EXTENDED ABSTRACT

Quantification of air entrainment in smoke plumes through rectangular openings in an intermediate floor

ir. Pieter Poppe

Supervisors : prof. dr. ir. Bart Merci, ir. Christian Gryspeert

Abstract : Two empirical formulas are proposed to quantify the air entrainment in smoke plumes through rectangular openings in an intermediate floor. The CFD-model FDS is used to quantify the entrainment. The two empirical formulas showed good agreement with the results of de FDS-simulations.

Keywords : air entrainment, smoke plume, rectangular opening, floor, smoke and heat exhaust ventilation system, FDS

I. Introduction

The quantification of air entrainment in smoke plumes has extensively been examined in case of an axisymmetric smoke plume or a spill plum. However no experiments have been carried out to investigate the behavior of a smoke plume passing through an opening in an intermediate floor. A very recent thesis has concluded that the air entrainment of such smoke plumes can be quantified using the formula from Heskestad for an axisymmetric plume. In the latter thesis, good results were obtained for square openings, but not for rectangular openings. The main objective of this thesis is to find an empirical formula to quantify the entrainment of air in smoke plumes through rectangular openings in an intermediate floor.

II. Empirical formulas

Not one, but two hypotheses for the air entrainment in smoke plumes through openings in an intermediate floor are formulated in this thesis. The plumes in question are called the “axisymmetric line plume” and the “perimeter plume”.

Hypothesis axisymmetric line plume

A rectangular opening is characterized by a long side (L) and a short side (B).

The first hypothesis considers the plume as a combination of an axisymmetric plume at the short sides of the rectangular opening (with area A_{axis}) and a line plume (with area A_{line}) in between the axisymmetric plume. This is demonstrated by the following figure :

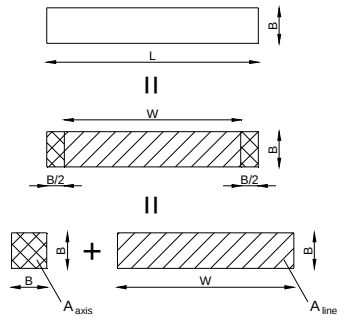


Figure 1 : Ratio area axisymmetric plume and line plume at the opening in the floor (i.e. z=0)

The above-mentioned figure refers to the location at the opening. Every line plume will eventually transform into an axisymmetric plume at a certain height.

This height (or transition height) is assumed here to be three times the length of the line plume at the opening (= L - B). This means that at a height lower than the transition height, the smoke plume can be regarded as follows :

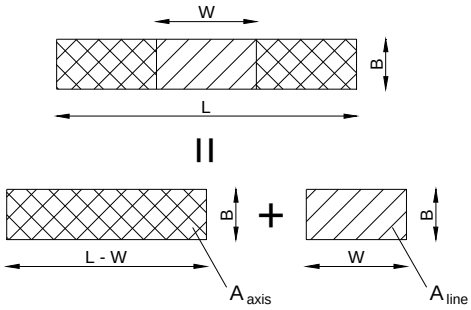


*Figure 2 : Ratio area axisymmetric plume and line plume at a height lower than the transition height (i.e. 0 < z < 3 * (L-B)*

Therefore the length of the line plume and the convective power of the part of the line plume are a function of the height above the opening.
The formula for the mass flow of the axisymmetric line plume ($\dot{m}_{al}$) is described as follows :

1) Height lower than 3 * (L - B)

$$\dot{m}_{al} = 0{,}16 * W^{2/3} * \dot{Q}_{conv,line}^{1/3} * z + 0{,}071 * \dot{Q}_{conv,axis}^{1/3} * (z - z_0)^{5/3} + 0{,}00192 * \dot{Q}_{conv,axis}$$

2) Height higher than 3 * (L - B)

$$\dot{m}_{al} = 0{,}071 * \dot{Q}_{conv,axis}^{1/3} * (z - z_0)^{5/3} + 0{,}00192 * \dot{Q}_{conv,axis}$$

Hypothesis perimeter plume
The second hypothesis considers the smoke plume as a line plume, where the "length" of the line plume is replaced by the perimeter of the opening. The formula for the mass flow of the perimeter plume ($\dot{m}_{pp}$) has the following form :

$$\dot{m}_{pp} = A * P * \dot{Q}_{conv}^{1/3} * z + B * \dot{Q}_{conv}$$

The constants A and B are derived from the FDS simulations as mentioned in the figure below :

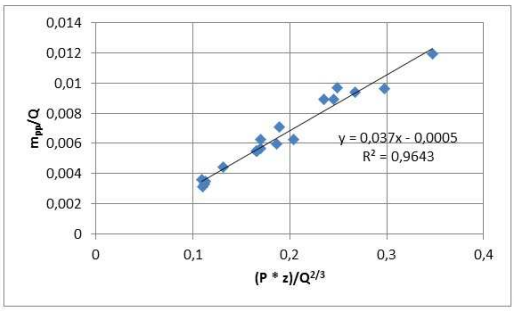


Figure 3 : Determination of the constants A and B on the basis of the obtained results from the FDS simulations

The formula for the mass flow of the perimeter plume ($\dot{m}_{pp}$) can therefore be rewritten as follows :

$$\dot{m}_{pp} = 0{,}037 * P * \dot{Q}_{conv}^{1/3} * z - 0{,}0005 * \dot{Q}_{conv}$$

III. FDS simulations

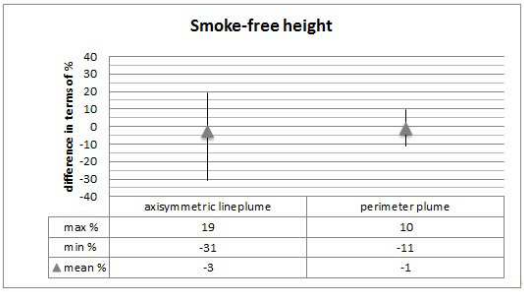
Several simulations using the CFD model FDS [2] were performed. Both mechanical and natural SHEVS were used during these simulations.

During the simulations with mechanical SHEVS, it appeared that the extraction rate, the position of the extraction area in the roof and the grid size have a major influence on the air entrainment in smoke plumes and the smoke-free height. Therefore the results obtained from the FDS simulations with mechanical SHEVS were not used for the verification of both empirical formulas.

During the simulations with natural SHEVS, numerous variations in the configuration have been examined, i.e. length/width ratio of the opening, fire load, orientation to the fire of the opening, distance to the fire of the edge of the opening, etc.

IV. Comparison

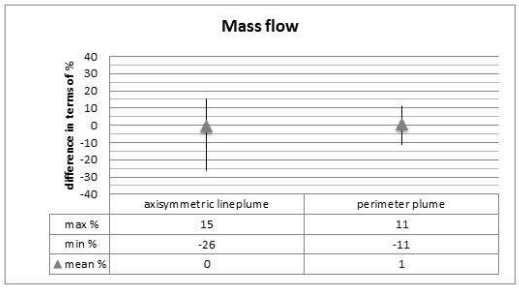
The difference in terms of percentage between the results of the FDS simulation and those obtained with the formula for the "axisymmetric line plume" and the "perimeter plume" for the smoke-free height are given in the figure below :



	axisymmetric lineplume	perimeter plume
max %	19	10
min %	-31	-11
mean %	-3	-1

Figure 4 : Difference in terms of percentage for the smoke-free height (axisymmetric line plume – perimeter plume)

The difference in terms of percentage between the results of the FDS simulation and those obtained with the formula for the "axisymmetric line plume" and the "perimeter plume" for the mass flow are given in the figure below :



	axisymmetric lineplume	perimeter plume
max %	15	11
min %	-26	-11
mean %	0	1

Figure 5 : Difference in terms of percentage for the mass flow (axisymmetric line plume – perimeter plume)

V. Conclusions

Both empirical formulas show good agreement with the results obtained from the FDS simulations. The formula for the "perimeter plume" gave better results compared to the formula for the "axisymmetric line plume".

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References

[1] C. Gryspeert, De invloed van rookverspreiding doorheen horizontale openingen op natuurlijke RWA in industriële gebouwen, 2012
[2] NIST, FDS (Fire Dynamics Simulator) version 5.5.3.