REVIEW ON DESIGN GUIDES FOR SMOKE MANAGEMENT SYSTEM IN AN ATRIUM

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ABSTRACT

Common design guides on smoke management in atria used will be reviewed in this paper. Different approaches adopted in those guides are outlined with the smoke physics behind explained. Engineering principles on smoke dynamics of these design guides are observed to be similar. Basically, methods are on imposing opposite strong airflow to prevent smoke spreading, applying pressure differentials against a physical barrier, dilution of smoke and extracting smoke. Smoke ventilation appears to be a common approach for smoke management in an atrium. An acceptable smoke layer interface height can be kept; or at least, reducing the descending rate of smoke layer. These guides give general principles for the design, but not cover all the atria, especially those in new construction projects of the Far East. Further, guidance on solving practical problems frequently encountered in these areas is discussed.

1. INTRODUCTION

Smoke generated from a fire in an atrium itself or in spaces adjacent to the atrium may spread rapidly. Consequence will be quite serious in exposing a number of occupants to risk. The time for escape will be reduced and the fire-fighting activities will be affected, though the smoke will be quite 'cool' due to the large atrium space. Smoke management systems [1-3], which are defined as engineered systems including all methods that can be used singly or in combination to reduce smoke production or to modify smoke movement, are essential to provide a tenable environment for the safe evacuation of occupants.

Approaches to smoke management design in atria have been introduced in some codes and engineering guides. While design approaches in these guides might be different, the engineering principles behind are similar. For example, a stable smoke layer might be assumed so that a fire zone model will work. By solving a set of equations describing smoke physics, smoke management systems can be designed. Smoke management systems are operated based on:

- Imposing opposite airflow to limit smoke spreading such as longitudinal ventilation in tunnels;
- Applying pressure differential against physical barrier, such as staircase pressurization;
- Diluting smoke by purging large amount of air;
- Extracting smoke away from spaces concerned.

Guidance to atrium smoke control systems designs within the UK are:

- The British Standards BS 5588: Part 7 *Code of practice for the incorporation of atria in buildings* [4];
- The CIBSE Guide E *Fire engineering* [5];
- The BRE Report 258 *Design approaches for smoke control in atrium buildings* [6]; and
- The BRE Report 368 *Design methodologies for smoke and heat exhaust ventilation* [7].

In USA, guidance on the design of smoke management systems in the atria are:

- *The NFPA 92B Guide for smoke management systems in malls, atria and large spaces* [2,3];
- BOCA *National building code* [8];
- The design book *Design of smoke management systems* [9,10].

Further, smoke control of atrium buildings can be designed by adopting the performance-based fire codes in Japan, Austria and Canada [11-14].

Approaches in the above design guides will be reviewed in detail in this paper. This would help engineers to understand the principle behind and capable to select a workable guide. Further, UK guides and the US guides will be compared.

2. DESIGN OBJECTIVES

The selection of various design methods depends on the fire safety goals and objectives [2,3]. Examples are protecting the egress paths, maintaining the areas of refuge, facilitating the fire department access, or protecting the property.
The following should be considered carefully:

- The height, cross-sectional area, and plan area of the large volume to be protected;
- The type and location of occupancies within and communicating with the large-volume space;
- Barriers, if any, that separate the communicating space from the large-volume space;
- Egress routes from the large-volume space and any communicating space;
- Areas of refuge;
- Design basis fire used to calculate the smoke production.

Smoke management in an atrium normally includes management of smoke within the large-volume space and any spaces that communicate with the large-volume space. Smoke source can be a fire within the large-volume space or within the communicating space. In providing fire safety for an atrium, utilizing smoke management would satisfy one or more of the following objectives, as pointed out in NFPA 92B [2,3] and BS 5588: Part 7 [4]:

- To maintain a tenable environment within all exit access and area of refuge access paths to allow sufficient time for occupants to exit or area of refuge;
- To maintain the smoke layer interface to a predetermined elevation;
- To assist the fire department personnel to approach, locate, and extinguish the fire;
- To limit the rise of the smoke layer temperature and toxic gas concentration, and reduction of visibility;
- To limit the spread of smoke between the spaces that would occur as a result of leakage paths in a construction.

The above list appears to be explicit statements of the desired achievements for a smoke management system. Critical values for parameters used to assess the smoke hazards would be provided in some guides. For example, a safety smoke interface height is recommended not to be less than 3 m for public buildings, and 2.5 m for non-public buildings in BS 5588: Part 7 [4] and BRE Report 368 [7]. Smoke layer temperature of the gas layer should be lying between the acceptable high and low temperature limits. The high limit is about 200 °C to avoid painful heat radiation on lightly clad people beneath the smoke layer. The low limit is more arbitrary, typically 20 °C above ambient to avoid loss of buoyancy. More critical values are found in guides such as CIBSE Guide E [5]. Tenability analysis should be performed to determine whether smoke is a hazard with detailed analysis reported by Klote.

3. DESIGN FIRE

In order to carry out a fire engineering design, most design calculations require the knowledge of the size of the fire. The design fire has a broad impact on the estimation of hazard in smoke management in large spaces. Ideally, the design fire would be based on the materials within an occupancy, suggesting that the choice of a design fire should be straightforward. Unfortunately, although the heat release rates for many materials are known, it is rarely possibly to say that a fire will consist of a known quantity of material. Within an occupancy, a fire will involve a combination of different materials, so that the heat release rate for that occupancy will be a function of all the materials present.

The development of a fire in a building depends on a number of factors, involving the type, quantity and arrangement of the fuel; the presence and effectiveness of the fire suppression devices; the availability of oxygen etc. Therefore, it is very difficult to calculate the development of a fire in any but the simplest fuel arrays [7]. The likely size of a fire can only be deduced from the analysis of the statistics of fires in the type of occupancy of interest, or from experiments on similar fuel arrays.

A design fire can either be a steady burning fire with constant heat output or an unsteady fire with a transient heat release rate.

3.1 Steady Burning Fires

Natural fires are usually unsteady, but a steady burning fire is useful in designing fire safety systems. Steady burning fires for design calculation in various occupancies are given in the relevant standards. The fixed fire size is often assumed to be a maximum limited by fire protection measures such as compartmentation or sprinklers [2-7]. This assumption allows the smoke control system to cater for all fires up to the design fire size, and not considering the growth of the fire. Fixed design fire sizes are often quoted in the UK guides [5]. Using a constant fire size in smoke control design will give simpler, but still workable procedures.

Various design fires have been suggested for occupancies associated with the atria in the design guide in the UK. Based on the statistical analysis and experimental work, steady burning design fires commonly used were summarized by Morgan et al. [7] with some results shown in Table 1. In NFPA 92B [2,3], a limited amount of heat release rate data for some fuel commodities used to predict the fire size were reported.

It is not possible to specify a fixed design size applicable to all the fire situations, especially when designing for means of escape or estimating the activation time of automatic detectors [5]. A transient growing fire might be more preferred. Possible reasons for not using the growing fires for design might be due to the lack of available data of fire growth rate in various occupancies and scenarios. Fire growth rates are characterized in different countries as [5]:

- USA: t^2-fires;
- Japan: standard fires, type 1, 2, and 3;
- Australia: growing fires.

3.2 Unsteady fires

- t^2-fire

A t^2-fire can be viewed as an appropriate approximation for the growing fires in the design guides including NFPA 92B [2,3], CIBSE [5], and *Design of smoke management systems* [9,10]. The heat release rate of the fire Q (in kW) at time t (in s) after ignition is given by:

$$Q = 1000(t / t_g)^2 \tag{1}$$

where t_g is the growth time, defined by the time taken for the heat output to reach 1055 kW.

It has been suggested that fires may be conveniently classified as 'slow', 'medium', 'fast' and 'ultra-fast', depending on the characteristic growth time [2,3,5]. The characteristic growth times related to each of these classes are shown in Table 2. Fire growth depends on the type of fuel and its arrangement. Some growth rates are suggested based on the experimental data in CIBSE Guide E [5]. The results are shown in Table 3.

Table 2: Characteristic growth time for various classes of fire [3]

Fire class	Characteristic growth time t_g / s
Ultra-fast	75
Fast	150
Medium	300
Slow	600

Table 3: Growth rates for growing fires [5]

Building area providing fuel	Growth rate
Dwelling	Medium
Office	Medium
Shop	Fast
Warehouse	Ultra-fast
Hotel bedroom	Medium
Hotel reception	Medium
Assembly hall seating	Medium-fast
Picture gallery	Slow
Display area	Slow-fast

Table 1: Steady-state design fire sizes in BR 368 [7]

<table>
<tr><th colspan="2">Occupancy type</th><th>Fire area (m^2)</th><th>Fire perimeter (m)</th><th>Heat release rate density (kWm^{-2})</th><th>Total convective heat flux (kW)</th></tr>
<tr><td rowspan="3">Retail areas</td><td>Standard response sprinklers</td><td>10</td><td>12</td><td>625</td><td>5000</td></tr>
<tr><td>Quick response sprinklers</td><td>5</td><td>9</td><td>625</td><td>2500</td></tr>
<tr><td>No sprinklers</td><td>Entire room</td><td>Width of opening</td><td>1200</td><td>Not known</td></tr>
<tr><td rowspan="3">Open-plan offices</td><td>Standard response sprinklers</td><td>16</td><td>14</td><td>255</td><td>2700 (close to the fire plume)
1000 (at the window)</td></tr>
<tr><td>No sprinklers: fuel-bed controlled</td><td>47</td><td>24</td><td>255</td><td>8000 (close to the fire plume)
6000 (at the window)</td></tr>
<tr><td>No sprinklers: full involvement of compartment</td><td>Entire room</td><td>Width of opening</td><td>255</td><td>Not known</td></tr>
<tr><td rowspan="2">Hotel bedroom</td><td>Standard response sprinklers</td><td>2</td><td>6</td><td>250</td><td>400 (close to the fire plume)
300 (at the window)</td></tr>
<tr><td>No sprinklers</td><td>Entire room</td><td>Width of opening</td><td>100</td><td>1000 (at the window)</td></tr>
<tr><td colspan="2">Car park (a burning car)</td><td>10</td><td>12</td><td>400</td><td>3000 (close to the plume)</td></tr>
</table>

- Other growing fire models for design use [7]

Apart from using t^2-fire, other fire growth rates and fire size were obtained from full-scale burning tests on the fuel load corresponding to a specific occupancy. With these data, the designers can predict the consequences of having the same fire in the building of interest to the design. This technique is useful in allowing a confident departure from the more usual design fires for a specific application where the fuel load is not likely to vary much from the arrangement studied in the experiment.

3.3 Effect of Sprinklers on Fire Size

In NFPA 92B [2,3] and CIBSE Guide E [5], the effect of sprinklers on the design fire size is accounted for by assuming that the fire stops growing when sprinklers are actuated. It is assumed that the fire continues to burn at this size until the involved fuel is consumed, with no further effect of the sprinkler spray on the burning process. Alternatively, if the fire test indicates that the fire will be controlled but not immediately extinguished by the sprinklers, an exponential decrease in heat release rate can be assumed. Full-scale fire tests for open-plan offices by Madrzykowski & Vettori [15] and Lougheed [16] showed that once the sprinklers gain control of the fire but are not able to extinguish it immediately due to configuration, the heat release rate decreases exponentially as follows:

$$Q = Q_{act} e^{-kt} \qquad (2)$$

where Q is the heat release rate after sprinkler activation, Q_{act} is the heat release at sprinkler activation, t is the time after sprinkler activation, and k is the decay constant.

However, effects of spinkler on stability the smoke layer should be considered. Smoke logging is a very complicated phenomenon which might only be studied theoretically by Computational Fluid Dynamics.

4. DESIGN APPROACHES

The design method selected depends on space where the smoke management systems are required and the space where the smoke originates [2,3,6,7].

4.1 Management of Smoke in Large-Volume Space [2,3,6,7,9,10]

Smoke management systems for large-volume spaces are intended to control the smoke layer to the upper portion of the large-volume space or to limit the amount of smoke from spreading to areas outside the large-volume space.

- For a fire originating in atrium space

The following approaches can be used to manage smoke in atria:

- Allowing smoke to fill the atrium space if the smoke filling time is sufficient for safe evacuation of the occupants;
- Removing smoke from the large-volume space to limit the depth of smoke accumulation within the space;
- Removing smoke from the large-volume space at a rate sufficient to increase the time for smoke filling of that space.

- For a fire originating in communicating space

The following methods are often recommended,

- Removing any smoke that enters the large-volume space to limit the depth of smoke accumulation or delay the smoke filling within the atrium space;
- Preventing smoke from entering the large-volume space by opposed airflow.

4.2 Management of Smoke in Communicating Spaces

Design method in NFPA 92B [2,3]

- For a fire originating in large volume space

The following methods are recommended:

- Maintaining the smoke layer interface at a level higher than that of the highest opening to the communicating space;
- Exhausting the largest-volume space so that it is at a negative pressure with respect to the communicating space;
- Providing opposed airflow or using smoke barriers to prevent the smoke spreading into the communicating space.

- For fire originating in communicating space

- Allowing the smoke to flow into the atrium, and then using the approaches for smoke management within the large-volume space;
- Containment of smoke to communicating spaces by:
  - ~ Removing the smoke from the communicating space by a sufficient exhaust so as to establish a minimum flow between it and the large-volume space to prevent the smoke spreading into the large-volume space.
  - ~ Using smoke barriers to separate the communicating space from the large-volume space.

It should be noted that it will not be possible to control smoke within such a space without the use of physical barriers to limit the smoke movement or methods to limit the smoke production.

Design method in BRE report [6,7]

For a fire occurring in the compartment adjacent to the atrium, the following methods are often recommended to be used to prevent the smoke flowing into other unaffected areas:

- Providing smoke ventilation to make sure that the minimum height of the smoke layer base is not lower than the soffit of the opening.
- Exhausting smoke from the balcony.
- Slit extract.
- Compartment separation. This might be rarely used for the smoke management system in atrium. In this instance, the building fire safety precautions can revert to those found in the absence of atrium.

For a fire that occurs on the atrium floor, natural depressurization or powered depressurization are recommended for protecting adjacent space to the atrium by raising the neutral pressure plane above the highest vulnerable leakage path.

5. ENGINEERING RELATIONSHIP FOR THE DESIGN OF SMOKE MANAGEMENT SYSTEM

Some typical plume equations were recommended to be used to describe the smoke filling process in the smoke management system design in the design guides. All the equations given were based on both theoretical and experimental data.

5.1 Equations on Height of First Indication of Smoke with No Smoke Exhaust Operating in NFPA 92B [2,3]

- Steady fires

The location of the smoke layer interface for steady fires at any time after ignition can be estimated by the following equation:

$$z/H = 1.11 - 0.28\ln\left[\frac{tQ^{1/3}/H^{4/3}}{A/H^2}\right] \qquad (3)$$

where H is the ceiling height above the fire surface, Q is the heat release rate of the steady fire, and A is the cross-sectional area of the space being filled with smoke.

The above equation is based on experimental data from investigations using uniform-sectional areas with respect to height with A/H^2 ratios in the range from 0.9 to 14 and for values of $z/H \geq 0.2$ [17-20].

- Unsteady fires

For a t^2-fire, the smoke layer descent rate may be estimated using the following equation:

$$z/H = 0.91\left[\frac{t}{t_g^{2/5}H^{4/5}(A/H^2)^{3/5}}\right]^{-1.45} \qquad (4)$$

where t_g is the growth time of t^2-fire.

The above equation is based on the experimental data from investigations with A/H^2 ratios in the range from 1.0 to 23 for the values of $z/H \geq 0.2$ [18].

For a given atrium and a given fire size, equations (3) and (4) can be used to predict the smoke filling time from the outset of the fire to the endanger time under the condition with no smoke ventilation system in the atrium. Since z in the equations relates to the height where there is a first indication of smoke, rather than the smoke layer interface position, these two equations can give a conservative estimate of the hazard.

For the varying cross-sectional geometries and complex geometries, other methods of analysis should be considered, such as scale models, CFD models, zone model adoption and bounding analysis.

5.2 Equations on Mass Flow Rate of Plume in NFPA 92B [2,3]

For fires in unsprinklered spaces, the exhaust rate from the large-volume space needs to be evaluated not only for a free plume from a fire in the large-volume space but also for a plume originating in the communicating space. When the mass rate of smoke exhaust is equal to the mass rate of smoke supplied by the plume to the base of the smoke layer, an equilibrium position of the smoke layer interface is expected to be achieved. If the rate of mass supply is greater than the exhaust rate, the smoke layer interface can be expected to descend, but at a slower rate than if no exhaust was provided. The rate of mass supplied by the plume depends on the configuration of the smoke plume. Three configurations are often used:

- Axisymmetric plumes

An axisymmetric plume is expected for a fire originating on the atrium floor or on the communicating space floor, remote from any walls. The mass flow rate can be predicted from [21]:

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

where $z > z_l$, z_l is the flame height, it can be given as:

$$z_l = 0.166Q_c^{2/5} \quad (6)$$

The mass flow rate below the flame tip is predicted from:

$$m_p = 0.032Q_c^{3/5}z \quad (z \le z_l) \quad (7)$$

Effects of the wall on the entrainment rate were not considered in NFPA 92B [2,3]. Conservative design calculations should be conducted based on the assumption that entrainment occurs from all sides.

- Balcony spill plumes

For situations involving a fire in a communicating space immediately adjacent to the atrium, air entrainment into the rising balcony spill plumes can be calculated by:

$$m_p = 0.36(QW^2)^{1/3}(z_b + 0.25h_b) \quad (8)$$

where W is the width of the plume as it spills under the balcony, z_b is the height above the balcony, and h_b is the height of balcony above the fuel. When z_b is approximately 13 times the width, the balcony spill plume is expected to have the same production rate as an axisymmetric plume.

- Window plumes

Plumes issuing from wall openings, such as doors and windows, into a large-volume, open space are referred to as window plumes. The mass entrainment for window plume is given as:

$$m_p = 0.071Q_c^{1/3}(z_w + a)^{5/3} + 0.0018Q_c \quad (9)$$

where

$$a = 2.40A_w^{2/5}h_w^{1/5} - 2.1h_w \quad (10)$$

For ventilation-controlled fires, the heat release rate can be related to the characteristics of the ventilation opening. The average heat release rate is given as:

$$Q = 1260A_w h_w^{1/2} \quad (11)$$

In the above equations, A_w is the area of the window, h_w is its height, and z_w is the height above the window.

5.3 Equations on Mass Flow of the Plume in BRE Report 258 [6] and BRE Report 368 [7]

- Plume equations on axisymmetric plumes

- Plume above large fires

Plume above large fires can be considered to be those where:

$$H_g \le 10A_f^{1/2}$$

where H_g is the smoke layer interface height, and A_f is the fire area.

Work by Hansell [22] drawing on work by Zukoski et al. [23] and Quintiere et al. [24] to modify earlier studies by Thomas et al. [25] and Hinkley [26] has shown that the rate of air entrainment into a plume of smoke rising above a fire can be calculated by:

$$m_p = C_e P z^{3/2} \quad (12)$$

where P is the perimeter of the fire, the coefficient C_e can be taken as various values under different fire conditions. For large-area rooms such as auditoria, stadia, large open-plan offices and atrium floors, it is taken to be 0.19; for large-area rooms such as open-plan offices, where $H_g < 3A_f^{1/2}$, the value is taken to be 0.21; and for small rooms such as unit shops, celluar offices and hotel bedrooms with ventilation openings predominantly to one side of the fire, the value is taken to be 0.34.

- Plume above small fires

Small fires are defined where

$$H_g > 10A_f^{1/2}$$

The mass flow can be calculated by [21]:

$$m_p = 0.071Q_c^{1/3}(z - z_0)^{5/3} + 0.0018Q_c \quad (13)$$

z_0 is the virtual source height, it is given as:

$$z_0 = -1.02D_f + 0.083Q_c^{2/5} \quad (14)$$

In the above equations, Q_c is the convective heat release rate of fire, and D_f is the diameter of fire source.

- Effects of adjacent walls on entrainment into the plume

  For large fires, it is assumed that the reduction in mass flow is the same as the reduction in the effective fire perimeter. With the same height of rise of a plume, the corresponding mass flux should then be m_p, $0.75m_p$ and $0.5m_p$ when the fire is in the middle of the room, near one wall or in the corner respectively.

  For small fires, from theoretical analysis, the walls will reduce the mass flow from the fire such that the entrainment will be 0.63 times that of the same fire in the middle of the room when the fire is close to one wall, and is 0.4 times that of the same fire in the middle of the room when the fire is in a corner.

- Plume equations on spill plumes

Four spill plume models are given for different plume forms in the design guide by Morgan et al. [7].

- The 'BRE' method [6]

  Detailed descriptions on the BRE method can be found in Appendix A. This method covers all free and adhered spill plumes. It can be used for large or small area smoke reservoirs, and can be used either with or without mixing of air into the free ends of the spill plume.

- Method using equations derived by Poreh et al. [27]

$$m_p = m_b + CQ_c^{1/3}(z_p + D_b) \tag{15}$$

  where m_b is the mass flow of gases beneath a balcony, z_p is the height of the smoke layer interface height above the balcony, D_b is the depth of the smoke layer beneath a balcony, and C is a constant, which is defined as:

$$C = 0.3C_m \rho_a W^{2/3} \tag{16}$$

  where C_m is the dimensionless entrainment coefficient, found experimentally to be 0.44 for a free plume, and 0.21 for an adhered plume; W is the width of the plume, and ρ_a is the density of the ambient air.

  The depth of the smoke layer under the balcony D_b can be calculated by the equation from Morgan [28] as:

$$D_b = \frac{0.36}{C_d}\left[\frac{m_b T_b}{\Delta T_b^{1/2} W T_a^{1/2}}\right]^{2/3} \tag{17}$$

  where T_b is the temperature of the smoke layer under the balcony, ΔT_b is the temperature rise of the smoke layer above ambient under the balcony, T_a is the absolute temperature of the ambient, and C_d is the coefficient of discharge, with its value taken to be 0.6 if a deep downstand is present, or 1.0 in the absence of a downstand.

  This method can be expected to apply to free and adhered plumes, but only to those rising between sidewalls which prevent any entrainment into the ends of the plume. From its source paper, it can be applied to large smoke reservoirs and not to small ones.

- Method using the equation by Thomas [29]

$$m_p = 0.58\rho_g\left[\frac{gQ_c W^2}{\rho_g C_p T_a}\right]^{1/3}(z_p + \Delta)\left[1 + \frac{0.22(z_p + 2\Delta)}{W}\right]^{2/3} \tag{18}$$

  where ρ_g is the density of the hot gas at height z_p, C_p is the specific heat of air, T_a is the absolute ambient temperature, and Δ is the empirical height of virtual source below the balcony, it can be calculated by:

$$\Delta = D_b + m_b/(CQ_c)^{1/3} \tag{19}$$

  where C is the constant which can be calculated by equation (16).

  This method only applies to free plumes, and cannot be used for adhered plumes. Entrainment into the ends of the spill plume is explicitly calculated. The method can only be used with confidence for large smoke reservoirs, and not for small reservoirs.

- Method to calculate the entrainment into a line plume derived by Thomas et al. [30]

  Considering the entrainment into both the free ends,

$$\Delta m_p = 0.09 z_p (Q_c / W)^{1/3} \tag{20}$$

  The total entrainment rate can be obtained by:

$$m_p = 1.2m_b + 0.16z_p(Q_c W^2)^{1/3} + 0.0027Q_c + 0.09z_p(Q_c / W)^{1/3} \tag{21}$$

This method can be expected to apply to free plumes and large smoke reservoirs only. End effect is also considered in this method.

Recommendations on the use of the above four balcony spill plume equations in design of smoke control in atrium were given by Morgan et al. [7] as follows:

- For free plumes rising less than 3 m above the spill edge, into a large smoke reservoir, method by Thomas et al. [30] can be used;
- For free plumes rising more than 3 m above the spill edge, the BRE method can be used for large or small reservoirs, and Thomas method [29] is recommended for large smoke reservoirs only;
- For all other spill plume scenarios, the BRE method can be used.

5.4 Extraction Rate for the Smoke Exhaust from Balcony Reservoir Adjacent to the Fire Room in BRE Reports [6,7]

If the smoke cannot be contained within the room of origin, the smoke and hot gas will flow out from the room, and will be collected within the balcony reservoir adjacent to the room, to prevent the smoke flowing into the atrium, the smoke can be exhausted from the balcony reservoir. The exhaust rate can be given as:

$$m_e = \frac{2C_e P W h^{3/2}}{\left[W^{2/3} + \frac{1}{C_d} \left(\frac{C_e P}{2} \right)^{2/3} \right]^{3/2}} \quad (22)$$

where W is the width of the opening, h is its height above the floor, and C_d is the effective coefficient of discharge for the opening.

5.5 Extraction Rate of Slit Extract [7]

When removing smoke from a common balcony reservoir and there is no possibility of using downstand screens to prevent the passage of smoke or wherever a physical barrier may not be used, a slit extract system may be employed over the length of the flow path to supplement the main reservoir exhaust system and replace the screens. The exhaust rate at the slit was at least 5/3 times the flow in the horizontal layer flowing towards the slit.

5.6 Smoke Layer Properties [2,3]

Equations to calculate the average temperature rise of the smoke layer, the optical density, and the specifies concentrations during the smoke filling stage and the quasi-steady vented stage are provided in NFPA 92B [2,3], as shown in Table 4. These equations apply to fires with constant heat release rates and t^2-fires, and they can also be used to calculate the conditions within the smoke layer once the vented conditions exist.

5.7 Opposed Airflow Requirements [2,3,5]

Opposed airflow refers to systems where airflow is provided in a direction opposite to smoke movement. Opposed airflow may be used in lieu of physical barriers to prevent smoke spread from one space to another, i.e., between the communicating space and the atrium. A minimum airflow velocity at all points of the opening must be provided in order to prevent smoke migration through the opening. This method of smoke control has been widely used in the USA.

- Airflow for a communicating space fire

The minimum average velocity to oppose smoke originating in the communicating space is evaluated using the flowing equation [31]:

$$v = 0.64\left[g h_o (T_g - T_a) / T_g \right]^{1/2} \quad (23)$$

where h_o is the height of the opening, g is the acceleration of gravity, T_g is the temperature of the smoke, and T_a is the temperature of the ambient air.

- Airflow for an atrium fire

Airflow can also be used to prevent smoke flowing from the atrium to the communicating space. Air can be supplied to the communicating space to achieve a specific average velocity at the opening to the atrium. This velocity should be such that smoke flow to the communicating space is prevented. For opening locations below the smoke layer and 3 m above the base of the fire, this velocity can be estimated from

$$v_e = 0.057 (Q / z)^{1/3} \quad (24)$$

where z is the distance above the base of the fire to the bottom of the opening, and Q is the heat release rate of the fire. If the velocity calculated from the above equation is greater than 1 ms^{-1}, then a velocity of 1 ms^{-1} should be used. This limit was made out of concern that greater velocities could disrupt the plume flow and have an adverse effect on atrium smoke management.

For opening above the smoke layer interface, equation (23) should be used to calculate the velocity.

Table 4: Equations for calculating properties of smoke layer [3]

Parameters	Unvented fires		Vented fires
	Steady fires	t^2-fires	
ΔT	$T_a[\exp(Q_n/Q_o)-1]$	$T_a[\exp(Q_n/Q_o)-1]$	$60(1-\chi_l)Q_c/(\rho_a C_p V)$
Y_i	$f_i Qt/[\rho_a \chi_\alpha \Delta H_c A(H-z)]$	$f_i \alpha t^3/[3\rho_a \chi_\alpha \Delta H_c A(H-z)]$	$60 f_i Q/(\rho_a \chi_\alpha \Delta H_c V)$
D	$D_m Qt/[\chi_\alpha \Delta H_c A(H-z)]$	$D_m \alpha t^3/[3\chi_\alpha \Delta H_c A(H-z)]$	$60 D_m Q/(\chi_\alpha \Delta H_c V)$

A = horizontal cross-sectional area of space
C_p = specific heat of ambient air
D = $L^{-1}\log(I_o/I)$, optical density
D_m = mass optical density
f_i = yield factor of species i
H = ceiling height
ΔH_c = heat of complete combustion
Q = heat release of fire
Q_c = convective portion of heat release rate
$Q_n = \int(1-\chi_l)Q\,dt$
$Q_o = \rho_a C_p T_a A(H-z)$
t = time from ignition
T_a = absolute ambient temperature
ΔT = temperature rise in smoke layer
V = volumetric venting rate
Y_i = mass fraction of species i
z = height from top of fuel to smoke layer interface
α = t^2-fire growth coefficient
ρ_a = density of ambient air
χ_α = combustion efficiency factor
χ_l = total heat loss factor from smoke layer to atrium boundaries

Note that the equations in the above table are not in US units.

5.8 Atrium Depressurization in the UK Guide

This method is based on the extraction of smoke from the fire-affected part of the building to reduce the pressure in the space to be less than that in the adjacent parts of the building. The induced pressure differential then inhibits the spread of smoke [5].

Corresponding to the natural ventilation and mechanical system in the atrium, natural depressurization and powered depressurization are recommended in BRE Report 258 [6] and BRE report 368 [7]

- Natural depressurization [6,7,32]

For an atrium with a natural ventilation system, any openings above the neutral pressure plane are found to be under a positive pressure, and the pressure below the neutral pressure plane will be at a pressure lower than the ambient. This will lead to a flow of smoke from the adjacent room into the atrium below the neutral plane, hence the levels below the neutral pressure plane will be protected.

Careful manipulation of the neutral pressure plane can raise it to a safe height above sensitive levels, where there is little or no threat from the positive pressure above. In the absence of wind effects, the height of the neutral plane can be calculated by [6,7,32]:

$$H_N = \frac{d_g T_a (A_v C_v)^2}{T_g (A_i C_i)^2 + T_a (A_v C_v)^2} \tag{25}$$

where H_N is the height of the neutral plane, d_g is the depth of the smoke layer, T_g is the temperature of the smoke layer, T_a is the temperature of the ambient air, A_v is the vent area, C_v is the discharge coefficient of the vent, A_i is the inlet area, and C_i is the entry coefficient for inlet.

With external wind, the wind effect on depressurization should be considered. According to Hansell and Morgan [32], for a successful depressurization design for all wind speeds, the following condition should be satisfied:

$$\left[(A-1)C_{wv} - AC_{wl} + C_{wi}\right] \le 0 \quad (26)$$

where C_{wv} is the wind pressure coefficient at the vent, C_{wl} is the wind pressure coefficient at the topmost leeward storey of the building, C_{wi} is the wind coefficient at the inlet, and

$$A = \frac{T_g}{T_a}\left(\frac{A_v C_v}{A_i C_i}\right)^2 + 1 \quad (27)$$

- Powered depressurization [6,7,32]

When it is impossible to employ a natural ventilator, powered system should be provided. Considering the wind effects, the required volumetric flow rate for the powered depressurization can be calculated from [32]:

$$G = \left(\frac{T_g A_i C_i}{T_a}\right)\left[(C_{wi} - C_{wl})v_w^{\,2} + \frac{2g(T_g - T_a)H_N}{T_g}\right]^{1/2} \quad (28)$$

where v_w is the design wind velocity.

6. SPECIAL CONSIDERATIONS FOR SMOKE CONTROL DESIGN

6.1 Impact of Stratification of Smoke on Smoke Management System Design [2,3,5-7,9]

The upward movement of smoke in the atrium depends on the buoyant smoke relative to the surroundings. The potential for stratification relates to the difference in temperature between the smoke and surrounding air at any elevation [33]. If the atrium is particularly tall, stratification of the smoke layer before reaching the ceiling is probable, especially in atria which are air-conditioned in the lower portion only, or have a high proportion of roof glazing. The detection mounted at the top of the atrium would not respond and the smoke management system would not be activated.
Two cases can often be observed on smoke stratification in the atria. One is the plume rises in a pre-stratified interior environment where the temperature of the air in the upper region is greater than at lower levels before the fire. And another one is that the discrete interior air has a discrete temperature change at some elevation above floor level [3].

For a linear temperature profile in an atrium, analysis of smoke stratification was given in the design guides of NFPA 92B [2,3] and CIBSE Guide E [5] based on the previous research work by Morton et al. [33].

The maximum height that smoke can reach is:

$$z_{max} = 5.54Q_c^{\,1/4}(dT/dZ)^{-3/8} \quad (29)$$

where Q_c is the convective heat release rate of the fire, and dT/dz is the rate of change of ambient temperature with respect to height.

The minimum Q_c required to overcome the ambient temperature difference and drive the smoke to the ceiling is given as:

$$Q_{c\,min} = 1.18 \times 10^{-3} H^{5/2} \Delta T_a^{\,3/2} \quad (30)$$

where ΔT_a is the difference between ambient temperature at the ceiling and ambient temperature at the level of the fire surface.

The ambient temperature increase from the floor to the ceiling, which is just sufficient to prevent a plume of heat release Q_c from reaching a ceiling height H is given as:

$$\Delta T_a = 96Q_c^{\,2/3}H^{-5/3} \quad (31)$$

Rewriting equation (31), the maximum height of the plume can reach for a given Q_c and ΔT_a can be obtained by:

$$H_{max} = 15.5Q_c^{\,2/5}\Delta T_a^{\,-3/5} \quad (32)$$

Impact of the stratification of smoke on smoke management system design was discussed in the design guide of NFPA 92B [2,3], BRE Report 258 [6], BRE Report 368 [7], Klote and Milke [9] and CIBSE Guide E [5]. Early stratification can, to some extent, be overcome by providing smoke detectors at many levels within the atrium [3,6,7].

6.2 Special Considerations on Smoke Ventilation System Design

- Plugholing effect [3,5-7]

When the smoke layer below an exhaust inlet is relatively shallow, a high exhaust rate could lead to entrainment of cold air from the clear layer. This is known as plugholing. For efficient exhaust, the number of exhaust inlets need to be chosen to ensure that the maximum flow rates for exhaust without plugholing are not exceeded. In BRE report 258 [6], CIBSE Guide E [5] and NFPA 92B [3], the maximum mass flow rate that can be efficiently extracted using a single vent was given as:

$$m_{max} = \beta[\frac{gd_g{}^5 T_a (T_g - T_a)}{T_g{}^2}]^{1/2} \quad (33)$$

where d_g is the depth of the smoke layer, T_g is the absolute temperature of the smoke layer, g is the acceleration due to gravity, and β is the exhaust location factor. Different values of β were taken in different design guides. In BRE report 258 [6], β = 1.3 for a vent near the wall, and β = 1.8 for a vent distant from a wall. In CIBSE Guide E [5] and NFPA 92B [3], β takes the value 2.0 where the extract point is near to a wall and 2.8 where the extract point is distant from the wall. Small value of β is expected to give a more pessimistic result. Research work conducted jointly by ASHRAE and NRC [16,34,35] showed that although equation (33) was developed for natural venting, it is also applicable to mechanical systems.

However, for a vent far away from the wall, different equation on the maximum mass flow is used in BRE Report 368 from the research work by Ghosh [36], the equation is:

$$m_{max} = \frac{2.05\rho_a (gT_a \Delta T_g)^{0.5} d_g{}^2 W_v{}^{0.5}}{T_g} \quad (34)$$

The required number of extract vents is then given by [6,7]:

$$N \geq m_p / m_{max} \quad (35)$$

where m_p is the mass flow entering the layer.

To minimize interaction between the flows near the inlets, the minimum separation between the inlets is given as [3]:

$$S_{min} = 0.03\beta^{3/2}\left[d_g{}^5 T_a (T_g - T_a)\right]^{1/4} \quad (36)$$

- Minimum smoke layer depth

The minimum design depth of the smoke layer is determined by both the thickness of the ceiling jet and the depth necessary to prevent plugholing. The thickness of the ceiling jet has been reported by Beyler [37] to be in the range of 10 to 20 percent of the distance from the source fire to the top of the space [3].

6.3 Limitation to the Use of Throughflow Ventilation [6,7]

The mass flow rate of the rising plume is known to be increased rapidly with increasing height of a plume. The large increase in mass flow with increase in height tends to suggest that there may be some cut-off point in the rise of the plume above which it might become economically impractical in terms of smoke control system. In the two BRE Reports by Morgan & Hansell [6] and Morgan et al. [7], mass flow of 150 to 200 kgs^{-1} was suggested to be the upper value for using the throughflow ventilation for the smoke control design in atrium. This was not discussed in the NFPA 92B [2,3] and design book by Klote and Milke [9].

6.4 Effect of the Cooler Ambient on Smoke Control in the Atrium [6,7]

For the atria with large areas of external glazing, stratification would occur in hot weather as a result of a solar load, this has been discussed in section 6.1. However, during the cooler weather, large heat loss of the smoke layer might occur, and the energy loss might cause the layer to increase beyond the desired depth. Experimental evidence [22] has shown that excess air movement in the atrium, which might be caused by air conditioning, ventilation or weather conditions, into a cool but a stable smoke layer can cause it to become unstable, spreading further throughout the building. Smoke layers which have temperatures approaching that of incoming replacement air supply will have a tendency to 'mix' with the air, rather than 'float' above it, thus leading to complete smoke logging in the atrium. As a result of practical experience, a minimum smoke layer temperature of 20 °C above ambient was recommended by Morgan at al. [6,7] to prevent this effect.

6.5 Make-up Air Supply

For any smoke ventilation systems, make-up air supply is essential [2-7,9]. The following factors should be considered carefully for a successful make-up supply:

- All make-up air should be provided below the smoke layer interface so as not to add the required capacity of the smoke exhaust [4,6,7,9,10];
- Make-up air should be provided at a low velocity so as not to adversely affect the plume, fire, or smoke layer. A maximum velocity of about 1 ms^{-1} is recommended in NFPA 92B [2,3] and by Klote and Milke [9] based on the flame deflection data [38]. However, in some UK Guides [6,7], the inflow airspeeds are recommended not to exceed 5 ms^{-1} to avoid adverse effects on people escaping through those doors.
- The mass rate of make-up supplied must be less than that being exhausted [4,6,7,9].

6.6 Smoke Management System Design for Atrium with Varying Cross-Sectional Geometries and Complex Geometries

For an atrium with complex interior features, using the plume equations introduced in section 5 to do the design calculations seems not suitable, since almost all the equations are only valid for the free environment. Scale models or Computational Fluid Dynamics (CFD) models are sure to be the best choice to assist in the system design when the basic methods above are not applicable.

7. CASE STUDIES ON SMOKE MANAGEMENT WITHIN THE ATRIUM SPACE

An atrium with height H of 15 m and cross-sectional area A of 250 m^2 was considered for the smoke control design. There is a compartment adjacent to the atrium at the ground level. The height of the compartment is 3.0 m, and the dimensions of the opening to the atrium are 5.0 m × 3.0 m (W × h).

Two design approaches will be considered:

- Using the passive smoke filling in the atrium space.
- Using smoke ventilation system to maintain the smoke layer interface at a predefined height.

In each method, two fire scenarios would be involved,

- Fire occurs on the atrium floor.
- Smoke originates from the adjacent compartment.

Two types of design fire – steady fire and t^2-fire will be considered for the design. The fire size is assumed to be 2.0 MW for both cases. Here, only fast or slow t^2-fire is considered.

Different engineering equations reported in the design guides will be used for the design calculation. All of the designs assume a flat horizontal ceiling and a uniform horizontal cross-sectional area with vertical sides. Ambient air temperature is taken as 20°C.

7.1 Smoke Filling

For the smoke filling design, two calculation methods will be investigated:

- Method 1: Using equation (3) or equation (4) in NFPA 92B [3] to predict the position of the smoke layer interface under steady fire or unsteady fire respectively.
  - For steady fire, the variation of the smoke interface position with time can be obtained by:

$$z/H = 1.44 - 0.28\ln t \qquad (36)$$

  - For t^2-fire, it can be calculated by:

$$z/H = 23.07 t_g^{0.58} / t^{1.45} \qquad (37)$$

- Method 2: Using the mass and energy conservation in the upper smoke layer, the position of the smoke layer interface is obtained by solving the following differential equation:

$$\rho_a A \frac{dz}{dt} + m_p + \frac{Q_c}{\rho_a C_p T_a A} = 0 \qquad (38)$$

where m_p is the mass flow of the plume. For fire occurring on the atrium floor, the axiymmetric plume equations are often used. For fire occurring in the compartment adjacent to the atrium, five spill plume equations reported in NFPA 92B [2,3] and BRE Report 368 [7] would be used for comparison. The smoke descent rate can be predicted by CL zone model [39].

Variations of the position of the smoke layer with time predicted by the different calculation methods are presented in Figs. 1 to 3. For fire occurring on the atrium floor, it can be seen that equation (3) or (4) predicts a lower smoke layer interface position than those predicted by using method 2. This is because the position of layer interface in equation (3) or (4) only means the first indication of smoke, rather than the smoke layer interface position. Therefore, these two equations can provide a conservative estimate of the hazard. In addition, results predicted by equations (3) and (4) implicitly include the transport lag. For steady fire, equation (3) indicates a delay of approximately 5 s before a layer forms; for slow t^2 fire, this time will be greater as 112 s. While results predicted by using method 2 indicate immediate formation of the layer, this might not be true in real case. Especially for a slow t^2-fire occurring in spaces with large ratio of A/H^2, the transport lag may be appreciable. Ignoring the transport lag would yield a more conservative result as the smoke is instantaneously added to the upper layer, resulting in a more rapid layer descent. The transport lag can be estimated by Tanaka et al.

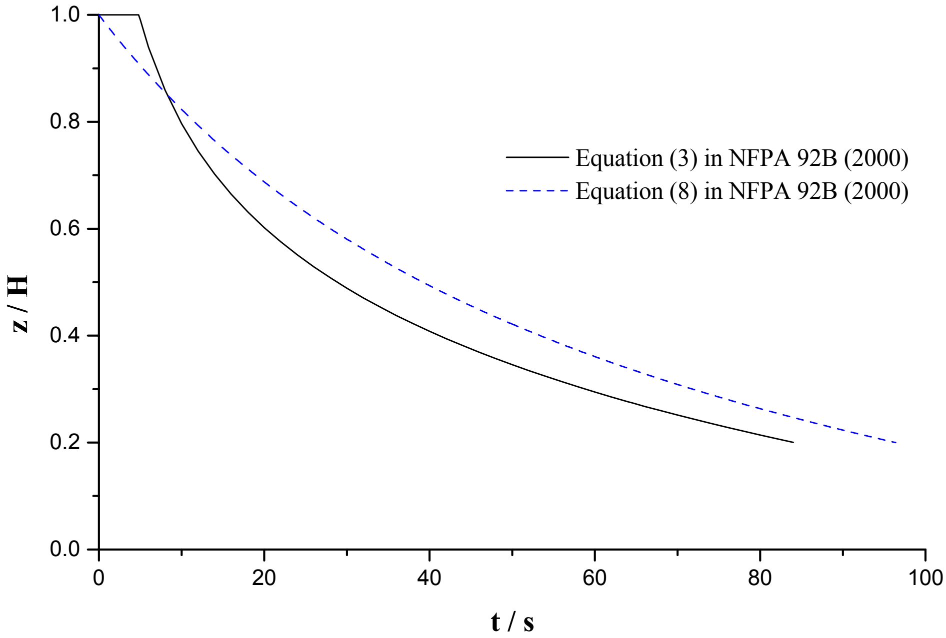

Fig. 1: Comparison of the smoke filling process predicted by different methods for steady fire occurring on the atrium floor

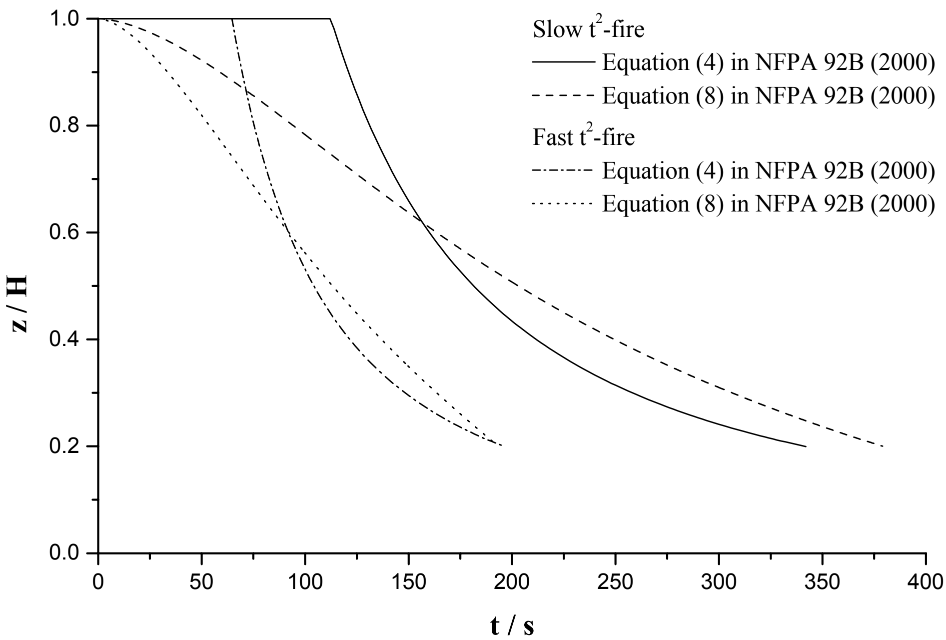

Fig. 2: Comparison of the smoke filling process predicted by different method for t^2-fire occurring on the atrium floor

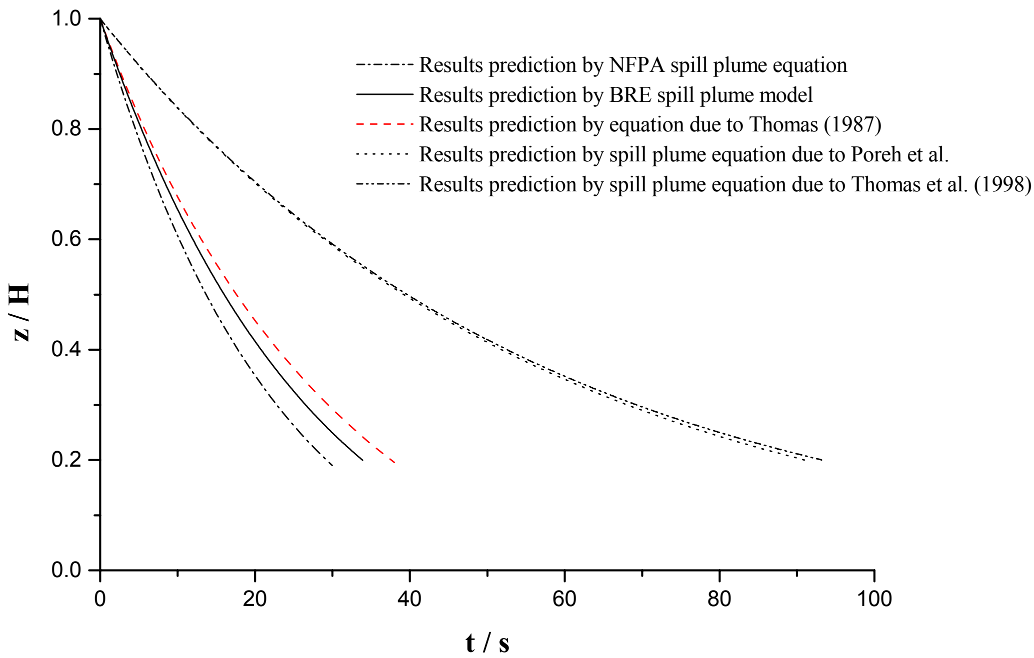

Fig. 3: Comparison of the smoke filling process predicted by different spill plume equations for steady fire occurring in the adjacent room

Comparisons of the smoke filling predicted by different spill plume equations are shown in Fig. 3. It can be seen that the BRE method, NFPA spill plume equation, and Thomas method give a faster smoke filling rates. While the methods due to Poreh et al. [27] and Thomas et al. [30] give a lower descent rate for the smoke layer interface. This is not surprising in view of the absence of end effect in plume in the equations due to Poreh at al. [27] and Thomas et al. [30]. Larger values of the mass flow mean the colder smoke layer with faster descending rates in the same structure. Therefore, BRE method and NFPA spill plume equation are expected to give a conservative design when the temperature is not the major hazard. And the method by Poreh et al. [27] or by Thomas et al. [30] is expected to provide a conservative deign when the smoke temperature is the main hazard.

For the smoke filling design, occupants evacuation should be analyzed. Provided that the available escape time is less than the required escape time, other smoke control measures should be provided.

7.2 Smoke Ventilation

For smoke ventilation design, exhaust rate should be calculated for an acceptable design smoke layer depth. The calculated exhaust rate and smoke layer temperature are shown in Table 5. It can be seen that larger quantity of smoke will be exhausted for fire originating in the adjacent compartment than for fire occurring on the atrium floor in order to maintain the same interface height in atrium. Lower layer interface height and lower extraction rate will be required. For smoke originating from the adjacent compartment, BRE method and NFPA equation are expected to give a more conservative design in terms of safety.

8. CASE STUDIES: SMOKE MANAGEMENT WITHIN THE COMMUNICATING SPACE

8.1 Using Opposed Airflow to Prevent the Migration of Smoke Between the Atrium and Adjacent Area

- Opposed airflow for an atrium fire

  For opening locations below the smoke layer and 3 m above the base of fire, the limiting average velocity can be calculated by equation (24). For openings above the smoke layer interface height, equation (23) should be used to calculate the velocity.

  Assuming the height of the smoke layer interface is 9 m, provided that the bottom of the adjacent room is 6 m above the atrium floor, the size of the opening is 5.0 m × 3.0 m (W × h), then the limiting average velocity which can prevent the smoke flowing from the atrium to the adjacent room can be calculated using equation (24):

Table 5: Exhaust rate required for the smoke ventilation

Design smoke layer depth (m)	For a fire in the atrium		For a fire in the compartment adjacent to the atrium)	
	Exhaust rate predicted by NFPA plume equation (kgs^{-1})	Exhaust rate predicted by BRE plume equation (kgs^{-1})	Exhaust rate predicted by NFPA balcony spill plume equation (kgs^{-1})	Exhaust rate predicted by BRE method (kgs^{-1})
2	67.9	49.3	142.6	134.2
4	52.3	38.4	116.1	108.1
6	38.4	28.4	89.5	84.3
8	26.5	19.5	63.0	59.0

$$v_e = 0.057(Q/z)^{1/3} = 0.4ms^{-1} \quad (39)$$

The opposed airflow rate is:

$$G_e = 0.4 \times 5 \times 3 = 6.0m^3s^{-1} \quad (40)$$

The capacity of the exhaust fans in the atrium to maintain the smoke layer interface can be calculated by:

$$G_{tot} = G_p + G_e = m_p / \rho_g + G_e = 43.3m^3s^{-1} \quad (41)$$

Assuming the height of the floor of the adjacent room is 12 m, then the limit average velocity can be estimated using equation (23):

$$v_e = 0.64\left[gh_o(T_g - T_a)/T_g\right]^{1/2} = 2.7ms^{-1} \quad (42)$$

The volumetric flow rate of the opposed airflow is:

$$G_e = 2.7 \times 5 \times 3 = 40.5m^3s^{-1} \quad (43)$$

The total volumetric exhaust rate can be calculated by:

$$G_{tot} = G_p + G_e = m_p / \rho_g + G_e = 117.6m^3s^{-1} \quad (44)$$

When using the opposed airflow to prevent smoke migration from the atrium to the adjacent area, more air should be exhausted to keep the same clear smoke layer height than those with no opposed air supplied. Where the area of the opening to be protected is large, the volumetric rate of exhaust required to provide an adequate opposed airflow may be very large to make this approach infeasible. If this occurs, a physical barrier is necessary in order to prevent smoke propagation into the communicating spaces.

- Opposed airflow for an adjacent compartment fire

  NFPA 92B [2,3] indicates that 74 ^oC is considered realistic for sprinklered fires. For this indicated temperature, according to equation (24), the limiting velocity to prevent smoke from propagating into the large space can be calculated as 1.37 ms^{-1}, and the volumetric opposed airflow rate should be 20.6 m^3s^{-1}. For an unsprinklered room, using the critical temperature of the flashover, the minimum average velocity can be given as 2.83 ms^{-1}, and the volumetric opposed airflow rate should be 42.5 m^3s^{-1}. This is also not a viable option where the area of the opening between the room and the atrium is large. This is because all of the supplied air must be continuously removed from within the fire room in order to maintain the flow. The quantities of air-handling plants required might exceed the size of smoke ventilation systems. A physical barrier is necessary under this condition.

8.2 Using Natural Pressure Depressurization

Assuming the smoke layer depth is 6 m, according to the calculation in section 7.1, the mass exhaust rate is 38.4 kgs^{-1} for a fire in the atrium, and 84.3 kgs^{-1} for a fire in the adjacent room on the ground floor. Assuming the adjacent area below 12.0 m should be protected, then the height of the neutral pressure plane should be set to be higher than 12.0 m. The ratio of the effective vent area to the inlet area can be obtained by using equation (25).

- For a fire in the atrium:

$$(\frac{A_v C_v}{A_i C_i})^2 = \frac{T_g}{T_a[d_g/(H_N - H_g) - 1]} = 1.18 \quad (45)$$

The required vent area can be calculated by:

$$A_v C_v = m_p [T_g^{\ 2} + (\frac{A_v C_V}{A_i C_i})^2 T_a T_g]^{1/2} / [\rho_a (2gd_g \Delta T_g T_a)^{1/2}] = 11.6 m^2 \quad (46)$$

- For a fire in the adjacent room:

$$(\frac{C_v A_v}{C_i A_i})^2 = \frac{T_g}{T_a[d_g/(H_N - H_g) - 1]} = 1.08 \quad (47)$$

The required vent area can be given as:

$$A_v C_v = m_p [T_g^{\ 2} + (\frac{A_v C_V}{A_i C_i})^2 T_a T_g]^{1/2} / [\rho_a (2gd_g \Delta T_g T_a)^{1/2}] = 35.5 m^2 \quad (48)$$

For a fire in adjacent room on the ground floor, the required vent area might be more than 3 times that for a fire in the atrium.

9. CONCLUSION

Several design guides on smoke management in atrium were reviewed in this paper. The basis for designing atrium smoke management system is also investigated. For the smoke management design in the atrium, the design option depends on the space in which the smoke is to be managed and the space in which the smoke originates.

Key points can be summarized as follows:

- Smoke ventilation seems to be the primary approach for smoke management in an atrium. The systems can be designed to maintain an acceptable smoke layer height, or slow down the smoke layer descent rate to extend the smoke filling time. Fire location is an important factor for the smoke ventilation system design.

- Natural ventilation system and mechanical systems can all be used for smoke ventilation. When the quantity of smoke is large, and the smoke is still sufficiently buoyant and there are no adverse wind effects, a natural smoke control system is likely to be the most viable and cost-effective solution. Conversely, if it is not possible to design to overcome adverse positive wind pressures, or a cooler non-buoyant smoke condition is critical, a mechanical system may be more appropriate. Analysis of these systems primarily consists of smoke transport calculations. The minimum smoke layer depth must be deep enough to include the ceiling jet and prevent plugholing.

- Smoke filling is another approach that can be applicable to some atria when the fire sizes are relatively small compared to the size of the space, the time taken to fill the space with smoke is relatively long compared to the times required for escape and firefighting. This approach is economic and particularly useful where there are adverse wind overpressures or it is difficult to incorporate vents or equipment into existing buildings such as historic buildings. In addition to smoke transport calculations, smoke filling systems require an evacuation analysis that accounts for both the time to make decisions and the time for occupants to leave the building. The time for evacuation is only investigated in CIBSE Guide E and BRE Report 368.

- The very high rates of air entrainment into the spill plumes entering a mall or an atrium space would create large increase in mass flow as the plume height increases. Experience suggests the practical limitations to the use of smoke ventilation are a maximum mass flow rate of 150 to 200 kgs^{-1} and a minimum smoke layer temperature of 20 °C above the ambient. These critical values are only found in the UK guides.

- Opposed airflow, depressurization and the barrier are often recommended to prevent smoke flowing from the communicating space to the atrium, or from the atrium into the communicating space. Opposed airflow has been widely used in the US but less so in the UK [5], while depressurization seems to be more often used in the UK. When the opening area is large, using the opposed airflow to prevent the smoke migration between the atrium and communicating spaces might not be feasible due to the large supply airflow capacity required to provide the minimum air velocity. In using the barriers, although it is very easy to realize, it is rather restrictive for building designers; the atrium cannot be utilized as a function space, and it becomes only a fire-resisting light-well [32].

- In order to protect the atrium from fires in adjacent rooms open to the atrium, smoke ventilation system can also be provided within the compartment or the balcony outside the room to prevent smoke flowing into other unaffected areas when the compartment layout is of large area. However, this should be considered carefully because it might often be very difficult, impracticable, or extremely expensive to fit a separate smoke extraction system to each and every room. This option is rarely found to be appropriate for most atrium buildings [6,7].

- The design fires can be steady fires or growing fires. Steady fires are often recommended in the UK guides. However, t^2-fire is sure to be more approximate to the real fires in NFPA and CIBSE Guide E [5]. Using the steady design fire is expected to yield a conservative resign. When there is a lack of reliable evidence to support the choice of either a growing or a steady-state fire, it is more practicable to assess the largest size that a fire might reasonably achieve rather than the time it might take to reach such a size. Growing fire is becoming a more frequent practice to evaluate the smoke control requirements of an atrium building based upon an assumed fire growth rate. The lack of empirical data for the fire growth rate chosen puts its design reliability in question. Further research into fire growth rates in various occupancies commonly found in atrium buildings is necessary.

- Plume equations are the most important factors for smoke control design. The empirical equations used in the UK guides and US guides are not all the same. This will result in a different smoke control system design following these guides. Since all the plume equations recommended are based on the theoretical analysis and experimental data, it is not easy to say which one is more suitable. For the safety reason, conservative design should be recommended. This will determine what critical condition you will concern. For example, if the critical condition is smoke layer temperature or smoke concentration, then the lower value of m_p gives a conservative solution. If the critical condition is smoke volume, then the higher value of m_p gives a conservative solution.

It should be noted that the above guides cannot cover all the atria. Only general principles for designing an efficient system can be provided, with procedures simplified for an ideal atrium. Further guidance on solving frequently encountered practical problems can be recommended. As the buildings become more complicated, both in size and geometry, and also with the introduction of new innovative materials and construction techniques, formulae normally used for designing smoke control system become less reliable and special care is needed in the design process. With the future research work, some of the calculation procedures given may be superseded by better or more accurate relationships as a result of continuing research worldwide. Scale models and CFD models are expected to be widely used for smoke management system design in the future.

NOMENCLATURE

A cross-sectional area of the atrium
A_f fire area
A_i inlet area
A_v vent area
A_w area of the window
C_d discharge coefficient
C_e dimensionless entrainment constant in equation (12)
C_i discharge coefficient of the inlet opening
C_m dimensionless entrainment coefficient in equation (16)
C_v discharge coefficient of the vent
C_{wi} wind pressure coefficient at the inlet
C_{wl} wind pressure coefficient at the topmost leeward storey of the building
C_{wv} wind pressure coefficient at the vent
C_p specific heat capacity of air at constant pressure
D_b smoke layer thickness under the balcony
D_f diameter of the fire source
d_g smoke layer depth
dT/dz rate of change of ambient temperature with respect to height
G volumetric flow rate of the smoke
h_o height of the opening open to the atrium
H height of the atrium
H_g smoke layer interface height
H_N height of the neutral plane
h_b height of the balcony
h_w height of the window
f_l fraction of heat loss of the fire source due to conduction and radiation
m_b mass flux of smoke layer flowing out under the balcony
m_{max} maximum mass flow rate that can be efficiently extracted using a single vent
m_p mass entrainment rate of the plume
N number of exhaust vents
P perimeter of the fire
Q heat release of fire
Q_c convective heat release of fire
S_{min} minimum separation between inlets of the vents

T_a temperature of the ambient air
T_b temperature of the hot gas under the balcony
T_g temperature of the upper smoke layer
t smoke filling time
t_g growth time in t^2-fires
v_e minimum average velocity of the opposed airflow
W width of the balcony spill plume
z smoke layer interface height in the atrium
z_l flame height
z_{max} maximum height that the smoke can reach
z_p height above the balcony
z_w height above the window
z_0 virtual source height
β exhaust location factor
ρ_a density of the ambient air
ρ_g density of the smoke layer
Δ empirical height of virtual source below the balcony
ΔT_b temperature rise of the smoke layer above ambient below the balcony

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Appendix A: BRE Spill-plume Calculations (Morgan and Hansell 1994; Morgan et al. 1999)

The calculation method strictly only applies to fire scenarios where a horizontally flowing, thermally buoyant layer of smoky gases approaches a void, through which those gases then rise. More specifically, the following assumptions are made:

- This approach flow is assumed to be beneath a flat ceiling at the edge of the void.
- It is channeled by downstands (which may be either walls or channel screens).
- The flow has flow-lines which are everywhere parallel and which approach the edge of the void at right-angle.
- The approach flow is also assumed to be fully developed.
- There is no immersed ceiling jet.
- The velocity of the clear air below the smoke layer has a value smaller than that of the layer itself.

Further, it should be noted that experimental evidence (Hansell et al. 1984-85) suggested that the calculation procedure should not be used for approach flow layer temperatures higher than about 350 °C.

Detailed calculation procedure

- Determining approach-flow parameters under the balcony

The mean layer temperature $\bar{\theta}_b$ can be calculated by:

$$\bar{\theta}_b = \frac{Q}{m_b C_p} \qquad \text{(A-1)}$$

From Morgan (1986), the mass flow rate $\dot{m}_b$ at the opening can be calculated by:

$$m_b = \frac{2}{3} C_d^{3/2} (2g\theta_{cb} T_a)^{1/2} \frac{W\rho_a}{T_{cb}} D_b^{3/2} \kappa_M \qquad \text{(A-2)}$$

where C_d is a discharge coefficient for the room opening. For the room with a deep downstand at the opening, C_d = 0.6, and for that without downstand, C_d = 1.0. κ_M is the profile correction for mass flow. W is the width of the opening, ρ_a and T_a are the density and temperature of the ambient air respectively.

The depth of the smoke layer D_b at the opening of the compartment is then given by (Morgan 1986):

$$D_b = \left[\frac{3 m_b T_{cb}}{2 C_d^{3/2} \kappa_M W \rho_a (2g\theta_{cb} T_a)^{1/2}} \right]^{2/3} \qquad \text{(A-3)}$$

The relationship between $\bar{\theta}_b$ and θ_{cb} was given by Morgan (1986) as:

$$\bar{\theta}_b = \frac{\kappa_Q}{\kappa_M} \theta_{cb} \qquad \text{(A-4)}$$

where κ_Q is the profile correction factor for heat flows. It was proposed by Morgan (1986) that constants of $\kappa_Q = 0.95$ and $\kappa_M = 1.3$ can be used for most typical flowing layers.

Following Morgan & Hansell (1987), in the buoyant layer approaching the edge of either the fascia or of the projecting balcony, an average velocity can be calculated by:

$$v_b = \frac{m_b}{W D_b \rho} = \frac{m_b \bar{T}_b}{W D_b \rho_a T_a} \qquad \text{(A-5)}$$

Combining with equations (A-1) to (A-4) gives:

$$v_b = \frac{2}{3^{2/3}} \frac{C_d \kappa_m}{\kappa_Q^{1/3}} \left[\frac{gQT_{cb}}{C_p \rho_a W T_a^2} \right]^{1/3} \qquad \text{(A-6)}$$

For a deep downstand, where C_d = 0.6, this becomes:

$$v_b = 0.76 \left[\frac{gQT_{cb}}{C_p \rho_a W T_a^2} \right]^{1/3} \qquad \text{(A-7)}$$

With no downstand at the opening, C_d = 1.0, and

$$v_b = 1.27 \left[\frac{gQT_{cb}}{C_p \rho_a W T_a^2} \right]^{1/3} \qquad \text{(A-8)}$$

The potential energy flux per unit width relative to the horizontal plane of the balcony can be calculated by:

$$B = \int_0^{D_b} \Delta\rho_b g v_b z dz = \frac{\rho_a}{2} \frac{\theta_{cb}}{T_{cb}} g v_b D_b^2 \qquad \text{(A-9)}$$

Substituting equations (A-4) and (A-5) into the above equation, combining with equation (A-1) gives:

$$B = \int_0^{D_b} \Delta\rho_b g v_b z dz$$

$$= \frac{1}{2} \frac{\kappa_M \dot{Q}}{(\kappa_M \dot{Q} + \kappa_Q \dot{m}_b C_p T_a)} (\frac{\dot{Q}'}{C_p T_a} + \dot{m}_b{}') g D_b \quad \text{(A-10)}$$

where

$$\dot{Q}' = \dot{Q} / W \quad \text{(A-11)}$$

$$\dot{m}_b{}' = \dot{m}_b / W \quad \text{(A-12)}$$

- Calculation on entrainment at balcony edge

From Morgan & Marshall (1975), the mass flux ($\dot{m}_y$) rising past the void edge can be calculated by:

$$\dot{m}_y = \frac{2}{3} \rho_a W \alpha' (2g \frac{\theta_{cb}}{T_a})^{1/2} D_b{}^{3/2} + m_b \quad \text{(A-13)}$$

where the entrainment constant $\alpha' = 1.1$, α' takes such a large value as a result of treating all anomalous entrainment above the spill edge as if it occurred in the rotation region. It is clear that such a high value for α' implies that the assumption of a near-ballistic flow gases in the 'turning region' is invalid. Nevertheless, the good agreement between prediction and measurement (of the plume axial temperature and of overall entrainment in the 'turning region' and in the subsequent plume (Morgan & Marshall 1979) suggests that approach can be used empirically with some success.

- Calculation on the equivalent Gaussian source

The spill plume rising up in the void of the atrium after the balcony edge can be treated as a plume rising above a line source. The behavior of line plumes has been studied both theoretically and experimentally by Lee and Emmons (1961). Following a similar approach by Lee and Emmons, some parameters were derived by Morgan and Marshall (1975) for the equivalent Gaussian source of the balcony spill plume.

The source Froude number (Fr) for the line plume is (Morgan 1975):

$$Fr = \left[\frac{2}{\pi}\right]^{1/4} \left[\frac{\alpha}{\lambda \left[\frac{\theta}{T}\right]_G}\right]^{1/2} \frac{w_G}{(g b_G)^{1/2}} \quad \text{(A-14)}$$

where α is the entrainment constant for plume. $\alpha = 0.16$ for double-sided (Lee & Emmons 1961) and 0.77 for single-sided (Hansell, Marshall & Morgan 1993) line plumes. Quantities with the subscript 'G' refer to characteristics at the equivalent Gaussian source. w_G is the vertical velocity at the source, b_G is the half width of the plume, $[\theta / T]_G$ is the temperature profile at the source, and λ is the ratio of the widths of buoyancy and velocity profiles, $\lambda = 0.9$ according to Lee and Emmons (1961).

w_G, b_G and $[\theta / T]_G$ can be calculated by:

$$w_G = \sqrt{\frac{\zeta}{\xi}} \quad \text{(A-15)}$$

$$b_G = \frac{\xi}{w_G} \quad \text{(A-16)}$$

$$\left[\frac{\theta}{T}\right]_G = \frac{\dot{Q}' \sqrt{1 + \lambda^2}}{T_a C_p \lambda \left[\dot{m}_t' + \frac{\dot{Q}'}{T_a C_p}\right]} \quad \text{(A-17)}$$

In the above equations, ξ and ζ can be expressed as:

$$\xi = \left[\dot{m}_t' + \frac{\dot{Q}'}{T_a C_p}\right] \frac{1}{\rho_a \sqrt{\pi}} \quad \text{(A-18)}$$

$$\zeta = \frac{2B}{\rho_a \left[\frac{1}{\sqrt{3}} - \left[\frac{\theta}{T}\right]_G \frac{\lambda}{\sqrt{1 + 3\lambda^2}}\right] \sqrt{\pi}} \quad \text{(A-19)}$$

From Lee and Emmons (1961), Fr < 1 means a restrained source; Fr > 1 means an impelled source; and Fr = 1 means an ideal line source.

Defining

$$z' = \frac{2}{\sqrt{\pi}} \alpha \frac{z}{b_G} \quad \text{(A-20)}$$

$$p' = \frac{\theta}{T} / [\frac{\theta}{T}]_G \quad \text{(A-21)}$$

$$b' = \frac{b}{b_G} \quad \text{(A-22)}$$

$$w' = \frac{w}{w_G} Fr \quad \text{(A-23)}$$

where θ / T, b and w are all functions of z, the height above the source (i.e. the balcony).

Since in practice, for a mall with Fr < 1, only the restrained source will be considered. The other cases are treated similarly (Lee & Emmons 1961). Lee and Emmons further defined two more variables:

$$\upsilon = \frac{N}{Fr(1-Fr^2)^{1/3}} \quad \text{(A-24)}$$

where N is the dimensionless 'mass flux', $N = w'b'$

and also

$$\upsilon_G = \frac{1}{(1-Fr^2)^{1/3}} \quad \text{(A-25)}$$

and $I_1(\upsilon)$ such that

$$I_1(\upsilon) - I_1(\upsilon_G) = \Delta I_1(\upsilon) = \frac{z'}{\{Fr^2(1-Fr^2)\}^{1/3}} \quad \text{(A-26)}$$

Results from Lee and Emmons (1961) showed that b', w' and p' are all functions of Fr and ν only.

Defining

$$b'' = \frac{b'}{[Fr^2(1-Fr^2)]^{1/3}} \quad \text{(A-27)}$$

$$w'' = \frac{w'}{Fr^{1/3}} \quad \text{(A-28)}$$

$$p'' = \frac{1}{(1-Fr^2)^{1/3}p'} \quad \text{(A-29)}$$

In practice, to determine the time-mean velocity and temperature distributions across the plume at height z_p (where z_p is the height between the balcony and the base of the smoke reservoir), provided that the parameter defining the source are known, one can proceed as follows:

- Calculate Fr from equation (A-14);
- Calculate z' from equation (A-20);
- Calculate ν_G from equation (A-25) and hence find $I_1(\upsilon_G)$ from Fig. A-1;
- Calculate $\Delta I_1(\upsilon)$ from equation (A-26), and hence $I_1(\upsilon)$;
- Referring once again to Fig. A-1, find the values of b'', w'' and p'' corresponding to this value of $I_1(\upsilon)$. Using Equations (A-27) to (A-29), combining with equations (A-20) to (A-23) find the values of b, w, $[\theta/T]$ at height z_p.

- Alternative method for determination of $I_1(\upsilon_G)$

If $\upsilon_G \geq 1.549$,
Then $I_1(\upsilon_G) = (\upsilon_G - 0.75)/0.9607$
If $\upsilon_G \leq 1.549$ and $\upsilon_G > 1.242$,
Then $I_1(\upsilon_G) = (\upsilon_G - 0.843)/0.8594$
If $\upsilon_G \leq 1.242$ and $\upsilon_G > 1.059$
Then $I_1(\upsilon_G) = (\upsilon_G - 0.9429)/0.6243$
If $\upsilon_G < 1.059$
Then $I_1(\upsilon_G) = (\upsilon_G - 1.0)/0.3714$

- Alternative method for calculating values of b', w' and p'

a. Determination of w''

If $I_1(\upsilon) > 1.896$
Then $w'' = 1.0$
If $I_1(\upsilon) > 0.786$ and $I_1(\upsilon) \leq 1.896$
Then $w'' = 0.0908 I_1(\upsilon) + 0.821$
If $I_1(\upsilon) \leq 0.786$
Then $w'' = I_1(\upsilon)^{0.35}$

b. Determination of p''

If $I_1(\upsilon) > 0.832$
Then $p'' = 0.9607 I_1(\upsilon) + 0.75$
If $I_1(\upsilon) > 0.464$ and $I_1(\upsilon) \leq 0.832$
Then $p'' = 0.8594 I_1(\upsilon) + 0.8429$
If $I_1(\upsilon) > 0.186$ and $I_1(\upsilon) \leq 0.464$
Then $p'' = 0.6243 I_1(\upsilon) + 0.9429$
If $I_1(\upsilon) \leq 0.186$
Then $p'' = 0.3714 I_1(\upsilon) + 1.0$

c. Determine of b''

If $I_1(\upsilon) > 2.161$
Then $b'' = 0.938 I_1(\upsilon) + 0.82$
If $I_1(\upsilon) \leq 2.161$ and $I_1(\upsilon) > 1.296$
Then $b'' = 0.89 I_1(\upsilon) + 0.95$
If $I_1(\upsilon) \leq 1.296$ and $I_1(\upsilon) > 0.896$
Then $b'' = 0.81 I_1(\upsilon) + 1.071$
If $I_1(\upsilon) \leq 0.896$ and $I_1(\upsilon) > 0.65$
Then $b'' = 0.619 I_1(\upsilon) + 1.214$
If $I_1(\upsilon) \leq 0.65$ and $I_1(\upsilon) > 0.543$
Then $b'' = 0.331 I_1(\upsilon) + 1.414$
If $I_1(\upsilon) \leq 0.543$ and $I_1(\upsilon) > 0.421$

Then $b'' = 0.0627 I_1(\upsilon) + 1.55$
If $I_1(\upsilon) \le 0.421$ and $I_1(\upsilon) > 0.348$
Then $b'' = 1.821 - 0.6 I_1(\upsilon)$
If $I_1(\upsilon) \le 0.348$
Then $b'' = I_1(\upsilon)^{-0.4}$

- Calculating the mass flux in the atrium

The total upward mass flow rate per unit length of the plume can be calculated by:

$$m_p' = 2\int_0^{z_p} \rho w dz = 2\int_0^{z_p} \rho_a \frac{T_a}{T} w dz \qquad \text{(A-30)}$$

With the Gaussian profiles assumption for vertical velocity and temperature rise,

$$m_p' = \sqrt{\pi}\rho_a wb\left[1 - p'\left[\frac{\theta}{T}\right]_G \frac{\lambda}{(1+\lambda^2)^{1/2}}\right] \qquad \text{(A-31)}$$

The total mass flowing per second into the reservoir is:

$$m_p = m_p' W + \delta m_p \qquad \text{(A-32)}$$

where δm_p is due to entrainment into the ends of the line plume.

The entrainment δm_p into both ends of the line plume can be calculated by:

$$\delta m_p = 4\bar{b}\bar{w}\alpha z \rho_a \qquad \text{(A-33)}$$

where

$$\bar{b} = \frac{(b_G + b)}{2} \qquad \text{(A-34)}$$

$$\bar{w} = \frac{w_G + w}{2} \qquad \text{(A-35)}$$

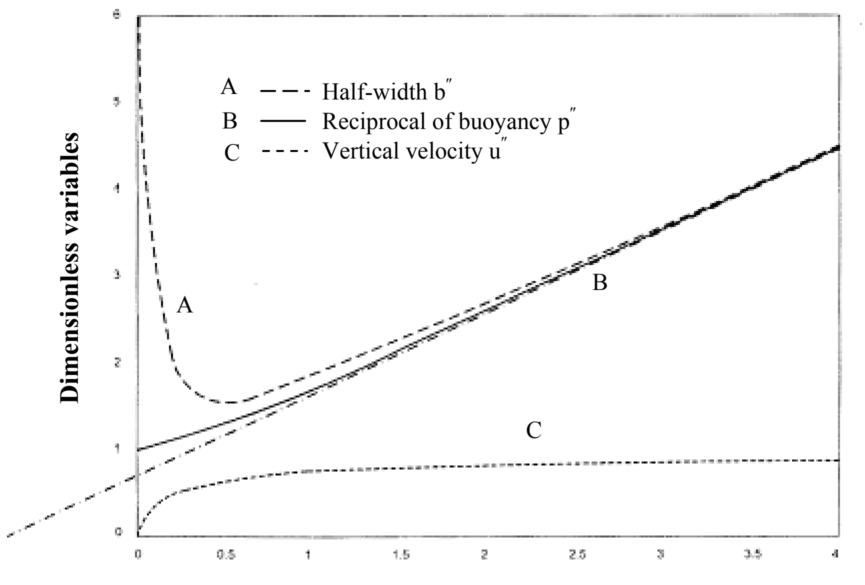

Fig. A-1: Graphical representation of the theoretical solution for a plume rising from a restrained source (Fr < 1)