Velocity Distribution in the Flow from a Wall-Mounted Diffuser in Rooms with Displacement Ventilation

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PAPER NO. 27

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SUMMARY

The paper describes experiments with wall-mounted air terminal devices. The airflow from an air terminal device will influence the thermal comfort of the occupants and it is therefore important to develop an expression for this flow. The velocity at the floor is influenced by the flow rate to the room, by the temperature difference and the type of diffuser. The flow is stratified at large temperature differences. The paper shows the development of an expression for the velocity distribution in the vicinity of the floor. It is shown that openings between obstacles placed directly on the floor will generate a flow similar to the air movement in front of a diffuser. An expression for the velocity distribution is given in the paper.

VELOCITY DISTRIBUTION IN THE FLOW FROM A WALL-MOUNTED DIFFUSER IN ROOMS WITH DISPLACEMENT VENTILATION

Peter V. Nielsen
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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 recently 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 velocity 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.

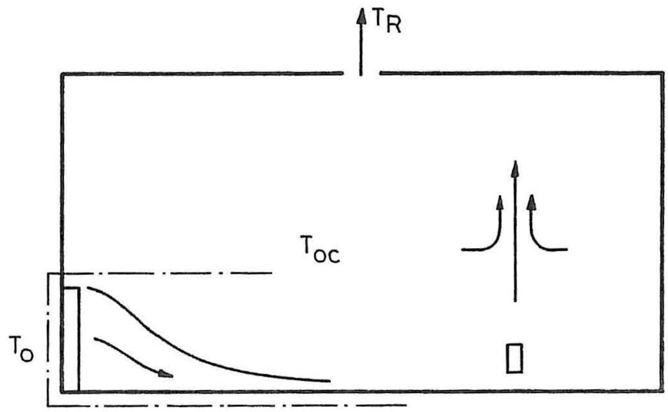

Figure 1. Room with low-level diffuser, heat source and displacement flow.

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 contaminated air. The vertical temperature gradient (or stratification) implies that fresh air and contaminated air are separated and the most contaminated air can be found above the occupied zone.

The design procedure for displacement ventilation deals with the velocity in front of a wall-mounted diffuser by defining the distance from the diffuser to an area where the velocity has decreased to 0.2 m/s (in many cases measured 0.1 m above the floor). The research described in this report is focused on the flow from wall-mounted low velocity air terminal devices. It is the aim of the work to obtain results which can simplify and improve the practical design procedure.

- It is important to examine the flow in front of an air terminal device and to investigate if this flow can be treated unconnected with parameters as room geometry (generally speaking), heat source location and location of exhaust opening, etc.

  The design procedure is simplified if the flow depends only on some main parameters as e.g. type of diffuser, obstacles on the floor, flow rate and Archimedes' number of the flow. It is especially a simplification if the influence of width and length of the horizontal section is small.

  The expectation of this simplification is indicated in figure 1 by the dotted line. An equivalent situation is known in mixing ventilation where the flow from air terminal devices can be described relatively independent of the recirculating flow in the room.

- Furthermore, it is important to obtain a quantitative description of the flow along the floor. The flow along the floor in a room with buoyancy driven ventilation is the only air movement which influences the comfort of the occupants. A description of this air movement will therefore make it possible to obtain a detailed picture of the thermal comfort of the room which is a valuable information compared to the knowledge of distance to the 0.2 m's velocity level.

- One of the main problems in connection with computational fluid dynamics used for the prediction of room air movement is to obtain a practical description of the boundary conditions at the supply opening. Experimental work on the flow from diffusers may give important information which can be used for the individual description of different supply openings.

Large parts of the experiments described in this report are based on a number of research activities made at Aalborg University in connection with the education of M.Sc. students. The research activities are dated back to 1987 and the participating students are mentioned in the reference list. All the experimental work has been supervised and tied together by the author who wants to use this opportunity to express his thanks to all participants.

WALL-MOUNTED LOW VELOCITY DIFFUSER

Figure 2 shows the wall-mounted low velocity diffusers which are tested and discussed in this paper. They are different products and they are designed for flow rates of 50 - 300 m^3/h, except diffuser type F which is designed for a flow rate of 500 - 1400 m^3/h.

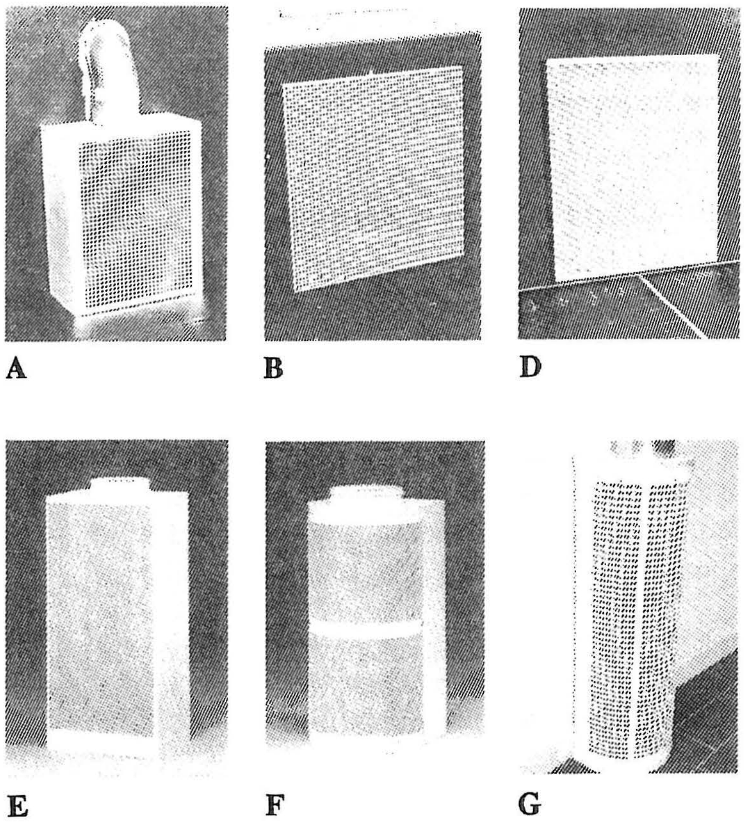

Figure 2. Six different wall-mounted low velocity diffusers for displacement ventilation.

Diffuser type A has a supply velocity profile which is very constant over the entire supply area, while diffuser type B has a supply velocity with a large variation over the supply area both in speed and in direction, see reference [1].

Diffuser type D can be adjusted to two different modes. It can either work as a traditional diffuser, D_1, or it can work with an internal induction unit, D_2, which increases the flow rate at the diffuser surface with a factor of 2.5 compared with the supply flow q_o. The supply temperature T_o will be increased accordingly. The diffuser with the induction unit is especially used for displacement ventilation in systems generally designed for mixing ventilation (low flow rate and high temperature difference). The diffuser generates a semi-radial flow at the supply surface.

Diffuser type E is a conventional diffuser for displacement ventilation without any devices for the generation of radial flow at the supply surface.

The experiments with diffuser F are mainly made to test the influence of the diffuser size. The diffuser is designed for a flow q_o of 500 - 1400 m^3/h, but in this paper it is tested in the range of 100 - 200 m^3/h. The flow from the diffuser is radial.

Diffuser type G generates a radial flow at the supply surface. The velocity distribution is varying over the surface from 70% to 140%. The diffuser is selected for the displacement flow experiments in the International Energy Agency Annex 20 work.

The flow from the diffusers is either given by the flow rate q_o or by a face velocity u_f calculated from

$$u_f = \frac{q_o}{a_f} \tag{1}$$

where a_f is the surface area of the perforated part of the diffuser. u_f is easy to calculate but it is different from the supply velocity measured in the opening of the diffuser. (It is very time-consuming to find the supply velocity u_o based on measurements in a number of openings in the diffuser).

The height h of the different diffusers is an important parameter because the cold flow is influenced by vertical acceleration due to the gravity. The height and the area of the diffuser are given in table 1.

Diffuser	A	B	D_1	E	F	G
$a_f (m^2)$	0.159	0.306	0.437	0.267	1.293	0.188
h (m)	0.48	0.58	0.73	1.00	1.42	0.56

Table 1. Area a_f and height h of the six different low velocity diffusers.

The Archimedes number Ar for a flow is given by

$$Ar = \frac{\beta \cdot g \cdot h \cdot (T_{oc} - T_o)}{u_f^2} \tag{2}$$

where β, g and $(T_{oc} - T_o)$ are volume expansion coefficient, gravitational acceleration and temperature difference between the temperature in the height 1.1 m and the supply temperature, respectively.

FLOW FROM A WALL-MOUNTED DIFFUSER

The flow from three different wall-mounted diffusers is shown in figure 3. The maximum velocity u_x close to the floor is given as a function of the distance x to the surface of the diffuser.

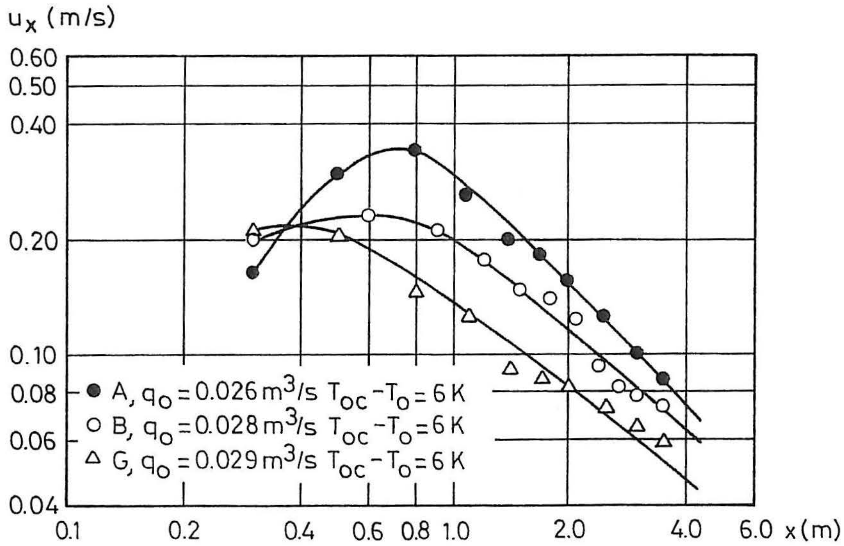

Figure 3. Maximum velocity close to the floor versus distance x. References [1, 2].

The cold air from supply opening A has a high initial acceleration due to buoyancy effect and a velocity of 0.34 m/s is obtained in a distance of 0.8 m from the diffuser. Type B has a larger diffusion of the supply flow, and the gravity will only increase the velocity to 0.23 m/s. The diffuser type G shows an even smaller velocity level although the flow to the room is almost the same in all three situations.

Figure 3 indicates that the maximum velocity in the symmetry plane is proportional to $1/x^n$ where the exponent n is close to 1.0 as pointed out by Nielsen et al. [3].

It is also obvious from figure 3 that different diffuser designs generate a different velocity level at the same flow rate and heat load.

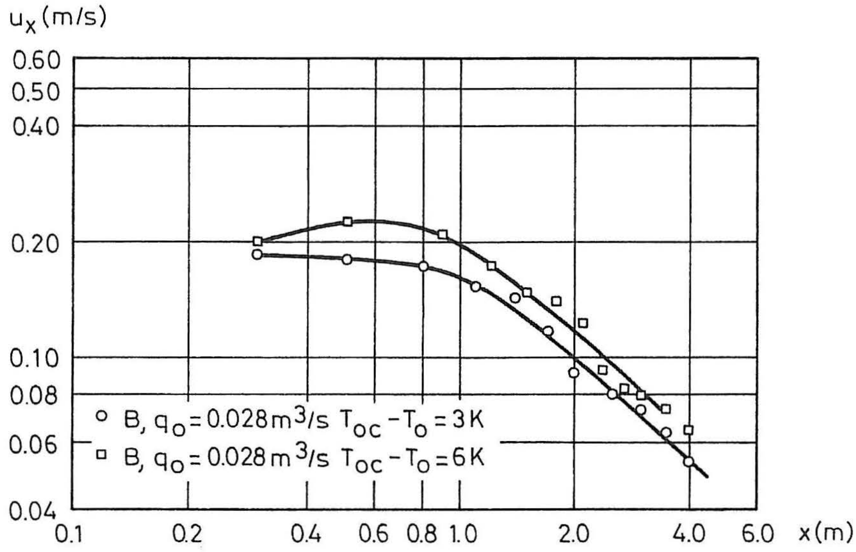

Figure. 4. Velocity decay along the floor at different Archimedes' numbers. Reference [4].

The velocity at the floor is not only influenced by the flow rate to the room and the type of diffuser. Figure 4 shows that the Archimedes number is an important parameter. A 3°C increase in temperature difference will for example increase the velocity from 0.10 m/s to 0.12 m/s in a distance of 2 m from the diffuser. The figure shows that it is the gravity which accelerates the flow close to the diffuser resulting in a higher initial velocity level at higher Archimedes' numbers. This effect is very important for the flow in rooms with displacement ventilation and the outcome can be surprising. The velocity level in a room may for example be uninfluenced although the flow rate is reduced because the heat load in the room requires a reduction of the supply temperature and consequently an increase of the relative velocity level u_x / u_f, see reference [4].

Profile measurements show that the flow in the vicinity of the floor can be characterized by a normalized velocity profile identical to the profile used for the description of wall jet flow, see references [2, 5, 6]. The length scale δ in this profile is defined as the distance from the floor to the height where the velocity has a level which is half of the maximum velocity close to the floor, $u_x / 2$.

Figure 5 shows the development in δ for three different Archimedes' numbers. It can be seen that the height of the flow region is much smaller than the height of the diffuser, even at a distance of 0.5 m from the diffuser. The cold air from the diffuser accelerates towards the floor due to gravity and it behaves like a stratified flow in its further progress along the floor. δ is rather constant while it is proportional to x in a wall jet as indicated by the dotted line in figure 5. The length scale or thickness δ is slightly decreased at increasing Archimedes' number.

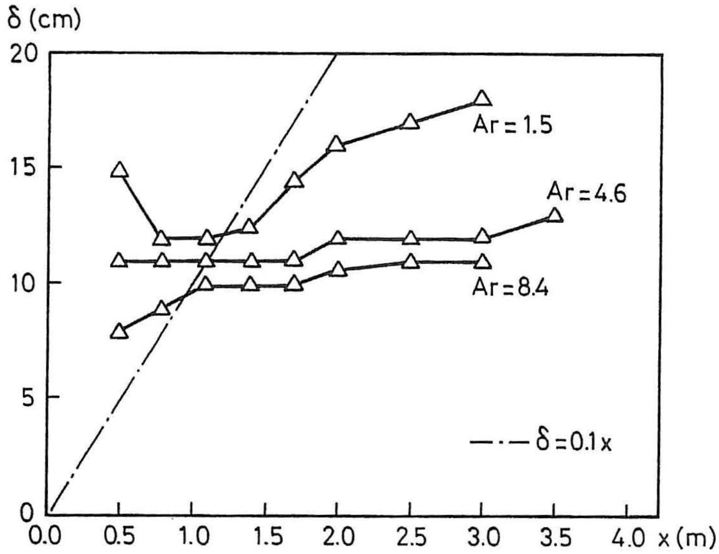

Figure 5. Length scale δ in the flow versus distance from the diffuser. Diffuser type G. Reference [2].

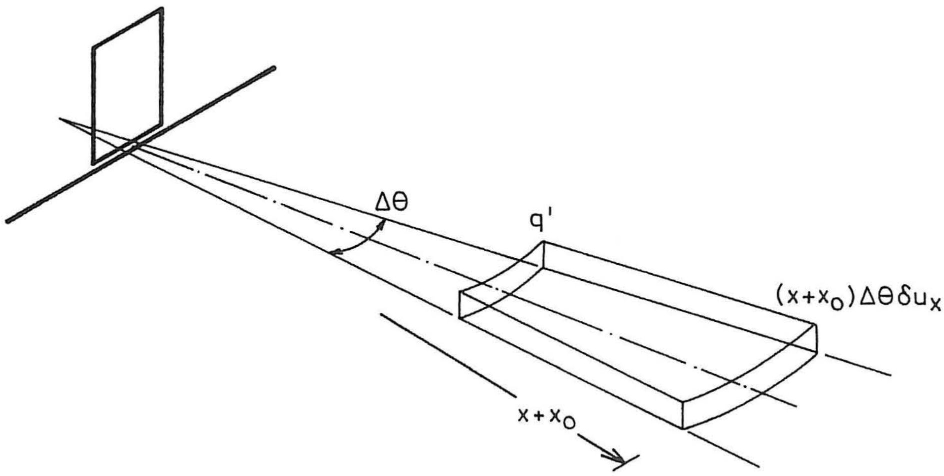

Figure 6. Stratified flow from a wall-mounted diffuser.

The entrainment of air into the flow, or the turbulent mixing process, is diminishing when a vertical temperature gradient is present because the gravity will work against upward movement of heavy fluid and downward movement of light fluid. This is shown in hydraulics by for example Turner [7] and it is shown for displacement ventilation by Jacobsen and Nielsen [6] and it is also discussed in reference [8].

It is possible to develop an equation for the stratified flow in front of a wall-mounted diffuser, see reference [4]. It is known from measurements that the flow is radial and figure 6 shows a small section $\Delta\theta$ of this flow which has a virtual origin located in a distance x_o from the diffuser. The flow within section $\Delta\theta$ is proportional to $(x + x_o)\Delta\theta\delta u_x$ where $(x + x_o)\Delta\theta$ is the width of the section at distance x, and δ is an expresssion for the height of the section. u_x is an expression for the velocity level in the velocity distribution. The flow is independent of the distance x because the entrainment is small and the following equation can therefore be obtained.

$$\frac{u_x}{q'} \sim \frac{1}{\Delta\theta\delta} \frac{1}{x + x_o} \tag{3}$$

It is also shown by experiments that the normalized velocity distribution is fairly independent of the Reynolds number in areas of practical relevance, see reference [1]. The following equation can therefore be obtained for stratified flow with a constant thickness δ

$$\frac{u_x}{q_o} = K \frac{1}{x + x_o} \tag{4}$$

where K is a function of the Archimedes number as well as an individual function for different types of air terminal devices. Both x and u_x are measured in the middle plane of the room.

The development of equation (4) assumes a high Archimedes number but the structure is also valid for cases where the Archimedes number is very small. In this case the flow will be a part of a potential core or a part of a radial wall jet. The velocity will in most cases be proportional to $1/(x + x_o)$, and equation (4) will therefore be able to predict the velocity u_x when the K-value is adjusted to the situation, see reference [4].

The variables in eqution (4) are easy to measure for a given diffuser and the equation is therefore simple to use in a practical design procedure.

It is possible to obtain a normalized version of the equation for a more general description of the flow. The velocity u_x is normalized by the face velocity u_f and the length x is normalized by the height of the diffuser h

$$\frac{u_x}{u_f} = K_{dr} \frac{h}{x + x_o} \tag{5}$$

where

$$K_{dr} = K \frac{a_f}{h} \tag{6}$$

Velocity distribution in rooms with displacement ventilation is also discussed by Mathisen [5] and by Sandberg and Mattsson [9].

VIRTUAL ORIGIN OF THE FLOW

Some of the tested diffusers discussed in this paper generate a velocity decay of $1/x^n$ where n is slightly different from 1.0. Figure 7 shows an example where the measurements are in agreement with equation (4) for $x > 2.0$ m, while the equation overestimates the velocity closer to the diffuser.

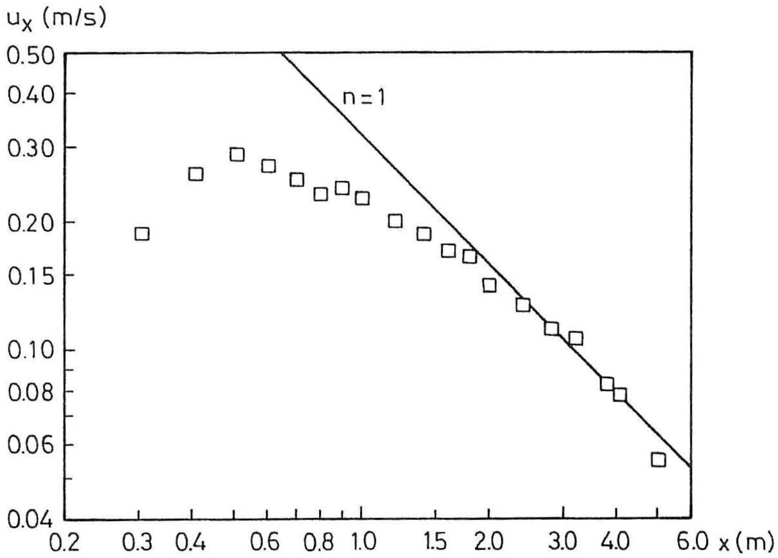

Figure 7. Velocity decay in the flow from a wall-mounted air terminal device type D_1. $q_o = 0.028$ m^3/s and Ar = 45.8. Reference [10].

The presence of a virtual origin located at some distance x_o behind the diffuser can explain the velocity decay shown in figure 7, but deviations of the same type will also take place if the flow is influenced by entrainment, by non-radial flow or by negative growth in the lenght scale δ. More detailed measurements are therefore necessary to determine if the influence especially is from the presence of a virtual origin located in some distance from the diffuser.

Figure 8 shows the flow direction measured with smoke close to the floor. The conditions for the experiment are close to the conditions in figure 7. It can be seen from the figure that the flow close to the symmetry line has a virtual origin x_o which is about 0.5 m, although the measurements are rather scattered. It is also obvious from the figure that the general flow is radial, even rather close to the side walls.

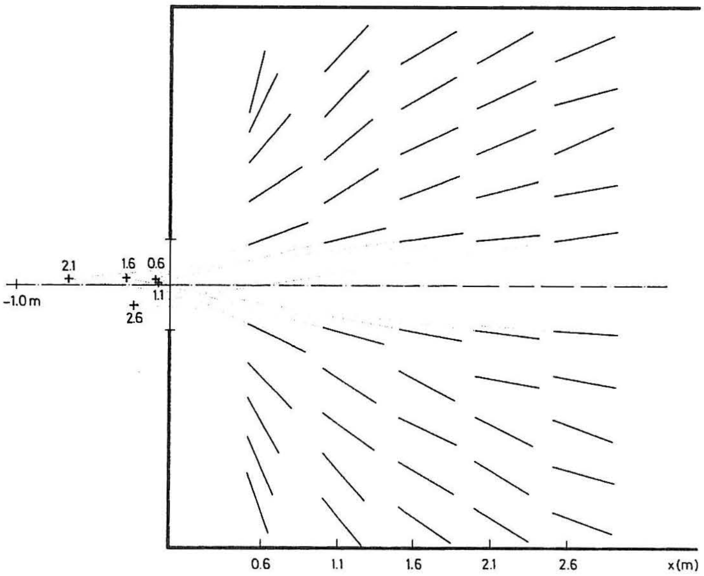

Figure 8. Flow directions at the floor. Diffuser type D_1. q_o = 0.028 m^3/s and Ar = 47. Reference [10].

Figure 9 shows the earlier measured velocity u_x versus $x + x_o$ where x_o = 0.5 m. It can be seen that the velocity decay is close to $1/(x + x_o)$ for $x > 1.5$ m which indicates that the measurement of a virtual origin will improve the presentation of the results close to the diffuser.

Many measurements show, however, that most of the diffusers have virtual origins which are located very close to the surfaces of the diffusers, which leads to small x_0. The influence of a small x_o is only important close to the diffuser and it is therefore ignored in the presentation in this paper, also because it is very difficult to measure in practice.

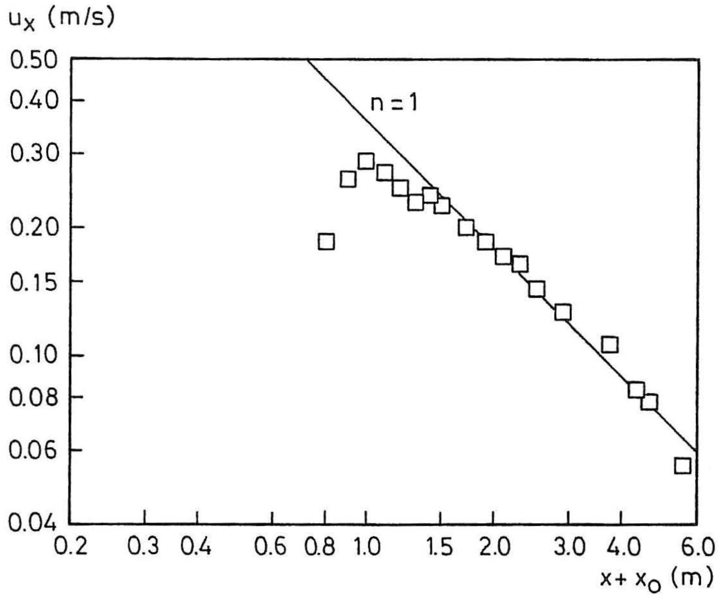

Figure 9. Velocity decay in the flow from diffuser D_1 versus$(x + x_o)$. q_o = 0.028 m^3/s, Ar = 45.8 and x_o = 0.5 m.

MAXIMUM VELOCITY IN THE FLOW CLOSE TO THE FLOOR

Equation (4) gives the description of the flow along the middle plane in a room with displacement ventilation. The equation is easy to use in practice because the variables are the primary variables in a design procedure.

The variable K is a product dependent variable which is also a function of the Archimedes number. A large number of experiments have been made to establish this variable and the results are shown in figure 10.

Figure 10 shows that K may be very different for different products as it varies from 5 to 12 m^{-1} at high Arhcimedes' numbers.

The figure shows that K increases with increasing Archimedes' number. This is due to the fact that gravity will accelerate the vertical flow close to the opening and generate a stratified air movement in a relatively thin layer along the floor where the obtained velocity level will be retained. This effect is also shown in figure 4. Diffuser A shows an increase in velocity at small Archimedes' number. This increase could be explained by the increase in radial flow which takes place for this diffuser at high Archimedes' number.

The high level of K for the diffuser D_2 can be explained by the induction unit used in this product.

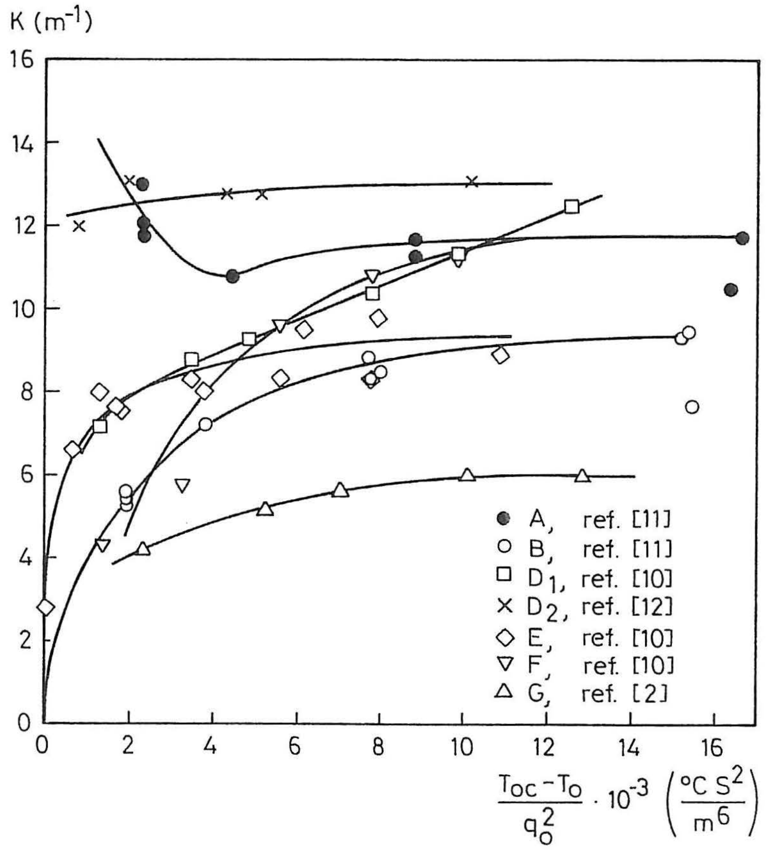

Figure 10. K versus temperature difference and supply flow rate for seven different wall-mounted air terminal devices. x_o = 0.0.

Equation (4) can only be used at some distance from the diffuser as it appears from the figures 3, 4 and 7 . This distance is 1.0 m to 1.5 m for most of the diffusers. The diffuser D_2 with an induction unit generates a flow which follows equation (4) for x > 1.5 m at high Archimedes' numbers, while the measurements show that x should be larger than 2 - 3 m for small Archimedes' number. Equation (4) will in any case give a velocity equal to or higher than the actual velocity and therefore a value which is suitable for a design procedure.

It is known from stratified flow in hydraulics that obstacles located downstream may influence the length scale δ of the flow, see references [7, 8]. Most of the measurements are made in test rooms of equal size, so it is difficult to determine the influence from the end wall and the side walls, but practical experience from the ventilation industry indicates that room dimensions are of minor importance, see reference [13].

It is typical that all diffusers, except diffuser F, have reasonable sizes compared to the test rooms. It might therefore be concluded that the diffusers are tested under conditions and dimensions close to the conditions which they are meant to cover in practice, and the velocity level given by the variable K, in figure 10, is therefore typical of a practical application.

The K-values in figure 10 are from measurements of flow in the middle plane. Measurements by Jacobsen and Nielsen [6] show that K is also a variable of the direction θ.

Equation (5) is a normalized version of the velocity decay formula. The face velocity u_f and the height of the individual diffusers h are reference values in this equation. Figure 11 shows that the dimensionless variable K_{dr} in equation (5) takes different values for different products. A normalization with the geometrical length scale h does not give a continuous description of the K_{dr}-values and it may therefore be concluded that the design details in the diffuser have a large influence on the K_{dr}-value.

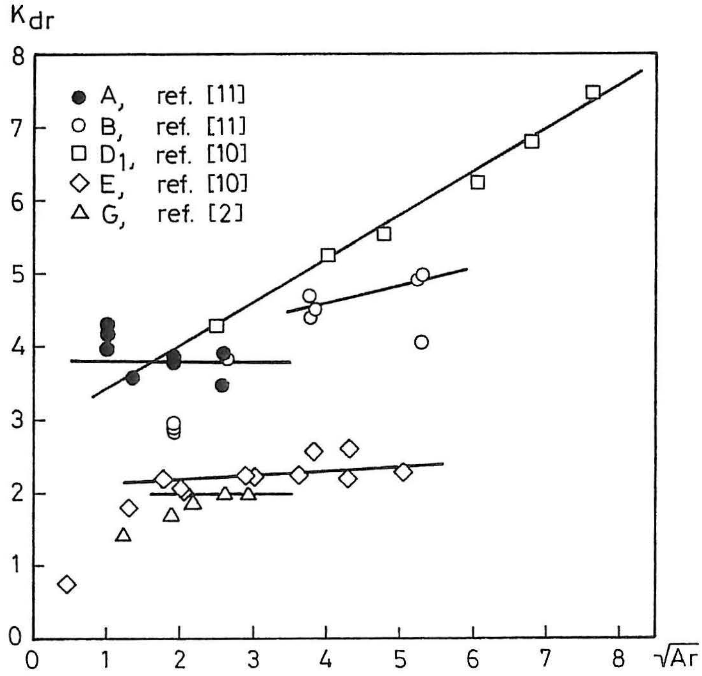

Figure 11. K_{dr} versus Archimedes' number for five different wall-mounted air terminal devices. x_o = 0.0.

Mathisen [5] has shown that the maximum velocity in the flow from a wall-mounted diffuser can be described as a linear function of $\sqrt{Ar}$. Figure 11 does confirm this assumption for large Archimedes' numbers, but deviations take place at smaller Archimedes' numbers.

FLOW BETWEEN OBSTACLES

The flow in the vicinity of the floor may be influenced by furniture and by other obstacles in the occupied zone. The maximum velocity in the flow is located rather close to the floor (between 1 to 5 cm above the floor), and a great deal of the air movement will therefore take place in this region. Conventional furniture will only have a small influence on the air movement while obstacles placed directly on the floor will block the flow. An opening between this type of obstacles will work as new supply opening because the flow in the room is stratified. Figure 12 shows an example from a room with short movable walls.

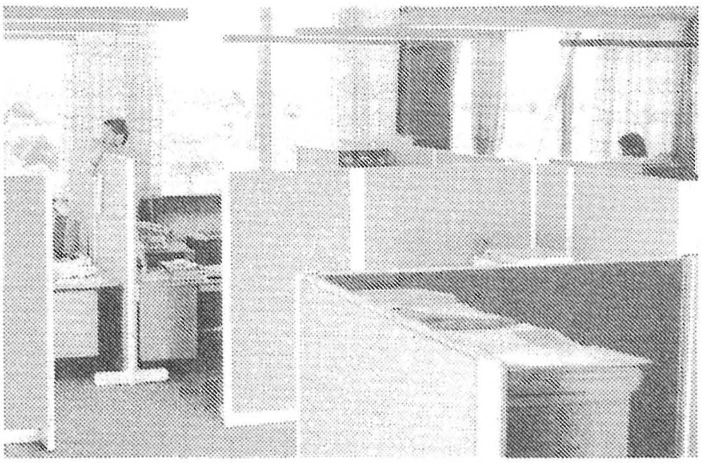

Figure 12. Room with short movable walls.

Experiments have shown that the flow from an opening between obstacles can be described as a semi-radial flow like the air movement from a wall-mounted supply opening. The velocity decay can be described by the equation

$$\frac{u_x}{q_o} = K_{ob} \frac{1}{x} \tag{7}$$

u_x is maximum velocity in distance x from the opening and q_o is the excess air supplied on the other side. u_x is measured in the symmetry plane.

Figure 13 shows the measurements of K_{ob} in equation (7). The structure of equation (7) and the distribution of K_{ob}-values are equivalent to the structure of equation (4) and the structure of K-values. The temperature difference T_{oc} - T_{ob} is the difference between the temperature in the height 1.1. m in front of the opening and the lowest temperature in the opening between the obstacles.

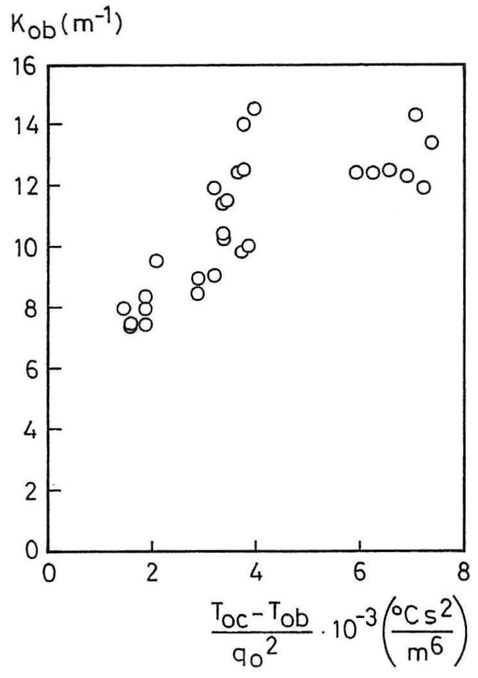

Figure 13. K_{ob} versus flow rate and temperature difference. Reference [14].

It is interesting to see that the level of the variable K_{ob} is only slightly larger than the level of K.

The width of the opening is varying from 0.1 m to 1.5 m in the experiment. Measurements show that the importance of the width is less obvious and results for different widths are given in figure 13.

CONCLUSIONS

Wall-mounted air terminal devices are often used in displacement ventilation. The flow from a device will accelerate in a vertical movement close to the opening due to the gravity effect when inlet air is colder than room air. The airflow will then move along the floor in a radial pattern and behave like a stratified flow. The airflow will influence the thermal comfort of the occupants and it is therefore important to develop an expression for the flow for design proposals.

Measurements show that the velocity at the floor is not only influenced by the flow rate to the room. It is also influenced by the temperature difference - or by the Archimedes number - and the velocity level may vary for different types of diffusers.

The flow is stratified at large temperature differences. This is indicated by a constant height of the cold flow independent of the distance from the supply opening. It is shown that the radial flow has a virtual origin close to the front of the diffuser. The velocity level in the flow along the floor is inversely proportional to the distance from the diffuser. The velocity decay can be described individually for each type of diffuser by a single equation and a variable which is a function of the Archimedes number. It is further shown that the maximum velocity can be described as a linear function of the square root of the Archimedes number.

The influence of side walls and the end wall has not been studied but it is known from stratified flow in hydraulics that obstacles located downstream may influence the height of the cold flow. Practical experience indicates that the room dimensions are of minor importance, but more work in this area is necessary.

Openings between obstacles placed directly on the floor will generate a flow similar to the air movement in front of a diffuser. It is shown that the velocity distribution can be described with an equation system with the same structure as the system describing the stratified flow from wall-mounted diffusers.

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