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A HYBRID DISPLACEMENT-MIXING VENTILATION REGIME IN A NATURALLY VENTILATED ROOM

Charlotte Gladstone and Andrew W. Woods

BP Institute, Bullard Laboratories, University of Cambridge, Madingley Road, Cambridge

ABSTRACT

The evolution of the temperature profile in a warm room driven by a natural ventilation flow which develops when the room is connected to a cold exterior by two openings at different vertical heights is explored. With the openings at the top and base of the room, we find the classical displacement ventilation regime provides a leading order description of the flow. With openings at the centre and top of the room, the ventilation is hybrid, with the lower part of the room being well-mixed, and the upper part being stratified by an upward displacement ventilation flow. We present some dimensional scaling, two end-member models and a series of analogue experiments of the process. The suite of experiments involve two different configurations of openings and a variety of temperature differences between the interior and exterior temperature.

KEYWORDS

Natural ventilation, displacement, mixing, buoyancy, mathematical modelling, experiments.

INTRODUCTION

Natural ventilation of a room develops when air of one temperature inside the room exchanges through one or more openings with air of a different temperature outside. The density differences associated with the temperature difference inside and outside the room lead to a higher internal pressure at the top of the room and a lower internal pressure at the bottom of the room in comparison with the external pressure. This leads to a natural ventilation flow. Depending on the number and positions of the openings, the exchange of warm and cold air may occur through mixing ventilation or through displacement ventilation as described by Linden, Lane-Serff & Smeed (1990). In a warm room linked to a cold exterior by a single opening located near the top of the room, mixing ventilation occurs. Cold exterior fluid enters and mixes with fluid in the room as it descends to the floor. In contrast, with two openings, one located high and one low, displacement ventilation occurs. Cold exterior fluid enters the room through the lower hole displacing warm interior fluid up and out of the upper hole. Linden *et al.* (1990) considered such displacement ventilation by studying the draining of warm fluid from a room which is connected to a cold exterior through holes in the ceiling and the floor of the room. In this paper we generalise the study to consider the natural ventilation of a warm room connected to a large col(exterior by two small openings, and now account for mixing of the inflowing fluid with that originall) in the room. We assume that one of the openings is located high in the room and examine the effect o positioning the second opening either in the centre or base of the room.

EXPERIMENTS

These analogue experiments are conducted using a small perspex tank with circular openings in onc wall, placed inside a large reservoir which acts as the exterior. The model room has a square floor are: of 311.5 cm^2 and is 28.7 cm deep. It includes three openings each with a diameter of 1.5 cm and wit midpoints located at 1.05, 13.50 and 25.95 cm above the floor. These are sealed by rubber bungs. Th external reservoir is filled with cold water of temperature T_{EXT}, typically 17.5°C to 20.5°C. The room i filled with warm fluid of temperature T so that the initial temperature difference between interior an(exterior fluids, ΔT_0 ranges from 15°C to 50°C. An experiment is started by removing bungs from two o the three openings. Two series of experiments were conducted, both with the same values of ΔT_0. I Series 1, the uppermost and centre of the three holes are opened, i.e. those with midpoints at 25.95 cı and 13.50 cm, while the bottom hole remains closed. During Series 2, the centre hole is closed with th top and bottom holes open. Flow patterns are observed using the shadowgraph method. The evolvin; temperature profile within the room is monitored using seven Type K thermocouples placed at 1.9 cm 7.4 cm, 11.4 cm, 15.0 cm, 18.4 cm, 22.2 cm and 25.6 cm above the floor of the room. These record th temperature profile every three seconds. An eighth thermouple monitors the external temperature, T_{EXT}.

Once the bungs are removed, cold exterior fluid flows into the room through the lower hole, while hc interior fluid flows out of the room through the upper hole. The room progressively becomes coole from bottom to top with time with contrasting temperature profiles resulting depending on whic configurations of openings is employed.

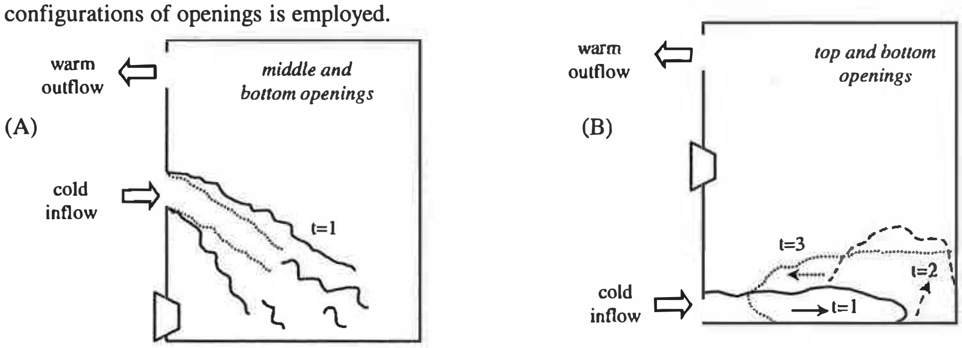

Figure 1: Schematic diagrams show the different mixing processes operating in (a) Series 1 with centre and top openings employed, and (b) Series 2 with top and bottom openings employed.

During Series 1, in which the top and centre holes are opened, cold exterior fluid enters the room aı gradually descends to the floor as an inclined, entraining plume (figures 1a and 2a). This causes tl lower section of the room to become well-mixed. During Series 2, with top and bottom holes opene exterior fluid enters as an advancing gravity current very near the base of the room. This reflects ba(and forth off near and far walls (figures 1b and 2b). The mixing caused by the gravity current of Series is confined to the beginning of an experiment and produces a thin mixed layer of 2-4cm. The ventilati(process then approximates the classical displacement ventilation process, as outlined by Linden *et (* (1990). The mixing driven by the descending plume in Series 1 is far more substantial, with much of tl fluid in the lower half of the room becoming well mixed. These two mixing processes produce differe evolving temperature profiles. In both series of experiments the bottom of the room cools first. The room then becomes progressively colder sequentially from bottom to top (figure 2). The temperature decrease is rapid at first, but becomes slower with time before reaching a constant value, which is slightly stratified with height. In Figure 2a, thermocouples below the centre hole show a similar temperature decrease indicating that this part of the room is mixed. The mixing is less pronounced in Figure 2b; indeed, over the first 500s, the temperature adjusts over a very narrow vertical range.

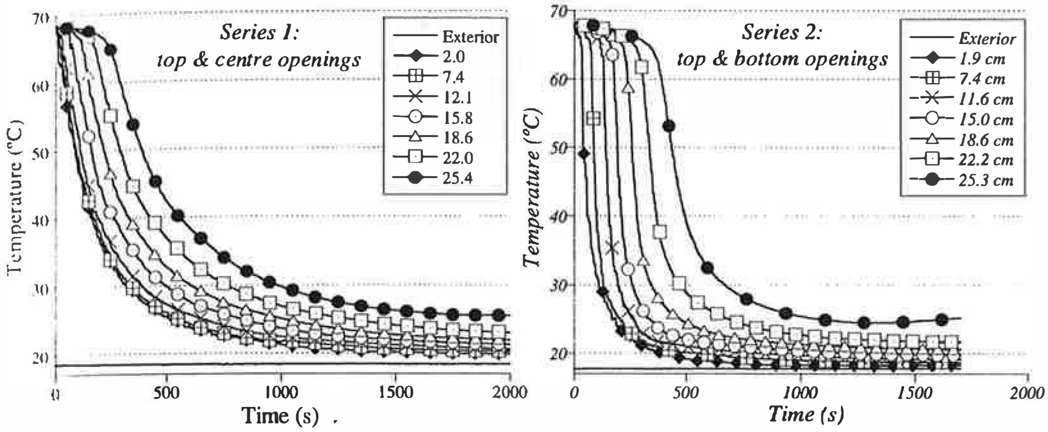

Figure 2: During both these experiments ΔT_0=50°C, and in (a) top and centre holes are opened (Series 1) and (b) top and bottom are opened (Series 2)

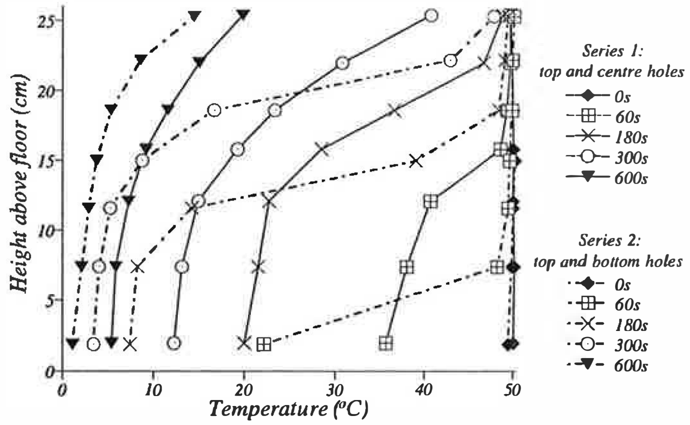

Figure 3: Two experiments, one from Series 1 and the second from Series 2, but both with ΔT_0 = 50°C, are shown here. Temperature T-T_{EXT} is plotted against height at different times t.

Temperature changes in the room can be compared by plotting T-T_{EXT} as a function of height at different times, t=60s, 120s, 180s, 300s, 420s and 600s (figure 3). Experiments from Series 1 and 2 are presented, both with ΔT_0=50°C. When t=0s, T-T_{EXT} =ΔT_0 and a slight stratification develops towards the base of the room. After t=60s, the Series 1 temperature profile (top and middle openings) shows a mixed lower half of the room and an unmixed upper half (figure 3). The fluid in the lower half of the room is substantially warmer than T_{EXT} indicating significant mixing. In Series 1, the mixed layer is still present at t=180s, and by 300s the top of the room is also beginning to cool. The temperature profile in the room evolves in a very different way in the Series 2 experiment (figure 3) where top and bottom holes are opened. The lower part of the room is colder than in Series 1, indicating that there is less mixing here, while the upper part of the room remains at the initial warm temperature for longer. By reference to the idealised model displacement processes, we infer that Series 2 approximates to the simple displacement ventilation process (Linden *et al.*, 1990) with only a small amount of mixing, whereas in Series 1, the mixing ventilation process operates in the lower part of the room, while the displacement process controls the flow in the upper part of the room.

MODELLING

The volume flux through the two holes has natural scale $Q=[g\Delta Th/\Delta T_0]^{1/2}A_{HOLE}$ where g is the gravitational constant, ΔT_0 is the temperature difference between the temperature of fluid inside the room, T, and fluid outside the room, T_{EXT}, h is the distance between the midpoints of the two holes and A_{HOLE} is the area of one of the (equally-sized) openings. The timescale for the temperature profile to evolve, τ, is given in terms of the volume of the room and Q (eqn 1), $\tau = A_{ROOM}H/Q$ where A_{ROOM} and H are the cross-sectional area and height of the room respectively. In order to compare all the experiments, we introduce the dimensionless height of the room, $z^*=z/H$, the dimensionless temperature of fluid within the room, $T^*=(T-T_{EXT})/\Delta T_0$ and the dimensionless time, $t^*=t/\tau$.

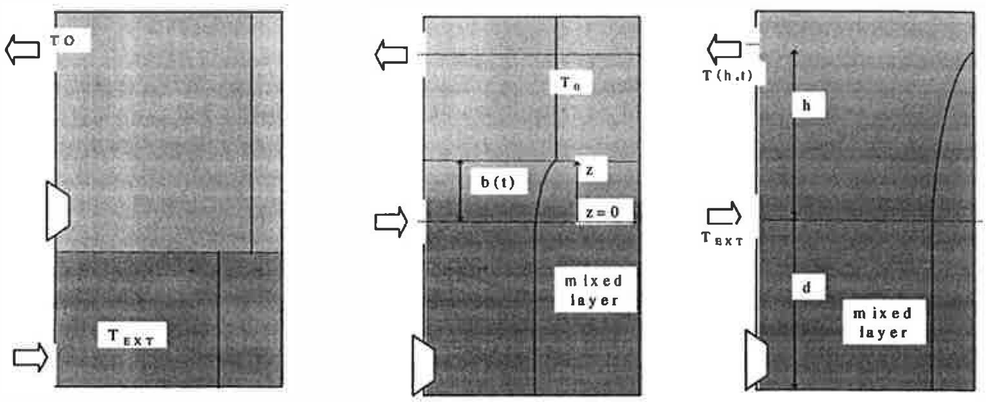

Figure 4. (a) displacement ventilation regime;
(bi) initial stages of hybrid ventilation regime; (bii) late stages of hybrid ventilation regime.

Displacement ventilation regime: This regime is essentially that described by Linden *et al.* (1990). If the interface has height h above the lower opening, and the buoyancy contrast between the interior and exterior fluid is $g'=g(T_0-T_{EXT})/T_{EXT}$, then the flow through each opening has volume flux $Q = A_{HOLE}(g'(H-h)/2)^{1/2}$. The rate of ascent of the interface between the two fluids is then given by the relation $dh/dt=Q/A_{ROOM}$, leading to the expression

$$h(t) = H - \left(H^{1/2} - \frac{A_{HOLE}}{2A_{ROOM}}\left(\frac{g'}{2}\right)^{1/2} t\right)^2 \quad (1)$$

This relation also describes the ascent of the isotherms upwards through the system, assuming that the thin mixed zone about the interface is established in the initial stages of the process, and then remains approximately fixed as the interface ascends.

Hybrid displacement-mixing regime

In the partially mixed regime the flow is more complex, with the region below the opening being approximately isothermal, while that above the opening is stratified in temperature. We may model this flow by assuming the incoming fluid mixes the region below the inflow opening uniformly, $0<z<d$, but that above this region, $d<z<h+d$, the upward flow of warm air to the outflow vent generates a region of gradually increasing temperature, where d is the depth of fluid below the midpoint of the centre opening and h is the depth of fluid between the midpoints of the centre and upper openings. If we denote the temperature in the fluid as $T(z,t)$, and the fluid in the mixed zone to be $T_M(t)$, then the exchange flux between the two openings has the form

$$Q = A_{HOLE}\left(\frac{g}{2}\int_{d}^{h+d}\left(\frac{T(z,t)-T_{EXT}}{T_{EXT}}\right)dz\right)^{1/2} \tag{2}$$

The conservation of thermal energy in the lower well-mixed zone requires that $(T_M - T_{EXT})Q = -A_{ROOM}\, dT_M / dt$ where $T(d,t)=T_m(t)$. Finally, we note that $T(z,t)=T_M(\tau)$ where $z = d + \int_{t-\tau}^{t}(Q / A_{ROOM})dt$. During this time the temperature in the ascending zone has value $T(z,t) = T_{EXT} + (T_0 - T_{EXT})\exp(-(b+d-z)/d)$ for $z<b+d$, where $b(t)$ represents height of the top of the stratified zone. Above this point, the fluid in the room is unmixed and the temperature equals the original temperature of the room T_0. Noting that the conservation of mass requires that $Q=A_{ROOM}db/dt$ we see that the system may be simplified to an equation for the ascent of the initial surface of mixed fluid, which has the dimensionless form

$$\frac{db}{dt} = \frac{A_{HOLE}}{A_{ROOM}}\left(\frac{g}{2}\frac{(T_0 - T_{EXT})}{T_{EXT}}[d(1-\exp(-b/d)) + (h-b)]\right)^{1/2} \tag{3}$$

This relation applies until the ascending front of the mixed fluid has reached the upper outflow opening, when $b=h$. Subsequently, the spatial structure of the temperature profile in the stratified region between the two openings, $d<z<h+d$, has the form $T(z,t) = T_{EXT} + (T(h+d,t) - T_{EXT})\exp(-(h+d-z)/d)$ so that the temperature in the mixed zone $0<z<d$ has value $T_M(t) = T_{EXT} + (T(h+d,t) - T_{EXT})\exp(-h/d)$. The temperature of the mixed zone then evolves at a rate given in dimensionless units by the relation

$$\frac{dT_M}{dt} = -\frac{A_{HOLE}}{A_{ROOM}}\left(\frac{g}{2dT_{EXT}}\right)^{1/2}(T_M - T_{EXT})^{3/2}\exp(h/2d)(1-\exp(-h/d))^{1/2} \tag{4}$$

starting at the time at which the ascending mixed fluid first reaches the outflow opening. At this time the temperature of the region $0<z<d$ is $T_M(t) = T_{EXT} + (T_0 - T_{EXT})\exp(-h/d)$. We take the time scale to be $\tau_s = 2\left(dT_{EXT}A_{ROOM}^2 / A_{HOLE}^2\, g(T_0 - T_{EXT})\right)^{1/2}$, the dimensionless thickness of the ascending stratified region to be $y=b/d$, and the dimensionless temperature of the mixed zone to be $\theta = (T_M - T_{EXT})/(T_0 - T_{EXT})$. Using the dimensionless time t_d we find that in the initial stage of the process $dy/dt_d = \sqrt{2}(1-\exp(-y) + Y - y)^{1/2}$ and $\theta = \exp(-y)$. Once $y=Y=h/d$, the distance between the two openings, then the temperature of the lower mixed zone evolves according to

$$d\theta / dt_d = -\sqrt{2}\theta^{3/2}\exp(Y/2)(1-\exp(-Y))^{1/2} \tag{5}$$

with solution

$$\theta(t_d) = \left(\theta^{-1/2}(t_c) + \frac{1}{\sqrt{2}} \exp(Y/2)(1-\exp(-Y))^{1/2}(t_d - t_c) \right)^{-2} \qquad (6)$$

where t_c is the time at which $y=Y$. We illustrate how the temperature profile in the fluid evolves wi time according to this model in figure 5.

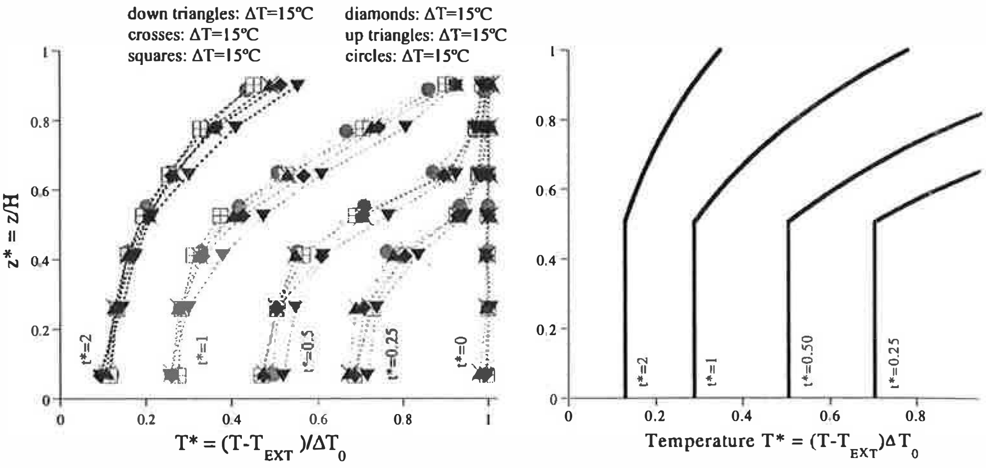

Figure 5: (A) experiments are scaled on z* and T*; (B) evolution of temperature profile as predicted b the model for the hybrid ventilation

We have described a series of experiments in which a room initially filled with relatively light fluid w allowed to exchange fluid with a relatively dense exterior through two openings at different heights ir closed room. The experiments and model identified two different regimes depending on the location the lower opening. When it was positioned at the base of the reservoir, the flow resembled the simp displacement ventilation flow regime (see also Gladstone and Woods, RoomVent 2000) whereas wh the opening was located at the midpoint of the room, the inflowing dense fluid mixed vigorously wi the interior fluid leading to formation of a relatively well-mixed zone at the base of the room. Howev above the lower opening a steady upward displacement flow developed, and this generated a stro stratification through the upper part of the room. The dimensional scalings presented of t experimental data provide a very good leading order collapse of the experimental data, and t theoretical predictions of the rate of ascent of the mixed zone are also in good accord with t observations. The work provides new insight into the thermal structure which might develop unc different natural ventilation regimes, illustrating that the location of the ventilation openings is key terms of limiting or promoting the formation of a mixed zone.

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