Design methods for air distribution systems and comparison between mixing ventilation and displacement ventilation

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ABSTRACT
The paper will discuss design models for the air distribution system in an office with two persons. The comparisons are made between mixing ventilation and displacement ventilation and they are based on a maximum velocity assumption and a restricted vertical temperature gradient in the room. The comparison is extended by considering both the local discomfort caused by draught rating (*DR*) and the percentage of dissatisfied due to the temperature gradient (*PD*). The two different systems are finally evaluated by measuring the variation of the equivalent homogeneous temperature (*EHT*) at the manikin when it is exposed to the environment generated by the two systems.

INDEX TERMS
Air distribution; Design; Mixing ventilation; Displacement ventilation; Comfort

INTRODUCTION
The aim of an air conditioning system is to remove excess heat in a room and replace room air with fresh air to obtain a high air quality. It is not just sufficient to remove heat and contaminated air, it is also necessary to distribute and control the air movement in the room in such a way that thermal comfort is obtained in the occupied zone. This paper addresses two air distribution systems, namely mixing ventilation and displacement ventilation, and discusses the design strategies for the two systems. The supply flow rate q_0 and the temperature difference ΔT_0 between return and supply are chosen as design parameters.

The local discomfort caused by draught rating, *DR*, and the dissatisfied due to the temperature gradient, *PD*, as well as an evaluation of the air distribution systems based on measurements from a thermal manikin are also addressed.

MIXING VENTILATION AND DISPLACEMENT VENTILATION
Two important parameters are considered in the design of room air distribution. The parameters are the air velocity and the vertical temperature gradient, and they both have to be restricted to certain levels to ensure thermal comfort in the room. The air velocity can either be the maximum velocity u_{rm} inside the occupied zone in case of isothermal flow or it can be the velocity u_{ocz} of the jet when it penetrates the upper boundaries of the occuped zone in the case of non-isothermal flow, see Figure 1A. A third expression for high velocities is connected to the length x_{s} of the wall jet below the ceiling (penetration length), see Figure 1A. A penetration length larger than half the room length, $x_s/L > 0.5$, will normally ensure restricted velocities in the occupied zone. The vertical temperature gradient is not considered to be important for mixing ventilation. Nielsen (1991), Nielsen *et al.* (2001) and Jacobsen *et al.* (2002a,b) show details of design models based on the above-mentioned restrictions on the velocity level in the occupied zone.

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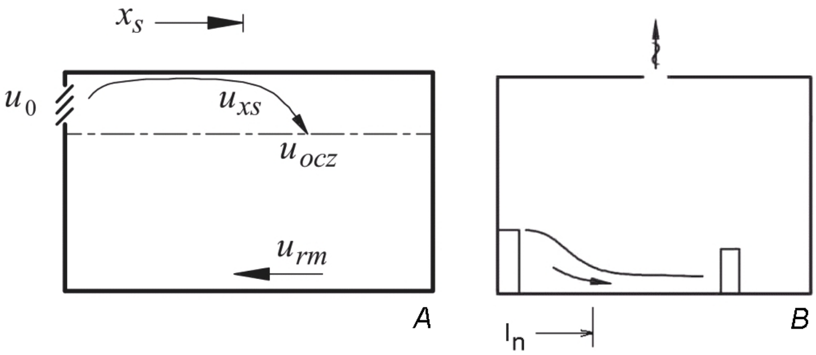

Figure 1 Room with mixing ventilation (A) and a room with displacement ventilation (B).

Displacement ventilation has a high air velocity in the stratified flow at the floor. Restricted velocity in the occupied zone is therefore obtained by restricting the velocity in the stratified flow where it enters the vertical boundary of the occupied zone in front of the diffuser. This is expressed by the length of the adjacent zone l_n, which is the distance from the diffuser to a given velocity level in the stratified flow, see Figure 1B and Nielsen (2000) and Skistad *et al.* (2002). The vertical temperature gradient is also important in displacement ventilation and it should be restricted to a certain level. A minimum stratification height is especially important when the air is contaminated. The idea behind a minimum stratification height is to keep the occupants' breathing zone in the low zone, or close to the low zone, enabling them to inhale clean room air, see Brohus and Nielsen (1996) and Skistad *et al.* (2002). This has not been considered in the paper.

COMPARISON BETWEEN MIXING VENTILATION AND DISPLACEMENT VENTILATION

The comparisons are made in a room of typical size for a small office. The room was a standard room for the International Energy Agency Annex 20 work, see Nielsen *et al.* (2001). The room has the dimensions; length, width, height equal to 4.2 m, 3.6 m and 2.5 m, respectively.

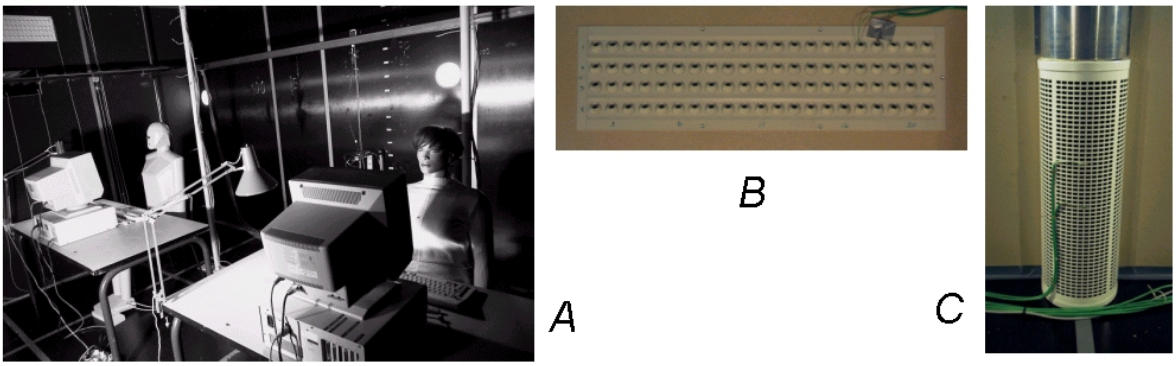

Figure 2 Office room with two manikins (A). 'Annex 20' diffuser (B), and diffuser for displacement ventilation (C). Two types of diffusers were used for displacement ventilation.

Figure 2A shows the heat load locations in the room. The heat load consists of two PCs, two lamps and two manikins giving a total load of 460 W. The manikin on the right side of the picture is the measuring manikin, and the manikin on the left side of the picture is a manikin that imposes an additional heat load on the room. The two manikins change place during the measurements. The arrangement in Figure 2A is called an A-case and the reverse location of the measuring manikin is called a B-case.

Figure 2B shows the 'Annex 20' diffuser for mixing ventilation mounted on the end wall below the ceiling, and Figure 2C shows the diffuser for displacement ventilation mounted in the same wall. Two different types of diffusers are used for the experiments on displacement ventilation described in this paper.

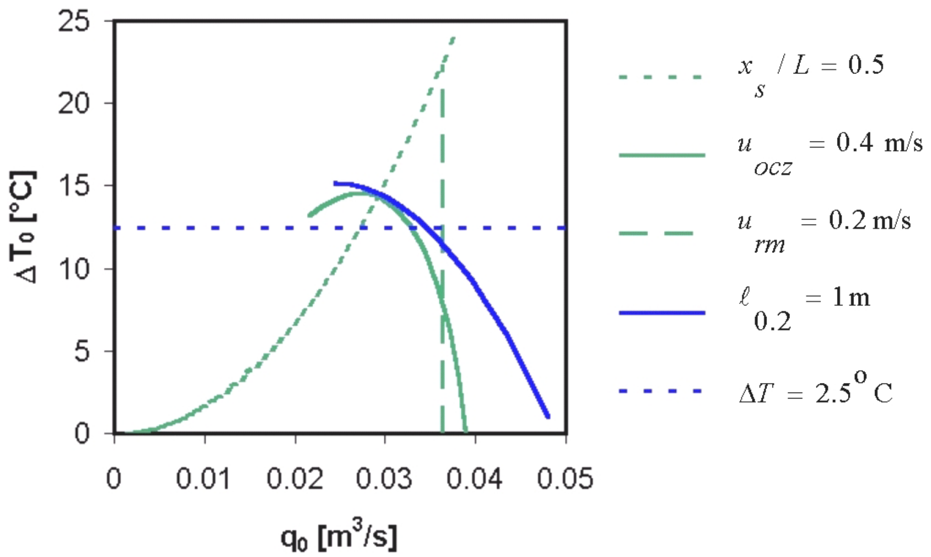

Figure 3 Design graph for the two ventilation systems based on the temperature difference ΔT_0 between return and supply and on the flow rate q_0 to the room. The curves show different limitations for the velocity levels and the temperature gradient, which ensure thermal comfort in the room.

Figure 3 can be considered as a design graph. The graph is based on temperature differences ΔT_0 between return and supply and on flow rate q_0 to the room. The curves, which are found by measurements in the two rooms, show the combination of ΔT_0 and q_0 which encloses an area that fulfils thermal comfort. A maximum velocity u_{rm} of 0.2 m/s restricts the flow rate to the room to 0.036 m^3/s, and the requirement of a penetration length of $x_x /L = 0.5$ is expressed by the dotted curve in Figure 3. The area between the two curves will thus express an area allowed for variation of ΔT_0 and q_0 in the room with mixing ventilation.

The combination of ΔT_0 and q_0 which gives the penetrating velocity $u_{ocz} = 0.4$ m/s is shown by another curve in Figure 3. The rather high velocity seems to give the same level of comfort as obtained by the consideration of the jet penetration length. An acceptance of a higher velocity in vertical downward direction is confirmed by Toftum *et al.* (1997).

The length of the adjacent zone l_n is given to 1 m with a reference velocity of 0.2 m/s in the case of displacement ventilation, and the temperature difference ΔT_0 is in principle restricted to 12.5°C corresponding to a vertical gradient of 2.5°C/m in the room. Two curves show the corresponding area for fulfilment of thermal comfort in the ΔT_0, q_0 diagram.

The figure indicates that the room to some extent will have the same level of comfort (with respect to maximum velocity and maximum temperature gradient) independent of the air distribution system. It became clear by this work that the results for displacement ventilation were very dependent on an efficient low-velocity diffuser. Generally, Figure 3 indicates that constant air volume systems (CAV) work well for mixing ventilation, while variable air volume systems (VAV) are easy to control in the case of displacement ventilation.

LOCAL DISCOMFORT OBTAINED BY THE DIFFERENT AIR DISTRIBUTION SYSTEMS

The design models discussed in the last two sections can only give the limits for the operation of the air distribution system. It is necessary to consider thermal comfort for all flow rates if the system has to be optimized.

The thermal environment often exhibits temperature gradients, velocity gradients, different turbulence levels and an asymmetric radiant temperature distribution. The local discomfort, which is the result of this environment, is judged from measurements of the local values of air temperature, air velocity, turbulence level and from measurements of surface temperatures or asymmetric radiant temperatures (see Fanger and Langkilde, 1975; Olsen *et al.*, 1979; Fanger *et al.*, 1989; Toftum *et al.*, 1997).

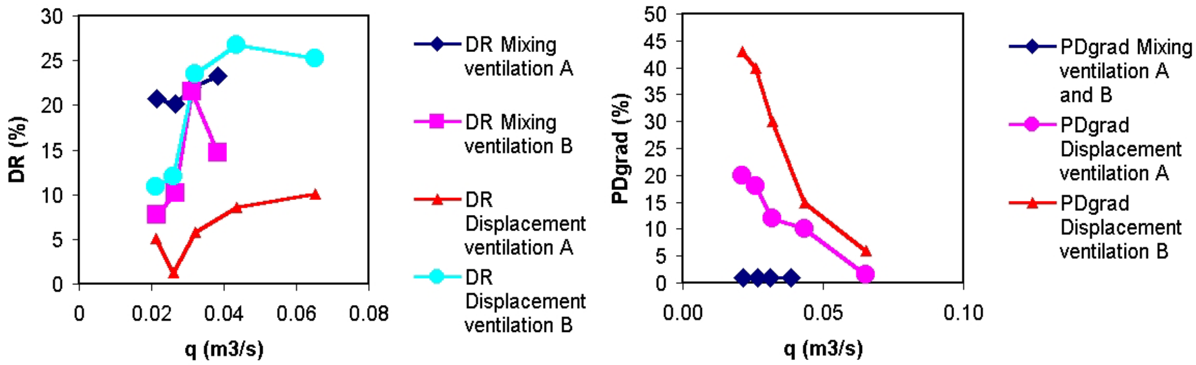

Figure 4 Draught rating *DR* versus flow rate, and percentage of dissatisfied PD_{grad} due to vertical temperature gradient versus flow rate. The cooling load in both rooms is constant and equal to 460 W.

Figure 4 shows the number of dissatisfied because of draught, *DR*. It is expected that the maximum velocity has a downward direction in the case of mixing ventilation, but the measurements show that this is only the case for the lowest air flow rate (n = 2.05 h^{-1}). Air velocity in horizontal direction measured 10 cm above the floor gave the highest velocity at all other airflow rates (up to n = 3.66 h^{-1}). The draught rating, *DR*, for displacement ventilation is in all cases a result of a horizontal flow from the wall-mounted diffuser. It is shown in Figure 4 that the draught rating, *DR*, for mixing ventilation has the highest level far away from the diffuser, while it is the opposite for displacement ventilation where a position close to the diffuser gives the highest risk of draught. The draught rating increases with increasing air change rate, independent of the type of air distribution system. Figure 4 also shows the percentage of dissatisfied due to the vertical temperature gradient in the occupied zone. There is a total lack of dissatisfied when the air distribution system is of the mixing type. Displacement ventilation shows a high percentage of dissatisfied at low flow rates, and the PD_{grad} decreases with increasing flow rate.

Comparison between the two graphs in Figure 4 indicates that mixing ventilation has the lowest level of local discomfort at low flow rates, while an optimal flow rate exists for displacement ventilation because the *DR* is increasing with the flow rate and the PD_{grad} is decreasing.

EVALUATION OF LOCAL THERMAL COMFORT BY A THERMAL MANIKIN

The thermal manikin used in the experiments is described in detail in Nielsen *et al.* (2002). The skin temperature and the heat output correspond to a person in thermal comfort. The thermal manikin can be used to quantify uniform and nonuniform thermal surroundings.

The equivalent homogeneous temperature *EHT* can be measured by a thermal manikin (Tanabe *et al.*, 1994; Nielsen *et al.*, 2002). *EHT* is defined as the temperature of a homogeneous environment in which the same amount of heat is lost as in the actual environment. Homogeneous conditions are achieved when the air temperature is equal to the mean radiant temperature, when air temperature gradients and radiant temperature asymmetry in all directions are negligible and when the air velocity is lower than 0.05 m/s.

It is not possible to measure the local thermal discomfort directly by the manikin, but the distribution of *EHT* values for the different body segments can be used as an expression of the inhomogeneous thermal surroundings. The value Δ*EHT*, which is the difference between the highest and the lowest measured *EHT* on the manikin, is used in this paper as an expression of local discomfort. A high level of Δ*EHT* is either the result of draught in the whole volume around a person (global effect) or it can be the result of local draught, high turbulent flow, air temperature gradients, asymmetric radiation or a combination of those effects.

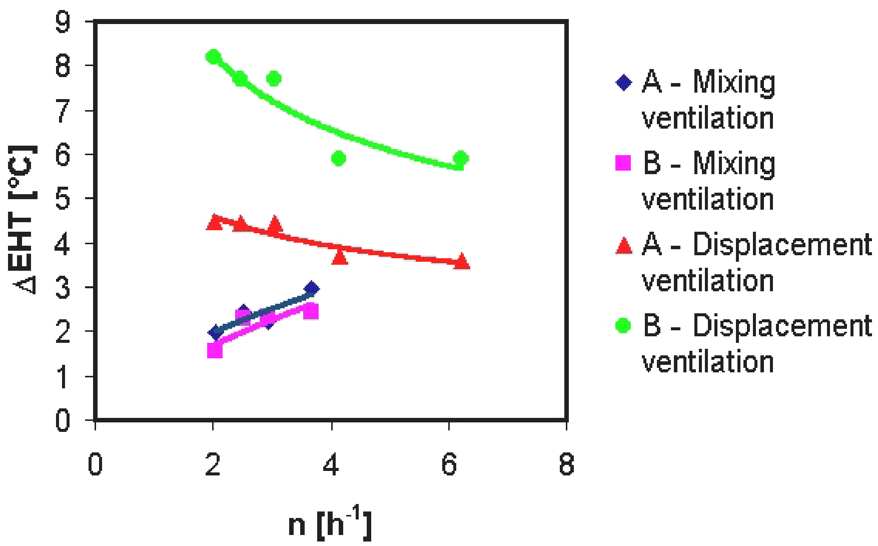

Figure 5 Δ*EHT* versus air change rate for two air distribution systems.

Figure 5 shows the variation of Δ*EHT* as a function of the air change rate *n* for the two air distribution systems. The displacement ventilation system shows the highest level of Δ*EHT*. The vertical temperature gradient seems to be an important reason for this high level, and an increased air flow rate will therefore decrease Δ*EHT*. The position close to the diffuser has the highest vertical temperature gradient because of a low temperature in the stratified flow in the floor region. Mixing ventilation shows a low level of Δ*EHT*. It increases with increasing flow rate probably due to the effect of draught.

CONCLUSION

Comparisons between mixing and displacement ventilation show that the office room can be designed to the same comfort level with respect to maximum velocity and maximum temperature gradient independent of the air distribution system.

Measurements of local discomfort give additional information about the optimal conditions for the air change rate at a given load in the room.

The difference between the largest *EHT* and the smallest *EHT* measured for the segments of a manikin, Δ*EHT*, can be used as an indication of local discomfort due to the temperature gradient, draught, turbulence and asymmetric radiation. Experiments with mixing ventilation and displacement ventilation address the connection between Δ*EHT* and the air change rate.

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