International Journal on Engineering Performance-Based Fire Codes, Volume 2, Number 2, p.68-76, 2000

SMOKE MOVEMENT IN ATRIUM BUILDINGS

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ABSTRACT

A computational fluid dynamics (CFD) model based on PHOENICS has been used to evaluate the distribution of fire-induced air flow, temperature and smoke concentration in an atrium. Two numerical experiments carried out in two atria with similar size, fan locations and fire type, but of different height have been examined. A physical model in an atrium with different size and fan locations, but of the same fire type has also been studied.

In the first numerical experiment where the fire source was located at the base of a 30 m high atrium, it was found that smoke was extracted effectively by the extraction system. In the second numerical experiment where the fire source was located at the base of a 60 m high atrium, smoke was not extracted effectively by the extraction system. Stratification was observed at 240 s.

In the physical model with the fire source located at the base of a 50 m high atrium, smoke was trapped at the ceiling of the atrium and moved into the shops of the same level. The extraction fans located at the smoke reservoir were not able to extract the smoke in the area effectively.

The results of the simulations highlight the effect of atrium height and locations of exhaust fans on the smoke movement in atrium buildings.

1. INTRODUCTION

In the 1960's, when Singapore had just joined the rank of newly independent countries, there were very few shopping complexes and hotels with atrium design. The first Singapore fire code was written in 1974 following the guidelines of the fire code in UK.

In the 1980's, the number of shopping complexes and hotels with large atrium increased rapidly. Among them were the China Town Point, Funan Centre and Marina Square. The atrium volume ranged between 25,000 m^3 to 35,000 m^3 and the atrium height ranged from 12 to 24 m. The dilution method with ventilation rate of about 4 to 6 air changes per hour was used as a smoke control guide. The revised fire code introduced in 1982 did not clearly define the methodology for smoke control design.

Larger atrium buildings emerged later included the Oriental Hotel, Regent Hotel and Marina Mandrain Hotel. The atrium volume ranged between 85,000 m^3 to 200,000 m^3 and the atrium height ranged from 45 to 65 m. Engineered smoke control for atrium was introduced in the revised fire code in 1997 [1] and the recommended atrium design shall be in accordance with:

- BR 186 - Design Principles for Smoke Ventilation in Enclosed Shopping Centres [2];
- BR 258 - Design Approaches for Smoke Control in Atrium Buildings [3]; or
- Other acceptable standards.

The development of atrium buildings in Singapore is to a large extent, similar to that of Hong Kong [4]. A typical shopping mall may comprise a large vertical column of space surrounded by open balconies leading to food courts, individual shops and offices. A fire at a lower level can be hazardous to higher levels due to the smoke and fire spreading through the atrium space.

It has been shown that the spread of smoke rather than fire poses more serious threat, as the heat released by the fire loads in an atrium is normally low [5,6]. Since forced-ventilation systems are installed in most commercial buildings in Singapore, an effective smoke control system is essential to ensure efficient fire escape and fire fighting. There are three essential features of a smoke control system:

- There must be some means of forming a smoke reservoir to prevent the lateral spread of smoke, which would result in excessive loss of buoyancy.

- There must be extraction of smoke from the reservoir to prevent the smoke layer building down below the design depth.
- There must be fresh air intake at a rate equal to the rate of extraction at a low enough height not to mix prematurely with the smoke.

A lot of works have been carried out on forced ventilated fires [7-17].

This paper summarises a study based on the new fire code [1]. The results of the computational fluid dynamics (CFD) simulations using PHOENICS [18-19] on two numerical experiments and one physical model with varying factors such as the positions and rate of exhaust, fresh air intake and fire type are discussed.

2. GEOMETRY AND PROPERTIES

The geometries for the two numerical experiments labelled as NA and NB are shown in Figs. 1 and 2. There are two openings of 5 m by 5 m at the first level for air inlet, and eight powered extraction fans with discharge capacity of 20 m^3s^{-1} each located at the smoke reservoir. Each level has a 10 m by 60 m floor plate on both sides with the central opening forming the atrium and the smoke reservoir. The numerical experiment NA is a 5-storey atrium of 30 m high and NB is a 11-storey atrium of 60 m high.

The geometry of the physical model labelled as PM is shown in Fig. 3. There are two openings of 5 m by 5 m at the first level for air inlet, and eight powered extraction fans with discharge capacity of 16 m^3s^{-1} each located at the smoke reservoir. Each level has a 20 m by 50 m floor plate on both sides with the central opening forming the atrium and the smoke reservoir. The model is a 5-storey atrium of 50 m high.

The following air properties were assumed for the initial condition:

- Density 1.18 kgm^{-3}
- Laminar kinematic viscosity 1.544 x $10^5m^2s^{-1}$
- Specific heat capacity 10005 $JKg^{-1}K^{-1}$
- Temperature 23 ^oC

The fire source was modelled by defining heat flux at one designated location of the fire outbreak. Mobile stores were located in the atrium. The fire size was assumed to be 5 MW [1].

The number of time steps set in the simulation was 10, and equal distance grid of 25, 25, 25 were set for the x, y, and z direction respectively.

Smoke obscuration, expressed in terms of optical obscuration (OD) per meter (ODP) and normally used for the evaluation of the field of human vision, affects significantly the evacuation time of people in the smoke. It has been shown that smoke obscuration is proportional to the conservation concentration in weight (kgm^{-3}) and can also be considered as a conservative quantity [16-17].

Equation (1) shows the relationship between smoke obscuration and the calculated density.

$$ODP = (G_S/-\rho) \times \rho_C + G_S \quad (1)$$

with

$$G_S = \rho\, C_g / A_s \quad (2)$$

and

$$C_g = \rho_d\, v_g\, D_c\, A_s \quad (3)$$

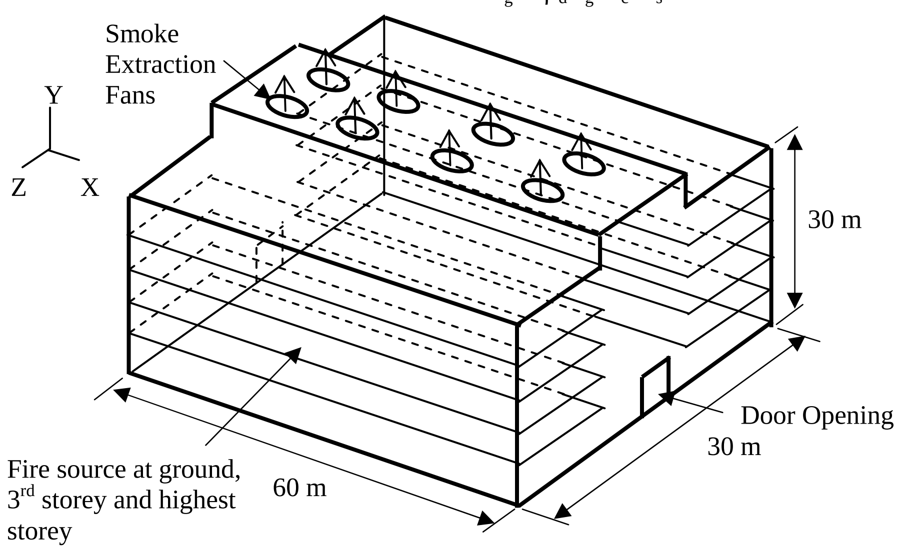


Fig. 1: Geometry of numerical experiment NA

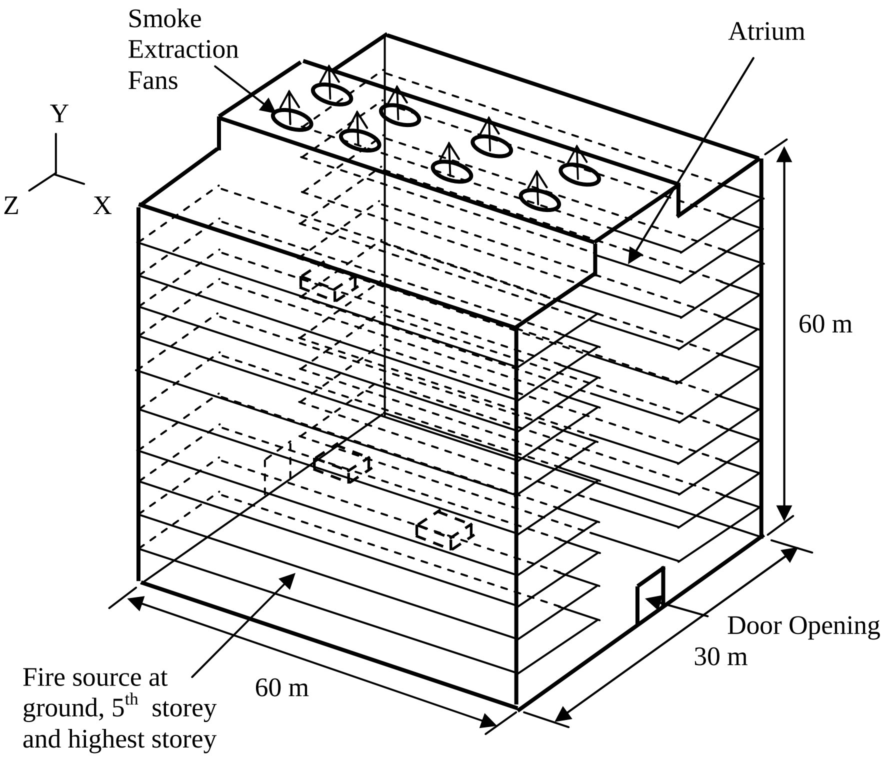


Fig. 2: Geometry of numerical experiment NB

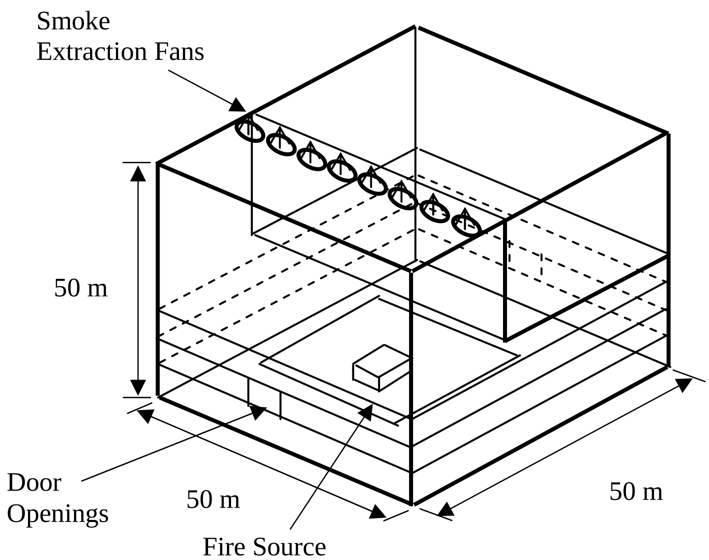


Fig. 3: Geometry of the physical model PM

where ODP is the smoke obscuration (in ODm^{-1}), G_S is the total smoke flux ($m^{-1}\cdot kgs^{-1}\cdot m^2$), C_g is the smoke generation rate ($m^{-1}\cdot m^3s^{-1}$), D_c is the coefficient of smoke obscuration ($m^{-1}\cdot m^3kg^{-1}$), v_g is the burning rate (kgs^{-1}), ρ is the density of air (kgm^{-3}), ρ_C is the calculated air density (kgm^{-3}), ρ_d is the density of burning material (kgm^{-3}) and A_s is the burning area (m^2).

3. RESULTS AND DISCUSSION

The results are summarised in Tables 1 to 3. The smoke concentration strength, density, temperature and velocity vector distributions of various configurations at the end of their respective simulations are shown in Figs. 4 to 6.

Table 1: Numerical experiment NA with fire at atrium

Parameter	Results at 30 s after the fire outbreak	Results at 240 s after the fire outbreak	Remarks
Smoke Concentration	At atrium & smoke reservoir: ranges from 0.21 to 0.29 At 1st to 5th level: 0	At atrium: ranges from 0.21 to 0.29 At 1st to 5th level: 0	The smoke concentration lost its strength at 240 s after the fire outbreak.
Density (Obscuration)	At atrium & smoke reservoir: ranges from 9 to 3 ODm^{-1} At 1st to 5th level: 0 ODm^{-1}	At atrium & smoke reservoir: ranges from 10 to 1.5 ODm^{-1} At 5th level corridor: ranges from 1.5 to 2.5 ODm^{-1} At 1st to 4th level: 0 ODm^{-1}	At 240 s after the fire outbreak, the 5th level corridor was filled with smoke.
Temperature	At atrium & smoke reservoir: ranges from 70 to 86 ^oC At 1st to 5th level: ranges from 23 to 37 ^oC	At atrium & smoke reservoir: ranges from 67 to 90 ^oC At 1st to 5th level: ranges from 23 to 43 ^oC	The temperatures in all areas are still within the acceptable limits.
Velocity Vector	Max. velocity: 7.5 ms^{-1}	Max. velocity: 4.1 ms^{-1}	Due to the smoke built up in the atrium and smoke reservoir, the velocity reduced.

Table 2: Numerical experiment NB with fire at atrium

Parameter	Results at 30 s after the fire outbreak	Results at 240 s after the fire outbreak	Remarks
Smoke Concentration	At atrium & smoke reservoir: ranges from 0.14 to 0.21 At 1st to 5th level: 0	At atrium: ranges from 0.14 to 0.21 At 1st to 5th level: 0	The smoke concentration rose up to mid way and quart way of the atrium at 30 s and 240 s after the fire outbreak respectively. This shows that the smoke concentration lost its strength due to the high atrium.
Density (Obscuration)	At atrium & smoke reservoir: ranges from 2.5 to 0.7 ODm^{-1} At 1st to 5th level: 0 ODm^{-1}	At atrium & smoke reservoir: ranges from 2.5 to 0.7 ODm^{-1} At 1st to 5th level: 0 ODm^{-1}	The smoke rose up to mid way the atrium at 240 s after the fire outbreak. This shows that the smoke lost its strength due to the high atrium.
Temperature	At atrium & smoke reservoir: ranges from 90 to 113 ^oC At 1st to 5th level: ranges from 23 to 37 ^oC	At atrium & smoke reservoir: ranges from 105 to 133 ^oC At 1st to 5th level: ranges from 23 to 43 ^oC	The temperatures in all areas are within the acceptable limits.
Velocity Vector	Max. velocity: 6.8 ms^{-1}	Max. velocity: 4.1 ms^{-1}	Due to the smoke built up in the atrium and smoke reservoir, the velocity reduced.

Table 3: Physical model PM with fire at atrium

Parameter	**Results at 30 s after the fire outbreak**	**Results at 240 s After the fire outbreak**	**Results at 600 s after the fire outbreak**	**Remarks**
Smoke Concentration	At atrium: ranges from 0.21 to 0.29 At basement to 3rd level: 0	At atrium & 3rd level ceiling: ranges from 0.21 to 0.29 At basement to 2nd level: 0	At atrium, smoke reservoir & 3rd level: ranges from 0.21 to 0.29 At basement to 2nd level: 0	The smoke was well contained in the atrium at 30 s after the fire outbreak. At 240 s, the smoke started to fill the 3rd level. At 600 s, the smoke filled the 3rd level as well as the smoke reservoir.
Density (Obscuration)	At atrium: ranges from 2.5 to 0.7 ODm^{-1} At basement to 3rd level:0 ODm^{-1}	At atrium, smoke reservoir & 3rd level ceiling: ranges from 10 to 1.5 ODm^{-1} At basement to 2nd level: 0 ODm^{-1}	At atrium, smoke reservoir & 3rd level: ranges from 10 to 1.5 ODm^{-1} At basement to 2nd level: 0 ODm^{-1}	The smoke was well contained in the atrium at 30 s after the fire outbreak. At 240 s, the smoke started to fill the 3rd storey. At 600 s, the smoke filled the 3rd level as well as the smoke reservoir.
Temperature	At atrium: ranges from 98 to 124 ^{o} C At basement to 3rd level: ranges from 23 to 37 ^{o} C	At atrium: ranges from 74 to 101 ^{o} C At basement to 3rd level: ranges from 23 to 43 ^{o} C	At atrium, smoke reservoir and 3rd level: ranges from 74 to 101 ^{o} C At basement to 2nd level: ranges from 23 to 43 ^{o} C	The temperatures in all areas are still within the acceptable limits.
Velocity Vector	Max. velocity: 7.9 ms^{-1}	Max. velocity: 7.9 ms^{-1}	Max. velocity: 4.1 ms^{-1}	Due to the smoke built up in the atrium and smoke reservoir, the velocity reduced.

In the numerical experiment NA where the fire source was located at the base of a 30 m high atrium, the smoke could be effectively extracted by the extraction fans located directly above the atrium. When the smoke reservoir was completely filled with smoke at 240 s after the outbreak of fire, the smoke started to move to the levels adjacent to the smoke reservoir. The smoke obscuration in this area exceeded the acceptable limits. Smoke curtains are proposed at this area to prevent smoke entering as shown in Fig. 4.

In the numerical experiment NB where the fire source was located at the base of a 60 m high atrium, the smoke was not able to rise to the top of the atrium. Hence, it could not be effectively extracted by the smoke extraction system. This stratification phenomenon was observed at 240 s after the fire outbreak as shown in Fig. 5.

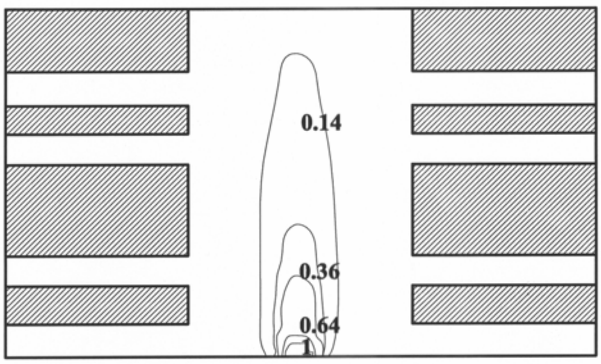
In the physical model with the fire source located at the base of a 50 m high atrium, it was observed that the smoke was trapped at the ceiling of the atrium and moved into the shops of the same level. The extraction fans located at the smoke reservoir could not effectively extract the smoke from this area as shown in Fig. 6.

4. CONCLUSION

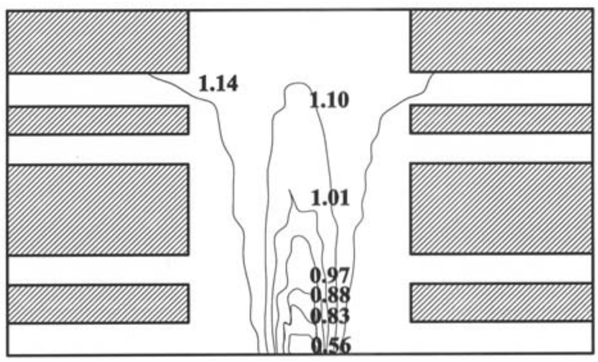
Two numerical experiments carried out in two atria with similar size and fire type, but of different height were examined. Another physical model with different fan locations was also examined. The results generated for the physical model was found comparable to the results obtained from the actual smoke test.

The results of the simulations highlight the significance of atrium height and fan locations on the efficient extraction of smoke. Atria higher than 30 m with exhaust fans located towards the ends may require attention to extract and control the smoke effectively.

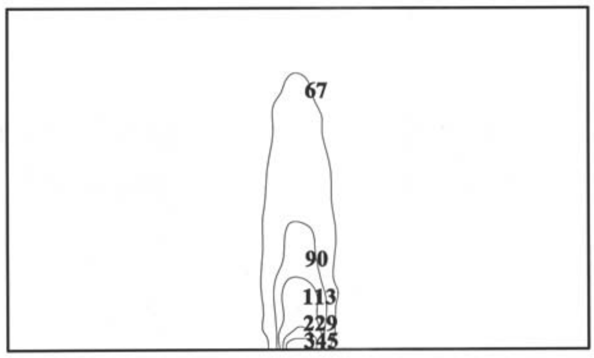
The simulation tool employed appears to be useful in the understanding, testing and justification of the effectiveness of fire safety systems in an atrium. However, careful experimental validation is needed before the results can be adopted as a quantitative guide.



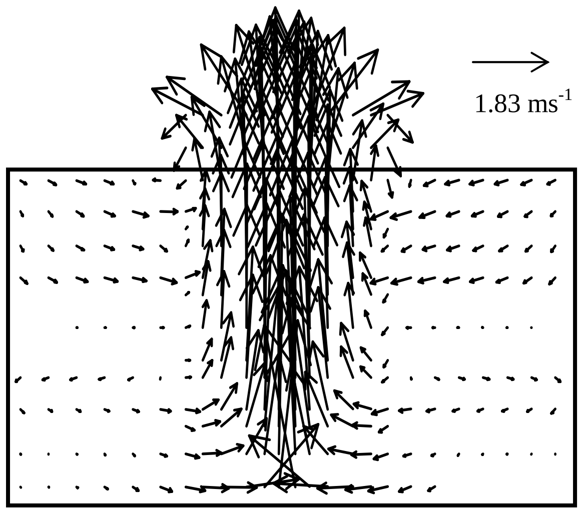
(a) Smoke concentration distribution (Y-Z plane, X=15)



(b) Density distribution (Y-Z plane, X=15)

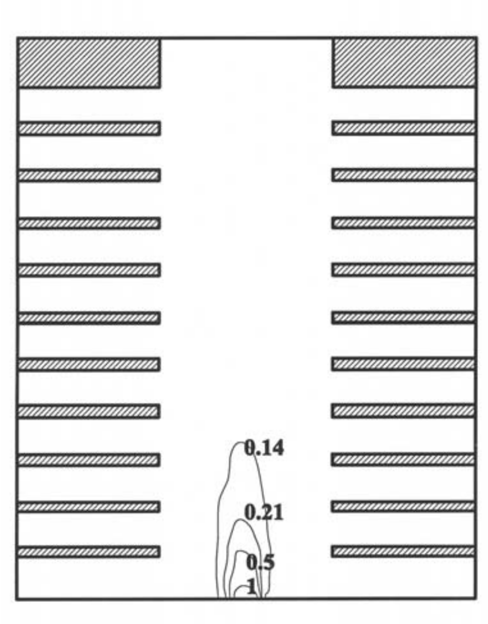


(c) Temperature distribution (Y-Z plane, X=15)

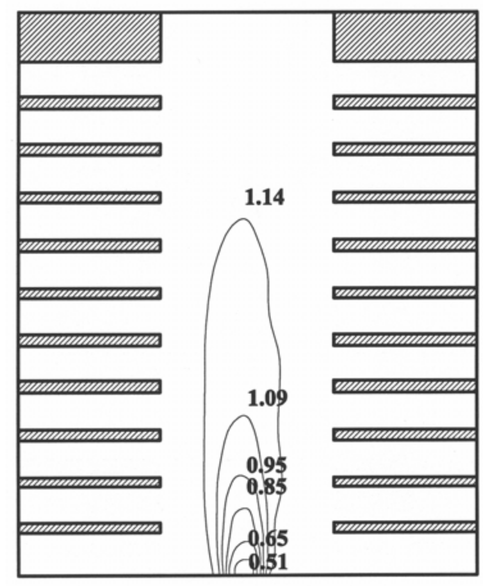


(d) Velocity vectors (Y-Z plane, X=15)

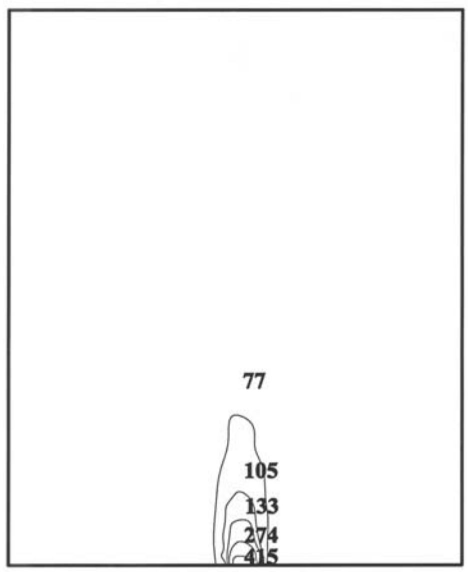
Fig. 4: Numerical experiment NA with fire at atrium at 240 s



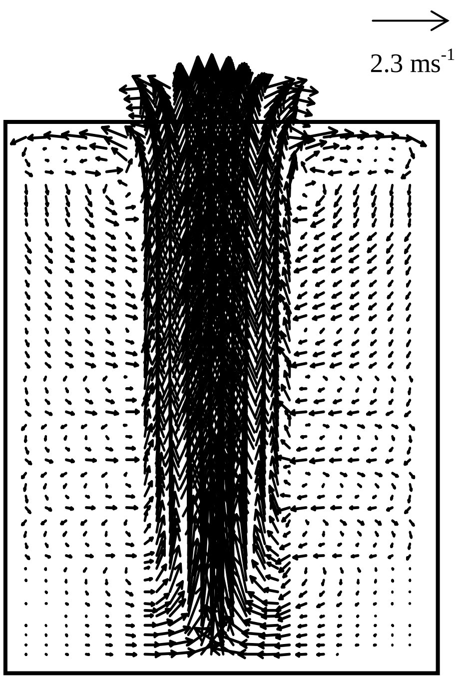
(a) Smoke concentration distribution (Y-Z plane, X=15)



(b) Density distribution (Y-Z plane, X=15)

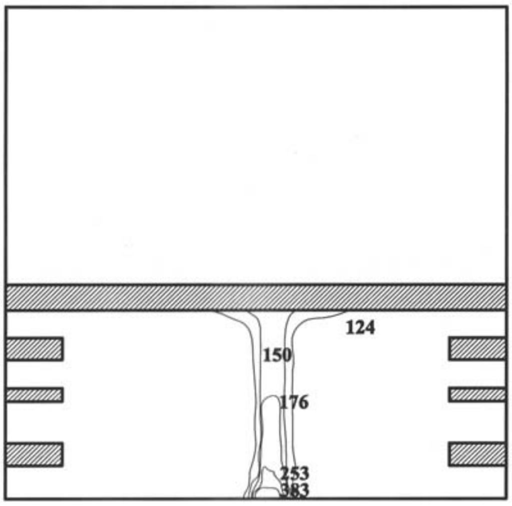


(c) Temperature distribution (Y-Z plane, X=15)

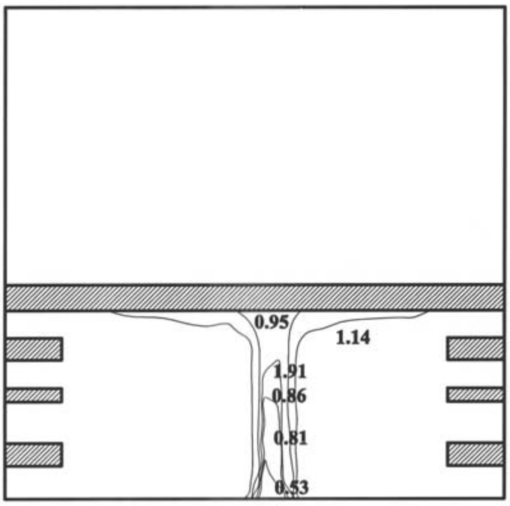


(d) Velocity vectors (Y-Z plane, X=15)

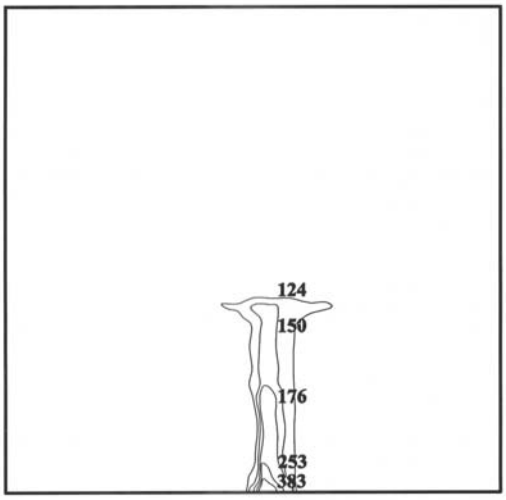
Fig. 5: Numerical experiment NB with fire at atrium at 240 s



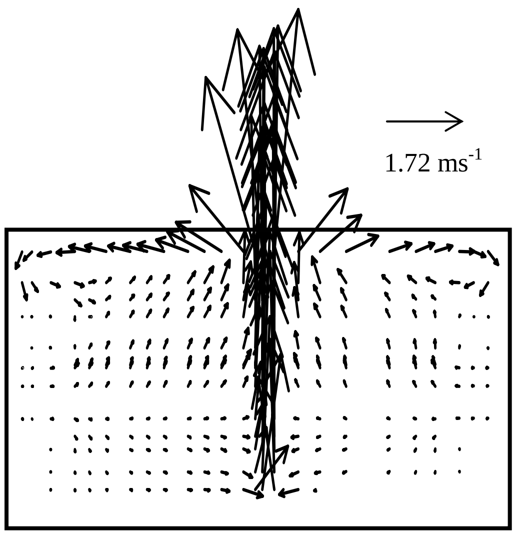
(a) Smoke concentration distribution
(Y-Z plane, X=12)



(b) Density distribution (Y-Z plane, X =12)



(c) Temperature distribution
(Y-Z plane, X=12)



(d) Velocity vectors (Y-Z plane, X =12)

Fig. 6: Physical model PM with fire at atrium at 240 s

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