14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Natural Ventilation by the Competing Effects of Localised & Distributed Heat Sources

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Abstract

We consider the steady natural ventilation of an enclosure with openings at high and low level, heated uniformly by the combination of a distributed source occupying the entire floor area and, simultaneously, by a localised heat source at the centre of the floor. The stratification and flow patterns produced by the combined heat sources were examined in a series of experiments using a small-scale model to represent a generic single-spaced room or building. We present results from these experiments which show that the general two-layer stratification and displacement flow produced by a localised source in isolation is maintained when the localised heat flux is greater than approximately one sixth of the distributed heat flux. For weaker localised sources a well-mixed interior is established.

Introduction

The steady airflow rates and thermal stratification produced by a heat source in an enclosure ventilated by high and low-level openings is dependent not only on the total heat input but on the distribution of the heat input. A localised heat input produces a thermal plume which establishes a steady displacement flow and two-layer stratification consisting of a warm upper layer and a lower layer at ambient temperature [5]. In contrast, if the heat input is distributed over the entire floor area then thermal convection establishes a well-mixed interior [1]. In both cases, ambient fluid enters through the lower openings and buoyant fluid leaves through the upper openings. However, if the supply heat fluxes are identical in both cases the distributed source drives a higher flow through the openings [2]. In practice, ventilated spaces may receive heat gains simultaneously from both localised sources, such as occupants or electrical equipment, and distributed sources, such as underfloor heating. When combined, the stabilising effect of the localised source competes with the destabilising effect of the distributed source, and the question of how the space stratifies arises. This question has been previously considered for an unventilated space [7], which was found to stratify when the buoyancy flux from the localised source was greater than that from the distributed source.

We expect analogous behaviour in this ventilated space, with a two-layer stratification when the distributed convection is weak (compared to the plume convection) and a well-mixed interior when the distributed convection is strong. The two extremes result in qualitatively different flow rates and temperatures and thus create very different environments in terms of occupancy comfort. The inflow of ambient (cool) fluid allows a true steady state to be reached.

In order to determine the range of conditions which produce stratified and well-mixed interiors a series of experiments were performed. The experimental apparatus is now described, and the results of the experiments are outlined.

Experiments

A rectangular tank (of internal dimensions L 44cm × W 40cm × H 34cm) immersed in a large reservoir of cool water represented the enclosure and the surrounding environment, respectively. The tank walls were double-skinned, with the inner and outer skins separated by a cavity. All boundaries, apart from the floor, were designed to be insulating boundaries, and the skins were of acrylic sheet separated by a 1cm air cavity. The floor was designed to be a distributed heat source, with an inner skin of brass plate (to provide good thermal contact), an outer skin of acrylic and warm water from a heated reservoir recirculated in the cavity. Warm water from a second reservoir was supplied to a 1cm diameter nozzle, located centrally in the heated floor. The rising plume of warm water from the nozzle provided a localised heat source. Rectangular holes in the tank at high and low level represented the ventilation openings and the total opening area was varied by adding or removing plastic inserts from the holes. The total effective area of the upper and lower openings, accounting for the reduction due to flow contraction [3], is denoted by A^* [5]. The experimental set-up is shown in figure 1. Flows were visualised using a shadowgraph and dyes were introduced to the flow through the openings and in the plume to aid visualisation.

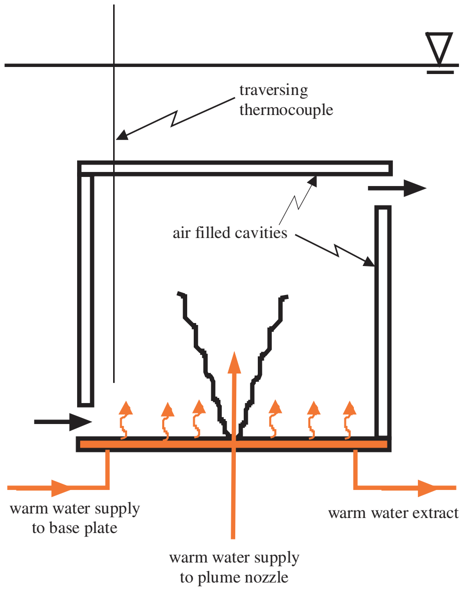


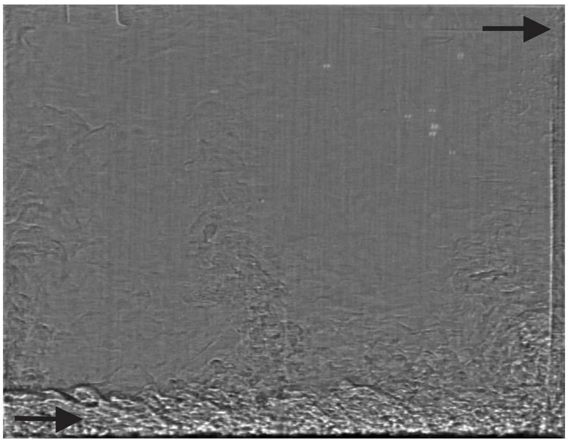
Figure 1. Schematic of the experimental set-up. Black arrows indicate the direction of flow through the space.

The volume flow rates of warm water supplied to the heated floor and plume nozzle were measured using in-line flow meters. Temperature measurements were made using 1mm diameter sheathed ungrounded J-type thermocouples positioned in the ambient fluid, within the plume nozzle, and within the supply and extract connections to the heated floor. Temperature measurements within the ventilated enclosure itself were made by vertically traversing a thermocouple over the entire depth H of tank. The thermocouples were connected through a NI TC-2190 and NI 4350 logging system and a record of the temperatures collected during each experiment. From the temperature and flow rate measurements the buoyancy fluxes supplied to the plume ($B_{localised}$) and from the heated floor ($B_{distributed}$) were deduced.

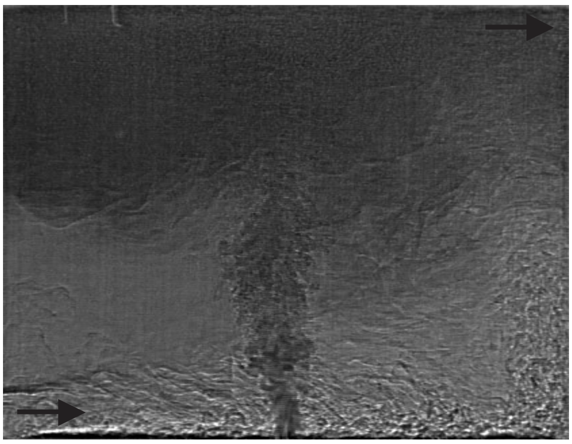
If the space stratified, the height of the interface above the tank floor was recorded, and a virtual origin correction [6, 4] made to this height to account for the non-zero fluxes at the plume source.

Results

In some experiments the localised and distributed sources were activated simultaneously and the resulting steady flow conditions recorded. In other experiments, either a steady two-layer stratification was established by the plume before the distributed source was activated, or conversely, a steady well-mixed interior was established by the distributed source before the localised source was activated. Experiments were conducted for a range of buoyancy flux ratios $\psi = B_{localised} / B_{distributed}$ and dimensionless vent opening areas A^*/H^2. Values of $\psi = 0$ (heated plate alone), $0.09 < \psi < 1$ and $\psi = \infty$ (localised source alone) could be attained. The distribution of opening area between the upper and lower openings could also be varied without changing the total opening area, for each value of A^*/H^2. For all the opening geometries studied, the heating within the tank drove a displacement flow or a mixing flow with an inflow of cold ambient water through the lower opening and an outflow of heated water through the upper opening. The displacement flow is characterised by a stratified interior whereas for a mixing flow no strong density gradients are present.



(a)



(b)

Figure 2. Shadowgraph images showing (a) a well-mixed interior at $\psi = 0.09$, $A^*/H^2 = 0.017$ and (b) a two-layer stratification, at $\psi = 0.87$, $A^*/H^2 = 0.036$. The direction of flow through the space is indicated by the arrows.

Steady flow

A steady mixing flow pattern established by a dominant distributed source (ψ small) is shown in figure 2a. Turbulent convection patterns are clearly visible in the lower regions of the space, and the weak plume rising from the centre can be identified. Plumes can also be seen rising up the side walls, due to either the momentum of the inflow towards the right wall or to attachment to the left wall as convective elements rise in the quiescent region between the vents. Turbulent temperature fluctuations are present throughout, and temperature profiles show a very weak linear stable temperature gradient, equivalent to a change of 0.7K over the height of the space. In the absence of the plume, a similar temperature gradient is measured, but with a mean 0.2K colder. Hence, the addition of weak localised heating has lead to a general warming of the entire space.

A steady displacement flow pattern established by a dominant localised source (ψ large) is shown in figure 2b. The plume fluid is dyed, and the two-layer structure is clearly visible. Turbulent density fluctuations visualised by the shadowgraph are weaker below the interface than above. Some shadowgraph visualisation of the interface is also possible, despite the fact that its mean width is approximately 3cm. Temperature profiles show an interface with a temperature jump of 1.2K, centred at $h/H = 0.61$, while in the absence of the distributed source there is an interface with a temperature jump of 2.7K, centred at $h/H = 0.47$. Hence, the addition of the distributed heating has raised and weakened the interface.

In all cases, the steady results obtained did not depend, within experimental error, on the order of activation of the heat sources. The steady interface height h/H and interfacial temperature step ΔT measured for a range of ψ and opening areas in the range $0.015 < A^*/H^2 < 0.020$, are shown in figure 3. As the buoyancy flux from the distributed source increases relative to the localised buoyancy flux (ψ decreases) the interface height increases gradually, while the temperature step across the interface decreases. As ψ decreases below 0.3, small decreases in ψ cause large increases in interface height and corresponding large decreases in the temperature step, until for $\psi \leq O(0.1)$, no interface could be distinguished.

Transient flow

Sequences of temperature profiles displaying the approach to steady state are shown in figure 4. In the experiment shown in figure 4a, the localised source was activated first, producing a two-layer stratification [5], with an upper layer temperature of 21.0°C. The introduction of a weak distributed heat source (just before the arrowed profile) generated turbulent convection, which broke through and disrupted the interface. A neutral or weakly stable temperature gradient was created throughout the whole space, while the mean temperature of the fluid rose significantly. Then the plume (a source of much hotter fluid than any within the ventilated space), re-established a two-layer stratification, with a steady upper layer temperature of 24.8°C and a lower layer temperature of 22.8°C. In the present experiments, in the range $\psi > 0.09$, we always observed the two-layer stratification break down during these transients.

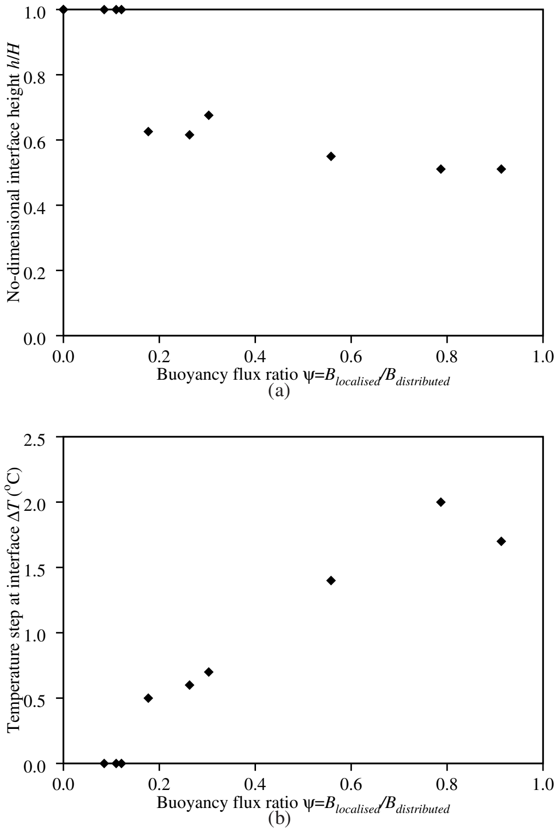


Figure 3. Variation of (a) dimensionless interface height h/H and (b) temperature step ΔT with the buoyancy flux ratio $\psi = B_{localised} / B_{distributed}$, for openings areas in the range $0.015 < A^*/H^2 < 0.02$. Note that for $\psi \lesssim 1/6$ an interface is not observed ($h/H = 1$) and the interior is well-mixed ($\Delta T = 0$).

The transients recorded when the distributed heating was activated first are shown in figure 4b. The distributed heating alone produced an approximately well-mixed interior, at a temperature that exponentially approached a steady-state value of 28.1°C. The introduction of a sufficiently strong localised heat source lead to the formation of a warm layer at the top of the space, which thickened until a steady state was reached. In the steady state, the upper and lower layer temperatures were 29.6°C and 28.2°C. Weaker heat sources caused only a uniform increase in temperature.

When both heat sources were activated simultaneously, and the localised source was sufficiently strong (figure 4c), a weak stratification developed, while the whole interior increased in temperature. After some time, two layers became visible, with an interface at about h = 19cm. In the steady state, the upper and lower layer temperatures were 17.6°C and 17.2°C. In z < 8cm, the thermocouple measurements show cooler fluid with large temperature fluctuations, which is flowing in through the lower openings and has yet to be incorporated into the lower layer.

Dependence on opening geometry

For a fixed ratio of buoyancy fluxes the stratification and fluid flow patterns were also observed for a range of dimensionless opening areas. It was found that both the opening area and the opening location had a significant effect on the flow patterns. In the displacement flow regime, increasing the vent area raised the interface position. This implied an increased flow rate through the tank, and also gave rise to a reduced temperature step across the interface. In the mixing flow regime, the mean temperature decreased as the vent area increased.

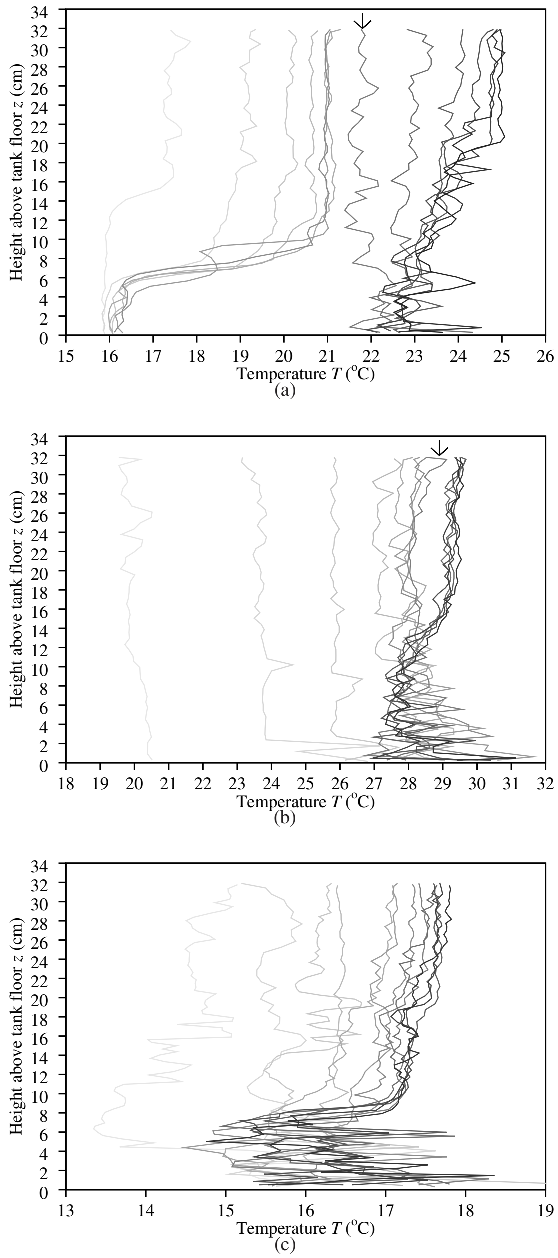


Figure 4. Temperature profiles at 3.1min intervals showing transient flow evolution. Darker profiles are at later times, and the arrow shows the introduction of the second heat source after 22min. (a) localised then distributed (ψ = 0.79, A^*/H^2 = 0.020), (b) distributed then localised (ψ = 0.56, A^*/H^2 = 0.018), (c) localised and distributed simultaneously (ψ = 0.18, A^*/H^2 = 0.047).

By varying the spatial location of openings at either high or low level the degree of horizontal inhomogeneity in the displacement flow, and the nature of the circulation in the mixing flow regimes, could be significantly altered. For mixing flows, a general anticlockwise (figure 1) circulation was established. For a fixed A^*/H^2, the circulation was more pronounced when the lower openings were large relative to the upper openings. For large lower openings, the inflow swept across and covered a large fraction of the heated base, and carried this heated fluid up the right-hand wall. For small lower openings, although jets of ambient fluid entered with a higher momentum, they occupied less of the floor area. Therefore most convection occurred in quiescent fluid, resulting in predominantly vertically rising fluid and the absence of a dominant circulation.

For displacement flows, inflows with significant momentum were observed to rise up the right-hand wall and impact on the interface. In figure 2b, the inflow has detrained a portion of dyed upper layer fluid, seen as the patch of darker fluid below the interface to the right of the plume. This detrainment contributes to the warming of the lower layer, and leads to horizontal inhomogeneity. The temperature profiles measured by thermocouple traverses were in the left-hand half of the tank away from the plume and were not directly affected by detrainment.

Conclusions

We have shown that a two-layer stratification and displacement flow is established and maintained when the buoyancy flux from the plume exceeds approximately one sixth of the distributed heat flux. For weaker plumes, a well-mixed interior is established and maintained.

The steady flow pattern attained is independent of the order in which the two heat sources are applied, although clear differences are observed during the transients. The steady two-layer stratification established by a localised source is always broken down by the distributed convection for $\psi > 1/10$ although the stratification was reestablished for $\psi \gtrsim 1/6$.

The overall flow pattern was found to depend not only on the ratio of the localised and distributed buoyancy fluxes and the dimensionless vent area but also on the spatial location of openings. For some locations and relative sizes of the inlet and outlet openings, the flows exhibit strong horizontal inhomogeneity (displacement flow) or different patterns of circulation (mixing flow).

Acknowledgements

GRH and JMH would like to thank the EPSRC and Leverhulme Trust for their financial support. We would all like to thank the technicians at DAMTP for their technical assistance, particularly David Page-Croft, Brian Dean and Chris Mortimer.

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