PASSIVE VENTILATION IN MULTI-STOREY ATRIUM BUILDINGS: A FIRST-ORDER DESIGN GUIDE

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ABSTRACT

Large, multi-storey buildings pose a particular challenge for natural ventilation design due to the interaction between heat and air flows through different building zones. We develop a demand-based preliminary design strategy for sizing ventilation openings in multi-storey buildings with heated atriums. This approach enables ventilation openings on each storey, and in the atrium, to be rapidly sized so that equal temperatures and per-person flow rates can be achieved on all storeys, regardless of the occupancy or usage. To achieve this, two key dimensionless parameters are identified which quantify the performance of the ventilation system and the effectiveness of the atrium in assisting ventilating flows. Simple analytical expressions for sizing vents are developed and an example design chart presented to provide quick and intuitive first-order design guidance.

INTRODUCTION

Passive stack ventilation has particular potential for use in multi-storey buildings. Tall vertical spaces such as atria, solar chimneys and double façades, which are common in such buildings, can enhance ventilation flows by providing a space in which buoyant air can accumulate. However, effective design remains a challenge; interacting air and heat flows can potentially result in undesirable flow patterns and an uncomfortable indoor environment **[1-3]**.

Whilst powerful computational tools – such as CFD simulations and multizone software **[4-6]** – are now commonly used for detailed design, simplified mathematical models – based on the fundamental physics governing the movement of air and heat through buildings – still form a crucial part of the preliminary design stage. Design charts and hand calculations – commonly used in best practice guidance **[7-10]** – allow designers to quickly balance core variables and provide an intuitive understanding of the behaviour of the ventilation scheme. Numerous experimental investigations, including studies of multi-compartment buildings **[11-13]**, have also shown that simplified mathematical models can capture a broad range of flow behaviours.

With this in mind, we develop a preliminary design approach for multi-storey atrium buildings based on a simplified mathematical model. We focus on sizing ventilation openings to meet design criteria for ventilation rate and thermal comfort. In particular, we use dimensionless parameters to inform design, an approach advocated and discussed by Etheridge **[14]**, for example. Some details of the mathematical model have been omitted for brevity; for a full discussion see Acred and Hunt **[15]**. Instead, we focus herein on outlining the design method and illustrating how it may be applied to an example four-storey building.

The aim of this work is to provide a rapid and intuitive first-order design method. It is not intended to be used for detailed design, but rather to provide a starting point for software modelling with the hope of reducing the time and computational overhead associated with the design process.

OVERVIEW OF THEORY

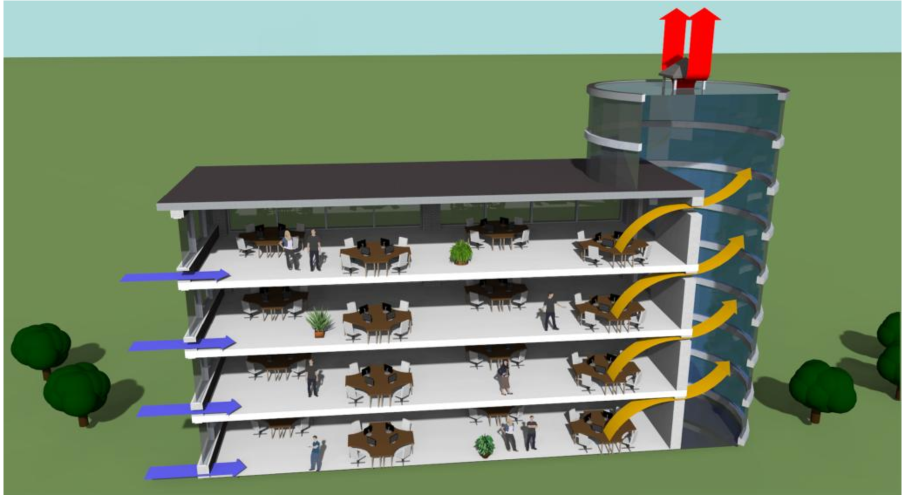

Figure 1: Visualisation of an example four-storey building with a glazed atrium. Arrows show the intended ventilation scheme: cool, fresh air enters the storey through floor-level vents, passes into the atrium via ceiling-level vents and leaves the building through the high-level atrium vent.

Figure 1 shows a visualisation of the example four-storey building considered herein, comprising open-plan occupied spaces connected to an atrium. Arrows show the intended ventilation scheme: ambient air flows into the storeys via floor-level vents, is warmed by heat gains (e.g. from office equipment, body heat and solar gains) in the storeys and passes into the atrium via ceiling-level vents. After being further heated in the atrium (e.g. due to solar gains), air then leaves the building via a high-level vent.

Building layout and core variables

Figure 2 shows a schematic in elevation of the example four-storey atrium building from Figure 1. Core ventilation variables are labelled:

The floor-to-ceiling height (m) of each storey is H; the atrium extends a height ΔH above the top storey. The flow rate (m^3/s) through each storey is Q_i, where $i = 1,2,3,4$ denotes the storey number. The flow rate through the atrium vent is $Q_a = Q_1 + Q_2 + Q_3 + Q_4$. The floor- and ceiling-level vents in the storeys have cross-sectional areas $A_{in,i}$ and $A_{out,i}$, respectively. The high-level atrium vent has cross-sectional area A_a.

The air temperature (°C), net heat input (W) and number of people in each storey are T_i, W_i and n_i, respectively. The air temperature and net heat input within the atrium are T_a and W_a, respectively. The external temperature is T_0. The temperature excesses within the storeys and atrium – upon which the driving stack pressure depends – are $\Delta T_i = T_i - T_0$ and $\Delta T_a = T_a - T_0$, respectively.

We have assumed a uniform temperature in each building zone. This model is valid for buildings containing distributed heat sources which occupy more than 15% of the floor area in each zone **[16,17]**. However, we note that some stratification is likely to exist in practice, particularly in the atrium, and is closely linked to the geometry and distribution of heat sources within the building – see **[18-21]**, for example.

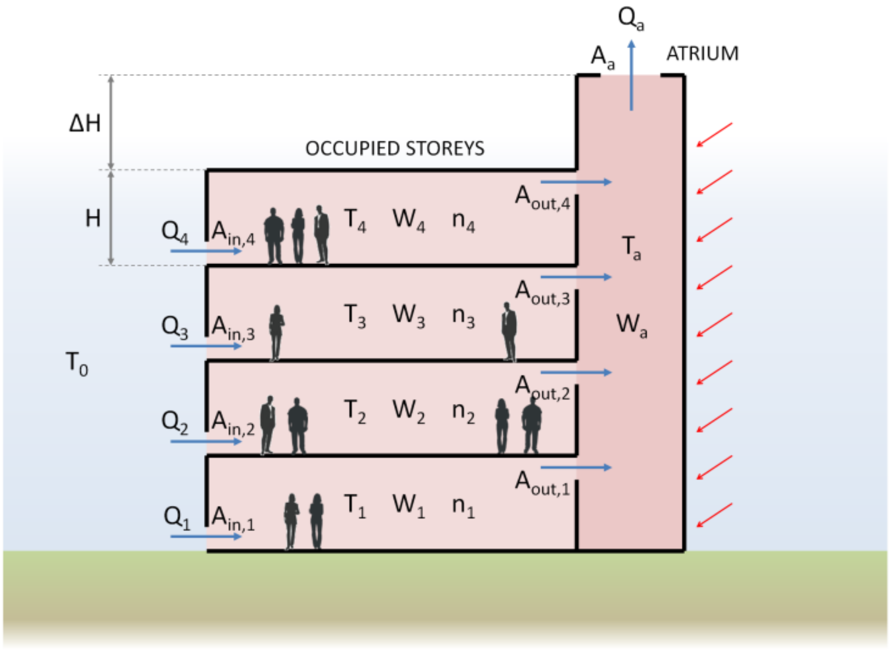

Figure 2: Schematic in elevation of a naturally ventilated four-storey atrium building. See main text for a description of the symbols shown.

Mathematical model of ventilation flows

Following **[18]** and **[22]**, the flow rates through the building can be calculated by balancing the driving stack pressure with pressure losses across vents around a closed flow loop through each storey. Pressure losses across vents are calculated using Bernoulli's theorem, which is common practice for 'purpose-built' vents **[8]**. The driving stack pressure is calculated by assuming a hydrostatic pressure distribution everywhere but at ventilation openings, and treating air as a perfect gas.

In practice, we note that other pressure terms – particularly wind – may play a role. Wind is typically harnessed to assist ventilation **[23]** (although it can also oppose stack pressure **[24]**). Flows driven by stack effect only may then be considered a 'worst case scenario', and the method presented herein gives conservative preliminary design guidance.

Applying the pressure balance to the building in Figure 2, four coupled flow equations – one for each storey – are required to describe the ventilation scheme. The flow equation for storey *i* is given by

$$\frac{Q_i^2}{a_i^2}+\frac{Q_a^2}{a_a^2}=\frac{g}{T_0}\quad H\Delta T_i + \quad N-i\ H+\ \Delta H\ \ \Delta T_a\ \ , \tag{1}$$

where

$$a_i = \quad \frac{1}{2c_d^2A_{in,i}^2}+\frac{1}{2c_d^2A_{out,i}^2}^{\ -\frac{1}{2}} \qquad\qquad a_a = \ \overline{2}c_dA_a \tag{2}$$

are effective vent areas for the storey and atrium vents, respectively, $N = 4$ is the number of storeys, and $g = 9.81\text{m/s}^2$.

Note that the effective storey vent area, a_i, is formed from a combination of the floor- and ceiling-level vent areas. The relative sizing of the two vents can have a significant impact on the ventilation flow **[25,26]**. Similarly, the value of the discharge coefficient, c_d – which relates effective and physical vent areas – can vary significantly based on opening geometry and flow conditions **[27,28]**. For simplicity, we do not consider these effects and focus only on how to select appropriate values of a_i and a_a.

Heat balance

The coupled equations in (1) allow the flow rates through the building to be calculated when the temperature distribution is known. The temperature distribution, in turn, depends upon the net heat gains within the building. Applying a steady heat balance to each building zone, the temperature excesses are given by

$$\Delta T_i = \frac{W_i}{\rho_0 c_p Q_i} \qquad\qquad \Delta T_a = \frac{W_{tot}}{\rho_0 c_p Q_a}, \tag{3}$$

where $W_{tot} = W_1 + W_2 + W_3 + W_4 + W_a$ is the total net heat gain within the building and ρ_0 and c_p are the density and heat capacity of ambient air, respectively. For calculations presented herein, we take $\rho_0 = 1.225\ \text{kg/m}^3$ and $c_p = 1.005$ kJ/kgK (corresponding to air at 15°C at sea level) **[29]**.

BALANCING DESIGN REQUIREMENTS

Typically, the coupled equations in (1) and (3) must be solved numerically to determine ventilation rates and temperatures, see **[30]** for example. However, by linking our mathematical model with ventilation design criteria based on *per-person* requirements, it is possible to solve the equations analytically and thereby allow for rapid preliminary design calculations.

Demand-based design criteria

Many ventilation guidelines are specified in terms of a minimum fresh air supply rate per person. CIBSE **[8]** and ASHRAE **[9]**, for example, stipulate a minimum requirement of 8-10l/s per person to maintain a healthy and comfortable indoor environment. Consider the case in our example building in which each building occupant receives a given fresh air supply rate, Q_p, where the subscript p denotes 'per person'. The flow rate through a given storey can then be expressed in terms of the number of people within the storey:

$$Q_i = n_i Q_p. \tag{4}$$

Similarly, consider the case in which the net heat inputs on all storeys are divided equally between occupants such that

$$W_i = n_i W_p, \tag{5}$$

where W_p is a per-person net heat input. Note that W_p is a net heat input and includes not only body heat but also heat gains due to office equipment, lighting and so on, as well as heat losses through the building fabric. When the conditions in (4) and (5) are met, the temperatures in all storeys are equal and given by

$$\Delta T_p = \frac{W_p}{\rho_0 c_p Q_p}. \tag{6}$$

These conditions are intended to provide a convenient 'base target design' for preliminary calculations. By aiming for equal temperatures on all storeys, we target a design in which thermal comfort can be achieved in all parts of the building and avoids overheating on the upper storeys, for example.

In practice, the net heat gain per person may vary between storeys; the upper floors may receive greater solar gains, for example. This could be catered for using a weighting factor – allowing for a greater flow rate per person to maintain the desired temperature on floors with greater heat gains. However, to avoid adding additional parameters to the problem, the calculations presented herein focus on the simple 'base target design' conditions presented above.

Ventilation performance index

The balance of design criteria can be quantified using a single dimensionless 'ventilation performance index' (or VPI), λ_p, given by:

$$\lambda_p = \overline{\frac{Q_p^2}{\Delta T_p} \frac{T_0}{gH^5}}\ . \tag{7}$$

By specifying or estimating values for two out of Q_p, W_p and ΔT_p, the corresponding VPI of the design can be determined using (6) and (7). Alternatively, a design chart can be used to rapidly determine the value, or range of values, of λ_p that relates to the desired balance of design criteria. An example design chart for a building in which H = 3m is shown in Figure 3.

Various regions of Figure 3 have been highlighted to show an example of its use; the corresponding ranges of ΔT_p, Q_p, W_p and λ_p are listed in Table 1. In this example, the desired temperature excess range is between 5 and 10°C, and the estimated per-person heat inputs lie between 100 and 200W. The region of the chart in which these ranges entirely overlap has been highlighted in dark blue. The upper and lower bounds of this range define the maximum and minimum values of λ_p for which all design criteria can be simultaneously satisfied. Flow rates within the target design range lie between 13 and 20l/s per person and therefore also satisfy the minimum flow rate requirement of 10l/s per person.

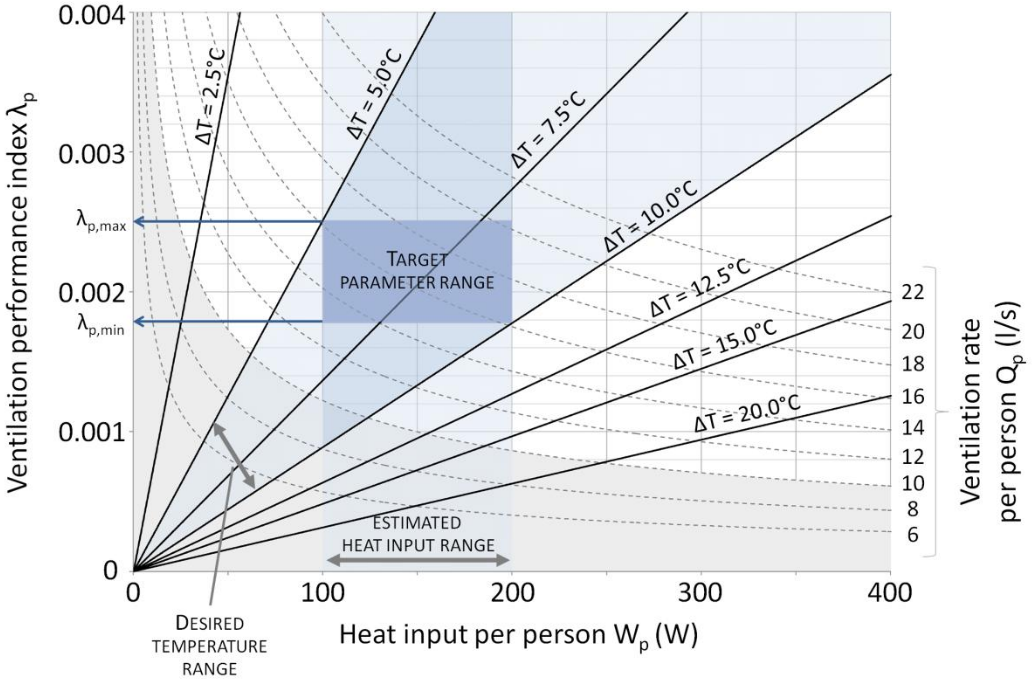

Figure 3: Design chart for selecting values of λ_p based on design requirements for a building with $H = 3$m. Contours of equal temperature excess (thick black lines) and equal ventilation rate per person (dashed grey lines) are shown. The chart shows an example in which the desired temperature excess is between 5 and 10°C, the estimated range of per-person heat inputs is between 100 and 200W, and the minimum required ventilation rate is 10l/s per person.

	Min	**Max**
Target temperature excess, ΔT_p (°C)	5	10
Minimum acceptable ventilation rate per person, Q_p (l/s)	10	-
Estimated heat input per person, W_p (W)	100	200
Ventilation performance index range, λ_p	0.0018	0.0025

Table 1: Ranges of ΔT_p, Q_p, W_p and λ_p for the design example shown in Figure 3.

Atrium enhancement

Atria, solar chimneys and similar vertical spaces spanning multiple storeys are typically intended to enhance stack driven ventilation flows in naturally ventilated buildings. However various studies have shown that in some cases the atrium can actually restrict flows through the building **[11,31,32]**. An effective design, therefore, should ensure that the atrium enhances ventilation flows relative to an equivalent building without an atrium. Following a similar approach to **[11]**, we quantify this effect in a dimensionless atrium enhancement parameter:

$$E_i = \frac{Q_{i\ with\ atrium}}{Q_{i\ without\ atrium}}, \tag{8}$$

where $Q_{i\ without\ atrium}$ is the theoretical flow rate through storey *i* when not attached to an atrium, which can readily be calculated following **[18]**, for example. The atrium enhances ventilation flows through a given storey when $E_i > 1$. An effective design should ensure that $E_i \geq 1$ on all storeys.

Since the atrium links all storeys, the values of E_i on all storeys are linked and decrease on ascending the building **[15]**. This is an intuitive result, since flows through the lower storeys are driven by a greater depth of warm air in the atrium than flows on the upper storeys. The top storey is the 'worst performing' storey, with the lowest value of E_i, since it receives the least amount of driving from the atrium. To achieve a design with $E_i \geq 1$ on all storeys therefore requires that $E_N \geq 1$, i.e. flows through the top storey are enhanced – or at least not restricted – by the atrium.

Acred and Hunt **[15]** showed that there are limits on the maximum achievable top-storey atrium enhancement, particularly due to the possibility of undesirable exchange flows developing at the atrium outlet vent. In most scenarios, however, achieving a value of $E_N = 1$ should be possible. For the example calculations presented herein, we therefore target a design in which $E_N = 1$, thereby ensuring the atrium enhances – or at least does not restrict – flows on all storeys.

SIZING VENTILATION OPENINGS

Substituting the target design conditions into the mathematical model for ventilation flows in (1) allows us to determine simple analytical expressions for appropriately sizing ventilation openings (see **[15]** for details). The required effective vent sizes to give equal flow rates and temperatures on all storeys, for the case in which the top storey atrium enhancement is $E_N = 1$, are given by

$$a_i = \frac{n_i \lambda_p H^2}{\overline{1 + R_W(N - i)}} \qquad a_a = \frac{n_{tot} \lambda_p H^2}{\overline{R_W R_H}} \tag{9}$$

STOREY VENTS ATRIUM VENT

where $R_W = W_{tot}/(W_{tot} - W_a)$ is a measure of the relative heat gains in the atrium and $R_H = \Delta H/H$ is the relative height of the atrium above the top storey.

Example calculations

Table 2 shows example vent area calculations based on the design requirements and corresponding values of λ_p shown in Figure 3 and Table 1. Effective vent areas are calculated for a building with H = 3m and 30 people on each storey (i.e. $n_i = 30$ on all storeys). Three illustrative cases are considered in which the atrium extension above the top storey and heat input within the atrium are varied.

	Case A Short, unheated atrium: $R_H = 1, R_W = 1$	**Case B** Short, strongly heated atrium: $R_H = 1, R_W = 4$	**Case C** Tall, unheated atrium $R_H = 4, R_W = 1$
	Effective vent sizes (m²)		
Atrium	$1.92 < a_a < 2.71$	$0.96 < a_a < 1.36$	$0.96 < a_a < 1.36$
Storey 4	$0.48 < a_4 < 0.68$	$0.48 < a_4 < 0.68$	$0.48 < a_4 < 0.68$
Storey 3	$0.34 < a_3 < 0.48$	$0.21 < a_3 < 0.30$	$0.34 < a_3 < 0.48$
Storey 2	$0.28 < a_2 < 0.39$	$0.16 < a_2 < 0.23$	$0.28 < a_2 < 0.39$
Storey 1	$0.24 < a_1 < 0.34$	$0.13 < a_1 < 0.19$	$0.24 < a_1 < 0.34$

Table 2: Example effective vent area calculations for a building with H = 3m, 30 people on each storey and a top-storey atrium enhancement of $E_N = 1$. The ranges of values are based on the design requirements from Table 1.

The key result from this example calculation is that, in order to maintain equal per-person ventilation rates and temperatures on all storeys, vent sizes must increase on ascending the building. This compensates for the corresponding decrease in driving stack pressure supplied by the atrium on ascending the building, an effect which is amplified by heating the atrium.

This result agrees well with studies on this type of building. **[33]**, for example determined similar sizing rules. Numerous experimental and numerical studies have also shown that, if equal vent sizes are used on all storeys, flow rates decrease on ascending the building with the potential for overheating on upper storeys, or overcooling on lower storeys **[30,34,35]**.

Summary of preliminary design method

The steps for sizing ventilation openings to give equal flow rate per-person and temperatures on all storeys are listed below. Each step requires the designer to specify or estimate design criteria.

Note that the third step – converting effective vent areas to physical vent areas – has not explicitly been discussed herein. Should the reader wish to calculate physical vent areas, we suggest using $A_{in,i} = A_{out,i}$ for a balanced design, and taking $c_d = 0.6$, which is the commonly accepted value of the discharge coefficient for flows through 'sharp-sided' vents **[8,36]** – although this may vary with choice of ventilation opening.

1. **Determine design range of VPI, λ_p**
    1. Specify minimum acceptable ventilation flow rate per person, Q_p
    2. Specify desired temperature excess range, ΔT_p
    3. Estimate expected range of per-person heat gains, W_p
    4. Use chart in Figure 3 to determine required range of λ_p
2. **Calculate required effective vent areas**
    1. Specify desired atrium enhancement on top storey, E_N
    2. Specify occupancy levels within the building, n_i
    3. Estimate expected heat gains within the atrium
    4. Use equations in (9) to calculate required effective vent areas, a_i and a_a
3. **Calculate required physical vent areas**
    1. Estimate vent discharge coefficients, c_d
    2. Specify relative sizes of storey floor- and ceiling-level vents
    3. Use equations in (2) to calculate physical vent areas, $A_{in,i}$, $A_{out,i}$ and A_a

CONCLUSIONS

We have developed a preliminary design method for passive stack ventilation in multi-storey atrium buildings. Two dimensionless parameters – λ_p and E – have been identified and used to quantify the balance of core design variables, and the effectiveness of the atrium in enhancing ventilation flows. A design chart is presented which allows for selection of a range of values of λ_p based on the required flexibility of the ventilation scheme. Simple expressions for sizing ventilation openings based on λ_p, E and the number of people within the building are presented.

This method is intended to be as simple as possible so as to provide quick and intuitive first order guidance. It is intended to allow designers to rapidly determine preliminary requirements for a stack ventilation scheme and evaluate its potential effectiveness. We have tried to highlight some of the key limitations of the model, or suggest how it might be adapted to include more detail.

A key result is that vent sizes must increase on ascending the building, to compensate for the corresponding decrease in stack pressure available to drive flows through the upper storeys. This result agrees well with existing studies of multi-storey atrium buildings. An experimental campaign to explicitly validate the method presented herein is planned for late 2013.

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