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Smoke Movement in an Atrium with a Fire with Low Rate of Heat Release

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SUMMARY

Results from small-scale experiments on smoke movement in an atrium are given, both with and without a vertical temperature gradient, and expressions for the smoke movement are developed on the basis of these experiments. Comparisons with a general analytical expression used for calculating the height to the location of the smoke layer are given. Furthermore, the paper discusses the air movement in a typical atrium exposed to different internal and external heat loads to elaborate on the use of the "flow element" expressions developed for smoke movement from a fire with a low rate of heat release.

INTRODUCTION

The smoke movement from a fire normally reaches the ceiling in an atrium because of the buoyancy effect on the smoke. The ceiling region is therefore used for location of smoke detectors. A vertical temperature gradient may exist in an atrium as a result of solar radiation or heat release in the building. Some kinds of fire may have such a low rate of heat release that the smoke is not able to reach the ceiling region due to the temperature gradient in the atrium, and it can therefore be difficult to detect the fire. This type of fire can e.g. be a fire which involves a smouldering process.

Figure 1. Smoke movement in a stadium hall. A vertical temperature gradient results in a stratified flow at a certain height.

Figure 1 shows the smoke movement in a stadium hall with a vertical temperature gradient. The smoke rises from the fire, and it entrains surrounding air on its way upwards in the hall. At a certain height it reaches the thermally neutral state, and continues to rise further upwards

because of the momentum flow, but it returns to the thermally neutral height as indicated in the photograph.

It is important to develop models (analytical and numerical) which can predict the flow in the case of a fire with low heat release in a room with vertical temperature gradients to make sure that all situations in the smoke management have been considered. Release of toxic gases in a building could also be addressed by such models.

EXPERIMENTS AND SIMULATIONS

Figure 2. Model scale room and measuring equipment.

The smoke experiments are carried out in a model with the dimensions height, width and length equal to 2.055 m, 1.325 m and 1.325 m, respectively. This corresponds e.g. to an atrium of 30 m x 20 m x 20 m on the scale of 1 to 15. The model is shown on the right-hand side in Figure 2, and registration and control equipment is shown on the left-hand side. The smoke generator is located below the table, and smoke is added to the heat source positioned in the middle of the floor in the model.

The model has "outdoor air" openings in the low part of the building, and openings for smoke ventilation in the "roof". This flow is controlled by two fans when the experiment concerns a conventional situation with smoke ventilation and high heat release.

It is necessary to establish a stable vertical temperature gradient in the model when the experiment concerns a situation with low heat release. The temperature gradient is generated by heating cables mounted horizontally in the model with a vertical distance of 19 cm as shown in Figure 2. The smoke ventilation system is closed in this situation corresponding to the absence of smoke detection in the "low heat release" situation. The temperature gradient is measured by thermocouples in the model, and the height of the smoke layer is measured by a laser beam. The results are documented by photographs and video recording.

Some numerical predictions are introduced at the end of the paper. They are made by the Fire Dynamics Simulator (FDS) by NIST. The program is a shareware, and it is based on large eddy simulation.

RESULTS

Model scale experiments are characterized by the Reynolds number Re and the Archimedes number Ar (Taehti and Goodfellow, 2001). It can be proven that the flow is independent of the Re number when the flow is a highly turbulent flow. A flow with thermal stratification contains relaminarization, but experiments confirm the independence of the Reynolds number even in this case (Nielsen et al., 2004).

Figure 3. Stratification in the model with a high rate of heat release and an active smoke ventilation.

Figure 3 shows the smoke movement in the model in the conventional situation with a high rate of heat release. The smoke layer is located in the upper zone, and the height to this zone is the stratification height y_{st}. The stratification height is a function of the Archimedes number, or a function of the heat release from the fire and the flow rate in the smoke ventilation system, (Nielsen et al., 2004).

The situation will be different if there is a vertical temperature gradient in the room and the heat release is small. The smoke movement is time dependent, and Figure 4 shows four sequences of the flow. In the first picture the plume rises to the height y_m because of the momentum flow in the plume, and then it stratifies in the room between the two heights y_{st1} and y_{st2}, because the temperature of the smoke corresponds to the local temperature at this height (the smoke is thermally neutral at this height). Later on the height y_{st1} moves downwards due to the entrainment in the plume, and the occupied zone will be filled with smoke. In the end, the upper part of the room will also be filled with smoke, and a smoke detector located in the ceiling region will start the smoke ventilation system.
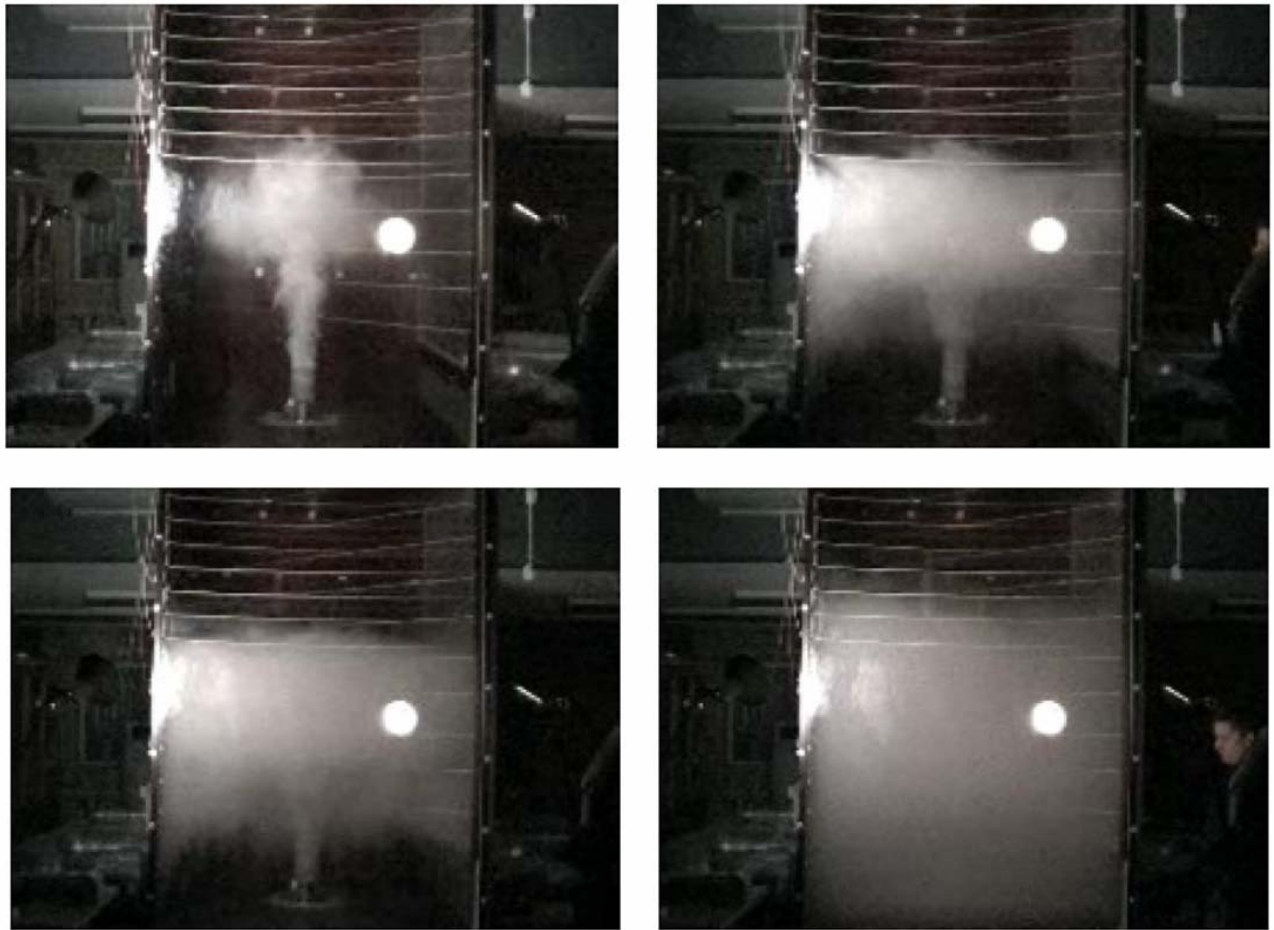
Figure 4. Four sequences of the smoke movement in a room with a vertical temperature gradient and a low rate of heat release from a fire.
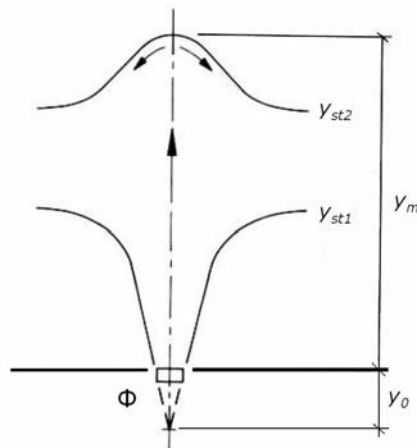

Figure 5. Flow in the plume and definition of the different stratification heights.

The flow, shown in Figure 5 and the first sequence in Figure 4, can be expressed as a flow element. This flow element is often used in the external and internal environment, as for example in the design process for displacement ventilation (Skistad et al., 2002), and it has also been used for the calculation of smoke ventilation (Heskestad, 1998). It can be expressed as

$$y_m = 0.98 \cdot \Phi_k^{1/4} (dT/dy)^{-3/8} + y_0 \tag{1}$$

$$y_{st1} = 0.55 \cdot y_m \tag{2}$$

$$y_{st2} = 0.77 \cdot y_m \tag{3}$$

where y_m, y_{st1}, y_{st2}, y_0 are defined in Figure 5. Dt/dy is the vertical temperature gradient, and Φ_k is the convective heat release from the fire (heat source).

A number of scale model experiments are conducted for the tests of the Equations (1) to (3), see Figure 6.
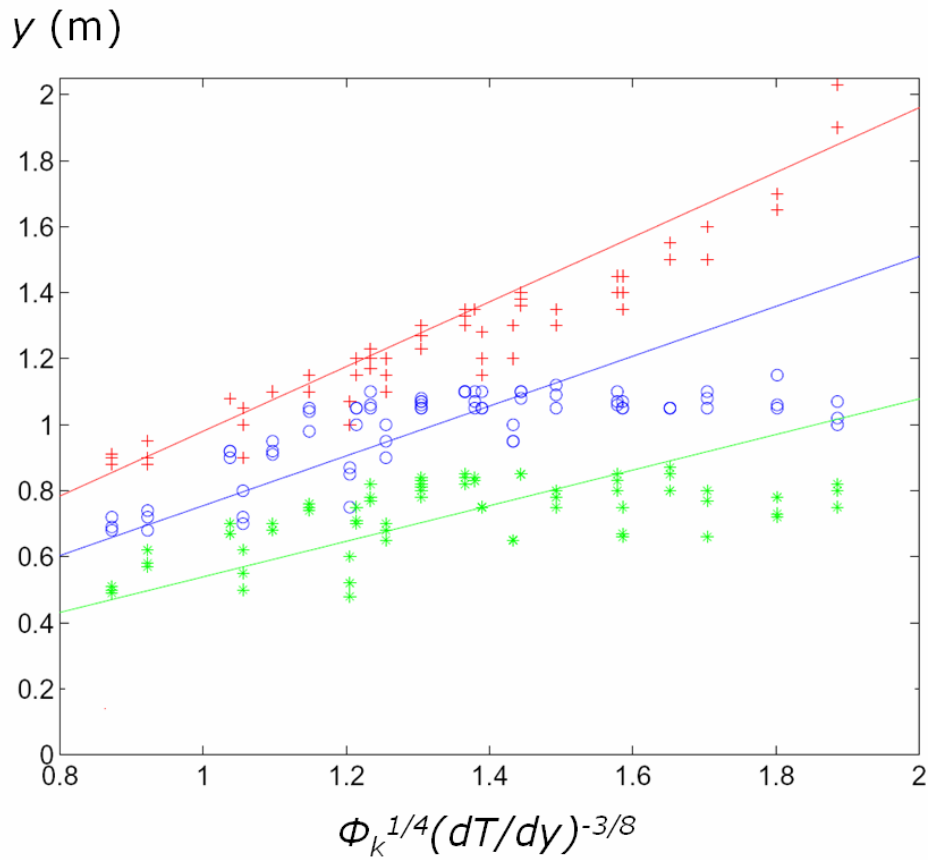

Figure 6. Measurements of the heights y_m, y_{st1}, y_{st2} shown as red, green and blue, respectively. The lines correspond to calculations made by Equations (1), (2) and (3).

Figure 6 shows that Equation (1) is a good representation of the maximum height of a plume in a scale model room, but it is also obvious that deviations are found in Equations (2) and (3). y_{st1} and y_{st2} seem not to be linear functions of y_m. The Equations (1) to (3) are developed in an open environment, and flow at the surfaces in the model, problems at generating linear vertical temperature profiles and the effect of radiation could be some of the explanations behind the deviation between measurements and the Equations (1) to (3).

The following expressions can be developed from the measurements

$$y_m = 0.75 \cdot \Phi_k^{0.25} (dT/dy)^{-0.26} \tag{4}$$

$$y_{st1} = 0.23 \cdot \Phi_k^{0.23} (dT/dy)^{-0.06} \tag{5}$$

$$y_{st2} = 0.44 \cdot \Phi_k^{0.21} (dT/dy)^{-0.04} \tag{6}$$

Those expressions give an improved representation of the experiments and a more conservative estimate of the two heights y_{st1} and y_{st2}. They can be used for smoke movement in an atrium with a fire with low rate of heat release.

SIMULATION OF SMOKE MOVEMENT IN AN ATRIUM

The air movement in a room with a fire with a low rate of heat release may be influenced by more parameters than the temperature gradient and the heat release. The reason is that the driving force from the fire is at the same level as the other convective forces in the room. A number of CFD predictions made by the FDS program illustrate this problem.

The first three cases illustrate the situation where the atrium has a cold ceiling (blue) and a warm side wall (red) due to solar radiation, a cold ceiling and a warm floor, and a cold side wall and ceiling opposite to a warm side wall and floor, respectively. The last case corresponds to the situation where the atrium is located on the side of the building.

The fire is of 15 kW corresponding to the fire in a dustbin. The cold surfaces are 15°C and the warm surfaces are 25°C. The initial temperature in the atrium is 23°C. The figures show the situation after 100 seconds of fire.
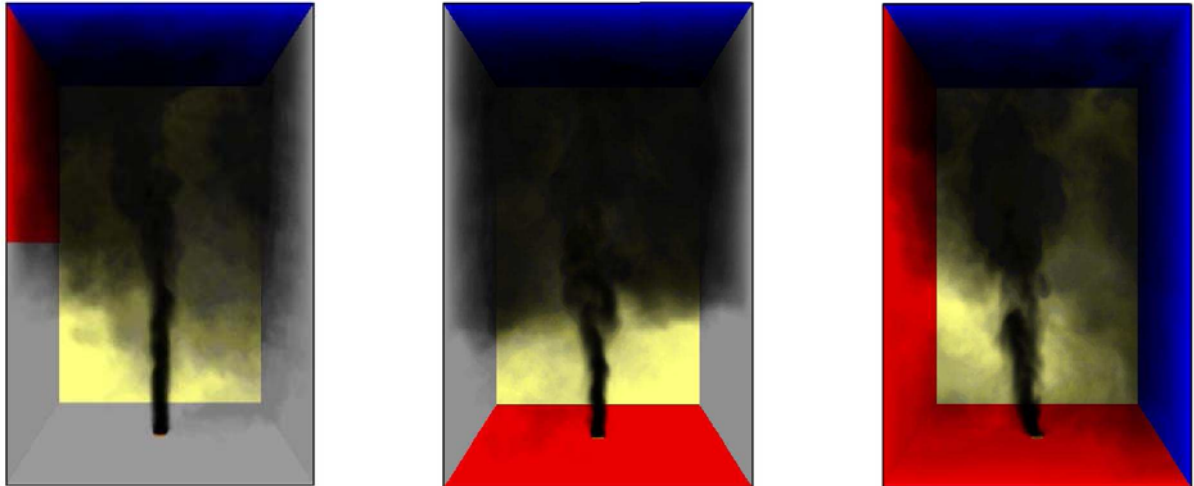

Figure 7. Smoke movement in an atrium with cold and warm surfaces and a fire of 15 kW.

The different temperature distributions in the atrium, Figure 7, are able to modify the smoke distribution. The turbulent flow in the atrium, generated by the buoyant flow, prevents the stratification of the smoke at the heights y_{st1} and y_{st2}. The flow, which has a level of 0.5 m/s

before the fire has started, is able to move the smoke down into the occupied zone, see the last picture in Figure 7.
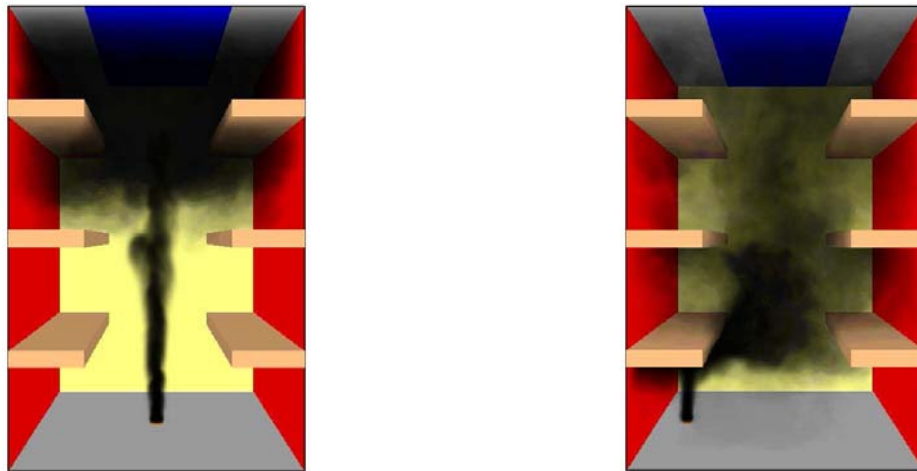

Figure 8. Smoke movement in an atrium with open storeys.

The air distribution in an atrium with open storeys is influenced by outgoing flow from the upper part of all the storeys because of the hot surfaces (~ 0.1 m/s), Figure 8. The turbulence in the atrium dissolves the expected stratification, and the flow will be similar to the one in Figure 3, where the fire has a large heat release. When the fire is located below a storey there are changes in the direction of the plume, and the flow is characterized as a balcony spill plume. A balcony spill plume has a large increase in entrainment of air compared to a conventional plume, resulting in a lower stratification height y_{st} as seen in Figure 8.

CONCLUSIONS
Small-scale experiments on smoke movement in an atrium are used for the development of expressions for the smoke movement in the case of a fire with a low heat release. The expressions are in good agreement with a commonly used flow element for the design of smoke movement.

Furthermore, the air movement in a typical atrium generated by different internal and external heat loads is exposed to smoke movement from a fire with a low rate of heat release. It is shown that turbulence in a room (atrium) will often influence the stratification in a fire with low rate of heat release.

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