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THE NATURAL VENTILATION OF A ROOM WITH AN AREAL SOURCE OF HEAT AND TWO OPENINGS

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ABSTRACT

The ventilation and flow dynamics of a room with a heated floor and high and low level openings to the exterior are investigated using a mathematical model and analogue experiments. The heated floor generates an areal source of buoyancy. Openings allow displacement ventilation to operate. When combined these produce a steady state environment, where the heat provided by the floor equals the heat lost by displacement. We present new theory based on balancing heat fluxes and validate this with observations from small-scale laboratory experiments. At some time, a steady state temperature, T_{SS} is reached. We investigate the effects of varying heat fluxes and vertical positions of openings on T_{SS}. The new model suggests that T_{SS} is related to the temperature of the floor, T_F, and temperature of the exterior, T_{EXT}, as $(T_F - T_{SS})^{4/3}=(T_{SS} - T_{EXT})^{3/2}$. Theoretical predictions and experimental observations agree well.

KEYWORDS

Natural ventilation, displacement ventilation, buoyancy, areal heat source, modelling, experiments

INTRODUCTION

In this study we consider the natural ventilation of a room which is in contact with the exterior by only two openings while being heated over the whole lower surface of the room. This is an analogue model for both the heating of a room by the floor, and cooling of a room through the roof. Ventilation occurs naturally by convection and displacement, driven by pressure differences between air of different temperatures alone rather than mechanical systems. Much recent work has focused on the application of localised heat sources to natural ventilation (Linden, 1999). In many modern buildings however, an areal source of heating or cooling may be as common, particularly if there is a large portion of glass through which sunlight will act as an areal source of heat, while areal cooling will occur at night. We extend the work of Linden *et al.* (1990) who investigated the two-layer stratification which results from a point source of buoyancy combined with displacement ventilation. Observations on temperature changes and flow dynamics from laboratory experiments are presented. A mathematical model describing these is developed, and predictions from the theory are compared with the experimental data. A simple example showing application of the new model to modern buildings is given.

EXPERIMENTS

Method

As an experimental analogue of a confined room connected to a cold exterior by two openings and subject to uniform heating of the floor of the room, we have conducted experiments in a perspex tank (the 'room') with a square floor area of 311.5 cm^2 and height 28.7 cm (figure 1). This is filled with water to a depth of 27.5 cm and placed in a large reservoir of water filled to the same depth. The floor of the room comprises a steel plate containing tubes through which antifreeze is circulated. This areal heat source is adjusted by changing the temperature of the antifreeze. Type K thermocouples placed at different heights within the room and exterior monitor the water temperature by scanning every 10 seconds. One wall of the room contains three circular holes each of diameter 1.5 cm with their midpoints at 1.05, 13.50 and 25.95 cm above the floor. The floor is preheated to T_F and the room filled with fluid of the same temperature. To start an experiment bungs are removed from two openings. The two selected openings, temperature of the floor, T_F, and exterior, T_{EXT}, were varied from experiment to experiment. 28 experiments were performed and the steady state temperature of the fluid inside the room, T_{SS}, was monitored.

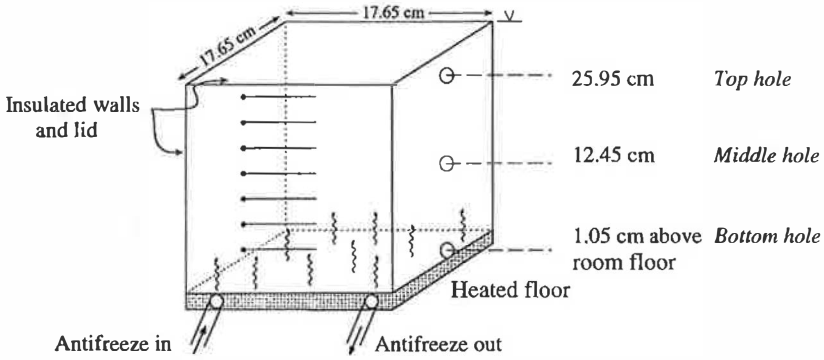

Figure 1: Analogue experiments are conducted in a perspex box with a floor heating plate providing an areal source of buoyancy. Thermocouples measure temperature changes.

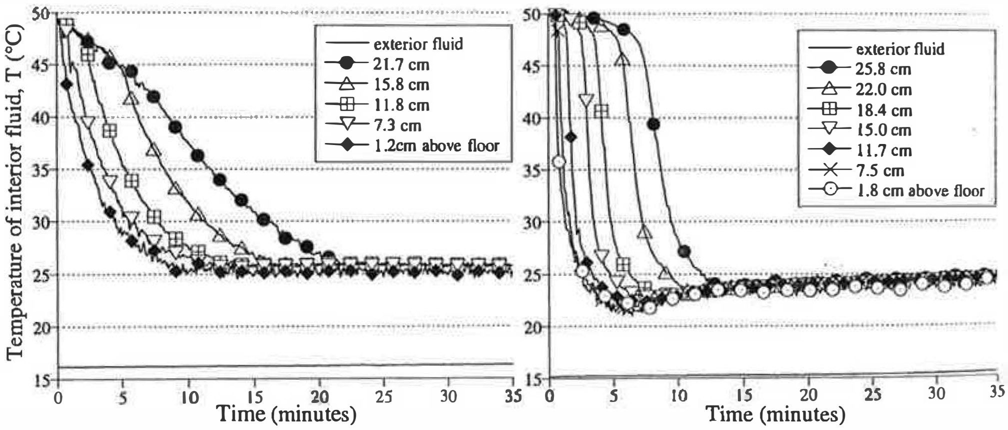

Figure 2a and 2b: In both experiments, T_F=50°C, T_{EXT}=16.5°C. The top and middle openings are employed in figure 2a while top and bottom openings are employed in figure 2b. T_{SS} is reached after 20 minutes in figure 2a, and 33 minutes in figure 2b.

Results

After removal of the bungs cold exterior fluid enters the room through the lower hole, displacing warm interior fluid upwards and out of the room through the upper hole. As the flow continues and the front between the warm and cold fluid ascends, the thermocouples in the room show a decrease in temperature sequentially from the bottom of the room to the top (figures 2a and 2b). However, as the lower layer deepens, convection driven by the heated floor becomes progressively more vigorous and the temperature in the room becomes more uniform with depth. A steady state temperature, T_{SS}, is attained once this front reaches the top of the room, typically after about 20 minutes. T_{SS} remains constant while T_{EXT} and T_F are held constant. The evolution of the temperature profile in the room also depends on the positions of the openings. Figure 2a shows temperature changes in a room ventilated through the top and middle openings, while in figure 2b the ventilation occurs through the top and bottom openings. The displacement ventilation, which dominates both experiments during early stages, is stronger when the distance between the openings is large. This process is so strong that the temperature of the room dips to a few degrees below T_{SS}, before convection from the floor becomes equally important, creating the steady state balance. The steady state temperature, T_{SS} depends on T_F and the positions of the two openings (figure 3). In all three configurations of openings, the higher the setting of T_F, the higher the value of T_{SS}.

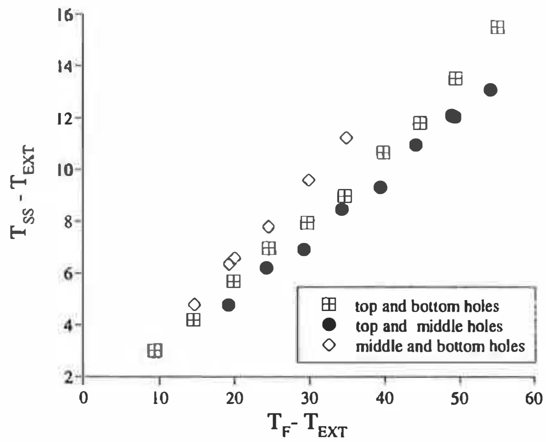

Figure 3: For a given configuration of openings, T_{SS} increases with T_F.

THEORETICAL MODEL

We now develop a leading order model of the heating and flow observed in the experiments. We assume that the fluid in the room is well-mixed by the convection produced at the heated floor. For openings whose vertical dimension is small compared to their separation, the volume flux through each of the openings during displacement ventilation, Q_V, is given from dimensional analysis by the relation (Linden *et al.* 1990)

$$Q_V = \left[\left(\frac{g(\rho_{EXT} - \rho_{INT})}{\rho_{INT}}\right)\frac{h}{2}\right]^{1/2} cA_{HOLE} \tag{1}$$

where g is the acceleration due to gravity, h the distance between the midpoints of the two openings, ρ_{EXT} and ρ_{INT} are the densities of the exterior and interior fluids respectively, A_{HOLE} is the average area of the openings and c is a constant describing the energy loss associated with flow through an opening.

The heat flux supplied by the hot floor may be estimated from previous work on the turbulent convectio generated by horizontal heated plates. As a good approximation, if the heating plate has temperature T and the fluid in the room has temperature T, the heat flux supplied to the room, Q_H, is given by

$$Q_H = \lambda A_{ROOM}\left(\frac{\alpha g}{\kappa \upsilon}\right)^{1/3} \rho C_P \kappa (T_F - T)^{4/3} \quad (2$$

where A_{ROOM} is the area of the room, ρ and C_P are the density and heat capacity of water respectively, is a dimensionless constant which characterises the heating from the plate, α, κ and ν are the expansio coefficient, thermal diffusivity and viscosity of water respectively (Denton & Wood 1979). Empiric measurements show that $\lambda = 2^{4/3}c_Q$ where c_Q is the heat transfer coefficient (Townsend 1959). Th conservation of heat in the system at steady state gives a balance of the heating and cooling fluxes,

$$Q_H = \rho C_P (T_{SS} - T_{EXT}) Q_V \quad (3$$

where T_{SS} is the steady state temperature to which the room evolves and T_{EXT} is the exterior temperatur It is convenient to scale Eqn. 3 to T_F and T_{EXT}, reducing it to the algebraic relation

$$(1-\theta)^{4/3} = Z\theta^{3/2} \quad (4$$

where $$\theta = \frac{T_{SS} - T_{EXT}}{T_F - T_{EXT}} \quad \text{and} \quad Z = \left(\frac{c}{\lambda}\right)\frac{A_{HOLE}}{A_{ROOM}}\left(\frac{g^{1/2}\alpha^{1/2}\upsilon}{\kappa^2}\right)^{1/3} \quad (5$$

Z is a dimensionless parameter incorporating the coefficients from the two transient processes. For sma Z, corresponding to large openings and rapid displacement flow, the temperature in the room, T_{SS} closer to that of the exterior fluid so $\theta \to 0$. In contrast, for large Z, corresponding to small openings ar relatively rapid heating by convection, T_{SS} tends to the temperature of the heated floor so $\theta \to 1$.

EXPERIMENTAL CALIBRATION

In order to make quantitative comparisons between the model and the experiments we need to constra the model parameters λ and c which quantify the efficiency of the heat transfer from the heated plate ar the energy loss through the doorway associated with the displacement flow, respectively. We hav therefore conducted two series of controlled calibration experiments.

Displacement Ventilation

In the first calibration experiment, the rate of ascent of a saline-fresh water interface inside the roo driven as a pure displacement flow, is examined so as to identify the value of the constant c. Extendi the model of the displacement flow from Eqn. 1, the rate of ascent of the interface between light interi fluid and dense exterior fluid, z, is given by

$$A_{ROOM}\frac{dz}{dt} = cA_{HOLE}\left[g'\frac{(h-z)}{2}\right]^{1/2} \quad (6$$

where $g' = g(\rho_{EXT} - \rho_{INT})/\rho_{INT}$. Eqn. 6 can be integrated, to give,

$$(h - z_0)^{1/2} - (h - z)^{1/2} = cBT \quad \text{where} \quad B = \left(\frac{A_{HOLE}}{A_{ROOM}}\right)\frac{g'^{1/2}}{2\sqrt{2}} \quad (7$$

In these experiments, the room is filled with dyed fresh water and the exterior reservoir filled with 2% or 3% saline solution by mass. Bungs are removed from two of the three openings, either top bottom, top and middle, or middle and bottom openings. The light interior fluid leaves the room thro the upper hole while dense exterior fluid enters the room through the lower hole. To reduce the impa mixing during initial stages on visualisation, the basal 2 cm of the room is filled with a layer of sa solution identical in concentration to that outside the room. The ascending interface is monitored u Digimage image analysis software. Twelve experiments were performed, using three configuration openings and three salinities; three experiments were repeated. The interface rises with time although rate of ascent decreases with time. The interface ascends more rapidly when there is a large den difference between the fluids (cf Linden *et al.*,1990). We scale our data on $(h-z_o)^{1/2}$ using Eqn. 7 (fig 4). The data for all experiments collapse to a straight line whose slope gives a value of c=0.98±0.15.

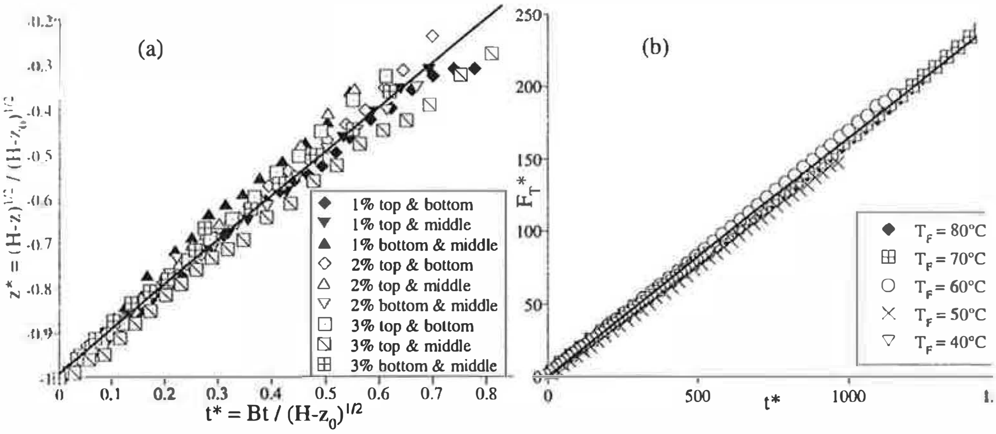

Figure 4: Scaled calibration experiments:
(a) displacement ventilation data collapse to a line with slope c=0.98 using Eqn. 7,
(b) transient heating data collapse to a line with slope λ=0.166 using Eqn. 8.

Transient Heating

The second calibration experiment involved heating the closed room by the floor plate and measuring the temperature of the room as a function of time, to identify the value of the coefficient λ from Eqn. 2 for our heating plate. Integrating Eqn. 2, and defining the resulting heating function as F_T gives,

$$F_T = \int_{T_{EXT}}^{T} \frac{1}{J_T (T_F - T)^{4/3}} dT = \lambda \int_{t_0}^{t} dt \qquad \text{where} \qquad J_T = \left(\frac{\alpha \kappa^2 g}{\upsilon} \right)^{1/3} \frac{1}{H} \qquad (8)$$

The room was filled with water of initial temperature T_{EXT}=15°C. Values for T_F of 40, 50, 60, 70 and 80°C were used. The water inside the room increases in temperature T rapidly at first and then more gradually as T approaches T_F. Temperature measurements at different vertical heights show that the room is well-mixed. Typically it takes five to eight hours for T to reach T_F.

Scaling Eqn. 8 using $J_{TF}(T_F-T_{EXT})^{4/3}$ provides expressions for the dimensionless heating function, F_T^*, with dimensionless time, t^*. When plotted until the time when T=0.95T_F these data collapse to a line with slope λ where λ=0.166±2%. Thus the heat transfer coefficient, c_Q is 0.066 comparing well with previous observations for single (Townsend 1959) and double plate (Denton & Wood 1979) turbulent convection experiments.

COMPARISON OF MODEL WITH EXPERIMENTS

The observations and theoretical predictions of T_{SS} agree well for our room when the top and bottom, or middle and bottom holes are opened (figure 5a). At high T_F, experimental measurements are slightly higher than values predicted by the theory. With the bottom hole open, cold exterior fluid entering the room passes directly over the heating plate allowing the floor to heat fluid of temperature T_{EXT} rather than the warmer mixed fluid. Consequently the transfer of heat is more effective, becoming pronounced at high T_F. When cold exterior fluid enters the room through the middle hole, experimental observations of T_{SS} are lower than theoretical predictions (figure 5b).

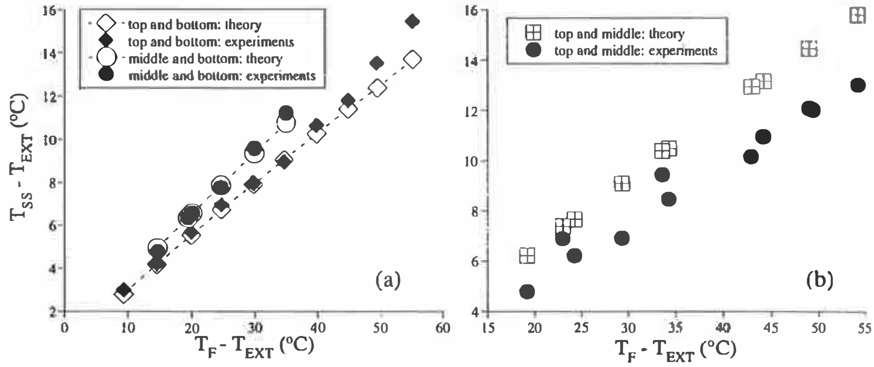

Figure 5: Theoretical predictions and experimental observations of T_{SS} using (a) top and bottom, or middle and bottom openings, and (b) top and middle openings.

CONCLUSIONS

This experimental and theoretical study has shown that a fully-mixed flow regime becomes established in a warm room which is in contact with a cold exterior by two openings, and heated by convection from the floor. This contrasts with the two-layer stratification that results from localised sources of heating (Linden *et al.*, 1990). We have developed an analogue experimental system and show that the steady state temperature, T_{SS}, can be predicted well by a new model in terms of floor, T_F, and exterior, T_{EXT}, temperatures, based on balancing heating, Q_H, and displacement, Q_V, fluxes. The model may be applied to modern buildings with large surface areas of glass, leading to areal heating by day and cooling at night. For example, we consider a large atrium with a glass ceiling which at night leads to a temperature difference ΔT=5°C between the interior and exterior. If A_{HOLE}/A_{ROOM}~0.01, using the following typical values for air, α~1/300, g~10 ms^{-2}, υ~10^{-5} m^{2}s^{-1} and κ~10^{-6} m^{2}s^{-1}, we estimate Z~0.1 and θ~0.9. Thus displacement ventilation is relatively rapid so T_{SS} tends to T_{EXT}, causing the atrium to be cold.

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