J. ENVIRONMENTAL SYSTEMS, Vol. 27(2) 151-162, 1999

SMOKE CONTROL BY AIR CURTAIN FOR SPACES ADJACENT TO ATRIA*

W. K. CHOW
The Hong Kong Polytechnic University, China

ABSTRACT

Smoke control design by using air curtains in spaces adjacent to "open-design" atria was evaluated using Computational Fluid Dynamics (CFD). The design mechanical installs systems for discharging air vertically downward (commonly known as an air curtain) to isolate spaces adjacent to the atrium for preventing smoke spreading to those areas. Performance of the design was evaluated by carrying out two sets of CFD simulations with heat release rates of the fire of 1 MW and 5 MW. An atrium of length 10 m, width 10 m and height 10 m with an adjacent area 6 m above the atrium floor was considered. Air speed of 1 ms^{-1} to 10 ms^{-1} discharged vertically downward, corresponding to volumetric flow rates of thirty-six air changes per hour to 360 air changes per hour of atrium volume space were studied.

INTRODUCTION

Many atria of "open design" character have been built in the Hong Kong Special Administrative Region (HKSAR) [e.g., 1]. These bring problems of fire safety where such atria are located in busy shopping malls. Current Hong Kong regulations [e.g., 2] on atrium smoke are not adequate to protect those spaces. The rules limit space volume (upper limit of 28,000 m^3) and fire load density (upper limit of 1,135 MJm^{-2}); smoke extraction systems with extraction rates from six to ten air changes per hour (ACH) are to be installed when those values are exceeded. To isolate the atrium space from adjacent levels known as communicating spaces

*The study is supported by the Research Grants Council, Hong Kong Special Administrative Region (project number HKP23/94E1; 357/001). The software PHOENICS was purchased from CHAM, UK.

as in NFPA 92B [3]), smoke curtains are commonly used to enclose the atrium. The design, however, is not preferred by most architects. Moreover, deflection of the smoke curtain [4] might result from buoyancy-induced air flow of a fire at the atrium floor.

An alternate solution is to discharge air horizontally at the openings (e.g., the balcony) of the communicating space adjacent to the atrium. Air has to be discharged at sufficiently high speeds across the whole opening. An empirical equation was found at the NFPA 92B [3] for the limiting average velocity v_e discharged from the communicating space adjacent to the atrium at height z above the atrium floor level and for a heat release rate Q of the fire at the atrium floor:

$$v_e = 17\ [Q / z]^{1/3} \tag{1}$$

where v_e is in ft/min, Q is in Btu/sec and z is in ft. Bearing in mind that 1 Btu/sec is 1.05 kW, 1 ft is 0.305 m; when v_e is in ms^{-1}, Q is in kW and z is in m, equation (1) becomes:

$$v_e = 0.614\ [Q / z]^{1/3} \tag{2}$$

For a 5 MW fire, the air speed v_e required in the communicating spaces adjacent to an atrium at height 5 m above the floor is 6.1 ms^{-1}. The volume of air discharged across the balcony of width 10 m and height 1 m will be 61 m^3s^{-1}. Further, the air discharged from the adjacent levels might be entrained to the fire plume so as to increase the smoke production rate. This was confirmed in earlier Computational Fluid Dynamics (CFD) studies [5, 6].

An alternative design proposed by local industry is to discharge air vertically downward, to establish an air curtain for isolating the communicating spaces adjacent to the atrium. However, no detailed studies on this kind of design were reported although there are some related works on air-conditioning design [7, 8]. The objective of this article is to evaluate this design with CFD. The commercial package PHOENICS with FLAIR menu [9] was used as the CFD simulator.

AIR CURTAINS

Brief reviews on the design and the associated literature were presented in the ASHRAE Applications Handbook 1995 [7]. There, air curtains are referred to as local ventilation devices that reduce air flow through building apartments and in process equipment [7]. This system is also used for localizing particulate emissions such as those of jet-assisted hoods. The main use of air curtains is to provide better environments for work-stations located near doorway. Curtains are commonly used in the HKSAR for isolating inside air-conditioning spaces (e.g., at 23°C) with outside air (e.g., at 35°C). Indoor spaces include buildings, vehicles, and train compartments. The air curtain concept is also proposed by local industry for smoke control in atria with open adjacent levels, as noted.

NUMERICAL EXPERIMENTS

Numerical experiments were carried out in an atrium of length 10 m, width 10 m and height 10 m as in Figure 1. There are two doors (D1 and D2) at the atrium floor, each of width 10 m and height 3 m. There are two levels (M1 and M2) open to the atrium through two openings (01 and 02) of height 1 m. The floor levels of M1 and M2 are 6 m above the atrium floor.

Air is discharged vertically downward from the fans F1 and F2, each of length 10 m and width 0.5 m. Different air speeds were studied to give different volumetric flow rates.

A fire of size 1 m by 1 m by 1 m and constant heat release rate was started at the centre of the atrium floor. Initial and ambient temperatures are 20°C. Two sets each of five CFD simulations with higher heat release rate 5 MW and lower heat release rate 1 MW, labeled as H0 to H4 and L0 to L4, were performed:

(i) *Higher heat release rate* : 5 MW

- *Simulation H0* : No air discharged from two fans. The openings M1 and M2 are taken as a free boundary with the same conditions as the doors D1 and D2, i.e., at zero relative pressure and 20°C. This simulation was performed to understand the fire environment in the atrium and the velocity of hot smoke flowing across openings M1 and M2 to the adjacent area.
- *Simulation H1* : Fans F1 and F2 are in operation and injecting air vertically downward at a speed of 1 ms^{-1}, corresponding to a volumetric flow rate of thirty-six ACH of the atrium space volume. This is a high design figure for smoke extraction rate in the HKSAR.
- *Simulation H2* : The fans F1 and F2 are discharging air vertically downward at a speed of 2 ms^{-1}, corresponding to a volumetric flow rate of seventy-two ACH of the atrium space volume.
- *Simulation H3* : The fans F1 and F2 are discharging air vertically downward at a speed of 7.5 ms^{-1}, corresponding to a volumetric flow rate of 270 ACH of the atrium space volume. Note that a very high flow rate is designed.
- *Simulation H4*: Again, the fans F1 and F2 are discharging air vertically downward at a speed of 10 ms^{-1}, corresponding to a volumetric flow rate of 360 ACH of the atrium space volume. Again, a very high flow rate is designed.

(ii) *Lower heat release rate* : 1 MW

Five sets of simulations L0, L1, L2, L3, and L4 were performed with air speeds same as H0, H1, H2, H3, H4, and H5 respectively, but the lower heat release rate of 1 MW was used.

The atrium was divided into 27 by 30 by 21 parts along the x-, y- and z-directions of the Cartesian co-ordinate system as in Figure 1b.

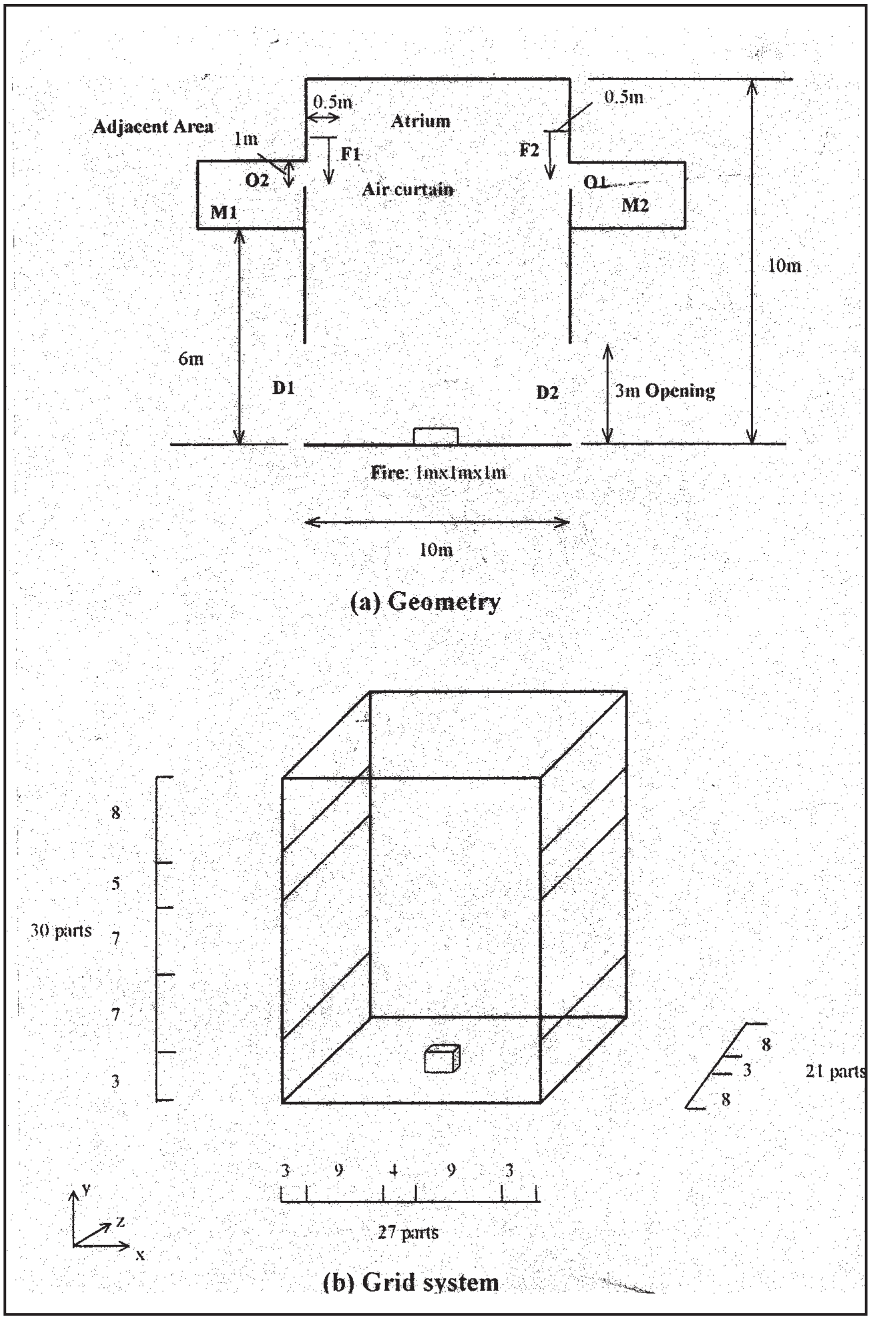

Figure 1. Atrium with adjacent space.

The CFD package PHOENICS version 2.2 with the FLAIR menu [e.g., 9] was selected as the simulation tool. The k-ε turbulence model was used in the computations. Transient simulations up to 100 s were performed and the time interval used in each case was 1s. Computing was performed in a Sun Sparsc-Ultra workstation with CPU time about two hours for each simulation.

RESULTS

Results on the velocity vectors and temperature contour for simulation H0 and L0 before operating the smoke control system are shown in Figure 2. A fire plume was formed in both cases and the upward-rising hot air was moving with a speed up to 10 ms^{-1} for H0. Cool air was drawn from the doors D1 and D2 at the atrium floor and hot air spread to the upper levels through openings 01 and 02. The horizontal component of the hot air moving to the adjacent space is of air speed 2.5 ms^{-1} and temperature above 100°C for H0 air speed, and 1.2 ms^{-1} with temperature above 50°C for L0. Hot smoke will spread from the atrium to the adjacent area if there are no smoke control system.

Simulations H1 to H4 and L1 to L4 were performed to demonstrate the performance of the mechanical smoke control systems (air curtain) in discharging air vertically at volumetric flow rates up to 360 ACH.

The CFD-predicted velocity vectors and temperature contours for simulations H1 and L1 with air discharged at 1 ms^{-1} and a volumetric injection rate corresponding to 36 ACH of the atrium space volume are shown in Figure 3. From the velocity vector diagrams, it is observed that the discharged air from the two fans cannot prevent smoke spreading from the atrium to the adjacent space for both values of heat release rate. Hot air would move through the openings of 01 and 02 as if there are no barrier. Air flows through the doors D1 and D2 are different.

Similar results were shown for simulations H2 with higher air speed of 2 ms^{-1}, corresponding to a discharged volumetric flow rate of 72 ACH of the atrium space volume as illustrated in Figure 4a. The downward air motion at openings 01 and 02 for the case with 1 MW fire would have some effect in stopping the smoke spreading, as shown in the velocity vectors diagram in Figure 4b.

Simulations H3 and L3 were performed to study the mechanical smoke control systems for air discharging with very high air speed of 7.5 ms^{-1}, corresponding to volumetric flow rate of 270 ACH of the atrium space volume. The predicted results on the velocity vectors and temperature contours are shown in Figure 5. From the velocity vectors diagram, it is observed that the downward air motion from F1 and F2 would be strong enough to stop smoke spreading through L1 and L2. The air entrainment rate to the fire plume becomes very high, making the lower part of the atrium very hot. A plume shape is formed for the higher heat release rate of 5 MW, but it is not so obvious with the 1 MW fire due to the downward movement of air induced by the air curtain.

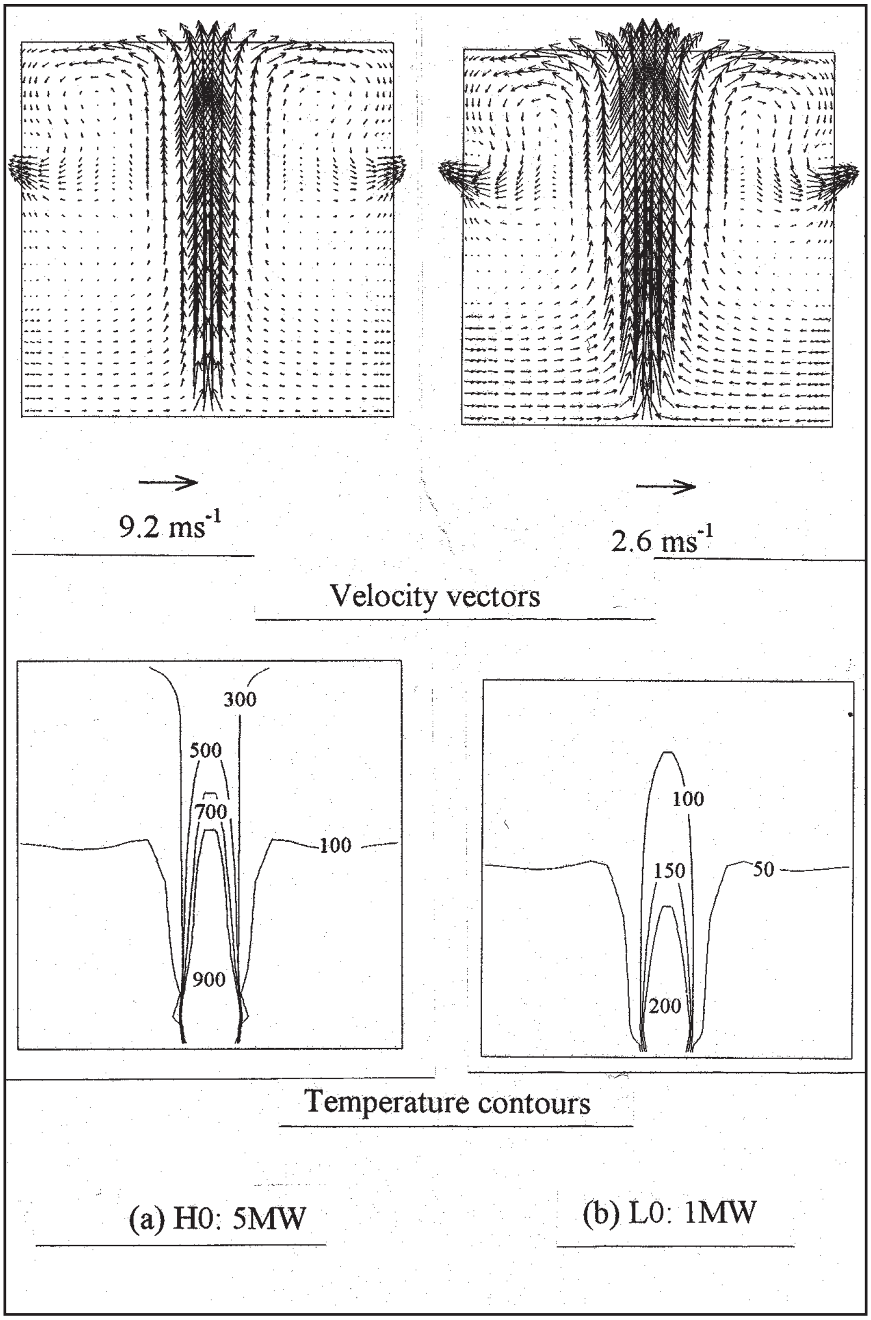

Figure 2. Simulations H0 and L0.

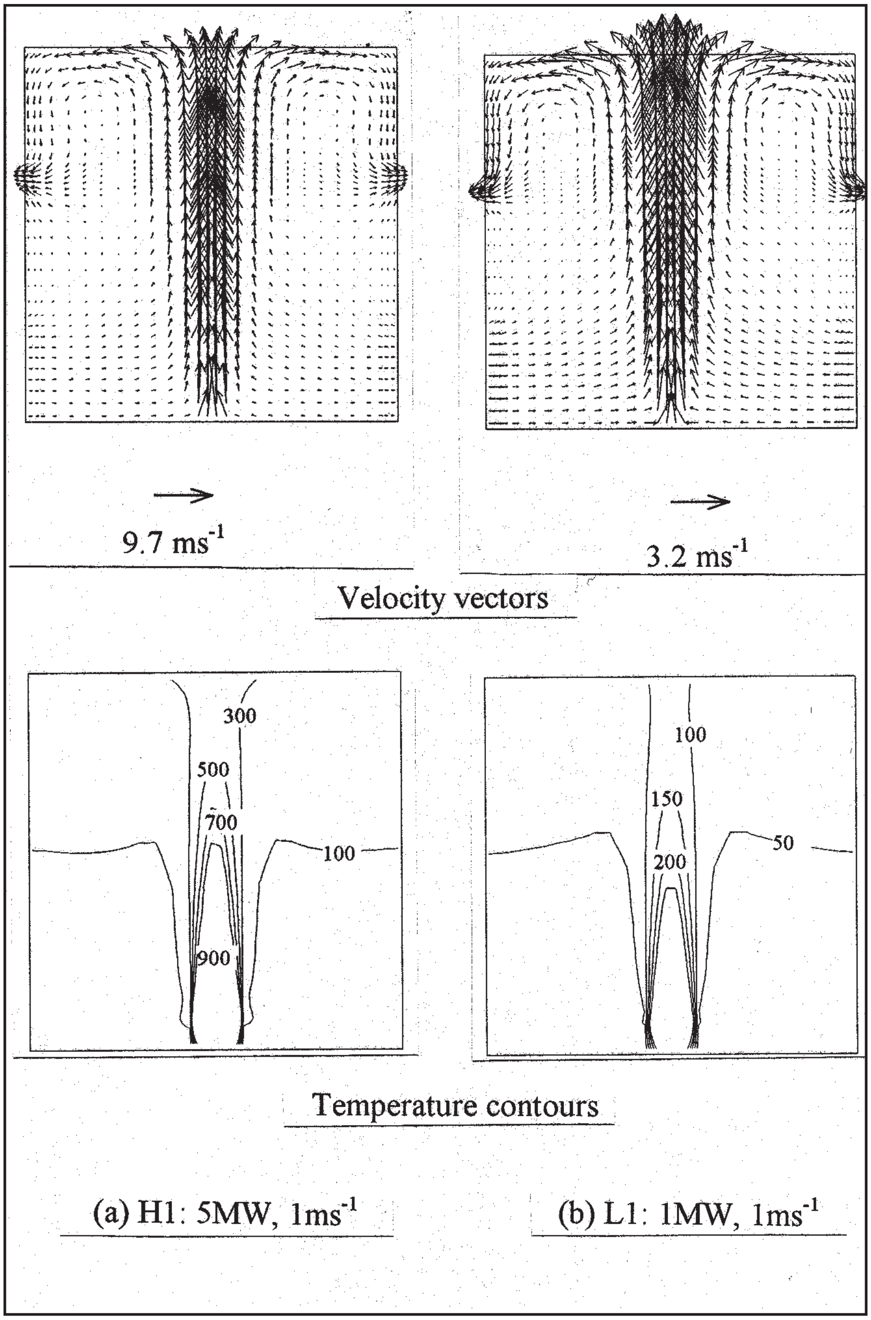

Figure 3. Simulations H1 and L1.

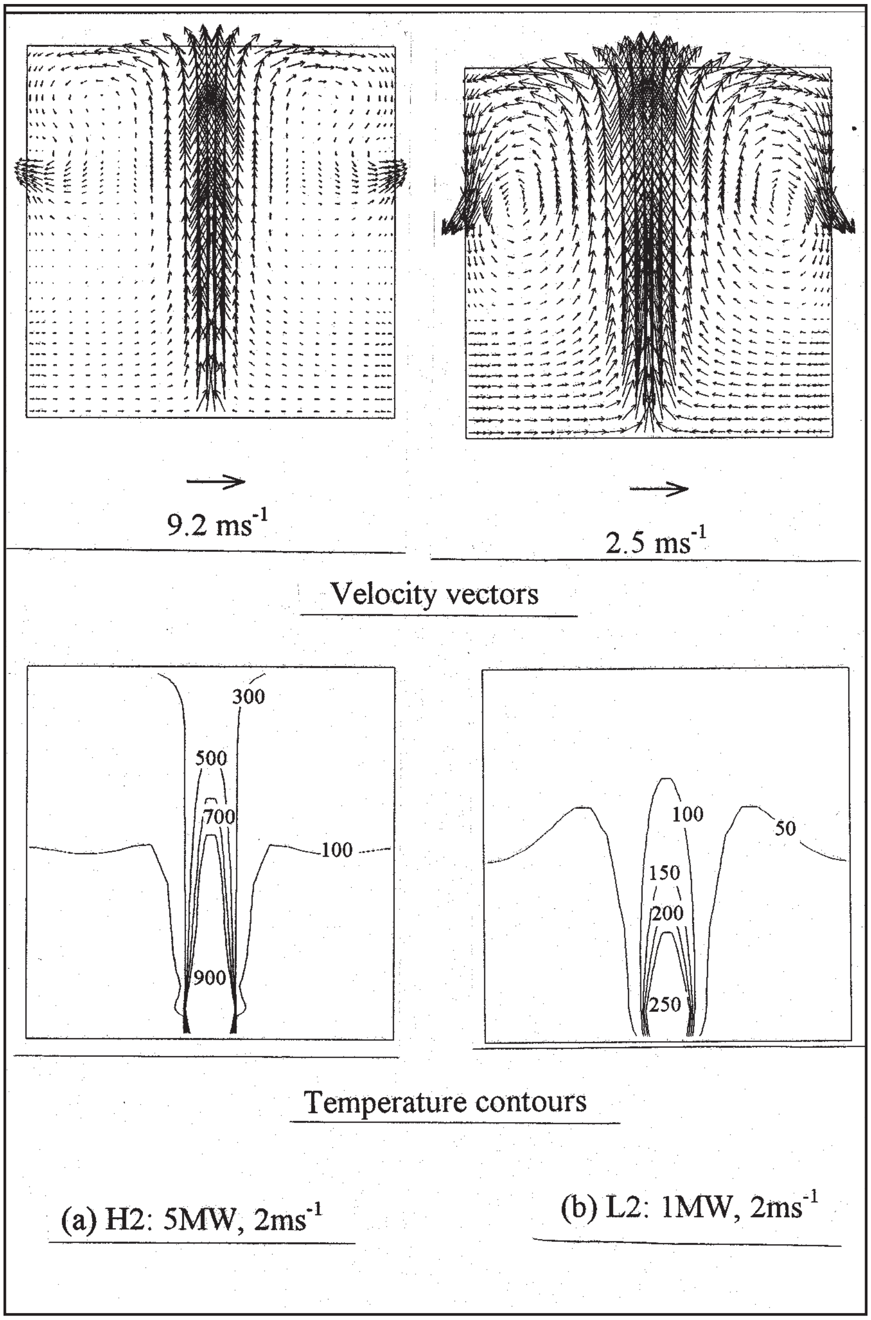

Figure 4. Simulations H2 and L2.

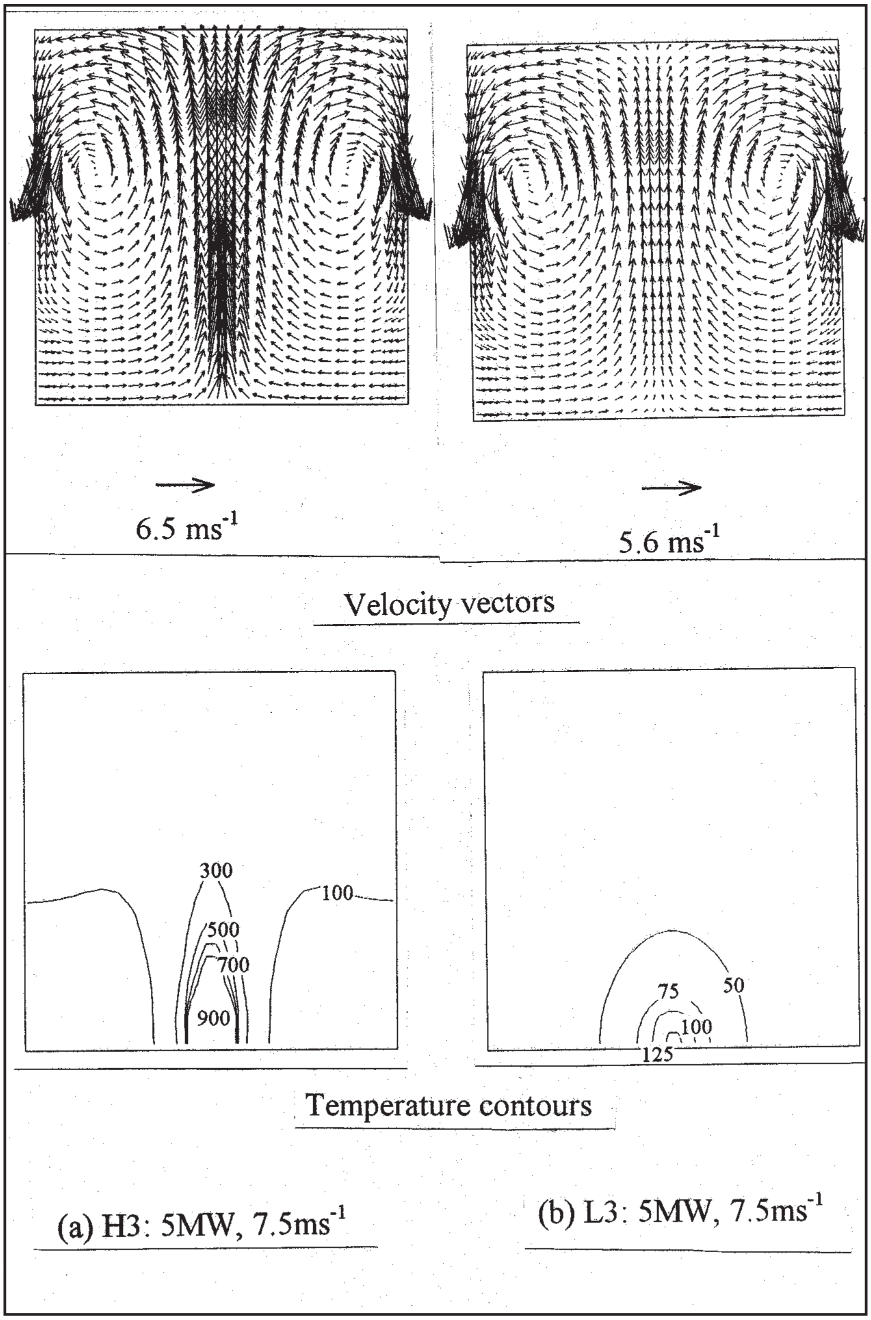

Figure 5. Simulations H3 and L3.

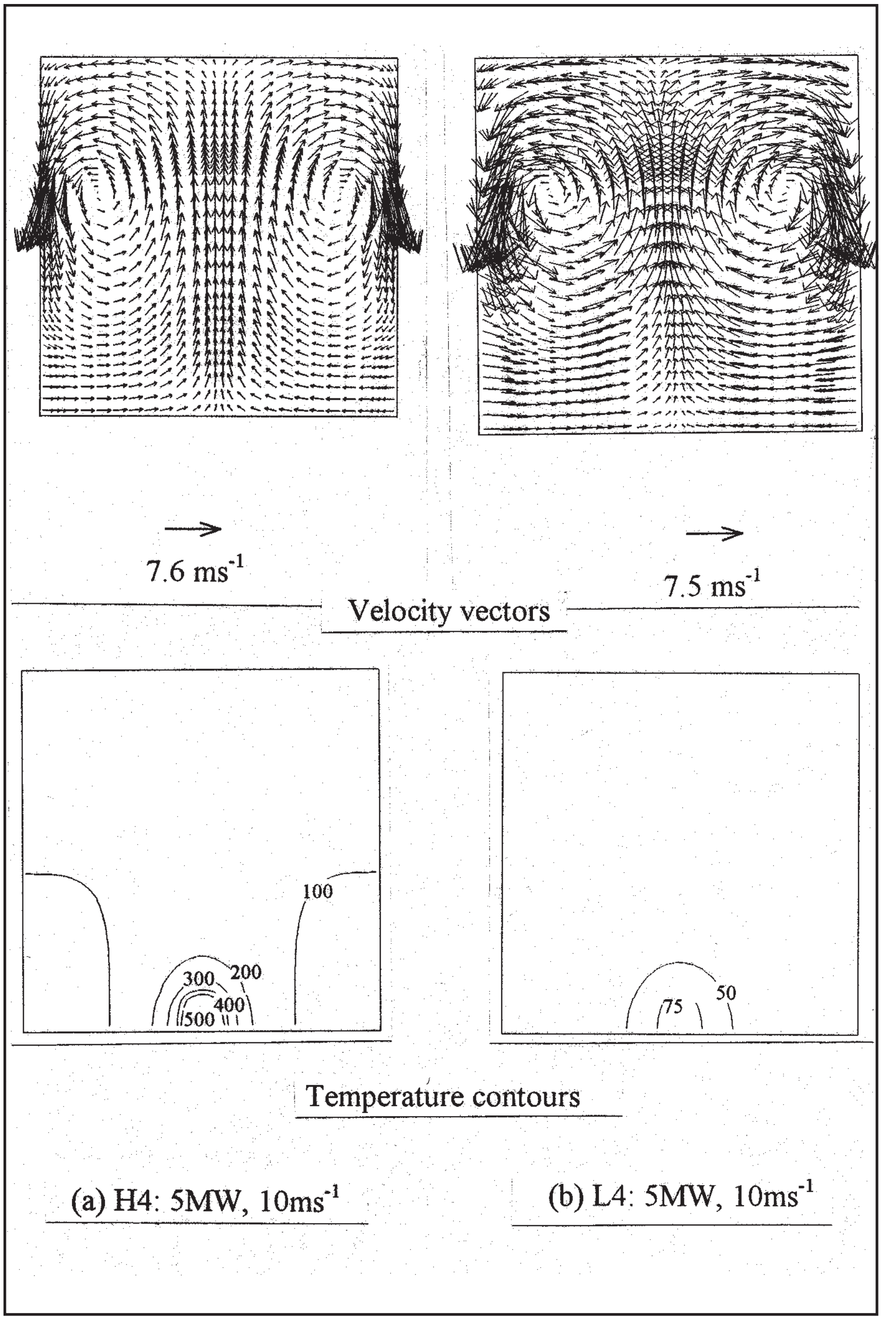

Figure 6. Simulations H4 and L4.

Similar results were predicted for simulations H4 and L4 using very high values of discharged air speed (10 ms^{-1}), corresponding to volumetric flow rates of 360 ACH of the atrium space volume, as shown in Figure 6. Smoke generated by fires up to 5 MW should be prevented from spreading to the adjacent area of the atrium.

CONCLUSIONS

Two sets of five CFD simulations were performed in a cubic atrium of volume 1,000 m^3 to assess the performance of air curtain systems for smoke control. The idea is to discharge air vertically to isolate spaces at levels adjacent to the atrium to preventing smoke from spreading. Simulations H0 and L0 were performed to understand the fire environment; simulations H1 and H4 and L1 and L4 were carried out to study the performance of the system under a 5 MW fire and a 1 MW fire respectively. The following conclusions can be drawn:

1. It is possible to stop smoke spreading to the adjacent area of the atrium if the air discharge rate is high. Discharging air with a high flow rate is feasible from the design view point in mechanical engineering. This is better than discharging air horizontally through the opening to counteract the smoke. For that case, very high flow rates are required [6]. The thermal comfort under high air speeds is not an important issue to be considered. People are not expected to “walk” through the balcony to the atrium!
2. Air discharged from the adjacent levels will be entrained by the fire plume. As a result, the atrium air moves rapidly with higher temperature as shown in the temperature contours in Figure 6b. The atrium has to be evacuated as soon as possible.
3. It is necessary to verify the CFD results by performing some full-scale burning tests. A full-scale burning atrium (known as the PolyU/USTC atrium) was constructed as a collaboration project between the Hong Kong Polytechnic University (PolyU) and the University of Science and Technology of China (USTC) at Hefei, Anhui, China. It is of length 24 m, width 18 m and height 27 m, and will be used for studying natural smoke filling processes, natural ventilation, mechanical ventilation, and atrium sprinklers [10]. The facility is useful in assessing various design alternatives such as imposing air flow [3] and pressurizing various areas [11].

REFERENCES

1. W. K. Chow, Simulation of Fire Environment for Linear Atria in Hong Kong, *ASCE Journal of Architectural Engineering, 3*:2, pp. 80-88, 1997.
2. Fire Services Department, *Code of Practice for Minimum Fire Services Installations,* Hong Kong, 1994.

3. NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas,* National Fire Protection Association, Quincy, Massachusetts, 1995.
4. H. P. Morgan, *Private Communications,* 1997.
5. W. K. Chow, Use of Computational Fluid Dynamics for Simulating Enclosure Fire, *Journal of Fire Sciences, 13*:4, pp. 300-334, 1995.
6. W. K. Chow, *Preliminary Studies on Smoke Control in Spaces Adjacent to Atria,* Research Report, The Hong Kong Polytechnic University, October 1997.
7. ASHRAE, *Ventilation of the Industrial Environment,* ASHRAE Applications Handbook, p. 24.14, ASHRAE, Atlanta, Georgia, 1995.
8. W. Xiang and S. A. Tasson, Numerical Simulation of the Performance of Air Curtains for Doorway Infiltration Control, *Proceedings of the 1st International Conference on Energy and the Environment—Efficient Utilization of Energy and Water Resources, October 12-14, 1997,* Limassol, Cyprus, Vol. 2, pp. 676-684, 1997.
9. Concentration, Heat and Momentum Ltd. (CHAM), *The PHOENICS-2.0 Companion,* Report TR3B, London, United Kingdom, 1993.
10. W. K. Chow, W. Fan, and L. Chen, Full-Scale Burning Facilities for Atrium Fire Research [in Chinese], *Fire Safety Science, 2*:2, pp. 60-63, 1993.
11. G. O. Hansell and H. P. Morgan, *Design Approaches for Smoke Control in Atrium Buildings,* BRE Report CI/SfB 981 (K23), Building Research Establishment, Watford, United Kingdom, 1994.

Direct reprint requests to:

W. K. Chow
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China