# NUMERICAL SIMULATION OF LAYER EFFECT IN A STAIRWELL

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## ABSTRACT

Layer effect in a stairwell under fire scenarios had been studied numerically using large eddy simulation. Simulation results show a fairly sharp layer between the hot smoke flow and air flow under different cases of fire scenarios when changing the total heat release rate (HRR) and the size of outlet door at top of the stairwell. It is found that HRR has remarkable effects on the distributions of smoke temperature, velocity and oxygen concentration. The change of the door height from 0.8 m to 2 m affected the layer effect slightly.

**Keywords:** fire, stairwell, layer effect, large eddy simulation

## 1. INTRODUCTION

The stairwell is a joint of each floor, and it is also an important pathway. When a fire happens in a building, the stairwell is to take the combustion products out of the building, and at the same time, to draw air into the building for combustion, so the stairwell is like a chimney where smoke spread in the vertical direction. The chimney effect of the stairwell will supply air to the fire and accelerate the smoke spread. Experimental and numerical studies of buoyancy-driven flow in the stairwell have been studied [1-4], but most of research efforts are focused on the gas flow in the stairwell by localized heating.

It has been found that there is a layer effect of the smoke spread in a typical stairwell with clapboard, but limited work has been performed on the layer effect due to a fire in a stairwell. Cooper et al. [5-6] had carried out a series of tests based on a two-room fire scenario experiment. The two rooms consisted of a fire (or burn) room and a second closed compartment (corridor). A tracer gas of ZnCl in the form of a smoke bomb was used to simulate smoke and make visualization of the layer effect possible. The fire size was constant for each test. These tests demonstrated a fairly sharp interface between the air and smoke. The temperature in each layer was not uniform, the “layer” really represented a thermocline, so the N-percent rule which is a criterion to judge the height of the smoke layer was established. Corridor is a horizontal pathway in a building, the smoke propagation in the corridor is similar to the propagation in the stairwell. The smoke propagation in a typical structure of buildings made of rooms and a corridor has been studied abroad [7]. It is a great help for the study of the smoke layer effect in a stairwell through the study of the smoke propagation in a corridor. Based on Cooper’s tests, Matsuyama et al. [8] carried out a series of full-scale experiments using $t^2$-fires in multi-rooms. They found that the corridor size and smoke curtain have beneficial effect to delay the smoke propagation to downstream corridors.

Due to the difficulties of quantitative study on smoke motion under real fire scenario, salt water simulation method is used commonly for investigating the flow pattern of smoke motion. The diffusion of salt water in clean water is similar to the propagation of smoke in air. Therefore, it can be used to simulate the spread of smoke. Similarly, the movement of clean water induced by the salt water can also be used to simulate the spread of air induced by the smoke. Zhang et al. [9-10] had simulated the smoke propagation in a corridor with salt water simulation method. These tests indicated two different zones, a salt water zone and a clean water zone existed in the corridor and there was nearly no interaction between the two zones. They found that the intensity and the position of the fire source would affect the height of the smoke layer. Zhang et al. [11] had studied the movement characteristics of smoke in the corridor of a room-corridor building with salt water simulation and double-liquid-dying methods. Salt water flow and water flow can be shown at the same time, and they measured the salt water layer and the water layer flow velocity and found the dimensionless velocity of the smoke layer was not affected by the heat release rate of the fire source in the room.

The above-mentioned investigations of the hot air flow in a stairwell and the smoke spread in a room-corridor were studied mostly experimentally. For numerical simulations of layer effect in fire scenario, only zone models were used. The aim of this study is to investigate detailed information for the estimation of fire-induced layer effect in a stairwell. Fire Dynamics Simulator (FDS) code, based on the concept of large eddy simulation, is used for the present simulations.

## 2. NUMERICAL MODELS

An approximate form of the Navier-Stokes equations appropriate for low Mach number applications is used in the model. In the fire process, the conservation equations of continuity, momentum and energy are filtered using Favre filtering. The filtered conservation equations are shown as:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + u \cdot \nabla \rho = -\rho \nabla \cdot u \qquad (1)$$

Momentum equation:

$$\frac{\partial u}{\partial t} + u \times \omega + \nabla H = \frac{1}{\rho}((\rho - \rho_\infty) g + f + \nabla \cdot \tau) \qquad (2)$$

Energy equation:

$$\nabla \cdot u = \frac{1}{\rho C_p T}(\nabla \cdot k \nabla T + \nabla \cdot \sum \int C_{p,l} dT \rho D_l \nabla Y_l - \nabla \cdot q_r + \dot{q}''') + (\frac{1}{\rho C_p T} - \frac{1}{p_0}) \frac{dp_0}{dt} \qquad (3)$$

Mixture fraction equation:

$$\rho \frac{DZ}{Dt} = \nabla \cdot \rho D \nabla Z \qquad (4)$$

where

$$p = p_0 - \rho_\infty g z + \tilde{p}$$

$$p_0(t) = \rho T R$$

$$\nabla H = \tfrac{1}{2} \nabla |u|^2 + \frac{1}{\rho} \nabla \tilde{p}$$

The viscous stress tensor in the momentum equation is given after filtering,

$$\tau = \mu(2 defu - \tfrac{2}{3}(\nabla \cdot u) I); \qquad defu = \tfrac{1}{2}\left[\nabla u + (\nabla u)^t\right]$$

Adopting Smagorinsky sub-grid scale model, the turbulence viscosity can be modeled as:

$$\mu = \rho (C_s \Delta)^2 (2(defu) \cdot (defu) - \tfrac{2}{3}(\nabla \cdot u)^2)^{1/2}$$

where $C_s$ is an empirical constant, which has a value of 0.2, $\Delta$ is a length in the order of the size of a grid cell.

The mixture fraction combustion model is used. The mixture fraction is defined as:

$$Z = \frac{s Y_F - (Y_O - Y_O^\infty)}{s Y_F^I + Y_O^\infty}, \quad s = \frac{\upsilon_O M_O}{\upsilon_F M_F}$$

Note that $Y_F^I$ is the fraction of fuel in the fuel stream. The mixture fraction varies from Z = 1 in a region containing only fuel to Z = 0 where the oxygen mass fraction takes on its ambient value. The mass fraction of each species can be determined using "state relations".

## 3. NUMERICAL SIMULATION RESULTS AND ANALYSIS

The fire process in a typical stairwell with clapboard is simulated. The length of the stairwell is 4.4 m, the width is 3.0 m and the height is 12 m. Fig. 1 shows the internal structure of the stairwell, there is only one door opened in the upper part of the stairwell, the width of the door is 1.0 m and the height is 2.0 m. There are four segments of staircase in the stairwell, and every segment has 12 steps. The size of every step is equal, the length of a step is 1.4 m, the width is 0.2 m and the height is 0.2 m. There is a clapboard in the middle of the stairwell. The fire source is located at the bottom of the stairwell, the fuel ejects with a stable velocity, the square of the fire source is 3.0 m × 1.0 m.

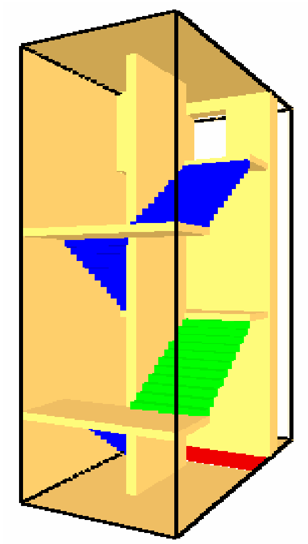
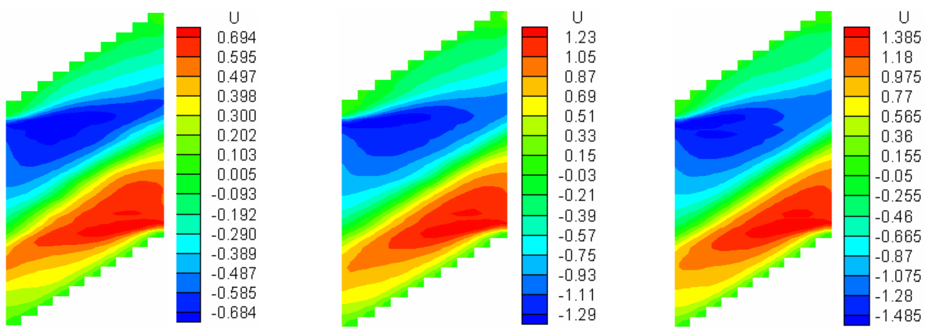


**Fig. 1: Sketch of stairwell**

### 3.1 Effect of Heat Release Rate on Layer Effect

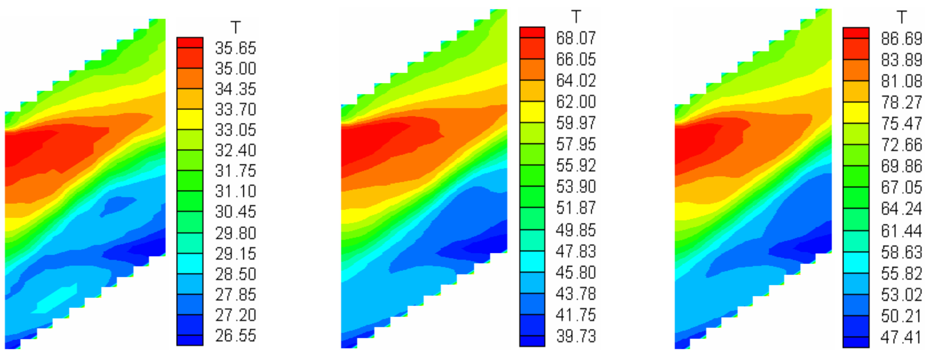
Predicted results of the second segment of staircase from lower to upper as shown in Fig. 1 are given in this paper. In a longitudinal section with a distance of 0.4 m away from the wall, the nephograms of predicted results of velocity, temperature, $O_2$ concentration, $CO_2$ concentration are shown in Figs. 2 to 5. These nephograms show a sharp layer between the upper smoke flow and lower air flow in the stairwell, and there is nearly no interaction between the upper smoke and lower air. A zero velocity cross-section can be found clearly in Fig. 2, the zero velocity section is defined as the interface of the smoke and air. It can be found that a forward flow of smoke propagates away from the fire source along the steps. Since buoyancy drives the flow, loss of buoyancy due to heat transfer from the smoke causes reduction of the smoke velocity in the upper region. Because of the conservation of mass and momentum, air is drawn from the outside of the stairwell and forms the lower layer. The air in the lower layer flows to the fire source to maintain the fire. In Fig. 2, it can be found that when the total HRR increases, the velocity of the upper smoke and the lower air increases rapidly. When the total HRR increases, the thermally driven force is stronger and the yield of the smoke increases, so it can accelerate the smoke out of the stairwell. Since the smoke displacement increases, air drawn from the outside of the stairwell increases too for the conservation of mass in the stairwell. In conclusion, when the total HRR increases, the increase of the air drawn from outside of the stairwell makes the fire behavior stronger and accelerates the hot smoke spread.

As shown in Fig. 3, the temperature in each zone of smoke and air is not uniform, so some criteria are necessary to describe the interface between the hot and cold zones when investigating layer effect according to the temperature distribution. The "layer" really represents a thermocline and, therefore, these criteria simply specify the effective discontinuity when the temperature gradient is the largest. The heated smoke propagates away from the fire source along the steps, and the heated smoke temperature gradually reduces due to heat transfer. In Fig. 3, the upper smoke temperature is higher than that of the lower air. When the total HRR increases, the temperatures of the smoke zone and the air zone increase at the same time, but the smoke zone and the air zone are still obvious. When the total HRR reaches 240 kw, the lowest temperature is higher to $47^0$C in the stairwell, so it will be very dangerous under this condition.




(a) HRR = 30 kw (b) HRR = 150 kw (c) HRR = 240 kw

**Fig. 2: Nephogram of velocity distribution with various HRR**




(a) HRR = 30 kw (b) HRR = 150 kw (c) HRR = 240 kw

**Fig. 3: Nephogram of temperature distribution with various HRR**

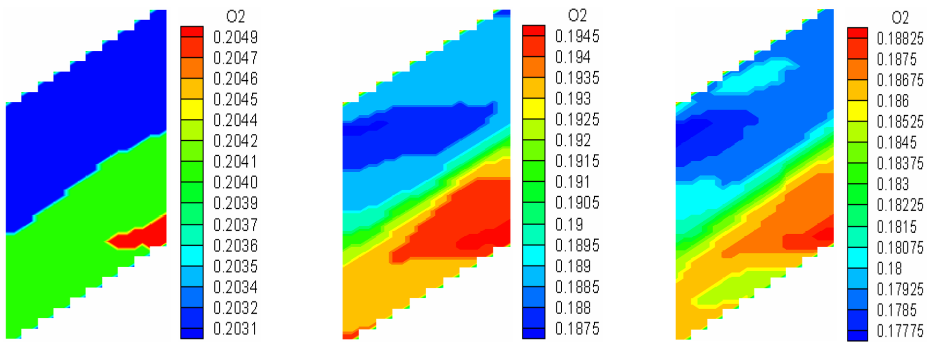
Fig. 4 and Fig. 5 show the layer effect according to species concentration distribution. It can be seen obviously that oxygen concentration is lower in the upper smoke flow region than in the lower air flow region. On the contrary, carbon dioxide concentration is higher in the upper smoke flow region than in the lower air flow region. When the smoke propagates away from the fire source, the oxygen concentration increases gradually due to the oxygen diffusion between the smoke flow region and the air flow region. With the total HRR increasing, the oxygen concentration becomes lower due to the larger consumption of oxygen.

### 3.2 Effect of the Door Size on Layer Effect

The opened door in the upper part of the stairwell plays a role of outlet for smoke flow and inlet for ambient air flow. Simulations had been carried out to investigate the effect of the door size on layer effect in the stairwell. Predicted results in a longitudinal section with a distance of 0.4 m away from the wall are also given. Fig. 6 and Fig. 7 show the velocity distribution and temperature distribution with various door sizes. When reducing the door size from 2 m to 0.8 m in height, the layer effect in the stairwell is still obvious. It can be found that the smoke flow velocity slightly reduces along the steps with reducing door size as shown in Fig. 6. With the decrease in the door size, the outage of the smoke reduces for the same fire size, so the ambient air drawn from outside of the stairwell reduces too because of the conservation of mass. So, the average temperature increases along with the door size reducing as shown in Fig. 7. However, compared with changing HRR, when changing the geometrical sizes of the outlet door, the changes of velocity and temperature are not significant.

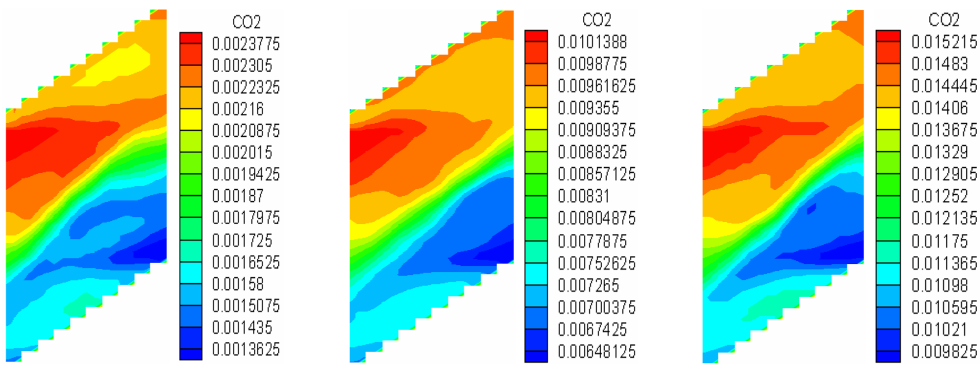
## 4. CONCLUSIONS

Large eddy simulation of layer effect of flow pattern in a stairwell had been carried out in this paper. A fairly sharp layer phenomenon between the smoke flow and air flow in the stairwell was found. It can be found that an upward flow of smoke propagates away from the fire source in the upper region, and cold air flows down to the fire source along the steps. With the total HRR increasing, more ambient air is drawn from outside of the stairwell, and the fire behavior becomes stronger, resulting in rapid increase of the velocity of the upper smoke flow and the lower air flow. Compared with changing HRR, when changing the door size from 2 m to 0.8 m in height, the layer effect in the stairwell is still obvious, but the changes in velocity and temperature are not significant.



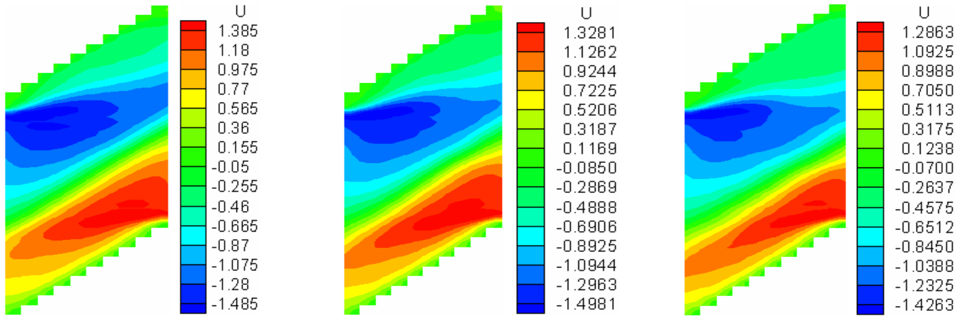

(a) HRR = 30 kw (b) HRR = 150 kw (c) HRR = 240 kw

**Fig. 4: Nephogram of $O_2$ concentration distribution with various HRR**



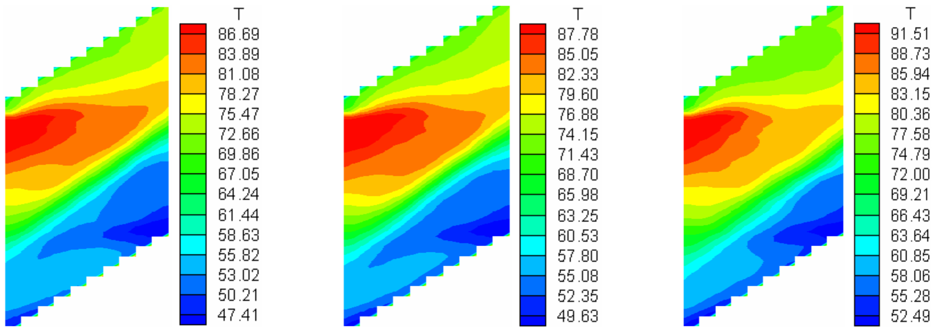

(a) HRR = 30 kw (b) HRR = 150 kw (c) HRR = 240 kw

**Fig. 5: Nephogram of $CO_2$ concentration distribution with various HRR**




(a) size = 1 m × 2 m (b) size = 1 m × 1.6 m (c) size = 1 m × 0.8 m

**Fig. 6: Nephogram of velocity distribution with various door sizes**




(a) size = 1 m × 2 m (b) size = 1 m × 1.6 m (c) size = 1 m × 0.8 m

**Fig. 7: Nephogram of temperature distribution with various door sizes**

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## REFERENCES

1. S. Ergin-Ozkan, M.R. Mokhtarzadeh-Dehghan and A.J. Reynolds, "The effect of different air inlet sizes on the air flow through a stairwell", Indoor Environment, Vol. 2(5/6), pp. 350-359 (1993).

2. S. Ergin-Ozkan, M.R. Mokhtarzadeh-Dehghan and A.J. Reynolds, "Experimental study of natural convection between two compartments of a stairwell", Heat Mass Transfer, Vol. 38, pp. 2159-2168 (1995).

3. A.A. Peppes, M. Santamouris and D.N. Asimakopoulos, "Buoyancy-driven flow through a stairwell", Building and Environment, Vol. 36, pp. 167-180 (2001).

4. A.A. Peppes, M. Santamouris and D.N. Asimakopoulos, "Experimental and numerical study of buoyancy-driven stairwell flow in a three storey building", Building and Environment, Vol. 37, pp. 497-506 (2002).

5. L.Y. Cooper, Estimating safe available egress time from fires, Nat. Bur. Stand. (U.S.), NBSIR 80-2172 (1981).

6. L.Y. Cooper. M. Harkeroad. J. Quintiere and W. Rinkinen, "An experimental study of upper hot layer stratification in full-scale multiroom fire scenarios", Journal of Heat Transfer, Vol. 104, pp. 741-749 (1982).

7. W.J. Walter and J.G. Quintiere, "Prediction of corridor smoke filling by zone models", Combustion Science and Technology, Vol. 35, pp. 239-253 (1984)

8. K. Matsuyama and T. Wakamatsu, Systematic experiments of room and corridor smoke filling for use in calibration of zone and CFD fire models, Nat. Bur. Stand. (U.S.), NBSTIR 6588 (2000).

9. R.J. Zhang, B.K. Ma, H.P. Zhang, W.C. Fan and J.X. He, "Simulation of smoke spread in a rooms-corridor building during initial stage of fires", Fire Safety Science, Vol. 4, No. 2, pp. 17-23 (1995).

10. H.P. Zhang, R.J. Zhang, B.K. Ma, W.C. Fan and R. Huo, "Experimental study of air motion induced by smoke plume and ceiling jet in a burning building by means of salt water modeling method", Journal

of Experimental Mechanics, Vol. 12, No. 1, pp. 70-79 (1997).

11. H.P. Zhang, Z.K. Xie, X.Q. Jiang, R. Huo and W.C. Fan, "Salt water modeling of the characteristics of fire smoke movement in a corridor", Journal of China University of Science and Technology, Vol. 29, No. 4, pp. 664-670 (1999).