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Impact of the room geometry on the smoke filling time due to a fire plume

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ABSTRACT

In this paper, the influence of a room geometry on the smoke filling time with a fire plume is studied by means of full-scale simulations with the CFD model Fire Dynamics Simulator (FDS) and two-zone models. The results show that the room aspect ratio has little impact on the smoke filling times in the case of small surface rooms. Consequently, the zone models can be used to predict the evacuation time. In the case of large surface rooms, such as atria and hangars, the dynamic of the ceiling jet when it hits the side walls cannot be neglected. In that case, the zone models overestimate the smoke filling time which directly impacts the evacuation time.

KEYWORDS:

Compartment fires; smoke filling time; CFD model; zone models.



INTRODUCTION

Ensuring safe evacuation of people during fires is one of the main objectives of fire safety. To evaluate the Available Safe Evacuation Time (ASET), zone models are still used in fire safety engineering, mainly due to the short simulation time compared to CFD models. In compartment fire, the ASET is strongly affected by the smoke filling time. It is therefore crucial to correctly estimate it.

After the ignition of a fire, the hot gases produced by the combustion generate a rising plume that entrains the surrounding fresh air. When the plume hits the ceiling of the enclosure, it spreads radially. Then, a smoke layer forms and thickens with time due to the mass flow supplied by the plume. This filling process was first studied by Baines and Turner [1]. They developed a filling box model to predict the thickness of the stratified layer resulting from a point source of buoyancy in a confined environment. In their model, the dynamics of the ceiling jet and the outflow when it hits the side walls are neglected. They have assumed that when the plume hits the ceiling, at the initial time ($t = 0$ s), a layer of infinitesimal thickness forms. Then it gradually fills the enclosure due to the volume supplied by the plume.

By balancing the rate at which the buoyant fluid is supplied by the plume with the rate at which the upper buoyant layer deepens, Baines and Turner [1] obtained the following relation describing the position of the horizontal interface between the ambient and buoyant layers Z_{int} :

$$\frac{Z_{int}}{H} = \left(\frac{2}{3} \frac{t}{t_f} + 1 \right)^{-\frac{3}{2}} \quad (1)$$

where $t_f = \frac{S}{c H^{\frac{2}{3}} B^{\frac{1}{3}}}$ is the filling box time scale, S is the surface area of the room, H is the height of the room, C is a constant which depends on the plume entrainment coefficient, and B is the buoyancy flux.

This approach is used in many zone models (see for instance [2]) to predict the smoke filling time. Actually, the fire plume is modeled using fire plume correlations such as Heskestad's model [3], Zukoski's model [4] and McCaffrey's model [5]. All these fire plume models are commonly based on the seminal work by Morton, Taylor and Turner [6]. To validate their model, Baines and Turner [1] performed experiments involving small scale salt plume. For rooms with aspect ratios $\Phi = R/H$ less than 1 (R and H being respectively half the width and height of the room), they observed that the dynamics of the ceiling jet resulting from the fire plume have a noticeable effect on the formation of the buoyant layer that cannot be neglected.

Following this work, several studies have been carried out to determine the filling process for room aspect ratios less than 1. Recently, Kaye and Hunt [7] [8] identified two sidewall flow patterns, depending on the room aspect ratio $\Phi = R/H$. They showed that for tall enclosures ($\Phi < 2/3$), when the ceiling flow hits the side-walls, it rolls over entraining an important amount of the ambient fluid into the buoyant layer (see Fig. 1-a). Indeed, this «Rolling mode» increases the smoke layer thickness and consequently reduces the filling time of the enclosure. However, for wide enclosures ($\Phi \geq 2/3$), they observed that when the ceiling flow hits the side-walls, it slumps back up into the buoyant layer entraining a small amount of the ambient fluid (see Fig. 1-b). Kaye and Hunt [8] proposed a correlation of the scaled time $\tau = t/t_f$, taken for the maximum buoyant layer depth h (see Fig. 1) to reach half height of the box, as a function of the room aspect ratio Φ which reads as:

$$\tau_{h=\frac{H}{2}} = \begin{cases} 0.8 \Phi + 0.066, & \Phi < 0.6 \\ 0.55, & \Phi > 0.6 \end{cases} \quad (2)$$

The study by Kaye and Hunt [8] highlights the major influence of the room aspect ratio on the filling time of the room, especially for the small aspect ratios. Furthermore, this work has been conducted in the Boussinesq case, i.e. for marginal density (temperature) difference between the plume and its environment. The fire plume is a non-Boussinesq plume due to the large density contrast caused by the temperature difference between the fire plume and its environment. Thus, one can expect to observe differences with experiments involving real fires.

In the present paper, the aim is to study, by means of full-scale simulations, the effect of the room aspect ratio on the smoke filling time, and to evaluate the filling time predicted by the zone models based on the approach of Baines and Turner [1] for the prediction of the interface position during the smoke filling process.

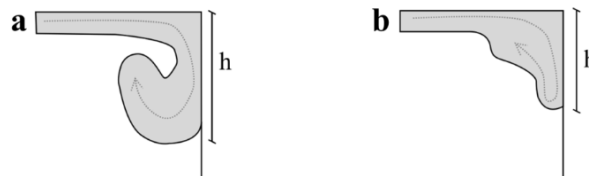


Fig. 1. A schematic of the two sidewall flow patterns: (a) «Rolling mode», (b) «Slumping mode».

TWO-ZONE MODEL

A two zone model is a simplified representation used to predict the smoke layer thickness that forms under the ceiling and its temperature. Fig. 2 presents the schematic of the studied configuration. We consider a square room of height H with a cross-sectional area S , connected to the outside by opening located at the bottom of the room. A fire, with heat release rate of \dot{Q}_t , is located at the floor level. We assume that, at the initial time ($t = 0$ s), a smoke layer of infinitesimal thickness forms and thickens with time due to the mass flow supplied by the plume \dot{m}_p . We also assume that the smoke layer is characterized by its average density ρ_{up} , its average temperature T_{up} and its thickness $h = H - z$. Note that T_0 and ρ_0 are, respectively, the temperature and the density of the ambient air.

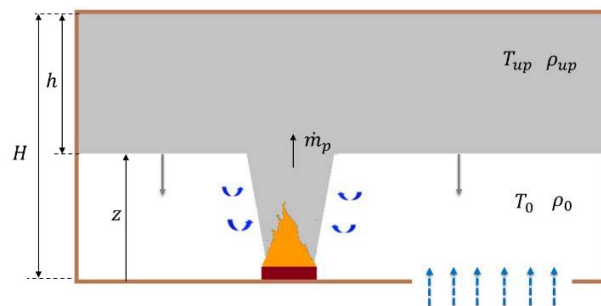


Fig. 2. Schematic of the studied configuration.

Assuming that the walls of the room, including the ceiling, are adiabatic, the conservation equations for mass and buoyancy flux can be written as:

$$\frac{d(\rho_{up} S h)}{dt} = \dot{m}_p \quad ; \quad \frac{d(g \frac{\Delta \rho_{up}}{\rho_0} S h)}{dt} = B \quad (3)$$

where $\Delta \rho_{up} = \rho_0 - \rho_{up}$ and B is the buoyancy flux which is related to the convective heat release rate \dot{Q}_c via the relation: $B = g \dot{Q}_c / (\rho_0 C_p T_0)$. C_p is the specific heat of air at constant pressure. Using the conservation equations (3), one obtains for the buoyant layer thickness, the following relation

$$\frac{dh}{dt} = \frac{\dot{m}_p}{\rho_0 S} + \frac{B}{g S} \quad (4)$$

To complete the model, a closure model is still required for the mass flow rate of the plume \dot{m}_p . It is generally evaluated using three different fire plume models, namely: McCaffrey [5], Zukoski [4] and Heskestad [3]. In what follows, equation (4) is solved numerically by a Runge-Kutta fourth order method to obtain the temporal evolution of the smoke layer thickness h . This evolution is subsequently compared to FDS numerical simulations.

FULL-SCALE SIMULATIONS

Fire Dynamics Simulator (FDS) version 6, is used here to study the effects of the room aspect ratio Φ on the smoke filling time. In what follows, a square room of height H with a cross-sectional area S is considered. The room is connected to the outside by openings located at the bottom of the room. A heptane pool fire, with heat release rate of 1 MW and surface area of 1 m², is located at the floor level in the middle of the room. All walls of the room, including the ceiling, are supposed to be adiabatic. A mesh size of 10 cm \times 10 cm \times 10 cm is adopted in all simulations based on mesh sensitivity study.

Two configurations are considered. In the first configuration, to vary the room aspect ratio, the surface of the room is kept constant ($S= 25$ m²) while its height is varied (see Table 1). In the second configuration, the surface area is varied while the height is fixed at 10 m (see Table 2). For each case, the time necessary for the maximum smoke layer depth h (see Fig. 3) to reach half height ($H/2$) of the room is evaluated and compared to the result of the two-zone model presented in the previous section.

Here, the three fire plume models are evaluated namely: McCaffrey [5], Zukoski [4] and Heskestad [3]. It should be noted that the height of the room is taken to be the distance between the virtual origin of the fire plume z_v and the ceiling, and the initial time ($t= 0$ s) is defined as the moment the plume hits the ceiling.

Table 1. Dimensions of the rooms simulated in series 1.

	S (m ²)	H (m)	$\phi=L/(2(H-z_v))$
Case 1	25	2.5	1.07
Case 2	25	3.6	0.73
Case 3	25	8	0.32

Table 2. Dimensions of the rooms simulated in series 2.

	S (m ²)	H (m)	$\phi=L/(2(H-z_v))$
Case 1	36	10	0.31
Case 2	64	10	0.41
Case 3	196	10	0.71
Case 4	400	10	1.02
Case 5	676	10	1.32
Case 6	1024	10	1.63

Configuration 1: variation of the height of the room ($S= 25$ m²)

To assess the influence of the aspect ratio Φ on the time taken for the smoke to reach half the height of the room, the time $t_{h=\frac{H}{2}}$ and the dimensionless time $\tau_{h=\frac{H}{2}} = t/t_f$ (t_f is the filling box time scale [1]) are plotted as a function of the aspect ratio Φ in Fig. 4. Fig. 4.a shows a clear dependency between the scaled time $\tau_{h=\frac{H}{2}}$ predicted by FDS and the room aspect ratio. It is also noticed that the results obtained by the two-zone models share similar qualitative behaviors with FDS results. In all cases, the two-zone models overestimate the filling time by a few seconds (Fig. 4.b).

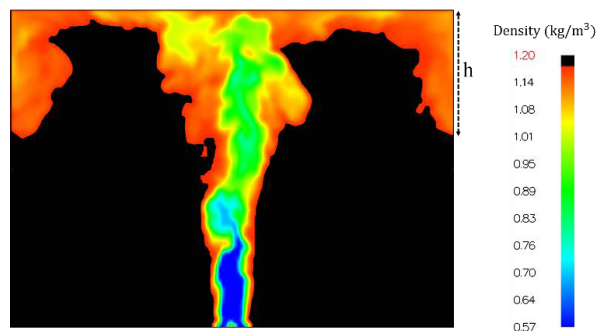


Fig. 3. Distribution of the density in the vertical median plane (Series 2 - case 3).

The behavior obtained by the two-zone models may be explained by the short smoke filling times. In fact, this fast filling time may hide the expected behaviors described by Kaye and Hunt [8]. Consequently, in this situation, the room aspect ratio has little impact on the smoke filling times.

Moreover, when comparing the FDS results with the experimental correlation by Kaye and Hunt [8], a complete mismatch is observed. These differences may be attributed to the fast filling time but also to non-Boussinesq effects (associated with a large temperature difference with the ambient), since the experiments of Kaye and Hunt are only related to Boussinesq plumes (salt water plume injected into fresh water). It can be concluded that the fresh-water / salt-water experiments may not be suitable for the description of the filling box with fire smoke.

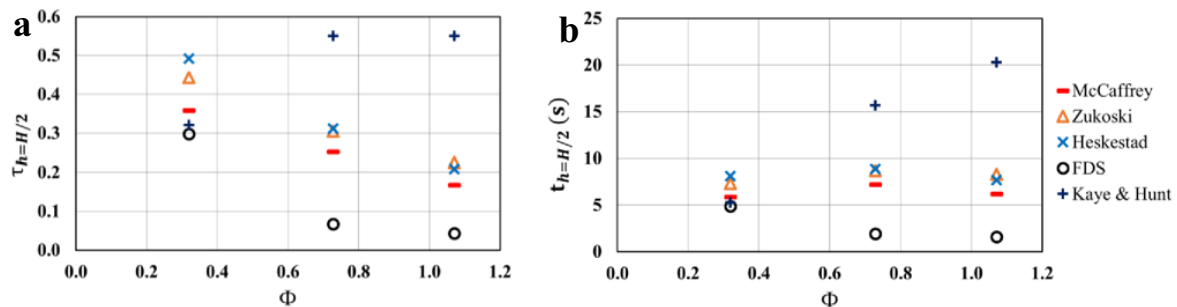


Fig. 4. Time taken for the smoke layer depth to reach half height of the room. (a) Variation of the scaled time with the aspect ratio, (b) Variation of the filling time with the aspect ratio.

Configuration 2: variation of the surface area of the room ($H=10$ m)

The Fig. 5-a shows the variation of the scaled time $\tau_{h=\frac{H}{2}}$ with the room aspect ratio Φ . The results obtained by FDS show a strong dependency between the scaled time $\tau_{h=\frac{H}{2}}$ and the room aspect ratio, which is not the case for the two-zone models. Moreover, it is seen in Fig. 5-b that for a room aspect ratios $\Phi \geq 1$, the time required for the smoke to reach one half of the room height is very long compared to the time obtained by FDS, especially with the Heskestad and Zukoski plume models. These discrepancies increase with the room aspect ratio. These discrepancies can be attributed, in some cases, to the dynamics of the outflow at the side-walls where the maximum penetration depth h of the smoke can rapidly reach the half height of the room, before the smoke fills half of the whole room volume. In zone models, these dynamics of the outflow at the side-walls are not taken into account, which explains partially why the smoke filling times are overestimated in the case of an important surface area such as hangars and atria. Thus, the volume being very large, the time required to fill half of it will be important. Fig. 6 compares the smoke flow obtained by FDS (Fig. 6.a) and that obtained by the two-zone model (Fig 6.b) at $t=23$ s after ignition and for the case: $S=676$ m² ($\Phi = 1.3$). We can observe that the maximum penetration depth reaches 48 % of the room height while in the two-zone model the smoke layer reaches only 9 % of the room height. We can conclude that, in this case, zone models cannot be used to evaluate the ASET, especially in the first moments when the outflow dynamics at the sidewalls are important.

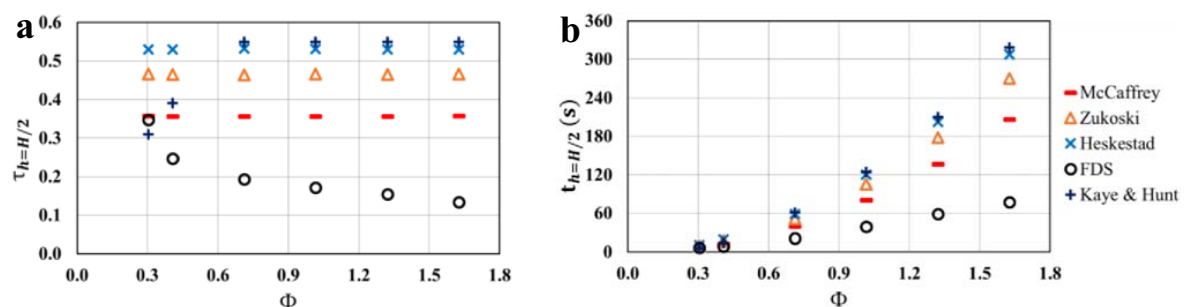


Fig. 5. Time taken for the smoke layer depth to reach half height of the room. (a) Variation of the scaled time with the aspect ratio, (b) Variation of the filling time with the aspect ratio.

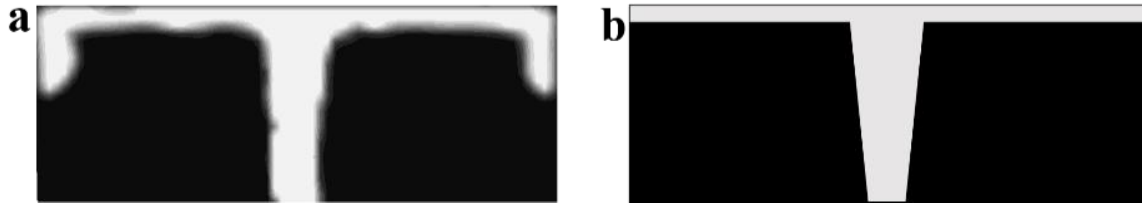


Fig. 6. Smoke configuration at $t = 23$ s: (a) obtained by FDS, (b) obtained by the two-zone model (using Heskestad's plume model).

CONCLUSION

In this study, full scale simulations with the CFD model FDS have been conducted to study the influence of the room aspect ratio on the smoke filling times, and to evaluate the smoke filling times predicted by the two-zone models. The results show that the room aspect ratio has little impact on the smoke filling times in the case of small room areas. Thus, the zone models can be used to predict the available evacuation time. However, in the case of a configuration with an important surface area, such as atria and hangars, the results found with the CFD model show that the maximum penetration depth of the smoke at the side walls can rapidly reach important values during its initial stage of development (after the outflow hits the side walls). This outflow dynamics are not considered in zone models, and consequently, the smoke filling times are overestimated. It can be concluded that zone models could be unfit to evaluate the available safe evacuation time when the flow dynamics at the side walls are important. This result does not call in question their usage in other situations, for example, where we are only concerned about the stationary phase of a filling emptying process.

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