ENHANCEMENT OF THE SMOKE LAYER CALCULATION

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ABSTRACT

The calculation of the mean smoke layer temperature is not sufficient to identify the hazardous conditions in case of a confined fire. The knowledge of the vertical temperature gradient is necessary, mainly in high compartments.

A new method is presented to calculate the vertical temperature distribution in the smoke layer using the discretized conservation equations.

It is shown that, when the smoke layer thickness increases, the mean temperature increases, and the difference between the mean layer temperature and the temperature near the ceiling increases. The results are compared with the previously published measurement. We conclude that the model gives an acceptable temperature prediction far from the ceiling.

1. INTRODUCTION

Whilst designing buildings or warehouses, a fire safety designer has to satisfy some criteria regarding the temperature and the depth of the smoke layer generated in case of fire. To this aim he can design the ventilation conditions.

The aims of the improved conditions are:

- to limit the spread and the development of the fire;
- to safeguard the occupants from exposure to hot gasses and high temperatures;
- to contribute to the stability of the building structure.

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The aim of these models is to predict a representative height of the smoke layer in a room and its mean temperature. However these simplified calculations are often not relevant to the study of some important locations in the room (e.g. near the roof), where the temperature is expected to be substantially higher than the mean value due to the thermal stratification of the hot layer. This can cause damage to the smoke extractors and to the roof itself.

This thermal stratification of the smoke layer is already mentioned in the literature. In 1982, Cooper et al. [3] published a paper which described an experimental study of the dynamical smoke filling in realistic fire scenarios and discussed clearly the thermal stratification of the hot layer.

Recent experimental study [4] showed that the temperature increases significantly with the height in the smoke layer.

In this part of the investigation, we develop a method to calculate the local temperature distribution in the smoke layer, in relation with the height.

2. FORMULATION AND METHOD

Most zone models use constant thermophysical properties. The danger of this assumption remains in the fact that most of the classical formulas disregard the thermal smoke layer stratification, which is manifested by the vertical thermal gradient in the smoke layer.

In the case of a high fire compartment and under given ventilation conditions, the smoke layer can become thick and the zone models hypothesis can be doubtful, because, with the buoyancy energy, the smoke layer tends to be thermally stratified and the vertical temperature gradient is likely to become significant.

If we consider the temperature obtained by the following global energy formula,
\[ T - T_o = \frac{\dot{Q}}{m_i c_p} \] 

where \( T \) is the spatial average temperature in the smoke layer, the temperature near the ceiling can not be identified when the smoke layer is thick.

The fact that the temperature profile is not linear with the height makes the phenomenon more difficult to evaluate.

In the present study, the temperature distribution is approached as one-dimensional problem where the temperature varies only with the height. The smoke layer is divided into a set of \( N \) stratified sublayers as shown in Fig. 1.

The following conservation equations must be satisfied for each sublayer \( i \).

Mass conservation:
\[ \rho_i V_i = \dot{m}_i , \quad i = 1 \ldots N \] 

Bernoulli-law:
\[ \frac{P}{\rho_o} + \frac{V_i^2}{2} + \rho_i g z_i = \text{constant, along a vertical streamline} \] 

(In equation (3), we consider that the pressure is constant over the whole smoke layer).

Density average:
\[ \frac{1}{N} \sum_{i=1}^{N} \rho_i = \rho \] 

\( \dot{m}_o \) and \( \rho \) are calculated from the global expressions of the smoke layer properties: equation (1) and equation (5).

\[ \dot{m}_o = C_o A_o \sqrt{\frac{2 \rho_o d g (\rho_o - \rho)}{\rho + \left( \frac{C_o A_o}{C_i A_i} \right)^2}} \] 

Equation (5) is extensively developed in the literature on smoke evacuation by ceiling vents [1,2,5].

In the steady state regime, the mass flow going out equilibrate the mass flow entering the smoke layer which is given by the Zuoski formula [6]:

\[ \dot{m}_{in} = 0.21 \left( \frac{\rho_o^2 g}{c_i T_o} \right)^{1/3} \frac{\dot{Q}^{1/3} (H - d)^{1/3}}{c_i T_o} \] 

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Fig. 1: The fire compartment - Set of the smoke sublayers
The preceding non-linear equation system (equations (1) to (6)) is solved by the Newton-Raphson iterative method to give the velocity and the density of each intermediate sublayer. The temperature is obtained using the ideal gas law ($\rho T_i = \text{const}$).

3. APPLICATION AND ANALYSIS

In Figs. 2, 3 and 4, a case of a 6 m high compartment, with $S = 50$ m$^2$, $Q = 500$ kW, and $A_v = A_i = 1$ m$^2$, is studied. Fig. 2 shows the solution dependence on the number of the sublayers N.

It is clear that a small number of sublayers is already sufficient to demonstrate the convergence of our model and we note also that the error made when using a simple zone model program ($N = 1$ or $\frac{T_i}{T} = 1$) can be important. The discrepancy between the calculated local value and the mean value is dramatically important toward the two edges of the smoke layer.

The evolution of the mean temperature versus the smoke layer depth is given in Fig. 3, while Fig. 4 represents the difference between the temperature near the ceiling and the mean temperature ($T_N - T$) versus the smoke layer depth.

The influence of the depth d is clearly shown. Indeed when the smoke layer is thick, the smoke mass flow entering (or living) the smoke layer is low (equation (6)), then following equation (1), the averaged temperature is high (Fig. 3) which represents a serious danger to the escape conditions. But the temperature close to the ceiling in this case is much higher, and until now it is seriously underestimated in the literature, which constitutes a danger to the roof integrity (Fig. 4).

**Fig. 2:** Dependence of the results on the number of the sublayers, $d = 3$ m

**Fig. 3:** The mean temperature versus the smoke layer depth
On the contrary, when the chosen smoke layer thickness is small, the temperature can be low and tenable for the occupant and the structure could remain under control.

The choice of this smoke layer thickness, during the building design, in case of fire, which is realised by the appropriate aeration surfaces (Aᵢ and Aᵥ), must be done in a close relationship with the nature of the use of the building.

Fig. 5 shows that for all heat release rates investigated, the local temperature increases with the height (following the buoyancy law). It is to note also that this evolution is significant, and by consequent the attribution of a mean value to the whole smoke layer is to ameliorate.

4. EXPERIMENTAL VALIDATION

In order to determine the degree of validity of our calculation method, a set of experiments are arranged to measure the temperature distribution inside the smoke layer.

Several tests are done varying the heat release of the fire and the openings sizes [4].

The experiments are carried out in a 3.6 x 3.2 x 2.25 m high room, with a door of 2.0 x 0.9 m and a ceiling vent of 0.7 m².

A hexane fuel burner is placed in the middle of the floor that serves to control the heat release rate at the desired value.

Several thermocouples are placed in the room in order to follow the horizontal and the vertical temperature evolutions.

A more detailed description of the test setup is given in Dhimdi and Vandevelde [4].

The temperature values presented in this section represent the horizontal average values inside the smoke layer at each vertical position.

Comparison of the modelling results and experimental results are shown in Fig. 6.
In these figures, we present the vertical temperature evolution inside the smoke layer for different heat release rates.

The comparison between the theoretical and the experimental curves gives an optimistic view on the model, the discrepancies remain acceptable and do not exceed 40% in the worst case.

We must note also that the model results do not fit well the experimental results closely to the ceiling, that is why we do not recommend the use of the model close to the solid boundaries.

This discrepancy can result mainly from neglecting the effect of walls, radiation and the one-dimensional hypothesis of the model.

5. CONCLUSION

We have shown that the smoke layer can be divided in several stratified sublayers giving a spatial temperature distribution. It is confirmed as predicted that the gradient in the smoke layer might be non-negligible, and the knowledge of the mean temperature and the layer depth values are not sufficient for the security requirements, thus the local temperature values must be calculated.

The vertical variation of this value is strongly dependent of the smoke layer depth. Consequently, the vertical properties variations must be added to the safety criteria in buildings.

An examination of the comparisons of the model predictions with the experimental data support the conclusion that the present model is generally capable of producing acceptable predictions for gas layer vertical temperatures.

NOMENCLATURE

- $C_i A_i$: aerodynamic area of the lower opening, $m^2$
- $C_v A_v$: aerodynamic area of the higher opening, $m^2$
- $c_p$: specific heat of the smoke layer, $kJkg^{-1}K^{-1}$
- $d$: smoke layer thickness, $m$
- $g$: gravity acceleration, $ms^{-2}$
- $\dot{m}_o$: mass flow of the evacuating smoke, $kgs^{-1}$
- $N$: total number of the subdivided smoke sublayers,
- $P$: pressure, $Pa$
- $\dot{Q}$: convective part of the heat release, $kW$
- $S$: floor area of the compartment, $m^2$
- $T$: mean temperature of the smoke layer, $K$
- $T_o$: ambient temperature, $K$
- $T_i$: temperature of the sublayer $i$, $K$
- $V_i$: vertical velocity of the smoke in the sublayer $i$, $ms^{-1}$
- $z_i$: height co-ordinate in the sublayer $i$, $m$
- $\rho_o$: ambient density, $kgm^{-3}$
- $\rho$: smoke layer mean density, $kgm^{-3}$
- $\rho_i$: density of the sublayer $i$, $kgm^{-3}$
REFERENCES


