |
| $v$       | (20, 40) | 0.7  | 0.5  | 1    | 1.5  | 1.4  | 1.4  | 2    | 2.6  | 0.7  | 2    | 1.7  | 2.7  |
|           | (20, 30) | 0.5  | 0.7  | 1.4  | 1.4  | 1.9  | 1.4  | 0.8  | 2.2  | 1    | 1.5  | 1.1  | 0.7  |
|           | (20, 20) | 0.2  | 0.8  | 0.7  | 1    | 2.1  | 1.4  | 0.4  | 2.1  | 1.2  | 0.8  | 1.8  | 1.1  |
|           | (20, 10) | 0.07 | 0.05 | 1    | 0.6  | 1    | 0.7  | 2.3  | 1.1  | 1.3  | 1.6  | 2.7  | 0.8  |
|           | (20, 60) | 0.06 | 0.08 | 0.9  | 0.7  | 1.3  | 0.2  | 1    | 1.2  | 1.2  | 0.5  | 0.8  | 0.6  |
|           | (20, 50) | 0.5  | 0.7  | 0.8  | 0.5  | 0.8  | 0.6  | 0.8  | 2.1  | 1.4  | 1.5  | 1.7  | 2.1  |
|           | (20, 40) | 0.7  | 0.5  | 1    | 1.5  | 1.4  | 1.4  | 2    | 2.6  | 0.7  | 2    | 1.7  | 2.7  |
|           | (20, 30) | 0.5  | 0.7  | 1.4  | 1.4  | 1.9  | 1.4  | 0.8  | 2.2  | 1    | 1.5  | 1.1  | 0.7  |
|           | (20, 20) | 0.2  | 0.8  | 0.7  | 1    | 2.1  | 1.4  | 0.4  | 2.1  | 1.2  | 0.8  | 1.8  | 1.1  |
|           | (20, 10) | 0.07 | 0.05 | 1    | 0.6  | 1    | 0.7  | 2.3  | 1.1  | 1.3  | 1.6  | 2.7  | 0.8  |
| $v_{rms}$ | (20, 60) | 0.06 | 0.08 | 0.9  | 0.7  | 1.3  | 0.2  | 1    | 1.2  | 1.2  | 0.5  | 0.8  | 0.6  |
|           | (20, 50) | 0.5  | 0.7  | 0.8  | 0.5  | 0.8  | 0.6  | 0.8  | 2.1  | 1.4  | 1.5  | 1.7  | 2.1  |
|           | (20, 40) | 0.7  | 0.5  | 1    | 1.5  | 1.4  | 1.4  | 2    | 2.6  | 0.7  | 2    | 1.7  | 2.7  |
|           | (20, 30) | 0.5  | 0.7  | 1.4  | 1.4  | 1.9  | 1.4  | 0.8  | 2.2  | 1    | 1.5  | 1.1  | 0.7  |
|           | (20, 20) | 0.2  | 0.8  | 0.7  | 1    | 2.1  | 1.4  | 0.4  | 2.1  | 1.2  | 0.8  | 1.8  | 1.1  |
|           | (20, 10) | 0.07 | 0.05 | 1    | 0.6  | 1    | 0.7  | 2.3  | 1.1  | 1.3  | 1.6  | 2.7  | 0.8  |
|           | (20, 60) | 0.06 | 0.08 | 0.9  | 0.7  | 1.3  | 0.2  | 1    | 1.2  | 1.2  | 0.5  | 0.8  | 0.6  |
|           | (20, 50) | 0.5  | 0.7  | 0.8  | 0.5  | 0.8  | 0.6  | 0.8  | 2.1  | 1.4  | 1.5  | 1.7  | 2.1  |
|           | (20, 40) | 0.7  | 0.5  | 1    | 1.5  | 1.4  | 1.4  | 2    | 2.6  | 0.7  | 2    | 1.7  | 2.7  |
|           | (20, 30) | 0.5  | 0.7  | 1.4  | 1.4  | 1.9  | 1.4  | 0.8  | 2.2  | 1    | 1.5  | 1.1  | 0.7  |
|           | (20, 20) | 0.2  | 0.8  | 0.7  | 1    | 2.1  | 1.4  | 0.4  | 2.1  | 1.2  | 0.8  | 1.8  | 1.1  |

Table A.37.: Early stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 80\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

|           | $t$ [ms]  | 0 | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|-----------|---|------|------|------|------|------|------|------|------|------|------|------|------|
|           | $t^*$ [-] | 0 | 0.04 | 0.08 | 0.12 | 0.16 | 0.2  | 0.24 | 0.28 | 0.32 | 0.36 | 0.4  | 0.44 | 0.48 |
| $u$       | (30, 60)  | 0 | 0.1  | 0.1  | 0.2  | 0.9  | 1.2  | 1.3  | 2.1  | 2.8  | 3.1  | 1.7  | 3.8  | 6.8  |
|           | (30, 50)  | 0 | 0    | 0.1  | 0.3  | 0.9  | 1.2  | 1.3  | 1.8  | 2.6  | 3    | 2.2  | 3.7  | 4.8  |
|           | (30, 40)  | 0 | 0    | 0.1  | 0.3  | 0.7  | 1.1  | 1.3  | 1.6  | 2.3  | 2.8  | 1.8  | 2.4  | 3.5  |
|           | (30, 30)  | 0 | 0    | 0.1  | 0.2  | 0.5  | 1    | 1.3  | 1.4  | 1.6  | 2.4  | 0.9  | 1.3  | 2.1  |
|           | (30, 20)  | 0 | 0    | 0.1  | 0.2  | 0.3  | 0.6  | 1    | 1.2  | 1.4  | 1.6  | 1    | 1.3  | 1.2  |
|           | (30, 10)  | 0 | 0    | 0    | 0.1  | 0.2  | 0.4  | 1    | 1.2  | 1.4  | 1.4  | 0.6  | 0.4  | -0.2 |
| $u_{rms}$ | (30, 60)  | 0 | 0    | 0.07 | 0.06 | 0.07 | 0.05 | 0.1  | 0.3  | 0.1  | 0.3  | 0.5  | 1.1  | 0.9  |
|           | (30, 50)  | 0 | 0    | 0.01 | 0.05 | 0.06 | 0.03 | 0.07 | 0.4  | 0.1  | 0.07 | 0.7  | 0.2  | 0.8  |
|           | (30, 40)  | 0 | 0    | 0.03 | 0.05 | 0.07 | 0.04 | 0.07 | 0.05 | 0.1  | 0.06 | 0.8  | 0.3  | 0.7  |
|           | (30, 30)  | 0 | 0    | 0.02 | 0.04 | 0.04 | 0.07 | 0.03 | 0.02 | 0.1  | 0.2  | 0.4  | 0.4  | 0.3  |
|           | (30, 20)  | 0 | 0    | 0.02 | 0.05 | 0.05 | 0.07 | 0.03 | 0.01 | 0.03 | 0.1  | 0.6  | 0.2  | 0.6  |
|           | (30, 10)  | 0 | 0    | 0.02 | 0.02 | 0.04 | 0.06 | 0.1  | 0.05 | 0.02 | 0.03 | 0.8  | 1.2  | 1    |
| $v$       | (30, 60)  | 0 | 0    | -0.1 | -0.2 | 0    | -0.1 | -0.3 | -0.4 | -0.3 | -0.6 | -0.5 | -1.1 | -1   |
|           | (30, 50)  | 0 | 0    | -0.2 | -0.2 | -0.1 | -0.2 | -0.4 | -0.6 | -0.6 | -1   | -1.3 | -1.4 | -1.4 |
|           | (30, 40)  | 0 | 0    | -0.1 | -0.2 | -0.2 | -0.3 | -0.5 | -0.7 | -0.9 | -1.2 | -1.2 | -1   | -2   |
|           | (30, 30)  | 0 | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.4 | -0.6 | -0.9 | -1.2 | -0.8 | -1.3 | -2.1 |
|           | (30, 20)  | 0 | 0    | 0    | 0    | -0.1 | -0.2 | -0.4 | -0.5 | -0.6 | -0.8 | 0.4  | -0.2 | -0.9 |
|           | (30, 10)  | 0 | 0    | 0    | 0    | 0    | -0.1 | -0.4 | -0.4 | -0.5 | -0.5 | 0.6  | 0.1  | 0.5  |
| $v_{rms}$ | (30, 60)  | 0 | 0    | 0.04 | 0.06 | 0.09 | 0.09 | 0.1  | 0.2  | 0.05 | 0.1  | 0.2  | 0.6  | 0.6  |
|           | (30, 50)  | 0 | 0    | 0.01 | 0.02 | 0.04 | 0.03 | 0.07 | 0.2  | 0.1  | 0.07 | 0.4  | 0.7  | 0.5  |
|           | (30, 40)  | 0 | 0    | 0.03 | 0.02 | 0.03 | 0.05 | 0.04 | 0.07 | 0.07 | 0.06 | 0.4  | 0.2  | 0.6  |
|           | (30, 30)  | 0 | 0    | 0.03 | 0.04 | 0.02 | 0.04 | 0.03 | 0.04 | 0.06 | 0.07 | 0.3  | 0.4  | 0.4  |
|           | (30, 20)  | 0 | 0    | 0.02 | 0.03 | 0.02 | 0.03 | 0.04 | 0.04 | 0.03 | 0.08 | 0.5  | 0.4  | 0.2  |
|           | (30, 10)  | 0 | 0    | 0.01 | 0.01 | 0.03 | 0.03 | 0.05 | 0.02 | 0.01 | 0.02 | 0.4  | 0.3  | 0.9  |

Table A.38.: Late stage flow field velocity data at a distance of 30 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   | 25  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|-----|
| $t^*$ [-] | 0.52     | 0.56 | 0.6  | 0.64 | 0.68 | 0.72 | 0.76 | 0.8  | 0.84 | 0.88 | 0.92 | 0.96 | 1   |
| $u$       | (30, 60) | 7.8  | 8.1  | 9.4  | 15   | 19   | 29   | 41   | 58   | 68   | 73   | 76   | 74  |
|           | (30, 50) | 7.7  | 8.4  | 9.9  | 15   | 22   | 32   | 45   | 59   | 59   | 54   | 40   | 33  |
|           | (30, 40) | 5.8  | 7.6  | 9.2  | 14   | 17   | 18   | 20   | 15   | 13   | 9    | 7.9  | 5.6 |
|           | (30, 30) | 3.1  | 2.9  | 3.9  | 2.6  | 3    | 7.8  | 6.9  | 3.9  | 3.5  | 3.4  | 0.9  | 5.3 |
|           | (30, 20) | 1.7  | 1.6  | 0.5  | -0.9 | -6.7 | -8   | -7.6 | -7.9 | -7.3 | -7.9 | -5.8 | -3  |
| $u_{rms}$ | (30, 10) | 1.4  | 1.2  | -0.1 | 0.6  | -2.2 | -6.2 | -8.5 | -10  | -12  | -11  | -6.6 | -2  |
|           | (30, 60) | 1    | 0.5  | 1.3  | 2.5  | 1.2  | 3.2  | 6.6  | 6.5  | 4.6  | 3.1  | 1.2  | 2.1 |
|           | (30, 50) | 0.7  | 1    | 0.8  | 2.2  | 2.6  | 3.9  | 6.4  | 5.1  | 3.2  | 3.9  | 6.2  | 5.8 |
|           | (30, 40) | 0.5  | 0.3  | 0.6  | 2.7  | 1.1  | 1.2  | 2.4  | 2    | 1.2  | 1.1  | 2.3  | 2.9 |
|           | (30, 30) | 0.9  | 0.9  | 1.1  | 0.3  | 1.3  | 1.6  | 1.6  | 0.5  | 0.9  | 1.9  | 1.9  | 1.4 |
| $v$       | (30, 20) | 0.8  | 0.4  | 0.3  | 1.2  | 1.6  | 1    | 0.8  | 0.7  | 1.1  | 1.5  | 0.8  | 2.4 |
|           | (30, 10) | 0.9  | 1    | 0.7  | 0.9  | 3.1  | 1.2  | 1.6  | 1.5  | 1.9  | 2.1  | 0.7  | 4.6 |
|           | (30, 60) | -0.7 | -1.1 | -2.7 | -3.2 | -4.3 | -3   | -5.5 | -1.6 | 1.4  | 3.1  | 7.4  | 5.9 |
|           | (30, 50) | -1.6 | -3.7 | -6.5 | -7.3 | -8   | -7   | -7.2 | -4.7 | 1.1  | 4    | 6.3  | 7   |
|           | (30, 40) | -4.3 | -5.8 | -9.3 | -12  | -11  | -5.2 | -3.9 | 4.3  | 11   | 15   | 19   | 17  |
| $v_{rms}$ | (30, 30) | -3.8 | -6.1 | -9.4 | -12  | -9.9 | -5.3 | 0.8  | 8.5  | 16   | 19   | 21   | 14  |
|           | (30, 20) | -1.3 | -3.4 | -4.7 | -6.7 | -7   | -1.5 | 4.3  | 10   | 17   | 19   | 19   | 16  |
|           | (30, 10) | 1.4  | 0.5  | -0.4 | -2.1 | -2.5 | -1.1 | 1.1  | 5    | 11   | 13   | 14   | 13  |
|           | (30, 60) | 0.9  | 0.5  | 0.6  | 1.5  | 0.9  | 0.4  | 0.9  | 0.5  | 2    | 1.7  | 1.8  | 1.4 |
|           | (30, 50) | 0.7  | 1.3  | 0.6  | 0.4  | 0.6  | 1.1  | 2.3  | 3.1  | 2    | 2    | 2    | 3.7 |
| $u_{rms}$ | (30, 40) | 0.4  | 0.9  | 1.1  | 1.2  | 1.1  | 1.1  | 1.6  | 3.5  | 2.5  | 2.5  | 1.1  | 2.2 |
|           | (30, 30) | 1.1  | 0.3  | 1.3  | 0.7  | 0.5  | 2    | 1.6  | 3.4  | 3.2  | 0.9  | 2.1  | 3.4 |
|           | (30, 20) | 0.7  | 0.6  | 0.5  | 0.9  | 1.3  | 1    | 2.1  | 2.5  | 2.6  | 2.2  | 1.5  | 3.2 |
|           | (30, 10) | 0.6  | 0.7  | 0.9  | 0.6  | 0.9  | 1.6  | 0.6  | 1.6  | 2.1  | 2    | 0.9  | 2.1 |
|           | (30, 60) | 0.6  | 0.7  | 0.9  | 0.6  | 0.9  | 1.6  | 0.6  | 1.6  | 2.1  | 2    | 0.9  | 2.1 |

Table A.39.: Early stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in  $H_2/CH_4$ /Air mixtures with  $H_2 = 80\%$  and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 0        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| $t^*$ [-] | 0        | 0.04 | 0.08 | 0.12 | 0.16 | 0.2  | 0.24 | 0.28 | 0.32 | 0.36 | 0.4  | 0.44 | 0.48 |
| $u$       | (40, 60) | 0    | 0    | 0.1  | 0.2  | 0.5  | 0.8  | 0.9  | 1    | 2.3  | 2.9  | 1.4  | 2.2  |
|           | (40, 50) | 0    | 0    | 0.1  | 0.3  | 0.5  | 0.8  | 0.9  | 1.2  | 1.7  | 2.9  | 1.6  | 2    |
|           | (40, 40) | 0    | 0    | 0.1  | 0.3  | 0.4  | 0.7  | 0.9  | 1.1  | 1.6  | 2.5  | 1.4  | 2.2  |
|           | (40, 30) | 0    | 0    | 0.1  | 0.2  | 0.3  | 0.6  | 0.9  | 1    | 1.3  | 2    | 1.6  | 1.7  |
|           | (40, 20) | 0    | 0    | 0.1  | 0.2  | 0.4  | 0.6  | 0.8  | 1.1  | 1.3  | 1.8  | 1.6  | 1.5  |
|           | (40, 10) | 0    | 0    | 0.1  | 0.1  | 0.3  | 0.6  | 0.9  | 1.1  | 1.2  | 1.4  | 0.3  | -0.1 |
| $u_{rms}$ | (40, 60) | 0    | 0    | 0.03 | 0.03 | 0.08 | 0.09 | 0.2  | 0.2  | 0.7  | 0.3  | 0.4  | 1.1  |
|           | (40, 50) | 0    | 0    | 0.01 | 0.02 | 0.08 | 0.1  | 0.3  | 0.5  | 0.5  | 0.1  | 0.4  | 0.3  |
|           | (40, 40) | 0    | 0    | 0.04 | 0.01 | 0.1  | 0.2  | 0.2  | 0.4  | 0.6  | 0.2  | 0.6  | 0.6  |
|           | (40, 30) | 0    | 0    | 0.01 | 0.02 | 0.06 | 0.08 | 0.1  | 0.1  | 0.2  | 0.2  | 0.06 | 0.5  |
|           | (40, 20) | 0    | 0    | 0.03 | 0.06 | 0.06 | 0.1  | 0.1  | 0.1  | 0.2  | 0.2  | 0.6  | 0.4  |
|           | (40, 10) | 0    | 0    | 0.01 | 0.04 | 0.03 | 0.1  | 0.1  | 0.07 | 0.07 | 0.8  | 0.4  | 0.8  |
| $v$       | (40, 60) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.4 | -0.9 | -0.8 | -0.7 |
|           | (40, 50) | 0    | 0    | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.5 | -0.4 | -0.3 | 0    | -1.3 |
|           | (40, 40) | 0    | 0    | 0    | -0.1 | -0.1 | -0.3 | -0.4 | -0.6 | -0.7 | -0.6 | -0.5 | -1.1 |
|           | (40, 30) | 0    | 0    | 0    | -0.1 | -0.1 | -0.2 | -0.3 | -0.5 | -0.6 | -0.6 | -0.7 | -0.9 |
|           | (40, 20) | 0    | 0    | 0    | 0    | 0    | -0.1 | -0.2 | -0.3 | -0.4 | 0    | 0.7  | 0.4  |
|           | (40, 10) | 0    | 0    | 0    | 0    | 0    | -0.1 | -0.2 | -0.2 | -0.2 | 0.6  | 0.5  | 1.3  |
| $v_{rms}$ | (40, 60) | 0    | 0    | 0.03 | 0.02 | 0.05 | 0.03 | 0.02 | 0.1  | 0.06 | 0.2  | 0.4  | 0.3  |
|           | (40, 50) | 0    | 0    | 0.03 | 0.01 | 0.02 | 0.07 | 0.06 | 0.1  | 0.07 | 0.1  | 0.4  | 0.7  |
|           | (40, 40) | 0    | 0    | 0.02 | 0.03 | 0.01 | 0.04 | 0.04 | 0.09 | 0.1  | 0.07 | 0.3  | 0.2  |
|           | (40, 30) | 0    | 0    | 0.02 | 0.03 | 0.03 | 0.04 | 0.06 | 0.07 | 0.03 | 0.1  | 0.04 | 0.6  |
|           | (40, 20) | 0    | 0    | 0.03 | 0.01 | 0.01 | 0.02 | 0.05 | 0.1  | 0.03 | 0.09 | 0.2  | 0.5  |
|           | (40, 10) | 0    | 0    | 0.05 | 0.02 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.03 | 0.7  | 0.3  |

Table A.40.: Late stage flow field velocity data at a distance of 40 mm downstream of the second obstacle in H<sub>2</sub>/CH<sub>4</sub>/Air mixtures with H<sub>2</sub> = 80% and  $\Phi = 0.60$ . The numbers in brackets (x, y) indicate the distance from the second obstacle (x) and height (y) in mm. The unit of the velocity is m/s.

| $t$ [ms]  | 13       | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   | 25  |
|-----------|----------|------|------|------|------|------|------|------|------|------|------|------|-----|
| $t^*$ [—] | 0.52     | 0.56 | 0.6  | 0.64 | 0.68 | 0.72 | 0.76 | 0.8  | 0.84 | 0.88 | 0.92 | 0.96 | 1   |
| $u$       | (40, 60) | 5.2  | 5    | 5.1  | 9    | 16   | 36   | 53   | 67   | 76   | 78   | 76   | 77  |
|           | (40, 50) | 3.9  | 5.2  | 6.3  | 9.1  | 16   | 27   | 39   | 55   | 56   | 35   | 33   | 29  |
|           | (40, 40) | 3.4  | 4.4  | 6.7  | 9.3  | 14   | 22   | 29   | 27   | 22   | 22   | 22   | 17  |
|           | (40, 30) | 2.3  | 2.6  | 3.5  | 5.7  | 6    | 8.3  | 11   | 9.4  | 8.2  | 11   | 11   | 8.4 |
|           | (40, 20) | 1.6  | 1.6  | 2.4  | 1.4  | 0.1  | -4.6 | -4.9 | -5.8 | -5.1 | -9.1 | -9   | -   |
|           | (40, 10) | 1.5  | 1.4  | 0.5  | 0.7  | 0.4  | -2.9 | -7.2 | -15  | -21  | -25  | -24  | -18 |
|           | (40, 60) | 1.9  | 0.7  | 1.1  | 2.8  | 4    | 4.5  | 4.3  | 8.1  | 7.6  | 3.4  | 1.3  | 1.9 |
|           | (40, 50) | 0.6  | 1.6  | 1.8  | 2.6  | 1.9  | 4.7  | 5.6  | 6.4  | 5.4  | 6.7  | 6.6  | 3.5 |
| $u_{rms}$ | (40, 40) | 0.5  | 0.9  | 0.3  | 1    | 1.4  | 2.6  | 4.4  | 2.3  | 1.7  | 0.9  | 1    | 1.6 |
|           | (40, 30) | 0.8  | 0.8  | 1.2  | 1.1  | 0.8  | 0.8  | 0.8  | 1.1  | 1.9  | 2.6  | 2.2  | 4.8 |
|           | (40, 20) | 0.7  | 0.7  | 0.7  | 1.1  | 0.7  | 1.7  | 0.6  | 2.9  | 2.2  | 4.3  | 1    | -   |
|           | (40, 10) | 1.5  | 0.4  | 0.4  | 0.9  | 1    | 0.8  | 0.9  | 4.4  | 2.4  | 2.7  | 2.4  | 4.3 |
|           | (40, 60) | -1.1 | -0.8 | -0.8 | -2.1 | -3.9 | -4   | -5.3 | -6   | -2.8 | 0.4  | 3    | 5.8 |
|           | (40, 50) | -1.1 | -1.4 | -3.4 | -6   | -8.5 | -8.1 | -10  | -10  | -3   | 2    | 7.3  | 9.5 |
|           | (40, 40) | -0.8 | -2.8 | -4.9 | -8.6 | -12  | -15  | -13  | -5.6 | 3.5  | 12   | 18   | 19  |
|           | (40, 30) | -1.4 | -1.9 | -3.7 | -7   | -12  | -15  | -9.5 | 1.7  | 9.3  | 12   | 18   | 22  |
| $v$       | (40, 20) | -1   | -1.1 | -2.8 | -4.2 | -7.9 | -9.4 | -6   | 2.2  | 10   | 16   | 18   | 23  |
|           | (40, 10) | 0.6  | 0.5  | 0.3  | 0    | -3.9 | -5   | -3.4 | 2.1  | 7.4  | 14   | 16   | 18  |
|           | (40, 60) | 0.5  | 0.5  | 0.3  | 1    | 0.7  | 0.3  | 1.2  | 0.8  | 2.6  | 0.9  | 0.9  | 2.3 |
|           | (40, 50) | 0.3  | 0.5  | 2.2  | 1.5  | 0.7  | 0.4  | 1.4  | 2.5  | 3.5  | 3    | 4    | 2.8 |
|           | (40, 40) | 0.3  | 0.9  | 1.5  | 1.5  | 1.9  | 0.9  | 1.9  | 3.8  | 2.4  | 4.4  | 1    | 1.6 |
|           | (40, 30) | 0.7  | 0.6  | 1    | 1.5  | 2.7  | 1.3  | 0.3  | 5.4  | 3.1  | 2.7  | 3.8  | 4.9 |
|           | (40, 20) | 0.6  | 0.4  | 0.9  | 1.1  | 1.3  | 1.1  | 1.2  | 4.6  | 3.2  | 3.3  | 2    | 1.8 |
|           | (40, 10) | 0.6  | 0.5  | 0.7  | 1.1  | 0.7  | 1.7  | 0.2  | 3.4  | 2.9  | 2.2  | 1.7  | 1.4 |
| $v_{rms}$ | (40, 60) | 0.5  | 0.5  | 0.3  | 1    | 0.7  | 0.3  | 1.2  | 0.8  | 2.6  | 0.9  | 0.9  | 2.3 |
|           | (40, 50) | 0.3  | 0.5  | 2.2  | 1.5  | 0.7  | 0.4  | 1.4  | 2.5  | 3.5  | 3    | 4    | 2.8 |
|           | (40, 40) | 0.3  | 0.9  | 1.5  | 1.5  | 1.9  | 0.9  | 1.9  | 3.8  | 2.4  | 4.4  | 1    | 1.6 |
|           | (40, 30) | 0.7  | 0.6  | 1    | 1.5  | 2.7  | 1.3  | 0.3  | 5.4  | 3.1  | 2.7  | 3.8  | 4.9 |
|           | (40, 20) | 0.6  | 0.4  | 0.9  | 1.1  | 1.3  | 1.1  | 1.2  | 4.6  | 3.2  | 3.3  | 2    | 1.8 |
|           | (40, 10) | 0.6  | 0.5  | 0.7  | 1.1  | 0.7  | 1.7  | 0.2  | 3.4  | 2.9  | 2.2  | 1.7  | 1.4 |
|           | (40, 60) | 0.5  | 0.5  | 0.3  | 1    | 0.7  | 0.3  | 1.2  | 0.8  | 2.6  | 0.9  | 0.9  | 2.3 |
|           | (40, 50) | 0.3  | 0.5  | 2.2  | 1.5  | 0.7  | 0.4  | 1.4  | 2.5  | 3.5  | 3    | 4    | 2.8 |

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