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Top-down natural ventilation of multi-storey buildings

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SYNOPSIS

We examine natural ventilation in buildings with multiple storeys, each storey linked to a common chimney or atrium, and ventilated using 'top-down chimneys' to draw in relatively unpolluted air from openings located high above street level. Two significant issues relating to ventilation design and management are addressed. First, the common stack provides connections between every storey and, consequently, the ventilation of each storey cannot be calculated in isolation, but must be calculated simultaneously for all storeys. Second, the introduction of the top-down chimney results in frictional losses whose magnitude depends, in part, on the chimney length and cross-sectional area. We develop a simple theoretical model to quantify the effect each storey has on others, and to predict how ventilation openings should be resized in order to overcome the pressure losses associated with the top-down chimney. The model describes the thermal stratification and ventilation flow rate in each storey, and leads to design curves for the sizing of vents to achieve the required ventilation. We focus on steady-state displacement ventilation and compare our theoretical predictions with paradigm small-scale laboratory experiments in a model two-storey building. Our study indicates that, with careful design, top-down ventilation of multi-storey buildings is a realistic strategy in urban environments.

LIST OF SYMBOLS

a	opening area (m^2)	n	number of storeys
A^*	'effective' opening area (m^2)	P	pressure (Pa ≡ $kgm^{-1}s^{-2}$)
c	plume entrainment constant	Q	ventilation flow rate (m^3s^{-1})
c_p	specific heat capacity of air ($Jkg^{-1}K^{-1}$)	Re	Reynolds number = UD/ν
C	loss coefficient	T	temperature (K)
D	diameter of top-down chimney (m)	U	mean velocity (ms^{-1})
E	power of internal heat gains (W)	V	volume of storey (m^3)
f	friction factor ≈ 5×10^{-3}		
g	acceleration due to gravity (ms^{-2})	β	coefficient of thermal expansion (K^{-1})
h	interface height (m)	ν	kinematic viscosity of air (m^2s^{-1})
H	room height (m)	ρ	density of air (kgm^{-3})
L	length of top-down chimney (m)		
M	stack (chimney or atrium) height (m)		

Subscripts - refer to quantities:

inlet	at top-down chimney inlet	*TDC*	in top-down chimney
j (= 0, 1,.., n-1)	on j^{th} storey	*total*	along a complete flowpath
stack	in stack (chimney or atrium)		

1. INTRODUCTION

Despite the energy-saving potential of natural ventilation systems, there remain a number of technical barriers restricting their implementation. These barriers must be overcome before natural ventilation is more widely accepted in urban areas as a realistic alternative to forced ventilation or air conditioning. The recent NatVent programme[1], involving seven European countries with temperate or cold climates, has identified the main technical barriers. These include problems associated with air and noise pollution in urban areas, the need for natural ventilation to provide a 'constant' supply of fresh air independent of short-term fluctuations in the driving pressure forces, and the need for controlled passive cooling. In cold climates, there may also be a requirement for heat recovery from natural ventilation, which could otherwise result in unacceptably high energy consumption. In this paper, we consider a technique for implementing natural ventilation in the urban environment which may significantly reduce the impact of noise and air pollution within the building.

In temperate and cold climates, in which indoor air is typically at a higher temperature than ambient (outdoor) air, the primary goals of ventilation are to supply fresh air and to remove excess heat generated within the building by internal and solar heat gains. A desirable and efficient mode of natural ventilation in these climates is displacement ventilation, in which cool ambient air is introduced at low levels, and warm, stale air leaves at high levels. The position of the openings leads to the development of a stratification within the space. The air inlets are typically at street level where pollution and noise levels may be high, which raises concerns over indoor air quality, and may restrict the use of natural ventilation. One possible solution to this problem, as described by Gage, Hunt and Linden[2] for a single space, is to locate the air inlet well above street level, where the air is typically less polluted, and to draw the air down through a duct before releasing it at low levels in the room. This strategy is aptly referred to as 'top-down' ventilation, as it involves drawing air from the *top* of the building *down* into the ventilated spaces below, see figure 1.

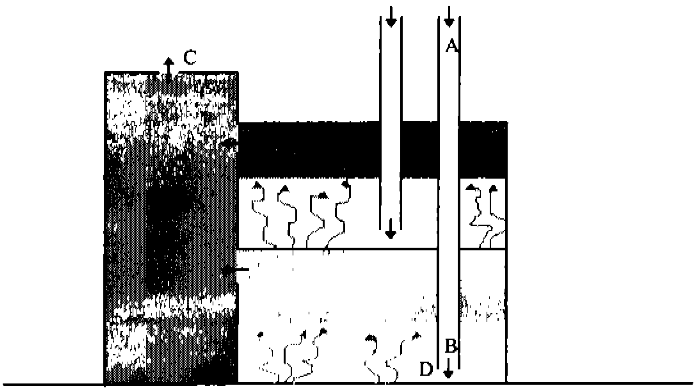


Figure 1. Schematic of top-down ventilation in a two-storey atrium building.

Although, at first sight, the concept of top-down natural ventilation may seem counter-intuitive, ambient air *will* be drawn down the top-down chimney (TDC), providing the difference in internal pressure between the top (A) and bottom (B) of the TDC is greater than the difference in pressure inside the building between the high-level ventilation outlet (C) and the base of the TDC (D). Internal heat gains in the room cause a build-up of warm air near the ceiling and in the stack, which provides this pressure difference. Note that it may be necessary to insulate the TDC from solar/internal heat gains to ensure that the air inside the TDC remains close to ambient temperature. Top-down ventilation in a single-storey space has been successfully demonstrated by Gage *et al.*[2], who simulated these flows at small scale in water tanks.

If there are constant heat gains within an enclosure, then, after some time, a steady situation develops, in which the rate of heat input is balanced by the rate of removal of heat by the ventilation flow. For a single room, this steady flow has been modelled by Linden, Lane-Serff and Smeed[3], using a point source of heat on the floor to represent heat gains, and was shown to depend on the 'effective' opening area A^* of the inlet and outlet. However, in multi-room buildings, the flowpaths between inlets and outlets are typically more complex, and may link numerous internal spaces. When there are isolated flowpaths through a building, in which each inlet/outlet pair is connected by an independent air route, the effective area A^* of each flowpath may be calculated by summing the areas of the individual openings:

$$\frac{1}{A^{*2}}=\sum_{j=1}^{n}\frac{1}{2C_j a_j^{\ 2}}, \tag{1}$$

where a_j ($j = 1, 2, .., n$) is the area of the j^{th} opening and C_j is the loss coefficient associated with that opening. Expression (1) is valid for flows driven by any combination of stack and wind effects[4,5,6].

In this paper we extend the work of Linden *et al.*[3] and Gage *et al.*[2] by considering the application of top-down ventilation to multi-storey spaces that are linked by a common atrium or chimney. Linking a number of storeys via a common stack creates a more complex building geometry, in which flowpaths are no longer isolated, but merge and divide. This poses a number of questions at the design stage such as '*how should the openings be sized on each floor to meet ventilation requirements*?' and '*how does the ventilation of one floor affect the ventilation of another*?' To address these and related questions we develop a simple theoretical model and determine the airflow rate and temperature stratification on each storey of a generic stack ventilated building. Additionally, in top-down ventilation, poor design may result in significant pressure losses through the relatively tall TDCs which link the lower storeys to inlet vents at the top of the building. Here, the additional losses associated with the use of TDCs are quantified.

Model predictions are presented in the form of design curves which may be used to determine the opening areas and TDC dimensions subject to specific design criteria, such as heating loads and required air changes per hour. These design curves are intended as an aid in the initial planning of multi-storey buildings with top-down ventilation. The predictions are compared with the results of salt-bath laboratory experiments, in which natural ventilation flows were produced in a small-scale model of a generic two-storey building.

2. THEORETICAL MODEL FOR NATURAL VENTILATION OF MULTI-STOREY BUILDINGS

2.1 Loss in driving pressure due to top-down ventilation

If the driving stack forces are weak, as is often the case, then any additional pressure losses that arise in top-down ventilation are undesirable, and designers must aim to minimise these losses in order to make best use of the driving forces. We now quantify the magnitude of the frictional pressure drop ΔP along a TDC, and illustrate its dependence upon the chimney's aspect ratio L/D, where L is the length and D the diameter. For a cylindrical TDC drawing air of density ρ at a mean velocity U into a building, the frictional pressure loss may be expressed as

$$\Delta P=\frac{2Lf\rho U^2}{D}, \tag{2}$$

where the friction factor f decreases with Reynolds number Re and may be approximated by

$$f=\begin{cases} 16/\mathrm{Re} & \text{for } 10<\mathrm{Re}<2000 \text{ - laminar flow;} \\ 0.079\,\mathrm{Re}^{-1/4} & \text{for } \mathrm{Re}<10^5 \text{ - turbulent flow,} \end{cases} \tag{3}$$

see Ward-Smith[7]. Here, the Re is based on the diameter of the TDC and mean air velocity, *i.e.* $\mathrm{Re}=UD/\nu=4Q/\pi D$, where Q is the ventilation flow rate. Since $U=Q/a_{TDC}$, we may write

$$\Delta P=\frac{\rho Q^2}{2C_{TDC}a_{TDC}^2} \quad \text{with} \quad C_{TDC}=\frac{D}{4Lf}, \tag{4}$$

where $a_{TDC} = \pi(D/2)^2$ is the cross-sectional area of the TDC and C_{TDC} is a loss coefficient for the TDC. From (4), it is clear that frictional losses increase with f, increase as the TDC area a_{TDC} decreases and increase as the aspect ratio L/D of the TDC increases.

In most building ventilation applications, we anticipate that the flow in the TDC will be turbulent and, in this case, relatively large changes in Re result in only small changes in f: for $5000 < \mathrm{Re} < 10^5$, f lies in the range $9.4\times10^{-3} > f > 4.4\times10^{-3}$. Therefore, we make the approximation that the friction factor f is independent of Re, over the range of Re expected, and take $f = 5\times10^{-3}$. This simplifies the representation of frictional losses, since C_{TDC} is then a constant for a given aspect ratio L/D.

In a similar way to (1), the two pressure loss contributions from the TDC, due i) to flow through the TDC inlet, of area a_{inlet} and loss coefficient C_{inlet}, and ii) to the frictional losses described above, can be shown to combine as a 'TDC effective area' A^*_{TDC} given by

$$1/{A^*_{TDC}}^2 = 1/2C_{inlet}a^2_{inlet} + 1/2C_{TDC}a^2_{TDC}\,. \tag{5}$$

Thus, the use of a TDC effectively reduces the area of the openings along the entire flowpath, and will therefore decrease the ventilation flow rate.

Frictional losses may be neglected only when they are significantly less than losses through the openings. As an example, for a TDC with $D = 0.5$ m and $L = 6$ m (*i.e.* $L/D = 12$), the loss coefficient $C_{TDC} = 4.2$. Then, from (5), for a typical loss coefficient of $C_{inlet} = 0.63^2 \approx 0.4$ at the inlet of the TDC, friction can only be neglected if $a_{inlet} \ll 3.2a_{TDC}$, *i.e.* only if there is a considerable constriction at the inlet. In most situations, therefore, friction in the TDC is likely to be sufficiently large that it should be taken into consideration.

2.2 Relationship between ventilation flow rate and stratification along a flowpath

For a two-storey building with displacement ventilation (figure 1), there are two flowpaths; the first through the lower storey and into the stack, and the second through the upper storey and into the stack. The solution for the steady airflow rate and stratification is then given by two simultaneous equations, one for each flowpath, and by conservation of volume and heat fluxes. By extension, n simultaneous equations can be written for a building with n storeys connected to a common stack. If each flowpath j comprises a TDC with effective area A^*_{jTDC}, leading into the j^{th} storey with effective area A^*_j and out into a common stack of height M with outlet effective area A^*_{stack}, then the n simultaneous equations describing the flow are

$$Q_j^2\left(\frac{1}{A_j^{*2}}+\frac{1}{A_{jTDC}^{*\;2}}\right)+Q_{stack}^2\left(\frac{1}{A_{stack}^{*\;2}}\right)=\frac{\Delta T_j}{T}g\left(H_j-h_j\right)+\frac{\Delta T_{stack}}{T}g\left(M-\sum_{k=0}^{j}H_k\right), \tag{6}$$

for $j = 0,\ldots n\text{-}1$, where the ventilation flow rate and the excess air temperature (*i.e.* temperature above ambient) in the stack are

$$Q_{stack} = \sum\nolimits_{j=0}^{n-1} Q_j \quad\text{and}\quad \Delta T_{stack}Q_{stack} = \sum\nolimits_{j=0}^{n-1} Q_j\Delta T_j\,, \tag{7}$$

on the assumption that the stack is well-mixed. Here, H_j, h_j, ΔT_j and Q_j are the room height, interface height (*i.e.* depth of cool lower layer), excess temperature of the warm upper layer and ventilation flow rate for storey j, respectively. The effective area A^*_j of the j^{th} storey is calculated by summing the upper and lower internal opening areas, as in (1).

2.3 Modelling heat gains

In this simple model, we assume that the heat gains within each storey can be represented as a point source of heat. In some situations this assumption may represent a considerable simplification, as heat gains may arise from distributed sources or from numerous interacting localised sources of heat. However, as in Linden *et al.*[3], we shall see that this simplification allows us to develop approximate design guidelines and rules of thumb. From the theory of turbulent plumes[8], the temperature departure from ambient ΔT_j and volume flow rate Q_j, at a vertical height h_j from a heat source of strength E_j, are

$$\Delta T_j/T = \left(\beta E_j/\rho c_p\right)^{2/3} / c g^{1/3} h_j^{5/3} \quad \text{and} \quad Q_j = c\left(g\beta E_j/\rho c_p\right)^{1/3} h_j^{5/3}, \qquad \text{(8a,b)}$$

respectively, where $c \approx 0.14$ is a parameter dependent upon entrainment into the rising thermal plume. The height h_j of the interface for the displacement flow within each storey is given by the solution of (6) and (7), with Q_j and ΔT_j given by (8), and may be obtained numerically using a simultaneous root-finding algorithm. Once h_j has been determined, Q_j and ΔT_j are found from (8), and the number of air changes per hour in the j^{th} storey (ACH_j) is given by $ACH_j = 3600Q_j/V_j$, where V_j is the volume of the j^{th} storey.

3. LABORATORY VALIDATION

In order to simulate natural ventilation flows in linked spaces, experiments were performed using a small-scale transparent Perspex model of a simplified two-storey building. The model was immersed upside-down in a large tank of fresh water, and heat gains were modelled as a continuous release of dense salt solution through a small opening in the floor of each storey. Salt solution is denser than the surrounding fresh water and creates a turbulent plume analogous to a thermal plume rising from a heat source in air. For clarity, the experimental observations will be described as if for a heat source in air. A food dye added to the salt solution distinguished it from the ambient (uncoloured) fresh water. A number of holes (diameter 2.0 cm) made in the ceiling of each storey connected to a common stack and acted as high-level outlet openings. An open-ended cylindrical tube (diameter 5.2 cm) represented the TDC and extended from the top of the model to close to the floor of each storey. An experiment began by supplying salt solution to the plumes. Following an initial transient period a steady flow was established and measurements of interface height and salinity (and hence temperature[3]) were made in each storey. When the experiment was illuminated from behind, the fraction of light transmitted through dyed regions could be directly related to the dye concentration, and hence to the fluid density. The motion of the ambient fluid was visualised by releasing a patch of neutrally buoyant dye into the region of interest.

The dye concentration image in figure 2, taken during a typical experiment, shows the geometry of the model building and the steady displacement flow established in both storeys, when there are heat gains in each. The common stack fills with warm air which descends to the level of the upper openings of the first storey. The heat gains and inlet/outlet areas in the two storeys are identical, however, the stratification height in the ground floor is greater than in the first floor. This implies a greater airflow rate and a reduced upper layer air temperature in the ground floor, and is a consequence of the enhanced stack at this floor.

By simulating heat gains in just one of the storeys, a displacement flow was set up only in the heated storey. However, due to the common stack, a ventilating flow was induced in the unheated storey — ambient air was drawn into this storey via its TDC and exhausted through the upper openings. A general upward movement of air through this storey was observed.

It was observed that ambient fluid at street level was not, in this quiescent environment, drawn into the TDCs. In contrast, street-level air was drawn into the model when low-level inlets were connected directly to the ambient.

4. DESIGN CURVES

For a specified building geometry and heating load, (6), (7) and (8) can be solved to give a prediction of stratification and *ACH*, within the assumptions of the model. In addition, the strength of the theoretical model is that it can aid an understanding of how the variable quantities scale with the controlling parameters of the flow. For example, the ventilation flow rate Q in single room ventilation driven by a heat source of power E is always equal to some scalar multiple of $(g\beta E/\rho c_p)^{1/3}H^{5/3}$, although the multiplication factor will vary with other flow parameters. It is therefore useful to explore how the *non-dimensional* variable $Q/(g\beta E/\rho c_p)^{1/3}H^{5/3}$ behaves. In this section, we present several design curves in non-dimensional variables.

As shown in §2.1, the addition of a TDC can reduce the effective opening area of a flowpath and so reduce the ventilation flow rate. However, expression (5) can be used to calculate by what amount the effective area of a particular storey A^*_j must be *increased* to compensate for the addition of a TDC, and so give no net reduction in flow rate:

$$\%\text{ increase in } A_j^* = \left[\left\{1-\left(A_j^*/A_{inlet}^*\right)^2 - \frac{L}{100D}\left(A_j^*/a_{TDC}\right)^2\right\}^{-1/2} - 1\right]\times 100. \tag{9}$$

This is displayed graphically in figure 3, and it is evident that the necessary change is greater for large aspect ratio ($L/D \gg 1$) TDCs and increases as the inlet effective area decreases.

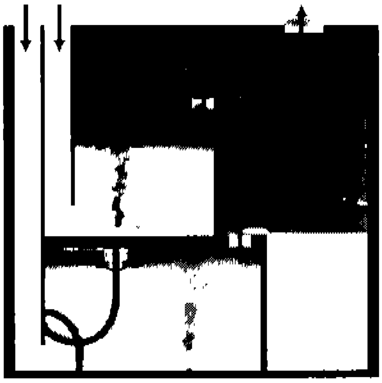


Figure 2. Inverted dye concentration image showing displacement flow in a two-storey enclosure. The common stack is on the RHS. The height of each storey $H = 14$ cm.

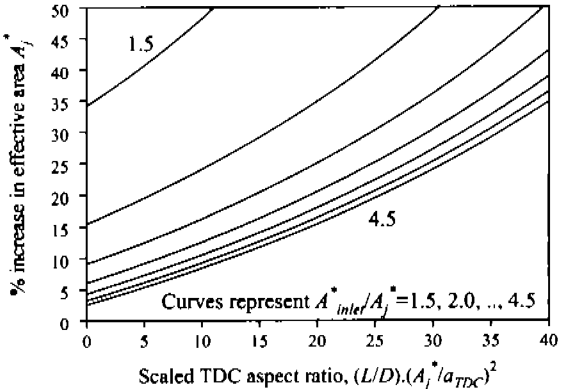


Figure 3. Percentage increase in A^*_j needed to compensate for the addition of a TDC of area a_{TDC}, aspect ratio L/D and inlet effective area A^*_{inlet}.

We now consider a possible design criterion for a multi-storey office building with a common stack. In our 'test' building, all the storeys are the same height $H_j = H$, and are subject to the same heating load $E_j = E$. One likely design requirement is for an equal ventilation flow rate on each storey, *i.e.* $Q_j = Q$. However, the lower storeys have a significantly larger driving force than the upper storeys due to the depth of the warm layer within the stack above them. The design solution is to choose larger opening areas for the higher storeys, to compensate for the reduced stack. From (6), it can be shown that, in this special case, the 'total' effective area A^*_{jtotal} for the flowpath through the j^{th} storey is

$$\frac{1}{A^*_{jtotal}} = \sqrt{\frac{1}{A^{*\,2}_{jTDC}} + \frac{1}{A_j^{*2}} + \frac{n^2}{A^{*\,2}_{stack}}} = \sqrt{\frac{1}{A^{*\,2}_{j(TDC+storey)}} + \frac{n^2}{A^{*\,2}_{stack}}}, \tag{10}$$

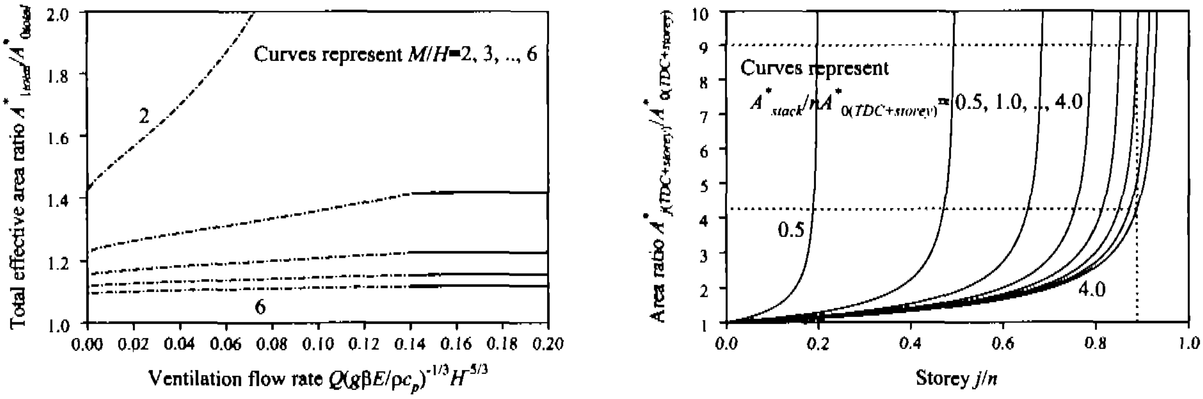
as n equal streams of air must share the common stack exit. Here, $A^*_{j(TDC+storey)}$ is the combined effective area for the TDC and rooms on the j^{th} storey. From (6), the ratio of the total effective areas for the j^{th} and ground storeys required to give identical airflow rates through each storey is given by

$$\frac{A^*_{jtotal}}{A^*_{0total}} = \sqrt{\frac{M-h}{M-h-jH}}. \tag{11}$$

Assuming the required airflow rate Q is specified, the interface position can be found from (8b), and hence, the area ratio (11) determined. Figure 4(a) illustrates this ideal area ratio in a two-storey building as a function of the specified airflow rate for various chimney heights M/H. For small stack heights the area of the first floor vents need to be considerably larger than for the ground floor. As the stack height increases, the area ratio approaches 1 and is less dependent on the specified airflow rate. For a typical stack height of $M/H \approx n$, it can be shown from (11) that for a building with many storeys, *i.e.* $n \gg 1$,

$$\frac{A^*_{jtotal}}{A^*_{0total}} \approx \sqrt{\frac{1}{1-j/n}} \quad \text{and hence} \quad \frac{A^*_{j(TDC+storey)}}{A^*_{0(TDC+storey)}} \approx \left[1-\frac{j}{n}-\frac{j}{n}\left(\frac{nA^*_{0(TDC+storey)}}{A^*_{stack}}\right)^2\right]^{-1/2} \tag{12a,b}$$

The effective area ratio (12b) is displayed in figure 4(b) for various stack outlet areas. As the stack outlet area decreases, the area ratio between the j^{th} and the ground floor rapidly increases, *e.g.* for the top storey of a 9-storey building (*i.e.* $j/n = 0.89$), reducing the dimensionless stack area from 4 to 3 more than doubles the required area ratio (from $A^*_{j(TDC+storey)}/A^*_{0(TDC+storey)} \approx 4.2$ to 9.0). The figure clearly shows how sharply the effective opening area $A^*_{j(TDC+storey)}$ must increase with each additional storey, until, at the highest storeys, it is no longer possible to match flow rates with the lowest storeys.



(a) (b)

Figure 4. Ratio of effective areas necessary for equal ventilation flow rates on each story. (a) For a two-story building: $A^*_{1total}/A^*_{0total}$, for various M/H and Q. The solid lines indicate that the interface has reached the level of the upper openings. (b) For an n-storey building: $A^*_{j(TDC+storey)}/A^*_{0(TDC+storey)}$, for storey j/n and various dimensionless stack areas $A^*_{stack}/nA^*_{0(TDC+storey)}$.

5. CONCLUSIONS AND IMPLICATIONS TO BUILDING DESIGN

Stack-driven top-down displacement ventilation of multi-storey linked spaces has been examined through the development of a theoretical model and complementary small-scale laboratory experiments in water tanks. The experiments allow the ventilating flows on each storey to be clearly visualised, and demonstrate that top-down displacement ventilation in multi-storey spaces is a feasible strategy, which avoids the introduction of street-level contaminants into the building. The theoretical model provides a useful tool for predicting airflow rates and thermal stratification on each storey and in the stack. Furthermore, it may be used for selecting the opening areas required to give equal ventilation in each storey — a common requirement in multi-storey office spaces.

A potential drawback of top-down ventilation is the reduction in the natural driving forces due to frictional losses in the TDC. These losses may be approximated as a Re-independent loss coefficient giving an "effective area" for the TDC, and are shown to increase as the aspect ratio L(length)/D(diameter) of the TDC increases. Design guidelines are presented in the form of non-dimensional curves. These depict the required percentage increase in the vent area of a storey in order to compensate for the addition of a TDC, with no net loss in pressure.

In conclusion, we have shown that the modelling techniques developed for single-spaced enclosures may successfully be applied to more complex multi-compartment linked spaces. Work is currently in progress to further validate and extend the theory in order to model the direct ventilation of an atrium and to predict the stratification within it.

ACKNOWLEDGEMENTS

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