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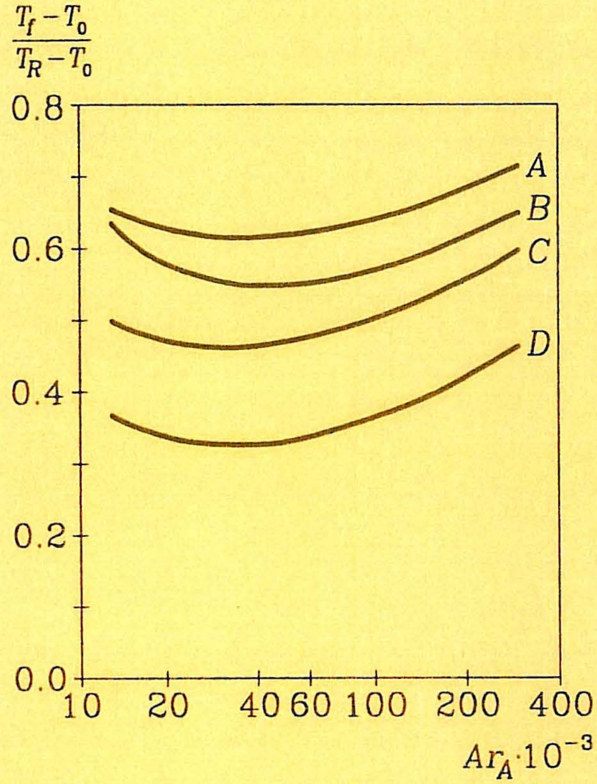

INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 67

Presented at the 5th International Conference on Air Distribution in Rooms
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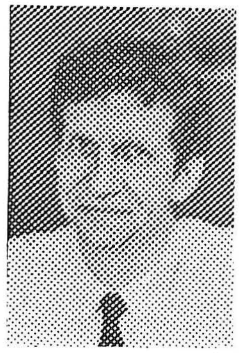

Temperature Distribution in a Displacement Ventilated Room

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ABSTRACT

The vertical temperature gradient is normally given as a linear temperature distribution between a minimum temperature close to the floor and a maximum temperature close to the ceiling. The minimum temperature can either be a constant fraction of a load dependent difference or it can be connected to the volume flow to the room.

This paper describes a new model which takes the different types of heat sources in the occupied zone as well as the characteristic Archimedes number of the flow into account. Full-scale experiments with different heat sources as: Distributed heat sources, Sedentary persons, Ceiling light and a Point heat source have been used in the development.

KEY WORDS

Displacement Ventilation, Vertical Temperature Gradient, Heat Sources, Experiments.

INTRODUCTION

It is necessary to have a design method for the calculation of temperature distribution used e.g. in connection with the flow element method and the energy calculations. The temperature distribution is also important in connection with the design of a displacement ventilation system and the evaluation of thermal comfort.

This paper will introduce a temperature distribution model which involves the different types of heat sources in the occupied zone as well as the characteristic Archimedes number of the flow.

FLOW AND TEMPERATURE DISTRIBUTION

The airflow to the room is supplied directly into the occupied zone by floor or by wall-mounted diffusers. The plumes from hot surfaces, from equipment and from persons entrain air from the surroundings in an upward movement, and the airflow is extracted from the room by return openings in the ceiling.

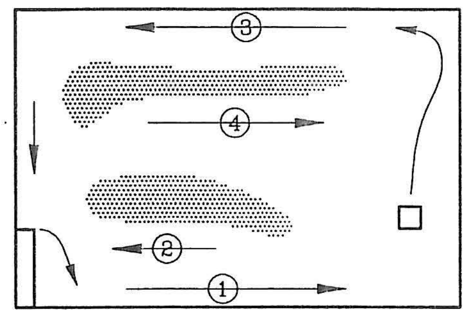


Figure 1. The main flow in the symmetry plane of a room ventilated by displacement ventilation.

Figure 1 shows a more detailed picture of the flow. Three areas with vertical flow are indicated. They are connected to a source or a sink to be able to penetrate the vertical temperature gradient. The flow from the diffuser has a downward direction because cold air is supplied at the full height of the diffuser. The vertical flow above the heat source obtains momentum from the buoyancy effect on the heated air, and a vertical cold downdraught exists at the walls due to gravity effect on the cooled air close to the surface. The downward flow at the wall may be connected to a detrainment effect where movement in the outer part of the boundary layer has stopped at density levels equal to the surrounding density. The detrainment effect has been measured by Etheridge and Sandberg (1996), and it can be predicted by Computational Fluid Dynamics, (CFD), Jacobsen and Nielsen (1994).

Figure 2 shows a typical temperature distribution in a room ventilated by displacement ventilation. The temperature distribution will force the remaining flow in the room to be horizontal and stratified. Figure 1 shows four areas with horizontal flow. A stratified radial flow from the diffuser exists at the floor (1), and above this area a return flow (2) is connected to the entrainment in front of the diffuser. The plume above the heat source will generate a stratified radial flow below the ceiling (3). The last flow (4) is located in the middle of the room and it is connected to the entrainment into the plume. This flow covers a large part of the room height, and it has a temperature which is increasing with the height. Areas with low velocity are shown between the flows of the opposite direction (2), (4) and (3).

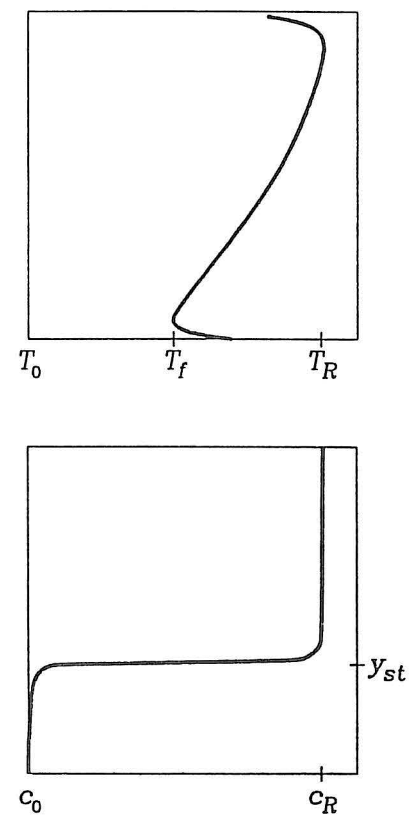


Figure 2. Typical vertical temperature distribution and simplified vertical concentration distribution in a room ventilated by displacement ventilation.

Figure 1 is predicted by CFD, but the four horizontal flows have also been visualized by Nielsen (1988) and measured with LDA by Kofoed and Kegel (1993), and they seem to be typical of a room with a single point heat source. The entrainment flow at the diffuser (2) will disappear when the Archimedes number is very small.

Figure 2 shows the vertical temperature distribution and a simplified vertical concentration distribution in cases where some of the heat sources are contaminant sources. The lowest sketch in Figure 2 shows that the concentration in a lower part of the room has the level c_o corresponding to the supply concentration. The plumes in the room will entrain fresh air (concentration c_o) up to a height where the total vertical volume flow is equal to the supply flow q_o. This height is called the stratification height y_{st}. The plumes continue above this height, and the entrainment will generate a full mixing in the upper region with a concentration c_R corresponding to the concentration in the return flow as shown in Figure 2. More complex profiles with stratified concentration peaks can be obtained when the contaminant sources are connected to weak heat sources as shown for example by Bjørn and Nielsen (1996).

The temperature distribution is described by the energy transport equation, the radiation and the conduction through the surfaces and it influences the flow via the buoyancy term in the vertical momentum equation. The energy transport equation and the transport equation for contaminant are identical in structure, and it is therefore possible to study the influence of radiation, conduction and buoyancy by comparing the two curves in Figure 2. The temperature close to the floor T_f is high in comparison with the equivalent concentration distribution. The high level of temperature is due to radiation from the ceiling, and the gradients close to the floor and the ceiling indicate the corresponding heat transfer by convection. The vertical temperature distribution varies almost linearly with height compared with the concentration distribution. This may be the result of an influence from the vertical temperature difference and detrainment at the walls. Radiation is important for the energy flow in rooms with displacement ventilation which has been discussed by Li et al. (1992, 1993) and Mundt (1996).

It is a general experience that the vertical temperature gradients are identical at any location in the room outside areas with large horizontal velocities.

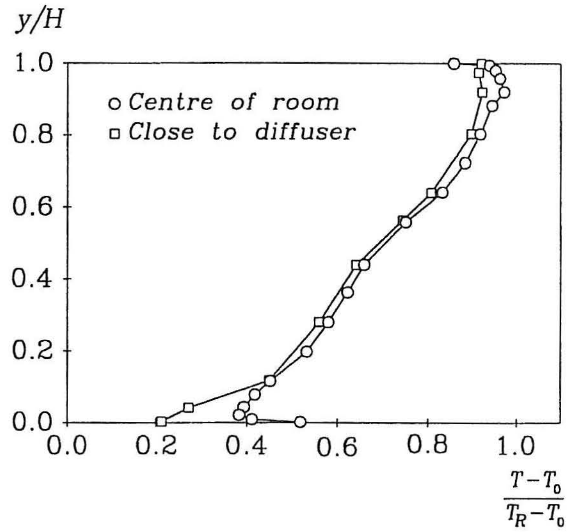


Figure 3. Two vertical temperature gradients in a room. One profile is located close to the diffuser, and the other profile is located in the centre of the room. $Ar_A = 18 \cdot 10^4$.

Figure 3 shows two vertical temperature gradients. They illustrate the identical temperature distribution in the main body of the flow ((4) in Figure 1), as well as different temperature distributions close to the floor and the ceiling ((1) and (3) in Figure 1). The temperature close to the floor T_f is defined as the average minimum temperature in the floor region. This temperature will often be linearly related to the temperature profile outside the stratified flow from the diffuser. The dimensionless temperature $(T_f - T_o)/\Delta T_o$ is for example 0.38 in the situation shown in Figure 3.

The primary flow in a room with displacement ventilation expresses the similarity which is typical of fully turbulent flow. The vertical temperature gradient and the stratification level of the contaminant can be described as a unique function of the Archimedes number independent of the velocity level in the room, see Nielsen (1988). This Archimedes number can be given as

$$Ar_A = \frac{\beta g H \Delta T_o}{u_A^2} \quad (1)$$

where β, g and ΔT_o are volume expansion coefficient, gravitational acceleration and temperature difference between return and supply flow respectively. H is the room height and u_A is defined as

$$u_A = q_o / A \quad (2)$$

where q_o is the flow rate to the room and A is the floor area. It is appropriate to use the floor area in the normalizing procedure, because the processes involved in the formation of the vertical temperature gradient (radiation, plumes above the sources, ...) seem to be independent of the room size.

It is also appropriate to normalize the temperature T by subtracting the supply temperature T_o and divide by the temperature difference between the return and the supply flow.

$$\frac{T - T_o}{T_R - T_o} \quad (3)$$

The measurements in Figure 4 show that the gradient has a limited variation when the flow rate is varied by a factor of 2.6, while a non-normalized gradient will show a very large variation with this change of the flow rate.

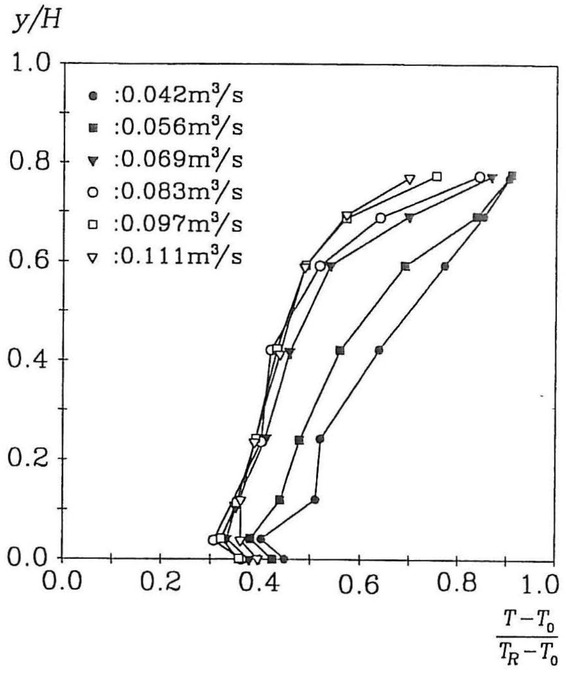


Figure 4. Vertical temperature distribution for different airflow rates, Nielsen et al. (1988).

TEMPERATURE GRADIENTS FOR DIFFERENT HEAT SOURCES

Measurements of vertical temperature gradients show that the type of heat source can be much more important than the flow conditions (Archimedes number). Figure 5 shows the vertical temperature gradient for different heat sources. The point heat source is a small cylindrical heater with open heating elements, 0.3 m × 0.1ø m. The thermal manikin is a black painted cylinder with the dimensions 1.0 m × 0.4ø m, and the floor heating consists of several electrical heating carpets covering a large part of the floor.

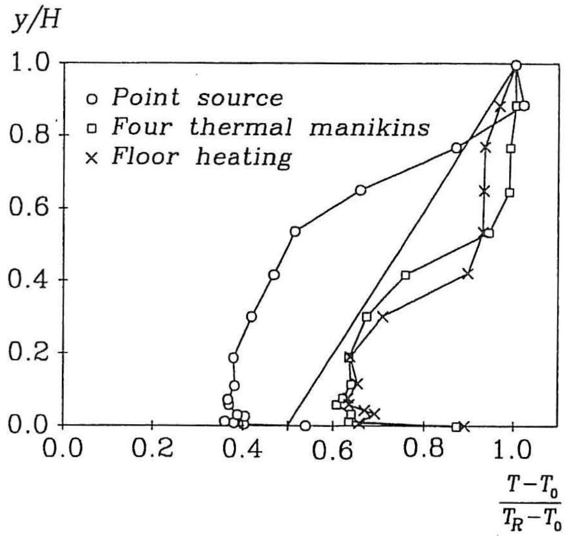


Figure 5. Vertical temperature gradients in a room with different heat sources. $Ar_A = 18 \cdot 10^3$, Nielsen (1993).

The location of the normalized temperature gradients in Figure 5 depends on the size and temperature of the heat source. A heat source as the point source will give a temperature distribution with relatively low temperatures in the occupied zone in comparison with the temperature in the return flow. This corresponds to a high system effectiveness. Four thermal manikins will generate a temperature distribution with a high level in the occupied zone and, consequently, a low system effectiveness. Floor heating shows a insufficient utilization of displacement flow.

The ratio of radiation to convection is an important parameter. A high level of this ratio will displace the curves to the right because it will increase the amount of heat supplied to the floor. Experiments with four thermal manikins (1.0 m × 0.4^{ø} m) support this theory. Figure 5 shows how the vertical temperature profiles are displaced to the right-hand side of the figure when the emission is increased. The low emission is obtained by covering the cylinders with aluminium foil, and the high emission (0.95) is obtained in the standard situation where the cylinders are painted in a dull black colour.

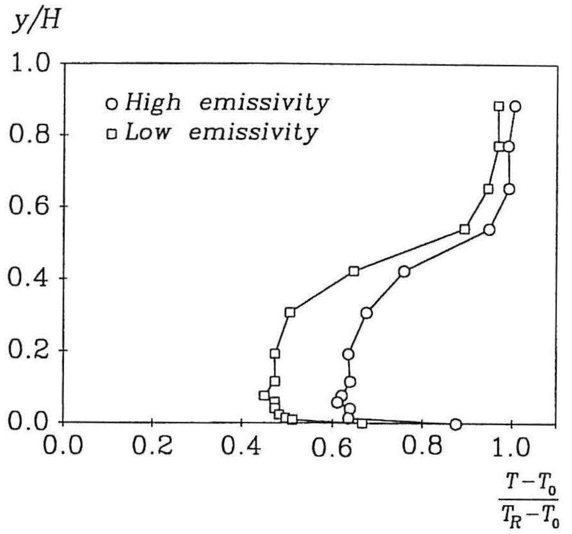


Figure 6. Vertical temperature gradients in a room with four thermal manikins which have a high and a low emissivity. $Ar_A = 18 \cdot 10^3$.

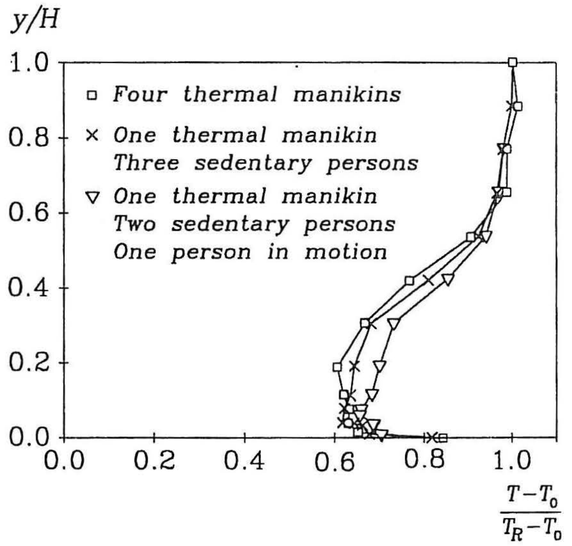


Figure 7. Vertical temperature gradients in a room with thermal manikins, sedentary persons and moving persons, Nielsen (1993).

Figure 7 shows the vertical temperature distribution in a room with thermal manikins and persons. The manikins seem to give a sufficient thermal description of a person. It is especially important to notice that a moving person is unable to spoil the stratification, and the measurements show only a slight reduction in the effectiveness of the system. Other measurements carried out during great activity, and with an open door to the test room, do also confirm the stability of the stratified flow in the room.

MODELS FOR TEMPERATURE GRADIENTS

Measurements indicate that often it is possible to make the simplified assumption that the temperature varies linearly with the height from the minimum temperature at floor level T_f to a maximum temperature at ceiling level. The ceiling level temperature is assumed to be equivalent to the return temperature T_R

$$T = \frac{y}{H}(T_R - T_f) + T_f \quad (4)$$

Skistad (1994) suggests the value 0.5 for the normalized temperature at floor level, because the temperature often appears to be approximately half way between the supply air temperature and the extract air temperature. This applies to rooms of conventional heights (2.5 m - 3.5 m) and normal heat loading. A comparison with Figure 4 shows that the minimum temperature T_f has a limited variation when it is given in a dimensionless form, which also may support the above-mentioned assumption. The straight line in Figure 5 shows this temperature distribution. It can be argued that the line represents a mean assumption for gradients from different types of heat sources.

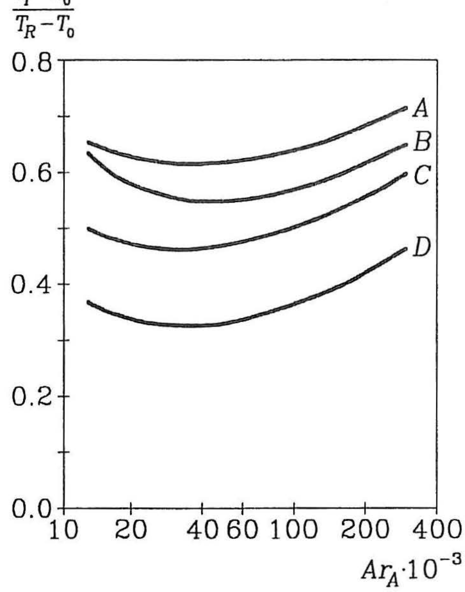
The normalized minimum temperature T_f is slightly dependent on the airflow rate to the room. Mundt (1990 and 1996) addresses this effect and shows the variation as a function of the specific airflow rate q_o/A in different situations.

Li et al. (1992) have worked with extensions of Mundt's model. They suggest a four point model which takes heat conduction at the ceiling into account and, furthermore, they suggest a multi point model which takes various heat transfer modes including radiation between walls and conduction through walls into account.

The temperature close to the floor T_f is strongly dependent on the heat sources in the room. Figure 5 shows that the dimensionless temperature varies from 0.35 to 0.65 for various heat sources and, therefore, it is important to develop a design procedure which can take this effect into account.

Figure 8 shows a design chart which gives the normalized temperature at floor level for different types of heat sources. The point heat source is a small cylindrical heater with open heating elements. This heat source represents the lowest possible level for T_f. The ceiling light consists of four fluorescent tubes mounted 10 cm below the ceiling. It should be expected that they would give a low value of T_f, but radiation (light) seems to limit the system effectiveness, although the tubes are mounted close to the ceiling. Sedentary persons are simulated by four black painted cylinders with the dimensions 1.0 m × 0.4$^{\varnothing}$ m, and the distributed heat source consists of three cylinders placed close to each other.

Experiments with people walking around in the room give the same variation in T_f as found for the distributed heat source.



A: Distributed heat source
B: Sedentary persons
C: Ceiling light
D: Point heat source

Figure 8. Minimum temperature at floor level T_f versus Archimedes number for different, typical heat sources.

It is assumed that the primary flow in a room with displacement ventilation is a fully developed turbulent flow. This means that a normalized temperature can be given as an unique function of the Archimedes number. Consequently, the Archimedes number Ar_A is used as a parameter in Figure 8. The Archimedes number contains information on both thermal load in the room and flow rate to the room.

The new model for a vertical temperature distribution will be a combination of a minimum temperature at floor level according to Figure 8, and a linear temperature distribution according to equation (4).

The results shown in Figure 8 are found by experiments in rooms of conventional sizes (2.5 to 4.5 m high), and they must not be extrapolated to dimensions which are very different from these sizes. The results are also based on sidewall-mounted low velocity diffusers. Other systems will influence the results. It is, for example, possible to show that a system with perforated raised floor and ventilating carpet will obtain a non-dimensional minimum temperature of 0.2 for several heat sources, see Akimoto et al. (1995).

Nielsen (1995) has earlier discussed models with a non-linear temperature distribution. The models took stratification of the flow from heat sources within the room height and raised positions of the heat sources into account.

CONCLUSIONS

Measurements show that the temperature distribution often can be given as a linear function of the height of the room. It is also shown from measurements that the vertical temperature distribution is strongly dependent on the type of heat source in the room and dependent on airflow rate and heat load. Normally, a model is used which has a linear temperature distribution between a minimum temperature close to the floor and a maximum temperature close to the ceiling. The minimum temperature can either be a constant fraction of a load dependent difference or it can be connected to the volume flow to the room.

A new model is described. This model takes the different types of heat sources in the occupied zone as well as the characteristic Archimedes number of the flow into account. The temperature distribution is expressed as a constant gradient. The new model shows a large difference in temperature effectiveness for different heat sources, and this effect will have a considerable influence on both the thermal comfort in the room and the energy consumption of the system.

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