ATRIUM SMOKE FILLING PROCESS IN SHOPPING MALLS OF HONG KONG

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

ABSTRACT

The smoke filling process in the atria of shopping malls in Hong Kong is studied. The atrium is located adjacent to a shop which is assumed to have a fire. Atria classified into seven different shapes with volumes varying from 2,500 to 35,000 m^3 were considered. The smoke filling time in those atria was simulated by the fire zone model CFAST Version 2.0. A total number of 63 atria were considered with the probable fire environment simulated. A time constant derived from the free plume expressions is proposed to specify the geometry of the atrium hall for studying the smoke filling process. It is found that the times required to fill 80% and 50% of the atrium space volume with smoke are related to this time constant. Linear relations between them were derived. Lastly, the effects of the smoke control systems are also studied: the horizontal ceiling vents of area 9 m^2 and mechanical ventilation system giving a smoke extraction rate of 6 air changes per hour.

INTRODUCTION

Many large multi-level shopping malls with an atrium have been constructed in Hong Kong[1] during the past fifteen years. They can be found in districts of high land costs, such as the central banking and commercial area, and in districts with lower land prices, such as the residential area of public estates.

A general feature of the shopping malls is several levels of shops connected by an enclosed atrium. Most of the malls are of 'open' design so that each level is linked directly to the atrium. In each mall, there might be shops, large department stores, restaurants, banks and supermarkets. The fire aspects in the shopping mall have to be considered carefully because there are many occupants and the fire load in a shop can be high. Even though there may not be much combustible material in the atrium itself, a fire originating in a shop could lead to smoke spreading to every part of the mall through the atrium. Therefore, information on the smoke filling process in the atrium, due to a fire in a shop adjacent to it, is important for designing appropriate fire protection systems.

There are few reports on smoke spreading from a shop to an atrium. Reviews of the current state of the art have been presented in the literature.[2–5] As mentioned in a previous review,[6] there are some codes on atrium smoke management in North America.[7] However, the architectural features for local atria are quite different. Further, Hong Kong is a dense urban area which would give even more problems when there is a fire.[8] Carrying out full-scale experimental studies[9–12] to study the atrium smoke filling process would be very expensive and there are many problems in using scale models.[13] However, many fire zone models[14] have been developed, and they are well validated for compartment fires. If used carefully, they can be applied to study the fire environment inside a shopping mall. Previous work reported on applying zone models to simulate atrium fires (e.g. Refs. 1, 10) with the fire located in the atrium itself. There are only a few examples of such an atrium fire[6] as the amount of combustible contents in most of the atria is quite low.

In this paper, the smoke filling process due to a fire in a shop located next to the atrium is considered. The fire zone model Consolidated Model of Fire Growth and Smoke Transport (CFAST) Version 2.0[15] developed at the Building and Fire Research Laboratory, National Institute of Standards and Technology, U.S.A. was used to study the smoke spreading process into the atrium. This model can predict the fire environment in a multi-compartment building.[11] The fire is specified in terms of either the mass loss rate of the fuel or the heat release rate. In Version 2.0, simulation of forced ventilation systems and horizontal ceiling vents are possible. Combustible items such as furniture with predetermined heat release rates can be specified. In specifying a forced ventilation system, ducts and fans are joined by 'nodes' at positions in different rooms. The fan curve can be incorporated into the data for the program. Shopping malls, with atria of volumes varying from 2,500 m^3 to 35,000 m^3, classified into the three types (and seven groups), are used as examples for simulating the smoke filling processes and evaluation of the performance of the smoke control system.

USE OF THE TIME CONSTANT

In Hong Kong, the Engineering Approach or Engineering Performance-Based Fire Codes for building fire safety is under active review.[16] At the moment, the local fire authority,[17] in addition to fire load density and total area of windows, sets limits on the volume of the atrium, above which smoke control systems are required. Critical values of the volumes are 7,000 m^3 in a basement; 7,000 m^3 for an atrium with a high fire load density (above 1,135 MJ m^{-2}), and 28,000 m^3 otherwise. It is not considered good enough to specify only the volume of the atrium hall for determining the smoke filling process. Previous simulations for atria with a fire located in it illustrated that spaces with the same volume but different shapes would have different fire environments. The geometrical shape including the height of the atrium has to be specified.

Two time constants[18-20] were defined for studying the smoke filling time for atrium using the empirical plume equation for calculating the amount of smoke produced defined by Thomas et al.[21] and the free plume expressions given by Zukoski et al.[22] The plume equation used in deriving the first time constant was criticized by Thomas.[23] For this equation, the flame tip must touch the smoke layer. This is unlikely for an atrium fire. The second expression for the time constant can be derived by using the free plume expressions by Zukoski et al.[22] The vertical upward speed, v, plume radius, r and central temperature rise, ΔT_o (i.e. $T_o - T_\infty$) where T_o is the central temperature and T_∞ is the ambient temperature at height z above a fire for thermal plumes in free spaces, are given in terms of the heat release rate $\dot{Q}$ in kW:

$$v = C_v\left(\frac{g}{C_p\rho_\infty T_\infty}\right)^{1/3}\dot{Q}^{1/3}(z - z_o)^{-1/3} \qquad (1)$$

$$r = C_r\left(\frac{T_o}{T_\infty}\right)^{1/2}(z - z_o) \qquad (2)$$

$$\Delta T_o = C_T\left(\frac{T_\infty}{gC_p^2\rho_\infty^2}\right)^{1/3}\dot{Q}^{2/3}(z - z_o)^{-5/3} \qquad (3)$$

The values for the empirical constants are: $C_v = 3.4$, $C_r = 0.12$ and $C_T = 9.1$. ρ_∞ is the ambient air density taken to be 1.21 kg m^{-3}, C_p is 1,015 $Jkg^{-1}K^{-1}$, T_∞ is 290 K and z_o is calculated from the effective diameter, D of the fire source but is neglected in this study.

The air entrainment rate of the plume, M_p is calculated by assuming that the horizontal air velocity, u is proportional to v through an entrainment coefficient, α with values varying from 0.098 to 0.1878 (e.g., Beyler[24]), and integrating z from 0 to the clear height y:

$$M_p = K_2y^{5/3} \qquad (4)$$

where

$$K_2 = \frac{6\pi}{5}\rho_\infty\alpha C_v\left[\frac{g}{C_p\rho_\infty T_\infty}\right]^{1/3}\dot{Q}^{1/3}C_r \qquad (5)$$

Using the smoke filling equation without thermal effect:

$$\frac{d}{dt}[\rho A_f(H - y)] = M_p \qquad (6)$$

A time constant τ_2 can be defined by taking the time dependent term after solving Eq. (6) for y as a function of time t (e.g., Chow[25]):

$$\tau_2 = \left(\frac{3\rho}{2K_2}\right)\left(\frac{A_f}{H^{2/3}}\right) \qquad (7)$$

Putting in the expression for K_2 with numerical values of ρ_∞ (1.21 kg m^{-3}), g (9.81 m s^{-2}), C_p

(1,015 $\mathrm{Jkg^{-1}K^{-1}}$), T_∞ (290 K) and T_o (1,500 K) would give:

$$\tau_2 \sim \frac{6.245}{\alpha \dot{Q}^{1/3}}\left(\frac{A_f}{H^{2/3}}\right) \tag{8}$$

There are two parts in the expression for τ_2 with the first part related to the fire itself given by the plume entrainment coefficient, α and heat release rate, $\dot{Q}$. The second part depends on the geometry of the atrium space. This is also similar to the time dependent term of the empirical equation for smoke filling time given in NFPA-92B.[7] The smoke layer interface height (more specifically, the height of the first indication of smoke above the fire pointed out by Klote[5]), y (in m) is expressed in terms of the ceiling height, H (in m) and heat release rate, $\dot{Q}$ (in kW) as:

$$\frac{y}{H} = 1.11 - 0.28\,ln\left[\frac{t}{T_{NFPA}}\right] \tag{9}$$

where

$$T_{NFPA} = \frac{A_f}{\dot{Q}^{1/3} \cdot H^{2/3}} \tag{10}$$

Note that this smoke filling equation holds only for $0.2 \le (A_f/H^2) \le 14$ and $0.2 \le (y/H) \le 1.0$. The time dependent term T_{NFPA} depends on the heat release rate of fire and the geometry of the atrium. In fact, it is related to τ_2 through a constant[25]:

$$\tau_2 \sim \frac{6.245}{\alpha} T_{NFPA} \tag{11}$$

THE SHOPPING MALLS

The shopping malls used as examples consist of two compartments. A shop of length 10 m, width 10 m and height 3 m, is located next to an open atrium as shown in Fig. 1. The atrium is labeled as Room 1 and the shop is labeled as Room 2. A door of height 2 m and width 5 m connects the shop to the atrium. There is an entrance of width 10 m and height 3 m connecting the atrium to the outside. A fire of size 3 m by 3 m with a burning time of 2,200 s is assumed. The heat release rate was increased linearly from 0 to 5 MW in 100 s (i.e. a rate of 50 kW s^{-1}), kept at a steady-burning period for 100 s to 2,100 s, and then decreased to zero in 2,200 s. Selection of this heat release rate curve is not to assess the transient behavior of the fire itself, but to study the consequence of a fire with a constant heat release rate of 5 MW in the shop.

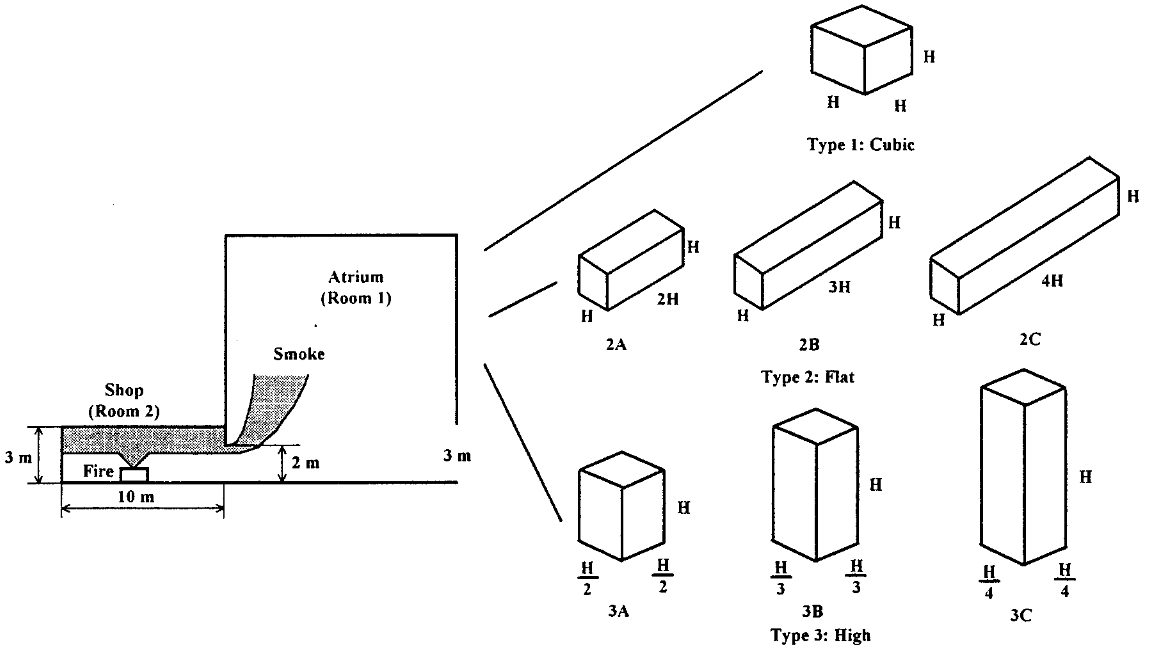


Figure 1. Shopping Mall.

According to a previous survey[20] on buildings containing an atrium in Hong Kong, atria can be classified as three types:

Type 1 (Cubic): The atrium is of cubic shape and the dimension (length × width × height) can be approximated by H × H × H, where H is the height as shown in Fig. 1.

Type 2 (Flat): The atrium has a large transverse dimension relative to the height. It can be classified into three sub-types as 2A, 2B and 2C with dimensions (length × width × height) specified as 2H × H × H, 3H × H × H, 4H × H × H, respectively as shown in Fig. 1.

Type 3 (High): This is the atrium with a height to width (or length) ratio of more than two. It is subdivided into Types 3A, 3B and 3C with dimension (length × width × height) approximated by H/2 × H/2 × H, H/3 × H/3 × H and H/4 × H/4 × H as shown in Fig. 1.

A total number of 63 fire simulations studying the smoke filling in the atrium due to a fire in an adjacent room for those three types of atria was performed. The results of these simulations are discussed in this paper. The effects of the smoke control system, including natural ceiling vents and mechanical systems, were also studied.

NUMERICAL SIMULATIONS

Simulations for atrium volumes of up to 35,000 m^3 were conducted using the zone model CFAST. The atrium geometry and the computed time constants, τ_2 (taking the entrainment coefficient of plume α to be 0.15), are shown in Table 1.

Table 1. Summary of the Geometry of the Atria

	Type 1 atrium (H × H × H)				Type 2A atrium (2H × H × H)				Type 2B atrium (3H × H × H)				Type 2C atrium (4H × H × H)			
Volume /m^3	Length /m	Width /m	Height /m	τ_2 /s	Length /m	Width /m	Height /m	τ_2 /s	Length /m	Width /m	Height /m	τ_2 /s	Length /m	Width /m	Height /m	τ_2 /s
2500	13.57	13.57	13.57	79	21.54	10.77	10.77	116	28.23	9.4	9.4	145	34.20	8.54	8.54	170
5000	17.10	17.10	17.10	108	27.14	13.57	13.57	158	35.57	11.85	11.85	197	43.09	10.77	10.77	232
10000	21.54	21.54	21.54	146	34.20	17.10	17.10	215	44.79	14.93	14.93	269	54.29	13.57	13.57	315
15000	24.66	24.66	24.66	175	39.14	19.57	19.57	256	51.03	17.10	17.10	322	62.14	15.53	15.53	378
20000	27.14	27.14	27.14	199	43.08	21.54	21.54	292	56.46	18.82	18.82	366	68.40	17.10	17.10	429
25000	29.24	29.24	29.24	219	46.4	23.20	23.20	322	60.82	20.27	20.27	404	73.68	18.42	18.42	474
28000	30.37	30.37	30.37	231	48.2	24.10	24.10	339	63.16	21.05	21.05	425	76.51	19.12	19.12	498
30000	31.07	31.07	31.07	238	49.32	24.66	24.66	350	64.63	21.54	21.54	437	78.28	19.57	19.57	514
35000	32.71	32.71	32.71	255	51.92	25.96	25.96	374	68.04	22.68	22.68	469	82.42	20.60	20.60	550

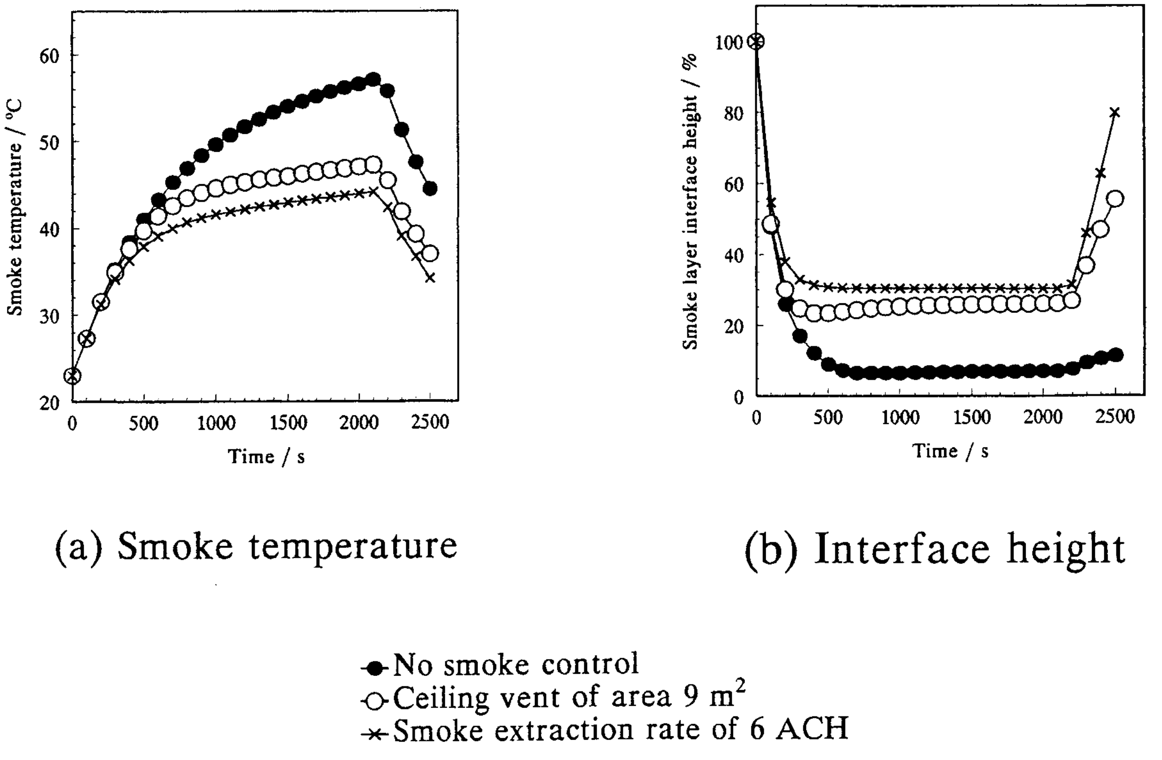
	Type 3A atrium (H/2 × H/2 × H)				Type 3B atrium (H/3 × H/3 × H)				Type 3C atrium (H/4 × H/4 × H)			
Volume /m^3	Length /m	Width /m	Height /m	τ_2 /s	Length /m	Width /m	Height /m	τ_2 /s	Length /m	Width /m	Height /m	τ_2 /s
2500	10.77	10.77	21.54	36	9.40	9.40	28.23	23	8.54	8.54	34.20	17
5000	13.57	13.57	27.14	50	11.85	11.85	35.57	32	10.77	10.77	43.09	23
10000	17.10	17.10	34.20	68	14.93	14.93	44.79	43	13.57	13.57	54.29	31
15000	19.57	19.57	39.14	81	17.10	17.10	51.30	52	15.53	15.53	62.14	37
20000	21.54	21.54	43.08	92	18.82	18.82	56.46	59	17.10	17.10	68.40	43
25000	23.20	23.20	46.40	102	20.27	20.27	60.82	65	18.42	18.42	73.68	47
28000	24.10	24.10	48.20	107	21.05	21.05	63.16	68	19.12	19.12	76.51	49
30000	24.66	24.66	49.32	110	21.54	21.54	64.63	70	19.57	19.57	78.28	51
35000	25.96	25.96	51.92	118	22.68	22.68	68.04	75	20.60	20.60	82.42	55

For the Type 1 atrium with a volume of 28,000 m^3 as an example, the transient development of the smoke temperature and smoke layer interface height are shown in Fig. 2. The smoke generated by the fire in the shop (Room 2) spread into the atrium. Because there was no smoke control in the atrium, smoke rapidly filled the atrium. A pictorial presentation of the fire environment during the steady burning period is shown in Fig. 2a. For the atrium without any smoke control system, the temperature in the fire room was up to 470°C. Smoke filled up to 58% of the space in the fire room. Because a fire occurred in the lower level, smoke filled up 93.1% of the atrium hall with the smoke temperature up to 51°C.

A summary of the average smoke temperature, T_{av} and the smoke layer interface height, y_{av} (in terms of the percentage of the ceiling height, H) during the steady burning period (taken from 500 s to 2,000 s) for the 63 simulations are shown in Table 2. No correlations can be derived between the average smoke temperature, T_{av} and the average smoke layer interface height, y_{av} (both at the steady burning period) with the time constants, τ_2. But, for a certain type of atrium (e.g., Type 1), the average smoke temperature decreased as the space volume of the atrium increased. Similarly, the average smoke layer interface height decreased as the volume of the atrium increased.

The literature was reviewed to determine criteria to assess the time required to fill the compartment with smoke. For example, a clear height of 1 m was used by Wikman[12] for simulations of ship fires. Unfortunately, this is not appropriate for atrium as the clear height must be high enough for the occupants to escape. For these simulations, two criteria are used to assess the smoke filling time. The first one is the time, t_{80} required to fill 80% of the atrium with smoke; and the other is the time, t_{50} required to fill 50% of the atrium with smoke. The value t_{50} is selected because smoke might not be able to fill 80% of the spaces where there is a smoke control system installed. Values of t_{80} (labeled as t_{80}^0 for this fire) are also shown in Table 2.

It is found that smoke filled up quickly in most of the Type 3 atria simulated as demonstrated by having t_{80} less than 100 s. In this way, fire environment in the atrium under full strength (5 MW) of the fire cannot be assessed. Therefore, the rate of rise of thermal power of the fire was increased to 500 kW s^{-1}, i.e., the heat release



(a) Smoke temperature

(b) Interface height

Figure 2. Predicted Fire Environment in the Type 1 Atrium of Volume 28,000 m^3.

Table 2. Summary of Results (No Smoke Control System)

Volume of atrium /m³	Type 1 atrium (H × H × H)					Type 2A atrium (2H × H × H)					Type 2B atrium (3H × H × H)				
	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s
2500	122	17	98	87	36	121	21.4	145	—	47	119	24.5	—	—	57
5000	97	13.3	138	117	44	96	16.7	178	166	60	94	19	222	211	74
10000	76	10.2	173	157	54	75	12.9	245	229	76	73	14.8	298	287	94
15000	64	8.7	203	186	61	64	11	289	274	87	63	12.7	360	345	119
20000	58	7.8	223	208	67	58	10	327	309	97	57	11.7	408	392	127
25000	53	7.2	243	229	73	53	9.4	357	339	105	52	11.2	447	430	137
28000	51	6.9	258	239	75	51	9.2	374	355	108	50	11	469	451	138
30000	50	6.8	263	246	77	50	9.1	384	364	117	49	11	481	464	139
35000	47	6.6	278	260	81	47	9	407	389	119	46	10.9	513	494	149

Volume of atrium /m³	Type 2C atrium (4H × H × H)					Type 3A atrium (H/2 × H/2 × H)					Type 3B atrium (H/3 × H/3 × H)				
	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s
5000	117	27.1	—	—	63	117	10.7	77	47	22	113	8.1	53	32	17
5000	92	21	—	—	87	93	8.3	78	61	26	89	6.3	61	41	19
10000	72	16.2	342	337	109	72	6.4	93	77	29	70	4.9	68	52	22
15000	62	14.1	419	404	127	62	5.4	103	88	37	60	4.1	77	57	24
20000	56	13.1	479	463	142	56	4.8	118	97	34	54	3.7	83	64	27
25000	52	12.7	526	510	154	52	4.4	124	106	36	50	3.3	88	68	28
28000	50	12.6	557	535	161	49	4.2	128	108	38	48	3.2	91	72	29
30000	48	12.6	569	550	165	48	4.1	133	112	39	47	3.1	92	73	28
35000	46	12.6	605	591	175	46	3.8	139	119	41	45	2.9	94	77	29

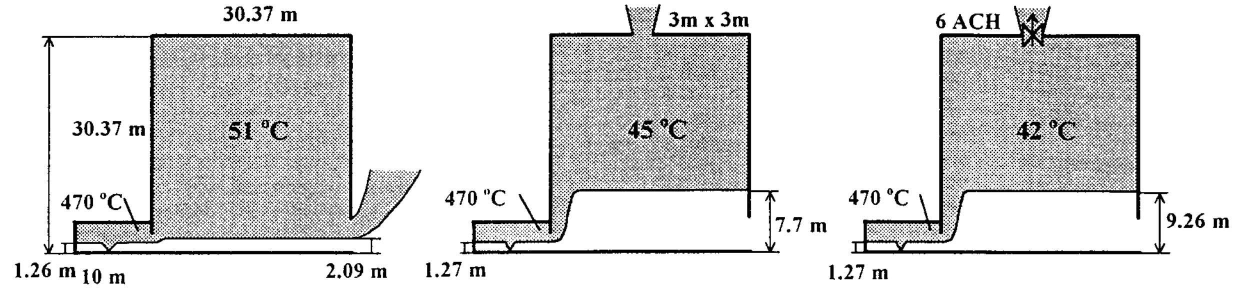
Volume of atrium /m³	Type 3C atrium (H/4 × H/4 × H)				
	T_{av} /°C	y_{av} /%	t^0_{80} /s	t_{80} /s	t_{50} /s
2500	109	6.7	47	27	14
5000	86	5.2	52	32	17
10000	68	4	59	39	19
15000	59	3.4	64	44	21
20000	53	3	68	48	23
25000	49	2.7	72	52	24
28000	47	2.6	76	53	24
30000	46	2.5	74	54	24
35000	44	2.4	77	57	24

rate became 5 MW at 10 s. This is a rapidly developed fire, applied to study the effect of a steady 5 MW fire in the shop on the atrium. A different set of values of t_{80} and t_{50} was found and shown in Table 2.

There is a clear correlation between the smoke filling time and the time constants. A linear relationship can be found between the smoke filling time t_{80} and the time constants τ_2. For the fire of rate of increase in thermal power of 50 kW s^{-1}, a linear straight line of correlation coefficient 0.9925 can be plotted as shown in Fig. 4:

$$t^0_{80} = 1.11\ \tau_2 \tag{12}$$

But as explained before, most of the Type 3 atria had a smoke filling time t^0_{80} less than 100 s for a fire with increasing heat release rate of 50 kW s^{-1}. A fire with an increasing heat release rate of 500 kW s^{-1} was used to get another set of t_{80} smoke filling times. The following linear relationship of correlation coefficient 0.9992 was found as shown in Fig. 5:



(a) No smoke control (b) With ceiling vent of 9 m^2 (c) With forced ventilation system of 6 ACH

Figure 3. Fire Environment During the Steady Burning Period for Type 1 Atrium of Volume 28,000 m^3.

$$t_{80} = 1.06\ \tau_2 \tag{13}$$

For this fire with thermal power increased at a rate of 500 kW s^{-1}, the values of t_{50} were also found for all the 63 simulations on different atria. Also, a linear relationship of correlation coefficient 0.9811 (shown in Fig. 6) was found:

$$t_{50} = 0.34\ \tau_2 \tag{14}$$

Therefore, it is quite obvious that the smoke filling time on the atrium due to a fire in a room next to it is related to the time constant τ_2. This is similar to the previous results[18-20] for the fire located in the atrium.

NATURAL HORIZONTAL CEILING VENTS

Smoke can be removed by natural vents or by forced ventilation systems. A common design is to have horizontal ceiling vents installed at the top of the atrium. Fire simulations with horizontal ceiling vents can be performed using CFAST Version 2.0. Its performance in removing smoke is now demonstrated. Suppose horizontal vents of area 9 m^2 were installed in each of the atrium and they were opened as soon as the fire was started. Again, taking the Type 1 atrium of volume 28,000 m^3 as an example, results for the

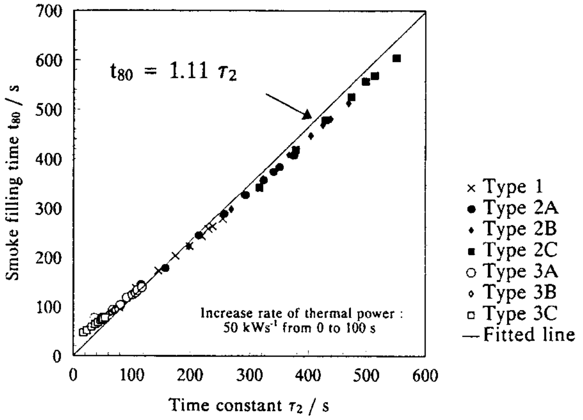


Figure 4. Smoke Filling Time Against Time Constant for the Atrium Without Smoke Control System.

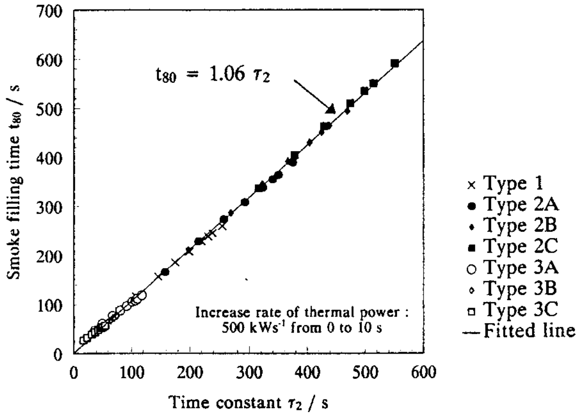


Figure 5. Smoke Filling Time Against Time Constant for the Atrium Without Smoke Control System.

transient smoke layer temperature and smoke interface height are shown in Fig. 2. A pictorial presentation of the steady burning period is shown in Fig. 3b. It can be seen that the average smoke layer temperature was reduced to 45°C and the smoke layer interface height was maintained at 25.4% of the ceiling height. The vents would be efficient in keeping the smoke layer at a higher level.

A summary of the average smoke temperature and the smoke layer interface height during the steady burning period for all the atria together with the 80% smoke filling time t_{80} and t_{50} are shown in Table 3. Note that the fire with the heat release rate increased to 500 kW s^{-1} was used to determine t_{80} and t_{50}. It can be seen that the smoke temperature was lower and the smoke layer was kept at a higher level.

The concept of time constant is also applied to correlate the smoke filling times t_{80} and t_{50} of the atria with a natural horizontal ceiling vent. Values of the smoke filling time, t_{80} are plotted against the time constant, τ_2 in Fig. 7. A linear relationship of correlation coefficient 0.9349 was found for the vent area of 9 m^2:

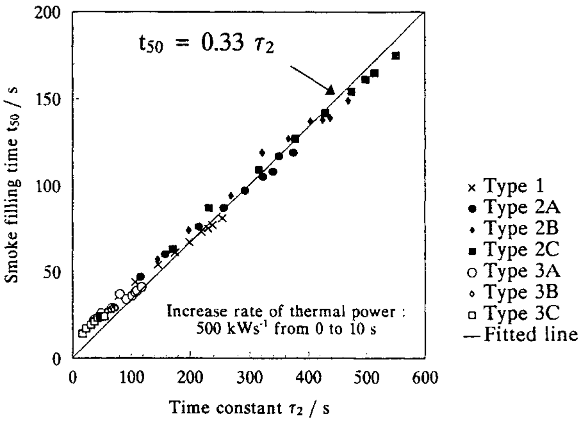


Figure 6. Smoke Filling Time Against Time Constant for the Atrium Without Smoke Control System.

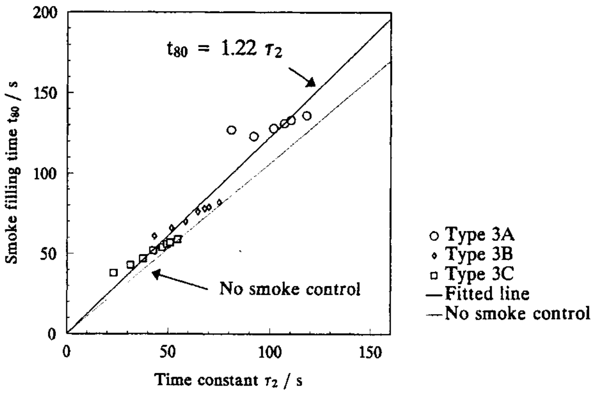


Figure 7. Smoke Filling Time Against Time Constant for the Atrium with Ceiling Vent of Area 9 m^2.

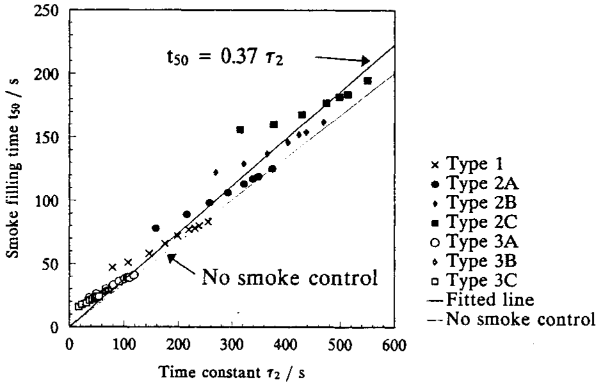


Figure 8. Smoke Filling Time Against Time Constant for the Atrium with Ceiling Vent of Area 9 m^2.

$$t_{80} = 1.22\ \tau_2 \qquad (15)$$

In comparing to the case without vents given by Eq. (13), the smoke filling time is extended by a factor of (1.22/1.06) or 1.16. The time for no smoke control given by Eq. (13) is also plotted in Fig. 7.

Similarly, the smoke filling time, t_{50} is also related to the time constant, τ_2. A linear relationship with a correlation coefficient of 0.9693 was found and is plotted in Fig. 8:

$$t_{50} = 0.37\ \tau_2 \qquad (16)$$

By comparing Eqs. (14) and (16), the smoke filling time is delayed by a factor of (0.37/0.34) or 1.08. The value is very similar to the delay factor 1.16 for t_{80}.

MECHANICAL VENTILATION SYSTEMS

The effect of installing mechanical ventilation systems can be studied using CFAST. A common practice is to install a mechanical system with a smoke extraction rate of 6 air changes per hour (ACH) in the atrium. Using the set of atria with volume varying from 2,500 m^3 to 35,000 m^3 as listed in Table 1, the effect of a mechanical ventilation system, with an extraction rate of 6 air

Table 3. Summary of Results (Horizontal Ceiling Vent 9 m^2)

Volume of atrium /m^3	Type 1 atrium (H × H × H)				Type 2A atrium (2H × H × H)				Type 2B atrium (3H × H × H)				Type 2C atrium (4H × H × H)			
	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s
2500	72	49.8	–	47	81	55.6	–	–	88	59	–	–	92	61.4	–	–
5000	63	42	–	51	67	49	–	78	70	52.5	–	–	73	54.8	–	–
10000	56	34.9	–	58	58	40.9	–	89	59	44.8	–	122	60	47.5	–	156
15000	51	30.9	–	66	53	36.4	–	98	54	39.9	–	129	54	42.5	–	160
20000	48	28.4	–	72	50	33.4	–	106	50	36.6	–	137	50	39	–	168
25000	46	26.3	–	77	47	31.1	–	113	47	34.1	–	146	48	36.5	–	177
28000	45	25.3	–	78	46	30	–	117	46	32.9	–	152	46	35.3	–	182
30000	44	24.8	–	80	45	29.3	–	119	45	32.3	–	154	45	34.4	–	184
35000	43	23.5	–	83	43	27.8	–	125	44	30.7	–	162	44	32.9	–	195

Volume of atrium /m^3	Type 3A atrium (H/2 × H/2 × H)				Type 3B atrium (H/3 × H/3 × H)				Type 3C atrium (H/4 × H/4 × H)			
	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s
2500	62	36	–	23	57	29.5	–	18	54	25.5	–	16
5000	56	30	–	26	52	24.4	–	20	50	21.1	38	18
10000	50	24.7	–	30	47	20.1	61	21	46	17.3	43	19
15000	47	21.9	127	33	45	17.8	66	24	43	15.3	47	21
20000	45	20.1	123	36	43	16.3	70	26	41	14	52	22
25000	43	18.7	128	38	40	15.1	76	28	40	13	54	23
28000	42	18	131	39	40	14.6	78	29	39	12.5	56	24
30000	41	17.5	133	39	40	14.3	79	29	39	12.3	57	24
35000	40	16.6	136	41	39	13.5	82	29	38	11.6	59	24

changes per hour, was studied. The volume flow rates in each simulation were specified in units of m^{3}s^{-1} and an allowance of vertical height 0.5 m above the ceiling was made to accommodate the fan. Fan curves were keyed into the program for each simulation. Again, taking the Type 1 atrium of volume 28,000 m^3 as an example, results of the transient smoke temperature and the descending of the smoke layer interface height are shown in Figs. 3a and 3b, respectively. A pictorial view of the fire environment during the steady burning period is shown in Fig. 2c. It can be seen that the smoke extraction system is very effective in removing smoke.

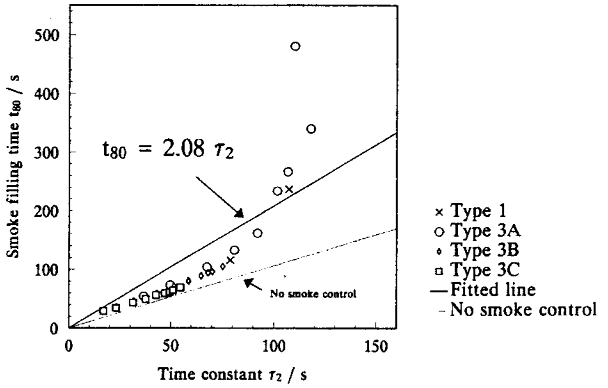


Figure 9. Smoke Filling Time Against Time Constant for the Atrium with Mechanical Ventilation System of Extraction Rate 6 Air Changes per Hour.

A summary of the average smoke temperature and smoke layer interface height during the steady burning period, and the smoke filling times, t_{80} and t_{50} for all the atria, are shown in Table 4. It can be seen that the smoke layers were kept at high levels until the fire stopped. In most cases (i.e. Type 1, 2A, 2B and 2C atria), the smoke layer did not fill up 80% of the atrium (i.e. clear height higher than 20% of the ceiling height) and so t_{80} was not shown.

Values of t_{80} (if available) are plotted against the time constant, τ_2 in Fig. 9, together with the fitted linear curve for the cases without any smoke

Table 4. Summary of Results (Smoke Extraction Rate of 6 ACH)

	Type 1 atrium (H × H × H)				Type 2A atrium (2H × H × H)				Type 2B atrium (3H × H × H)				Type 2C atrium (4H × H × H)			
Volume of	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s
2500	119	18.9	116	37	119	23.8	–	52	117	27.3	–	67	116	30.2	–	78
5000	94	17.4	237	47	93	22.1	–	71	91	25.5	–	92	90	28.3	–	113
10000	67	24.2	–	63	66	30.5	–	98	66	35.1	–	136	65	38.5	–	175
15000	55	26.5	–	74	55	33.4	–	122	54	38.4	–	174	54	42.5	–	239
20000	48	28.3	–	87	48	35.8	–	143	48	41	–	207	48	45.1	–	312
25000	44	29.7	–	97	44	37.6	–	163	44	43	–	257	44	47.5	–	420
28000	42	30.5	–	97	42	38.5	–	174	42	44.1	–	282	42	48.8	–	525
30000	41	30.9	–	99	41	39	–	182	41	44.9	–	302	39	49.3	–	610
35000	39	31.9	–	107	39	40.3	–	200	39	46.2	–	357	39	51.3	–	–

Volume of atrium /m³	Type 3A atrium (H/2 × H/2 × H)				Type 3B atrium (H/3 × H/3 × H)				Type 3C atrium (H/4 × H/4 × H)			
	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s	T_{av} /°C	y_{av} /%	t_{80} /s	t_{50} /s
2500	115	11.9	54	22	110	9.1	36	18	107	7.5	29	17
5000	90	11.1	73	26	86	8.5	46	20	83	7.1	34	18
10000	64	15.3	104	31	62	11.7	59	22	60	9.7	43	19
15000	53	16.8	133	34	51	12.8	71	24	50	10.6	49	21
20000	47	17.8	162	38	46	13.6	80	26	45	11.3	56	22
25000	43	18.7	234	41	42	14.3	89	28	41	11.8	59	23
28000	41	19.2	267	43	40	14.7	94	29	39	12.1	61	24
30000	40	19.5	480	44	39	14.9	96	29	39	12.3	64	24
35000	38	20.1	340	44	37	15.4	105	31	37	12.7	69	24

control system given by Eq. (13). It can be seen that the smoke filling time was delayed.

A clear linear relationship between t_{80}, for the atria with a forced ventilation system, and τ_2 was not found. However, a linear straight line of correlation coefficient 0.6494 can still be plotted and is shown in Fig. 9:

$$t_{80} = 2.08\ \tau_2 \qquad (17)$$

From values of the slope of the two linear lines given by Eqs. (13) and (17), the smoke filling time is delayed by a factor of (2.08/1.06) or 1.96.

Values of the smoke filling time t_{50} are plotted against the time constant τ_2 in Fig. 10. The fitted linear line for no smoke control system given by Eq. (14) is also shown. Again, the smoke filling time t_{50}, is delayed. A linear relationship between t_{50} for the halls with a forced ventilation system and its time constant, τ_2 of correlation coefficient of 0.8155 can be found:

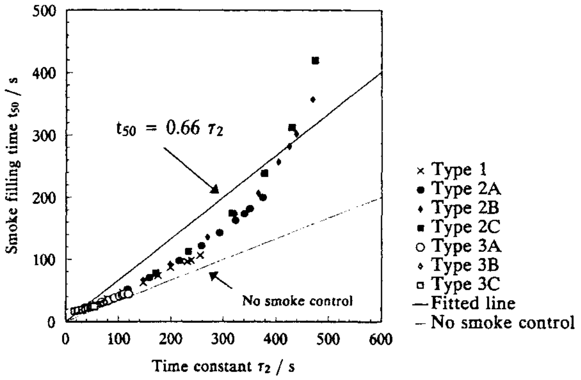


Figure 10. Smoke Filling Time Against Time Constant for the Atrium with Mechanical Ventilation System of Extraction Rate 6 Air Changes per Hour.

$$t_{50} = 0.66\ \tau_2 \qquad (18)$$

This is plotted in Fig. 10 as well. The smoke filling time is delayed by (0.66/0.34) or 1.95. This value is comparable to the delay factor for t_{80}.

CONCLUSIONS

Simulations of the smoke filling process from a shop to an atrium were performed with the zone model CFAST Version 2.0.[15] Shopping malls with an atrium of volumes varying from 2,500 m^3 to 35,000 m^3 classified into the three types of 'cubic', 'long' and 'high' were used as examples for fire simulation. A fire of area 9 m^2, heat release rate of 5 MW and burning time 2,200 s was assumed to occur in a shop adjacent to the atrium. A total number of 63 simulations were performed for the atria without smoke control systems. It was found that smoke can spread rapidly into the atrium and fill up at least 80% of the atrium if there is no smoke control system. Therefore, studying the smoke filling time is important although the smoke temperature is not too high (less than 122°C for this 5 MW fire). The average smoke temperature during the steady burning period decreased when the volume of the atrium increased. However, the values of the smoke layer interface height expressed as a percentage of the ceiling height also decreased when the volumes of the atria increased. This indicated that the 'smoke' volume in the atrium was increased.

A time constant given by Eq. (8) derived from the fire plume expressions is used to correlate with the smoke filling time. Linear relationships between t_{80} and t_{50} with the time constant given by Eqs. (13) and (14) were derived. These two expressions are useful in deciding whether smoke control systems have to be installed in the atrium. For example, if the escape time for the occupants is specified to be 3 min (180 s) and this value is taken to be the smoke filling time t_{80}, the time constant of the atrium has to be greater than 169 s as calculated from Eq. (13). Smoke control systems have to be installed if this condition is not satisfied. The approach is much better than the current practice[17] in using the atrium space volume, and so is strongly recommended to be considered in establishing Engineering Performance-Based Fire Codes.[16]

Another 63 simulations were performed on the seven groups of atria with the same fire and the same horizontal ceiling vent with an area of 9 m^2 in the atrium. The values of the average smoke temperature during the steady burning period were reduced. This was decreased by a value down to 50°C for the Type 1 atrium hall of volume 2,500 m^3. The smoke layer interface height in each atrium was kept at a much higher level as shown in Table 3. The smoke filling times t_{80} and t_{50} were delayed by a factor of values approximately 1.16 and 1.08, respectively. Therefore, installing a horizontal ceiling vent in the atrium is effective in removing both the heat and smoke as demonstrated by the simulations using the fire zone model CFAST Version 2.0. Of course, this has to be verified by experimental studies.

The effects of installing mechanical ventilation systems in the atrium were also studied. Another 63 simulations were performed on those atria for the smoke extraction rates of 6 air changes per hour. The values of the average smoke temperature during the steady burning period were reduced slightly. However, the smoke layer interface height in each atrium was kept at a much higher level as shown in Table 4. The smoke filling times t_{80} and t_{50} were delayed by factors of 1.96 and 1.95, respectively. They are much higher than the delaying factors for the same atria installed with a ceiling vent of area 9 m^2. Therefore, installing a mechanical ventilation system in the atrium is effective in removing smoke as simulated by the fire zone model CFAST Version 2.0. Again, experimental studies are required to verify this.

It is obvious that experimental verifications on the above results are necessary. To the best of the knowledge, no long-term systematic experiments were performed to validate a zone model for studying the smoke filling process in an atrium.[9-12] An atrium[26] of length 30 m, width 18 m and height 30 m was just constructed in Anhui, China for performing long-term experimental studies on atrium fires. One of the objectives is to validate fire models in simulating atrium smoke filling process. Reports will be published later.

ACKNOWLEDGEMENT

The project was funded (with account number HKP23/94E, 357/001) by the Research Grants Council, Hong Kong.

NOMENCLATURE

A_f	floor area of atrium, m^2
C_v, C_r, C_T	coefficients in plume equation
D	effective diameter of fire source, m
K_1, K_2	empirical constants depend on plume equation
H	height of atrium, m
r	plume radius, m
M_p	air entrainment rate of plume, kg s^{-1}
$\dot{Q}$	heat release rate of fire, kW
t	time, s
t_{50}	time required to fill 50% of atrium with smoke, s
t_{80}^0	time required to fill 80% of atrium with smoke for a fire of thermal power increased at a rate of 50 kW s^{-1}
t_{80}	time required to fill 80% of atrium with smoke, s
ΔT_o	central temperature rise of plume, °C
T_∞	ambient temperature, 290 K
T_{NFPA}	a constant in the equation for smoke filling process
v	upward speed of plume, m s^{-1}
y	clear height of smoke layer, m
z	height above a fire, m
z_o	elevation of virtual origin of fire, m

Greek Letters

α	entrainment coefficient
ρ	density of smoke, kg m^{-3}
ρ_∞	ambient density of air, 1.21 kg m^{-3}
τ_2	time constant derived from Zukoski's plume equations

REFERENCES

1. Chow, W.K., "Simulation of Fire Environment for Linear Atria in Hong Kong," ASCE Journal of Architectural Engineering, Vol. 3, No. 2, 1997, pp. 80–88.

2. Morgan, H.P. and Gardner, J.P. "Design Principles for Smoke Ventilation in Enclosed Shopping Centres," Building Research Establishment Report C1/SIB 981 (K23), Fire Research Station, Borehamwood, U.K., 1990.

3. Klote, J. and Milke, J., "Design of Smoke Management Systems," ASHRAE Publication 90022 ASHRAE, Atlanta, GA, 1992.

4. Hansell, G.O. and Morgan, H.P., "Design Approaches for Smoke Control in Atrium Buildings," Building Research Establishment Report, CI/SfB 981 (K23), Fire Research Station, Borehamwood, U.K., 1994.

5. Klote, J.H., "Method of Predicting Smoke Movement in Atria with Application to Smoke Management," NISTIR Report 5516, National Institute of Standards and Technology, Gaithersburg, MD, 1994.

6. Webb, W.A., "Development of Smoke Management Systems," ASHRAE Transactions, Vol. 101, Part 1, 1995, pp. 995–1000.

7. NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria and Large Areas," National Fire Protection Association, Quincy, MA, 1995.

8. Chow, W.K., "Preliminary Studies of a Large Fire in Hong Kong," Journal of Applied Fire Science, Vol. 6, No. 3, 1997, pp. 243–268.

9. Tanaka, T. and Yamana, T., "Smoke Control in Large Scale Space—Part 1," Fire Science & Technology, Vol. 5, 1985, pp. 31–40.

10. Tanaka, T. and Yamana, T., "Smoke Control in Large Scale Space—Part 2," Fire Science & Technology, Vol. 5, 1985, pp. 41–54.

11. Soderbom, J., "Smoke Spread Experiments in Large Rooms, Experimental Results and Numerical Simulations," SP Report 1992: 52, Swedish National Testing and Research Institute, Sweden, 1992.

12. Wikman, J., "Ship Fire Safety Engineering," Report ISRN LUTVDG/TVBB-1012-SE, Department of Fire Safety Engineering, Institute of Technology, Lund University, Lund, Sweden, 1995.

13. Tsujimoto, M., Nagaoka, T. and Uehara, S., "A Scaling Law of Smoke Movement in Atrium," Private Communication, 1990.

14. Jones, W.W., "Modeling Smoke Movement Through Compartmented Structure," Journal of Fire Sciences, Vol. 11, No. 2, 1993, pp. 172–183.

15. Peacock, R.D., Forney, G.P., Reneke, P., Portier, R. and Jones, W.W., "CFAST, The Consolidated Model of Fire Growth and Smoke Transport," NIST Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

16. Chow, W.K. and Wong, L.T., "On the Fire Safety Codes for Buildings in Hong Kong," Building Services Engineering Research and Technology — Accepted for publication, December, 1997.

17. Code of Practice for Minimum Fire Service Installations and Equipment and Testing of Installations and Equipment, Fire Services Department, Hong Kong, 1994.

18. Chow, W.K., "Smoke Development and Engineering Aspects of Smoke-Extraction System for Atria in Hong Kong," Fire and Materials, Vol. 17, No. 4, 1993, pp. 71–77.

19. Chow, W.K., "On the Evaluation of a 'Time Constant' for Studying the Smoke Filling Process in Atrium Spaces," Fire and Materials, Vol. 18, No. 5, 1994, pp. 327–331.

20. Chow, W.K., "Fire Aspects for Atrium Building in Hong Kong," Proceedings of the 7th International Research and Training Seminar on Regional Development Planning for Disaster Prevention "Improved Fire Safety system in Developing Countries," United Nations Centre for Regional Development (UNCRD), October 17, 1994, Tokyo, Japan UNCRD Proceedings Series No. 7, Nagoya Japan, 1995, pp. 99–109.

21. Thomas, P.H., Hinkley, P.L., Theobald, C.R. and Simms, D.L., "Investigation into the Flow of Hot Gases in Roof Venting," Fire Research Technical Paper No. 7, HMSO-London, U.K., 1963.

22. Zukoski, E.E., Kubota, T. and Cetegen, B., "Entrainment in Fire Plumes," Fire Safety Journal, Vol. 3, No. 1, 1980/81, pp. 107–121.

23. Thomas, P.H., "Smoke Control System Clarification," Fire Engineers, December, 1992, p. 6.

24. Beyler, C.L., "Fire Plumes and Ceiling Jets," Fire Safety Journal, Vol. 11, No. 1, 1982, pp. 53–75.

25. Chow, W.K., "On the Use of Time Constant for Specifying the Smoke Filling Process in Atrium Halls," Fire Safety Journal, Vol. 28, No. 2, 1997, pp. 165–177.

26. Chow, W.K. and Fan, Weicheng, "PolyU/USTC Atrium: A Full-Scale Burning Facility for Atrium Fire Studies," Information Leaflet, The Hong Kong Polytechnic University, Hong Kong, China, 1998.