zeer interessant voor displacement ventilation!

basisonderzoek
nieuwe modellen voor airflows..
↓ daaruit
guidelines
rules of thumb

VENTILATION AND COOLING

18TH ANNUAL AIVC CONFERENCE
ATHENS, GREECE, 23-26 SEPTEMBER, 1997

(zeer interess!)

NEW SIMPLE STRATIFICATION MODELS

(Title) Passive cooling by natural ventilation: Salt bath modelling of combined wind and buoyancy forces

opstelling in Labo om model te chequen

(Authors) G.R. Hunt & P.F. Linden

Salt = warmte die komt v/e warmtebron.

(Affiliation) Department of Applied Mathematics and Theoretical Physics
The University of Cambridge
Silver Street
Cambridge
CB3 9EW

Waarom water
— omdat in groot gebouw
α wrijving diffusie v. lucht
klein zy
→ voor water ook op die kleine schaal

wat 's nachts → geen uit gaing
(of toch (voor) die afkoelt)

Passive cooling by natural ventilation: Salt bath modelling of combined wind and buoyancy forces

G. R. Hunt and P. F. Linden
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge, CB3 9EW, U.K.
Tel: +44 1223 337840. Fax: +44 1223 337918. E-mail: g.r.hunt@damtp.cam.ac.uk.

Synopsis

We examine conditions under which the natural forces of wind and buoyancy may be harnessed in order to provide ventilation for cooling. Steady-state, displacement flows driven by combined buoyancy and wind forces are simulated at small scale in the laboratory using a Perspex box to represent a generic room or single-spaced building. Density differences necessary to simulate the stack effect are produced using fresh and salt water solutions. Wind flow is simulated by placing the box in a flume tank; the flume produces a flow of water past the box and this flow is used to represent the wind. By measuring salinity and the position of the stratification within the box, equivalent temperature profiles and ventilation flow rates in naturally ventilated buildings are deduced.

Results of these experiments are compared with the predictions of a theoretical model. It is shown that if ventilation openings are located so the wind assists the stack-driven flow the ventilation may be significantly enhanced and passive cooling achieved. The cooling capacity of the ventilation system is shown to depend upon the relative magnitudes of the wind and buoyancy produced velocities, the area of the openings and the height of the space. It is shown that by harnessing the wind to assist the buoyancy-driven flow it is possible to i) reduce the temperature of the warm upper layer, ii) increase the depth of the lower layer at ambient temperature and iii) increase the ventilation flow rate.

List of symbols

A^*	effective area of openings (m^2)
ACH	number of air changes per hour
a_t , a_b	areas of upper and lower vents (m^2)
B	strength of source (m^{4}s^{-3})
C_e	coefficient of expansion
C_d	coefficient of discharge
C_{pi}	pressure coefficient at inlet
C_{po}	pressure coefficient at outlet
C	plume entrainment constant
c_p	specific heat capacity (J kg^{-1}C^{-1})
d_c	distance between midpoint of upper opening and ceiling (m)
E	power of source (W)
Fr	Froude number
g	acceleration due to gravity (ms^{-2})
H	height of the enclosure (m)
h	height of interface above floor (m)
Q	total ventilation flow rate (m^{3}s^{-1})
T_a	temperature of ambient layer (°C)
T_u	temperature of warm layer (°C)
U_{wind}	mean wind speed (ms^{-1})
V	volume of enclosure (m^3)
β	coefficient thermal expansion (°C^{-1})
Δ	wind pressure drop (kg m^{-1}s^{-2})
$\Delta\rho$	density step across interface (kg m^{-3})
ΔT	temperature step across interface $= T_u - T_a$ (°C)
ρ	density of ambient fluid (kg m^{-3})

1. Introduction

The cooling capacity of a ventilation system is determined by the rate of air exchange through a space and the air flow patterns within it. By supplying cool ambient air, either at low levels, in order to displace the warm air through high-level openings, or at high levels so as to mix with and temper the internal air, 'passive' cooling may be achieved. In displacement ventilation warm air is collected in an upper zone and cooling is achieved by flushing the lower zone with ambient air. The rate of flushing is determined by the area of the openings, the temperature and depth of the upper zone, and the driving produced by the wind.

If the system is designed to take advantage of the prevailing driving forces then energy may be saved as the periods in which mechanical cooling is needed may be reduced.

For stack-driven flows to be effective, the upper zone must be maintained at a depth and temperature sufficient to drive a ventilating flow at the required rate. The ventilation rate may be enhanced by increasing the depth and temperature of the upper layer, however, careful design is needed to ensure that occupants are not exposed to the high air temperatures and pollutant levels carried in this layer. If the area of the openings is too small or if their location is not carefully chosen the upper layer can descend to the occupied levels of the building which can have a dramatic effect on indoor air quality. The size and location of the ventilation openings and their effect on the depth and temperature of the upper zone must therefore be considered at the design stage of a naturally ventilated building to ensure the required ventilation will be provided. This task is further complicated as, over the majority of the year, the additional driving produced by the wind must also be taken into account.

In order to develop an understanding of temperature distribution and air movement within naturally ventilated enclosures a laboratory technique has been developed, see for example [1], which accurately reproduces stack-driven ventilation flows in small-scale models of buildings in water tanks. This technique, which is often referred to as the 'salt-bath' technique, has now been extended to include flows driven by the *combined* forces of wind and buoyancy, see for example [2]. In parallel with the development of these laboratory techniques, simple theoretical models have been developed which provide further insight into the parameters controlling these flows.

A theoretical model for natural ventilation flows in an enclosure containing a localised source of heat on the floor of the space is presented by [1] who show that a steady-state displacement flow is established when openings are made at high and low levels. The stratification developed consists of two homogeneous fluid layers, a warm upper layer and a lower layer at ambient temperature, separated by a horizontal interface. A key result of [1] is that the depth h of the layer at ambient temperature is determined by entrainment into the rising thermal plume and can be increased only by increasing the dimensionless area A^*/H^2 of the openings :

$$\frac{A^*}{H^2} = C^{3/2}\left(\frac{(h/H)^5}{1-(h/H)}\right)^{1/2}, \tag{1}$$

where the 'effective' area of the openings A^* is given by

$$A^* = a_t a_b\left(\frac{2C_e C_d}{C_d a_t^2 + C_e a_b^2}\right)^{1/2}, \tag{2}$$

H is the total height of the space, C_e and C_d denote the coefficients of expansion and discharge, respectively, C (≈ 0.14) is a constant dependent upon the entrainment into the plume, and a_t and a_b denote the respective areas of the upper and lower openings. Their results show that increasing the strength B of the source increases the temperature step across the interface but it does not alter the position of the interface. It has been shown by [3] that this latter result holds for any number of buoyant sources.

In this paper, we extend the work of [1] by considering the effect of a flow of wind past an enclosure containing a point source of heat. We focus our attention on steady-state displacement flows driven by buoyancy forces *assisted* by wind and present the results of laboratory experiments. These results are compared with the predictions of a theoretical model.

2. Laboratory Experiments

Laboratory experiments to simulate steady-state air flow patterns and temperature profiles in naturally ventilated buildings were conducted in a Perspex box (29.5 cm long, 25 cm high and 15 cm wide) which was suspended in a flume tank (length 2.65 m x width

0.30 m x depth 0.57 m) filled with fresh water. The box was used to represent a generic building or room and the large volume of water contained in the flume represented the external environment. The box had a number of circular holes in both windward and leeward faces and the total area of these ventilation openings could be varied by removing plastic plugs from the holes.

To simulate stack-driven flows, brine and fresh water were used to create density differences; brine is denser than fresh water and therefore the buoyancy forces act downwards. In order to model a localised source of heat in a building, brine was injected continuously, and at a constant rate, through a circular nozzle in the top of the box. This fluid descended as a turbulent plume and is the analogue of a thermal plume rising in air from a source of heat.

Wind flow past the box was simulated by a flow of water in the flume tank. The flow of water generated by the flume flowed around the box and resulted in a 'wind' pressure drop Δ between the windward and leeward openings which was measured using a manometer tube; details of this procedure are given in [4].

Flows were visualised by adding dye to the brine injected into the box and using a shadowgraph. The dye colours only the salty fluid so that regions of dense fluid (coloured) and regions of fluid at ambient density (uncoloured) can be clearly distinguished. The shadowgraph enhances the contrast between regions of different density and allows fine scale structures in the flow to be seen.

An experiment was started by removing a number of plugs from openings in the box, at high-level on the windward face and at low-level on the leeward face, and supplying dense salt solution to the plume. After some time a steady-state flow was established. The height of the interface and the density difference between the ambient fluid and the salty layer of fluid inside the box were then measured. Ventilation rates and equivalent temperature differences for air flows in buildings were then deduced from these measurements, see §4.

Using the techniques described to create wind and buoyancy forces it was possible to simulate natural ventilation flows for a wide range of conditions. The effect of the wind speed on the ventilation rate and stratification was examined by varying the mean flow speed in the flume; the effect of the strength of the heat source was examined by increasing the density and volume of salt solution injected into the box, and the effect of the area of the openings was investigated by varying the number of openings in the box.

3. Theoretical model

In order to determine the steady-state height h of the interface and the temperature of the warm zone when a displacement mode of ventilation is assisted by wind we make use of the theory of transient, wind-assisted displacement flows developed by [5] and apply the method described by [1]. By matching the flow in a turbulent plume with the flow driven through an enclosure by a warm upper layer, taking into account the additional driving produced by the wind, it is possible to show that the steady-state density step across the interface may be expressed as

$$\Delta\rho = \frac{\rho(B^2 h^{-5})^{1/3}}{gC}, \tag{3}$$

and the height of the interface may be deduced from

$$\frac{A^*}{H^2} = C^{3/2}(h/H)^{5/3}\left(\frac{1-(h/H)-(d_c/H)}{(h/H)^{5/3}} + CFr^2\right)^{-1/2}, \tag{4}$$

where Fr denotes the Froude number

$$Fr = \frac{(\Delta/\rho)^{1/2}}{(B/H)^{1/3}}. \tag{5}$$

The derivation of expressions (3)-(5) is given in [6]. The Froude number is a measure of the relative magnitudes of the wind-produced velocity $(\Delta/\rho)^{1/2}$ and the buoyancy-produced velocity $(B/H)^{1/3}$: for $Fr \ll 1$ buoyancy provides the dominant driving force and for $Fr \gg 1$ wind forces dominate the ventilation flow.

The theoretical model (3)-(5) predicts that when a displacement flow is assisted by wind, the height of the interface h/H is dependent upon entrainment into the rising plume, the wind pressure drop Δ, the dimensionless area of the openings A^*/H^2 *and* the strength B of the heat source. This is in contrast to flows driven by buoyancy forces alone where the position of the interface is independent of the strength of the source and depends only upon entrainment into the plume and the dimensionless area of the openings, see equation (1).

4. Application to building ventilation

The steady-state temperature distribution in a naturally ventilated enclosure may be determined from the model as follows. First, the power E (Watts) of the heat source in the space must be converted into an equivalent source strength B using

$$B = \frac{g\beta E}{\rho c_p}, \tag{6}$$

where the physical properties of the ambient air at $15°C$ are $\beta = 3.48x10^{-3}°C^{-1}$, $c_P = 1012$ J kg^{-1}C^{-1} and $\rho = 1.225$ kg m^{-3}. The wind pressure drop is related to the square of the wind speed, and hence, the Froude number (5) may be expressed as

$$Fr = U_{wind}\left(\frac{C_{pi} - C_{po}}{2}\right)^{1/2}\left(\frac{H\rho c_p}{g\beta E}\right)^{1/3}, \tag{7}$$

where U_{wind} denotes the mean wind speed, and C_{pi} and C_{po} denote the pressure coefficients at the inlet and outlet openings, respectively. By specifying the area of the openings and the height of the space, the height h of the interface separating the warm and cool layers of air can now be predicted from (4). Alternatively, a minimum acceptable interface height, e.g. $h = H/2$, may be specified by the designer and the area of openings required to achieve this height predicted from (4).

The density step $\Delta\rho$ across the interface (3) can be converted into an equivalent temperature difference using the equation of state, namely, $\Delta\rho/\rho = -\beta(T_u - T_a)$, where T_u and T_a denote the respective temperatures of the warm upper layer and the cool lower layer. Substituting for (6) into (3) yields the temperature of the warm layer of air, namely

$$T_u = T_a + \frac{1}{g\beta C h^{5/3}}\left(\frac{g\beta E}{\rho c_p}\right)^{2/3}. \tag{8}$$

Thus, by raising the height of the interface and/or reducing the power output of the heat source it is possible to decrease the temperature of the upper layer, and hence, passively cool the space.

Ventilation rates in buildings are normally expressed in terms of the number of air changes per hour ACH, and hence, if V is the total volume of the enclosure we have

$$ACH = 3600\ \frac{Q}{V} = 3600\frac{C}{V}\left(\frac{g\beta E h^5}{\rho c_p}\right)^{1/3}. \tag{9}$$

5. Results and Discussion

Results of the laboratory experiments are now described and compared with the theoretical predictions. In order to avoid confusion, these results will be described assuming the direction of motion in the plume is upwards as it is for the case of a thermal plume rising from a heat source in a building.

In the absence of wind, the plume ascends entraining ambient fluid as it rises. Due to entrainment, the volume of fluid carried in the plume increases with height and its temperature decreases. On reaching the ceiling of the space the plume spreads horizontally creating a layer of warm air that gradually increases in depth and temperature and drives a flow through the enclosure. Inflow of cool ambient air is through the low-level openings and outflow of warm air is through the upper openings and thus a displacement flow is set-up. A steady state is eventually established when the ventilation flow rate through the space is equal to the flow rate in the plume at the height of the interface which separates the warm and cool layers of air. The upper layer is then well-mixed and its temperature is identical to the temperature in the plume at the height of the interface.

a) Effect of wind speed. If the low-level openings are located in regions of positive wind pressure and the leeward openings in regions of negative wind pressure then the effect of a flow of wind around the building is to raise the height of the interface toward the ceiling. The interface continues to rise until a new steady-state flow is established. Both the depth and temperature of the warm upper layer are then less than for the no-wind case and the ventilation flow rate through the enclosure is increased. These effects are illustrated schematically in figure 1. Increasing the wind speed is equivalent to increasing the Froude

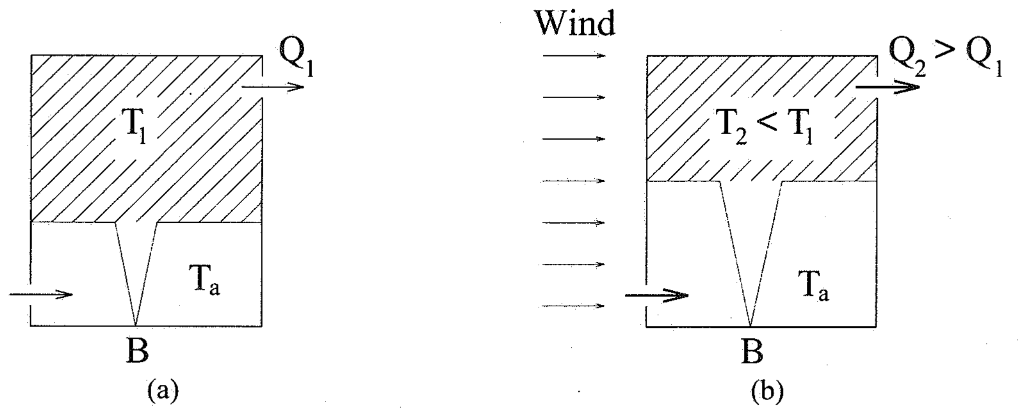

Figure 1. Schematic diagram showing the effect of wind on the interface height, temperature and flow rate established by displacement ventilation in an enclosure, a) stack-driven flow, and b) stack-driven flow assisted by wind.

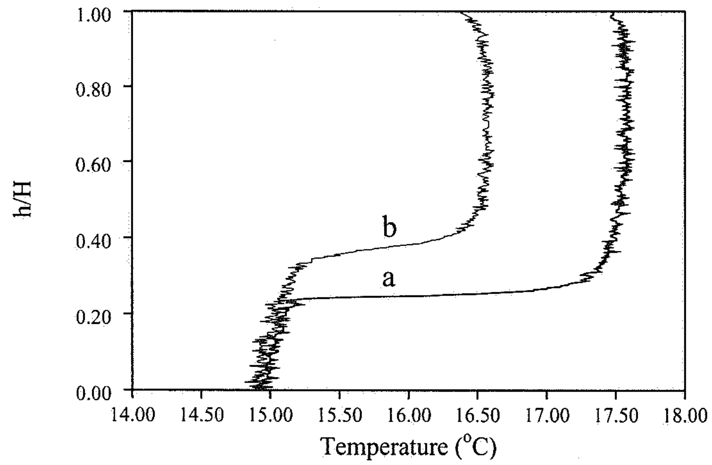

Figure 2. Typical temperature profiles for displacement flows driven by a) buoyancy forces alone ($Fr = 0$), note the interface at approximately $h/H = 0.25$, and b) buoyancy forces assisted by wind ($Fr = 9$), note the interface at approximately $h/H = 0.4$. The temperature step between the upper and lower layers is significantly reduced in b). In both a) and b) $A^{*}/H^{2} = 4.3x10^{-2}$, $B = 2.3x10^{-6}$ m^4s^{-3}.

number and it has been demonstrated during the experiments that the displacement mode of ventilation is maintained for a wide range of Froude numbers. Typical temperature profiles, deduced from measurements of salinity, are illustrated in figure 2, where it can be seen that the wind has increased the depth of the ambient layer and decreased the temperature step across the interface.

b) Effect of opening area. Passive cooling may also be achieved by increasing the dimensionless area of the openings. The effect of an increase in the dimensionless area of the openings on the steady-state interface height and upper layer temperature is shown in figure 3. The experimental measurements are shown by symbols and the theoretical predictions by the continuous line. For a fixed wind speed and source strength, the interface height rises as the dimensionless area of the openings is increased (figure 3a). As a consequence of the rise in the interface height, the temperature (figure 3b) of the warm upper layer decreases and the ventilation rate increases. A factor of two increase in the dimensionless area of the openings A^*/H^2 represents the equivalent of a factor of two increase in the area A^* of the openings or a factor of $2^{-1/2}$ decrease in the height of the space.

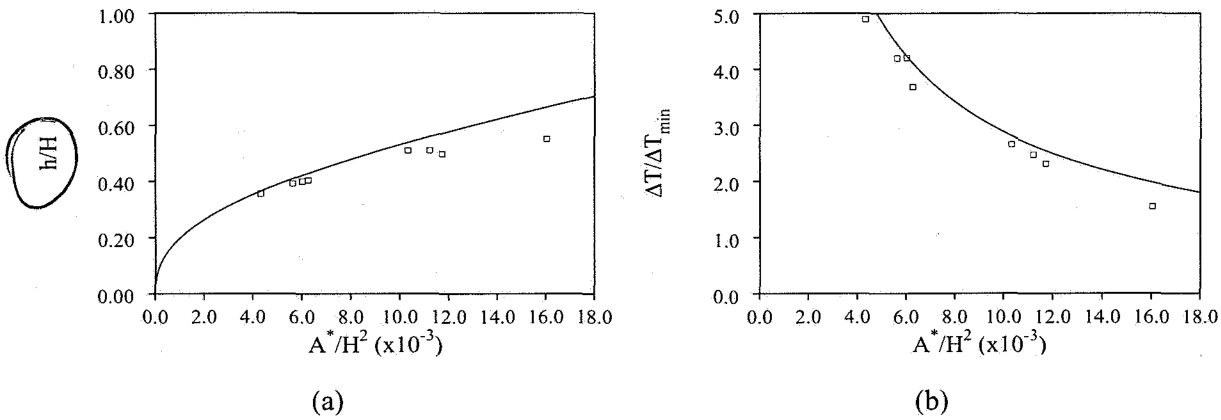

Figure 3. Effect of opening area: a) dimensionless interface height h/H *vs.* dimensionless area of the openings A^*/H^2; b) dimensionless temperature step across the interface $\Delta T/\Delta T_{min}$ *vs.* dimensionless area of openings A^*/H^2. ΔT_{min} is the difference in temperature between the ambient air and the air in the plume at ceiling height.

c) Effect of source strength. An increase in the source strength B results in a decrease in the Froude number, see (5), and hence, buoyancy forces become more significant and the depth of the ambient layer decreases (figure 4a). Furthermore, as B increases the temperature of the upper layer increases (figure 4b) thereby enhancing the buoyancy-driven flow and the overall ventilation flow rate. In this case cooling may be achieved only by decreasing the source strength. If, for example, we consider a wind speed of 2 ms^{-1} incident with a building 5m in height then, in figure 4b, a non-dimensional source strength of 0.5×10^{-2} corresponds to a temperature step across the interface of approximately 12°C in air (assuming T_a = 15°C and C_{pi} - C_{po}=1). Increasing the non-dimensional source strength to 1×10^{-2} results in a temperature step of approximately 20°C.

The interface height depends weakly upon the source strength as a large increase in B produces only a relatively small decrease in the interface height. However, the temperature step across the interface, and hence, the temperature of the upper layer, is strongly dependent upon the source strength.

Paradoxically, the effect of reducing the Froude number by increasing the strength of the source is to *increase* the ventilation flow rate through the enclosure. Recall that a reduction in the Froude number which results from a decrease in the wind speed *decreases* the ventilation flow rate (see §5b). These results are described in greater detail in [6].

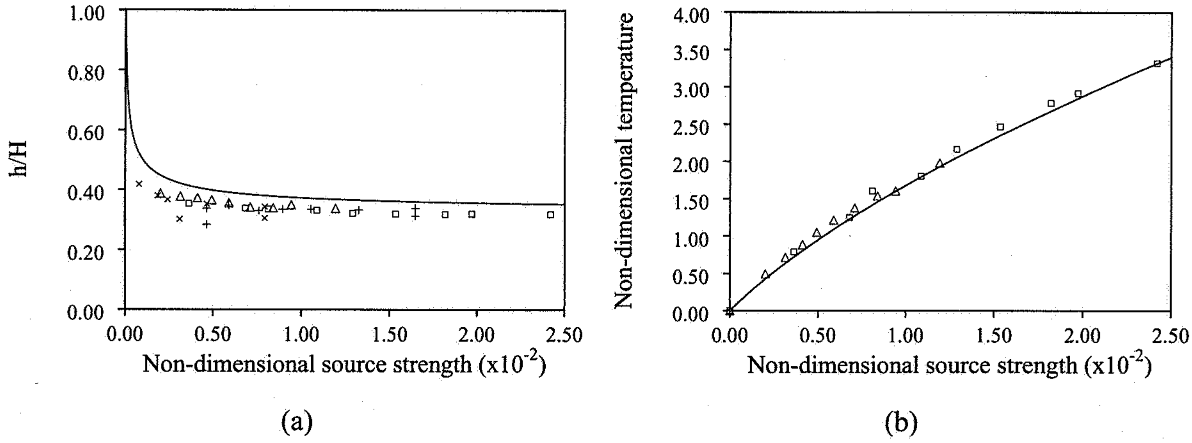

Figure 4. Effect of source strength: a) dimensionless interface height h/H *vs.* dimensionless source strength and b) dimensionless temperature step across the interface $\Delta T g\beta H/(\Delta/\rho)$ *vs.* dimensionless source strength $B/(H(\Delta/\rho)^{3/2})$.

6. Conclusions

Displacement flows driven by buoyancy forces *assisted* by wind have been simulated at small scale in the laboratory and the results of these experiments compared with the predictions of a theoretical model. The theoretical predictions are in good quantitative agreement with experimental measurements and the model may be used to estimate temperature profiles and ventilation flow rates within naturally ventilated buildings. Air flow and temperature conditions within an enclosure have been found to be dependent upon the relative magnitudes of the wind and buoyancy produced velocities (i.e. the Froude number), the area of the openings and the height of the space. Displacement flows established by a point source of buoyancy on the floor of the space are maintained for a wide range of Froude numbers when low-level openings are located in regions of positive wind pressure and high-level openings are located in regions of negative wind pressure. In this case, wind flow has a three-fold effect on the buoyancy-driven flow in the space: an increase in the wind speed i) raises the height of the interface above the floor of the space, thereby increasing the depth of the layer at ambient temperature; ii) results in a decrease in the temperature of the buoyant upper layer and iii) increases the ventilation flow rate through the enclosure. An increase in the strength of the heat source: i) decreases the depth of the layer at ambient temperature, ii) increases the temperature of the upper layer and iii) increases the ventilation flow rate. The height of the stratification is one of the main design parameters for displacement ventilation and by raising the height of the interface the reduced temperature of the upper layer may be used to provide additional cooling of the building fabric. In addition a greater area of the fabric is exposed to the ambient air thereby increasing the potential for cooling.

Acknowledgements

The authors would like to thank the Building Research Establishment for their financial support of this project through the Department of the Environment's Energy Related Environmental Issues (EnREI) in Buildings programme.

References

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

2. HUNT, G.R., LINDEN, P.F., KOLOKOTRONI, M. and PERERA, M.D.A.E.S.
"Salt bath modelling of air flows"
Building Services Journal, CIBSE, January 1997, 43-44.

3. LINDEN, P.F. and COOPER, P.
"Multiple sources of buoyancy in a naturally ventilated enclosure"
J. Fluid Mech., **311**, 1996, 177-192.

4. HUNT, G.R. and LINDEN, P.F.
"Laboratory modelling of natural ventilation flows driven by the combined forces of buoyancy and wind"
To be published as proceedings of the CIBSE National Conference 1997.

5. HUNT, G.R. and LINDEN, P.F.
"The fluid mechanics of natural ventilation - displacement ventilation by buoyancy-driven flows assisted by wind"
Building & Environment (in press).

6. HUNT, G.R. and LINDEN, P.F.
"Steady-state flows in an enclosure ventilated by buoyancy forces assisted by wind"
J. Fluid Mech. (submitted).