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PAPER NO. 2

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ABSTRACT

The room ventilation is investigated for three different air terminal devices under isothermal conditions.

Velocity distribution in the occupied zone is measured for each air terminal device at different air exchange rates. The maximum air exchange rate is determined on the base of both the throw of the jets and the comfort requirements applied to measured air velocities in the occupied zone.

Normalized concentration distribution in the test room is determined along a vertical line through the middle of the room as a function of the air exchange rate and the density of the tracer gas.

The relative ventilation efficiency, $\langle\varepsilon\rangle$, based on the room average concentration is also determined as a function of the air exchange rate and the density of the tracer gas.

The influence from the position of the return opening on the relative ventilation efficiency is found for one air terminal device.

INTRODUCTION

One of the main tasks of room air distribution is to supply clean air (outdoor air) so that the contaminant concentration is kept at an acceptable level, from a hygienic point of view. In recent years there has been an increased international interest in drawing up criteria to evaluate the efficiency of different ventilating systems, i.e. how efficient they are to exchange the air in a room, see e.g. Sandberg (1).

This paper deals with the contamination in a ventilated room under stationary conditions, with flow rates below and above comfort limits in the room. The investigations are made under isothermal conditions in a room of the dimensions $L \times W \times H = 5.4 \times 3.6 \times 2.4$ m. The supply opening is placed close to the ceiling at one of the end walls. Two return openings are located at the other end wall 0.7 m above the floor (0.7 m below the ceiling in a few experiments).

A nozzle or a rectangular grille with adjustable blades are used as supply opening. The nozzle (A) is made in the laboratory and has a diameter of 132 mm. A GTH-20-10 grille from STIFAB is also used as air terminal device. The grille consists of a frame with adjustable horizontal and vertical blades, which allows variation of the air distribution and throw from the grille. In this investigation two settings are used, namely situation (B), where all blades are parallel with the flow, and situation (C), where the vertical blades are adjusted so that they form angles from 0^{o}-45^{o} from the middle of the grille to the edge. The horizontal blades are directed upwards at an angle of 20^{o}. Other measurements on the GTH-grille are given in reference (2).

VELOCITY MEASUREMENTS

It is important that the investigations of ventilation efficiency are made under conditions where the comfort requirements for air velocity in the occupied zone are not exceeded, and a thorough investigation of the air distribution in the occupied zone is therefore necessary.

The velocity decay of the primary jet is measured for all three air terminal devices. The measurements are carried out with the nozzle or the GTH-grille mounted in the room. The result describes the properties of the air terminal device very well and it is possible to derive the maximum permissible supply velocities and volumetric flow rates based on the "throw" of the jets.

The maximum velocity of the recirculating flow is measured as a function of the volumetric flow rate. Applying these results and the comfort requirements by Fanger & Christensen (3) to the air velocity in the occupied zone it is also possible to find the maximum supply velocities and the volumetric flow rates based on comfort requirements.

WALL JET CONDITIONS

For a three-dimensional wall jet the expression for the maximum velocity of the primary jet as a function of the distance to the supply opening is given by:

$$\frac{V_x}{V_o} = K_a \frac{\sqrt{a_o}}{x+x_o} \qquad (1)$$

The K_a-value, the effective supply area, a_o, and the distance to virtual origin, x_o, are found for each air terminal device (A), (B) and (C). The result is shown in figure 1.

Air terminal device	Distance to ceiling (m)	K_a	a_o (10^{-3} m^2)	x_o (m)
A	0.067	9.2	14.0	0.55
B	0.036	7.1	11.2	-0.5
C	0.036	5.8	9.9	0.32

Fig. 1. K_a-value, effective supply area, a_o, and distance to virtual origin, x_o, are given for each air terminal device (A), (B) and (C).

Figure 1 shows that the K_a-values differ considerably. As expected, the nozzle has the highest value and the GTH-grille with diffusing blades has the lowest value. Further, it is seen that the location of the virtual origin of the jet is changed radically when the setting of the blades is changed.

AIR EXCHANGE AT CONSTANT THROW

The maximum permissible supply velocity v_o is found for each air terminal device for a throw which is equal to the room length L and the corresponding terminal velocity equal to 0.25 m/s. The result is shown in figure 2 together with the air supply flow rate and the air exchange rate.

The nominal air exchange rate is defined as:

$$n = \frac{Q}{HWL} \tag{2}$$

where Q is the air supply flow rate.

Air terminal device	v_o m/s	Q m^3/h	n h^{-1}
A	1.4	69.0	1.5
B	1.6	65.7	1.4
C	2.5	88.4	1.9

Figure 2. Maximum permissible supply velocity, air supply flow rate and nominal air exchange rate for each air terminal device for throw which is equal to the room length.

ROOM AIR VELOCITIES

The air velocities in the occupied zone are measured at 5 different nominal air exchange rates. In the figures 3a, b, and c the velocities are shown for air terminal device (A). Similar results are found for the air terminal devices (B) and (C).

The result of the velocity measurements in the occupied zone contains several characteristics.

At an air exchange rate exceeding 2 - $3h^{-1}$ there is a linear correlation between air velocity and air exchange rate. This means that the flow has a fully developed turbulent level in the room, and that the normalized values are independent of the velocity, see (4). The flow conditions are clearly asymmetric. Figure 3c shows that the measured air velocities in the occupied zone are considerably higher at one half of the room than at the other. The asymmetric conditions are prevailing already in the primary jet which is bent to one side. Smoke visualisations have shown that the deflection at the end wall is of the magnitude 0.5 - 1.0 m from the middle plane.

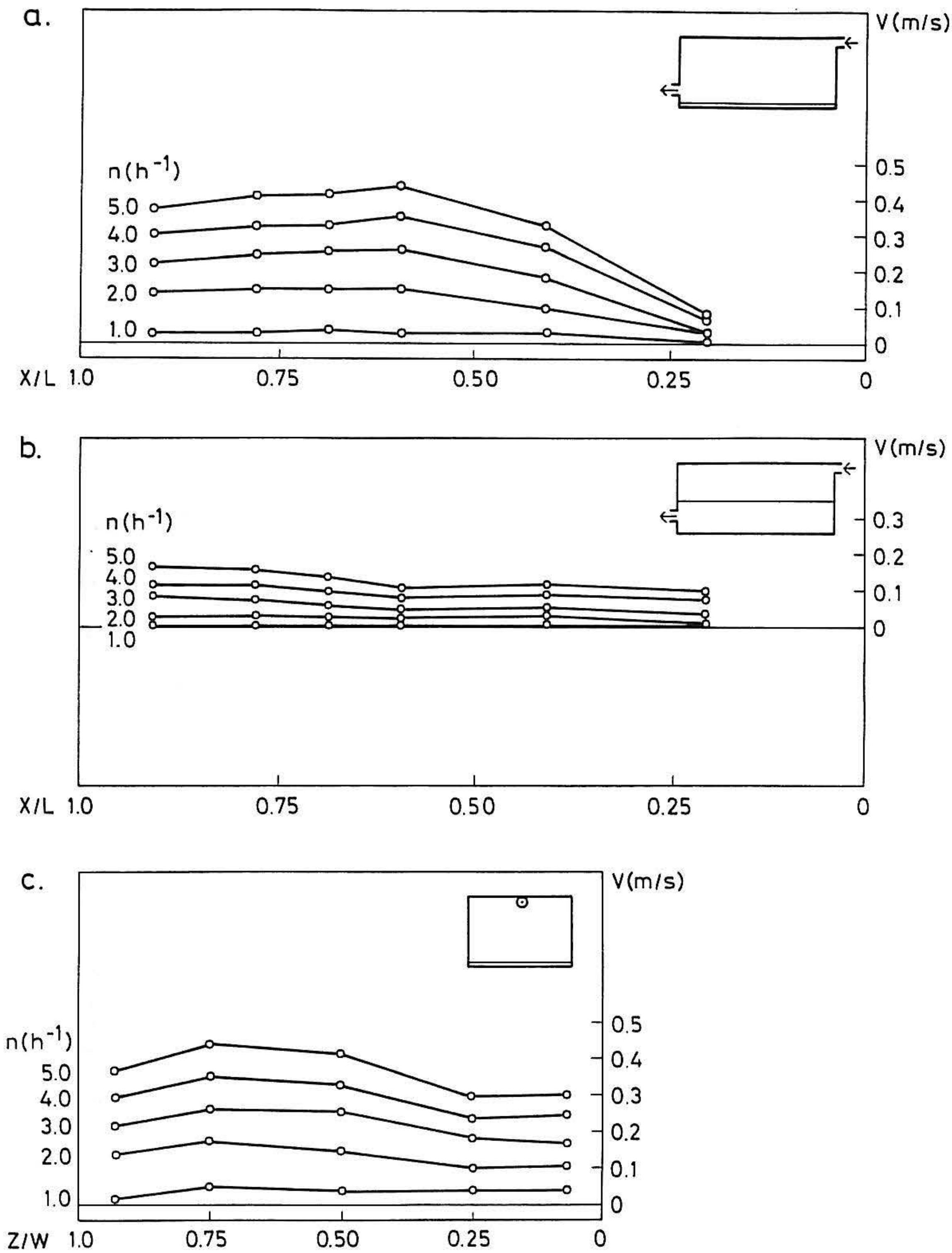

Figure 3. Air velocities in the occupied zone at 5 different nominal air exchange rates. Measurements are performed: a) 0.1 m above the floor. b) 1.1 m above the floor, in the middle of the room, and c) 0.1 m above the floor transversely in the room, 3.6 m from the supply opening.

The maximum air velocity in the occupied zone cannot be completely determined from the measurements carried out. However, it is estimated from among other things figures 3a, b, and c that the correct value is not considerably higher than the measured value. Therefore, in the following, the maximum air velocity in the occupied zone is assumed to be equal to the maximum measured air velocity.

In figure 4 the maximum measured air velocity is shown as a function of the nominal air exchange rate for each air terminal device.

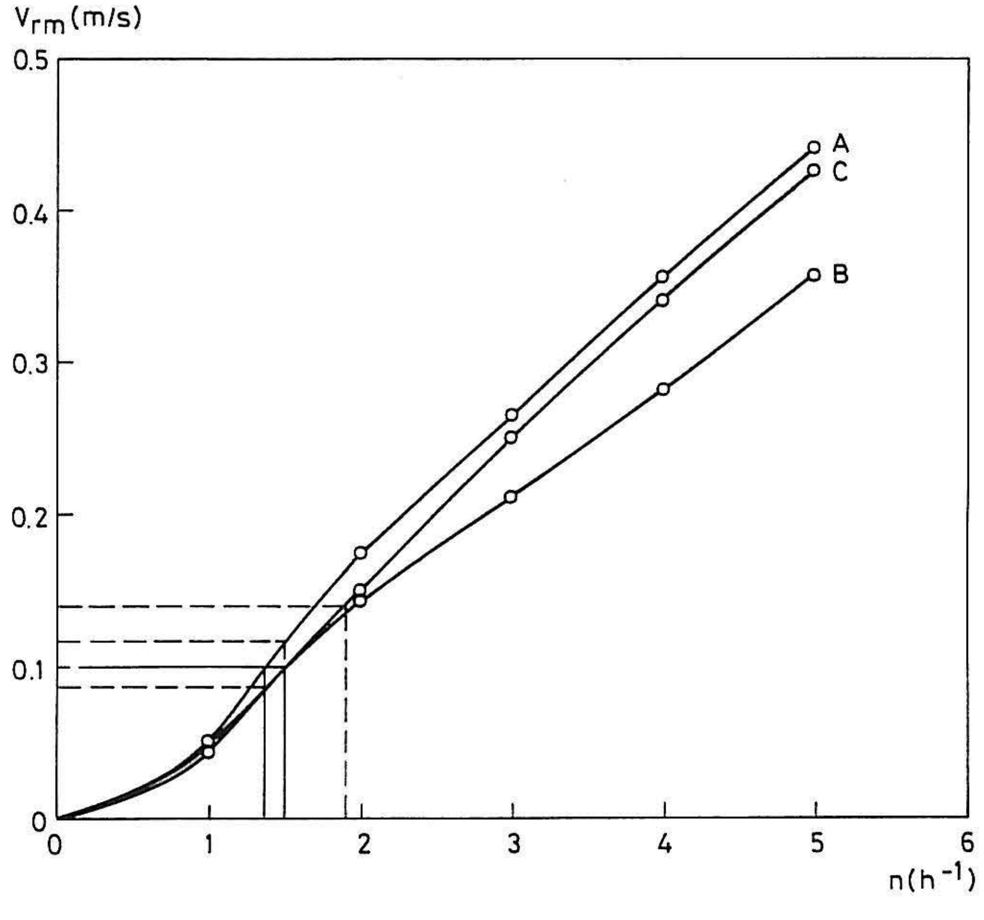

Figure 4. The maximum air velocity in the occupied zone as a function of the nominal air exchange rate.

Figure 4 shows that, at low air exchange rates, the air terminal devices (B) and (C) result in the same maximum air velocity in the occupied zone. This may seem unexpected, since air terminal device (c) should allow the highest flow rates at the given throw, see figure 2. The reason may be that the wall jet at (C) takes up more space of the cross-sectional area of the room than the wall jet at (B), which may increase the air velocities in the re-circulating flow in the occupied zone. At high air exchange rates the air velocities in the occupied zone become even higher for air terminal device (C) than for (B).

COMFORT DEMANDS

Determination of the comfort limit for air velocity in the occupied zone in a room depends on the acceptable level of discomfort. In an ordinary office a dissatisfaction rate of 10% is acceptable. According to Fanger & Christensen (3) the comfort limit for air velocity should in this case be $V_{rm} = 0.1$ m/s. This value applies within the normal temperature range in ventilated workrooms. From the comfort limit and figure 4 the maximum nominal air exchange rate can be found. In figure 5 the result is shown for each air terminal device.

Air terminal device	n h^{-1}	Q m^3/h
A	1.4	65.5
B	1.5	70.6
C	1.5	70.6

Figure 5. Maximum nominal air exchange rate and air supply flow rate for each air terminal device in accordance with reference (3).

The result from figure 2 is included in figure 4 together with the comfort requirements. Apparently a design with a throw equal to room length functions satisfactorily for the air terminal devices (A) and (B). For (C) the method results in a maximum air velocity of 0.14 m/s in the occupied zone. Hereby the dissatisfaction rate is increased to 20%. A dissatisfaction rate of 20% in a single area seems to be too high, although the rate in the remaining part of the room is generally lower (e.g. not exceeding 10%).

The calculated maximum nominal air exchange rates are very low. A maximum air exchange rate of 1.4 - 1.5 h^{-1} is not adequate for ventilating the room, if for example the room is used as a conference room with space enough for 6 - 8 persons. In accordance with the Danish Standard for ventilating systems (5) the necessary exchange rate of fresh air in the room will be either 5.4 h^{-1} or 3.7 h^{-1} depending on whether or not smoking is allowed in the room.

CONCENTRATION MEASUREMENTS

The concentration measurements were performed to determine the distribution of contamination in the room under different circumstances. The measurements are performed under stationary contaminant and air distribution conditions. The measuring points are evenly distributed along a vertical line through the middle of the room. Tracer gas of high, neutral and low density is used. The tracer gas is supplied through a point source (diameter 30 mm) placed 1.1 m above the floor in the middle of the room. The ventilation of the room is only effected by the air terminal devices (A) and (C), at the nominal air exchange rates of $1h^{-1}$, $2h^{-1}$, and $3h^{-1}$, respectively. The air exchange rates were chosen from the results of air velocity measurements in the occupied zone. They will result in conditions that are both above and below the comfort limit.

NORMALIZED CONCENTRATION DISTRIBUTION

The concentration measurements are normalized because they are given in relation to the concentration m_R of the return. A concentration of m/m_R of e.g. 2.0 will indicate that the local concentration is twice as high as the concentration of the return.

The results in figures 6 and 7 show a concentration distribution in the wall jet created by entrainment of the contaminated room air into the primary air. The concentration is highest around and directly below the source. The source is placed in an area of the occupied zone where the air velocity is very low, and the tracer gas will reach a high concentration level before it is entrained and discharged with the other air in the room. Measurements by Oppl (6) show a similar effect when the source is placed in an area with a low velocity.

It is seen that, with increasing air exchange rates the contaminant distribution m/m_R is approximating the distribution at high turbulent flow conditions in the room. It is characteristic of this distribution that it is independent of the air exchange rate, see reference (7).

It is seen that the tracer gas density affects the distribution. Above the source level the highest concentrations were measured by using tracer gas of low density, and the lowest concentrations were measured by using tracer gas of high density. The reverse condition applies below source level. However, the influence decreases at increasing air exchange rates.

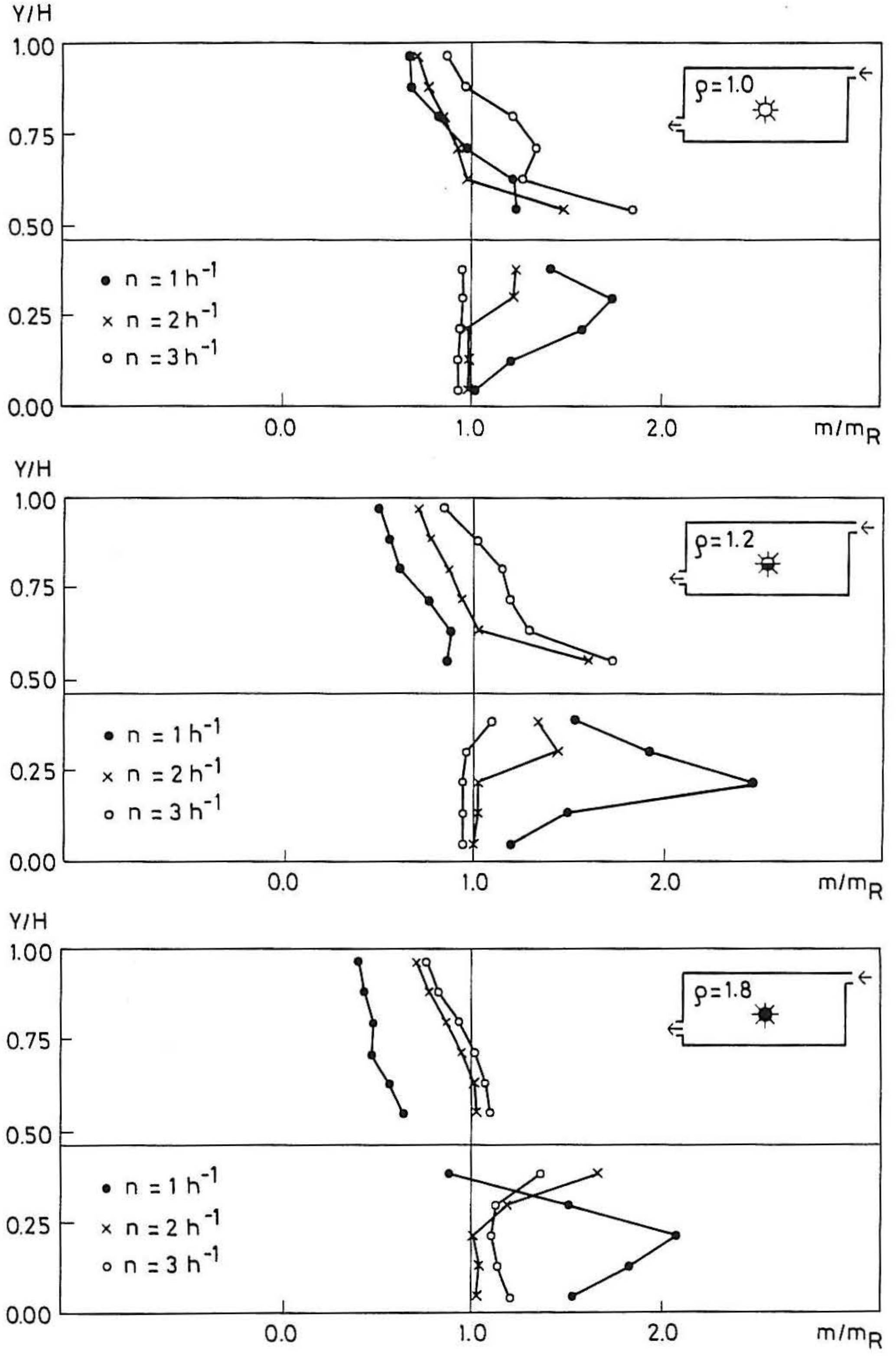

Figure 6. Normalized concentration distribution along a vertical line through the middle of the room for air terminal device (A), nominal air exchange rates of $1h^{-1}$, $2h^{-1}$, and $3h^{-1}$, and the tracer gas densities of 1.8 kg/m³, 1.2 kg/m³, and 1.0 kg/m³.

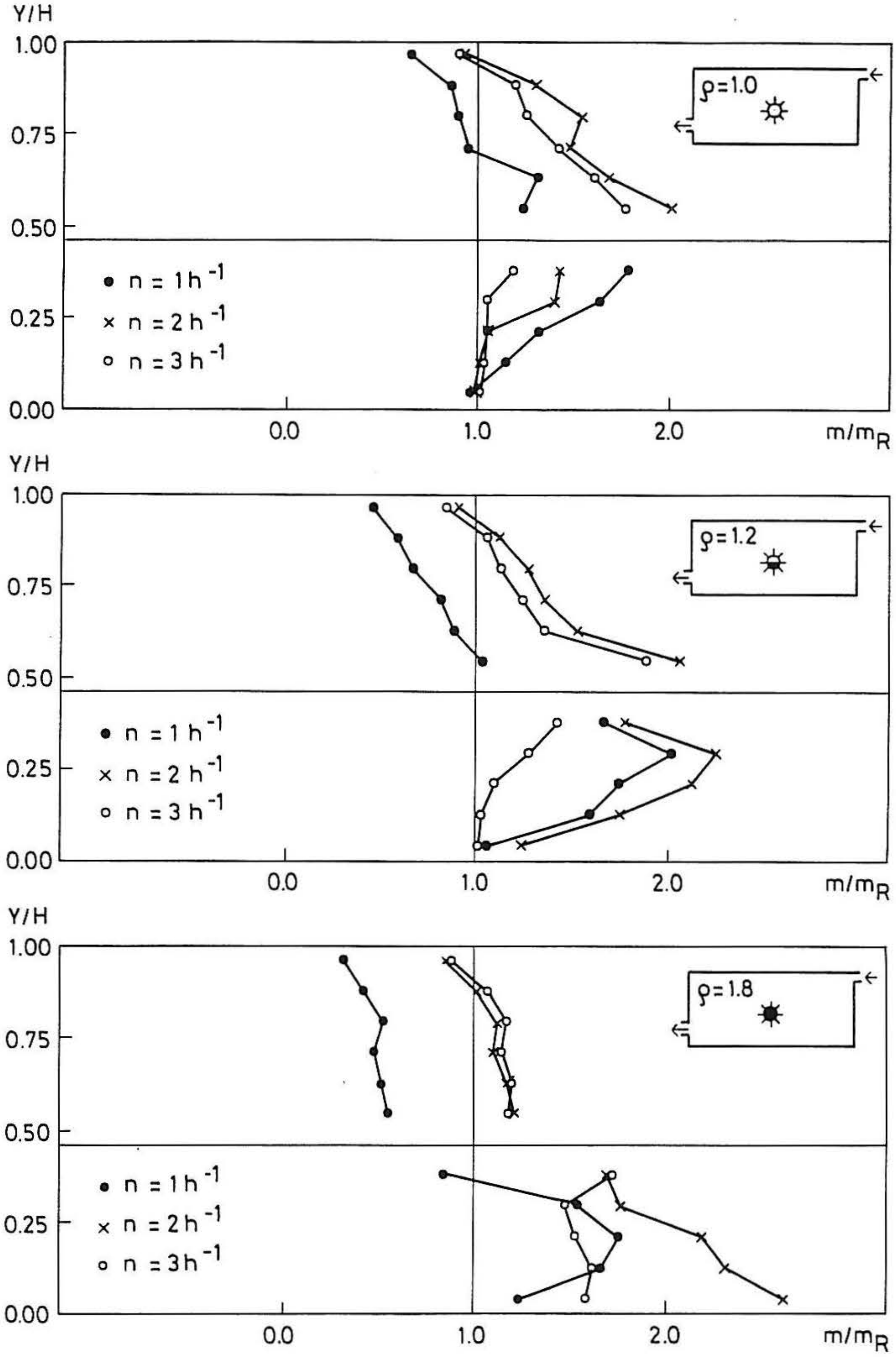

Figure 7. Normalized concentration distribution along a vertical line through the middle of the room for air terminal device (C), nominal air exchange rates of $1h^{-1}$, $2h^{-1}$, and $3h^{-1}$, and the tracer gas densities of 1.8 kg/m^3, 1.2 kg/m^3, and 1.0 kg/m^3.

The contaminant distribution derived is almost identical for the two air terminal devices.

RELATIVE VENTILATION EFFICIENCY

The relative ventilation efficiency $<\varepsilon>$ is based on the room average concentration. The average concentration $<m>$ in the room is measured by a final mixing of room air, while the ventilating plant and the tracer gas supply are discontinued. The relative ventilation efficiency is then calculated from equation (3), see e.g. (8).

$$<\varepsilon> = \frac{m_R}{<m>} \qquad (3)$$

In the figures 8 and 9 the relative ventilation efficiency is shown as a function of the air exchange rate for the air terminal devices (A) and (C), respectively.

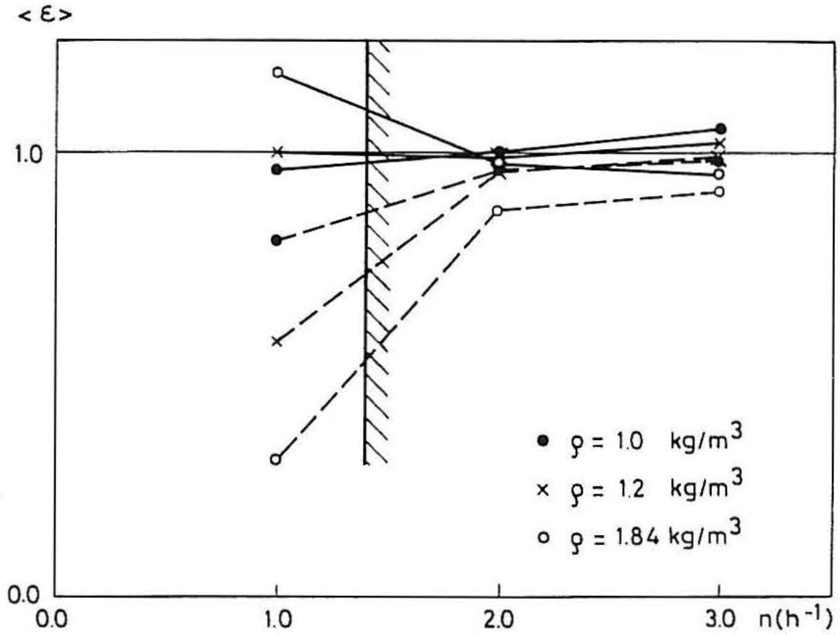

Figure 8. The relative ventilation efficiency as a function of the air exchange rate for air terminal device (A). The dotted lines denote the relative ventilation efficiency in the case where the return is placed 0.7 m from the ceiling. The cross-hatched area shows the upper limit for the air exchange rate taking into account the comfort limit for air velocity, see figure 5.

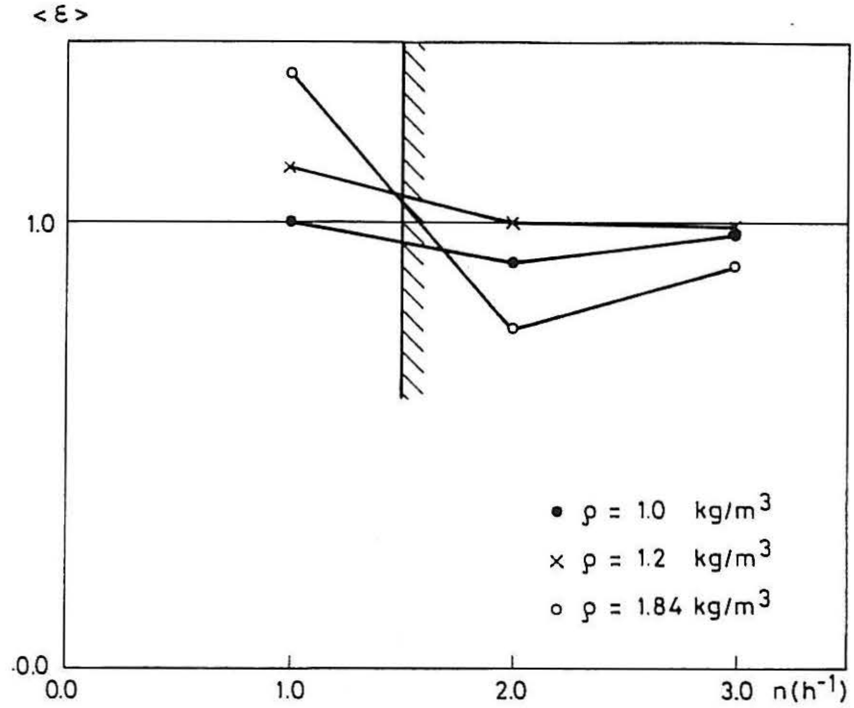

Figure 9. The relative ventilation efficiency as a function of the air exchange rate for air terminal device (C). The cross-hatched area shows the upper limit for the air exchange rate taking into account the comfort limit for the air velocity, see figure 5.

Generally, the relative ventilation efficiency is high at an air exchange rate of $n = 1h^{-1}$, and it approximates the value of high turbulent flow conditions at higher air exchange rates.

At an air exchange rate of $1h^{-1}$ the highest relative efficiency is obtained for the tracer gas with the highest density, and the lowest relative efficiency is obtained for the lowest density. However, the high relative ventilation efficiency gives a false picture of the ventilation in the occupied zone. Probably it arises because the fresh air from the ventilating system does not reach the occupied zone. Hereby the concentration will be very low in the upper part of the room, and in the lower part of the room, the occupied zone, where the return is located, the concentration will be high, see figures 6 and 7. The tracer gas will either counteract or intensify this effect dependent on its density in relation to the air density.

When the return opening is placed at a low height (0.7 m above the floor) the ventilation of the occupied zone will probably show a form of displacement ventilation at low air exchange rates. This is confirmed by measurements where the return is placed at a high position (0.7 m from the ceiling), and where the relative ventilation efficiency at a high tracer gas density is very low, see figure 8.

CONCLUSION

The dimensioning of air terminal devices in ventilated rooms with a throw equal to the room length is not an absolutely safe method to ensure thermal comfort. The air velocity in the occupied zone does not only depend on the properties of the supply opening.

In a room with re-circulating flow a high nominal air exchange rate will give rise to a low and equally prescribed concentration m/m_R in the room.

However, the comfort limit for the air velocity in the occupied zone puts tight limits to the level of the air exchange rate. The figures 8 and 9 show the upper limit for the choice of the air exchange rate.

The measurements show that the position of the return may have a considerable influence on the concentration distribution in the room. Further, it is seen that the relative ventilation efficiency based on room average concentrations does not always give the best foundation for estimating the ability of the ventilating system to remove contamination from the occupied zone.

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