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Publication date:
1988

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Nielsen, P. V. (1988). *Displacement Ventilation in a Room with Low-Level Diffusers*. Dept. of Building Technology and Structural Engineering, Aalborg University. Indoor Environmental Technology Vol. R8836 No. 10

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PAPER NO. 10

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INTRODUCTION

Ventilation systems with vertical displacement flow have been used in industrial areas with high thermal loads for many years. Quite resently the vertical displacement flow systems have grown popular as comfort ventilation in rooms with thermal loads e.g. offices.

The air is supplied directly into the occupied zone at low velocities from wall mounted diffusers. The plumes from hot surfaces, from equipment and from persons entrain air into the occupied zone and create a natural convection flow upwards in the room, see figure 1.

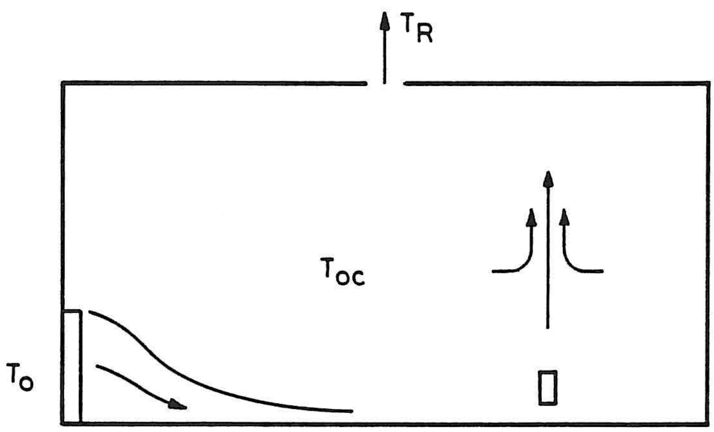

Fig. 1. Room with low-level diffuser, heat source and displacement flow.

The displacement flow systems have two advantages compared with traditional mixing systems.

- An efficient use of energy. It is possible to remove exhaust air from the room where the temperature is several degrees above the temperature in the occupied zone, which allows a higher air inlet temperature at the same load.
- An appropriate distribution of contaminant air. The vertical temperature gradient (or stratification) implies that fresh air and contaminant air are separated. The most contaminant air can be found above the occupied zone and the air flow rate can be reduced.

A general description of the displacement ventilation system has recently been given by Skåret [1] and by Fitzner [2]. Model experiments have been shown by Sandberg and Lindström [3], and measurements in plumes have been given by Kofoed and Nielsen [4]. The flow from different types of low-level diffusers has been described by Mathisen [5] and by Nielsen et al. [6].

The present paper will deal with the flow from different types of low-level diffusers. The main characteristics of the air movement which takes place in the room will be shown. The air movement is expressed by the velocity distribution along the floor, temperature efficiency and stratification level. Special emphasis will be put on an analysis of the velocity and temperature distribution at different Reynolds' numbers and the general importance of the Archimedes number.

FLOW FROM LOW-LEVEL DIFFUSERS

Figure 2 shows two different diffusers used in the experiments. The diffusers of types A and B are both low-level diffusers giving a horizontal air flow directly into the occupied zone. They both have a height of about 500 mm, but a different design. The diffuser A has a supply velocity profile which is very constant over the entire supply area, while the diffuser of type B has a supply velocity with a large variation over the supply area, see figure 3. This variation applies to velocity level as well as to direction, and it means that the local entrainment - or diffusion - is very high close to the opening.

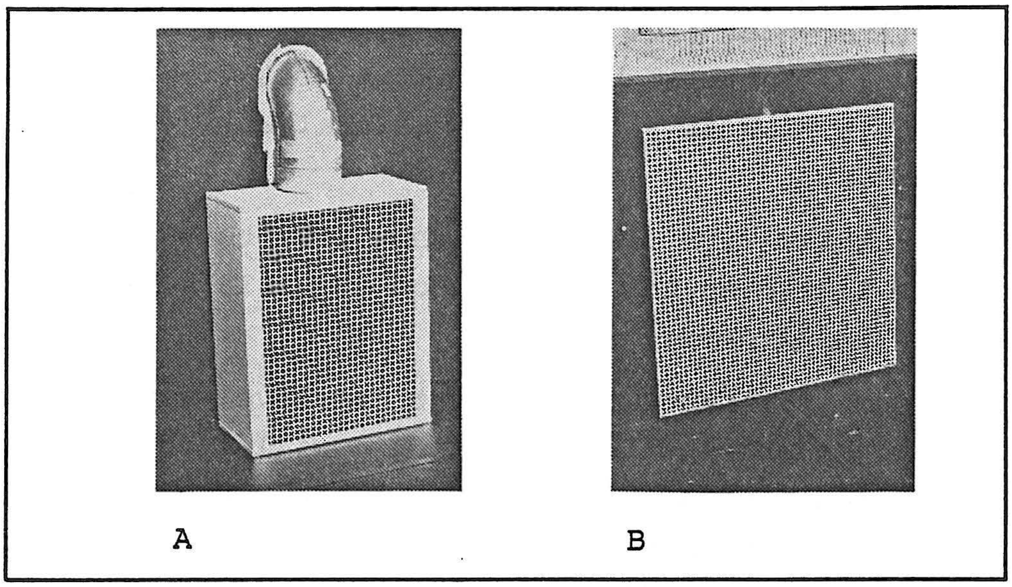

Fig. 2. Two low-level diffusers, type A and type B.

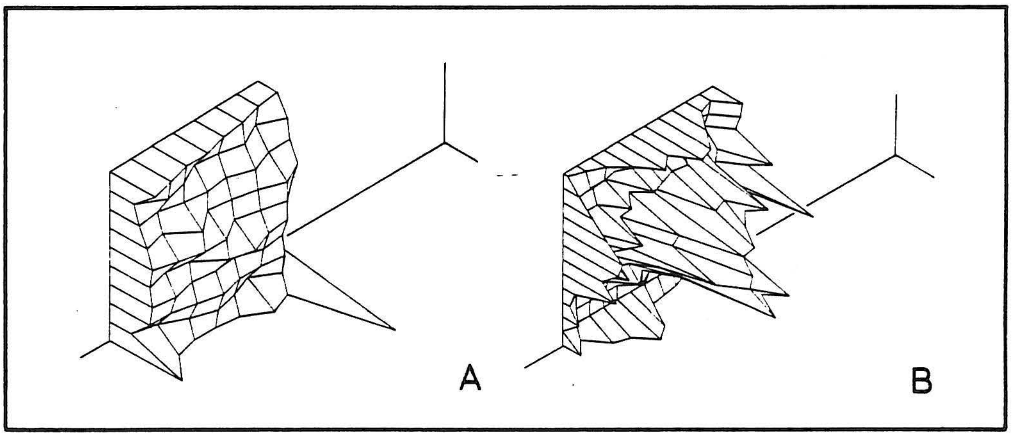

Fig. 3. Supply velocity profiles for diffusers A and B.

The experiments take place in a test room of the dimensions $L \times W \times H = 5.4 \times 3.6 \times 2.6$ m. The diffusers are mounted in the middle of the short end wall. The heat source is installed in the middle plane at a distance of $0.75 \times L$ from the diffuser. The return opening is in the middle of the ceiling.

The flow pattern close to the openings and the local entrainment of room air influence the air movement in the room. Smoke experiments show that the flow from diffuser A spreads out within a 90° area downstream along the floor. Large temperature differences ($T_{oc} - T_o \sim 12$ K) will increase the angle and small temperature differences will decrease the angle giving a flow of a three-dimensional wall jet type for $T_{oc} - T_o \sim 0$ K.

Smoke experiments with diffuser B show that this diffuser spreads the flow over the whole floor area (180°) at all temperature differences.

It is obvious that the two different low-level supply openings - with various initial diffusion - will give a different air movement in the room. Figure 4 shows the velocity decay in the air movement along the floor for both supply openings. The figure indicates that the maximum velocity u_x along the floor is proportional to $1/x^n$ where the exponent n is about 1. The low diffusion in supply opening A results in a high initial acceleration of the air movement due to buoyancy effect on the cold supply air. The velocity level obtained, results in a high velocity in the whole flow along the floor.

The flow from diffuser B is also dependent on buoyancy but the acceleration close to the supply opening is smaller due to the high initial entrainment of room air.

The height of the flow along the floor is typically 0.2 - 0.25 m and the maximum velocity is located 0.03 - 0.04 m above the floor surface independently of the distance from the diffuser.

It is shown by the experiments that the flow is dependent on diffuser type and diffuser location in the room, as well as room width, implying that it is difficult to separate the influence of diffuser design from the influence of room geometry, see reference [6].

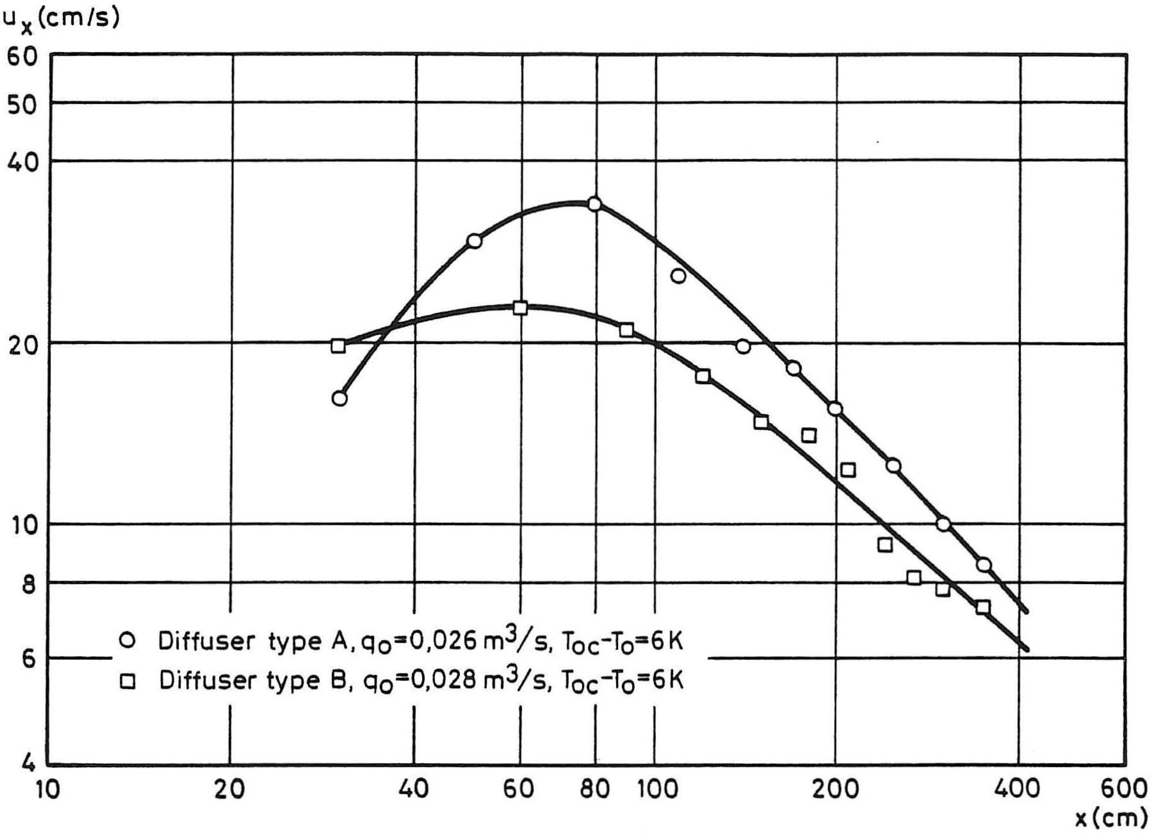

Fig. 4. Maximum velocity in the flow versus distance from diffuser.

It is important that the diffuser used for displacement ventilation is able to generate good thermal conditions in the occupied zone of the room. It is also important that the ventilation system - including the diffusers - is able to generate a high ventilation efficiency, which will be discussed in the following.

The ventilation efficiency based on temperature is given by the equation

$$\varepsilon_T = \frac{T_R - T_o}{T_{oc} - T_o} \tag{1}$$

where T_{oc} is defined as the average temperature of the occupied zone measured at 24 points up to a height of 2.1 m.

Figure 5 shows the ventilation efficiency for diffusers A and B. The efficiency varies between 1.5 and 2.3 dependent on the flow rate and it seems to obtain the same level rather independently of the type of diffuser.

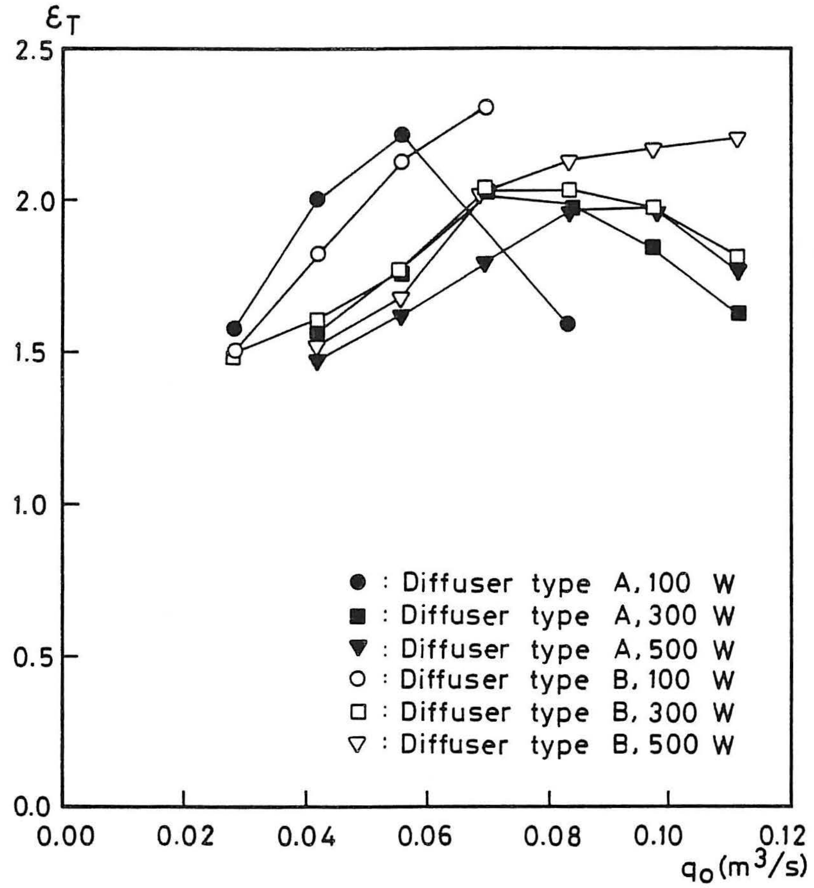

Fig. 5. Ventilation efficiency for diffusers A and B for different flow rates. Measurements by Andersen et al. [7].

THE ARCHIMEDES NUMBER AND THE FLOW

It is possible to describe the flow in a room by a set of dimensionless transport equations as demonstrated in reference [8]. All lengths involved are for example normalized with room height H, velocities with supply velocity u_o and temperatures T with ΔT_o, so they are given as $(T - T_o)/\Delta T_o$, where ΔT_o is the difference between the return temperature T_R and the suppply temperature T_o.

The following dimensionless numbers will appear in the transport equations

$$Re = \frac{u_o H \rho}{\mu} \qquad (2)$$

$$Ar = \frac{\beta g H \Delta T_o}{u_o^2} \qquad (3)$$

$$Pr = \frac{\mu c_p}{\lambda} \qquad (4)$$

where μ, ρ, β are viscosity, density and volume expansion coefficient, respectively, and g, c_p and λ are gravitational acceleration, specific heat and thermal conductivity of the air.

The flow in the room is governed by the transport equations and the boundary conditions. This means that the air flow in the room will be uniquely described by the Reynolds number (2) and the Archimedes number (3), see reference [8].

Experiments show that the high turbulence level in a ventilated room generates a flow which is more or less self-similar and thus independent of the Reynolds number as shown for example by Müllejans [9] for the jet trajectory in a room with jet ventilation. It may also be shown that some details in the flow are dependent on the Reynolds number at low - but realistic - air flow rates, as for example the maximum velocity in the occupied zone of a room with jet-ventilation, see [10].

Assumption of self-similar flow (Reynolds' number independent) simplifies full-scale experiments as well as model experiments, and it is a useful tool in the formulation of simple design procedures. This chapter will show some examples of self-semilar flow where the Archimedes number is the only important parameter.

Figure 6 shows the results of three experiments with similar Archimedes' number and different Reynolds' number. In practice a flow is independent of the Reynolds number. It may be concluded that the air movement has a sufficient turbulence level for q_o > 0.023 m³/s to obtain some self-similarity in the velocity decay along the floor. Other details in this flow may still be dependent on the Reynolds number.

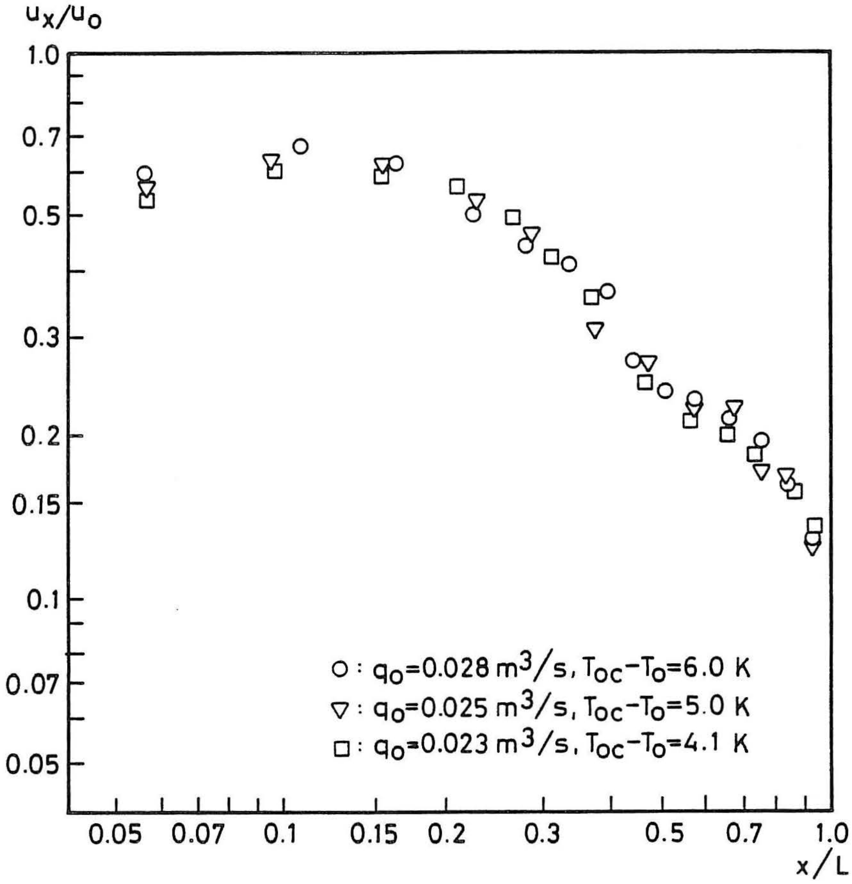

Fig. 6. Velocity decay versus distance measured for identical Archimedes' numbers for three different Reynolds' numbers. Diffuser type B. Reference [6].

Figure 7 shows vertical temperature profiles in the room for three different experiments with the same Archimedes' number. The dimensionless profiles are rather similar although the vertical profiles involve areas with a low turbulence level.

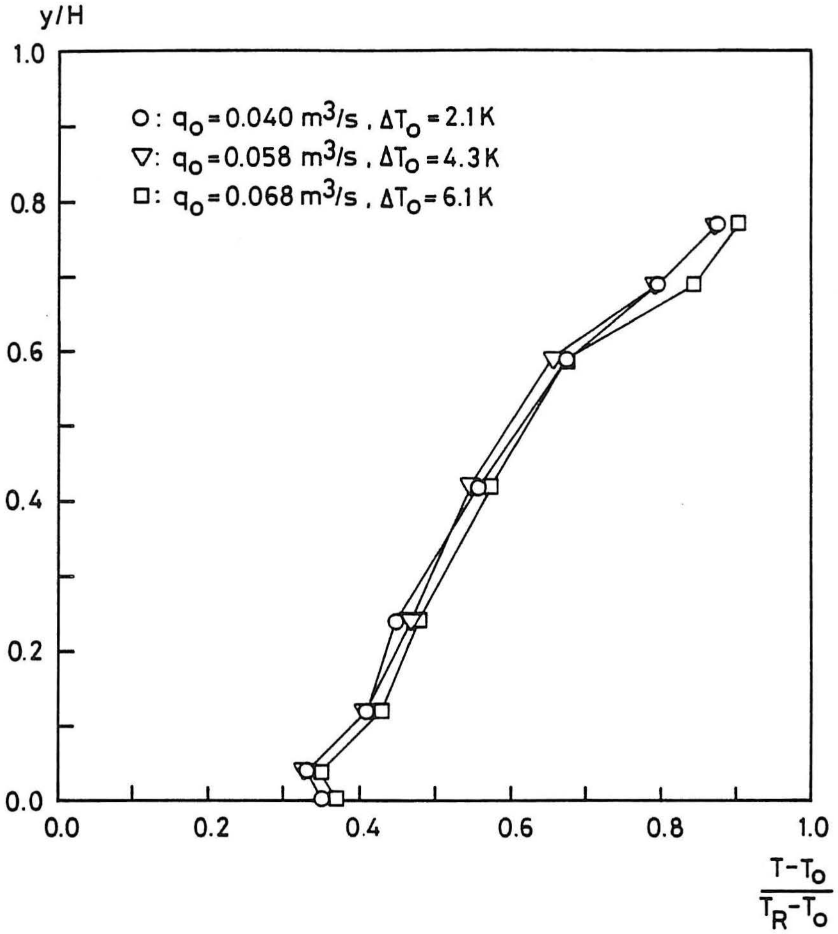

Fig. 7. Vertical temperature profile in the room for three different experiments with identical Archimedes' number. Diffuser type A. Reference [7].

The temperature efficiency is the inverted value of the dimensionless mean temperature in the occupied zone. The results in figure 7 indicate that this temperature efficiency may be a function of the Archimedes number more or less independent of the Reynolds number. It is therefore interesting to rearrange the measurements of ε_T in figure 5 so they are given as a function of Ar. Figure 8 shows this rearrangement and it is obvious that the measurements of ε_T show a fair dependence on the Archimedes number. An identical level of ε_T for the two diffusers A and B at the same Archimedes number implies that the temperature efficiency is rather independent of the diffuser design and the local induction close to the diffuser. It is probably more dependent on other parameters which are constant in the experiments, such as heat source location and room geometry. ε_T is a function of Ar and thus a function of heat emission and air flow rate. ε_T is also influenced by the surface temperature and therefore influenced by the conductions through the walls, floor and ceiling.

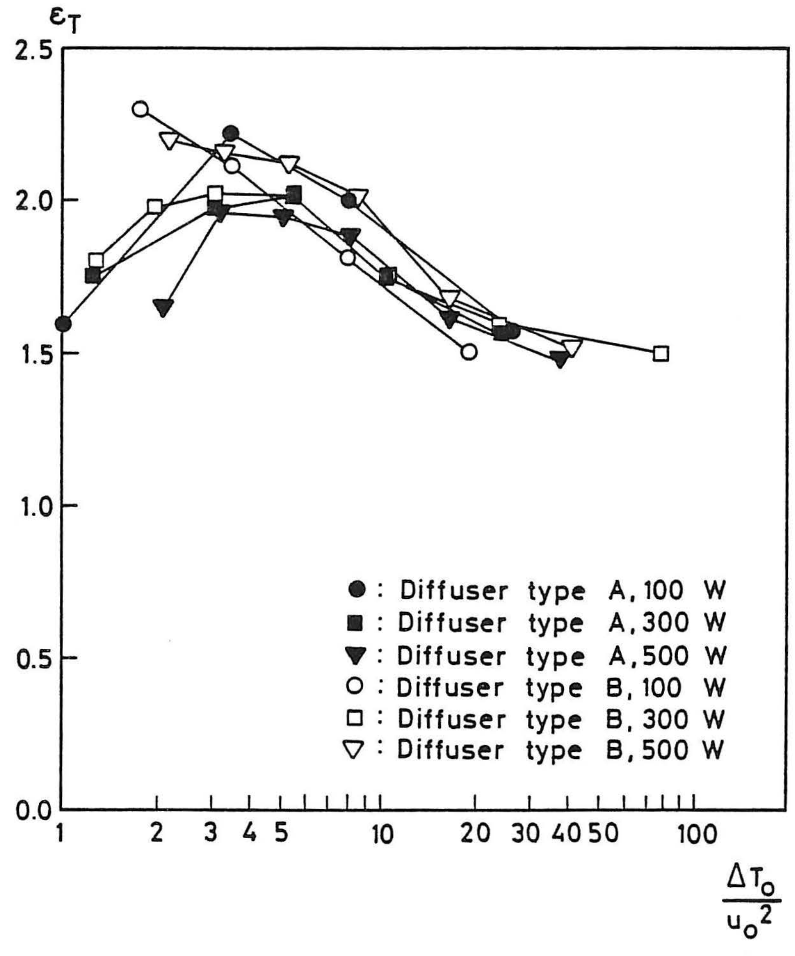

Fig. 8. Temperature efficiency ε_T versus the Archimedes number. The Archimedes number is given as $\Delta T_o/u_o^2$ $^oCs^2/m^2$.

Figure 8 shows a maximum value of the temperature efficiency of $\varepsilon_T \sim 2.0$ for an Archimedes' number of $\Delta T_o/u_o^2 \sim 4.0$ $^oCs^2/m^2$. This situation corresponds for example to the values $(\Delta T_o, u_o)$ $\sim$ (2°C, 0.71 m/s) or (4°C, 1.0 m/s). The flow rates for

u_o = 0.71 m/s are 0.059 m³/s and it is 0.084 m³/s for u_o = 1.0 m/s.

Part of the energy transport in the room takes place as radiation. This radiation is governed by other equations than the flow equations. This will influence the results in figure 7 and in figure 8 in a way which is described by other parameters than the Reynolds numbers and the Archimedes number.

DISPLACEMENT FLOW AND STRATIFICATION LEVEL

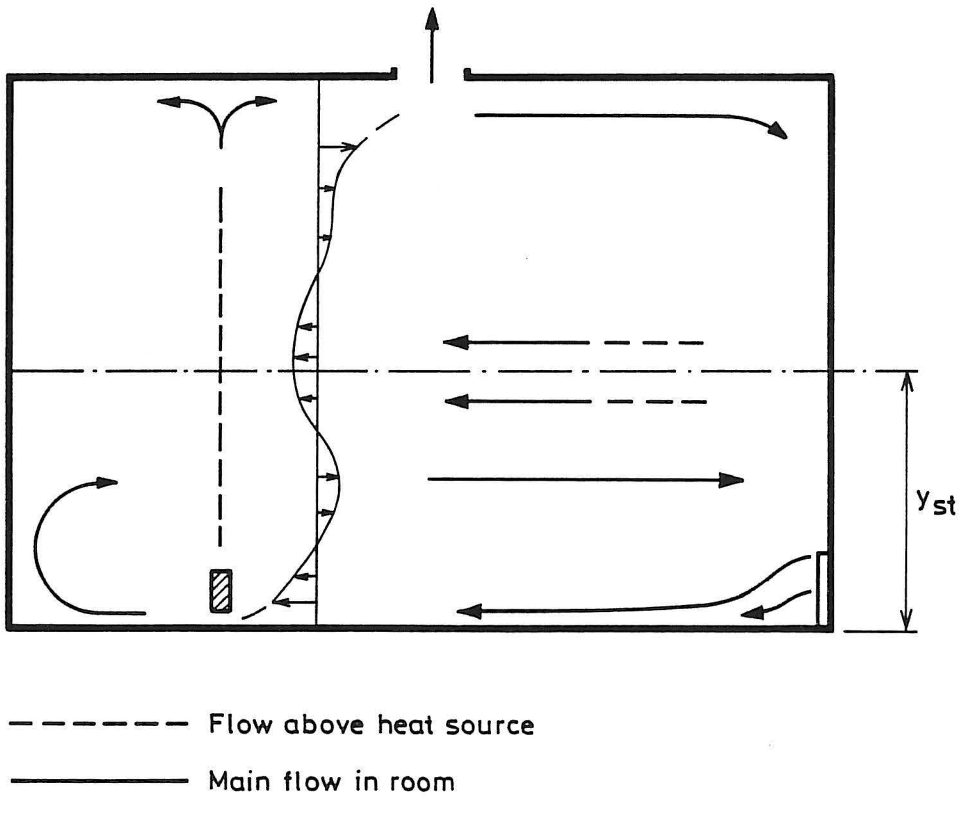

Fig. 9. Air movement and stratification level in a room with displacement flow. Diffuser type B, q_o = 0.069 m³/s, Q = 500 W and y_{st} = 1.70 m.

Figure 9 shows the air movement in a room with displacement flow. The flow from the diffuser follows the floor along the whole room as described in connection with figure 4. There is an air movement backwards in the room at a very low velocity above the supply flow, and it is possible to identify a second flow with a direction parallel to the supply flow. The horizontal flow in the room is connected to the vertical temperature gradient in such a way that a higher level of air movement corresponds to a higher temperature.

The heat source generates a vertical thermal plume as shown by the dotted lines in figure 9. The volume flow in this plume is given by

$$q_y = 0.005 \cdot Q^{1/3} (y + d)^{5/3} \qquad (m^3/s) \qquad (5)$$

where Q, d and y are the convective heat emission, diameter of the heat source and the vertical height, respectively, see reference [11].

The thermal plume will entrain the supply air flow q_o in the lower part of the room. The entrainment in the upper part of the room will be recirculated hot air from the plume. The stratification height y_{st} is defined as the height in the thermal plume where q_y is equal to q_o. It is possible to observe a temperature stratification at this height in rooms with a high thermal load, while it is not so easy to observe in normally loaded rooms.

The stratification height can be found by flow visualization. Smoke is added to the plume at the heat source and it will follow the thermal plume and fill the upper part of the room down to the height y_{st}. The stratification height y_{st} in figure 9 is 1.70 m.

The flow in the upper part of the room is especially characterized by a radial flow below the ceiling from the thermal plume. It is possible to observe another air movement at a lower level which is parallel to the flow in the lower part of the room.

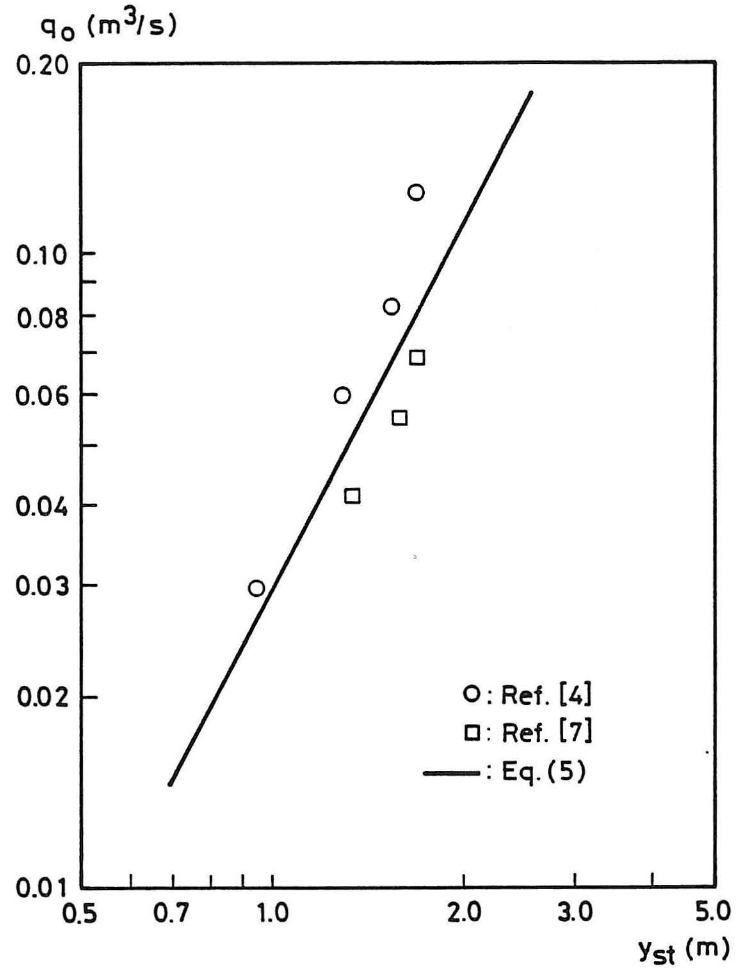

Fig. 10. Stratification height y_{st} as a function of measured supply air flow q_o or flow in plume q_y. Q = 500 W.

Theoretically it should be possible to calculate the stratification height from equation (5) for $q_o = q_y$. Figure 10 shows this calculated stratification height and measured values by flow visualizations in two different full-scale rooms. It is obvious that the measurements show the same relations between q_o and y_{st} as equation (5), but there are different levels of flow. The deviation could be explained by a natural convection along the walls in the rooms or by other disturbances. Figure 11 shows, as an example, a room with a cold downdraught which increases the stratification height, and it is obvious that a hot surface will reduce the stratification height compared to the value calculated from equation (5) for $q_y = q_o$.

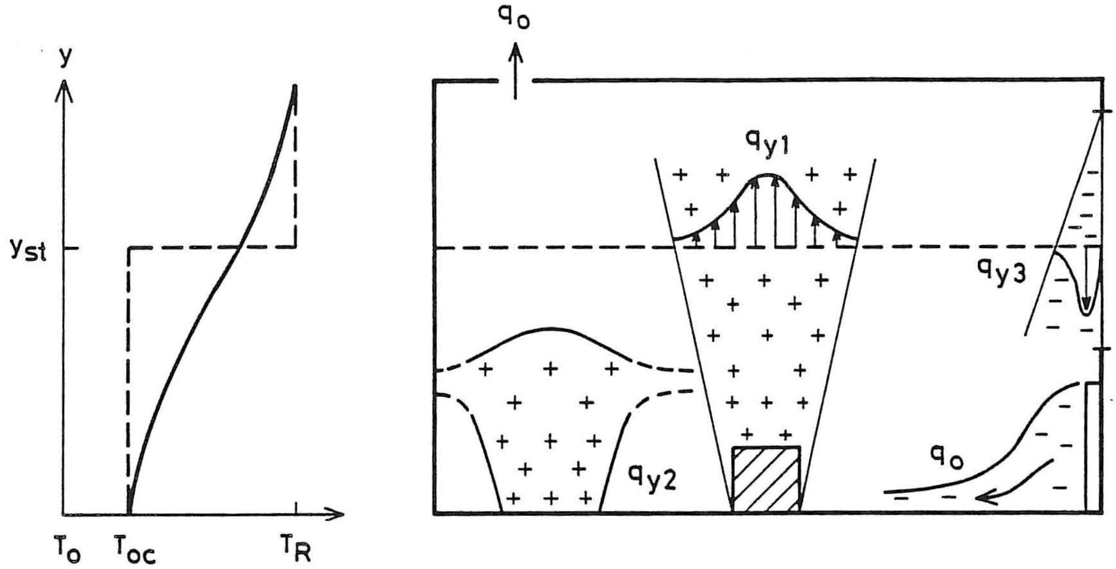

Fig. 11. Room with displacement flow and natural convection.

The stratification level in figure 11 is established at the height where $q_{y1} = q_o + q_{y3}$. The vertical temperature distribution shown in the left hand side of figure 11 is maintained by the combined effect of radiation between the surfaces, the low temperature of the supply flow, which is gradually heated by the movement in the occupied zone - see figure 9 - and by the warm flow below the ceiling. Cold downdraught and plumes from heat sources with low heat emission density - as q_{y2} - will dissolve at a height where the temperatures correspond to the ambient temperatures, and all in all it will maintain a vertical temperature distribution as shown in left hand side of figure 11.

The vertical temperature gradient in the room may have an influence on the volume flow q_y in the plumes. Equation (5) assumes a small temperature gradient, but the equation is used in practice for larger temperature gradients if the heat source is concentrated and have a high intensity. Equation (5) cannot be used for sources with very low intensity, and it cannot be used in areas where the ambient temperature will begin dissolving the plume, reference [4].

The entrainment in the plume will depend on the location of the heat source. The entrainment will be reduced to 70% when the heat source is placed close to a single wall, and it is reduced to 60% when the heat source is placed in a corner, reference [4].

CONCLUSIONS

Measurements on two different low-level diffusers show that a high initial entrainment close to the diffuser will reduce the velocity in the flow along the floor. A low entrainment will increase the velocity along the floor due to an initial acceleration genereated by the buoyancy effect.

The velocity level and velocity decay in the flow along the floor are dependent on room geometry, and therefore, it is difficult to obtain a general description of the flow which is connected to the diffuser design.

The ventilation efficiency based on temperatures is given for the diffusers for different levels of air exchange rates and thermal loads. The ventilation efficiency varies between 1.5 and 2.3 and it is rather unaffected by the type of diffuser.

Examples show that the general flow and the temperature distribution can be described as self-similar and thus as a fully developed turbulent flow. This means that the air movement can be described by the boundary values and the Archimedes number rather independently of some variations in the Reynolds number. Measurements show a distinct connection between ventilation efficiency and Archimedes' number.

It may be difficult to identify a thermal stratification in a room with displacement ventilation. Flow from plumes and cold downdraught at different levels, as well as thermal radiation, will maintain a vertical temperature profile which is more or less linear.

LIST OF SYMBOLS

Ar	Archimedes' number	
c_p	Specific heat capacity	J/kgK
d	Diameter of heat souce	m
g	Gravitational acceleration	m/s^2
H	Height of room	m
L	Length of room	m
n	Exponent	
Pr	Prandtl's number	
Q	Heat emission	W
q_o	Volume flow supplied to the room	m^3/s
q_y	Volume flow in thermal plume	m^3/s
Re	Reynolds' number	
T	Temperature	^oC
T_o	Supply temperature	^oC
T_{oc}	Mean temperature in the occupied zone	^oC
T_R	Return temperature	^oC
u_o	Supply velocity	m/s
u_x	Maximum velocity along floor	m/s
W	Width of room	m
x	Coordinate	m
y	Coordinate	m
y_{st}	Stratification height	m
β	Volume expansion coefficient	K^{-1}
ΔT_o	Temperature difference T_R-T_o	K
ε_T	Ventilation (temperature) efficiency	
λ	Thermal conductivity	W/mK
μ	Dynamic viscosity	Ns/m^2
ρ	Density	kg/m^3

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