Numerical study of the adhered smoke plume for fire in an atrium

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Abstract

In case of fire in an adjacent room to an atrium, one of the most important parameters in fire safety design is the smoke free height in the atrium. A recent article [1] reports on a series of small-scale experiments and the development of a new one-line equation for the mass flow rate of the spill plume. In our paper, we first describe a calculation method to determine the smoke layer interface height in CFD-simulations. A series of CFD-simulations is validated, based on the experiments of [1]. Large-scale atria are also simulated and discussed. The presence of a "more-dimensional" effect is detected and discussed.

Notations

Δh	Cell height	m
D_b	Smoke layer depth at spill edge	m
g	Gravity acceleration	m/s^2
H	Height of atrium	m
M	Mass flow rate	kg/s
M_b	Mass flow rate at spill edge	kg/s
N	Value in N-percent rule	
Q	Heat release rate	kW
T	Local temperature	K
T_0	Ambient temperature	K
$T_{av,s}$	Average temp. of smoke layer	K
T_{int}	Temp. at smoke layer interface	K
$T_{\max}$	Max temp. on vertical line	K
W	Atrium width	m
z_s	Height above spill edge	m
z_{int}	Interface height above ground	m
ρ	Density	kg/m^3

Introduction

Over the past decades, atria have become an increasingly popular type of architectural structure, e.g. in shopping malls, hotels or office buildings. In case of fire, a smoke and heat exhaust ventilation system (SHEVS) can be an effective way to ensure safety for occupants, firemen and building structures. One of the most important parameters in the design of these SHEV systems is the smoke free height in the atrium.

A specific and commonly studied situation is when the fire occurs in a room or corridor, adjacent to the atrium. The smoke plume, coming from the adjacent room and turning into the atrium (Figure 1) is called the spill plume.

In the past, several authors [2-8] have already developed a simple one-line equation to calculate the mass flow rate of this spill plume at a specific height.

However, these equations are often based on a limited set of mostly small-scale experiments. Although each equation may be correct for the set of experiments it is based on, limitations to its range of applicability must be considered.

The goal of our research is to develop a similar simple one-line equation, applicable to a larger range of values of different parameters. Instead of using 'real' experiments (either large- or small-scale), CFD simulations will be used as 'numerical experiments'.

Before using these 'numerical experiments' the CFD-simulations have to be validated. In this paper, a validation study based on a set of recently carried out small-scale experiments, is discussed.

In order to use the simulations, however, a numerical calculation method has to be developed first to determine the smoke layer interface height in a CFD-simulation.

The simulations of some large-scale atria, based on the small-scale atria of the studied experiments [1] are also discussed.

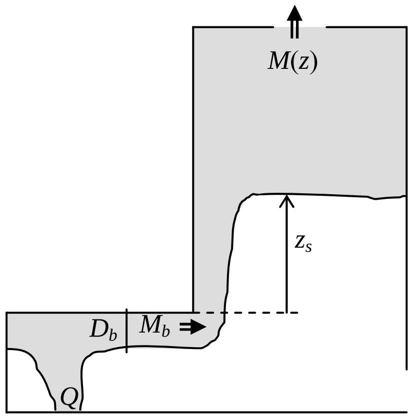

Figure 1. Atrium configuration.

Specific Objectives

The objectives in this paper are first to find a numerical calculation method to determine the interface height of the smoke layer. Afterwards, a validation of the CFD-simulations, based on a set of small-scale experiments, is discussed. Finally, we present some results of the CFD-simulations of two large-scale atria.

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The CFD-simulations are carried out with FDS (Fire Dynamics Simulator), version 5, by NIST [9,10]. A Smagorinsky LES (C_S = 0.2) is used as turbulence model. A constant fire heat release rate is imposed in the simulations.

Smoke layer interface height

Figure 2 shows a temperature profile on a vertical line in one of the studied atria. In the atrium configuration (Figure 1), an opening to the outside air is present at the right hand side of the atrium, as in the experiments of [1]. The temperature profile in Figure 2 corresponds to a vertical line close to this opening.

Beneath the top height of the air inlet opening (at 0.6 m), temperatures are 20°C, as in the outside air. Above the opening, a sudden rise in temperature is noticed (Figure 2). However, this increase in temperature should not be mistaken for the smoke layer interface. The calculation method to define the smoke layer interface height should thus be designed so that this mistake is not made.

Four different calculation methods will be discussed here to find a smoke layer interface height.

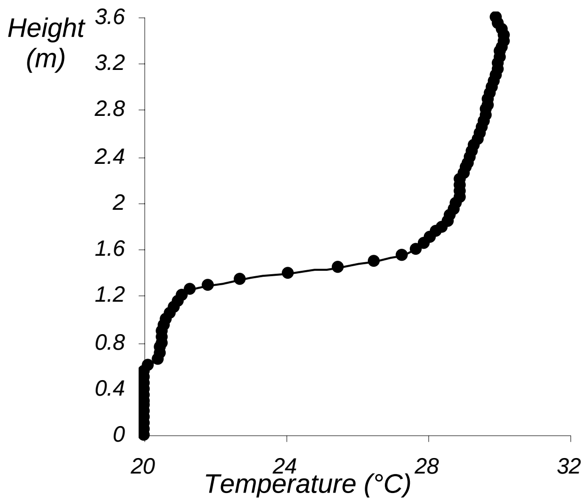

Figure 2. Temperature profile on vertical line in atrium.

Thomas

$$H - z_{\text{int}} = \frac{\int_0^H \frac{T - T_0}{T} dz}{\frac{T_{av,s} - T_0}{T_{av,s}}} \quad (1)$$

A first calculation method to determine the smoke layer interface height is the formula by Thomas [11] (Equation 1). The temperatures in the simulation results are used to perform the integration.

However, two difficulties arise in the use of this formula. First of all, it is an iterative, and therefore time intensive, procedure to determine the smoke layer height. Indeed, to define the smoke layer interface height (z_{int}), the average temperature of the smoke layer is needed ($T_{av,s}$). Of course, this temperature can only be calculated with knowledge of z_{int}. Therefore, an iterative procedure has to be carried out.

Secondly, numerical integration has to be performed. The approximation of the integral can be performed in a number of ways. Either a simple sum of the values is taken, or Simpson's rule can be applied, in which case a user still has to choose what kind of interpolation to use.

He

Another method is described in [10], and is based on a calculation method by He [12]. The parameters I_1 and I_2 are calculated first, T_l is set equal to the lowest temperature on the vertical line, and z_{int} can be calculated:

$$I_1 = \int_0^H T dz \text{ and } I_2 = \int_0^H \frac{1}{T} dz \quad (2)$$

$$z_{\text{int}} = \frac{T_l \left(I_1 I_2 - H^2 \right)}{I_1 + I_2 T_l^2 - 2 H T_l} \quad (3)$$

Again, the simulation data temperatures are used to perform the integration, and thus to obtain a smoke layer interface height.

While this procedure is not iterative, a user will still have to choose the approximation of the integrations (Equation 2).

Second derivative

Based on a relevant temperature profile (Figure 2), the conclusion can be drawn that the second derivative of the temperature can also provide a way to determine an interface temperature. The maximum of the second derivative indicates the interface temperature where the smoke layer starts. We use a central scheme to calculate the second derivative, and divide by the local temperature difference:

$$\frac{\partial^2 T}{\partial z^2 \Delta T} \approx \frac{T_{i-1} - 2T_i + T_{i+1}}{\left(\Delta h\right)^2 \left(T_i - T_0\right)}. \quad (4)$$

Figure 3 displays the values corresponding to the temperature profile of Figure 2. A maximum is found at temperature 22.2°C (dotted line).

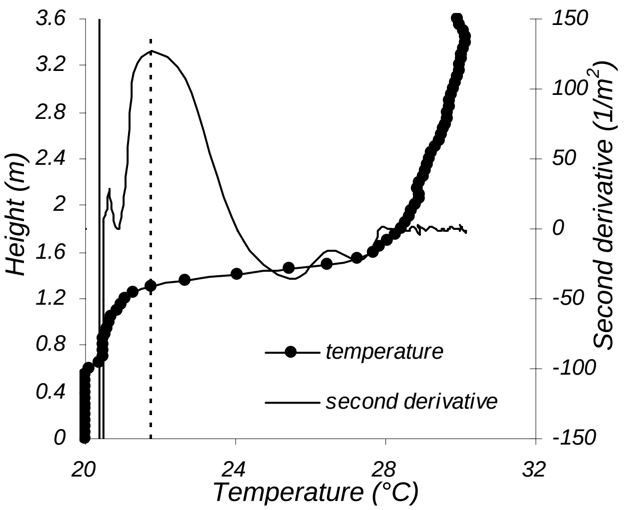

Figure 3. Temperature profile and second derivative.

However, this is a local maximum. An extremely large value (outside the range of the axis in Figure 3) corresponds to temperature 20.2°C. Since the user has to decide whether or not the local maximum is already in the smoke layer, this procedure is not an unambiguous way to determine the interface temperature.

N-percent rule

The final calculation method is the N-percent rule [13], where an interface temperature is defined as

$$T_{\text{int}} = T_0 + \left(T_{\max} - T_0\right) N/100 . \quad (5)$$

However, this equation results in a (slightly) different temperature for each vertical line in the atrium. Consequently, one might choose a single interface temperature for the entire atrium in order to determine a uniform smoke free height in the atrium. Two simple ways to determine this single temperature seem obvious: either the average or the minimum of all interface temperatures. We choose the minimum, as this corresponds to a worst case scenario.

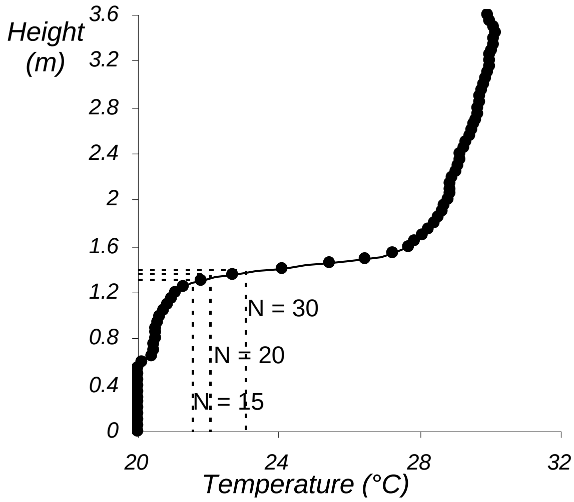

Figure 4. N-percent rule applied to temperature profile.

Interface temperatures can be calculated according to different values of N (Figure 4). For some of the large-scale atria, interface temperature values for N = 15 and N = 20 can result in temperatures within the first small temperature rise range in the atrium (at the top of the opening). Since these temperatures are not yet in the smoke layer, a value N = 30 is chosen here to provide the interface temperature in the atria. The N-percent rule with N = 30 is used in every simulation discussed below.

Conclusion

To conclude this paragraph, the four different methods are used in the data analysis of an atrium simulation (Figure 5). The formula, derived from the experimental results (Equation 6, see below), calculates an interface height 1.37 m.

Figure 5 shows that by using the N-percent rule with N = 30, the smoke layer interface is closest to the one measured in the experiment. Furthermore, with this procedure, the smoke layer has the most uniform height.

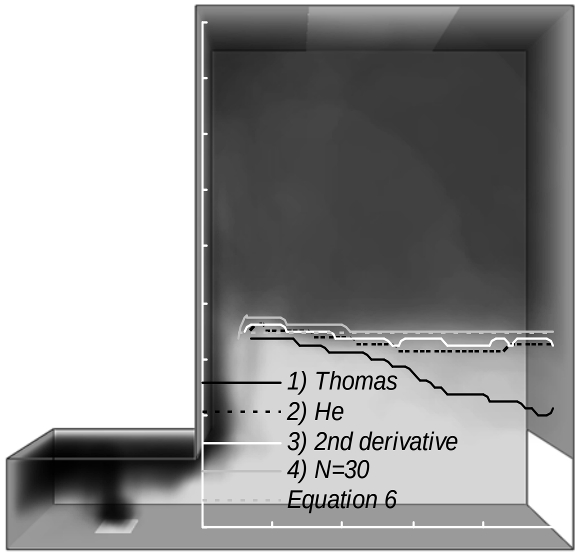

Figure 5. Interface height defined by different methods.

Results and Discussion

Small-scale atrium

In a recently published article by Poreh et. al. [1], experiments were carried out in a small-scale atrium (Figure 1). Four different heat release rates (Q) were studied and for each heat release rate, four different extraction mass flow rates (W). For every combination of heat release rate and extraction mass flow rate, the smoke free height above the spill edge (z_s) was measured. These experiments have led to the proposal of a new one-line equation for the mass flow rate in adhered spill plumes [1] for a specific configuration of the atrium (width W):

$$M\left(z_s\right) - M_b = 0.07\left(W^2 Q\right)^{1/3}\left(z_s + D_b\right). \quad (6)$$

Values of the horizontal mass flow rate emerging from the adjacent room (M_b) and the thickness of this emerging layer (D_b) are assumed to be known, as they can be calculated with well-established formulae for fire in enclosures.

In [1], it is also stated that a spill plume is adhered as long as the 'Froude-number' of the horizontal smoke layer, emerging from the adjacent room, is below 1. This Froude-number is defined as

$$Fr = \frac{M_b}{\rho D_b W \sqrt{g D_b \Delta\rho / \rho}} . \quad (7)$$

With FDS-simulations, we repeated these experiments. A constant extraction velocity was imposed at the ceiling of the atrium, corresponding to a constant extraction mass flow in a quasi-steady-state situation. The small-scale simulations are performed on a grid containing 70200 cells of size 5 x 5 x 5 cm^3. No difference in results is found with a grid refinement study. First, the simulations lying within the range of the mass flow rates in the experiments (Table 1) are discussed.

Q	(kW)	2.887	5.377	8.792	11.901
M_{min}	(kg/s)	0.071	0.090	0.112	0.116
M_{max}	(kg/s)	0.149	0.219	0.393	0.434

Table 1. Mass flow rate range of the experiments.

Figure 6 depicts the experimental and simulation results, along with Equation 6. Good agreement is found between the one-line equation, the experimental values and the simulation results within the same mass flow rate range. Thus, we can conclude that the simulations are hereby validated for the case under study.

Simulations outside the range of the experimental mass flow rates were also carried out (Figure 6). Some of these simulations no longer show good agreement with Equation 6. This is due to what we call a "more-dimensional" effect, which occurs at higher mass flow rates than studied in the experiments.

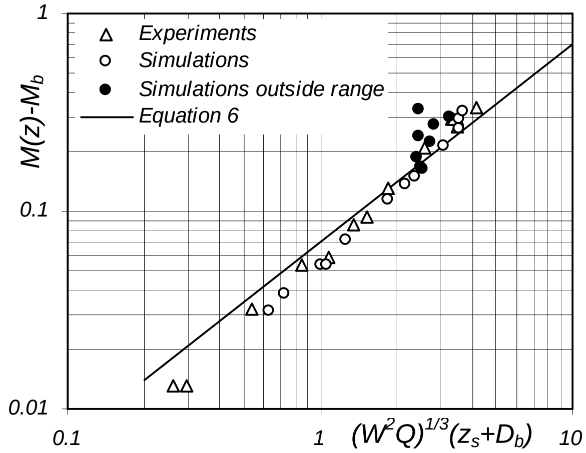

Figure 6. Experimental and simulation results for the small-scale atrium.

By the term "more-dimensional" effect, we mean that the depth of the smoke layer is not uniform in the entire atrium (Figure 7). The minimal smoke free height present in the atrium is chosen in the representation of the results, according to a worst case scenario for occupants and firemen in the building.

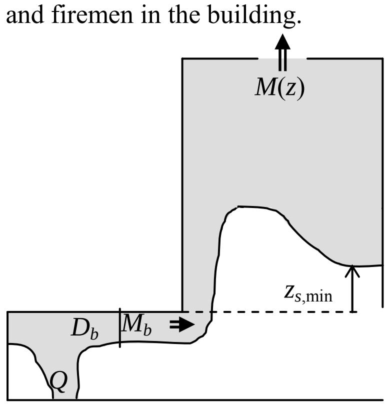

Figure 7. "More-dimensional" effect of smoke layer.

Unfortunately, Equation 6 does not provide a conservative design for the smoke control system in the atrium under such circumstances. For a certain configuration and heat release rate, the equation results in a lower mass flow rate than what is really necessary to maintain a certain smoke free height in the atrium.

Large-scale atria

After validation of the FDS-results with the small-scale atrium, the dimensions of the atrium were increased proportionally to obtain two large-scale atrium setups, with the same configuration of atrium, adjacent room and inlet opening. Two atrium widths are studied (4 m and 7.2 m). The 7.2 m wide atrium contains 561600 cells of size 20 x 20 x 20 cm^3. In the 4 m wide atrium, 749520 cells of size 10 x 10 x 10 cm^3 are present.

Since the configuration is kept the same, but simply scaled up, the heat release rates need to be scaled up as well. This is done by "Froude-scaling". To keep the Froude-number equal in the scaled up configuration (so that it remains below 1, keeping the spill plume adhered), the heat release rate has to be scaled up as

$$Q \sim L^{5/2} \,. \qquad (8)$$

Table 2 presents the heat release rates in the 4 m (Q_2) and 7.2 m (Q_3) wide atria, corresponding to the original heat release rates (Q_1) in the small-scale atrium configuration.

Q_1	(kW)	2.887	5.377	8.792	11.901
Q_2	(kW)	120	224	366	495
Q_3	(kW)	523	973	1591	2154

Table 2. Heat release rates in the large-scale atria.

These heat release rates are in the same order of magnitude as the design heat release rates in [14]. Thus, the large-scale simulations represent realistic fire scenarios. The simulation results in the 4 m wide atrium are depicted in Figure 8, along with Equation 6.

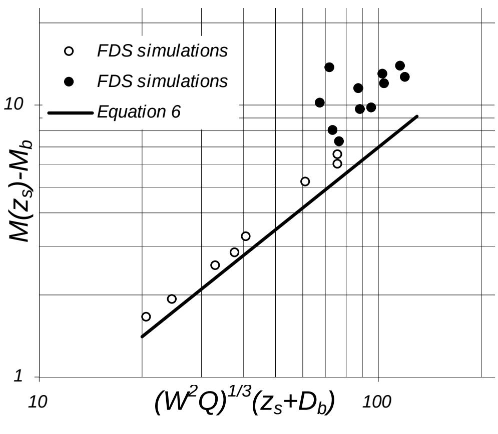

Figure 8. Simulation results in the 4 m wide atrium. White dots (○): one-dimensional smoke layer; black dots (●): more-dimensional smoke layer.

Distinction is made between the results with a "more-dimensional" effect of the smoke layer, and the "one-dimensional" results. As long as the smoke layer can be considered as "one-dimensional", the simulation results agree well with the proposed formula (Eq. 6). However, when a "more-dimensional" smoke layer is present in the atrium, Equation 6 no longer provides a conservative smoke control system design in the atrium.

The results of the 7.2 m wide atrium are very similar to those in the 4 m wide atrium. The same more-dimensional effect and corresponding underestimation of the necessary extraction mass flow rate is noticed.

Results with FDS4

Earlier, the same simulations were carried out in a previous version of FDS (version 4.0.7). Figure 10 depicts the results of the small-scale atrium, simulated with FDS 4 and FDS 5, along with Equation 6. Only the simulation data with extraction mass flow rate within the same range as in the experiments of [1], are shown here.

Similar as with FDS 5, the results of the FDS 4 simulations agree well with the proposed one-line equation.

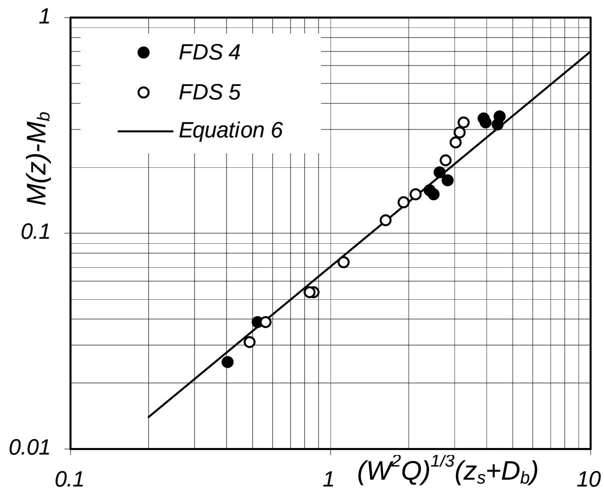

Figure 10. Small scale atrium simulation results.

Conclusions

To calculate the smoke layer interface in a numerical simulation, the N-percent rule is an unambiguous and easy to implement calculation method. For the atrium simulations, N = 30 was chosen, so that the first temperature rise in the atrium is not mistaken for the interface of the smoke layer. The minimal interface temperature of all vertical lines in the atrium is chosen as a single interface temperature to determine the smoke layer interface height. The results obtained with this method correspond well to the experimental results.

A validation of CFD-simulations was performed, using experimental data [1]. Good agreement was shown between the experiments, numerical simulations within the same range and the proposed one-line equation of [1] for the small-scale atrium. However, simulation results with higher mass flow rates than studied in the experiments, showed the existence of a "more-dimensional" effect, where the smoke layer depth is not uniform in the entire atrium. In this case, the minimal smoke free height is chosen as interface height in the representation of the results.

The small-scale configuration was scaled up by Froude-scaling to obtain two large scale atria. Simulations with these atria confirmed the accuracy of the proposed one-line equation, as long as the smoke layer can be considered as "one-dimensional". However, the presence of a "more-dimensional" effect in the atrium results in higher necessary mass flow rates than calculated with the proposed equation.

Further research will be performed to explain the origin of this 'more-dimensional" smoke layer effect. Possibly, a criterion can be determined to predict whether the smoke layer will be "more-dimensional" or not. If this criterion can be found, a new simple one-line equation will be developed for the mass flow rate of "more-dimensional" smoke layers.

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