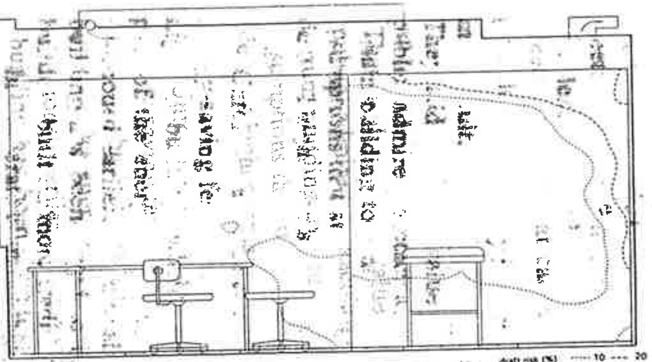

Fig. 4. Measured draft risk (%) (outdoor air temperature - 5 °C)

DISCUSSION

Experiences from this full-scale modelling showed that it is possible by good planning to help prevent faults in design. This experiment has ensured that it is possible to gain desired results with properly planned HVAC equipment, acoustic environment and materials. Special attention has to be paid to the building construction, so that designs are realized as planned.

This kind of modelling can be recommended particularly in cases where several similar rooms are built. Building costs can be saved because of the possibilities of finding alternative, better and cheaper constructions. In cases where planned constructions do not work, repairing or changing the constructions is much more expensive than making full-scale tests.

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DRAUGHT RISK FROM COLD VERTICAL SURFACES

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ABSTRACT

Glazed facades and atria have had a boom in the 1980's as an architectural feature in building design. Natural convective flows from these cold surfaces are in winter time, however, often the cause of thermal discomfort and there is a need for research to improve the design methods.

The objective of the research is to develop expressions for the airflow beyond the floor area, which influences the thermal comfort in the occupied zone.

Measurements of velocities and temperatures are carried out in a two-dimensional test case. They show that the characteristics of the flow in the near floor region are very similar to the characteristics of stratified flows. Expressions have been developed for the rate of decrement of the maximum velocity with distance from the surface and for the maximum temperature difference between the cold airflow along the floor and the rest of the occupied zone.

INTRODUCTION

Cold surfaces often generates thermal discomfort in rooms, due to cold radiation effects and down draught problems caused by the cold natural convective flows from these surfaces. As we design preventive actions we should note that the surfaces may also cause an unnecessary increase in energy consumption. There is a need for research in order to improve design methods for natural convective boundary layer flows, and under which circumstances there will be thermal comfort problems in the occupied zone, and how to solve them considering also the energy consumption?

The development of natural convective boundary layer flows along a vertical plane surface, and the velocity distribution and temperature gradients of such flows, have been thoroughly investigated theoretically and experimentally by several researchers (1,2,3,4).
The interest of the research has, however, ceased at the bottom edge of the surface and only a few researchers (5,6) have investigated what happens to the boundary layer flow as it hits a surface normal to it, here the floor, and continues into the occupied zone.

The objective of the research is to contribute to improved design methods for natural convective flows along cold, vertical and plane surfaces, and especially continue the experimental work (5,6) to develop expressions for the velocities and temperatures in the airflow into the occupied floor area, which influence the thermal comfort in the occupied zone.

EXPERIMENTAL ARRANGEMENT

The experiments mentioned in this paper were performed in a full-scale test room located in a laboratory hall. The dimensions of the room were 7 m × 6 m × 3 m (length × width × height). 18 cooled panel radiators (18 m²) covered one of the end walls. There were no mechanical ventilation or heat sources in the room.

The radiators were cooled by water and the surface temperature could be held within ± 5% of the average surface temperature. The measurements took place under steady-state conditions. The average surface temperature did not alter more than 0.3 °C during the measurements, and the temperature difference between the cooled surface and the occupied zone did not deviate more than ± 4% from the average value. The reference temperature in the occupied zone was measured 1.1 m above the floor in the middle of the room.

Various temperature differences between the cooled surface and the occupied zone were studied. The velocities and temperatures in the two-dimensional airflow along the floor were measured at different heights (y = 0.01 - 0.5 m) above the floor and at different distances from the cooled surface (x = 0.2 - 6.0 m). The velocities were measured by hot-spheres (DISA low velocity anemometer type 54R10) as a mean velocity for an integration period of 5 minutes. The temperatures were measured at one minute intervals with thermocouples.

THE MECHANICS OF COLD DRAUGHT

If a vertical plane wall is cooled to a temperature lower than the surroundings, the layer of air adjacent to the wall is cooled by conduction. In this way, buoyant forces are generated which cause this layer to flow in a downward direction. This layer of air adjacent to the wall, to which the vertical motion is confined, is called the natural convection boundary layer. The boundary layer begins with zero thickness at the top of the vertical wall and increases in thickness in the downward direction. If the wall is placed in calm surroundings, the boundary layer flow at the top of the wall will be laminar and at a certain distance from the top it will become turbulent.

Solution of the boundary layer equations in the turbulent case, (1), gives the following relation for the maximum velocity, U_{max}, at the base of the cold vertical surface:

$$U_{max} = k \sqrt{h \, \Delta t} \qquad (m/s) \tag{1}$$

where h is the height in metres of the vertical surface and Δt is the temperature difference between the cooled surface and the reference in the occupied zone. The value of k obtained in previous experiments (1,5,6) varies between 0.052 and 0.10.

The important issue in relation to thermal discomfort is, however, not the maximum velocity at the foot of the surface, but the maximum velocity in the occupied zone after the boundary layer flow has reached the floor, the rate of decrement of the maximum velocity with distance from the surface and the maximum temperature difference between the cold air flow along the floor and the rest of the occupied zone.

MEASUREMENT RESULTS

Figure 1 shows the measured maximum velocity in the occupied zone, $U_{max,oc}$, as a function of the height of the cold surface and the temperature difference between the surface and the reference in the occupied zone. It is seen that the maximum velocity can be expressed by equation (1) and that these experiments suggest the value of k to be 0.055.

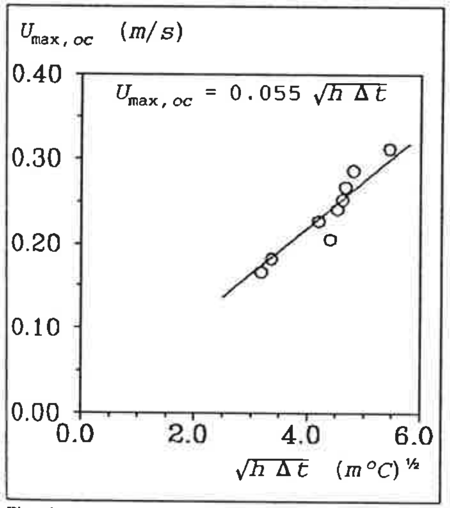

Fig. 1. Maximum velocity in the occupied zone as a function of height of the surface and temperature difference between surface and room.

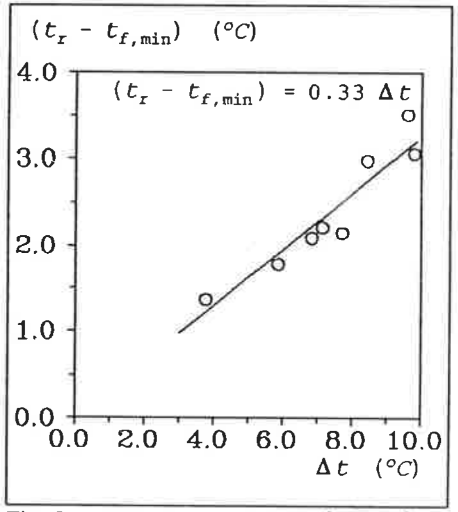

Fig. 2. Temperature difference $(t_r - t_{f,min})$ as a function of the temperature difference Δt.

Figure 2 shows the difference between the reference temperature and the minimum temperature in the cold airflow along the floor, $(t_r - t_{f,min})$, in the occupied zone as a function of the temperature difference Δt between the reference temperature and the average surface temperature. It is seen that the relation is linear and that the maximum temperature difference in the occupied zone is 33% of Δt.

The maximum velocities and minimum temperatures shown in the figures 1 and 2 are measured at distances less than 0.4 m from the cold surface and less than 0.03 m from the floor. But what happens when the airflow penetrates further into the occupied zone? This is shown by figures 3-6.

The measurements along the floor show that the flow field induced by the cold boundary layer flow at the vertical surface can be divided into three different zones.

A zone close to the vertical surface where the flow changes from vertical to horizontal direction and a dense current is established. A second zone where the flow is basically a buoyant jet. Profile measurements in this zone show that the flow in the vicinity of the floor can be characterized by a normalized velocity profile. In figure 3, the velocity profile is compared with the profile used for the description of isothermal wall jet flow, (7), and it can be seen that the profiles do not have the same shape. The length scale δ in the profiles is defined as the height from the floor where the velocity has decreased to half the maximum velocity. In figures 4 and 5 it is shown that the height of the flow region is increasing linearly from a virtual origin behind the vertical surface, (x_o= 1.31 m). The maximum velocity is decreasing proprotionally to the distance from this origin and not

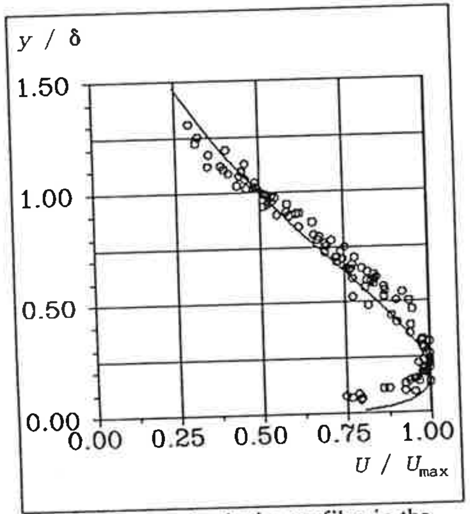

Fig. 3. Measured velocity profiles in the airflow along the floor compared with theoretical velocity profile for isothermal wall jet flow.

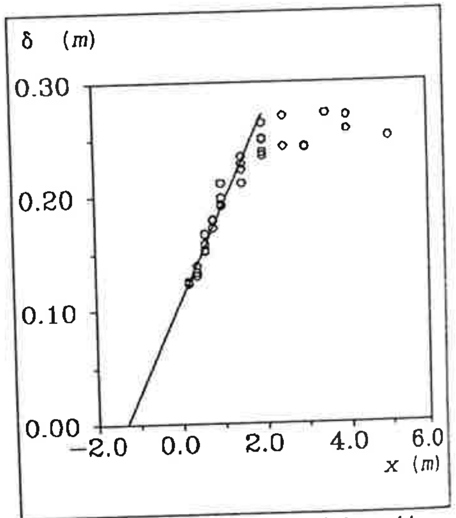

Fig. 4. Growth of thickness of the cold airflow region along the floor with distance from the cold vertical surface.

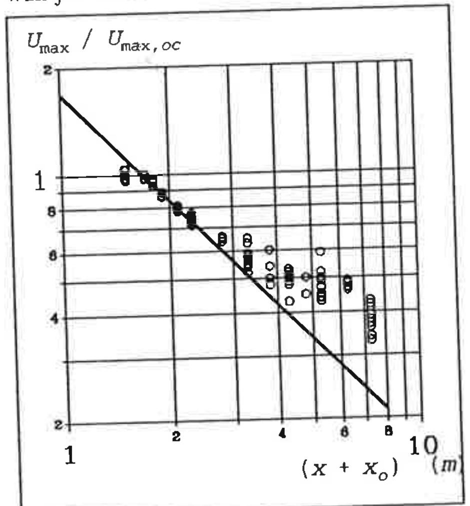

Fig. 5. Normalized maximum velocity in the airflow region close to floor versus distance from the virtual origin.

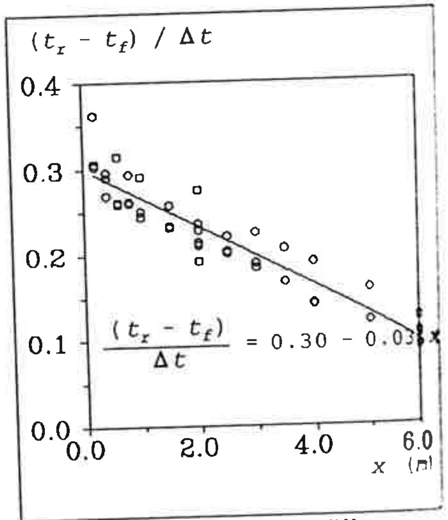

Fig. 6. Decay of temperature difference between the reference temperature and the minimum temperature in the airflow along the floor.

proportionally to the square root of the distance, as an isothermal wall jet. In the last zone the measurements show that both the height of the flow region and the velocities are rather constant with a constant maximum velocity of nearly half the level of the overall maximum velocity in the occupied zone. Figure 6 shows that the minimum temperature in the flow region close to the floor, except for the zone close to the vertical surface, increases linearly with the distance.

DISCUSSION

The experiments indicate that the characteristics of the flow in the near floor region are very similar to the characteristics of stratified flows as they are shown in hydraulics, (8,9), and lately also in displacement ventilation, (10). In the stratified flow theory, the flow is divided into subcritical and supercritical flow domains. In the supercritical flow domain the flow will entrain room air with a lower density in a similar way as a wall jet. The entrainment decreases due to increasing local Richardson number and, in a certain distance, the flow becomes subcritical with no or very little entrainment of room air.

The results also show two flow domains. One domain with growth of thickness of the flow region, indicating entrainment of room air into the cold air flow, and one with both a constant thickness and a constant velocity indicating no or very little entrainment of room air as typical for stratified flow. Further analysis of the measurements is needed before any final conclusions can be drawn.

The results give the following expressions for the maximum velocity and the minimum air temperature in the near floor region as a function of the distance from the cold vertical wall:

$$U_{max}(x) = 0.094 \frac{\sqrt{h\,\Delta t}}{x + 1.31} \qquad 0.4 \le x \le 2.0 \qquad (2)$$

$$U_{max}(x) = 0.028 \sqrt{h\,\Delta t} \qquad x > 2.0 \qquad (3)$$

$$t_f(x) = t_r - (0.3 - 0.034x)\,\Delta t \qquad (4)$$

The expressions are found for Grashof numbers between 1.12 - 3.85 10^{10}. The measuring results give a maximum velocity in the occupied zone of only half the value of the calculated maximum velocity at the cold vertical surface. At a distance of more than two metres from the cold surface the maximum velocity has decreased to 25 % of the maximum velocity at the cold surface. The expressions should be used with caution, because the room geometry might influence the flow development along the floor and the location of the transition between the two flow domains.

The equations (2) - (4) make it possible to estimate the "Percentage of Dissatisfied", PD, as defined in (11) because of cold downdraught. The percentage of dissatisfied is shown in figure 7 as a function of the temperature difference between the occupied zone and

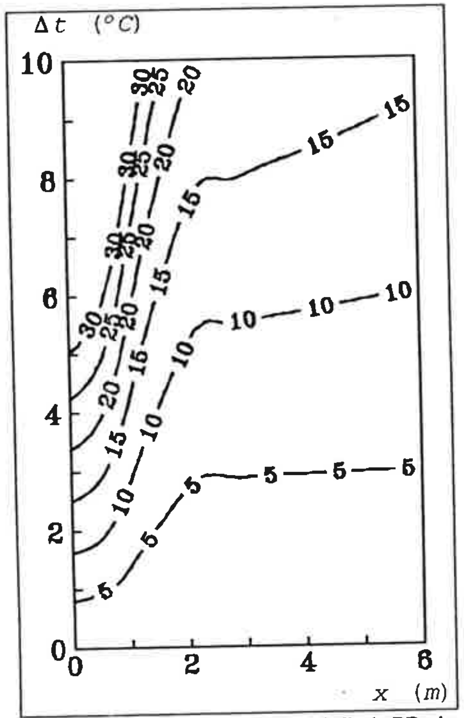

Figure 7. Percentage of dissatisfied, PD, in a room with a cold vertical wall.
h = 3 m, t_r = 22 °C.

the cold vertical surface and the distance from the surface. The percentage of dissatisfied occupants decreases rapidly within the first two metres from the surface because of the decrement of the maximum velocity. Then, it becomes nearly constant in the rest of the room, with a percentage of dissatisfied occupants below 20 % for a temperature difference between the occupied zone and the cold surface below 10 °C.

Further research will concentrate on partly cold surfaces which give a three-dimensional airflow along the floor area and on further analysis of the characteristics of stratified flow

ACKNOWLEDGEMENTS

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TURBULENCE INTENSITIES AND BUOYANCY EFFECTS IN A DISPLACEMENT VENTILATED ROOM MEASURED WITH LDA

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SUMMARY

The objective of this paper is to examine the air flow patterns and air turbulence behaviour in a displacement ventilated room. LDA (Laser-Doppler-Anemometry) technique produces data, not only on the average velocities and their fluctuations, but also on the direction of air flow. Three individual counter-flowing horizontal strata were observed. The mean vertical air velocities, outside of the buoyant plumes arising from the heat sources, were minimal. However, the presence of turbulence creates a different form of behaviour. High turbulence values were apparent throughout the whole room. This was a result of the unstable turbulent situation near the floor, where a negative temperature gradient increased the vertical turbulence, or the exchange of air pockets. Cooling of the floor surface temperature resulted in the reduction of this temperature gradient and the elimination of turbulence at this point. This may result in an improvement of the comfort conditions.

INTRODUCTION

It is commonly believed that turbulence levels in a displacement ventilated room are lower than those in a room with a mixing ventilation system. This is based primarily on the fact that lower supply air velocities are used. It is possible that this relationship is actually more complex than at first envisaged.

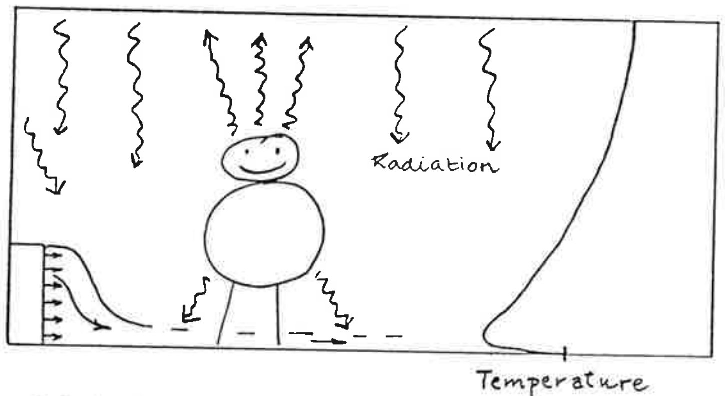

Fig.1. A typical situation representing displacement ventilation. The vertical temperature gradient is shown to the right of the diagram. The floor temperature is higher than that of the air which flows just above it. This is caused by radiation from heat sources, the ceiling and walls.