1. Introduction

Thermal stratification is often a dominant feature of the flow characteristics within ventilated buildings. There may be many heat sources such as occupants and equipment within a room that act like heat sources and thermal plume develop around them resulting into a vertical temperature gradient. These sources may develop pure buoyancy driven plumes or mixed convection jets as in the supply of hot air in mechanical heating systems. Generally such jets or plumes propagate entraining air from ambient to a height where the temperature within the jets becomes equal to the ambient temperature. At this height flow becomes stratified and there may be a zone above or below the stratified zone where flow is mixed i.e. the temperature profile is uniform.

It has been shown that the flow region is usually divided into zones characterised by temperature gradient. The temperature gradient within the enclosure is influenced by ventilation flow rate and not so much by the position of the heat sources. Thus contaminant removal effectiveness, in displacement ventilation, is influenced by the ventilation flow rate and also sensitive to the level of the source and its position [1, 2]. The vertical position of the interface is also related to the ratio of the upper and lower vent areas depending on the nature of the heat source as shown by Fitzgerald and Woods [3].

For maintaining air quality and thermal comfort any ventilation system must ensure that (1) the interface between the thermally stratified zone and clear zone is adequately high to keep the working zone at a desirable temperature and clear of any pollutants and (2) the thickness of the stratified zones are large enough to contain all the pollutants within. Therefore the understanding of the mechanisms of the flow patterns leading to stratification is particularly important for displacement ventilation systems and naturally ventilated buildings.

Various experiments have been reported on the study of the flow characteristics for displacement and natural ventilation and information is available on plume development due to single and multiple heat sources and the development of zones within confined spaces [5, 6, and 7]. Most experiments by Linden et al were performed using scale models and salt-bath technique [5]. However, it is not always possible to maintain similarity for both momentum and heat transfer in the model due to differences in the properties of air and water. The current experimental study investigates the flow characteristics within enclosures due to the temperature and momentum differential across the enclosure. In particular the focus is on studying the effect of positioning of the inlet and outlets and the flow rates on the vertical temperature profiles in order to evaluate the characteristics of stratification namely height of the interface, the thickness and the stability of stratified layers.
2. Experimental setup:

All tests were conducted in the environmental chamber at the University of Hertfordshire (Figure 1). The test chamber (enclosed by another room) was 7.5m long, 3.6m wide and 3.0m in height. The walls floor and ceiling were well insulated by polyurethane foam. During the tests the temperature in outer space was also maintained close to the inside temperature to minimise the heat transfer from the test room to the surroundings.

The inflow parameters were controlled by the environmental control systems. The air treatment plant consisting of heating batteries and a cooling unit, can supply airflow up to 14m3/min. The system can supply air at temperatures ranging from -40˚C to +50˚C. The supply and extract locations can be positioned at any position within the room. The vertical temperature measurements within the chamber were made using a vertical array of eighteen K-type thermocouples ~15cm apart as shown in Figure 1. Supply and extract flow rates and velocities were also monitored using a rotating vane anemometer was used to measure airflow rates at the supply inlets. The accuracy of the velocity measurements was ±2% for the readings from 5-30 m/s, and ±0.1 m/s for the readings between 0.25-4.99 m/s.

Experimental Procedure

Preliminary experiments were performed by adjusting the supply air flow rates and temperatures to set up zones of stratified flow within the enclosures. The input location for cold and hot air supply was at different heights. The hot and cold air was supplied into the chamber to create a temperature differential across the height of the enclosure so that stratified flow is established. Initially cold air was entered at the bottom of the environmental chamber and the hot air was near the top of the chamber. Flow visualisation was done using an oil-based smoke machine in order to study flow characteristics identifying the location of the interface and stratification layer thickness. To study the characteristics of the stratification of the flow vertical temperature measurements were taken at the centre of the environmental chamber, where walls would not have any significant effect on the measurements. Measurements were also made at other locations in the horizontal plane in the flow direction (x-axis) and across the flow (z-axis) to study the temperature variation within the wider space and to estimate the influence of the momentum source on the interface height. The experiments studied the effect of the location and flow rate of in flow of hot air and cold air on the stratified flow characteristics. The air inflow rate was varied from (1-5m3/min). The tests allowed us to study the effect of both hot and cold air in flow rates and locations of the supply ports on the stratified flow.

3. Results and discussion

Flow visualisation

The flow visualisation using smoke provides the qualitative information of the flow characteristics within the room. Figure 2 shows a typical photograph of the three flow zones.

Smoke penetrates the lower mixed zone and spreads horizontally at certain height and stay within this region to form a layer of certain thickness where the flow direction is only in the horizontal plane. In this case flow is driven by the extract and moves in the direction of the exhaust opening. The interface between the stratified and mixed zones is also clearly visible. The thickness of the stratified layers and the location of the interface depend upon flow parameters. Generally there is always an increase in temperature with the height and flow stratifies from the floor to the ceiling without zone establishment. However, when designing displacement ventilation installation it is important that there is stable stratified zone located above the working zone. Thus vertical temperature gradients are presented to study the conditions that lead
flow to form into distinct zones. From these the interface location, stratified layer thickness and degree of stratification can be estimated. Temperature profiles are plotted in terms of the dimensionless temperature \((T - T_c)/(T_h - T_c)\) along a vertical height with \(T_h\) and \(T_c\) being respectively the temperatures at the ceiling and the floor of the chamber and versus dimensionless height \(z/H\). Figures 3a and 3b show the non-dimensional vertical temperature variation with respect to the non-dimensional height for two different cases. The hot air input location is fixed at 1.5m for both cases. The flow is divided into three zones (Figure 3a), whereas there are only two flow regimes as shown in the Figure 3b. Flow is stratified starting from the floor to some height \((z/H\sim0.2)\) and then temperature gradient becomes smoother in the upper region. In this case the hot air flow rate was increased from 2m3/min to 3m3/min, which not only resulted in higher momentum but there was slight increase in the heat input into the enclosure. Initial momentum is increased which resulted in better heat transfer due to mixing and the higher temperatures are extended further down towards the floor. The stable stratified layers are also pushed towards the floor. Although the flow parameters were estimated using the overall dimensions of the enclosure in order to investigate the combined effect of different mechanisms within the room, the change in parameters (Re) is due to change in the hot-air supply, thereby the change in the flow characteristics is more apparent in the upper region which is more affected by these changes. Figure 4 shows the vertical temperature profiles for a changed position of the hot air supply for the same range of flow parameters as in Figure 3a. Despite a shift from 1.5m to 2m the temperature profiles are similar and the flow region is divided into three zones. It is obvious from the figures (Figure 3a and Figure 4) that for the same flow parameters by changing the location of hot air supply from 1.5 m to 2.0 m there is no change in the thickness of the stratified layer. However there is a shift in the location of the interface which depends linearly on the shift in the vertical location of the hot supply terminal. In both cases flow is divided into three zones; two mixed zones divided by a clear stably stratified layers. The temperature profile also varies from a mild gradient in mixed zone to a steep gradient within the stratified layers. The Richardson number (Ri) is large enough for flow to be stratified. However, as the input location shifts upward the interface also moves upwards towards the ceiling of the chamber. When the input height is at 1.5m the lower zone also show some stratification as the local Ri number is approximately 0.15. The thickness of stably stratified region (for local Ri >0.25) is similar in both cases. The effect of buoyancy is more significant than the momentum forces in this case. The overall effect of various mechanisms that influence the flow characteristics within the enclosures are defined by Re and Ri. Figures 5 and 6 show the dimensionless temperature profiles for various values of global flow parameters controlled by the flow rates of cold and hot air. For both cases shown in Figure 5, Ri is of the same order and the profile shows stable stratification and the interface forms. However, due to the difference in the momentum forces i.e. Re number, the location of interface is not the same. For a higher Re number which was achieved by increasing the momentum of air supply at the floor level, the interface is shifted towards the floor and is below the exhaust level. For weak momentum (Re=9700) the interface is at the exhaust location. Increase in momentum also results in decrease in global temperature difference. The flow is stratified right from the floor level to the exhaust location for both cases shown in Figure 6. The location of interface is below the exhaust location for both cases but very different to on another. As shown in the temperature distribution i.e. the position of the interface and the level of stratification is both affected by the momentum and buoyancy forces.

![Figure 3a: Vertical temperature profile at the mid plane (Re: 9710-19430)](image)

![Figure 3b: Vertical temperature profile at the mid plane (Re varies from ~1300-25000)](image)

![Figure 4: Vertical temperature profile at the mid plane (Re varies from 9710-19430)](image)
4. Conclusions

The effects of input location on the stratified flow characteristics were investigated. When a location of hot air input terminal is high towards the ceiling, supply is in terms negatively buoyant jet. The ratio of momentum and buoyancy forces is such that sufficient flow stratifies across the height of the room and the flow region shows a clear stratified zone with an interface, while for a low level input location, the interface level moves downward yielding unstable stratified flow leading to mixed flow in both zones. The temperature distribution in the upper zone is somewhat independent of the location of input location unlike the lower zone. Although air supply at high momentum tends to de-stratify the flow, leading to vertical uniform temperature profiles and high temperature differences lead to stratification of the flow, it is the relative influence of inertial and buoyancy forces that determine the position of the interface and degree of stratification.

References


