When Does An Atrium Enhance Natural Ventilation ?

Joanne M. Holford & Gary R. Hunt ‡

Department of Applied Mathematics and Theoretical Physics,

Silver Street, University of Cambridge, CB3 9EW, UK

Synopsis

This paper investigates passive displacement flows in a simple, two-compartment building that comprises a single storey connected to an atrium. Heat gains in the storey and solar gains in the atrium create a stack pressure which drives a ventilating flow. A model is developed to determine the steady flow rate and thermal stratification for a range of heat gains, storey and atrium heights, and ventilation opening areas. We show that the accumulation of warm air in the atrium serves to enhance the flow rate through the storey only if the upper atrium opening is not too small, and the lower atrium opening is not too large.

List of Symbols

a	opening area (m^2)
A	'effective' opening area (m^2)
B	buoyancy (heat) flux (m^4s^{-3})
c_d	discharge coefficient of an opening
g	acceleration due to gravity (ms^{-2})
g'	reduced gravity (ms^{-2})
h	interface height (m)
H	room height (m)
M	atrium height (m)
p	pressure ($kgm^{-1}s^{-2}$)
Q	ventilation flow rate (m^3s^{-1})
T	temperature (°K)
Δ	difference in
ρ	density (kgm^{-3})

Subscripts

atrium	in atrium
interior	between storey and atrium
isolate	in isolated storey (*i.e.* without atrium)
lower, upper	lower and upper atrium opening
room	in storey
solar	solar heat flux in atrium
total	along a complete flowpath
0	a reference value

Superscripts

*	dimensional quantity

1. Introduction

Buildings based around an atrium are an increasingly popular design for larger commercial and business uses. The tall, open space of the atrium allows natural light to penetrate to lower levels, even in a building with a large floor area. Atria are often used as communal spaces for the building, housing central facilities such as restaurants, as well as the links between floors.

‡ present address: Department of Civil & Environmental Engineering, Imperial College of Science, Technology and Medicine, LONDON, SW7 2BU, UK.

One of the oldest designs to improve the passive ventilation of a building is the chimney. When filled with warm air, the pressure drop across the height of the chimney is less than the pressure drop across the same height in the ambient air, giving a stack pressure that causes air to rise up the chimney. Over a fireplace, for example, a chimney ensures that combustion gases are drawn out of the room, and that a supply of fresh air is fed to the fire.

Solar chimneys are used to enhance natural ventilation in some modern buildings, for example in the BRE's Environmental Building (Riain *et al.* [1]). Solar chimneys tend to be tall, narrow, glazed structures designed to be heated both by the sun and by collecting heat from sources within the building. As in a classical chimney, the stack pressure created by the tall column of warm air in the solar chimney draws ambient air through the building. Essentially, the solar chimney increases the stack height of the connected space.

In many atrium buildings, the atrium itself is designed to serve as a solar chimney, and the upper portions are often glazed which enhances solar heat gains. In general, this is a successful strategy, as the atrium is linked directly to many of the building's occupied spaces, thereby assisting the ventilation. Warm, stale air can be drawn out of these spaces into the atrium, and exhausted through the atrium roof opening. There are drawbacks, such as the need to insulate or shade occupied parts of the building from the top portion of the atrium, which may become very hot. The main difference between an atrium and a solar chimney is that the occupied portion of the atrium must itself be supplied with a ventilating flow of fresh air. The simplest and most effective solution is to provide ventilation inlets for ambient air at low level in the atrium. In practice, doors may provide these inlets.

In this paper we investigate the enhancement of natural ventilation through a building that is provided by an atrium (either with or without direct solar heating). In order to understand the basic principles, we consider the simplest case of a single storey, with floor-level and ceiling-level openings, in which the ceiling-level openings lead into a taller atrium, vented at the roof. If the atrium is closed at the base we term the atrium 'unventilated'. Alternatively, if the atrium connects directly to the exterior via floor-level openings, we term the atrium 'ventilated'. Determining the flow through a storey with a ventilated atrium is significantly more complicated than for a single storey or a storey with an unventilated atrium, because there are now two different possible flowpaths, or routes for air, through the building.

In §2, we outline a theoretical model of the steady ventilation flow and thermal stratification that is produced, following the approach used by Linden, Lane-Serff & Smeed[2] for a single room. In §3, we discuss the range of typical flow patterns that can occur for various values of the parameters governing the flow. Pictorial representations are used to emphasise the differences that can occur. A sample regime diagram for a storey of a given height and effective opening area is given in §4, and the controlling parameters are discussed. Conclusions are drawn in §5.

2. Theoretical Development

Ventilation flows in buildings are driven by differences in pressure between one part and another. Pressure differences are greatest across openings such as windows and vents. The volume flow rate Q^* through an opening of area a^* is proportional to the square root of the pressure drop Δp^* across it, and is given by

$$Q^* = c_d a^* \sqrt{\frac{2\Delta p^*}{\rho_0^*}} = A^* \sqrt{\frac{\Delta p^*}{\rho_0^*}}\,, \tag{1}$$

where ρ_0^* is the fluid density and c_d is the discharge coefficient of the opening. For sharp-edged openings at moderate and high Reynolds numbers, $c_d \approx 0.6$ in the absence of strong density contrasts (Hunt & Holford[3]). In (1) the discharge coefficient has been combined with the actual opening area to give the effective opening area $A^* = 2^{1/2} c_d\, a^*$. Away from openings, the air in a building is relatively stagnant and the fluid pressure is, to a good approximation, equal to the hydrostatic pressure field due to the temperature stratification.

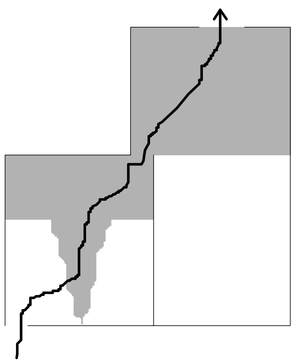
If air is forced through n openings in *parallel*, then the effective opening areas sum directly, giving a total effective area :

$$A^*_{total} = A_1^* + A_2^* + \ldots + A_n^* = \sum_{i=1}^{n} A_i^*\,. \tag{2}$$

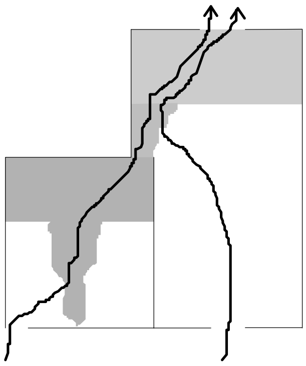
Alternatively, if air is forced through n openings in *series*, then the effective opening areas sum as inverse squares :

$$\frac{1}{{A^*_{total}}^2} = \frac{1}{A_1^{*2}} + \frac{1}{A_2^{*2}} + \ldots\ldots\ldots + \frac{1}{A_n^{*2}} = \sum_{i=1}^{n} \frac{1}{A_i^{*2}}\,. \tag{3}$$

This formula is only valid if the volume flow rate through each opening in the series is the same. If air can flow along several different routes, dividing and merging, then the total effective area cannot be calculated in this simple way. The unventilated atrium building studied here has only one flowpath, or route for air, see figure 1(a). Adding a further opening to ventilate the atrium introduces a second flowpath, see figure 1(b).



(a)



(b)

Figure 1. A schematic of the flow in a single-storey building connected to a taller atrium. If the atrium is 'unventilated' (a) there is only one flowpath. If the atrium is 'ventilated' (b) two flowpaths merge in the atrium.

For ease of modelling, and for comparison with laboratory salt-bath experiments, heat gains in the single storey of height H^* are modelled as a point source of heat at floor level generating a buoyancy flux B^*. The floor and ceiling-level openings in the storey have a combined effective opening area A^*_{room} , summed as in (3). Heating leads to a displacement ventilation flow in which a warm layer of air overlies a layer of ambient air, separated by an interface at height h^*_{room}. The temperature difference ΔT^*_{room} between the layers is expressed in terms of a reduced gravity g'^*_{room}, given by

$$g'^{*}_{room} = g^{*} \frac{\Delta T^{*}_{room}}{T_0^{*}}, \tag{4}$$

where g^* is the acceleration due to gravity and T_0^* is the temperature of the ambient air.

The opening in the ceiling of the storey connects to an atrium of height M^*, which has a floor-level opening of effective area A^*_{lower} and a ceiling-level opening of effective area A^*_{upper}. In an unventilated atrium $A^*_{lower} = 0$, and in a ventilated atrium $A^*_{lower} \neq 0$. Warm air from the storey rises into the atrium and exits through the opening in the atrium ceiling. In the atrium, a warm layer of reduced gravity g'^*_{atrium} builds up above a layer of ambient air, separated by an interface at a height $H^*+h^*_{atrium}$ above the floor. The atrium receives direct solar heating, corresponding to a buoyancy flux B^*_{solar}, which is assumed to be distributed evenly across the upper, warm layer. The variables can be non-dimensionalised using only H^*, B^* and ρ_0^*, giving non-dimensional (unstarred) variables

$$h = \frac{h^*}{H^*}, \quad Q = \frac{Q^*}{B^{*1/3} H^{*5/3}}, \quad g' = \frac{g'^*}{B^{*2/3} H^{*-5/3}} \quad \text{and} \quad p = \frac{p^*}{\rho_0{}^* B^{*2/3} H^{*-2/3}}. \tag{5}$$

The governing parameters are now the non-dimensional effective areas of the openings, the non-dimensional atrium height $M = M^*/H^*$ and the ratio of buoyancy fluxes $B_{solar} = B^*_{solar}/B^*$.

It is assumed that away from the ventilation openings the pressure is hydrostatic, and that the flow through openings is governed by (1). Following Hunt & Holford[4], we derive two linked equations for the steady volume flow rates, Q_{room} through the storey, Q_{lower} through the lower atrium opening and Q_{upper} through the upper atrium opening. Along the flowpath through the storey,

$$Q_{room}^2 \left(\frac{H^{*2}}{A^*_{room}} \right)^2 + Q_{upper}^2 \left(\frac{H^{*2}}{A^*_{upper}} \right)^2 = g'_{room}(1 - h_{room}) + g'_{atrium}(M - 1 - \max(h_{atrium}, 0)), \tag{6}$$

and along the flowpath through the lower atrium opening,

$$Q_{lower}^2 \left(\frac{H^{*2}}{A^*_{lower}} \right)^2 + Q_{upper}^2 \left(\frac{H^{*2}}{A^*_{upper}} \right)^2 = g'_{atrium}(M - 1 - h_{atrium}). \tag{7}$$

Conservation of volume flux shows that the flow rates drawn in through the storey and lower atrium opening must sum to the flow rate discharged through the upper atrium opening, *i.e.*

$$Q_{upper} = Q_{room} + Q_{lower}. \tag{8}$$

In addition, conservation of heat for an insulating building requires that the sum of the heat supplied in the storey and in the atrium is equal to the heat removed by the ventilation flow. Hence, in the storey,

$$1 = Q_{room} g'_{room}, \tag{9}$$

and in the atrium,

$$1 + B_{solar} = Q_{upper} g'_{atrium}. \tag{10}$$

Finally, the dynamics of the plume of rising warm air in the storey links the flow rate and interface position,

$$Q_{room} = Q_{room}(h_{room}), \tag{11}$$

where Q_{room} is an increasing function of h_{room}. The flow rate of warm air rising in the atrium depends on the (relatively large) area of the opening $a_{interior}$ and the volume flux through the opening Q_{room}, as well as the height of rise h_{atrium} :

$$Q_{upper} = Q_{upper}(Q_{room}, a_{interior}, h_{atrium}), \tag{12}$$

and again Q_{upper} is an increasing function of h_{atrium}. The exact form of (11) and (12) is given by the theory of turbulent plumes (see Morton, Taylor & Turner[5]), with extension to plumes from finite volumes sources (see Hunt & Kaye[6]).

Equations (6) to (12) govern the steady flow patterns that develop in this building, under the assumptions of an insulating building fabric and idealised heat inputs. The equations can be solved numerically to predict the flow rates and thermal stratification for any building geometry, opening areas and imposed buoyancy fluxes. In a number of simpler limits, analytical results can be derived. Results from the model agree well with the results of laboratory-scale salt-bath experiments.

A useful diagnostic for understanding the flow pattern is the pressure p_{atrium} at the base of the atrium. In terms of the pressure p_0 at floor level outside the building, this is given by

$$p_{atrium} = p_0 + \frac{(1-h_{room})}{Q_{room}} - Q_{room}^2 \left(\frac{H^{*2}}{A^*_{room}} \right)^2, \tag{13}$$

for an unventilated atrium, and for a ventilated atrium

$$p_{atrium} = p_0 - Q_{lower}^2 \left(\frac{H^{*2}}{A^*_{lower}} \right)^2. \tag{14}$$

3. Results

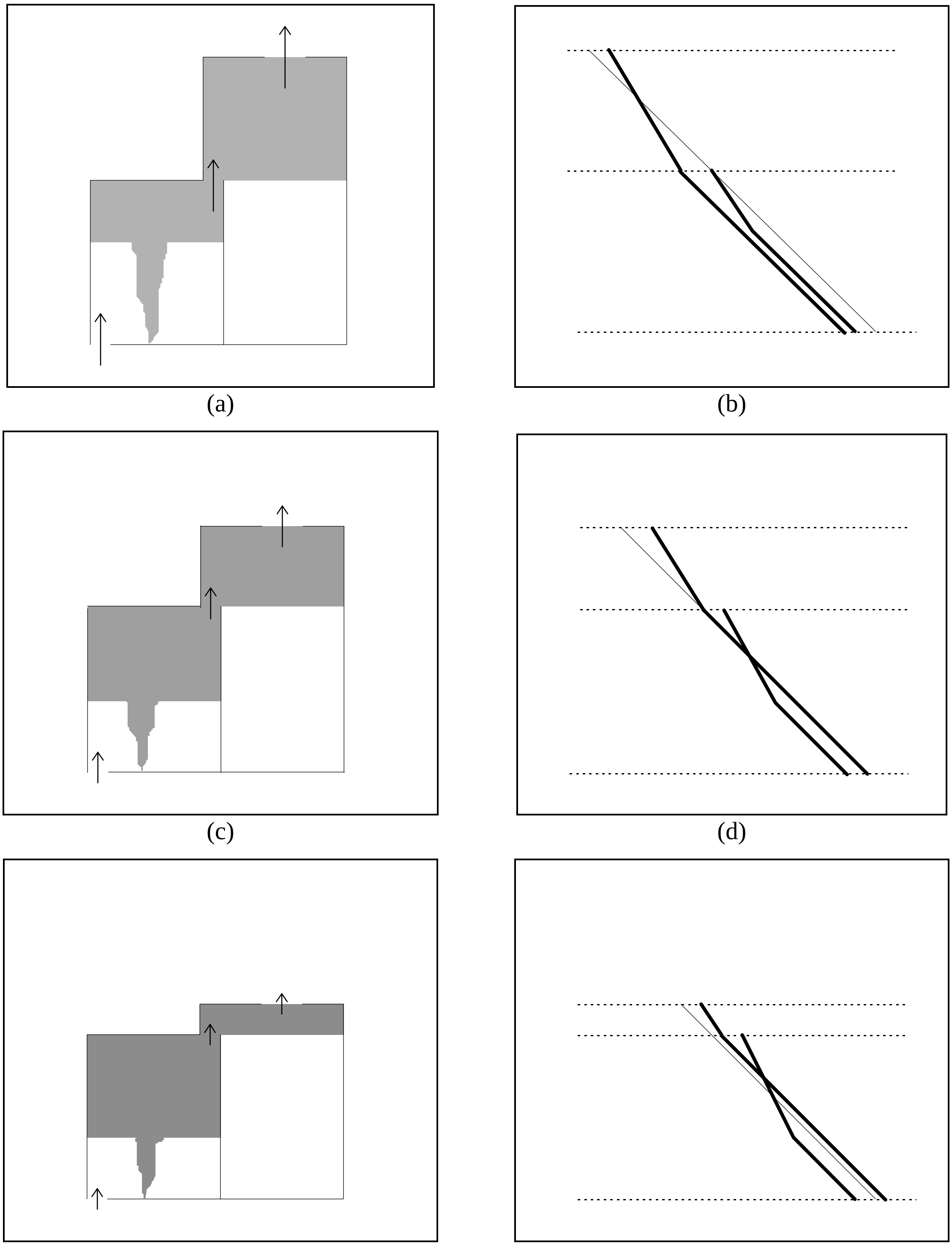
We consider the effect of adding an atrium to a single storey of fixed geometry and heat load. Through the storey alone, we would expect a displacement flow with flow rate $Q_{isolate}$ and a two-layer stratification with an interface at $h_{isolate}$. The simplest extension is the addition of an atrium which receives no solar heating and has no opening at its base, *i.e.* the atrium is unventilated. Heat released in the storey collects in the atrium which fills with warm air down to the level of the opening connecting the atrium and storey. In this situation, analysis shows that the flow rate through the building is the same as that in a single space of height M^*, heated by a point source of strength B^*, and with total effective opening area A^*_{total}, where

$$\frac{1}{{A^*_{total}}^2} = \frac{1}{{A^*_{room}}^2} + \frac{1}{{A^*_{upper}}^2}. \tag{15}$$

The warm air in the upper parts of the storey and the atrium is at the same temperature. However large the upper atrium opening, (15) shows that the total effective area will always be no larger than the effective area of the original storey. We also see from (15) that if the upper atrium opening is significantly smaller than that of the storey, then the total effective area can be much reduced. In fact, the total effective area can be reduced sufficiently that the ventilation through the combined space is *worse* than through the storey alone, even when the atrium height is greater than the storey height. The flow rate through the building is only greater than the flow rate through the isolated storey if

$$A^*_{upper}\sqrt{M-1} \;>\; A^*_{room}\sqrt{1-h_{isolate}}. \tag{16a}$$

It is unlikely that a single-storey atrium building such as the one modelled here would be designed with too small an upper opening. However, when this theory is generalised to an n-storey building, an atrium outlet area of only A^*_{upper}/n (approximately) carries the flow from each storey and, hence, constriction at this outlet is more likely to occur in practice.



(a) (b) (c) (d) (e) (f)

Figure 2. Pictorial representation of the effect of changing the height M^* of the atrium connected to the single storey. Left column - thermal stratification; darker colours represent higher temperatures, arrow length represents flow rate. Right column - pressure vs. height plots; fine lines represent ambient pressure and solid lines represent pressure inside the building. (a) and (b) show an atrium that is tall enough to enhance the flow rate through the storey. (c) and (d) show an atrium of the critical height to give the same flow as through an isolated storey. (e) and (f) show an atrium that is short enough to reduce the flow rate through the storey.

Increasing the atrium height M increases the flow rate through the building, and cools the warm air, as shown in figure 2. For large enough M (figures 2(a) and (b)), the pressure below the atrium interface is below atmospheric pressure, drawing a larger flow rate through the storey than $Q_{isolate}$. At some critical M, given by equality in (16), the flow rate becomes equal to $Q_{isolate}$ (figures 2(c) and (d)). The pressure in the atrium below the interface is then equal to atmospheric pressure. For smaller values of M (figures 2(e) and (f)), the flow rate is reduced below $Q_{isolate}$, and the pressure below the atrium interface is above atmospheric pressure.

The effect of an unventilated atrium of height M^*, with direct solar heat gains B^*_{solar} , on the flow through the connecting storey can be shown to be equivalent to the effect of an unventilated atrium of greater height $M^*_{eff} = M^* + B_{solar}(M^* - H^*)$. Hence, as the heating of the atrium increases, the flow rate through the room increases and the temperature of the warm layer in the room decreases. However, the local heating in the atrium ensures that the atrium temperature increases as B^*_{solar} increases. The counterpart of (16a), giving the range of atrium geometries for which flow through the storey is enhanced, is now modified to

$$A^*_{upper}\sqrt{M_{eff} - 1} \;>\; A^*_{room}\sqrt{1 - h_{isolate}}\,. \tag{16b}$$

In summary, the taller and hotter the atrium, the greater the increase in the flow rate and reduction in temperature in the storey. These benefits justify the use of atria as solar chimneys to enhance the flow through connected parts of the building. However, without any low-level openings in the atrium, the air there is not replenished. In order to avoid this situation, the atrium can be ventilated, as in figure 1(b).

The complexity of the flow with a ventilated atrium, in general, requires a numerical solution of (6) to (12). There is no simple correspondence of the flow rates with flow rates in a equivalent single space, as there is for an unventilated atrium.

The effect of ventilating an atrium is most easily understood by considering the transient flows that occur if a vent is opened at the base of an unventilated atrium. If (16) is satisfied, so that the unventilated atrium enhances the flow through the storey, then a flow pattern such as depicted in figures 3(a) and (b) is attained, and the pressure in the lower regions of the atrium is below atmospheric pressure. If a vent in the atrium floor is opened, as in figures 3(c) and (d), ambient air is sucked in and the interface in the atrium rises. The interface rises until the flow rate Q_{lower} in at the atrium base is equal to the flow rate entrained into the rising plume of warm air in the atrium. The warm air in the atrium is cooler than in (a) and (b) due to the entrainment of ambient air. However, the pressure difference between the atrium and the ambient has been reduced, and so the enhancement of the flow through the storey is not as great. Therefore, in the storey the flow rate is smaller, the interface is lower and the upper layer is warmer.

As the lower atrium opening becomes larger, these changes are exacerbated, until with a very large opening the situation in figures 3(e) and (f) is attained. The interface has risen high in the atrium, and there is now little difference between the pressure in the lower atrium and ambient pressure. Hence, the flow rate through and stratification within the storey are little different from those in an isolated storey, and the atrium gives no ventilation enhancement. Therefore, if (16) is satisfied, the flow rate through the storey is bounded below by the flow rate through the isolated storey, and above by the flow rate with an unventilated atrium.

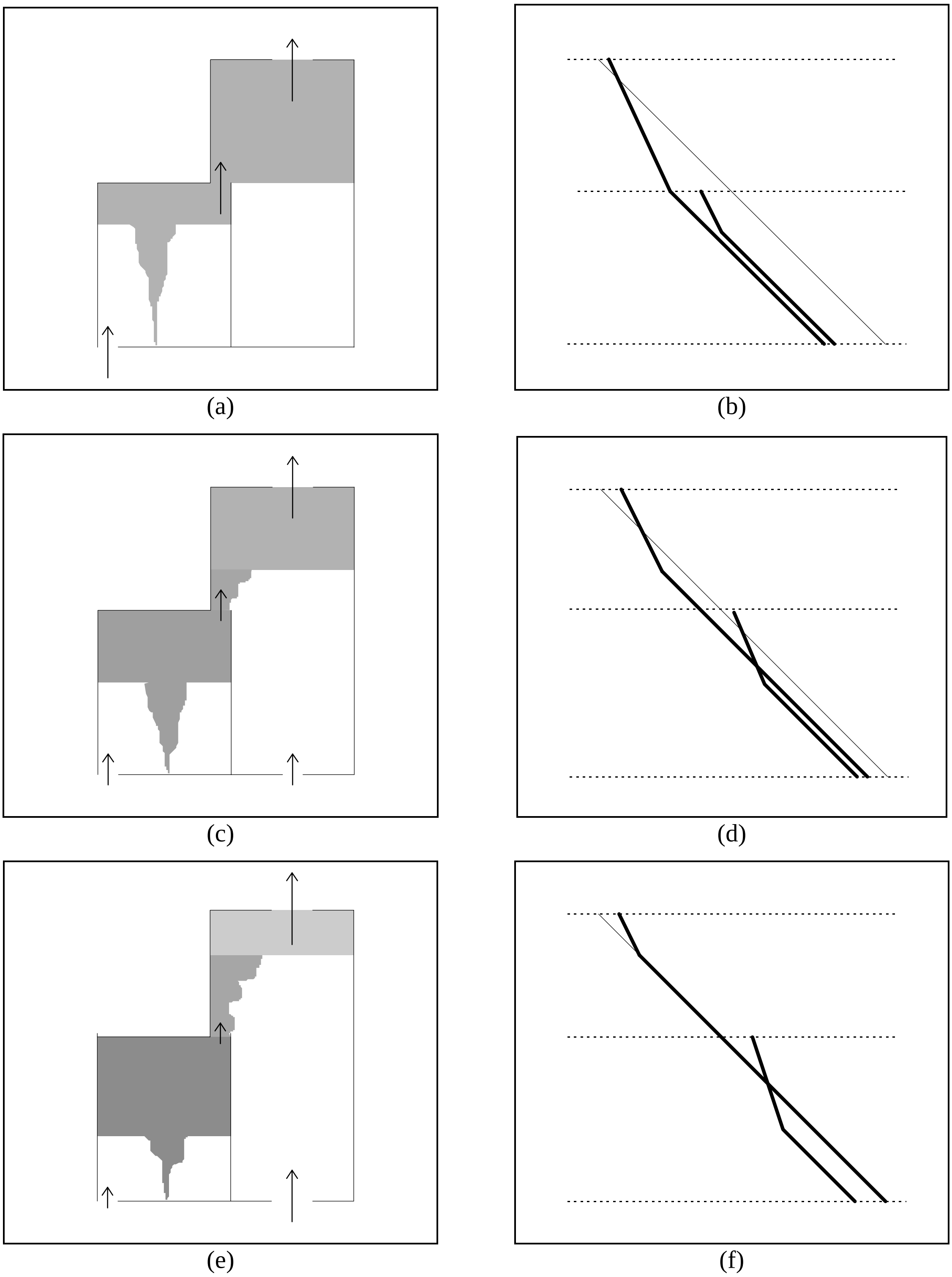


Figure 3. Pictorial representation of the effect of opening a vent at the base of an atrium which enhances the flow through the connecting storey. Left column - thermal stratification; darker colours represent higher temperatures, arrow length represents flow rate. Right column - pressure vs. height plots; fine lines represent ambient pressure and solid lines represent pressure in the building. (a) and (b) show an unventilated atrium, (c) and (d) a ventilated atrium with a moderate lower opening area, and (e) and (f) a ventilated atrium with a large lower opening area.

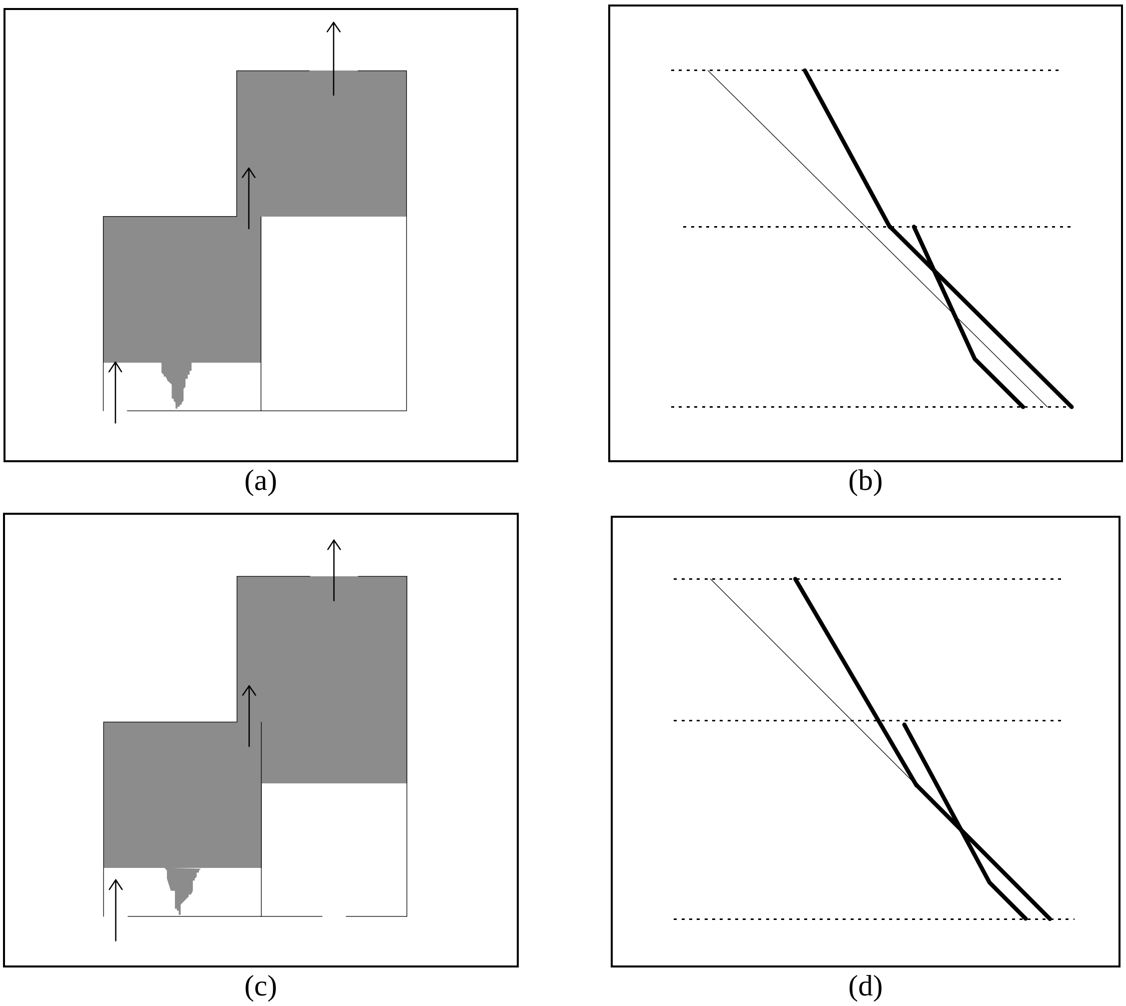


Figure 4. Pictorial representation of the effect of opening a vent at the base of an atrium which constricts the flow through the connecting storey. Left column - thermal stratification; darker colours represent higher temperatures, arrow length represents flow rate. Right column - pressure vs. height plots; fine lines represent ambient pressure and solid lines represent pressure in the building. (a) and (b) show an unventilated atrium, and (c) and (d) a ventilated atrium.

A very different flow pattern develops if (16) is not satisfied, so that the unventilated atrium restricts the flow through the storey. Then a flow pattern such as that depicted in figures 4(a) and (b) is attained; the pressure in the lower regions of the atrium is above atmospheric pressure. If a vent in the atrium floor is opened, as in figures 4(c) and (d), air is expelled through the atrium floor and the interface in the atrium falls. The interface falls until the pressure in the atrium base is equal to atmospheric pressure, when there is no further flow through this lower opening and the lower part of the atrium becomes stagnant again. The temperature and flow rate through the storey do not alter from their values with an unventilated atrium. Therefore, if (16) is not satisfied, so that the atrium restricts the flow through the storey, the flow rate is always equal to that with an unventilated atrium.

4. Regime Diagrams

In the previous section the results of connecting an atrium to a single-storey building were discussed, concentrating on changes to the ventilation flow rate through the storey. However, the main reason for ventilating an atrium is to provide a flow of fresh air through the occupied space of the atrium, even at a cost of some reduction to the flow rate through the storey. In most situations, the best design solution will be a compromise which provides adequate ventilation in both the storey and the atrium. In order to illustrate this compromise, and to clarify the regimes of flow introduced in §3, the consequences of varying the non-dimensional atrium opening areas A^*_{upper}/H^{*2} and A^*_{lower}/H^{*2} are considered. All other parameters, namely, the atrium height M, solar buoyancy flux B_{solar} and room opening area A^*_{room}/H^{*2}, are fixed.

Figure 5 shows contours of constant flow rate through (a) the storey and (b) the lower atrium opening, as the opening areas of the atrium are varied. For the parameters chosen, the critical value of the upper atrium opening area is about $A^*_{upper}/H^{*2} = 0.014$. If the upper opening is smaller than this value, then the flow through the building is restricted. There is no flow into the lower atrium, and the flow into the storey is reduced below the value for the isolated storey. If the upper opening is much larger than this value, then the flow rates are not sensitive to the exact size of that opening. If the lower atrium opening area decreases to zero, the flow rate into the lower atrium reduces to zero, and the flow rate through the room rises to the value for the unventilated atrium. If the lower atrium opening area becomes large, the flow rate into the lower atrium rises to an asymptotic value, and the flow rate through the room reduces to the value for the isolated storey.

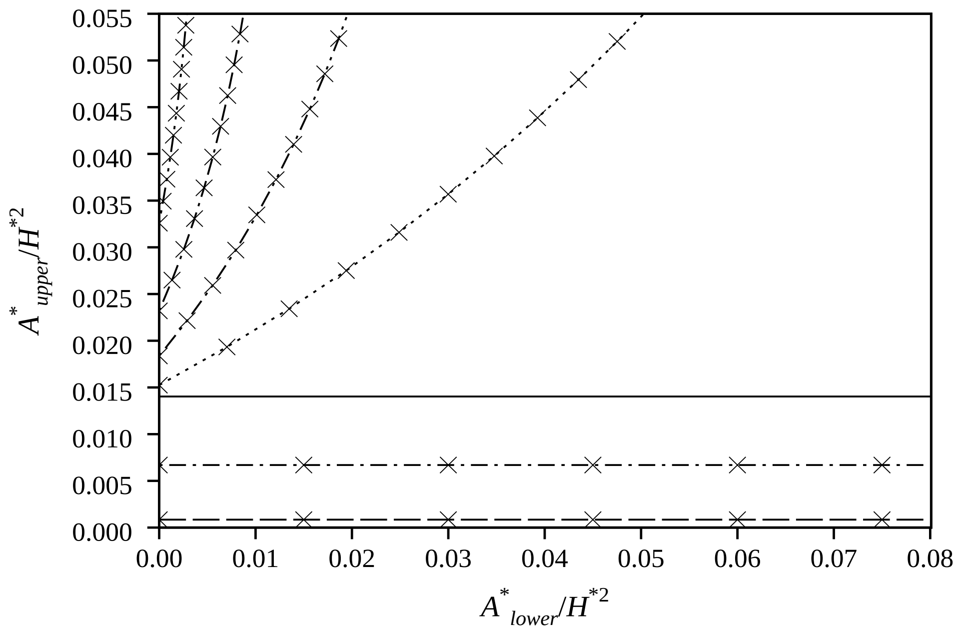
For high flow rates in the lower atrium, large upper and lower atrium openings are required. For high flow rates in the storey, a large upper atrium opening and a small lower atrium opening is required. In practice, the upper atrium opening size will be limited by weatherproofing requirements, and will support exchange flows not modelled by this theory if it is too large. Figure 5(a) emphasises that, for an atrium to enhance the ventilation flow through a connected storey significantly, the upper atrium opening should be relatively large and the lower atrium opening relatively small.

5. Conclusions

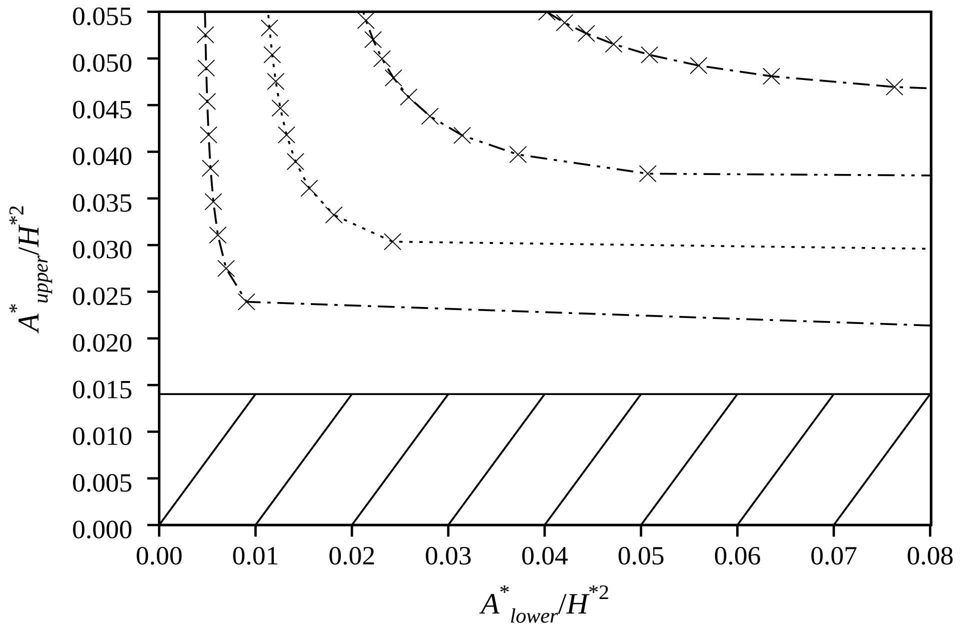
The glazed atrium is a feature central to the design of many modern multi-storey naturally-ventilated buildings. An atrium creates a sense of space, brings natural light down to the surrounding floors, and can provide a communal zone. The large glazed area attracts high solar heat gains which, because of the height of the space, create a deep warm layer of air at the top of the atrium. If this layer extends down to occupied levels it can cause overheating. On the positive side, it has long been understood that the stack pressure due to the warm layer can enhance the ventilation through connected parts of the building.

A theoretical model for steady flow has been developed in which heat inputs are balanced by the removal of heat by the ventilation flow. The model provides estimates of the air exchange rate and thermal stratification in the building. The predictions compare well with the results of small-scale experiments, in which salt and fresh water solutions are used to generate passive stack-driven flows.

We have presented results of the model for the simplest situation: an atrium connected to a high-level outlet of a single-storey space, which, in turn, is connected to the exterior by a low-level inlet. An additional inlet from the exterior to the atrium base provides a fresh air supply (and access) to the atrium itself. If this lower atrium opening is closed, we term the atrium



(a)



(b)

Figure 5. Contour plots of flow rate through (a) the storey, and (b) the lower atrium opening, as functions of the opening areas of the atrium. In (b), the hatched area is a region of no flow through the lower atrium opening. The fixed parameters are $A^*_{room}/H^{*2} = 0.014$, $M = 1.5$ and $B_{solar} = 0$. Contour values are (a) Q_{room} = 0.010, 0.034, 0.046, 0.047, 0.050, 0.052, 0.054 and (b) Q_{lower} = 0.011, 0.023, 0.034, 0.046.

'unventilated', and if the opening is open, we term the atrium 'ventilated'. In terms of the ventilating flow, a space with a ventilated atrium is significantly more complicated than a single space or a space with an unventilated atrium, because there are now two different possible flowpaths, or routes for air, through the building.

The model outlines the effect on the ventilation flow of changing the atrium height and the solar gains the atrium receives. The model shows that the addition of even a *heated* atrium may reduce the flow through the storey, if the upper opening of the atrium is too small.

The greatest enhancement to the flow through the storey occurs if the atrium is unventilated, when all the stack pressure in the atrium pulls air through the storey. Direct ventilation of the atrium causes the atrium stack pressure to be shared between the storey and the lower atrium opening. This reduces the enhancement of flow through the storey, while supplying the atrium with a ventilating flow, and thereby cooling the atrium. If the opening in the base of the atrium is very large, the atrium stack pressure pulls a large flow into the atrium, but there is no enhancement of flow through the storey.

In summary, an atrium enhances the natural ventilation through the connected storey providing that the upper atrium opening is large enough, and that the lower atrium opening is small enough. The introduction of ventilation requirements for the atrium itself causes the ideal design to be a compromise that gives acceptable conditions in both spaces.

Acknowledgements

JMH and GRH would like to thank Professor Paul Linden for many helpful discussions, and the technical staff at the Fluid Dynamics Laboratory at DAMTP for the construction of the laboratory model. JMH was supported by the Leverhulme Trust and GRH by the EPSRC.

References

1. RIAIN,C.N., KOLOKOTRONI,M., DAVIES,M., FISHER,J., WHITE,M. and LITTLER,J. "Cooling effectiveness of south facade passive stacks in a naturally ventilated office building - Case study". 1999, Indoor Built Environment, 8: (5) 309-321, Sep-Oct.

2. LINDEN, P.F., LANE-SERFF, G.F. and SMEED, D.A.
"Emptying filling boxes: the fluid mechanics of natural ventilation"
1990, *J. Fluid Mech*., **212**, 300-335.

3. HUNT, G.R. and HOLFORD, J.M.
"The discharge coefficient - experimental measurement of a dependence on density contrast"
2000, *Proc. 21st AIVC Conference on Innovations in Ventilation Technology*, The Hague. NL.

4. HUNT, G.R. and HOLFORD, J.M.
"Top-down ventilation of multi-storey buildings"
1998, *Proc. 19th AIVC Conference on Ventilation in Urban Areas*, Oslo, Norway, 197-205.

5. MORTON, B.R., TAYLOR, G.I. and TURNER, J.S.
"Turbulent gravitational convection from maintained and instantaneous sources"
1956, *Proc. Roy. Soc. A*, 234, 1-23.

6. HUNT, G.R. and KAYE, N.G.
"Virtual origin correction for lazy turbulent plumes"
2000. Submitted for publication *J. Fluid Mech*.