NATURAL DISPLACEMENT VENTILATION OF AN ENCLOSURE WITH A DISTRIBUTED BUOYANCY SOURCE APPLIED TO ONE VERTICAL WALL

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ABSTRACT

This paper describes fundamental research into the behaviour of a naturally displacement ventilated space with one vertical heated wall. The experimental methodology involved the use of a water-filled scale model of a naturally ventilated room where salt solution was uniformly injected through one porous vertical wall to simulate uniform heating of the latter at full-scale. A computer-based image capture and analysis system was used to determine the resulting salt concentration profile within the enclosure as a function of time from video film of the experiments. Salt concentration was then used to infer temperature profiles at full-scale.

Experimental results are presented including the depth of the ambient air layer in a natural displacement ventilated room as a function of the non-dimensional vent size. Details of the transient development of the stratification profile are also given. The non-dimensional steady state stratification profile is found to be approximately linear and varies relatively little with respect to the magnitude of the buoyancy flux applied at the vertical wall.

KEYWORDS

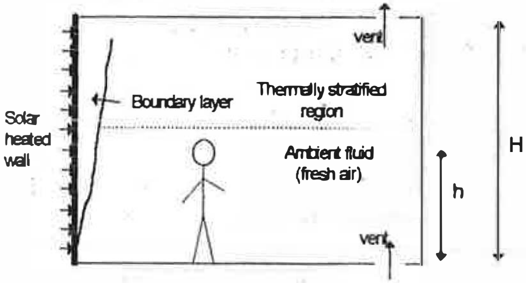
Natural Ventilation, Displacement Ventilation, Model Experiments, Measuring Methods, Temperature Gradient.

INTRODUCTION

Natural ventilation of buildings is becoming increasingly important for a number of reasons. These include the potential for reduction in greenhouse gas emissions from energy consumption by mechanical ventilation systems and the potential to provide healthier and more pleasant indoor environments for building occupants. A great deal of fundamental research is ongoing around the world into the fundamentals of buoyancy driven natural ventilation processes. This paper reports on recent research at the University of Wollongong, Australia, where saline solution scale modelling techniques have been used to study natural displacement ventilation processes.

The current work follows on from that at the University of Cambridge by Linden *et al.* (1990) who developed both experimental and analytical models of the natural displacement ventilation flows resulting from a point source of buoyancy on the floor of an enclosure. This work was later extended to cover multiple sources of buoyancy (Cooper and Linden, 1996, Linden and Cooper, 1996) and also combinations of wind and buoyancy driven flows (Hunt and Linden, 1997).

In the present study the geometrically simple situation of a naturally ventilated enclosure with one heated (or cooled) side wall is considered as shown schematically



in Figure 1.

Figure 1 Schematic of a naturally ventilated space with one heated vertical wall.

There has been an enormous amount of research effort devoted to the similar situation of a sealed enclosure with purely natural convection arising from opposite vertical walls being heated and cooled, respectively. However, there has been relatively little research reported in the literature on the situation of Figure 1 despite its practical significance in building design.

The significance of the present work lies in the fact that we are seeking a simple quantitative analytical model of the thermal stratification that will arise in practical buildings with a heating situation as shown in Figure 1. Such a model was proposed by Linden *et al.* (1990) who suggested that multiple horizontal layers of buoyant fluid might form as a result of de-entrainment from a plume or natural convection boundary layer as shown schematically in Figure 2. They proposed an analytical solution for the depth of such layers using an assumption that the depth of all layers is equal.

The purpose of the present experimental work is to determine the fundamental fluid mechanics that are involved in the situation of Figure 1. Some preliminary results of this work were reported previously by Cooper and Linden (1996) and Cooper and Mayo (1997). Since that time the experimental techniques and apparatus have been refined and the present paper reports on experimental results obtained using video film image processing for measurement of salt concentration fields in the scale model.

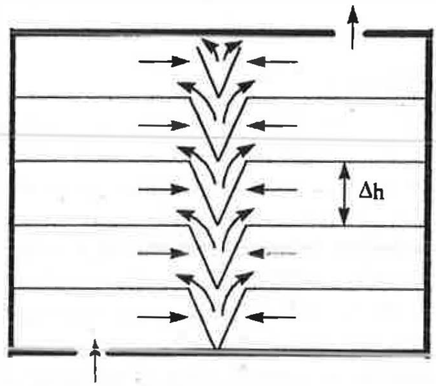


Figure 2 Steady displacement flow hypothesised by Linden *et al.* *(1990)* to occur in a box containing a vertically distributed source of buoyancy.

METHODS

The experimental technique employed a water-filled scale model injected with salt solution through one vertical wall to represent the non-isothermal case at full scale. The experimental apparatus is shown schematically in Figure 3 and comprised a cubic enclosure of internal dimension 250mm with one vertical porous wall fed with salt solution. This enclosure was suspended in a large tank of ambient fresh water which was continually fed/drained to maintain constant ambient conditions. The ceiling and floor both had a number of vents of different sizes for the purpose of varying the non-dimensional vent area of the enclosure, A^*/H^2, where A^* is the effective vent area and H the overall height of the enclosure (see Cooper and Linden, 1996).

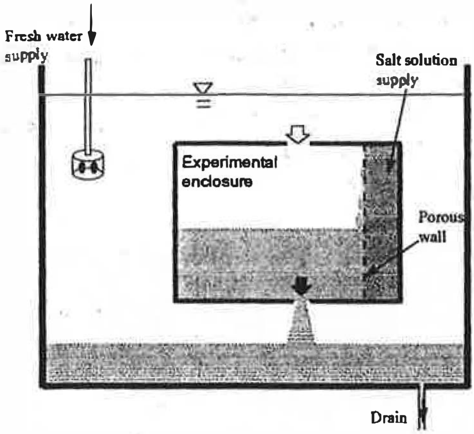


Figure 3 Schematic of enclosure in ambient fresh water tank.

In the scale model salt concentration was analogous to temperature at full-scale and an image processing methodology was used to permit evaluation of the essentially two-dimensional salt concentration field at any given time. Food dye was dissolved in the salt solution supply and the flow visualised by back-lighting the apparatus with an approximately parallel light source and this was recorded as a shadowgraph using a Sony XC77RR CCD video camera and VCR. The video images were then analysed using a specially developed macro program for the DigImage software image processing system (Dalziel, 1993). Corrections were made for background lighting levels and the image processing system was calibrated both against salt solution samples taken in situ and against a traversing electrical conductivity probe.

A number of experiments were conducted to determine the relationship between the stratification within the enclosure as a function of the non-dimensional vent area A^*/H^2 and to determine if the non-dimensional stratification is independent of the magnitude of the buoyancy flux supplied to the active vertical wall.

In all experiments the overall vent area at the exit of the enclosure was considerably smaller than at the entry (of ambient fluid).

It should be noted that the injection of salt solution through the porous wall clearly means there is a deviation from the dynamic similarity between the model and full-scale (where there is obviously no mass flow through the heated wall). At low vent effective areas the flow through the porous wall did represent a significant fraction of the total volume flow exiting the enclosure. The depth of the ambient layer found in these experiments is therefore likely to be somewhat less than would be found at full scale.

RESULTS

The main features of the flow field and stratification within the enclosure are shown in Figures 4 and 5. (Note: throughout this paper the images from experiments have been inverted to match the situation that would be found in a full-scale building with one heated wall). A turbulent natural convection boundary layer was present over virtually the whole of the active wall. The thickness of this boundary layer increased dramatically at the interface between the ambient fluid layer in the enclosure and the buoyant layer of fluid. At this point a very significant proportion of the boundary layer fluid could be seen to be de-entraining horizontally into the bulk of the enclosure.

Of particular interest was the non-dimensional height, h/H, of the ambient fluid layer as a function of the non-dimensional effective vent area, A^*/H^2. Figure 6 shows experimental results from two sets of experiments (Buykx, 1995 and Mayo, 1997). This is compared with the non-dimensional height that would occur with a naturally ventilated enclosure with one point source of buoyancy on the floor (Linden *et al.*, 1990).

It should be noted that since the lighting of the experiments produced a shadowgraph image there is some modification of the light intensity resulting from the presence of dye in the salt solution. Refraction effects in regions of intense salt concentration gradients (eg at the interface between the ambient and buoyant layers) cause some irregularities on the image, but also serve to highlight where intense concentration gradients are present.

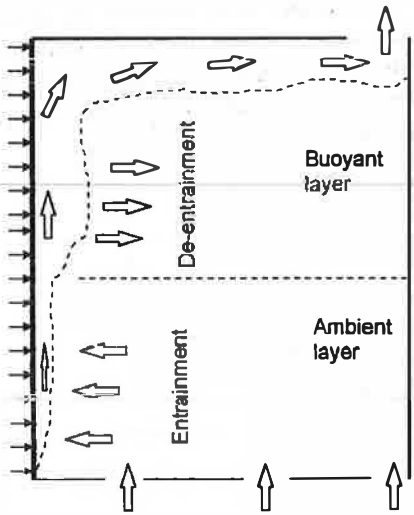


Figure 4 Main features of flow

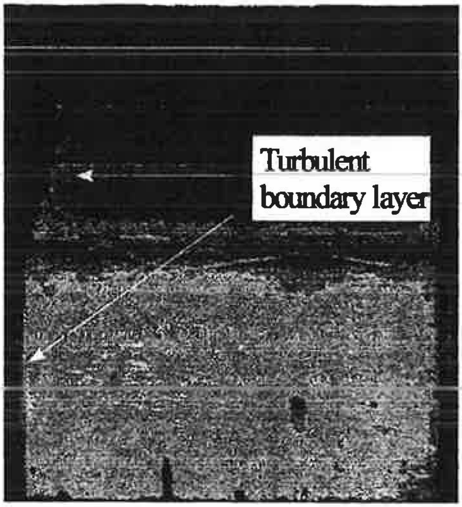


Figure 5 Image captured during a typical experiment

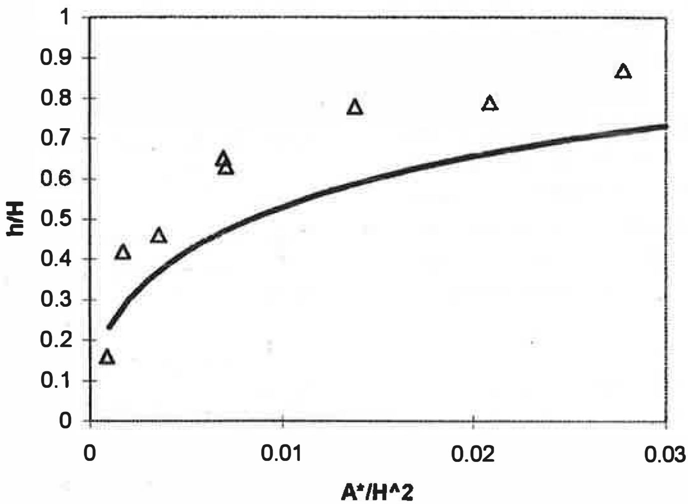
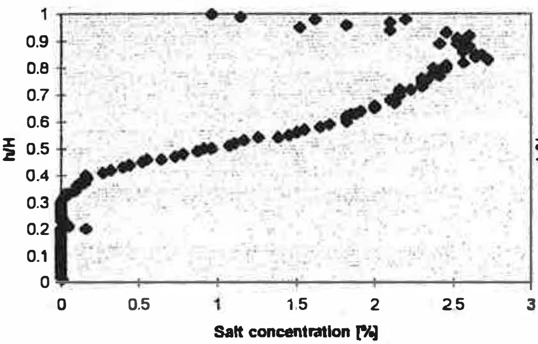


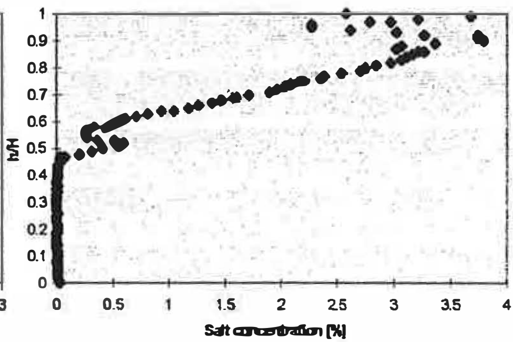
Figure 6. Comparison of experimental results of non-dimensional ambient layer depth as a function of non-dimensional vent area. (Symbols are experimental data from the present study; solid line is theoretical prediction for the situation with a single point source of buoyancy on the floor of the enclosure from Linden *et al.*, 1990).

Our most recent experimental results give quantitative values to the stratification in the buoyant layer generated by the active vertical wall. Evaluation of the stratification in the enclosure did not include the region in the immediate vicinity of the active wall which was disturbed by the associated boundary layer. Rather the mean concentration at a given height, h, above the floor was determined by averaging the image intensity horizontally across the enclosure excluding the boundary layer region.

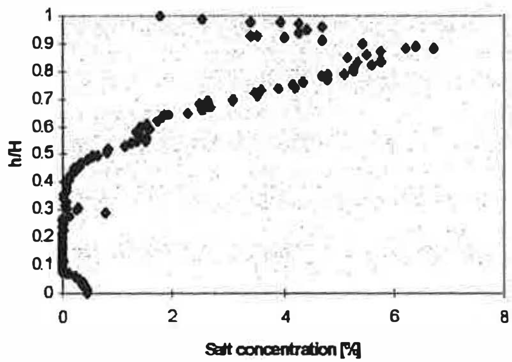
A typical set of experimental data generated from light intensity analysis is shown in Figure 7. The salt concentration has been calculated from the direct calibration of the video recording and image processing system. Full details are provided in Mayo (1997) and Sørensen (1998).



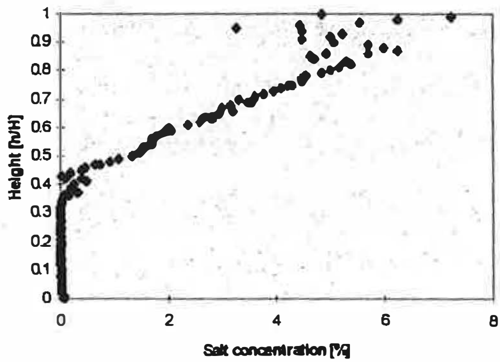
a) Supply concentration C_0=5%



b) Supply concentration C_0=10%



c) Supply concentration C_0=15%



d) Supply concentration C_0=20%

Figure 7 Stratification in enclosure A^*/H^2=0.0036

DISCUSSION

The flow fields in the experiments reported here was complex. There appeared to be four main regions in the flow field: a) the ambient fluid layer; b) a region of one or more buoyant layers; c) a gravity current moving across the horizontal exit wall of the enclosure generated by the boundary layer on the porous vertical wall, the presence of which can be seen in the graphs of figure 7 for h/H>0.8; d) the natural convection boundary layer region.

The ambient layer depth as a function of the non-dimensional vent area for the situation of interest is in seen to follow the same general form as that for the enclosure with a point source of buoyancy but with a significant offset (Figure 6). The ambient layer depth is greater for the vertically distributed buoyancy source than that for the point source.

The ambient layer depth was not found to be strongly dependent on the magnitude of the buoyancy flux at the porous wall. The results shown in Figure 7 indicate that at supply concentrations C_0>10% the height of the ambient layer was virtually independent of the wall buoyancy flux. For C_0<10% there was greater mixing in the enclosure due to a reduction in magnitude of the overall stratification.

Between the top of the ambient layer and the gravity current, the buoyant layer appeared to have an approximately linear concentration profile. This finding is consistent with several full scale studies however there is significant scatter in the experimental data and further work is required to determine the precise nature of the stratification in the enclosure.

In some experiments the presence of more than one distinct buoyant layer has been found, evidenced by light refraction from intense concentration gradients between such layers. Figure 8, for example, shows the transient development of a particular experiment where intense concentration gradients were present. The video images have been processed such that a narrow vertical band of pixels has been extracted from images spaced at regular intervals in time to produce a qualitative plot of light intensity over the vertical extent of the experimental enclosure as a function of time. Note that the light horizontal bands indicate the development of intense vertical salt concentration gradients.

Whether these regions of intense stratification are an artefact of the experimental methodology or whether they are a phenomenon associated with the fundamental fluid flow situation is a question to be addressed in future research.

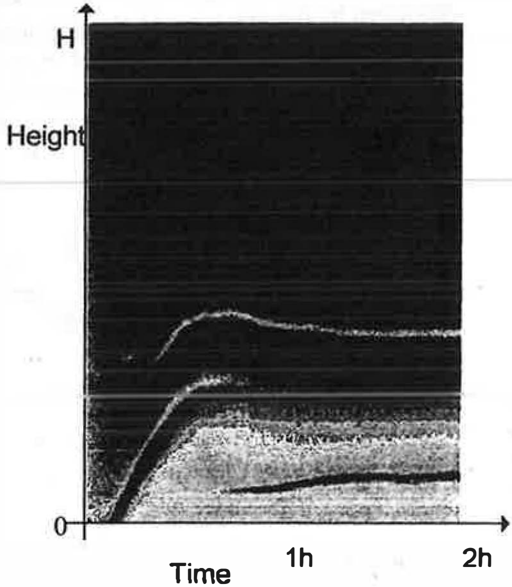


Figure 8 Qualitative plot of stratification as a function of time in the naturally ventilated enclosure - dark regions correspond to high salt concentration A^*/H^2= 0.00089. The light bands are a result of the influence of refraction on the shadowgraph. NOTE: images have been inverted to show situation in Figure 1.

CONCLUSION

An experimental methodology has been developed whereby the salt concentration profiles in a two dimensional flow field may be determined by video image analysis of a water-filled scale model injected with coloured salt solution.

The experimental results for a naturally ventilated enclosure with an approximately uniform buoyancy flux injected through one vertical wall show that the ambient layer depth in the enclosure is determined primarily by the non-dimensional effective vent area, A^*/H^2. The ambient layer depth was found to be greater than that for an enclosure containing a single point source on the floor.

The flow field in the enclosure comprised four main elements: the ambient layer; an approximately uniformly stratified layer; a boundary layer region on the active wall; and a gravity current on the ceiling of the enclosure which is fed by the boundary layer flow.

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