Laser ignition of methane jets in homogenous and isotropic turbulence

Chaoxu Chen[1], Georgios Charalampous[2] and Yannis Hardalupas[3]
Mechanical Engineering Department, Imperial College London, London, SW7 2AZ, UK

The ignition of a pulsed methane jet by a laser-induced spark was investigated in air under the influence of homogenous and isotropic turbulence with zero mean flow. In this way, the contribution of the turbulent velocity fluctuations of the environment can be isolated from the mean flow component. The fuel jet Reynolds number (Re_{jet}) was fixed at 160, while the turbulent Reynolds numbers (Re_λ) of the environment was in the range of 0-220. The influence of the surrounding turbulence on the spatial distribution of the flame luminosity was evaluated and an increasingly random distribution of the flame was obtained under higher turbulent intensity. The Minimum Ignition Energy (MIE) was determined by measuring ignition probability for three different ignition locations. The MIE was found to increase with the surrounding turbulent intensity and had a significant dependence on ignition location. A disagreement between the spatial distribution of MIE and mixture fraction was observed. This is probably due to the finite size of the plasma, which has a more significant influence on the ignition probability at locations near the nozzle tip. The increase rate of the MIE with the level of turbulence was different at different ignition locations; this might be caused by the difference in the extent to which turbulence influences the mixture fraction at these locations. This effect is likely to be larger at positions near the methane/jet interface and at a distance from the nozzle exit, while it is smaller at positions near the centreline and the nozzle exit.

Nomenclature

E_1	=	Incident energy of the laser beam
E_2	=	Transmitted energy of the laser beam
E_3	=	Absorbed energy by the laser induced spark
MIE	=	Minimum Ignition Energy
R	=	Radial distance of the ignition kernel from the nozzle tip
Re_{jet}	=	Methane jet Reynolds number
Re_λ	=	Turbulence Reynolds number based on the Taylor scale
U_{jet}	=	Methane jet velocity
Z	=	Axial distance of the ignition kernel from the nozzle tip

I. Introduction

Laser ignition is an alternative approach for the initiation of combustion. This approach has attracted interest in the aerospace industry due to a number of advantages over conventional sparkplug ignition, which include the ability to select and modify the ignition location during operation of an engine, the lack of the electrodes, which disturb the flow and can also cause cooling and quenching of the flame kernel, lack of physical presence of the ignitor in the flame, which can cause erosion, and the ability to ignite lean mixtures.

A number of ignition investigations have been performed in both premixed [1-5] and diffusion flames [6, 7] with the former type being more common. Minimum ignition energy (MIE) has been identified as an important parameter for ignition studies, which has a great dependence on mixture fraction and flow conditions around the ignition point. The influence of the mixture fraction on MIE has been studied extensively both in quiescent conditions [8-10] and

[1] Research Student, Department of Mechanical Engineering, c.chen16@imperial.ac.uk
[2] Research Associate, Department of Mechanical Engineering, georgios.charalampous@imperial.ac.uk.
[3] Professor, Department of Mechanical Engineering, y.hardalupas@imperial.ac.uk, AIAA Associate Fellow.

laminar premixed flows [11, 12]. The MIE was found to be the lowest at mixture fractions near stoichiometric and increase towards the lean and rich sides of stoichiometry. However, there are only few investigations into the influence of turbulence on laser ignition [4, 5, 13, 14]. Bradley et al. [13] investigated this influence in propane/air and isooctane/air mixtures in a isotropic turbulent environment, which was created in an combustion bomb by four variable-speed fans. It was observed that increasing RMS of turbulent velocity fluctuations narrows the flammability of the mixtures. Cardin et al. [4, 5] measured the MIE of lean methane/air mixtures in a premixed turbulent flow. Various grids were used in a wind-tunnel facility to create different levels of turbulence, which is isotropic and homogeneous. MIE was found to increase with the turbulent intensity and a transition in the increase was reported; MIE increases slightly with Re_λ at low turbulent intensities and increase linearly past a critical value of Re_λ. This behaviour was attributed to the relation between the characteristic chemical time scale and the time scale of the turbulence.

The influence of turbulence on laser ignition of a pulsed fuel jet (diffusion mode flame) has rarely been studied. A challenge in this case is to identify the contribution of the turbulent flow of the surroundings in isolation. An initial investigation in this direction was conducted by Sung et al. [14] in an environment of homogenous and isotropic turbulence without mean flow. The investigation examined the laser ignition of a pulsed methane with emphasis on the morphology of the flame and the MIE. It was found that the randomness of the flame luminosity increases with increasing surrounding turbulence and that MIE has a transition behaviour with turbulent intensity similar to the one reported in premixed flames [4, 5]. It was also reported that the critical Re_λ, where the transition happens increases with Re_{jet}. A limitation of that investigation was that the ignition location was fixed. Hence, the effect of the evolving local air-fuel ratio in the mixing layer of the fuel jet was not considered.

In the present study, the investigation of [14] is extended to consider the influence of the ignition location. Laser ignition was carried out at three different ignition locations in a pulsed methane jet. An environment of homogeneous and isotropic turbulence without mean flow was generated using a 'box of turbulence' facility. In this way, the combined effect of the ignition location and the surrounding turbulence on laser ignition can be examined.

II. Experimental Arrangement

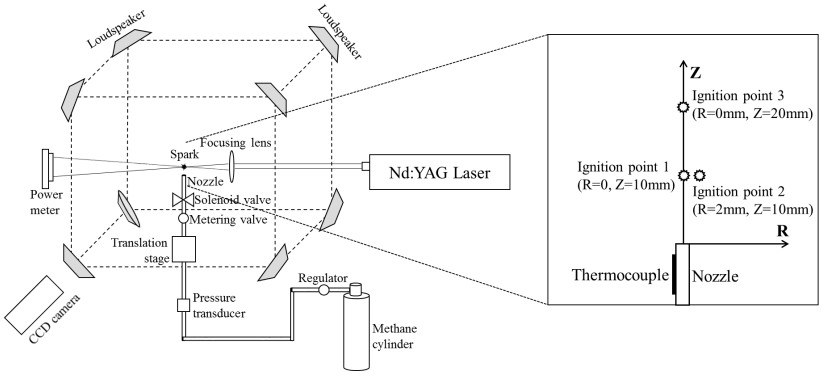


Figure 1 Schematic of the experimental setup

Figure 1 shows a schematic of the experimental setup. An environment of turbulent air was generated using a 'box of turbulence' facility [15, 16]. The facility is composed of 8 loudspeakers (Davis Acoustics, 20MC8A) located at the vertices of a cubical frame and pointing towards the cube centre; each loudspeaker is capped with a perforated plate of 55 circular holes 6 mm in diameter that are arranged in a triangular mesh pattern. The loudspeakers were driven independently at 50 Hz with sinusoidal voltages generated by an 8 channel National Instruments 16 bit PCI 6733 analogue output card and amplified by 4 stereo Behringer Europower EP2500 amplifiers. 8 sets of synthetic jet arrays were formed by the vibrating loudspeakers and interacted at the centre of the cube to create a volume of turbulence. By adjusting the amplitude of the driving signals, the turbulence was made to be homogenous and isotropic with a near zero mean flow component. PIV measurements of the flow field in the central region of the box of turbulence confirmed that the size of the homogeneous and isotropic region is about $40 \times 40 \times 40$ mm^3. Three levels of turbulence were considered which with the addition of the quiescent condition correspond to a range of turbulence Reynolds numbers of $Re_\lambda = 0$, 142, 195 and 220.

The methane jet was ejected in pulses within the environment of homogenous and isotropic turbulence from a circular stainless steel nozzle. The nozzle has an inner diameter of 2 mm and a lip thickness of 0.6 mm. The methane

injection was controlled by a solenoid valve (Series 9, Parker Hannifin) with a response time less than 5ms. The velocity of the methane jet was controlled by a pressure regulator together with a metering valve (S series, Swagelok); a digital pressure transducer (IND series, RS) was used to monitor the pressure in the pipe system. The fuel injection pressure was set at 0.27 bar and the resulting injection area-averaged velocity was set at U_{jet} = 1.34 m/s throughout the tests. The corresponding Reynolds number of the methane jet is Re_{jet} = 160. This was selected to maximise the interaction between the jet flow and the surrounding turbulence. The nozzle was mounted on a two-axis translation stage (composed of two Thorlabs PT1/M linear translation stages with 25 mm translation distance); the coordinate system for the translation of the nozzle is shown in Figure 1. A thermocouple was attached to the nozzle external surface to monitor the nozzle temperature during the ignition test.

The laser-induced spark was generated by focusing the laser beam from a 5ns pulse of the 2nd harmonic (532nm) of a New Wave Research Nd:YAG laser. A plano-convex lens (LA1131-A, Thorlabs) with a focal length of 50 mm was used and the volume of the energy deposition is about 79,000 μm^3. The incident energy of the laser beam (E_1) and the transmitted energy after the laser-induced spark (E_2) were measured with a laser power meter (FieldMaxII-TOP, Coherent) before and after the plasma spot, respectively; the absorbed energy (E_3) was estimated from the difference between E_1 and E_2. The location of the spark was fixed at the centre of the 'box of turbulence'. Therefore, the position of the nozzle was adjusted, so that ignition took place at different locations downstream of the nozzle tip. Three locations were considered in the test, denoted as point 1 (R = 0, Z = 10 mm), point 2 (R = 2 mm, Z = 10 mm) and point 3 (R = 0, Z = 20mm) using the RZ coordinate shown in Figure 1.

Imaging of the flame luminosity was performed using a PCO Sensicam QE CCD camera pointing perpendicular to the RZ plane in Figure 1. The camera resolution is 1024 × 1024 pixels and the size of the imaged region is 66mm × 66mm, which corresponds to a spatial resolution of 64.5 μm/pixel. This is sufficiently small to resolve the flame structure to a scale below the smallest Kolmogorov scale of the turbulence of this investigation.

For each ignition attempt, the solenoid valve was activated by a triggering signal 10 ms before the laser was fired and the injection duration was set at 100 ms. The CCD camera was activated 30 to 70 ms after the laser and the exposure time was set between 100 to 3000 μs. The camera delay time and exposure duration were adjusted depending on the ignition condition, because the flame behaviour was more random under turbulent conditions than at quiescent condition, making it more difficult to be captured by the camera. In order to estimate the ignition probability, 300 images were obtained at a fixed frequency of 1 Hz for each test case.

III. Results

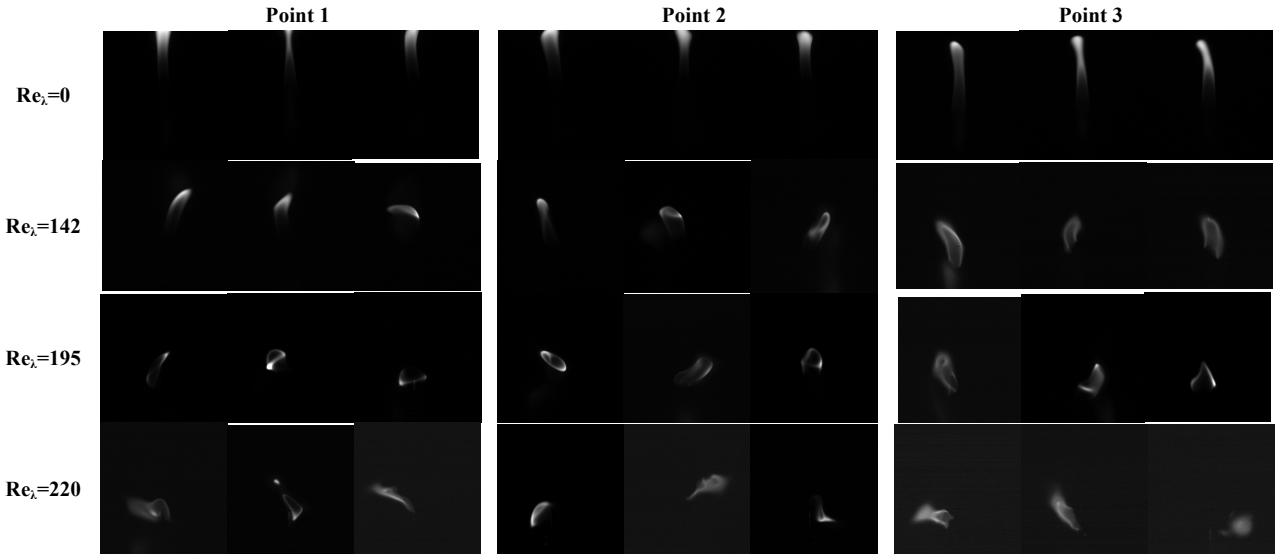


Figure 2 Examples of flame luminosity of ignited fuel jet for different ignition positions under various levels of turbulence. The ignition point can be seen at the top of the graph and the corresponding turbulent Reynolds number at the left hand side of the graph.

Some examples of the distribution of the flame luminosity are presented in Figure 2, for ignitions at three different locations across Re_λ between 0 and 220. It can be seen that, when the surrounding air is quiescent, the

ignited flame develops in a relatively axisymmetric way. When turbulence is introduced in the environment, the flame develops randomly and the randomness increases with Re_λ. The luminosity of the flame can vary greatly and while the general trend is for the flame to become less luminous with increasing Re_λ. However, the reverse is also possible, as it can be seen from some highly luminous flames at Re_λ= 195 and 220, showing the randomness introduced by turbulence. This randomness can also be seen from the temperature history of the nozzle during the ignition test, which is shown in Figure 3. The temperature was measured using a thermocouple under the highest laser energy output. In the case of quiescent air, the nozzle temperature increases rapidly and reaches a nearly steady state about 100 seconds after the start of an ignition test case. However, a considerable fluctuation is present in the temperature when the surrounding air is turbulent. This is attributed to the randomness in the flame position introduced by the turbulence. As can be seen from the first row of images in Figure 2, when turbulence is absent, the most intense part of the flame always appears at the top of the image, resulting in a nearly steady heat transfer rate from the flame to the nozzle. This heat transfer rate becomes unsteady under turbulence due to the random flame position; when the intense part of the flame develops at a shorter distance from the nozzle exit, the heat transfer rate increases and vice versa. The temperature history at point 3 under high level of turbulence (Re_λ= 195 and 220) is relatively different from others, as shown in Figure 3c. The low temperature under these conditions is caused by the low ignition probability, which will be discussed below.

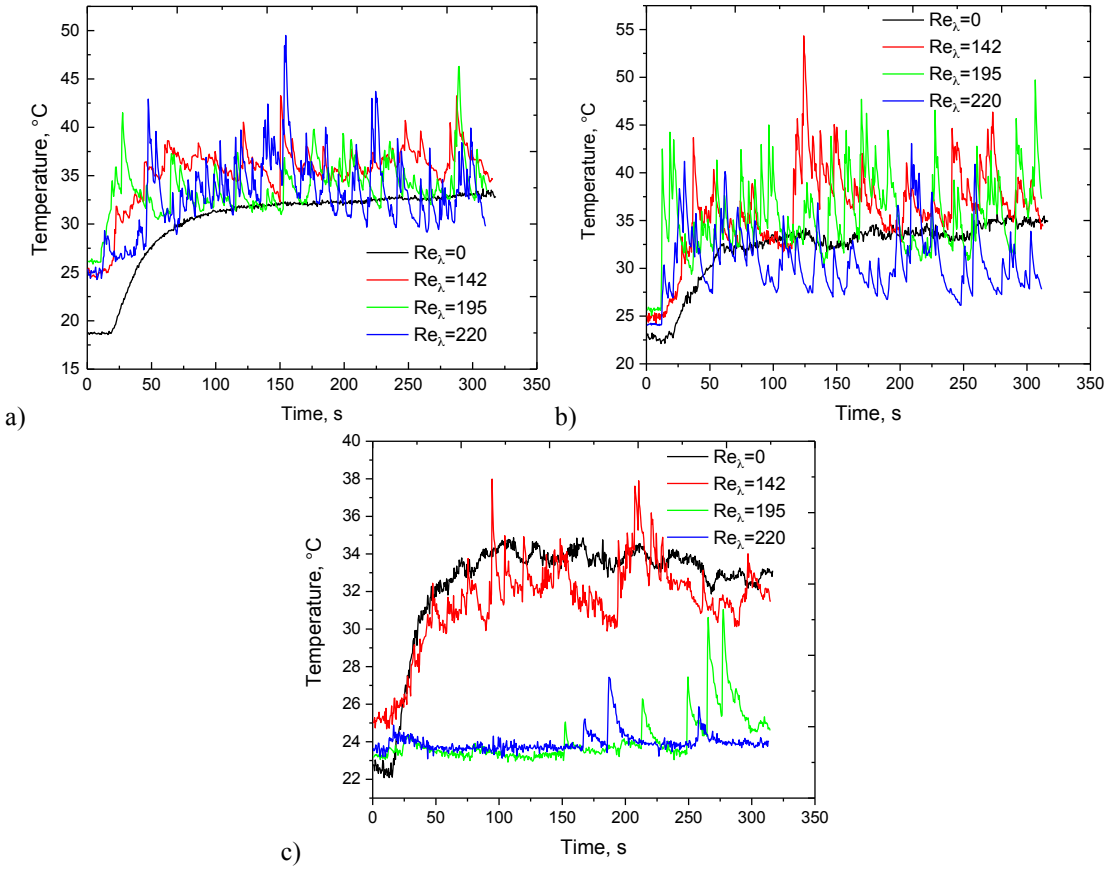


Figure 3 Temperature history of injection nozzle for different levels of turbulence at different ignition locations a) point 1; b) point 2 and c) point 3

For each test case, an ignition attempt was counted as successful when a self-sustained flame was obtained and ignition probability was defined as the percentage of the successful ignitions out of the 300 ignition attempts. The absorbed energy was estimated from the incident energy and transmitted energy of the laser beam as $E_3 = E_1 - E_2$. Figure 4 shows the effect of the ignition location on the ignition probability. Three ignition locations were examined under four levels of turbulence. Point 1 has the highest ignition probability in the whole range of absorbed energy under all levels of turbulence. Point 2 always has a higher ignition probability than point 3 at lower absorbed energy; this is also the case at higher absorbed energy when the turbulence is more intense, i.e., Re_λ = 195 and 220.

However, the ignition probability is roughly the same at higher absorbed energy for these two points with lower turbulence intensity, i.e., $Re_\lambda = 0$ and 142.

MIE is an important parameter for ignition studies. Following previous ignition studies [3, 5, 14], MIE is defined as the absorbed energy for which 50% ignition probability is obtained; it is generally estimated from the interpolation of absorbed energy at around 50% ignition probability, as shown in Figure 4. The effect of ignition location on MIE is similar to that on the ignition probability; under the same level of turbulence, MIE is lowest for point 1 and highest for point 3. It is worth noting that the highest ignition probability of point 2 at $Re_\lambda = 220$ and point 3 at $Re_\lambda = 192$ and 220 is lower than 50%, meaning that MIE at these cases cannot be determined. However, it is reasonable to assume that MIE of point 3 should be much higher than point 2 at these cases due to the much lower ignition probability at point 3 than point 2.

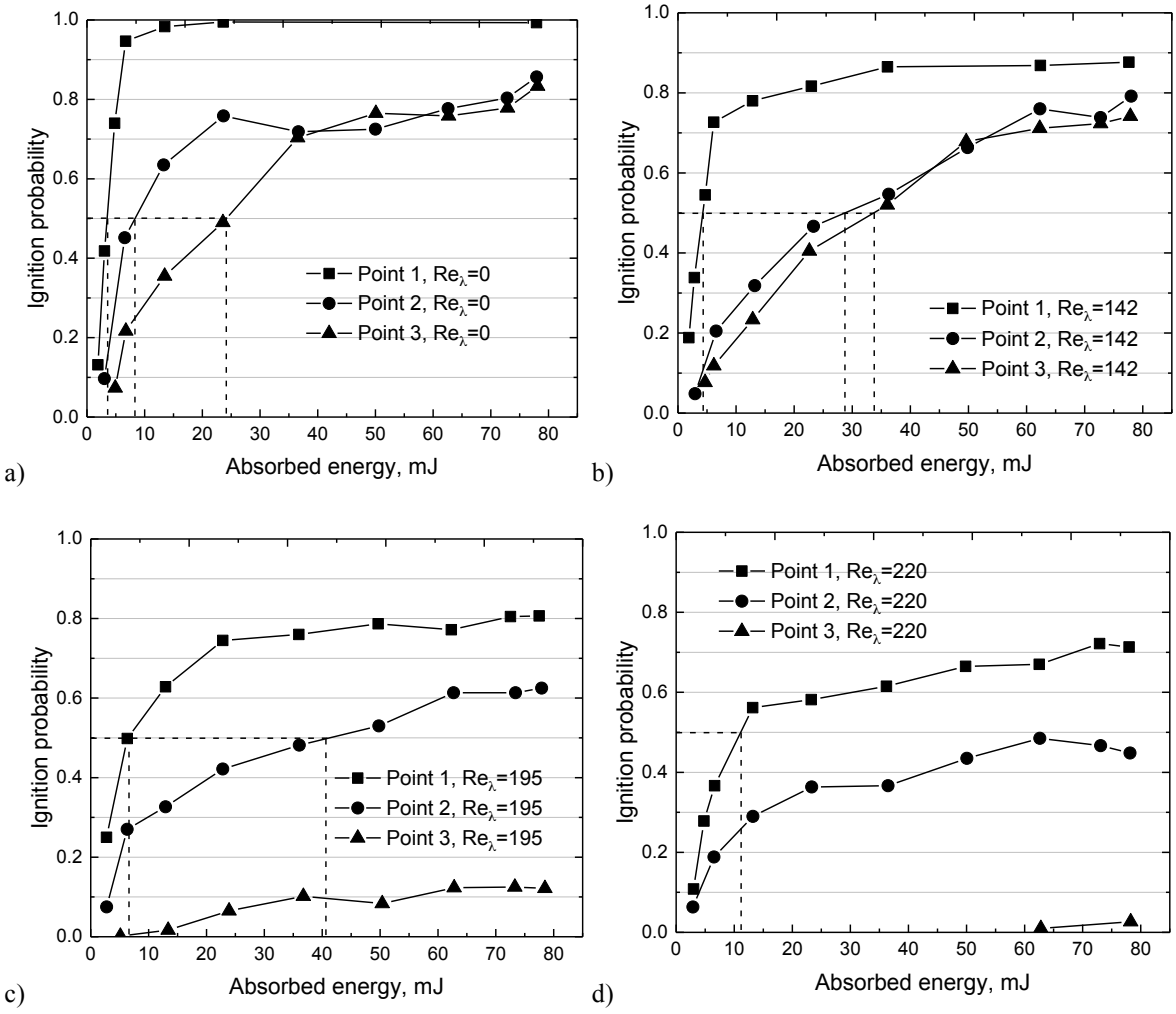


Figure 4 Ignition probability for different ignition positions for various levels of surrounding air turbulence a) $Re_\lambda = 0$; b) $Re_\lambda = 142$; c) $Re_\lambda = 195$ and d) $Re_\lambda = 220$

Previous ignition studies [8, 11] in premixed methane/air mixture have shown that MIE has a U-shape relation with equivalence ratio. This means the MIE is lowest for stoichiometric and near stoichiometric methane/air mixtures, but increases when the mixture becomes leaner or richer. A similar relationship between MIE and local equivalence ratio in a diffusion methane jet flame has been reported by [6]. In the present study, Point 1 is located on the centreline and 5 diameters downstream the nozzle exit, point 2 is located 1 diameter off the centreline and 5 diameters downstream the nozzle exit, while point 3 is located on the centreline and 10 diameters downstream the nozzle exit. According to the mixture fraction of a starting jet measured in [17], and considering the 10 ms delay between the injection and laser triggering signals of the present study, the local mixture fraction at point 1 should be much higher than stoichiometric, while the mixture at point 2 should be near stoichiometric. The local mixture

fraction at point 3 is expected to be in between points 1 and 2. This does not appear to be in agreement with the MIE results obtained from Figure 4. This discrepancy might be caused by the finite size of the plasma, which was measured to be about 1 mm long in the direction of the laser beam at 0.5 μs after the laser was fired. When the plasma centre is at point 1, since the jet width at this distance from the nozzle tip is about 2 to 3 nozzle diameters (i.e. 4 to 6 mm), it might expand to ignite the more flammable mixture near the jet/air interface, thereby leading to a high ignition probability and low MIE. A similar ignition probability result on the centreline near the nozzle exit was also observed in a fully established methane jet by T.X. Phuoc et al [6]. However, when the plasma centre is at point 2, which is already near the jet/air interface, about half of the plasma is located in the surrounding air side. This means that nearly half of the energy of the plasma has no contribution to the ignition, which results in a higher value of MIE than point 1. The effect of the plasma size is less significant at point 3, because the jet width is about 5 diameters (i.e. 10 mm); the key parameter for the ignition at this point is the mixture fraction, which is still much richer than at point 2, leading to a higher MIE.

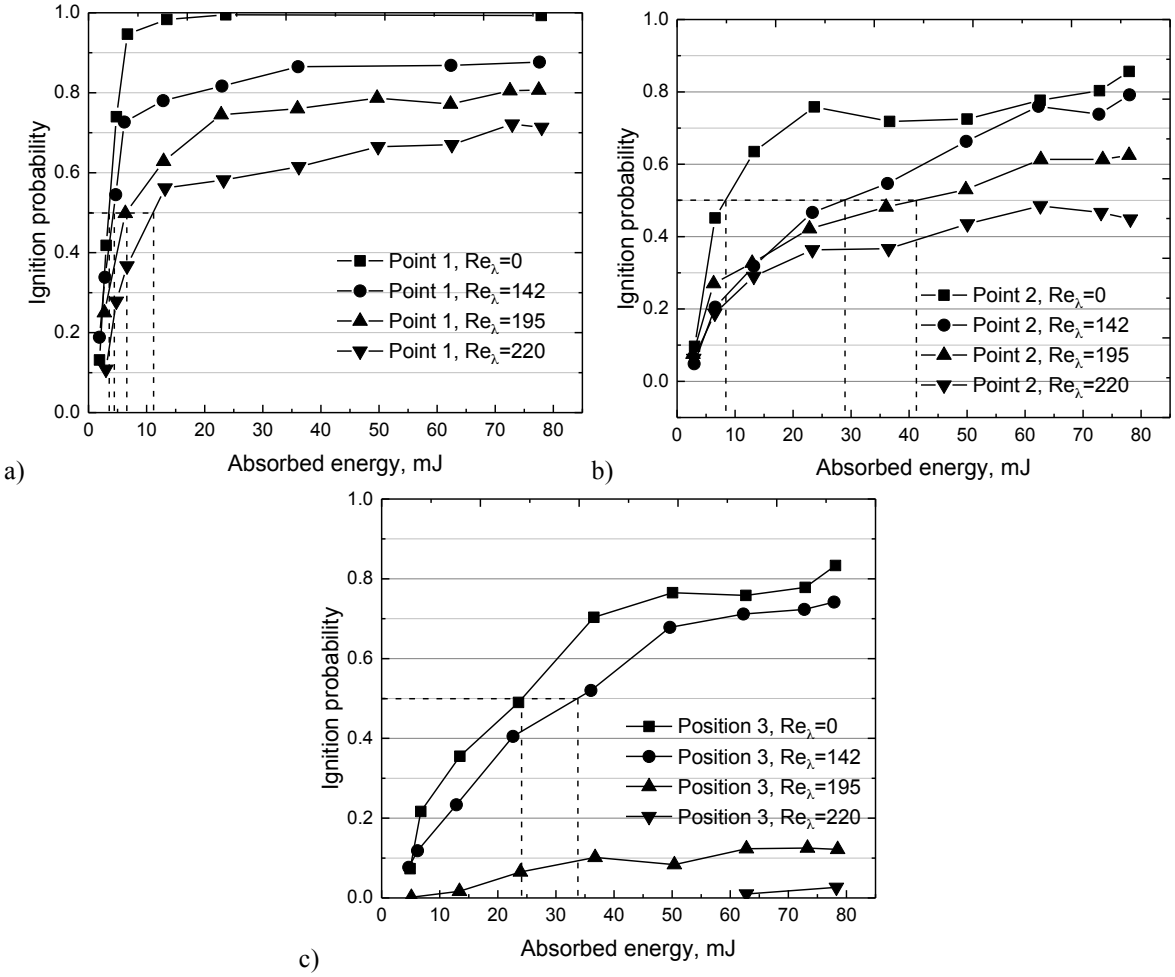


Figure 5 Ignition probability of the injected fuel jet for different levels of surrounding air turbulence for ignition location at a) point 1; b) point 2 and c) point 3

The influence of the level of turbulent in the surrounding air on the ignition was examined at the three ignition locations. The ignition probability results are shown in Figure 5. It can be found that the ignition probability decreases with increasing turbulent intensity, while MIE increases for all three points. This trend is in good agreement with previous results reported in [4, 5, 14] and it may be explained by the increasing scalar dissipation rate introduced at the ignition position by the surrounding air turbulence. The MIE values at different positions are plotted against Re_λ in Figure 6. It is interesting to note that, although MIE increases with turbulent intensity at all three points, the degree of the influence of turbulence is relatively different; the increase in MIE is more rapid at point 2 than at point 1, while the increase at point 3 is a bit slower than at point 2, when Re_λ is less than 142, but

much more rapid at higher turbulent intensity. At Re_λ = 220, nearly no ignition can be obtained even with the highest laser energy at point 3, while point 2 still has an ignition probability of about 50%.

When the surrounding air is quiescent, point 2 is located at the jet/air interface; when turbulence is present in the surrounding air, it introduces a significant fluctuation of the position of the jet/air interface. This leads to an increasing probability that the mixture at this position may become too lean or even pure air when the laser pulse is fired. Point 1 and point 3, however, are located on the centreline of the jet in the case of no surrounding turbulence. Therefore, even though turbulence can promote the entrainment of the surrounding air into the jet, it is more likely that a certain amount of methane is present at these two points than at point 2 when the laser pulse is fired. As a result, MIE at point 2 has a higher dependence on air turbulence than the other two points.

The dramatically high MIE at point 3 under more intense turbulence (Re_λ = 195 and 220) might be attributed to the low injection velocity of the methane jet. At higher turbulent intensity, the momentum of the methane jet dissipates more rapidly, resulting in a shorter penetration length of the jet. It is likely that the penetration lengths at Re_λ = 195 and 220 are shorter than the axial distance of point 3 from the nozzle exit. Therefore, only a relatively small amount of methane (at Re_λ = 195) or nearly no methane (at Re_λ = 220) can reach point 3, when the laser pulse is fired, which significantly reduces the ignition probability and leads to a substantial increase in MIE.

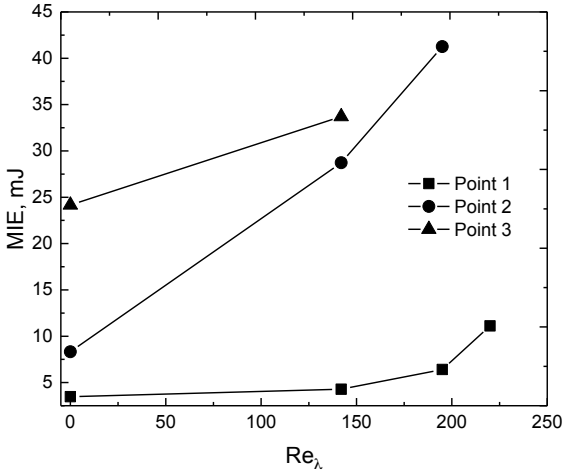


Figure 6 MIE for different ignition positions with various levels of surrounding air turbulence

IV. Conclusions

Laser ignition was investigated in a pulsed methane jet with a fixed injection velocity at three different ignition locations and a range of surrounding air turbulence (Re_λ= 0 - 220). The air turbulence was generated in a 'box of turbulence' and had homogeneous and isotropic characteristics without the presence of mean flow. MIE was evaluated under different ignition conditions by measuring the ignition probability with a wide range of laser energy. The main results are summarised as follows:

(1) Compared to the quiescent environment, the turbulent environment introduces substantial randomness in the propagation of the ignited flame and the randomness becomes more significant with increasing air turbulence levels. This randomness also leads to a great fluctuation of the nozzle temperature during the ignition tests, which occurs due to variations of heat transfer rate from the flame to the nozzle.

(2) Under all levels of turbulence, MIE is highest at point 3 and lowest at point 1, while point 2 is in between. The discrepancy between the MIE results and the local mixture fraction at these points might be caused by the finite size of the plasma, which is about 1 mm long at 0.5 μs after the incident laser. The plasma at point 1 may expand to ignite flammable mixtures near the mixing layer, while half of the plasma at point 2 is located in mixtures that are too lean to be ignited. The effect of plasma size is less significant at point 3 due to the larger fuel jet width.

(3) MIE increases with the intensity of the surrounding turbulence at all three points. The increase is less significant at point 1 than point 2. This is attributed to the influence of surrounding air turbulence on the local mixture fraction. The influence is more significant at point 2, since it is located near the jet/air interface, while point 1 is on the centreline. The dramatic increase in MIE at point 3 at higher levels of turbulence is caused by the substantial decrease in the penetration length of the pulsed fuel jet, leading to inadequate methane concentration at point 3 at the time of ignition.

In the future, more ignition locations will be examined to obtain a spatial distribution of MIE under various levels of surrounding air turbulence. Instantaneous spatial distributions of the mixture fraction will be measured

using planar laser induced fluorescence (PLIF) technique, and its correlation with MIE distribution will be investigated.

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