Three Dimensional Simulation of Atrium Smoke Movement

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ABSTRACT

Three-dimensional fire-induced air-flow, temperature and smoke concentration in an atrium is simulated and visualised. The field modelling approach employing Computational Fluid Dynamics (CFD) techniques is adopted with turbulence being modelled by the two-equations k-ε model. The simulation shows that ordinary exhaust rate of 6 ACH and 10 ACH failed to hold the safe evacuation time to more than two minute. A higher exhaust rate might induce more recirculation of heated air inside the atrium space and thus is not able to remove it effectively.

NOMENCLATURE

c	smoke obscuration concentration
C_μ ,C_1,C_2,C_3	turbulent constants
g	gravitational acceleration
G	generation rate of turbulence energy
k	turbulence kinetic energy
OD	optical density
S	general source term
t	time
u	velocity vector
x,y,z	co-ordinates
β	thermal expansion coefficient
ε	turbulence dissipation rate
ρ	density
μ	viscosity coefficient
ϕ	general dependent variable
Γ	general diffusion coefficient
σ_k , σ_ε , σ_c	turbulent Schmit number
σ_t	turbulent Prandtl number
Δt	time step
Δx	x-direction width of the control volume

INTRODUCTION

The rapid economic growth of fast developing economies in this region has resulted in the building of more modern shopping complexes and hotels. Many of these buildings are designed with the atrium as a feature. As the boundary between such atriums and the rooms or shops are either glazed or completely opened, smoke and hot gases may spread to other parts of the building through the atrium opening during a fire. Thus the study of fire-induced smoke movement in such atria is very important for the design of effective smoke control systems.

Conventional smoke control in atrium buildings can be broadly divided into two categories: within a compartment; and in the atrium. Smoke and heat can be prevented from entering into the atrium by using physical blockage like a downstand or smoke curtain, together with some kind of exhaust system within the compartment. When the smoke and heat cannot be confined to the room of origin or that the fire occur on the floor of the atrium, the use of 'throughflow' or steady-state ventilation from the atrium itself is usually considered. This ventilation system uses the buoyancy of the smoke to provide the driving force for extraction. Inlet replacement is required. In many cases, powerful exhaust fans are installed at the roof of the atriums to provide the necessary extraction force.

In the study of building fires, more attention have been devoted to the field modelling techniques for the last 15 years. These techniques employ the computational fluid dynamics (CFD) approach in which general flow equations of conservation of mass, momentum, heat, along with other governing differential equations are discretised and solved numerically. The rapid development of computing technology and power has enabled fire development to be predicted with reasonable accuracy and the field model has becomes an increasingly popular tool for such purpose. G Cox, *et al.*(1990) used the field model in the code JASMINE to evaluate the efficiency of smoke control systems designed using traditional methods and planned for installation in a very large, six story atrium complex. The model simulated a growing fire by assuming the heat release rate to increase exponentially with time, doubling every one minute. On the activation of the first sprinkle head, the heat release rate would be halved instantaneously. Xue and Chew(1994) used a two-dimensional turbulence k-ε model to predict distribution of fire-induced air flow, temperature, and smoke concentration in an atrium. The numerical treatment adopted a source term linearization method for artificial sources converted from boundary control surfaces to obtain stable calculation and fast convergence.

The present study simulates the fire-induced air flow and smoke movement in a full scale atrium by a three-dimensional k-ε turbulence model. The building is a single envelope of overall dimension 50m long, 35m wide by 25m high. Inside, the design envisaged six floors of shops or rooms, each of 10 m in depth. A downstand of 1 m separate the shops from the corridors of 2 m in wide. A central atrium approximately 28 m by 10 m stands at about 25 m. Each floor (except the first floor) is 4 m high. The main entrance situated at both front and rear of the building is 10 m wide, and four emergency exit of 3m wide are located at the sides of the building. The plan of the model is as shown in Figure 1. This model assembles many medium-sized shopping malls or hotels that are gaining increasing popularity in many developing economies.

The common smoke control method for atrium building using powered exhaust fans at the ceiling is simulated in this model. The exhaust rates of 6 ACH and 10 ACH are simulated with the fire of size 3m x 3m located at the atrium floor at about 10m from the north boundary of the building and 8m from the first exit at the west boundary. This location is chosen to simulate the worst scenario whereby fire and smoke is highly possible to affect both the rooms and the corridors at all levels in the building. Furniture fire is assumed primarily because this is the most likely fire source in such buildings as many shopping malls have regular exhibitions being held in the atrium space. Exhibition stands, temporarily stage, etc. are usually made of wooden materials, thus furniture fire is chosen as the fire source in this simulation.

DESCRIPTION OF THE MATHEMATICAL MODEL

Three-dimensional turbulent buoyant flow and heat transfer are considered for the mathematical model. The time-averaged balance equations for mass, momentum, energy and smoke concentration are adopted. The unsteady term in the mass conservation equation is retained. The fluctuation of the density is ignored so that the density is only related to the temperature of the air through the equation of state $\rho = \rho(T)$. The physical properties of air such as thermal expansion coefficient β, viscosity coefficient μ, etc. are given as polynomial functions of temperature.

In the evaluation of smoke concentration, the smoke obscuration concentration is used. It is expressed in optical density (OD) per meter and can be related to human visibility as

$$\text{visibility (in metres)} = \frac{1}{\text{OD per meter}} \quad \text{for front illumination,}$$

and

$$\text{visibility (in metres)} = \frac{2.5}{\text{OD per meter}} \quad \text{for rear illumination.}$$

Visibility is an important factor in the assessment of speed and ability of evacuation in a fire outbreak. Since smoke obscuration is in proportion to the conservative concentration in weight (kg/m^3), it can be also considered as a conservative quantity. Therefore the smoke obscuration distribution *c* can be predicted by solving the corresponding conservative equation.

The time-averaged continuity, momentum, and general transport fluid scalar equations written in a conserved Cartesian tensor form are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u'_i u'_j}) + g_i(\rho - \rho_0) \qquad (2)$$

$$\frac{\partial(\rho \phi)}{\partial t} + \frac{\partial(\rho u_j \phi)}{\partial x_j} = \frac{\partial}{\partial x_j}(\Gamma_\phi \frac{\partial \phi}{\partial x_j} - \rho \overline{u'_i \phi'}) + S_\phi \qquad (3)$$

where ϕ represents *c, k* or ε, which are the smoke obscuration concentration, turbulence kinetic energy, and turbulence energy dissipation. The term S_ϕ represents the appropriate source or sink of the variable ϕ concerned.

For the closure of the governing equations, the two-equation k-ε model of turbulence is used. The eddy viscosity is obtained by the Prandtl-Kolmogorov relation

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

where C_μ is an empirically determined coefficient.

The source term of the k-ε equation are

$$S_k = G_k + G_B - \rho\varepsilon \tag{5}$$

$$S_\varepsilon = C_1 \frac{\varepsilon}{k}(G_k + G_B)(1 + C_3 R_f) - C_2 \frac{\rho\varepsilon^2}{k} \tag{6}$$

where $$G_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \tag{7}$$

and $$G_B = -\beta g_i \frac{\mu_t}{\sigma_t} \frac{\partial T}{\partial x_i} \tag{8}$$

In the above equations, G_B represents an exchange between the turbulence kinetic energy and the potential energy. In stable stratification G_B becomes a sink term so that the turbulent mixing is damped while the potential energy increases. In unstable stratification, the buoyancy will enhance turbulence since G_B is positive. The constant C_3 control the effect of buoyancy on the ε equation. Rodi[8] suggested that a flux Richardson number can be defined as

$$R_f = -\frac{G_B}{G_k + G_B} \tag{9}$$

for horizontal shear layers and $R_f = 0$ for vertical shear layers. The constants used in the model are given in Table 1 (Xue, Chew and Cheong, 1995).

Table 1. Constants in the k-ε model

C_1	C_2	C_3	C_μ	σ_k	σ_ε	σ_t	σ_c
1.44	1.92	0.80	0.09	1.00	1.30	1.00	0.70

There are generally two types of boundary conditions: the solid wall boundaries and the inlet/exhaust free surfaces. No-slip conditions are assumed for the velocity components over the whole solid walls. As for temperature and smoke obscuration concentration, no-flux boundary conditions are employed except on the surface of the fire source where specific heat and smoke flux are prescribed.

At the low-turbulence region close to the walls, the standard logarithmic velocity, temperature and smoke concentration profiles are assumed to hold between the solid wall and the first grid point next to it.

At the inlet, all dependent variables are prescribed. The smoke concentration is zero. The values of k and ε are empirically given as $k_{in} = 0.02u_{in}{}^2$ and $\varepsilon_{in} = C_\mu k_{in}{}^{1.5}/0.05$. At the outlet, zero-gradient conditions are prescribed for all dependent variables.

The program commences with the computations for the ventilation air flow to its steady state before the introduction of the heat and smoke sources at time $t = 0$. A uniform temperature (set at 28°C) and a zero smoke obscuration distribution are assumed as initial conditions.

In an actual fire, the rate of fire and smoke spread depend on many factors such as the material properties, the convective heat transfer to the flammable surface from the fire, conduction heat transfer within the surface material, etc. The mechanism involved in the combustion process is very complicated but these details are not simulated in this model. Rather, the fire and smoke sources are represented as local heat and smoke release rates given as boundary conditions in the numerical model.

NUMERICAL EXPERIMENTS

Numerical computations are conducted to study the fire and smoke behaviour in the atrium. The total computational field contains 57720 grids. The time step used in the calculation was 0.05 second. Applying Courant stability guide,

$$\left| u_{max} \times \frac{\Delta t}{\Delta x_i} \right| \leq 1 \tag{10}$$

the computation will only be unstable if the maximum flow exceeds 20 ms^{-1}. Since the maximum exhaust rate is set at 2 ms^{-1}, the above time step was adopted.

The numerical computational conditions in this study are listed in Table 2.

Table 2. The different cases studied in the three-dimensional simulation

Case	Ventilation rate	Fire source	Fire area	Heat release rate	Smoke generation rate
1	Exhaust - 6ach	Furniture	9 m^2	28.6 kW/m^2	14.7 (1/m.m)/s
2	Exhaust - 10ach	Furniture	9 m^2	28.6 kW/m^2	14.7 (1/m.m)/s

RESULTS AND DISCUSSION

In the analysis of the three-dimensional results, the front corridor, the back corridor and the central atrium planes were considered. This is because the success evacuation of occupants depends very much on the conditions of these escape routes.

The transient conditions at 30 seconds, 1 minute, 2 minute and 3 minute after the fire has fully developed were analysed. These first few minutes after the fire break out is often considered as crucial moments for the safe evacuation of occupants.

As noted by Beard (1992), the maximum tolerable temperature above eye level (taken to be 1.5 m) would be 183°C and that below would be 100°C. As for visibility, Butcher (1979) claimed a minimum visibility of 5 m is required for successful evacuation under fire conditions. This work out to be a smoke density of 0.2 OD/m (assuming front illumination) and 0.5 OD/m (assuming rear illumination). This critereon is used in the analysis.

The results of Case 1 - Furniture fire with 6 ach exhaust are presented in Figures 2 - 5. At this exhaust rate, heat has not been able to build up in the first two minutes of the fire. Except for the part near to the fire, the rest of the escape routes are safely below 80°C (Figs. 2 - 3). By the third minute, temperature at the first and sixth floor would hit as high as 200°C, while the other levels at the back corridor would also reach about 100°C, except for the portions nearer to the exits. As for that of the front corridor, temperature below eye-level on these floors are still below the critical mark (Fig. 4).

The smoke is prevented from entering the floors in the earlier stages by the downstands. However, due to an excessive accumulation in the atrium, the smoke will penetrate into the rooms or shops eventually, bringing visibility to below one metre (Fig. 5).

In view of the temperature and smoke conditions, the safe evacuation time for this configuration would be around 2 minutes after the fire has fully developed. It should be noted that the present model of fire assume that the heat flux and smoke generated at a constant rate of a developed funiture fire from the time t = 0 when the fire breaks out. This certainly will predict a fire and smoke spreading speed faster than that in a practical atrium fire. A combustion model of furniture fire is needed in the future study.

In addition, this simulation is based on a simplified flow model where only convective and diffusive heat transfer is accounted for. The effect of radiation is not modelled.

The results of Case 2 - Furniture fire at 10 ach exhaust are shown in Figures 6 - 8. It was hoped that with a higher exhaust rate of 10 ach, heat and smoke can be removed more effectively from the atrium building. However, the simulation proved otherwise.

Since the fire source is located nearer to the north-west corner of the atrium floor (it is not directly below the exhaust outlet), the hot plume rises faster from one side of the atrium. This is more prominent at this higher rate. As the adjacent sides are still cooler, thermal stratification occurs, resulting in the circulation of air flow inside the atrium (Fig. 6). Thus smoke is not removed effectively but instead, it spread into the corridors even more rapidly (Fig. 8). Because of the fast accumulation of the thick smoke, the safe evacuation time is less than 2 minutes in this case.

CONCLUSIONS

The predictions of heated air flow and smoke in a full scale atrium have provided a direct simulated visualisation of a real atrium fire. The computer simulation captured the fire-induced air flow, heat and smoke propagation in a complex atrium geometry.

The simulation result also show that a higher exhaust rate may not necessarily remove smoke more effectively. As seen from the comparison between Case 1 and Case 2, a higher 10 ach rate may induced more recirculation of air inside the atrium, this hinder the smoke from rising to the exhaust outlet. In a lower 6 ach rate, the hot plume does not rise as rapidly and the thermal stratification is not too noticeable in the early stages of the fire. This interesting observation is especially prominent for furniture fire that has a high smoke release rate.

Our simulations have generally given a insight of the very complex fire and smoke behaviour in an atrium. With further improvements to the model, it can definitely simulate the real fire situation with greater precision.

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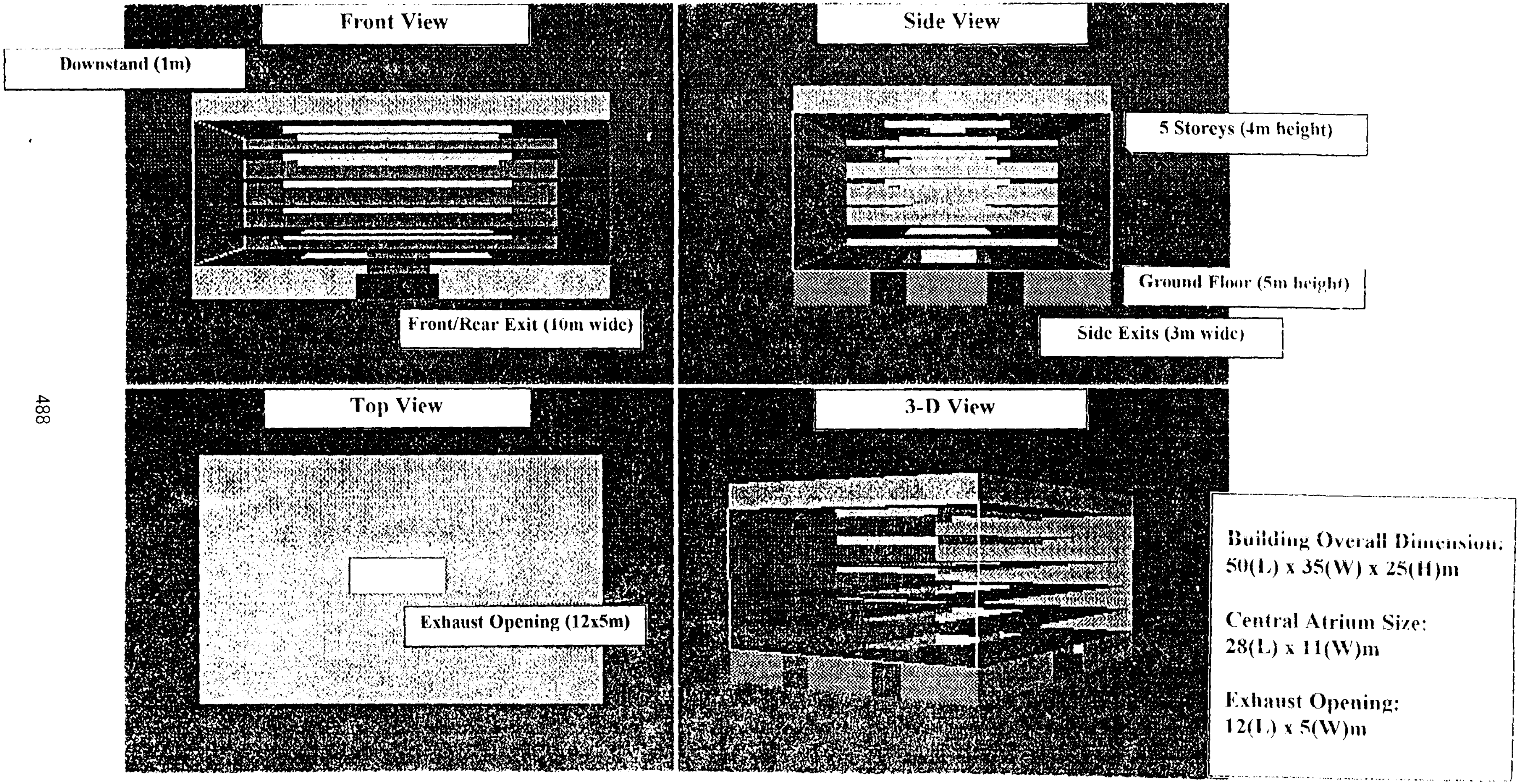
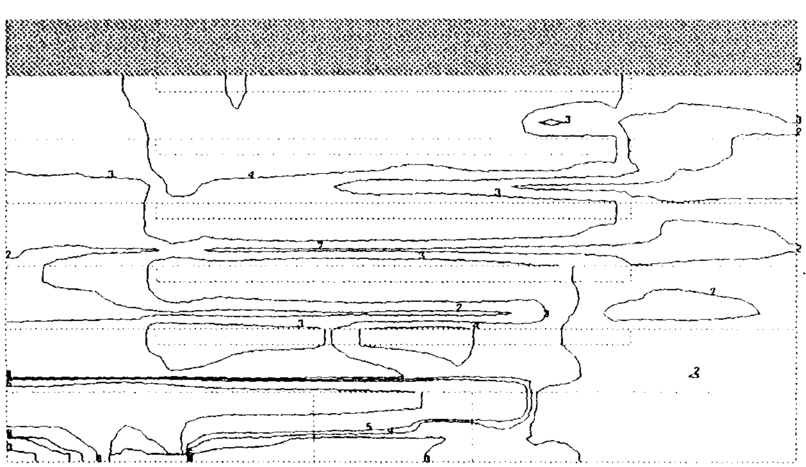
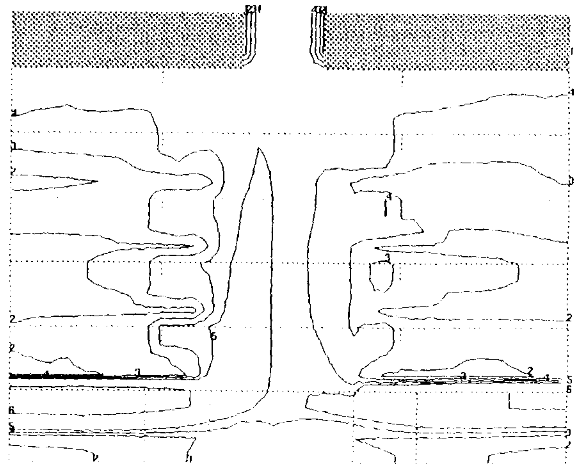


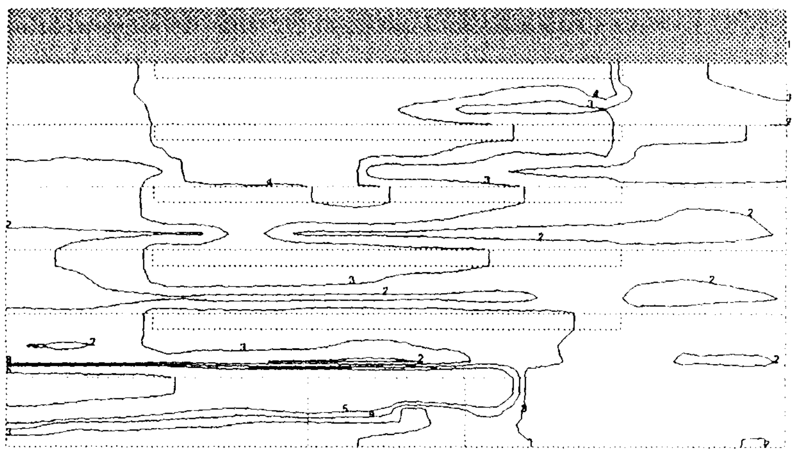
Figure 1. The 3-D Atrium Model



Back Corridor (X-Y Plane, Z=10.5)



Central Atrium (Y-Z Plane, X=24.5)

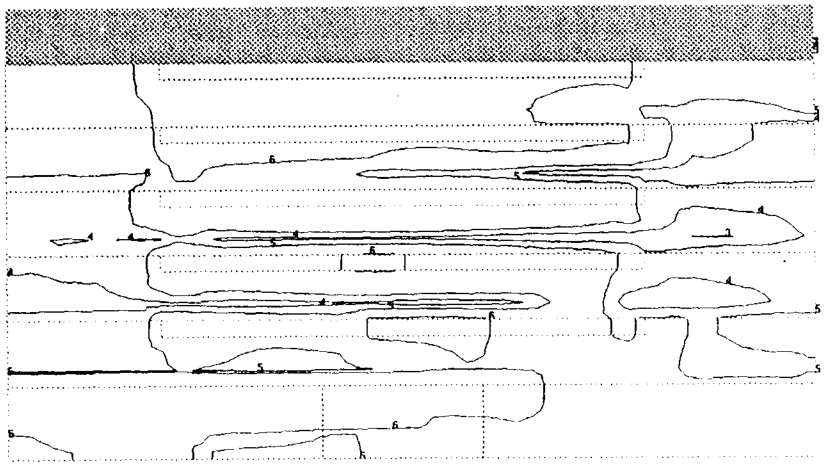


Front Corridor (X-Y Plane, Z=23.5)

Level	1	2	3	4	5	6	7	8
(°C)	30.0	40.0	60.0	80.0	100.0	200.0	500.0	800.0

<u>Case 1</u>
Fire Source: Furniture
Exhaust Rate: 6 ACH
Time Elapsed: 120 sec.

Figure 2. Temperature Contours of Case 1 at t = 120 seconds



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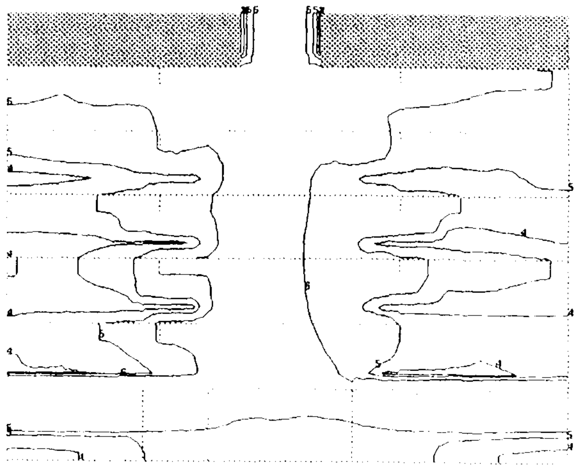
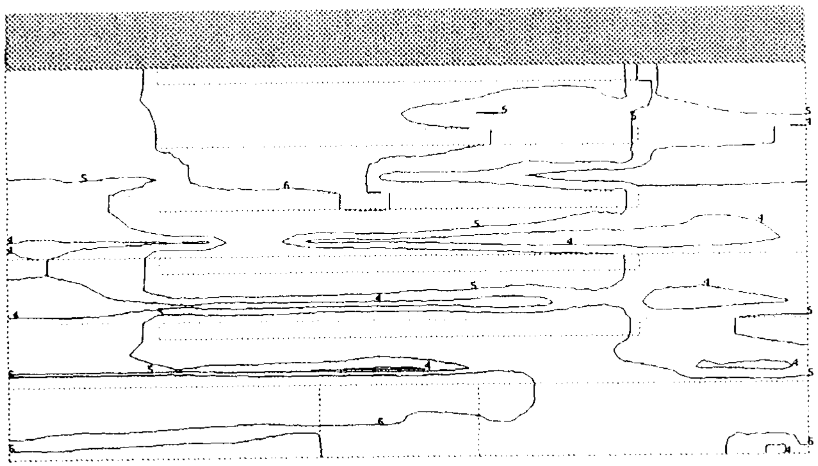


Central Atrium (Y-Z Plane, X=24.5)

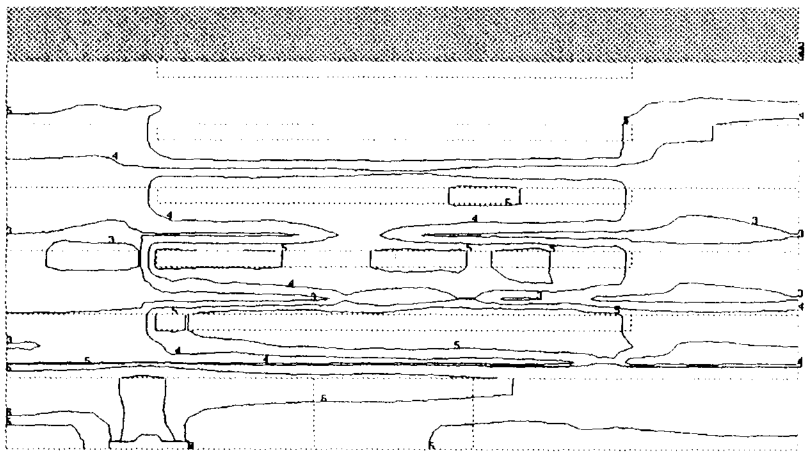


Front Corridor (X-Y Plane, Z=23.5)

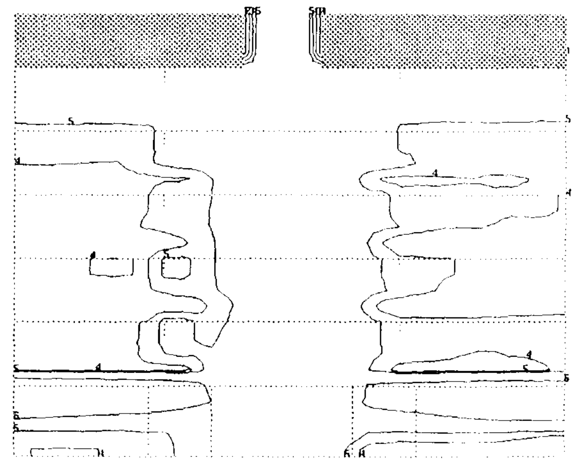
Level	1	2	3	4	5	6
(OD/m)	0.1	0.5	1.0	5.0	10.0	20.0

Case 1
Fire Source: Furniture
Exhaust Rate: 6 ACH
Time Elapsed: 120 sec.

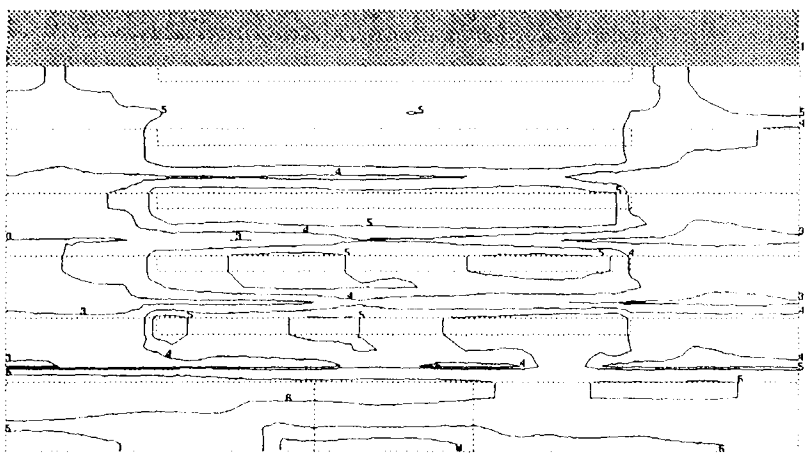
Figure 3. Smoke Contours of Case 1 at t 120 seconds



Back Corridor (X-Y Plane, Z=10.5)



Central Atrium (Y-Z Plane, X=24.5)

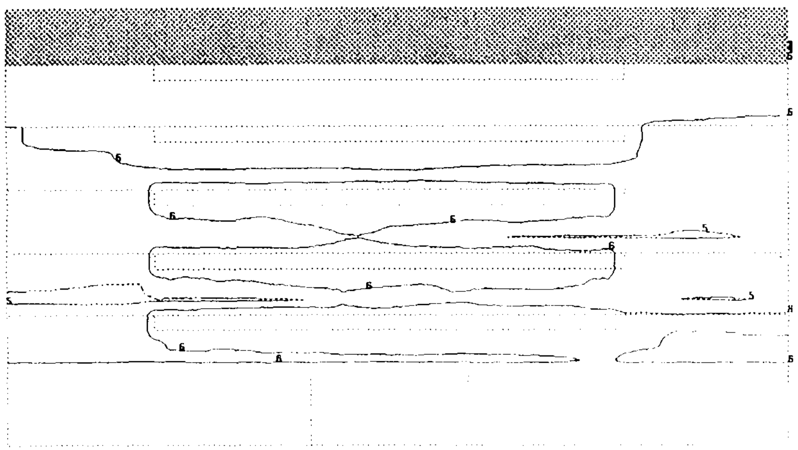


Front Corridor (X-Y Plane, Z=23.5)

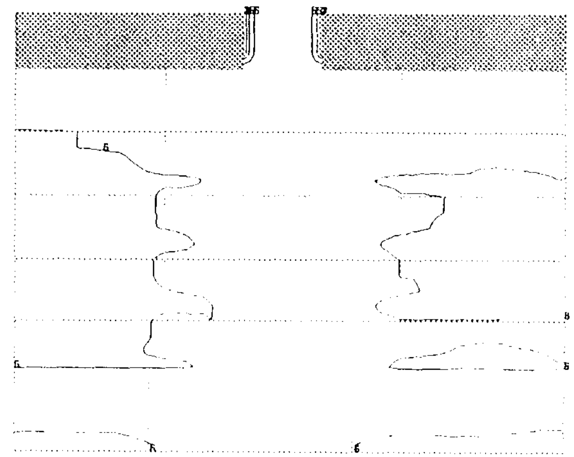
Level	1	2	3	4	5	6	7	8
(°C)	30.0	40.0	60.0	80.0	100.0	200.0	500.0	800.0

<u>Case 1</u>
Fire Source: Furniture
Exhaust Rate: 6 ACH
Time Elapsed: 180 sec.

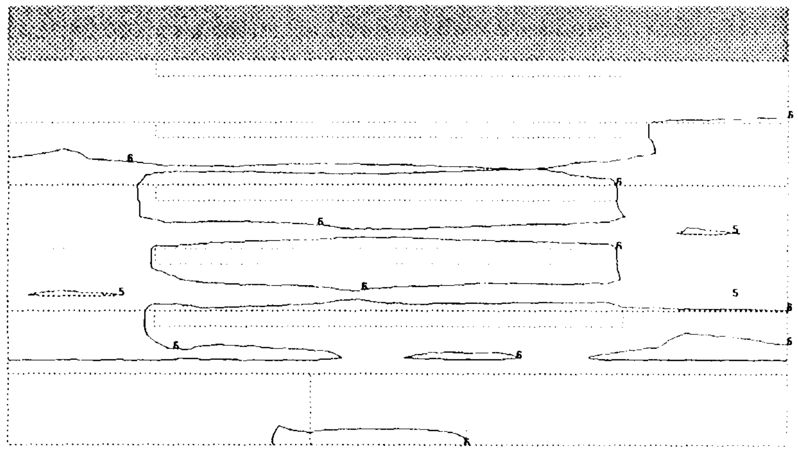
Figure 4. Temperature Contours of Case 1 at t = 180 seconds



Back Corridor (X-Y Plane, Z=10.5)



Central Atrium (Y-Z Plane, X=24.5)

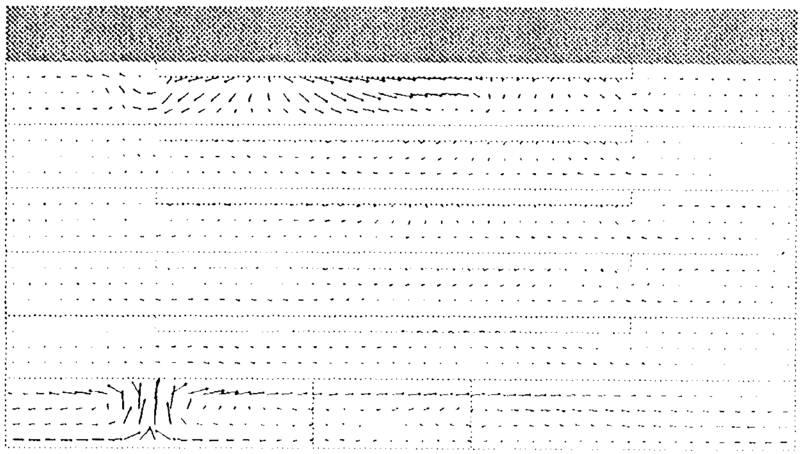


Front Corridor (X-Y Plane, Z=23.5)

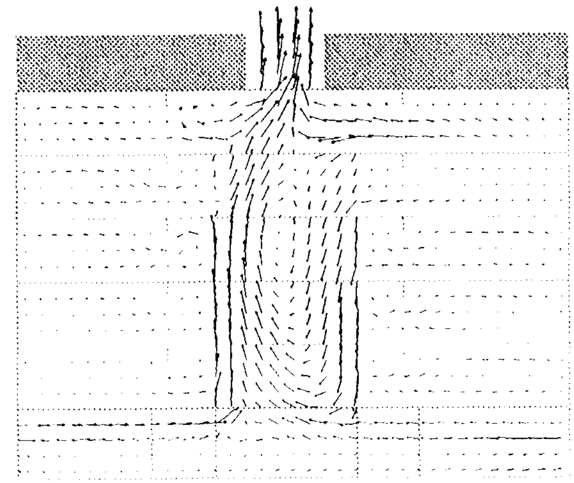
Level	1	2	3	4	5	6
(OD/m)	0.1	0.5	1.0	5.0	10.0	20.0

<u>Case 1</u>
Fire Source: Furniture
Exhaust Rate: 6 ACH
Time Elapsed: 180 sec.

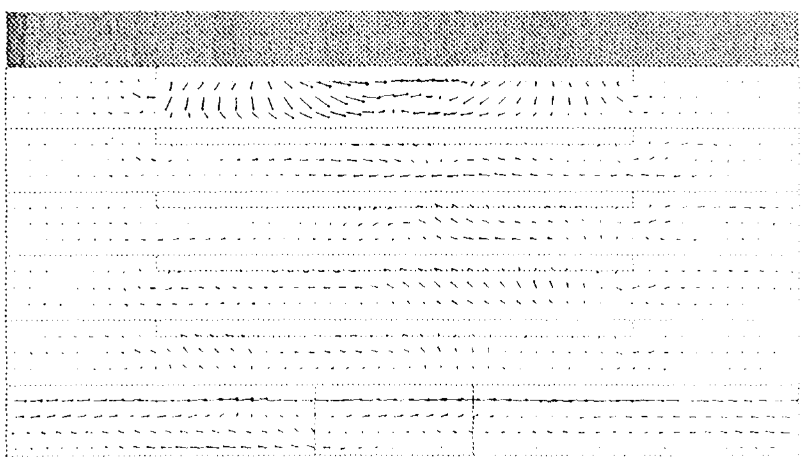
Figure 5. Smoke Contours of Case 1 at t = 180 seconds



Back Corridor (X-Y Plane, Z=10.5)



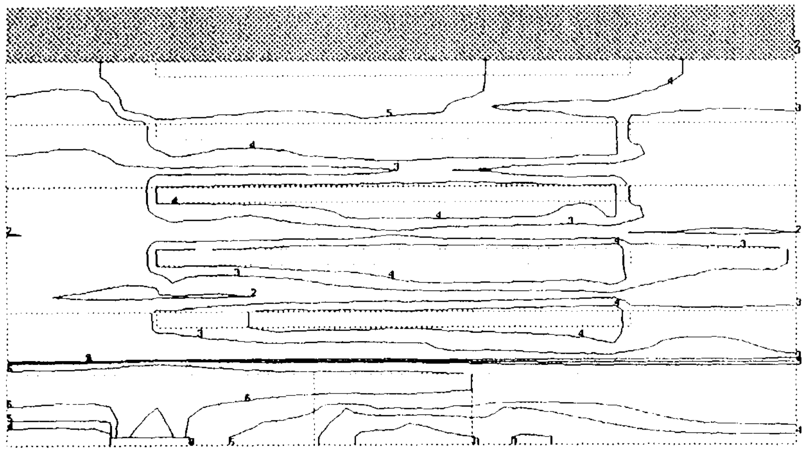
Central Atrium (Y-Z Plane, X=24.5)



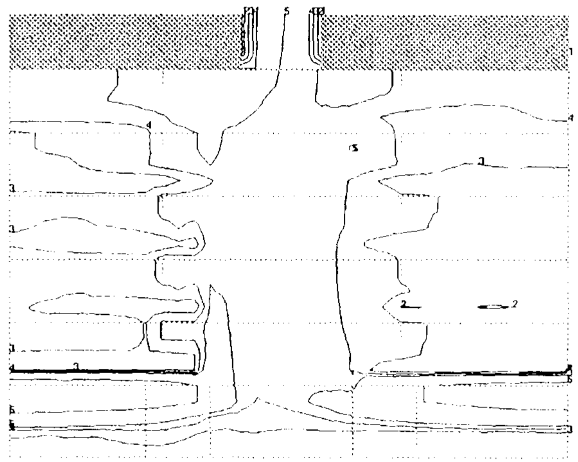
Front Corridor (X-Y Plane, Z=23.5)

Case 2
Fire Source: Furniture
Exhaust Rate: 10 ACH
Time Elapsed: 120 sec.

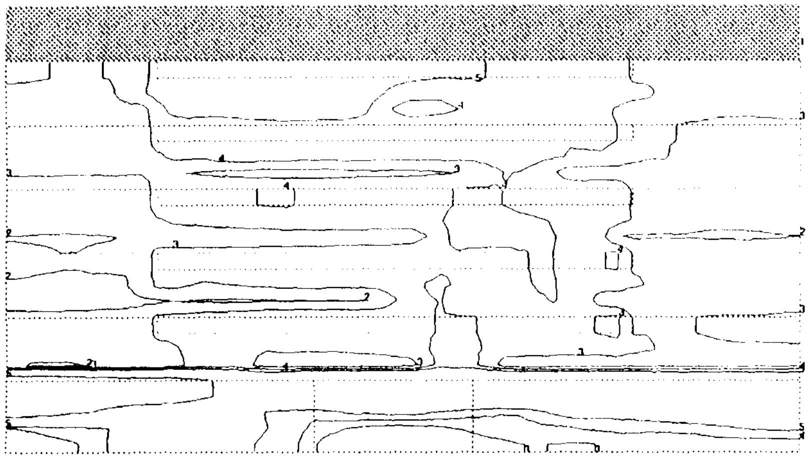
Figure 6. Velocity Vectors of Case **2** at t = 120 seconds



Back Corridor (X-Y Plane, Z=10.5)



Central Atrium (Y-Z Plane, X=24.5)

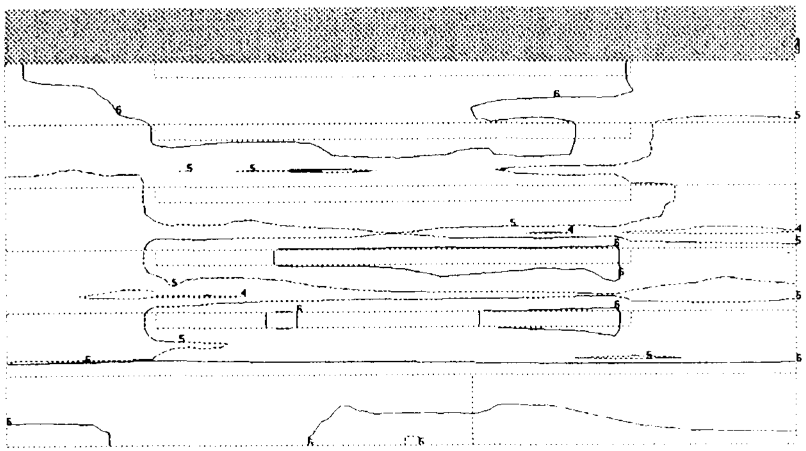


Front Corridor (X-Y Plane, Z=23.5)

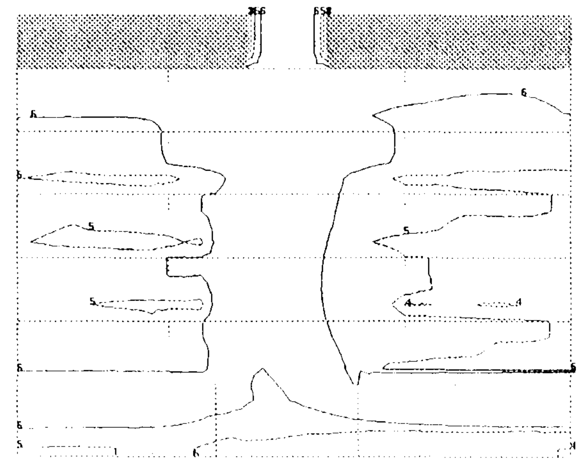
Level	1	2	3	4	5	6	7	8
(°C)	30.0	40.0	60.0	80.0	100.0	200.0	500.0	800.0

<u>Case 2</u>
Fire Source: Furniture
Exhaust Rate: 10 ACH
Time Elapsed: 120 sec.

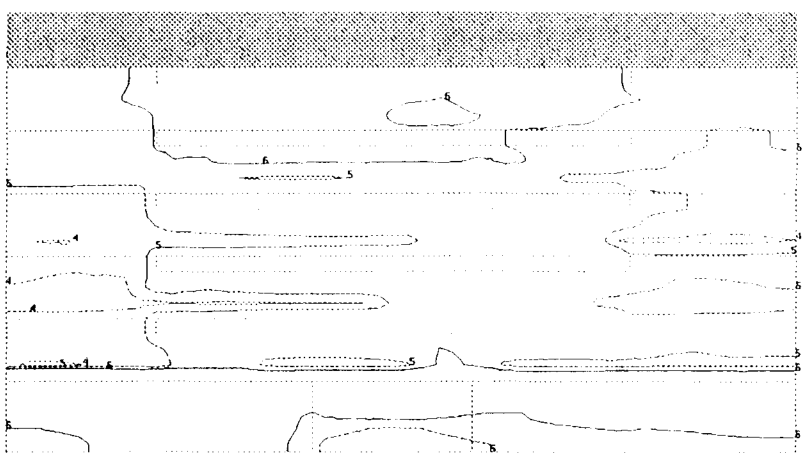
Figure 7. Temperature Contours of Case 2 at t = 120 seconds



Back Corridor (X-Y Plane, Z=10.5)



Central Atrium (Y-Z Plane, X=24.5)



Front Corridor (X-Y Plane, Z=23.5)

Level	1	2	3	4	5	6
(OD/m)	0.1	0.5	1.0	5.0	10.0	20.0

<u>Case 3</u>
Fire Source: Furniture
Exhaust Rate: 10 ACH
Time Elapsed: 120 sec.

Figure 8 . Smoke Contours of Case 2 at t = 120 seconds