



AN ANALYTICAL MODEL ON STATIC SMOKE EXHAUST IN ATRIA

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Abstract. Static smoke exhaust systems with natural vents are starting to be installed in big shopping complexes, warehouses and cargo terminals in the Far East. These systems are used for natural ventilation as well as for letting out smoke. This paper responds to concerns over the performance of static smoke exhaust systems, which remain less popular than dynamic smoke exhaust systems with mechanical fans. We propose a modification of a simple flow model found in the literature, adapting this to study smoke layer interface height with natural vents opened. We compare and justify our results, as generated by both Computational Fluid Dynamics and zone models, alongside reports of historical field tests. The model of smoke exhaust is applied in an illustrative example of a large hall, leading to the suggestion that a flow model could be used for designing natural vents. As the key driving force in removing smoke through natural vents is smoke's own buoyancy, the system might only be effective for bigger fires.

Keywords: smoke exhaust systems, natural vents, buoyancy, smoke layer interface height.

1. Introduction

Smoke management systems (Klote and Milke 1992; NFPA 2000) have to be installed to provide fire safety in large spaces. Burning even a small amount of modern synthetic materials generates a large quantity of smoke. Smoke exhaust systems are effective in keeping smoke above a certain level, thereby permitting fire fighting and the evacuation of blazing rooms. In East Asia, particularly Hong Kong, dynamic smoke exhaust systems with mechanical fans have been specified as the desired and sometimes mandatory means of clearing smoke from large halls (Fire Services Department 2005). Yet mechanical systems typically encounter serious difficulties in being able to supply a required exhaust rate of 8 air changes per hour in these spaces (Fire Services Department 2005). Further, it is difficult to allocate space within buildings' structure for installing fans and air ductworks. In consequence, many new projects are starting to put in alternatives such as static smoke exhaust systems. These natural vent devices include vertical vents inserted into side walls and horizontal ceiling vents; tall halls, such as atria located at the core of a building, will typically feature ceiling vents on account of the easier availability of roof space. A pressure difference is required for a vent to pass fluid from one side to the other—that is, from the area of high to the area of low pressure. This is the parameter in which it is feared that natural vents, despite their cost, space and energy advantages, would not work as well as mechanical fans.

The driving forces for natural ventilation (Klote and Milke 1992; NFPA 2000), which natural vents systems will have to harness, are stack effect, wind action and

buoyancy. Wind-induced air motion (Poreh and Trebukov 2000) occurs dynamically, such that a well-designed natural venting system could function efficiently by exploiting windward and leeward pressure distributions. Especially in sultry climates, wind-induced pressure, though, might not be always available, and thus would not be reliable for letting out smoke in an emergency. Further, natural designs would have adverse effects in cases where wind blew into a hall with an adjacent tall building (Chow 2004). In places with a small difference between indoor and outdoor temperatures, stack pressure is also low, possibly being significant (Zhang *et al.* 2006) only in lift shafts or staircases with a large height to length ratio. In halls of a large cross-sectional area, there is some likelihood that stack pressure could be sufficiently high to open numerous air flow paths (for instance, in such open design as multi-storey shopping malls). Reverse stack pressure might also pull smoke down under some conditions.

The performance of static exhaust systems depends on factors affecting flow rates through ceiling vents, including the smoke layer temperature, smoke layer thickness, fire size and wind conditions. There is therefore a need to investigate smoke layer temperature and interface height under different fire sizes so as to explore the practicality of natural vents. The key driving force in smoke exhaust is buoyancy (Andersen 1995). If smoke is hot enough to be sufficiently buoyant, a static smoke extraction system may be able effectively to remove smoke from big halls. The bigger the fire size, the stronger smoke's buoyancy and hence the higher the exhaust rate (Andersen 1995; Klote 2000; Klote and Milke 1992;

Li and Chow 2002–2003). Therefore, static smoke exhaust system might not work as expected for a small fire with low heat release rate. However, the damage in such small fires is not significant. In terms of the characteristics of exhaust systems’ design, vent area, vent location and the time for which fires are allowed to burn are all important. It is not necessarily the case that larger-area vents will give a superior system performance under small fires. Equally, a vent designed for coping with big fires might see cool air pushing down, rather than hot gas moving up, if operated in the case of a small fire. The implication is that designs should feature a larger number of smaller-area vent to take advantage of smoke buoyancy. The literature reports numerous studies of vent flow induced by buoyancy (e.g. Andersen 1995; Cooper 2002; Klote 2000; Klote and Milke 1992; Li and Chow 2002–2003; Morgan and Gardner 1990; NFPA 1998, 2000). Li and Chow (2002–2003) review a number of these papers on calculating vent size by buoyancy. Reading this work offers a preliminary confirmation of the research that a flow model can be useful in evaluating the performance of natural vents.

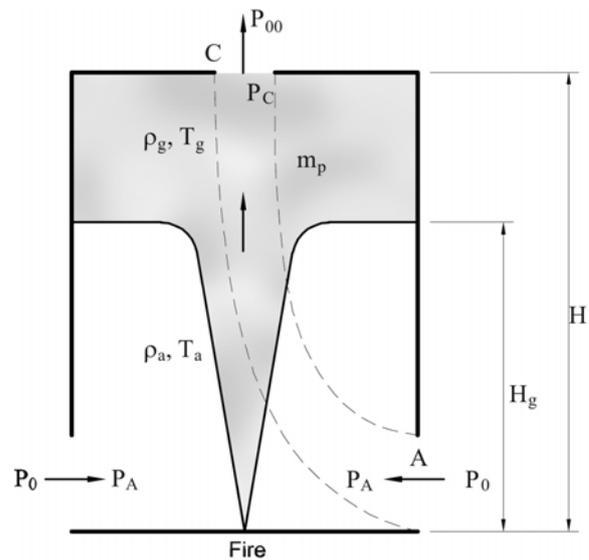
In this paper, we will discuss a flow model approach to the design of a smoke exhaust system. The paper’s proposed model will be put to use studying smoke exhaust from natural vents. Experimental results (Tanaka *et al.* 1987; Yamana and Tanaka 1985; Yang and Yeh 2005) available in the literature will be applied to justify model predictions, which will be generated by both Computational Fluid Dynamics (CFD) (McGrattan *et al.* 2008a, 2008b) and zone models (CFAST 2007). In our experimental simulations, smoke flows through a large hall as observed by the model (Chow 2006). The findings of these experiments are that natural vents may be efficient in extracting smoke from large atrium spaces if properly designed.

2. Standard Buoyancy-Driven Flow Model

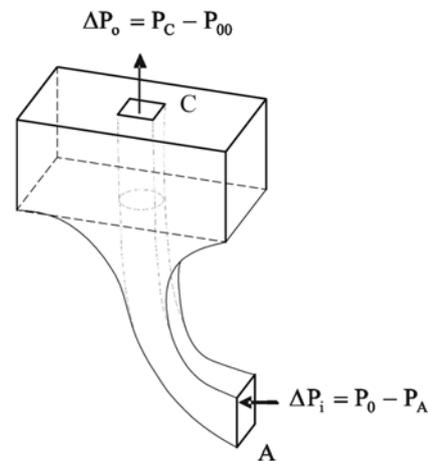
Hot smoke generated by a building fire rises up to the ceiling on account of its own buoyancy. There are two layers in the building with an upper hot smoke layer and a lower cool air layer. Heat and mass will be transferred from the burning object at lower level to the upper hot smoke layer through the plume. The cross-sectional area of the building is assumed to be much larger than the areas of both the intake and exhaust openings. Physical properties of the upper smoke layer and the thickness would change with time. However, physical properties and thermal parameters such as air temperature of the layer are assumed to be uniform in space at any time. For purposes of fire management, it is important not to open ceiling vents immediately in case of fire, but only when the upper smoke layer is hot enough. Smoke can then be extracted effectively through the natural vent through taking advantage of its buoyancy as shown in Fig. 1a.

We can illustrate this by considering a hall of height H (in m) with a smoke layer interface height H_g (in m). Taking the ambient air density as ρ_a (in kgm^{-3}), the density of the hot gas as ρ_g (in kgm^{-3}), the atmospheric pressure at the floor level as P_0 (in Pa), and the atmospheric

pressure at the ceiling level as P_{00} , the smoke exhaust flow can be visualized as a fluid bundle (e.g. Chow 2005; Li and Chow 2002–2003) moving between two points A and C at pressures P_A and P_C respectively, as in Fig. 1b. The pressure drop across the ceiling vent at C is $P_C - P_{00}$ and the pressure drop across the air inlet vent at A is $P_0 - P_A$.



(a) Two-layer zone model under steady-state



(b) A smoke bundle for deriving the key equation

Fig. 1. Ceiling vent

The pressure drop ΔP_o (in Pa) across the ceiling vent caused by the difference in densities of the smoke layer and the surrounding cold air as shown in Fig. 1 can be given as:

$$\Delta P_o = P_C - P_{00} = (P_A - P_0) + (\rho_a - \rho_g)g(H - H_g). \quad (1)$$

This can be expressed as the pressure drop across the inlet vent ΔP_i (in Pa) as:

$$\Delta P_o = \rho_a g'(H - H_g) - \Delta P_i. \quad (1a)$$

The reduced gravity due to buoyancy g' (in ms^{-2}) is defined by:

$$g' = \frac{\Delta\rho}{\rho_a} g. \quad (2)$$

ΔP_o can be further simplified in terms of the pressure difference due to buoyancy or ΔP_F as:

$$\Delta P_o = \Delta P_F - \Delta P_i, \quad (3)$$

where

$$\Delta P_F = \rho_a g'(H - H_g). \quad (4)$$

Applying Bernoulli's theorem on the fluid bundle shown in Fig. 1b, the velocity across the ceiling vent v_o (in ms^{-1}) can be calculated by:

$$v_o = \left[\frac{2g(\rho_a - \rho_g)(H - H_g)}{\left(1 + \frac{\rho_g C_o^2 A_o^2}{\rho_a C_i^2 A_i^2}\right) \rho_g} \right]^{1/2}. \quad (5)$$

In the above equation, C_i and C_o are the discharge coefficients of the inlet and outlet vents respectively, and A_i and A_o the areas of the inlet and outlet opening respectively. Detailed derivations of the vent flow velocity are presented in the paper by Li and Chow (2002–2003).

Applying the ideal gas law gives the relation between ρ_g and temperature T_g (in K) of the hot gas layer, density ρ_a and temperature T_a of ambient air:

$$\rho_g T_g = \rho_a T_a.$$

Equation (5) can be rewritten as:

$$v_o = \left[\frac{2g(T_g - T_a)(H - H_g)}{\left(1 + \frac{T_a C_o^2 A_o^2}{T_g C_i^2 A_i^2}\right) T_a} \right]^{1/2}. \quad (6)$$

The mass flow rate across the ceiling vent m_e (in kg s^{-1}) may then be calculated by:

$$m_e = C_o \rho_g A_o v_o = C_o \rho_a A_o \left[\frac{2g(H - H_g)(T_g - T_a)T_a}{T_g \left(T_g + \frac{T_a C_o^2 A_o^2}{C_i^2 A_i^2} \right)} \right]^{1/2}. \quad (7)$$

It is generally considered a requirement of a good design that the total surface area of the inlet vents is relatively larger than the area of the exhaust. In this way, adequate make-up air can be supplied. In practice, there are many openings at the lower levels and so area of inlet vents is higher, except some poorly designed examples. This would mean that the pressure drop across the inlet vents would be negligible in comparison with the pressure drop ΔP_o across the open ceiling vents (Cooper 2002). The minimum stipulation for a design's vent area is defined as the least area meeting fire safety criteria for a given building (NFPA 1998). This is often derived by build-

ing the design of smoke management systems around an assumption of steady-state vent flow.

To satisfy the design objective of keeping the smoke layer at height H_g , the mass flow rate out of the vents m_e should be of a value similar to the mass production rate of smoke m_p (in kg s^{-1}) at the interface height:

$$m_e = m_p. \quad (8)$$

The required vent area to keep smoke at this interface height H_g can be calculated by:

$$C_o A_o = m_p / \rho_a \left[\frac{2g(H - H_g)(T_g - T_a)T_a}{T_g \left(T_g + \frac{T_a C_o^2 A_o^2}{C_i^2 A_i^2} \right)} \right]^{-1/2}. \quad (9)$$

Ignoring heat loss through the atrium, energy conservation of the upper hot gas layer gives T_g in terms of the convective heat release rate of the fire Q_c (in W):

$$\frac{T_g}{T_a} = \frac{Q_c}{m_p C_p T_a} + 1. \quad (10)$$

Substituting the above equation into equation (9), we get:

$$C_o A_o = \frac{m_p}{\rho_a} \left\{ \frac{\left(\frac{Q_c}{m_p C_p T_a} + 1 \right) \left[\left(\frac{Q_c}{m_p C_p T_a} + 1 \right) + \frac{C_o^2 A_o^2}{C_i^2 A_i^2} \right]^{1/2}}{2g(H - H_g) \frac{Q_c}{m_p C_p T_a}} \right\}. \quad (11)$$

Assuming $A_i \gg A_o$, the required ventilation area can then be calculated by:

$$C_o A_o = \frac{m_p \left(\frac{Q_c}{m_p C_p T_a} + 1 \right)}{\rho_a \left[2g(H - H_g) \frac{Q_c}{m_p C_p T_a} \right]^{1/2}} = \quad (12)$$

$$\frac{F^{1/2} \left(m_p^{1/2} + \frac{m_p^{3/2} C_p T_a}{Q_c} \right)}{g[2\rho_a(H - H_g)]^{1/2}},$$

where F is the buoyancy flux of the hot smoke defined (Li and Chow 2002–2003; Hu *et al.* 2004) by:

$$F = \frac{g Q_c}{\rho_a C_p T_a}. \quad (13)$$

The mass flow rate of the plume m_p (in kg s^{-1}) depends on the location of the fire in the hall. For a fire at the floor level, axisymmetric plume equations such as Heskestad's (1984) can be used to calculate the required vent area. Axisymmetric plume equation due to Heskestad is:

$$m_p = 0.071 Q_c^{1/3} z^{5/3} + 0.0018 Q_c. \quad (14)$$

Substituting the above plume equation in equation (12) gives:

$$C_o A_o = \frac{F^{1/2} [0.266 Q_c^{1/6} (H_g^{5/3} + 0.0254 Q_c^{2/3})^{1/2} + 0.0189 Q_c^{-1/2} C_p T_a (H_g^{5/3} + 0.0254 Q_c^{2/3})^{3/2}]}{g [2\rho_a (H - H_g)]^{1/2}} \quad (15)$$

3. Effect of Smoke Layer Temperature

Defining ϕ as the ratio of T_g to T_a for a ceiling vent with area A_o in an atrium with smoke interface height H_g :

$$\phi = \frac{T_g}{T_a} \quad (16)$$

If we then rewrite the vent flow equation (7) as:

$$m_e = C_o \rho_a A_o \left[\frac{2g(H - H_g)(\phi - 1)}{\phi \left(\phi + \frac{C_o^2 A_o^2}{C_i^2 A_i^2} \right)} \right]^{1/2} \quad (17)$$

the effect of smoke temperature on ventilation capacity is shown in Fig. 2. The vent flow rate need not always increase proportionately with the smoke layer temperature

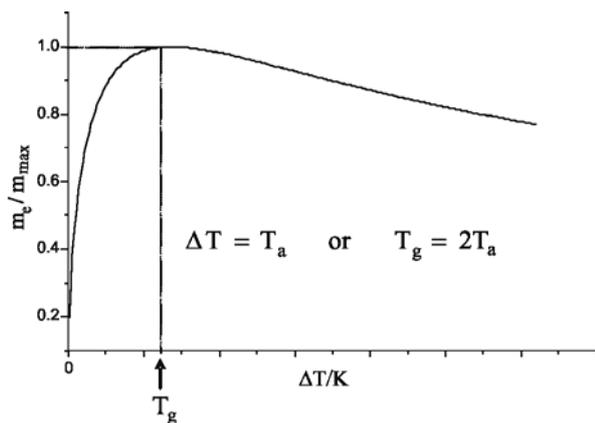


Fig. 2. Effects of smoke temperature on the extraction mass flow rate through the vent

for the smoke layer thickness to remain at a fixed value. Rather, a maximum value of m_e denoted by m_{max} is reached at a certain smoke layer temperature. A vent flow rate greater than m_{max} will then fall as the gas temperature goes up. The value of m_{max} can be derived by taking:

$$\frac{dm_e}{d\phi} = 0, \quad (18)$$

giving:

$$\phi = 1 + \left(\frac{C_o^2 A_o^2}{C_i^2 A_i^2} + 1 \right)^{1/2} \quad (19)$$

Detailed derivation of equation (19) can be found in Appendix A. Assuming the large inlet area, $A_i \gg A_o$,

$$\phi \approx 2 \quad (20)$$

therefore, T_g will be given by:

$$T_g \approx 2T_a \quad (21)$$

or

$$\Delta T = T_g - T_a \approx T_a \quad (22)$$

Under this condition of $T_g = 2T_a$ or $\Delta T = T_a$, the vent flow rate tops out at the maximum value m_{max} .

4. Effects of Heat Release Rate on Smoke Layer Interface Height

The heat release rate of fire being modeled is a key factor in the design of smoke management systems. This creates design difficulties in that change of atrium uses would lead to fires of a different release rate. This rate depends not only on the fire load, but also on the types of combustibles found in the indoor environment and consumed in the fire. This in turn leads to variation, and this to deviation from design predictions, in the smoke layer interface height satisfying the mass balancing of the exhaust rate and the plume entrainment rate. In these instances, we need to keep the interface height at a higher value than the minimum that would facilitate a safe evacuation. There is an obvious need to study relations between interface height and fire size in designing natural vents.

We can begin by defining a parameter A as:

$$A = C_o A_o g (2\rho_a H)^{1/2} \quad (23)$$

As shown before, the vent flow equation is:

$$m_e = A \left[(1 - \xi) \frac{\rho_a}{g} \left(\frac{T_g}{T_a} - 1 \right) \right]^{1/2} \left(\frac{T_g}{T_a} \right)^{-1} \quad (24)$$

where ξ is the smoke layer interface height expressed as a ratio of the ceiling height H:

$$\xi = H_g / H \quad (25)$$

Combining this with equation (10) and using mass conservation to take m_p as m_e , supposing equation (12) on F, ξ can be calculated by:

$$\xi = 1 - \frac{F m_p}{A^2} \left[1 + \frac{m_p C_p T_a}{Q_c} \right]^2 \quad (26)$$

Substituting Heskestad's axisymmetric plume equation (Heskestad 1984),

$$\xi = 1 - \frac{F}{Q_c A^2} [Q_c^{2/3} (0.071 H^{5/3} \xi^{5/3} + 0.0018 Q_c^{2/3})^{1/2} + (0.071 H^{5/3} \xi^{5/3} + 0.0018 Q_c^{2/3})^{3/2} C_p T_a]^2 \quad (27)$$

As A_i might not be larger than A_o for some projects, a more general equation on the smoke layer height is presented as:

$$\xi = 1 - \frac{(0.071Q_c^{1/3}\xi^{5/3} + 0.0018Q_cH^{-5/3})^2 H^{7/3}}{2gC_o^2 A_o^2 \rho_a^2} \cdot \frac{1}{[(1 + (0.071Q_c^{-2/3}\xi^{5/3} + 0.0018H^{-5/3})C_p T_a H^{5/3})]} \quad (28)$$

$$\left[\frac{1}{(0.071Q_c^{-2/3}\xi^{5/3} + 0.0018H^{-5/3})C_p T_a H^{5/3}} + 1 + \frac{C_o^2 A_o^2}{C_i^2 A_i^2} \right]$$

Solving the above equation numerically yields smoke layer interface heights under different fire sizes. Detailed derivations of equations (27) and (28) are shown in Appendix B.

5. Field Tests at Japan

The flow model on static smoke exhaust system given by equation (28) can be justified by tests reported in the literature. Good-quality data has been reported from field tests carried out at the SR hall (Tanaka and Yamana 1987) for Scientific and Technology Exhibitions in Japan. The hall is of length 21.3 m, width 21.3 m and height 9.9 m and had a 2.5 m² pool fire set up in positions described in Fig. 3. The heat release rate per unit area of the pool fire was estimated from an earlier study on an experimental hall to come in at 0.4 MWm⁻², for a total heat release of about 1 MW.

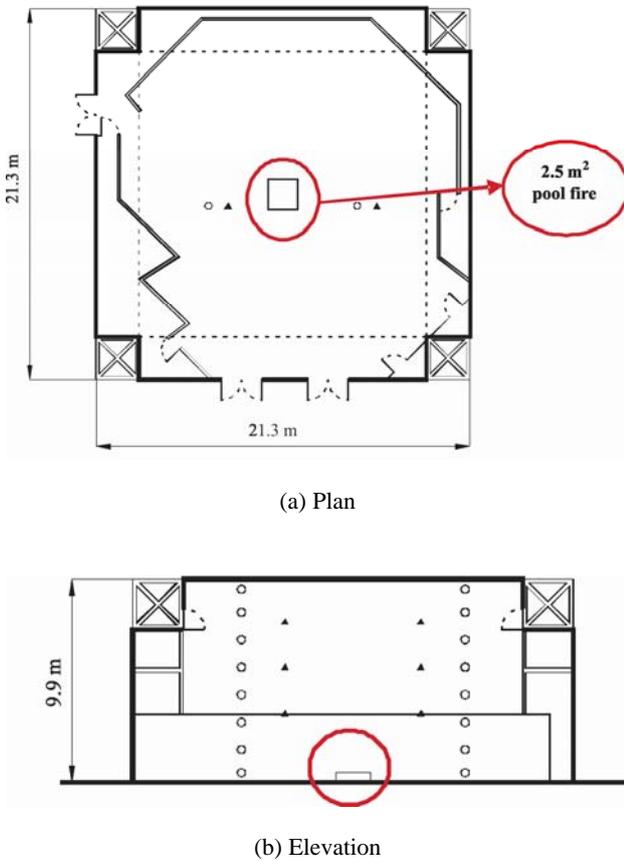


Fig. 3. The SR hall

Five tests were carried out in the SR hall relevant to this study:

- SR01: Natural smoke filling with 1 air inlet opening of area 2.47 m².
- SR02: Natural smoke filling with 4 natural smoke exhaust vents of a total area 11.5 m²; 1 air inlet opening of area 2.47 m².
- SR03: Natural smoke filling with 4 natural smoke exhaust vents of a total area 11.5 m²; 4 air inlet openings of total area 9.98 m².
- SR04: Natural smoke filling with 2 natural smoke exhaust vents of a total area 5.76 m²; 4 air inlet openings of total area 9.98 m².
- SR05: Natural smoke filling with 4 natural smoke exhaust vents of a total area 5.76 m²; 4 air inlet openings of total area 9.98 m².

Results for transient smoke layers are shown in Fig. 4. In test SR01 and SR02 with natural smoke filling, smoke fell to the ground, not being held at an interface or evacuation height; the air inlet vent area was thus inadequate. However, tests SR03, SR04 and SR05 suggest that well-designed inlet vents would have led to smoke layers falling down slowly and being kept at an interface height above 2.4 m. This would seem once again to imply that an appropriately-designed natural vent can be effective in keeping the smoke layer above a certain height.

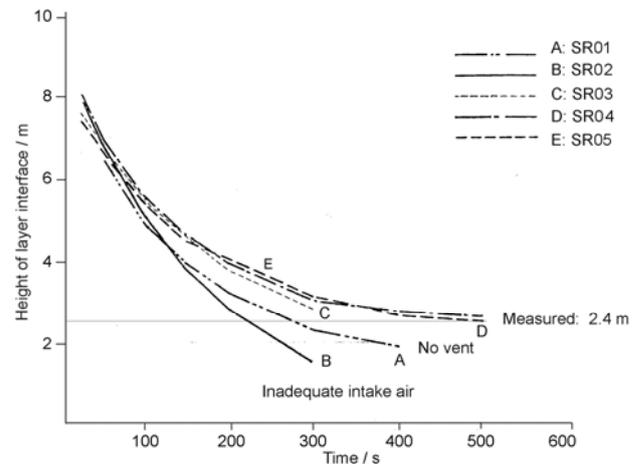


Fig. 4. Smoke layer interface heights at the SR hall

The smoke layer interface heights for cases SR02, SR03 and SR04 were calculated using the flow model given by equation (28) as shown in Table 1. The results predicted by the flow model suggested that designing a venting system with the wrong air intake rate would not fail to keep the smoke layer at a safely high level. This is similar to the field tests' observations. However, the results as they concern smoke layer interface heights at the final stage of burning differ to some degree from those of tests. As the heat release rate was not clearly stated, its value might come in at over 1 MW, going up to 3 MW, based on data reported earlier (Tanaka *et al.* 1987; Yamana and Tanaka 1985).

Table 1. Comparison of the smoke layer heights predicted by different methods

Japan SR hall	H_g / m			
	Field test	Flow model	FDS	CFAST
SR01	< 2		1.2	0.3
SR02	1.8	3.6	1.4	4.0
SR03	> 2.4	6.8	5.6	5.8
SR04/SR05	2.4	5.8	5.3	5.1

6. Field Tests in a Railway Terminal Building in Taiwan

Another set of data on smoke filling and exhaust has been recently reported, describing the performance of a static exhaust system dealing with a hot smoke test in the hall of a railway terminal in Taiwan (Yang and Yeh 2006). The building is of ceiling height between 20 to 25 m as shown in Fig. 5. Natural vent areas were designed to have a surface area of 379 m². The fire in field tests of this static exhaust system was a fast t²-fire with a cut-off value of 5 MW. A total of 25 gasoline pans of 0.45 m diameter were burnt, with each pan giving off about 0.2 MW.

Fig. 6 shows results for the smoke layer interface height with smoke dispersing through a natural vent. The vent successfully kept the smoke layer at a height above 17 m, about 68% of the maximum ceiling height, again demonstrating natural systems’ efficacy in allowing smoke to dissipate.

Our flow model, meanwhile, estimated the smoke layer interface at a height of 19.7 m by equation (28). This is very similar to the value measured by observation and can be counted as a good agreement, bearing in mind the simplicity of our equation and the irregular shape of the large hall.

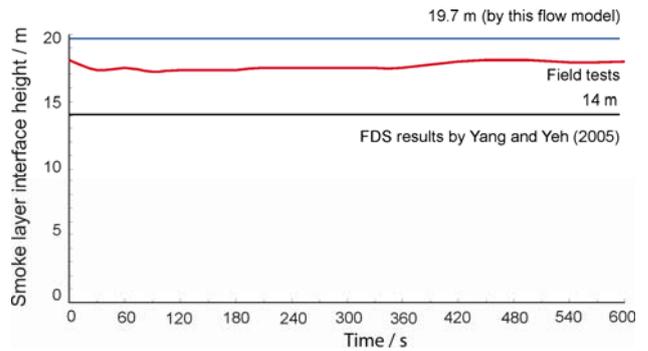


Fig. 6. Smoke layer interface heights at a Taiwan railway hall (Yang and Yeh 2005)

7. Fire Model Simulations

Smoke exhaust systems’ performance may also be evaluated by CFD. The CFD software Fire Dynamics Simulator (FDS), developed at the Building and Fire Research Laboratory at the US National Institute of Standards and Technology may be used (McGrattan *et al.* 2008a, 2008b) as a further justification of the flow model given by equation (27). We can also cross-compare the estimations of the FDS simulator, the flow equation and observations in order to get some sense of the validity of the simulated methods. The input heat release rate Q_c curve for fire simulation is shown in Fig. 7. The walls and ceiling are taken to be adiabatic. Sensitivity of the grid system was studied and the optimum grid system is determined to be 108×108×50 for simulating all SR cases.

Further, smoke layer interface heights in the SR hall have also been predicted by the zone model CFAST (2007). Results are compared with empirical equations, experiments and FDS simulations in Fig. 8. Table 1 presents a summary of the predicted smoke layer interface heights at the steady burning stage of the pool fire for different tests. The table shows that measured values in the SR Hall across the five tests SR01 to SR05 differ from the predictions of the flow model, FDS and CFAST. However, the predicted results of the flow model agree well with CFAST, as both assume a two-layer picture.

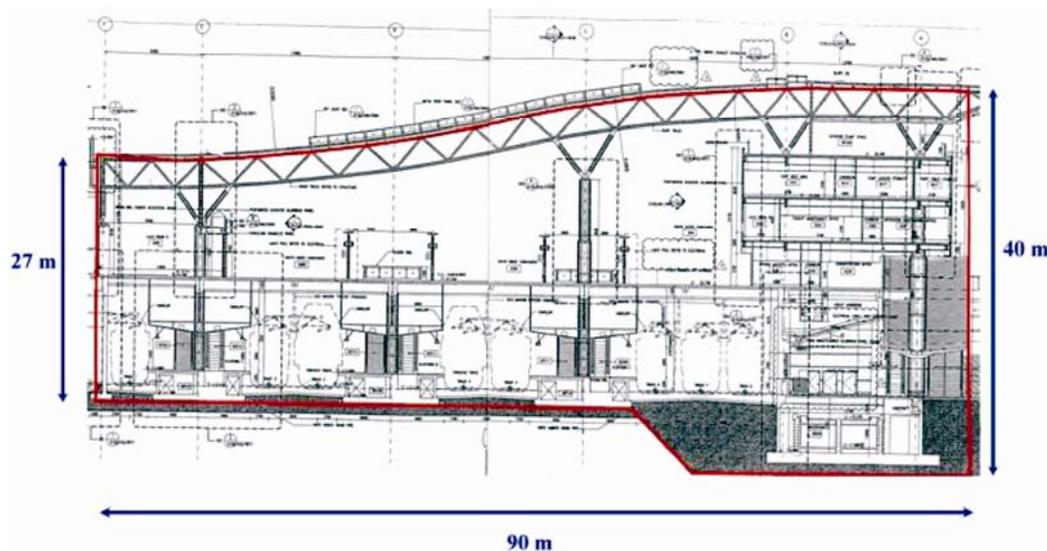


Fig. 5. The railway hall in Taiwan (Yang and Yeh 2005)

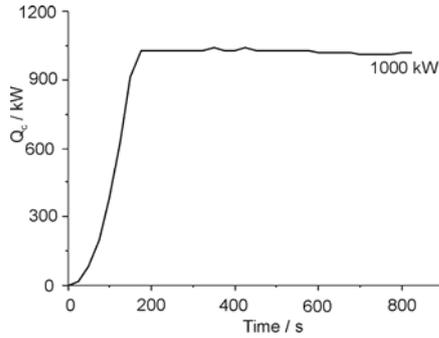
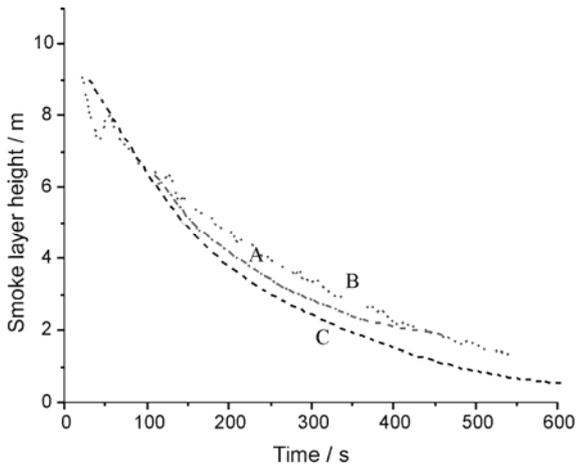


Fig. 7. Heat release rate curve for the SR hall

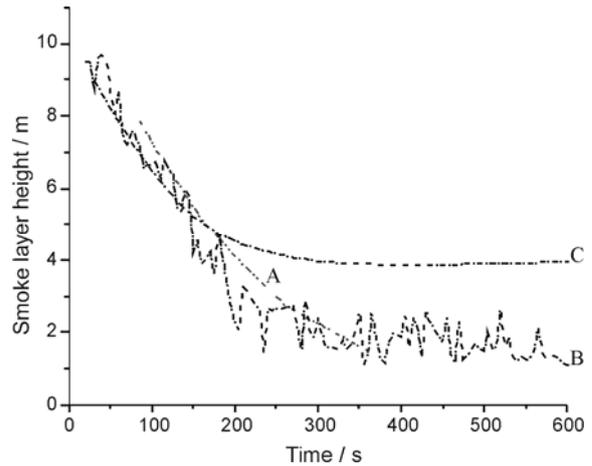
Table 1 again shows the predictions of the flow model, CFAST and FDS. The predicted smoke layer interface heights were lower for higher heat release rates, agreed better with experiments.

Smoke layer interface height at the Taiwan Railway Terminal was predicted by FDS at 14 m as shown in Fig. 6, very close to the predictions of both simple flow model and CFAST.

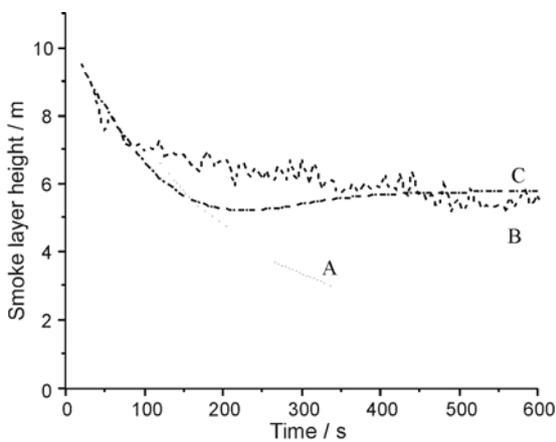
As illustrated by Fig. 8, showing transient smoke layer interface predictions, all real and projected data agreed reasonably well at an early stage. However, results at later stages of burning deviated, as the smoke layer interface height is not easy to determine experimentally during the later stages of a fire. It is easy to suppose in such instances that temperature profiles and visual observation, which are likely to be obscured, will give different results. Test fires in field tests are thus vulnerable to special problems when it comes to evaluating the performance of smoke exhaust systems coping with smoke generated in atria. Different smoke generation methods have been studied in detail on large halls and tunnels in Taiwan (Yang and Chow 2008) over the past ten years. Some commentators have concluded that white smoke generated from smoke guns would give a clearer position of the height of the smoke layer interface. Further, this would provide a clean environment (Yang and Chow 2008) after carrying out tests with black smoke while burning gasoline. However, the smoke would not necessarily be of the required temperature and buoyancy.



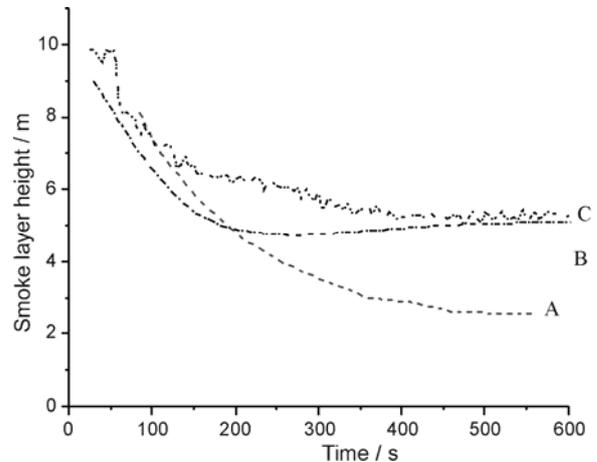
(a) SR01



(b) SR02



(c) SR03



(d) SR04

A: Measured results B: FDS results C: CFAST results

Fig. 8. Comparison of smoke layer interface heights with a 1 MW fire

Variation of the interface height ξ and smoke vent flow rate with the convective heat release rate Q_c for case SR04 are shown in Figs. 9 and 10 with the ambient temperature taken to be 20 °C. For this smoke vent system, smoke layer interface would decrease, but mass vent flow rate would increase while increasing the fire size.

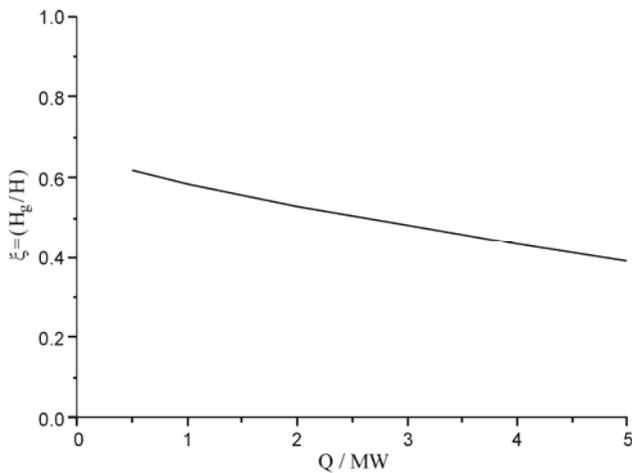


Fig. 9. Effects of fire size on the vent flow for Case SR04

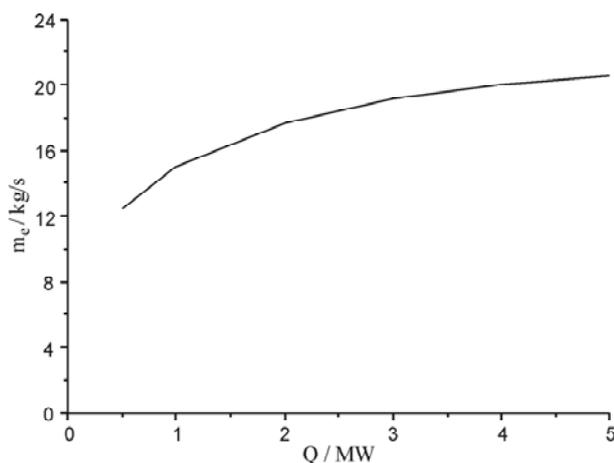


Fig. 10. Variation of the mass exhaust rate with the fire size for SR04

8. Conclusion

This paper modified a simple buoyancy-driven flow model to determine the smoke layer interface heights for a static smoke exhaust system. The development of such a model can be useful in preliminary hazard assessment of many scenarios with big halls where static exhaust systems will be preferable for space and environmental reasons. Our model flow predicts that smoke layer interface heights will flow out of natural vents more quickly the hotter the smoke. Maximum exhaust rates will be achieved when the temperature of the smoke layer comes in at twice the ambient value. Note that a zone model does not include initial lateral flow of smoke across the ceiling. Results predicted by this model should be justified for spaces with large ceiling areas of irregular shape and rough ceiling. As proposed by Cooper (1993, 1995), the

approach would not work very well for the cases with very low pressure drop across the vent.

This study referred for the purposes of validating its model to actual field tests of static smoke exhaust systems in big halls carried out in Japan and Taiwan. Data from all these sources bore out the suggestion that appropriately-designed natural vents can be effective in removing smoke, even in small fires. All five tests at the Japanese SR Hall indicated that a good design of static smoke exhaust system with an adequate inlet vent area can maintain a smoke layer at a safe height. The test in a hall in Taiwan suggested that an appropriate design of the static smoke exhaust system can keep the smoke layer as far up as 70% of the ceiling height above ground level. The flow model's results for smoke layer interface height agreed well with the Taiwanese test, though less well with the Japanese test. A possible explanation can be found in terms of different criteria for determining the smoke layer interface, especially insofar as visual observations in this parameter in the latter stages of hot smoke fires may be inaccurate. The Taiwanese data may be considered the more reliable in examining smoke generation in great detail for the purposes of evaluating smoke exhaust systems (Yang and Chow 2008). Further, the simulation predictions of FDS, CFAST and the proposed flow model results agreed well with each other. These tests concurred with the central finding that a natural vent is effective in keeping smoke above a certain height.

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Appendix A: Derivation of equation (19)

The mass flow rate across the ceiling vent m_e is given in terms of the ratio ϕ of the absolute temperature of the hot smoke layer T_g to the temperature of the ambient air T_a :

$$m_e = C_o \rho_a A_o \left[\frac{2g(H - H_g)(\phi - 1)}{\phi \left(\phi + \frac{C_o^2 A_o^2}{C_i^2 A_i^2} \right)} \right]^{1/2}, \quad (A1)$$

where

$$\phi = \frac{T_g}{T_a}. \quad (A2)$$

The vent flow rate might not increase with the temperature of the smoke layer. There is a maximum value m_{\max} at a certain smoke layer temperature. The vent flow rate cannot be greater than m_{\max} as T_g increases. Value of m_{\max} can be deduced by taking:

$$\frac{dm_e}{d\phi} = 0. \quad (A3)$$

Differentiating m_e with respect to ϕ gives:

$$\frac{dm_e}{d\phi} = \frac{1}{2} C_o \rho_a A_o [2g(H - H_g)]^{1/2} \cdot \frac{1 - \phi^2 + 2\phi + \frac{C_o^2 A_o^2}{C_i^2 A_i^2}}{[\phi(\phi - 1)(\phi + \frac{C_o^2 A_o^2}{C_i^2 A_i^2})]^{1/2} \left[\phi(\phi + \frac{C_o^2 A_o^2}{C_i^2 A_i^2}) \right]}. \quad (A4)$$

Equating to zero gives:

$$\phi^2 - 2\phi - \frac{C_o^2 A_o^2}{C_i^2 A_i^2} = 0. \quad (A5)$$

Solving equation (A5) would get:

$$\phi = 1 \pm \left(\frac{C_o^2 A_o^2}{C_i^2 A_i^2} + 1 \right)^{1/2}. \quad (A6)$$

As ϕ is greater than 1 for $T_g > T_a$, ϕ is taken as:

$$\phi = 1 + \left(\frac{C_o^2 A_o^2}{C_i^2 A_i^2} + 1 \right)^{1/2}. \quad (A7)$$

Appendix B: Derivation of equations (27) and (28)

From equation (7), the mass flow across the vent m_e is:

$$m_e = C_o \rho_g A_o v_o = C_o \rho_a A_o \left[\frac{2g(H - H_g)(T_g - T_a)T_a}{T_g \left(T_g + \frac{T_a C_o^2 A_o^2}{C_i^2 A_i^2} \right)} \right]^{1/2}. \quad (B1)$$

When $A_i \gg A_o$, m_e can be expressed in terms of the smoke layer interface height ratio ξ to the ceiling height H .

$$m_e = C_o A_o g (2\rho_a H)^{1/2} \left[(1-\xi) \frac{\rho_a}{g} \left(\frac{T_g}{T_a} - 1 \right) \right]^{1/2} \left(\frac{T_g}{T_a} \right)^{-1}, \quad (\text{B2})$$

where

$$\xi = H_g / H. \quad (\text{B3})$$

Defining

$$A = C_o A_o g (2\rho_a H)^{1/2}. \quad (\text{B4})$$

Equation (B1) can be written as:

$$m_e = A \left[(1-\xi) \frac{\rho_a}{g} \left(\frac{T_g}{T_a} - 1 \right) \right]^{1/2} \left(\frac{T_g}{T_a} \right)^{-1}. \quad (\text{B5})$$

Energy conservation of the hot gas layer would give the smoke layer temperature as:

$$\frac{T_g}{T_a} = \frac{Q_c}{m_p C_p T_a} + 1. \quad (\text{B6})$$

Using mass conservation to take m_p as m_e , ξ can be calculated by:

$$\xi = 1 - \frac{F m_p}{A^2} \left[1 + \frac{m_p C_p T_a}{Q_c} \right]^2, \quad (\text{B7})$$

where F is the buoyancy flux of the hot smoke:

$$F = \frac{g Q_c}{\rho_a C_p T_a}. \quad (\text{B8})$$

Calculating the smoke production rate m_p by the axisymmetric plume equation such as that by Heskestad (1984) for a fire at the floor level:

$$m_p = 0.071 Q_c^{1/3} z^{5/3} + 0.0018 Q_c \quad (\text{B9})$$

Putting the above plume equation into equation (B6) gives:

$$\xi = 1 - \frac{F}{Q_c A^2} [Q_c^{2/3} (0.071 H^{5/3} \xi^{5/3} + 0.0018 Q_c^{2/3})^{1/2} + (0.071 H^{5/3} \xi^{5/3} + 0.0018 Q_c^{2/3})^{3/2} C_p T_a]^2 \quad (\text{B10})$$

As A_i might not be larger than A_o for some design, putting the plume equation (B9) into equation (B1) would give a general equation on the smoke layer height as:

$$\xi = 1 - \frac{(0.071 Q_c^{1/3} \xi^{5/3} + 0.0018 Q_c H^{-5/3})^2 H^{7/3}}{2g C_o^2 A_o^2 \rho_a^2} \quad (\text{B11})$$

$$[(1 + (0.071 Q_c^{-2/3} \xi^{5/3} + 0.0018 H^{-5/3}) C_p T_a H^{5/3})]$$

$$\left[\frac{1}{(0.071 Q_c^{-2/3} \xi^{5/3} + 0.0018 H^{-5/3}) C_p T_a H^{5/3}} + 1 + \frac{C_o^2 A_o^2}{C_i^2 A_i^2} \right].$$

STATINIO DŪMŲ ŠALINIMO ATRIUOSE ANALITINIS MODELIS

Ch. L. Chow, J. Li

S a n t r a u k a

Tolimuosiuose Rytuose statinės dūmų šalinimo sistemos su natūralios ventiliacijos angomis pradedamos įrengti dideliuose prekybos kompleksuose, sandėliuose ir krovinių terminaluose. Tokios sistemos naudojamos ir natūraliai ventiliacijai, ir dūmams šalinti. Šis straipsnis parengtas susirūpinus, kad statinės dūmų išmetimo sistemos yra ne tokios populiaros nei dinaminės dūmų išmetimo sistemos su mechaniniais ventiliatoriais. Autoriai siūlo literatūroje aprašomo paprasto srauto modelio modifikaciją, pritaikant šį modelį dūmų sluksnio sąlyčio su natūralios ventiliacijos angomis aukščiui tirti. Straipsnyje palyginti ir pagrįsti rezultatai, gauti taikant tiek skaičiuojamosios skysčių dinamikos, tiek zonavimo modelius kartu su eksperimentiniais tyrimais vietovėje. Pateiktas dūmų šalinimo modelio taikymo pavyzdys didelėje salėje ir padaryta išvada, kad srauto modelis galėtų būti taikomas įrengiant natūralią ventiliaciją. Kadangi pagrindinė varomoji jėga šalinant dūmus per natūralias ventiliacijos angas yra dūmų plūdrumas, sistema gali būti veiksminga tik esant didesniems gaisrams.

Reikšminiai žodžiai: dūmų šalinimo sistemos, natūralios ventiliacijos angos, plūdrumas, dūmų sluksnio sąlyčio aukštis.

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