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Review and Validation of the current Smoke Plume Entrainment Models for Large-Volume Buildings

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Abstract:

The design of smoke management systems in large-volume enclosures is of utter importance for life safety, property protection, and business continuity in case of fire. Despite the recent international trend in smoke control design towards the use of advanced fire models, simple plume entrainment correlations are the basis of the discipline and are still a common practice since they are often incorporated in technical documents for the design of smoke control systems. Different plume entrainment correlations have been developed over the years and are cited in different national codes and design guides. These correlations have been widely investigated for fires in small enclosures, but their applicability and accuracy in large enclosures is not clear. The present work studies the suitability and applicability of these approaches to properly predict the fire induced conditions within large volumes. The results obtained from the plume entrainment correlations have been compared with full scale experimental data in an 8.000 m^3 enclosure. Based on the results obtained by this analysis performed in a large-volume enclosure, the current methods available of modelling fire and determining the smoke produced by the fire might not be suitable. It was observed that for the steady state, the McCaffrey correlation gave results closest to the experiments, and for the transient evolution of the smoke layer, the Zukoski correlation. On the contrary, the popular Thomas method underpredicted smoke production and entrainment, giving the highest smoke layer interface heights and leading to estimations that are not conservative (with errors between 36.5% and 101%). The authors analyze the reasons for the discrepancies and give some practical recommendations for the design of smoke control in large volume buildings, such as that the use of such models to predict the smoke production of a given fire shall be only a first approximation and not a design tool, especially when using those models that have not shown a good match to the experimental data.

Nomenclature Listing

$\dot{m}$	Mass flow rate (kg/s)
g	Acceleration due to gravity (m/s^2)
Q	Energy (kJ)
$\dot{Q}$	Energy Released rate (kW)
A	Area (m²)
D	Fire diameter (m)
h, z	Distance measured vertically from floor to the bottom of layer of hot gases (m)
L	Flame height (m)
c_p	Specific heat (kJ/kg·K)
r	Distance (m)
T	Temperature (°C or K)
ρ	Density (kg/m^3)
Θ	Temperature above ambient
HRR	Heat Release Rate (kW)
P	Fire perimeter (m)

Subscripts

∞	Ambient
b	Plane of the bottom of layer of hot gasses
c	Convective
h	Plane of flat ceiling or the horizontal plane through the centre of the vent in a pitched roof
e	Entrained air
f	Fire
fl	Flame
min	Minimum
max	Maximum
P	Into the plume
y	Distance above the floor

1 Introduction

1.1 Smoke management in large-volume enclosures

Smoke management in large-volume enclosures pose separate and distinct challenges from well-compartmented spaces. A large-volume space is an uncompartmented space, generally two or more stories in height, within which smoke from a fire either in the space or in a communicating space can move and accumulate without restriction[1].

Without physical barriers, smoke propagation is unimpeded, spreading easily throughout the entire space. The tall ceiling heights in many large-volume spaces create additional challenges in terms of substantial quantities of smoke production and delayed detection times.

When a fire takes place in large-volume enclosures the smoke can travel along vertical distances, affecting multiple floors simultaneously and threatening life safety of occupants far away from the fire origin [2]. Detection, control and extinction of fires in large volumes differ significantly from those in small enclosures.

The distinctive features of large-volume spaces, such as large volume and height, can also be considered as a positive feature. Firstly, due to the increased volume of the smoke reservoir the time necessary to fill the compartment with smoke is prolonged, and the smoke layer is diluted. Dilution reduces the level of hazard posed by the smoke. Secondly, due to the available height of the space, less resources might be required to maintain the smoke layer at a tenable height. Finally, due to the typical occupancy of such spaces, the fire threat is limited, although this may not be the case in atria, hotel lobbies and similar spaces, in which large temporary gathering of combustible materials can occur (commercial stands, festive decorations, gathering of luggage, etc.). In large-volume spaces such as warehouses, airports, stations, etc., there is an increasing need of maintaining very large compartments without physical barriers, often due to operational requirements.

The design of the smoke management in large-volume enclosures is of utter importance for life safety, property protection, fire brigade access and business continuity. Despite its importance and the increasing use of CFD models, the design is often performed using basic formulas. Those basic formulas, presented in national codes and design guides, are currently used to design the number of smoke reservoirs, the smoke exhausting system, the makeup air, etc., because it is frequently assumed that the rationale behind the quantification of the prescriptive requirements embedded in building codes is based on previous ''good practices'' and partial empirical evidence [3]. However, the use of these basic formulae in atria or large-scale construction projects should be carefully examined, as it has not been demonstrated that such specifications in existing codes are supported by systematic research with experimental justifications [4]. Simple correlations should be used only as a first order approximation, helping to the final design in terms of preliminary values and reducing the cost of a more detailed approach. In fact, fire engineers in a building design process should start with an initial assessment using simple methods and gradually continue with the use of more complex methods [5]. For example, the use of performance-based fire engineering design approaches is now a common practice in many jurisdictions. Nevertheless, in some countries, authorities having jurisdiction tend to prefer this simplified approach to a more complex design through advanced fluid dynamics models since local codes legally authorized those simplified methods. Yet many regulatory authorities are slow to reach the level of competence needed to assess new design approaches, which implies an inability to assess non-prescriptive designs and resulting in refusal to approve engineered designs. Unfortunately, this is leading designers to move away from more specific methods like performance-based designs and going back to prescribed criteria[6] .

1.2 Smoke control design and Plume models

Engineers have a number of options available for evaluating the performance of a smoke management system and, depending on the jurisdiction, different design guides are used. The methods indicated in codes and design guides are usually empirical entrainment correlations, most of them originated from the plume theory of Yih [7], Morton et al. [8], and Yokoi [9]. This theory was improved through full-scale and reduced-scale fire experiments, which will be further described in section 2. The plume models are included in zone models, and their time-integrated form did cause an emergence of lumped-parameter hand calculation models, that will also be addressed in section 2. Summary of the research and practical recommendation on use of plume models can be found in [10].

Further development of simple mathematical correlations describing the flow of smoke did include the interaction of the plume and the building features, in form of adhered plumes [2,11–13], window plumes [14], and balcony spill plumes [15–20]. A thorough review of literature referring to complex flow of smoke in buildings can be found in [21].

The most popular and used parameters used in the description of the flow of smoke in a thermal plume are: height of the plume (z, h), which is assumed to correspond with the height of smoke free layer, mass flow of the smoke in the plume ($\dot{m}_p$), and the temperature of the smoke in the plume (T_p), which is sometimes presented as the difference between ambient and plume temperature (θ). Some plume correlations use the values of flame height (L) or virtual point of origin (z_o) in order to account for flame region entrainment, which differs from the entrainment into the plume.

Plume models are often incorporated in technical documents for the design of smoke control systems, as a useful tool to dimension the system. Some of these documents are design guidelines or recommendations, and some of them are national guides that are considered the only one valid in a given country.

It may happen that the same engineer needs to make similar calculations in different countries encountering a non-homogenous approach to the smoke modelling. Given the fact that every country has its history and traditions, methods used in one country may be questioned by authorities in another. As a result, there is not a single plume model used universally. Nevertheless, the most popular plume models used in design are the so-called Thomas (section 2.2) and Heskestad (section 2.2) plumes. A summary of the approaches used in a wide range of chosen countries is shown in Table 1.

Table 1. Plume models used in chosen codes and design guidelines

Code or design guide	Type	Country of origin	Plume entrainment correlations (relevant section of the paper)
NFPA 92 [1]	national code	USA	Heskestad (2.5)
EN 12101-5 [22]	international code	EU	Thomas (2.2) and Heskestad (2.5)
TM19 [23]	design guideline	UK	Heskestad (2.5) Thomas (2.2) as an alternative
NBS S21-208-1 [24]	national code	Belgium	Thomas (2.2)
BRE 368 [25]	design guideline	Europe	Thomas (2.2) Zukoski (2.3)
BS 5588-7 [26]	design guideline	UK	Redirect to BS EN 12101-5 [22]
BS 9999:2017 [27]	national code	UK	Redirect to BS EN 12101-5 [22]
AS 1668.3-2001 [28]	national code	Australia	Thomas (2.2)
Handbook of Smoke Control Eng. [30]	design guideline	USA	Heskestad (2.5)

More advanced approaches include time-integration of the plume equation, in order to obtain the smoke layer height in the compartment as a function of time [25,31]. Despite the dominant role of CFD calculations in modern design process, zone models are still a valuable tool [5], and they are widely used for specific uses that lie within the limits of the empirical correlations on which they are based – such as the design of nuclear power facilities [32], warehouses (applying the empirical correlations to single smoke reservoirs), different types of atria, stadiums, etc.

Zone models [33] are simple models that divide the considered fire compartments into distinct gas zones (upper and lower layers), where the condition in each zone is assumed to be uniform. The theoretical background of zone models is the conservation of mass and energy in fire compartments. After the ignition, the fire plume as a source of energy and mass is formed. It acts as a "pump" of mass from the lower zone to the upper zone [10,34]. The zone modelling of compartment fires is more detailed, compared to that in parametric fires and time equivalence methods. As zone models were designed to enable transient evaluation of fire in a single (or series of) enclosure, they use time-integration of plume equations to predict the parameters of smoke layer in a prescribed domain. In many of the models available it is possible to choose different plume entrainment correlations (Table 2), e.g. Heskestad and McCaffrey in CFAST, Heskestad, McCaffrey, Thomas and Zukoski in Ozone, and McCaffrey and Delichatsios in BRANZFIRE. This flexibility of zone models results in a great variety of results that not always help to find the right answer for a given scenario. A comprehensive review of zone modelling of fire may be found in [35,36].

A comparison of the plume correlations used in the chosen zone models is shown in Table 2.

Table 2. Plume correlations used in some important zone models

Model	Author	Country	Plume entrainment correlations (relevant section of the paper)
CFAST [37]	NIST	USA	Heskestad (2.5) McCaffrey (2.4) – *removed in v7.0.0. (2015)*
Ozone [38]	University of Liège	Belgium	Thomas (2.2) Zukoski (2.3) McCaffrey (2.4) Heskestad (2.5)
BRANZFIRE [39]	Branz	New Zealand	McCaffrey(2.4) Delichatsios (--)
B-RISK [40]	Branz	New Zealand	McCaffrey (2.4) Heskestad (2.5)

Comparison of plume correlations and of some design approaches in which they are implemented were widely reported in the literature, e.g. [31,41–45]. Despite the profuse amount of studies, only few compare the modelling approaches with large-scale fire experiments, mainly due to the lack of high-quality experimental data. Large-scale fire experiments are essential in order to properly validate numerical models, given the fact that those models (in this context the algebraic formulas) are normally the results of scaled experiments or experiments performed with particular conditions and extremely small fires. This paper presents results of several large-scale fire experiments, with HRR varying from 1.43 MW up to 2.3 MW, under different exhaust flow rates and make-up air supply configurations, with the smoke layer interface as the main result reported in this paper, both for the experimental and numerical analysis.

The aim of this paper is to compare the commonly used plume models (Section 2) with two sets of large-scale experiments [46,47] performed in the Fire Atrium of the Centro Tecnológico del Metal (CTM) facility in Murcia, Spain. A description of the facility and experiments is shown in Section 3, whilst results and discussion are shown in Sections 4-5.

2 Plume entrainment correlations

In the following sections, the most relevant plume entrainment correlations will be presented and discussed, including how the convective HRR fraction is treated in them and how the time integrated approach was used in determining the smoke filling. A direct comparison between these models is difficult (when possible) due to the underlying theory behind them and the different treatment of important variables, such as heat release rate or the smoke layer interface height. Also, these methods were validated with different experiments and in different scales, and have different assumptions, which define their area of applicability. In case of large-volume enclosures, the differences in the treatment of layer height, which can also be considered as the difference in the calculation of air entrainment into the plume, can be very significant. This is why the authors decided to pursue the validation of the described methods with a large-scale experiment.

2.1 Introduction

The buoyant axis-symmetric plume, caused by a diffusion flame formed above burning fuel, is the most commonly used plume in fire safety engineering. An axis of symmetry is assumed to exist along the vertical centerline of the plume, and air is entrained horizontally from all directions [44,48]. The assumption of central symmetry of the plume requires no sources of disturbance of the plume, such as walls, non-uniform fire source or flow of air nearby the plume. Considering Cetegen et al. [49,50], the experiments behind the fire plume theory were done in the quiet atmosphere of the laboratory, and that small ambient disturbances could provide a great (20-50%) increase in the measured plume mass flows. Such conditions may be met only in laboratory, where the experimental chamber is symmetric, and the sources of disturbance are under control. Moreover, in the design of smoke control systems in atria perfect plume symmetry may be difficult to achieve. However, in some cases where the air inlets are sufficiently large and do not generate strong/long streams of air and the potential fire sources are located far away from walls, the plume symmetry is achievable and in such conditions the spatial location of the plume in the compartment will not affect the dimensioning of smoke control system [51].

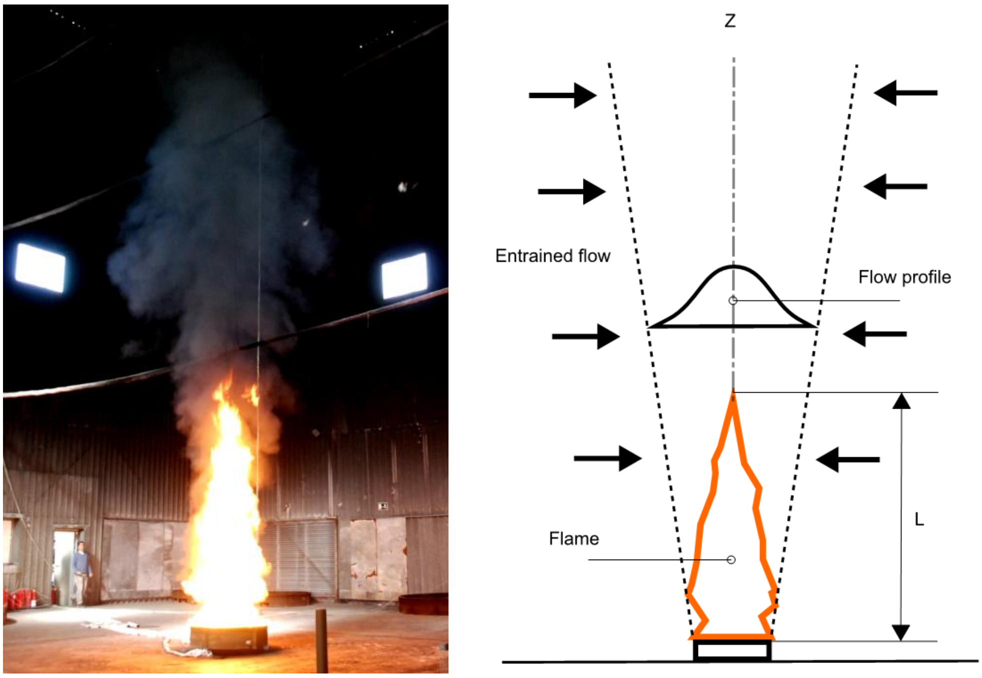


Figure 1. – Photo of the fire plume in one of the GX experiments (1a) and analytical representation of the fire plume (1b).

The first mathematical models of axis-symmetric buoyant plumes in fire are attributed to the work of Morton et. al. [8], who often refers to earlier studies by Yih [7]. In this work, three main assumptions were defined: (i) the rate of entrainment at the edge of plume is proportional to characteristic velocity at given height; (ii) the velocity profiles of mean vertical velocity (and buoyant forces) are similar at horizontal sections in different heights; (iii) the local variations of density are small, compared to the difference between average density of plume and surroundings. These assumptions were transferred to all further models of plumes, based on the theory of Morton et. al. Furthermore, the model by Morton et. al. assumed a point of line source, and conservation of mass, momentum and heat.

2.2 **Thomas plume** [41]

One of the most widely adopted and cited plume models is the so-called Thomas plume model. The origin of the model widely adopted in practical design, (eq. 4) is usually mistakenly attributed to the *Fire Research Technical Paper No. 7 (1963)* [52], while it was developed in the further work of its authors, reported for example by Hinkley [41].

The Thomas plume model can be considered as a landmark in the smoke flow theory. Thomas did use buoyancy considerations in scaled fires, to correlate the characteristic height dimension, velocity and the temperature of the plume to the Energy Released Rate (Q). This technique is commonly used in modern fire safety engineering, and known as Froude-number based scale modelling [33,53]. However, in the work of Thomas the Froude number of the fire was not calculated explicitly. The base of the mathematical model presented by Thomas, was the work of Yih [7] and Bernoulli's theorem. The fire was assumed as a source of plume (point source), and the hot layer underneath the ceiling was considered as stagnant, and thermally uniform. An equilibrium between the smoke incoming to the layer, and removed through natural vents, was assumed. From these boundary data, the depth of the layer of hot gasses could be estimated, as well as the temperature and the rates of flow.

This plume theory is applicable to plumes where $\frac{\Theta}{T_\infty} \ll 1$, and that density of air in plume is constant at the chosen height. This theory also requires the use of virtual source point, at a distance r_y below the floor.

$$r_y \cong 1.5A_f^{1/2} \quad (1)$$

$$r_b = r_y + h_c - D_b \quad (2)$$

The use of this is only possible for plumes at heights that are large compared with $A_f^{0.5}$. This means that the base of the smoke layer is at a height several times greater than $A_f^{0.5}$, which is possible if $z >> D$. The error of the method increases with $A_f^{0.5} / r_b$. Knowing the virtual origin, mass flow in the layer may be calculated with equation (3).

$$\dot{m}_p = 0.043\ \rho_c r_b^{\frac{5}{2}} \left(\frac{2g\Theta}{T_0}\right)^{\frac{1}{2}} \quad (3)$$

The original work of Thomas did focus on the performance on natural ventilation of compartment, and the methods used to design such systems, and it was further improved by Hinkley [41]. The form commonly used in design standards has only two variables – the perimeter of the fire (P) and the height of the layer above the seat of fire (z) (4).

$$\dot{m}_p = 0.188\ \mathrm{P}\ z^{3/2} \quad (4)$$

Hinkley verified the equation (4) against a series of full scale experiments, with the most important being the work of Keough [54]. The parameter space of the experiments discussed by Hinkley included compartments with height of 0.70 – 15 m, fires from 8 kW to 30 MW, and heat output per unit area in range 250 – 630 kW/m² (in Keough experiments the convective heat output was greater, up to 1800 kW/m²). The mass of smoke in the plume was in good agreement with the equation (4), however it was noted that Heskestad's model may be better for fires with small height and large heat release per unit area. This validation work was used as the justification to use equation (4) in smoke control design. As Hinkley pointed, despite the purely empirical nature of this equation, its validity has been established for the parameter space described above.

2.3 **Zukoski plume** [34]

The work of Zukoski et al. [34] focused on obtaining a correlation for axisymmetric plumes in the far field. The experiments assumed that the mass flow in the plume $\dot{m}_p$ consists of a mass flow pyrolyzed by fire $\dot{m}_f$, entrained air $\dot{m}_E$, and recirculation at the area where the plume enters the layer, $\dot{m}_1$. They also considered that additional mass flow can occur at the interface between hot layer and cold air, referred as $\dot{m}_2$. Therefore, by maintaining the smoke layer at the height of the hood, the measurement of the mass of smoke removed through the hood allowed the direct measurement of total mass flow in plume. These results were further correlated into a mathematical model by Cetegen et. al. [50]. By using ideal plume theory, the results of Zukoski can be approximated into equation (5) [44].

$$\dot{m}_p = 0.21\ \left(\frac{\rho_\infty^2 g}{c_p\ T_\infty}\right)^{1/3} \dot{Q}^{1/3} z^{5/3} \quad (5)$$

This equation is also commonly shown in the form below where the ambient air properties are assumed to be T_∞ = 293 K, ρ_∞ = 1.1 kg/m^3, c_p = 1.0 kJ/kg·K and g = 9.81 m/s².

$$\dot{m}_p = 0.071\ \dot{Q}^{1/3} (z)^{5/3} \quad (6)$$

2.4 McCaffrey plume [55]

McCaffrey used experimental data and dimensional analysis to obtain plume correlations for upward velocity and temperature [56]. He divided the plume into three regions, the continuous flame region, the intermittent region, and the plume, where he found the next expression for $\dot{m}_p$. The boundaries between the distinct regions are:

- $\frac{z}{\dot{Q}^{0.4}} < 0.08$ for the flame region;
- $0.08 < \frac{z}{\dot{Q}^{0.4}} < 0.20$ for the intermittent region;
- $0.20 < \frac{z}{\dot{Q}^{0.4}}$ in the plume region.

The corresponding mass flow calculations are given in equations (7), (8) and (9) [57].

$$\dot{m}_p = 0.011\,\dot{Q}\left(\frac{z}{\dot{Q}^{0.4}}\right)^{0.566} \text{ for } 0 < \frac{z}{\dot{Q}^{0.4}} < 0.08 \tag{7}$$

$$\dot{m}_p = 0.026\,\dot{Q}\left(\frac{z}{\dot{Q}^{0.4}}\right)^{0.909} \text{ for } 0.08 < \frac{z}{\dot{Q}^{0.4}} < 0.20 \tag{8}$$

$$\dot{m}_p = 0.124\,\dot{Q}\left(\frac{z}{\dot{Q}^{0.4}}\right)^{1.895} \text{ for } 0.20 < \frac{z}{\dot{Q}^{0.4}} \tag{9}$$

The model was derived based on reduced scale experiments for fires with heat release rates varying between 14.4kW and 57.5 kW. McCaffrey reports that to obtain valid data for modelling a time-averaged approach had to be used, through integration for a time of 100 s. This mean that if one compares the model (averaged) results to results of CFD (instantaneous), large discrepancies may be noted. Further discussion on the time-averaging approaches used in plume modelling can be found in [56]. Moreover, some disagreements between the approach of McCaffrey and earlier plume theory can be found in [58].

McCaffrey plume was used as one of the plume correlations in the zone model CFAST [37]. However, it was recently replaced by Heskestad's model. Karlsson and Quintiere reported [44] that for both plume temperatures and velocities the McCaffrey approach will give results roughly 10% higher than those by Heskestad.

2.5 Heskestad plume [59]

Heskestad, in his paper [43], compared existing plume models based on the theory of Yih [7], Thomas et al., Cetegen et al., with entrainment predictions for strong plumes, that assume profiles for velocity and temperature rise (density). The theory was later refined with the use of flame height correlation [59] (10):

$$L_{fl} = 0.235\,\dot{Q}^{2/5} - 1.02D \tag{10}$$

A summary of Heskestad's assumptions with respect to the ideal plume theory of Morton [8] is given in [44], with the main changes:

- The point source assumption is relaxed by introducing a "virtual origin" at height z_0 [60] (11). Also, account will be taken of the fact that some plume properties depend on the convective energy release rate, $\dot{Q}_c$.

$$z_0 = 0.083\,\dot{Q}_c^{2/5} - 1.02D \tag{11}$$

- The "top hat" profiles across the plume for velocity and temperature will be replaced by a more realistic Gaussian profile.
- The Boussinesq approximation ($\rho_\infty \approx \rho$) is removed.

The plume mass flow rate above the flame height ($z > L_{fl}$,) is given by [61] (12):

$$\dot{m}_p = 0.071\,\dot{Q}_c^{1/3}(z - z_0)^{5/3} + 1.92\,10^{-3}\dot{Q}_c \tag{12}$$

Finally, the plume mass flow rate below or at the flame height ($z < L_{fl}$,) is given by (13):

$$\dot{m}_p = 0.0056\, \dot{Q}_c \left(\frac{z}{L_{fl}}\right) \quad (13)$$

2.6 Treatment of the convective HRR

Depending on the plume correlation, the total ($\dot{Q}$) or convective fraction ($\dot{Q}_C$) of the heat release rate (HRR) needs to be provided. A summary of the needed HRR is shown in Table 3.

Table 3. Inputs in different plume theories.

Approach	$\dot{Q}$ (total)	$\dot{Q}_c$ (convective)
Zukoski	YES	NO
McCaffrey	YES	NO
Heskestad	NO*	YES
Thomas	NO**	NO**

(*) In Heskestad's model, the total HRR is used only when estimating the mean flame height and the position of the virtual origin, (**) Thomas' formulae does not use the HRR as an input

As can be seen , the Zukoski's model requires the total HRR (this can be explained by the origins of his theory, based on work of Yih [7] and Morton[8], and the ideal plume theory). In Heskestad's model, the total HRR is used only when estimating the mean flame height and the position of the virtual origin. When estimating the other plume properties – such as the air plume entrainment – the convective energy release rate needs to be used. McCaffrey includes the convective fraction already into the formula, so the total HRR, $\dot{Q}$, must be used. In the Thomas' formulae, the HRR is not used, as the user defines only the fire perimeter/diameter. However, the user must be aware of the model limitations, explained in section 2.2.

According to [44] the energy losses due to radiation from flames are typically in the order of 20% to 40% of the total energy release rate. The higher values represent the sootier and more luminous flames. For the calculations with Heskestad model in this paper, a radiation value of 20% was assumed.

2.7 Time integrated approach

Smoke filling is a transient process, and as such the environmental conditions inside the protected space will vary in space and time. This process can be integrated in time with the use of a lumped-parameter mathematical model [62]. The investigation of these parameters as a function of time may be of importance when the Available and the Required Safe Egress Times (ASET vs RSET) are compared to determine the safety of the building [63]. The concept of time-integrated solution was presented in the past, e.g. by Morgan et al. [25] and Wu and Chen [31].

There are two parameters for which the time integration is used and are important to this paper – (i) the smoke layer interface height and (ii) the smoke production.

The smoke layer interface height may be calculated using a time integration approach. As the volume of the atrium and the mechanical volumetric exhaust are constant in time, the smoke that enters the reservoir causes a descent of the layer proportional to the difference between the volume of smoke that enters the layer and that is removed from it. This parameter was investigated in the experimental comparison presented in this paper.

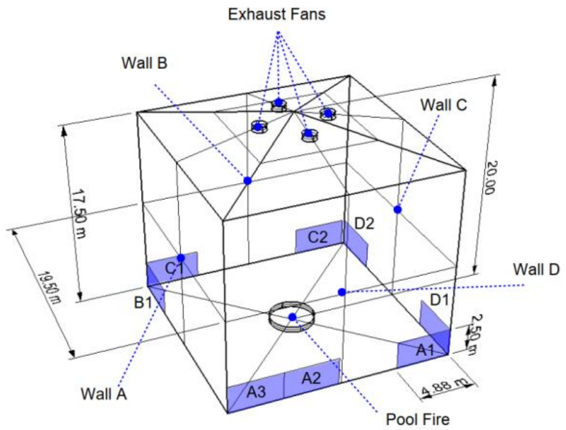
For the smoke production integration, the HRR of the fire is replaced with an unsteady function, out of which the most widely used is a parabolic curve known as a *t-squared fire*. *T-squared* fires are defined through fire growth rate coefficient α [kW/s²] and the time of their growth. The standardized growth rates are described by NFPA 92 [1] and are widely used in various fire protection engineering applications [64,65]. The change in HRR = f(t) will also cause a change in the diameter of the fire (if HRR per unit of area is assumed constant) or the change of HRR per unit of area (if the diameter of fire is assumed constant). The effects of these changes to the plume model were discussed in [31].

3 Full scale validation experiments

In order to validate the aforementioned plume entrainment correlations [41],[34],[55],[59], several large-scale fire experiments, with HRR varying from 1.43 MW up to 2.3 MW under different exhaust flow rates and make-up air supply configurations have been performed.

3.1 Experiments setup

The experimental facility that has been used to perform the fire experiments is the Fire Atrium of the Centro Tecnológico del Metal (CTM), in Murcia, Spain, Fig. 2. The Fire Atrium characteristics make this the ideal and unique facility for this kind of research. This section provides a summary of [46,66,67].



(a) (b)

Figure 2. – Geometry (2a) and Photo (2b) of the Fire Atrium of the Centro Tecnológico del Metal, Murcia, Spain.

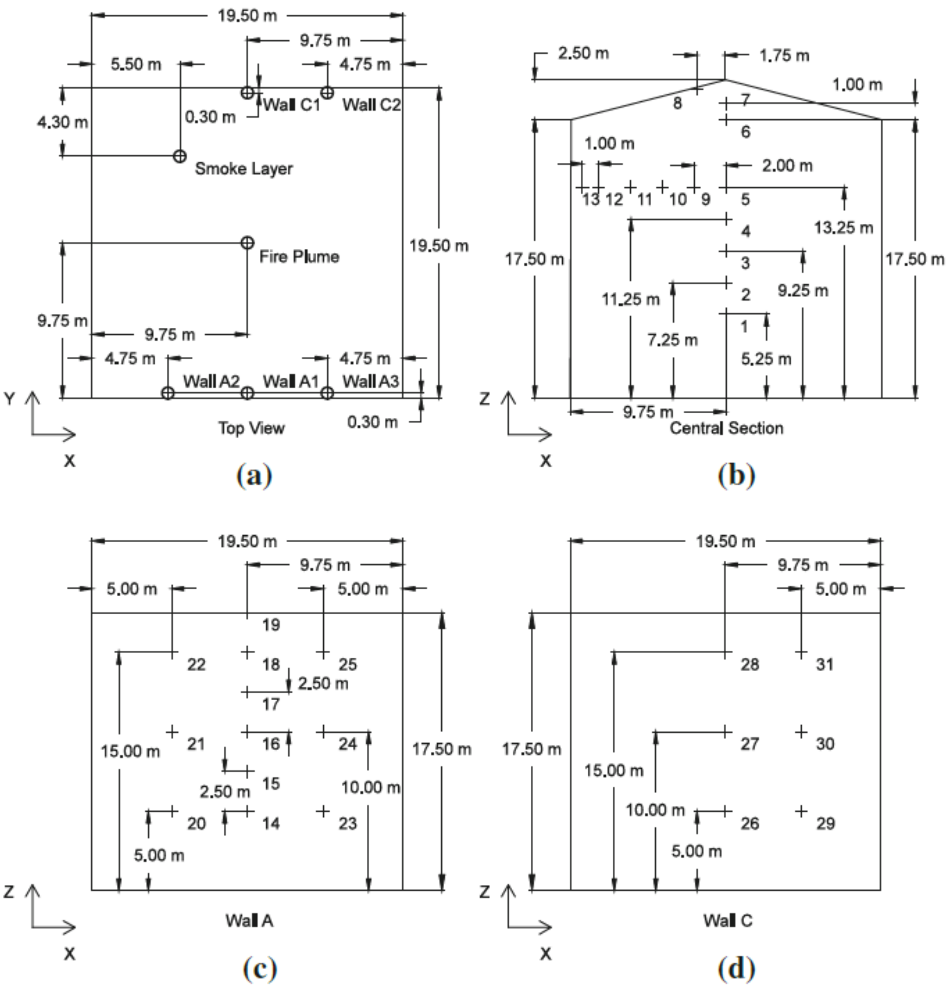


Figure 3. Thermocouple layout on the atrium. (a) thermocouple tree locations, (b) central section, (c) at 30 cm from wall A and (d) at 30 cm from wall C [66].

The Murcia Fire Atrium is a full-scale facility consisting of a prismatic structure of 19.5 m x 19.5 m x 17.5 m and a pyramidal roof raised 2.5 m at the center. The walls and roof are made of 6 mm thick steel sheets whilst the floor is made of concrete. The atrium is provided with four exhaust fans installed on the roof. For the make up air, there are eight identical grilled vents arranged at the lower parts of the walls whose dimensions are 4.88 x 2.5 m^2. They can be partially or fully opened, or completely closed. The fire experiments used in the present analysis have been carried out in four different periods. Among these experiments, six experiments have been chosen in which ventilation conditions, pan diameter, ambient conditions and HRR were similar.

The burning fuel was heptane contained in circular steel pans placed at the center of the atrium floor. In all experiments, a layer of 2 cm of water was added to the pan before the heptane was poured to insulate the metal from the burning pool heat, thus providing a more stable steady burning regime. At the end of each experiment the volume of water was measured again to confirm that no water had been lost. Each pool size showed a different burning time proportional to the initial volume of fuel in the pan. A fully description of the experiments can be found in [46,66,67].

The atrium was equipped with temperature, pressure and velocity sensors, in order to study the thermal and flow fields induced by the fire. Up to 61 sensors have been installed. Measurements of walls and roof metal temperature, and air temperature at several locations (next to the walls, at a central section, through the exhaust fans and through the inlet vents) were recorded. Differential and absolute pressure sensors at the exhaust fans have been also installed to check from the fan performance curves the mass and volume flow rate evacuated.

3.2 First series of experiments [67]

Several experiments have been performed by C. Gutierrez-Montes et. al [67]. Three of them have been studied (referred further as experiments #M1-3), having all the same pan diameters of 0.92 m (therefore similarity in HRR), filled with n-heptane and with the same extract rate and similar overall ambient conditions.

The smoke layer interface was extrapolated from the vertical temperature profiles using the N-percent method [68]. The smoke layer interface was then identified as the position where the temperature rise dropped to N % of the maximum temperature rise. In large-volume spaces with a relatively small fire, temperature rise of smoke is relatively low. Therefore, the smoke layer interface was determined at the position where the temperature rise started to be larger than 30% of the highest temperature rise along the vertical direction. A summary of the experimental data utilized in this analysis can be found in the table 4.

Table 4 – Summary of laboratory and ambient conditions during the set of fire experiments #MX

Parameter	#M1	#M2	#M3
Pool diameter (m)	0.92	0.92	0.92
Pool area (m²)	0.665	0.665	0.665
Fuel volume (l)	44	52	52
Burning time (s)	837	883	1094
Extract rate (m^3/s)	15.2	15.2	15.2
Temperature (ºC)	16.7	28.9	27.5
Pressure (mbar)	1018	1008	1007
Calculated average HRR (MW)	1.58	1.77	1.43
Open vents	A1,A3,C1,C2	A1,A3,C1,C2	A1,A3,C1,C2
Free Area of Open Vents (m²)	48.8 (4x12.2)	48.8 (4x12.2)	48.8 (4x12.2)
HRRPUA (kW/m²)	2377	2661	2150

3.3 Second series of experiments [47]

Several experiments were performed later in the same facility, out of which three were chosen as relevant to this study based on the size of fire and ventilation conditions (referred further as experiments #G1-3). In these experiments the source of fire were pans filled with n-heptane in two dimensions – 0.92 m and 1.17 m.

The smoke layer interface was determined using the Least Square Method through the thermocouple tree place in the atrium as part of the instrumentation [47,69]. A summary of the experimental data utilized in this analysis can be found in the table 5.

The atrium was equipped with a total of 59 thermocouples distributed at different positions to assess the smoke temperature in the fire plume as well as close to the walls. Additionally, three load cells were installed under the pool fire to measure the mass loss rate and determine the HRR of the fire.

Table 5 – Summary of laboratory and ambient conditions during the set of fire experiments in #GX

Parameter	#G1	#G2	#G3
Pool diameter (m)	1.17	0.92	1.17
Fuel volume (l)	36.5	28.8	36.5
Burning time (s)	647	708	671
Extract rate (m^3/s)	18.3	18.3	18.3
Temperature (°C)	18	20.1	18
Pressure (mbar)	1016	1016	1016
Calculated average HRR (MW)	2.30	1.70	2.30
Open vents	A1,A3,C1,C2	A1,C1	A1,A3,C1,C5
Free Area of Open Vents (m^2)	48.8 (4x12.2)	48.8 (4x12.2)	48.8 (4x12.2)
HRRPUA (kW/m^2)	2199	2559	2199

4 Results and discussion

In this section, the main experimental and numerical results are presented and discussed. Initially, the different phases of the smoke filling are discussed in order to get a correct interpretation of what is subsequently presented. Finally, a discussion of the results together with the impact of them on the design are presented.

As the discussion is based on the smoke layer interface height, it is important to define how this has been evaluated. The models estimate how much smoke is traveling into the smoke reservoir and based on that an assessment of the smoke control performance is performed. We consider that if a model predicts that the smoke layer interface is higher than it was in the experiment, it is an over-prediction. On the other side, if a model predicts a smoke layer interface lower than it was in the experiment, it is considered as under-prediction.

For each presented experiment, relevant important parameters (such as heat release rate and exhaust fan flow rate) were accordingly fed into the analytical models. For the Heskestads' model an additional assumption was that the radiative fraction of HRR is 20% (see chapter 2.6). For Thomas model, two different scenarios have been analyzed – one in which the fire perimeter is equal to the perimeter of the pan used in the experiment, and one in which the fire perimeter is calculated based on the value of HRRPUA = 1000 kW/m². Further discussion on the impact of HRRPUA in Thomas approach is presented in section 4.4.

4.1 Interpretation of the results

All of the performed experiments show similar smoke-layer behavior in relation to the change of layer height Z = f(t). In the early phase of the experiment (first 200 s – 300 s) the layer interface was changing, but after that time it stabilized and remained in roughly the same place until the end of the fire. This behavior can be simplified into two distinct regimes – a transient regime (when the layer height is changing as the compartment is filling up with smoke), and steady state phase, where a state of equilibrium is reached between a steady source of fire and the steady state exhaust. As the layer height will fluctuate through the fire, the transition between transient to steady state phase is blurred. For the purpose of comparison of the methods, the authors chose that after 300 s of the experiment, the layer may be considered as "steady-state". The illustration of these two regimes is shown on Fig.4, through an example.

As the experimental results were compared to time-integrated smoke plume formulae, it is possible to assess their validity separately for both regimes – the time-dependent smoke filling phase, and the stabilized layer phase (which corresponds to the minimum layer height obtained with steady-state formulae).

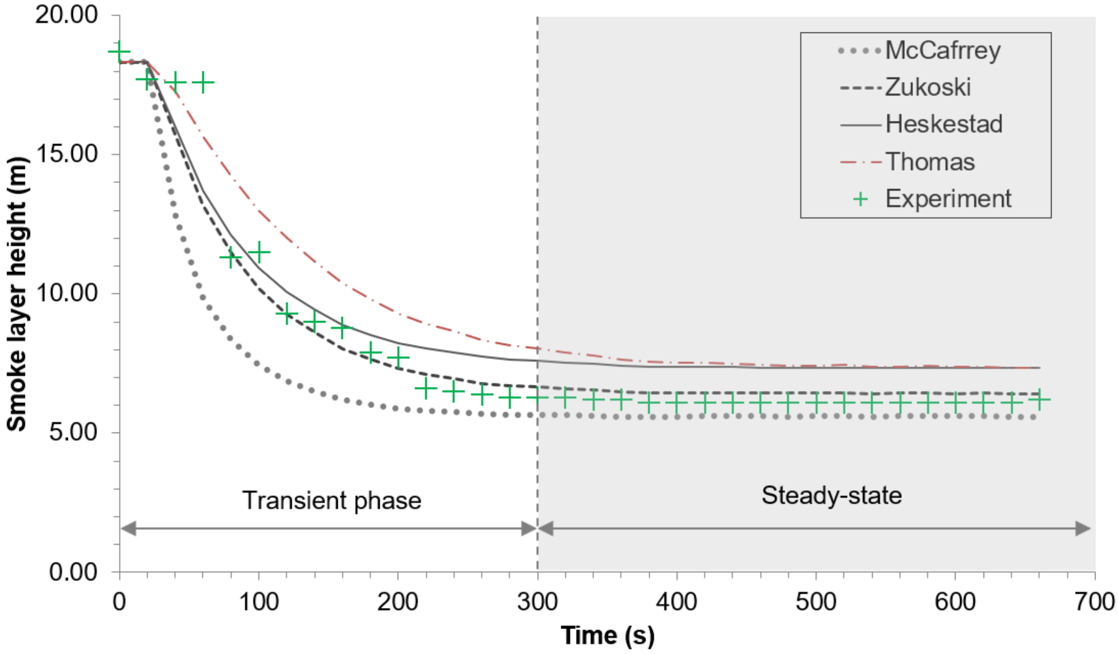


Figure 4. Example of the results of the smoke layer height measurements from experiment and hand calculations with visible regimes of transient and steady-state phases.

4.2 First series of experiments

As shown in Table 2 the first series of experiments employed 0.92 m diameter pan with 44 – 52 l of n-Heptane. These yielded fire sizes between 1.43 – 1.77 MW. As the experimental data relevant to the layer interface height is limited for this series, the comparison between experiment and analytical methods is possible only in a limited scope. Due to scarcity of data in the transient phase, the evolution of the layer height in experiment may not be precisely determined. The points presented on Fig. 5 – 7 represent the time values in which the smoke layer interface reached values of respectively 15, 10 and 5 m in each of the experiments. However, the results of the calculation of the transient analytical methods may be compared with the time values from the experiment. Also, as the last measured point in #M2 and #M3 can be considered as within the steady-state regime, these results may be compared with the respective steady state predictions of analytical models. It must be noted, that for this comparison the N30% method was chosen, based on [68] and the discussion presented in [67].

In the transient phase of the layer development in all of the experiments, the McCaffrey, Zukoski and Heskestad models predict the layer lower than it was estimated in the experiment (in relevant points in time). The Thomas model predicted the layer height at similar levels for the 15 m measurement point. For the 10 m measurement point the Thomas model with 1000 kW/m² did yield a value close to the experiment, however for the 5 m measurement point both calculations with Thomas model were significantly off.

Based on the measurements with the thermocouple tree with the N30% method, the final layer height was estimated as close to 5 m above the floor. The time to reach this point in experiments #M2 and #M3 was sufficient to assume this height is reflecting the steady-state phase and could be compared with the results of analytical modelling. Based on the data from these experiments, the McCaffrey model did yield the closest value of smoke layer height, followed by Zukoski and

Heskestad. Prediction of the Thomas model was significantly different from the results of the experiment and predictions of other models. The discussion of the significant discrepancy between the Thomas model and the experiment is given in Chapter 4.4.

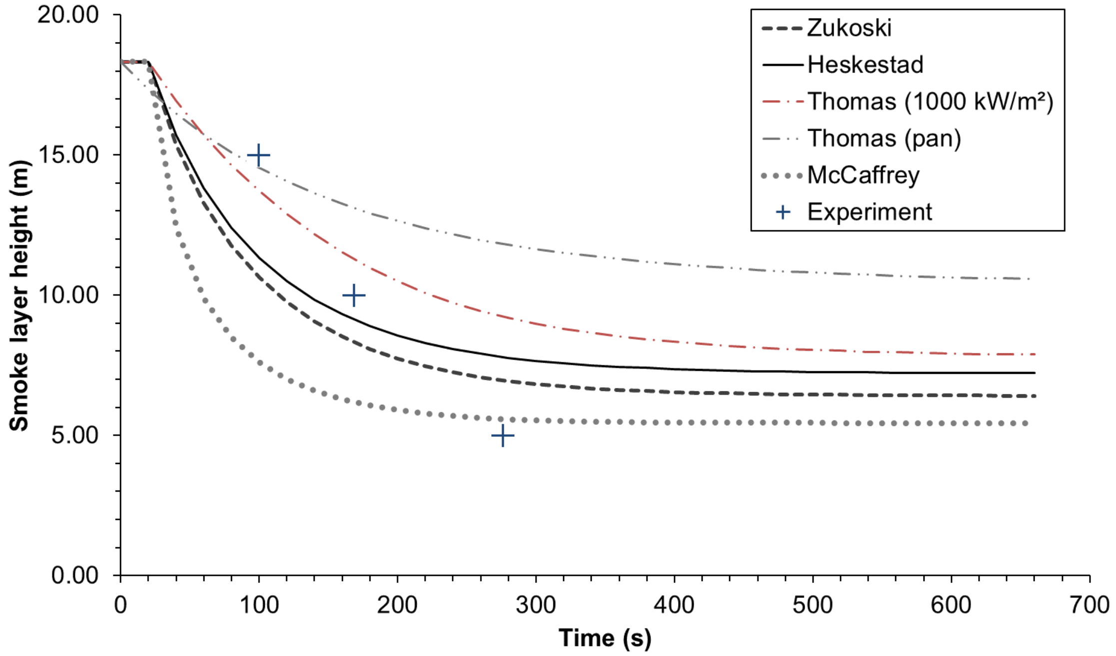


Figure 5. Measured (30 N% method) and predicted smoke layer interface height for experiment #M1

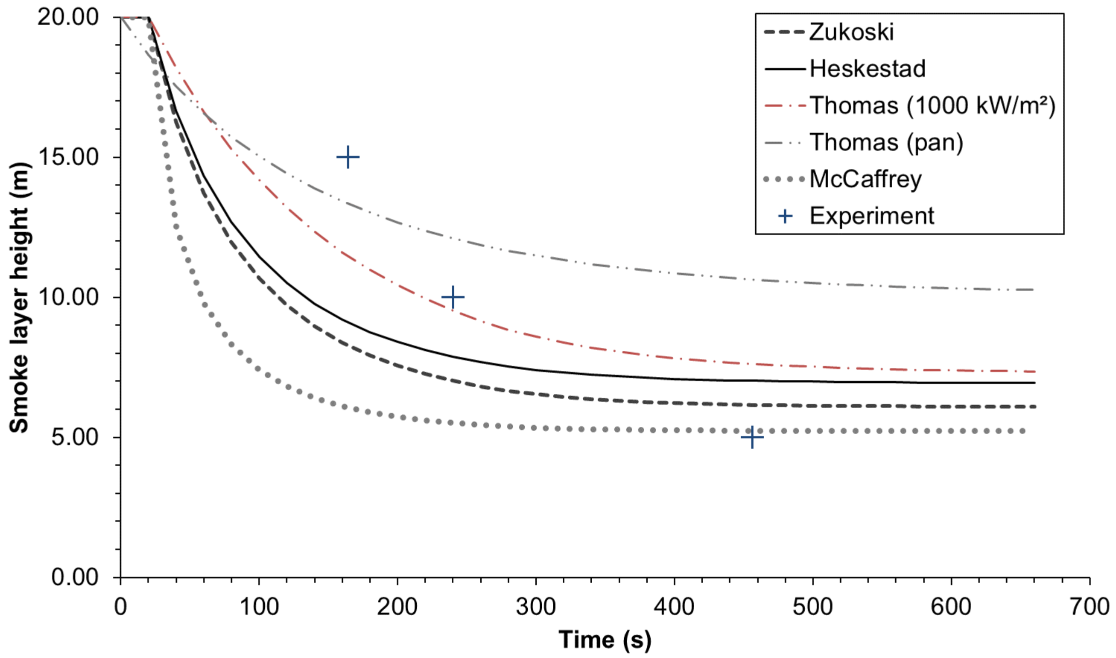


Figure 6. Measured (30 N% method) and predicted smoke layer interface height for experiment #M2

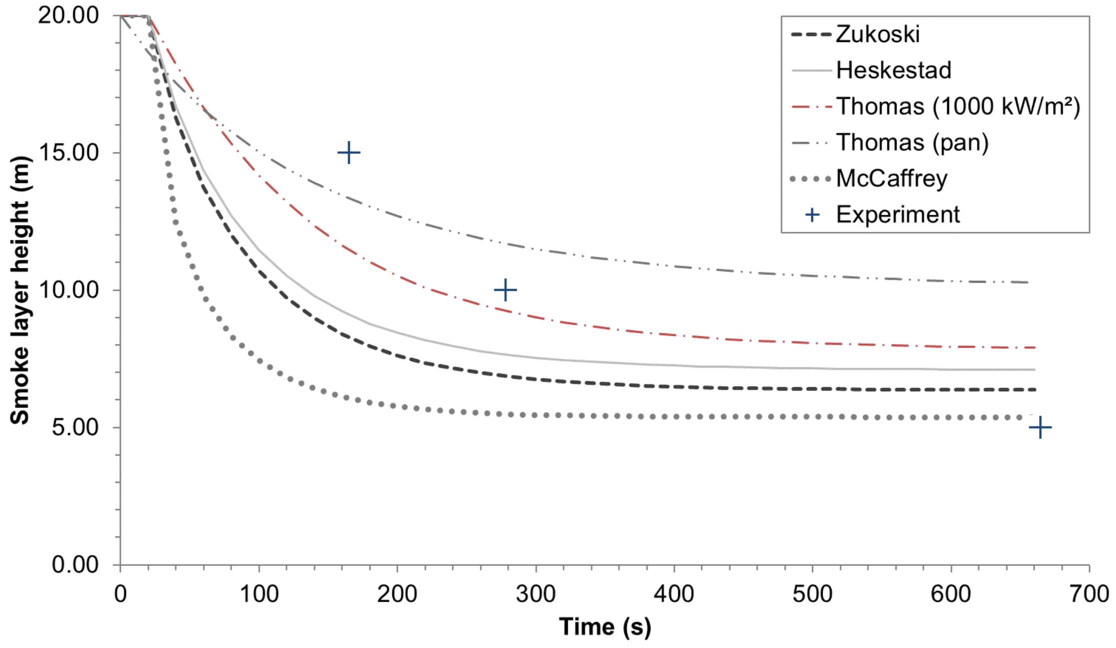


Figure 7. Measured (30 N% method) and predicted smoke layer interface height for experiment #M3

4.3 Second series of experiments

The temporal resolution of measurements in the second series of experiments were significantly improved compared to the first series. This allowed for more detailed analysis of the transient phase of the smoke layer evolution in the atrium. Another improvement over the first series was the use of least-squares method for the definition of the layer boundary with discussion on this choice presented in [47]. The fires used in the experiments and the exhaust ventilation rates were comparable with these in series one. However, due to these changes in the data processing, the results of both experiments should be analysed separately.

Analysing the temporal evolution of the layer height, it may be noted that the Zukoski and Heskestad models yielded the results closest to the experiments. In the transient phase, the McCaffrey model yielded a lower layer height and Thomas model yielded higher layer height compared to the measurements in the experiments. It should be also noted that the McCaffrey model predicted the quickest decay of the layer. The steady state phase was reached between 220 – 260 s, while other models and the experiment showed a state of equilibrium between plume and smoke exhaust after approx. 260 – 320 s.

To compare the steady-state results, the layer height measured or calculated between 300 and 600 s was averaged with respect to time, and detailed results are presented in Table 6. In the steady state phase of the experiments the Zukoski model was the closest in the prediction of layer height in experiment #G1, and the McCaffrey model in experiments #G2 and #G3. The worst predictions were obtained with Thomas model, with relative error to the experimental results ranging from 36.5% to 101%.

Table 6 – Comparison of the average layer height for different experiments and calculation methods

Model	#G1		#G2		#G3	
	Height [m]	Relative error vs exp. [%]	Height [m]	Relative error vs exp. [%]	Height [m]	Relative error vs exp. [%]
Experiment	6.13		6.08		5.75	
Zukoski	6.47	**5.5%**	7.13	17.2%	6.62	15.1%
Heskestad	7.40	20.5%	8.15	34%	7.48	30%
Thomas (HRRPUA=1000 kW/m²)	9.67	57.7%	8.90	46.3%	7.85	36.5%
Thomas (P = pan perimeter)	10.43	70.1%	12.23	101%	10.43	81.3%
McCaffrey	5.61	-8.4%	5.96	**-1.9%**	5.69	**-1%**

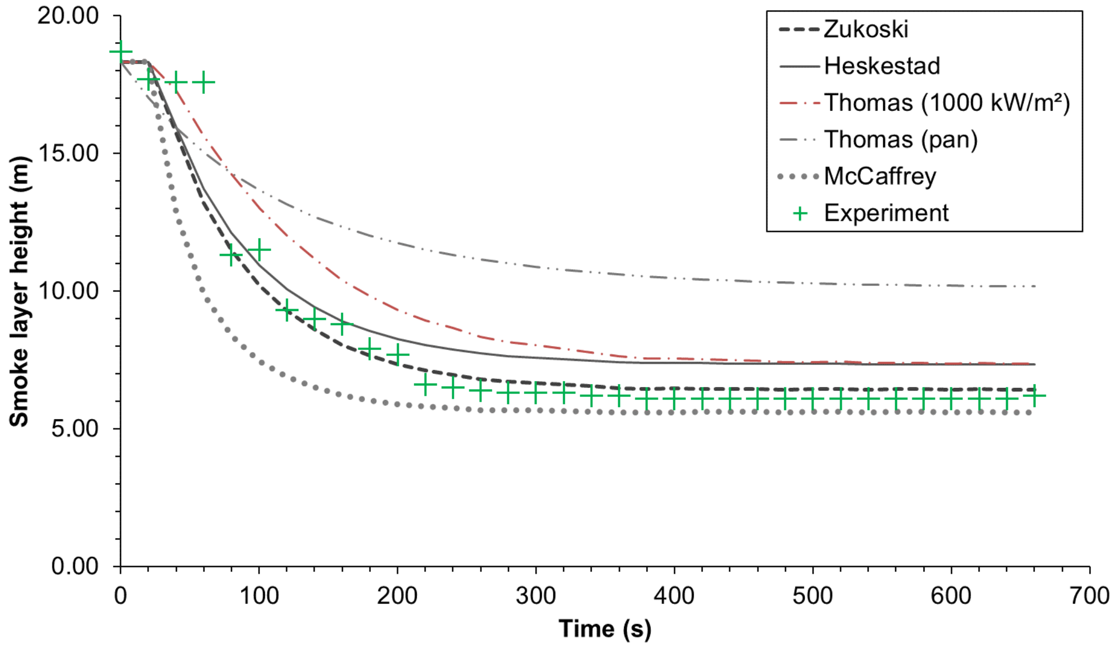


Figure 8. Measured (Least-Squared method) and predicted smoke layer interface height for experiment #G1

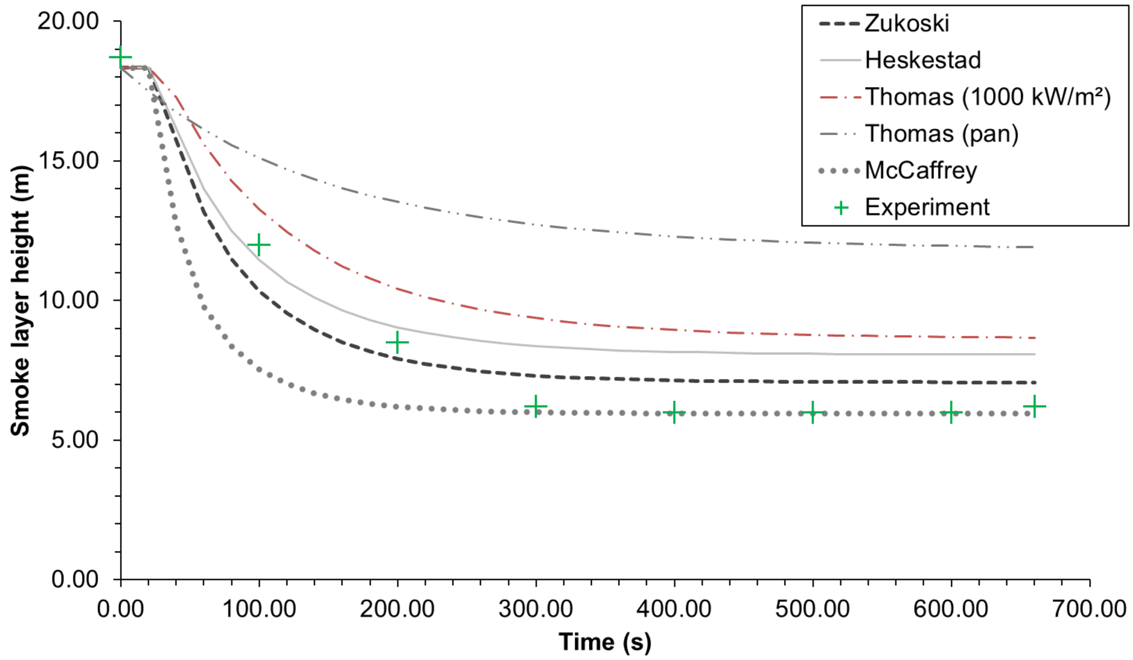


Figure 9. Measured (Least-Squared method) and predicted smoke layer interface height for experiment #G2

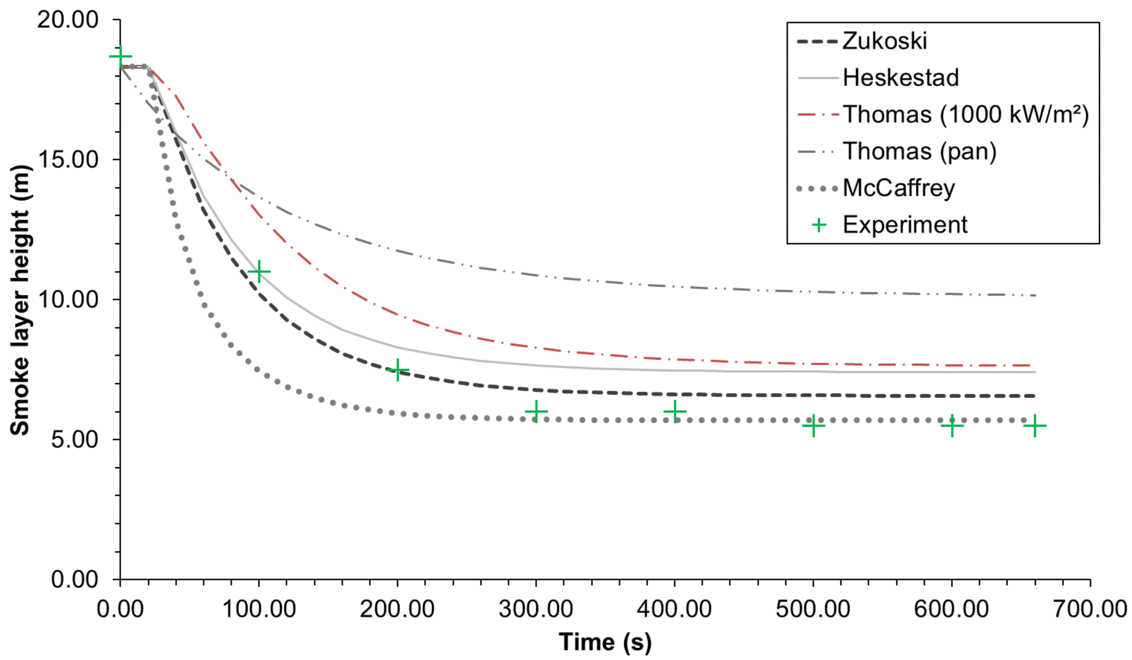


Figure 10. Measured (Least-Squared method) and predicted smoke layer interface height for experiment #G3

4.4 Discussion of the results

In the six fire scenarios analyzed, the McCaffrey approach is the one that best fits the experimental data in the steady state phase, while the Zukoski model gives the best results in the transient phase. However, it may be argued that the transient evolution of the layer is used less in engineering practice since the steady state value is used in designing the smoke control systems and thus, based on the results shown - the McCaffrey model was the better overall solution.

An important observation of the study is that in all of the experiments the Thomas model produced results significantly different from the experimental data, with errors up to 101%. As this model is widely used in Europe and Australia for the design of smoke control systems in atria (see Table 1), the observed discrepancies between measurements and model must be further discussed. Authors attribute them mainly to how the fire is introduced into the model (through only the fire perimeter). The fuel used in the experiments was n-heptane, which is known to have high values of Heat Release Rate per Unit of Area, due to its high Heat of Combustion. The perimeters of the pans used in the experiments were 2.89 m (for D = 0.92) and 3.67 m (for D = 1.17 m). The measured HRRPUA in the experiments varied between 2140 kW/m² (#G1) and 3.190 kW/m² (#M2), while the Thomas model was widely validated by Hinkley in a range between 225 kW/m² and 625 kW/m².

Since one of the main assumptions for the use of the Thomas approach is that the fire flames are considerably smaller than the diameter, this needs further investigation. One of the most used equations to calculate the mean flame height, L_{fl} is presented by Heskestad [10] which provides good results for the different flame regime, except for the jet flame regime. The equation gives the mean flame height as a function of energy release rate and diameter:

$$L_{fl} = 0.235\, \dot{Q}^{2/5} - 1.02D \qquad (14)$$

Where the heat release rate is given in kilowatts (kW) and the diameter given in meters (m), resulting in the mean flame height in meters.

Although the Heskestad's equation is shown [10,59] to be reliable to calculate the mean flame height, there is a lack of experimental data where the mean flame height is significantly smaller than the fuel source diameter, D. Thomas found that in the continuous flame region or in the near field the plume mass flow rate was more or less independent of the energy release rate and more a function of the diameter of the fire, D, and the height above the fire source, z. This has been found to be particularly valid for fires where the mean flame height is considerably smaller than the diameter [16].

A brief analysis has been done for typical design fires used in fire engineering (involving cellulosic and/or plastic materials). For localized fires it is very unlikely to have a design fire where the diameter is significantly larger than the flame height, since the HRRPUA is usually higher than 1000 kW/m^2. Figure 11 shows the relationship between mean flame height and diameter for a 1000 kW fire using the Heskestad's equation (equations 14 and 15 to determine the minimum D and maximum L) (the point where the diameter is equal to the flame height has been outlined through a red circle).

$$D_{min} = L_{fl\,max} = \frac{0.235\, \dot{Q}^{2/5}}{2.02} \qquad (15)$$

The Thomas theory is valid only after that point (to be rigorous, significantly after that point). The result of formula (15) for a 1000 kW fire is D_{min}=$L_{fl\,max}$=1.844 m. Using the resulting D_{min}, assuming a circular fire and thus an area of 2.67 m², the HRRPUA would be 374.64 kW/m² that is far below the 1000 kW/m² suggested for a fire involving cellulosic and/or plastic materials.

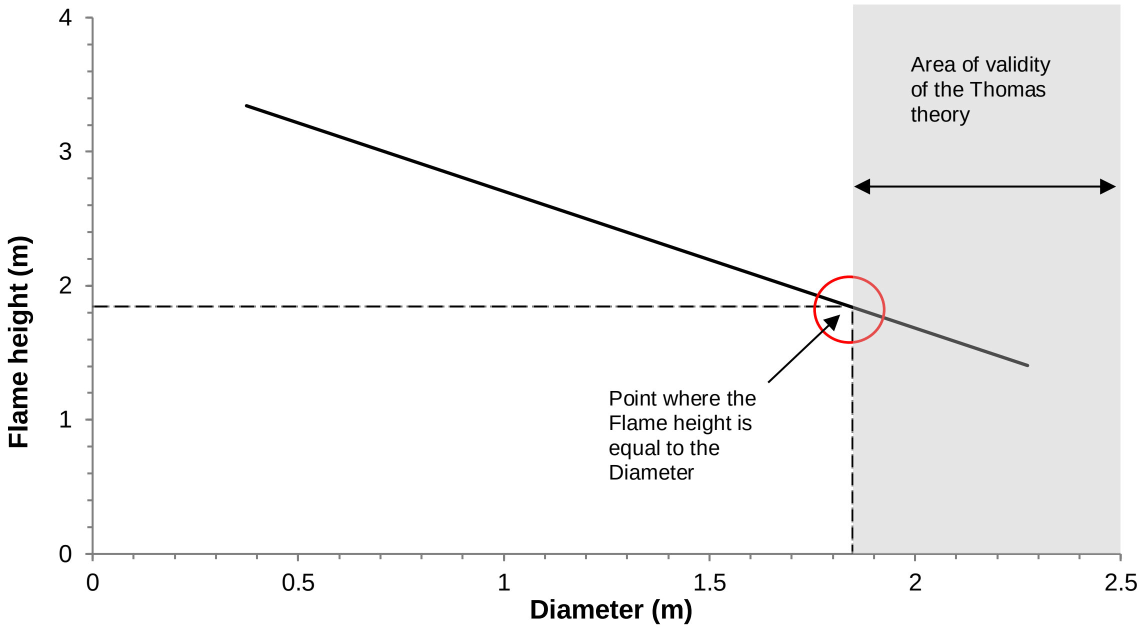


Figure 11. Mean flame height vs diameter for a 1MW fire with emphasis on the area of applicability of the Thomas theory and the point where the Flame height is equal to the Diameter.

The Thomas model can give predictions of layer evolution close to the measured for a certain value of the HRRPUA parameter of the design fire. An example of such a posteriori data fit to the results of experiment #G1 is shown on Fig. 12. It can be noted that the Thomas model with a HRRPUA = 500 kW/m² give results very close to the experiment. However, it must be noted that the value of 500 kW/m² does not meet the flame height requirement described above – this is explicitly met by the 250 kW/m² scenario, for which the smoke generation was over-predicted.

It must also be noticed that the values of HRRPUA for design purposes presented in standards and national codes are often misused. Fire Codes assume that the HRR is the average of the total heat released generated by the fuel divided by the area of the compartment and that the fire burns uniformly in the area of the compartment. However, this approach does not consider at all a localized fire. In reality, a fire can easily exceed 1000 kW/m^2 (as for example the heptane fire, ~3000kW/m^2) resulting in flame heights considerably bigger than the perimeter clearly against the hypothesis in which the Thomas theory is based on.

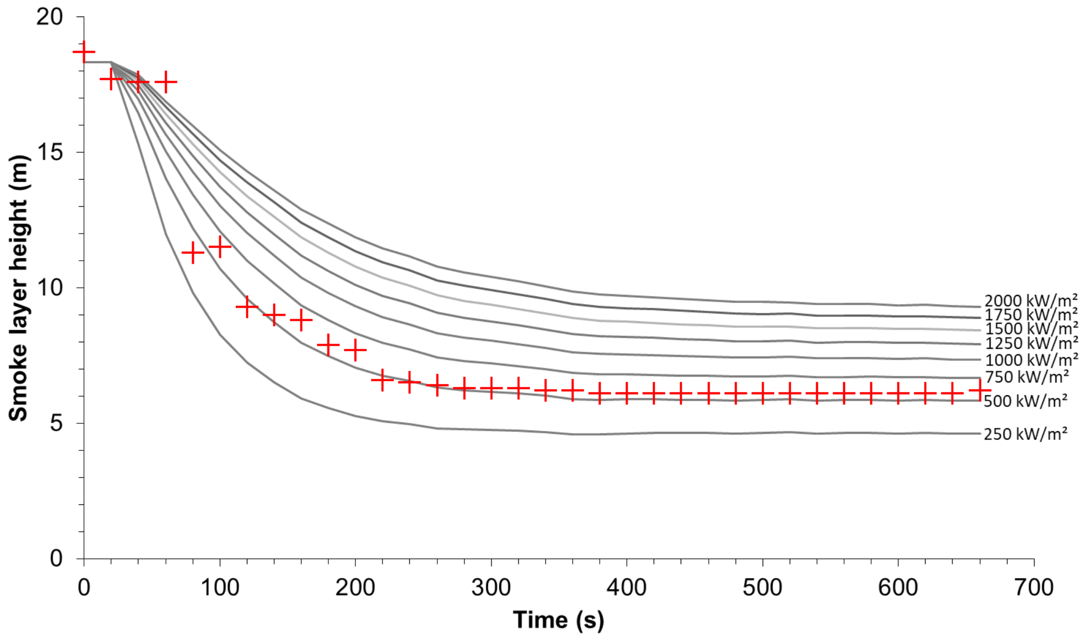


Figure 12. Transient analysis of smoke layer height with Thomas equation for different values of HRRPUA. Red crosses mark the results of experiment #G1

5 Conclusions

The use of smoke plume entrainment models for the design of large-volume buildings may be questionable as such application may extend beyond the application range of the aforementioned models. The choice of the most appropriate model is difficult due to the large amount of approaches presented in the literature, standards and national codes. To assess their validity, a series of experiments was performed in a large-scale atrium facility and the experimental results have been compared to plume theory-based models focusing on the transient and steady state layer interface height predictions.

Based on the results obtained by this analysis performed in a large-volume enclosure, the current methods available (and recommended by the national regulations) of modelling fire and determining the smoke produced by the fire might not be suitable. The best results for the prediction of the layer height were consistently obtained with the McCaffrey model, and the best results for the evolution of the smoke layer with the Zukoski model. The popular Thomas model under-predicted the smoke generation in the atrium, yielding significantly higher smoke layer heights than measured. It was further shown, that this result may be improved by carefully choosing value of HRRPUA parameter to fit the results with experimental data. However, in practical design, the engineer is not able to choose reliable values for this parameter, thus being exposed to a significant error.

The results presented in this study show that the smoke layer height and its temporal evolution may be predicted with satisfactory accuracy with simple methods. This prediction does improve the whole design process as the first approximation is often considered as a boundary condition for further costly numerical modeling. Use of simple plume models should be further investigated by the fire safety engineering community as they can still be considered as a valuable tool. However, the use of such models to predict the smoke production of a given fire shall be only a first approximation and not a design tool, especially using those models that have not shown a good match to the experimental data.

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