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Local Thermal Discomfort Due to Draft and Vertical Temperature Difference in Rooms with Displacement Ventilation

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ABSTRACT

The present paper evaluates the thermal comfort conditions in 18 spaces in practice ventilated by the displacement ventilation principle recently developed in Scandinavia. The risk of local discomfort due to draft and vertical temperature difference is estimated by comprehensive measurements of mean velocity, turbulence intensity, and air temperature. The results indicate a high risk of draft and vertical temperature difference in the occupied zone of some of the spaces. The draft risk and vertical temperature difference varied substantially within the occupied zone. They may create serious complaints in the half of the occupied zone nearest to the outlets. In several cases there was a potential risk of combined discomfort due to draft and vertical temperature difference. This combined discomfort should be studied by subjective experiments.

The measuring heights for air temperature and air movement recommended in the standards (0.1, 0.6, 1.1, and 1.7 m) were not sufficient to estimate draft risk in the occupied zone. Mean velocity, turbulence intensity, air temperature, predicted percent dissatisfied due to draft, and vertical temperature difference were found to be functions of exhaust and supply air temperature difference and airflow rate.

INTRODUCTION

It is important that a ventilation system provide the acceptable thermal comfort conditions in the occupied zone of a space described in the present standards (ISO 1984; ASHRAE 1981).

In practice it is relatively easy to satisfy the general thermal comfort requirements so that a person feels thermally neutral for the body as a whole, i.e., he does not know whether he would prefer a higher or a lower ambient temperature level. It is more difficult to avoid local thermal discomfort. A person may feel thermally neutral for the body as a whole, but might not be comfortable if some part of his body is warm and another is cold. Such local discomfort may be caused by an asymmetric radiant field, by local convective cooling (draft), by contact with a warm or a cold floor, or by a vertical air temperature difference.

Recently the displacement ventilation principle (Skaret 1987; Sandberg and Sjoberg 1984) has become popular for ventilating spaces occupied by people with a low activity level, for instance, offices, conference rooms, computer rooms, and lecture rooms. In such spaces the air is supplied directly into the occupied zone from large outlets with low velocity. The outlets are located near the floor. The supply air, with a temperature of 2° to 4°C below room air temperature, spreads near the floor in a relatively thin layer and subsequently rises to the ceiling, displacing the contaminated room air. The vertical temperature differences in the occupied zone are larger than in rooms with traditional mixed ventilation and relatively high velocities and low temperatures could be observed near the floor. Therefore, local discomfort due to draft and vertical temperature difference may be critical in rooms with displacement ventilation.

Draft is defined as an unwanted local cooling of the human body caused by air movement. For a long time it has been well known that the risk of draft increases with increasing mean air velocity and decreasing air temperature. Fanger and Pedersen (1977) recognized that fluctuations in air velocity also contribute to the sensation of draft. Typically the air velocity in rooms fluctuates randomly, e.g.,

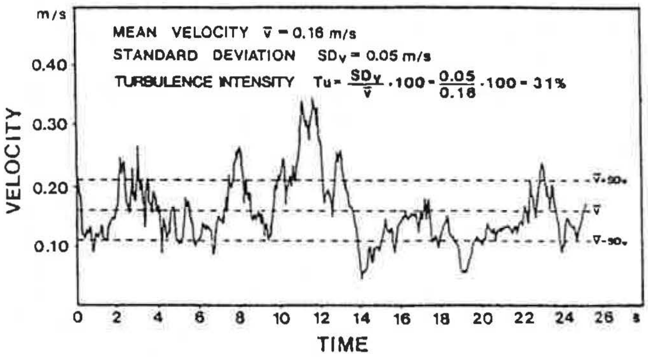

Figure 1 *Record of instantaneous velocity in the occupied zone*

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the airflow is turbulent. A characteristic of the velocity fluctuations is the turbulence intensity defined in Figure 1. The impact of the turbulence intensity on the sensation of draft has been investigated recently (Fanger et al. 1987, 1988). A mathematical model of draft risk has been established (Fanger et al. 1988) which predicts the percentage of people dissatisfied due to draft, PD, as a function of air temperature, t_a (°C), mean air velocity, $\bar{v}$, (m/s), and turbulence intensity, Tu (%):

$$PD = (34 - t_a)(\bar{v} - 0.05)^{0.62}(3.14 + 0.37\ \bar{v}\,Tu) \quad (1)$$

for $\bar{v} < 0.05$ m/s insert $\bar{v} = 0.05$ m/s

for PD > 100% use Pd = 100%

The model may be used for all heights in the occupied zone of a space, although it may tend to overestimate the draft risk on arms and feet when these parts of the body are covered with clothing (e.g., long sleeves, trousers, and socks).

There are only a few laboratory studies (Holmberg et al. 1987; Lindquist and Ljungqvist 1987; Sandberg 1988; Palonen et al. 1988) that provide information about the airflow characteristics in rooms with displacement ventilation. There is little information available on the performance of this ventilation principle in practice.

The purpose of this study is to estimate the risk of local discomfort due to draft and vertical temperature difference in the occupied zone of a wide range of rooms with displacement ventilation in practice. Such information is essential for further practical improvement of the displacement ventilation principle.

EXPERIMENTAL CONDITIONS

The results presented in this paper are based on two comprehensive field studies made by Melikov et al. (1989) and Nielsen (1988) in a total of 18 spaces with displacement ventilation. Only rooms used by people with a sedentary occupation were studied (offices, conference rooms, computer rooms, etc.), as the risk of draft exists mainly at this low activity level (~ 1.2 met). The floor area of the space ranged from 7 to 80 m². The heat production in the rooms was different, from 10 to 51 W/m². In one of the rooms it was 105 W/m². The spaces were selected to cover typical locations and types of outlets with different shapes (flat and semicylindrical cross section). The spaces were furnished and the measurements were performed under normal operating conditions. At least two persons were in the room (those taking the measurements). In larger spaces the occupants were simulated by laminated heated iron cylinders. Experiments were performed at steady-state temperature conditions in the rooms.

Comprehensive measurements of mean velocity, turbulence intensity, and air temperature were performed at six different heights above floor level (0.033, 0.1, 0.3, 0.6, 1.1, and 1.7 m) in the occupied zone of the rooms. The measurements were performed using a multichannel flow analyzer with omnidirectional temperature-compensated probes. The integration time was 10 minutes. In each space the probes were placed at nine or more measurement locations equally distributed and covering the occupied zone. The measuring equipment was of the same kind as used in developing Equation 1. Supply and exhaust air

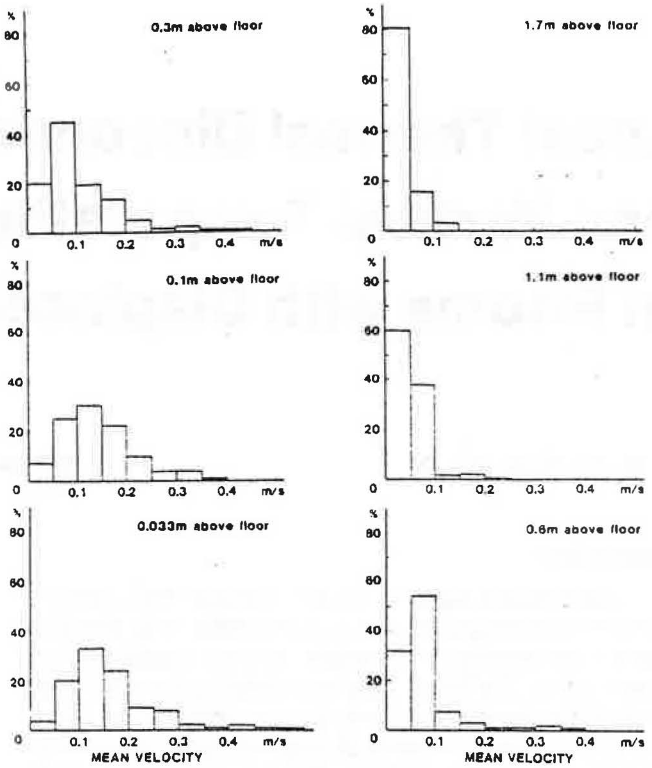


Figure 2 Histograms of the mean velocity, v, distribution at different heights

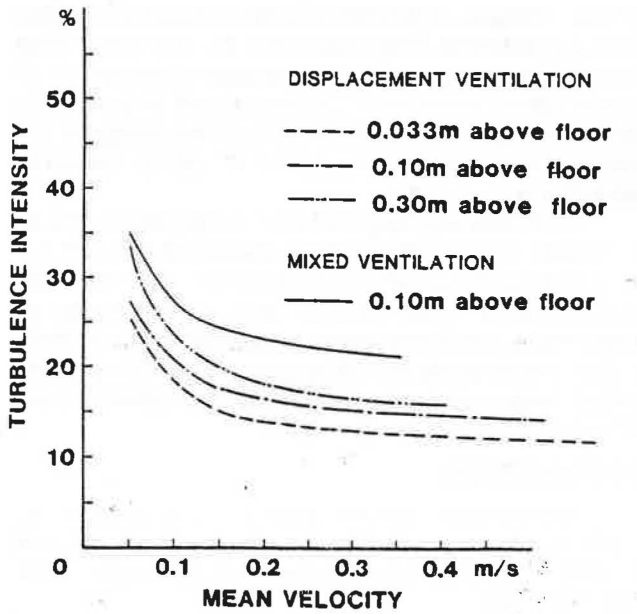


Figure 3 Turbulence intensity, Tu, as a function of mean velocity, v, at different heights in the occupied zone

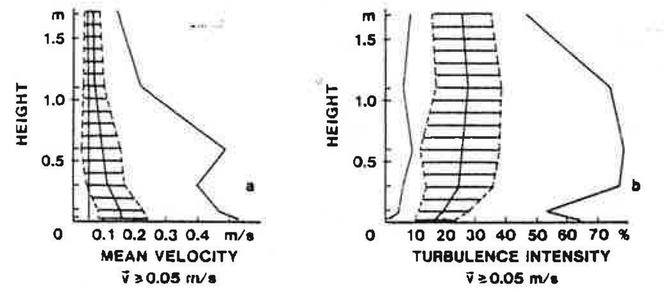
temperatures were registered. Exhaust and supply air temperature difference in the rooms ranged from 1.8° to 8°C. The experimental conditions are described in detail by Melikov et al. (1989) and Nielsen (1988).

RESULTS

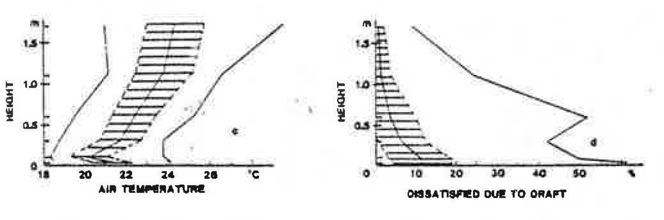
The results presented in this paper are based on more than 1300 measurements of mean velocity, turbulence intensity, and air temperature in the occupied zone.

TABLE 1
Regression Equations for the Turbulence Intensity, Tu, as a Function of the Mean Velocity, v, at Different Heights in the Occupied Zone

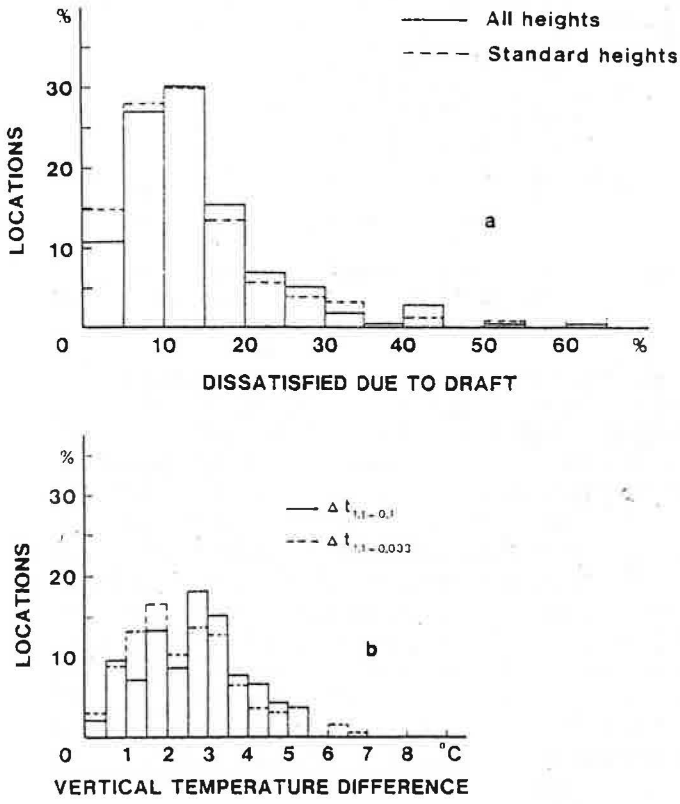
Height m	Equation %	Correl. Coeff. R	Total Observ.	Maximum v, m/s
		DISPLACEMENT VENTILATION		
0.033	$Tu = 0.72/\bar{v} + 10.6$	0.712	207	0.53
0.10	$Tu = 0.70/\bar{v} + 13.1$	0.614	217	0.46
0.30	$Tu = 0.97/\bar{v} + 13.6$	0.595	171	0.40
		MIXED VENTILATION (Melikov et al. 1987)		
0.10	$Tu = 0.78/\bar{v} + 19.1$	0.668	275	0.29



Figures 4a and 4b *Vertical profiles of average mean velocity and turbulence intensity in the occupied zone. Standard deviation, maximum and minimum limits are shown as well.*



Figures 4c and 4d *Vertical profiles of averaged air temperature and percent dissatisfied due to draft in the occupied zone. Standard deviation, maximum and minimum limits are shown as well.*



Figures 5a and 5b *Histograms of percent dissatisfied due to draft, PD, and vertical temperature difference, $\Delta t_{1.1-0.1}$, in the occupied zone of rooms. PD calculated by the model of draft risk*

A percentage distribution of the mean velocity from all the measurements of the six heights is shown in Figure 2. As expected, the highest velocities were measured near the floor, especially at 0.033 and 0.1 m. At 0.6, 1.1, and 1.7 m above floor level more than 85% of the measurements had a mean velocity of less than 0.1 m/s. At these heights the risk of draft was low.

The turbulence intensity as a function of the mean velocity is shown in Figure 3 for the three heights nearest the floor (0.033, 0.1, and 0.3 m) where the highest velocities were measured. In general the turbulence intensity increases when the mean velocity decreases and the height increases. The relationship between the turbulence intensity and the mean velocity at 0.1 m above the floor, identified by Melikov et al. (1987) in rooms with mixed ventilation, also is shown in the figure. The comparison shows lower turbulence intensity in the rooms with displacement ventilation than in the rooms with mixed ventilation. The regression equations of the relationships in Figure 3 are listed in Table 1. The correlation coefficients indicate substantial deviation of the turbulence intensity.

The vertical profiles of the average mean velocity, turbulence intensity, and air temperature in all investigated spaces are shown in Figure 4 together with the vertical profile of the predicted PD due to draft. The standard deviation, and minimum and maximum deviations are included in Figure 4 as well. PD was calculated for each point in the occupied zone of the rooms by means of the model of draft risk. The results shown in Figures 4a and b indicate highest mean velocity and lowest turbulence intensity near the

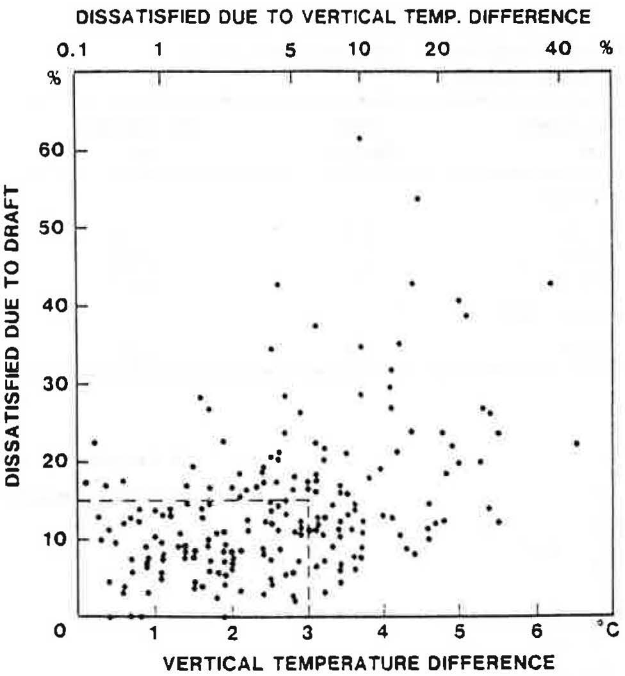


Figure 6 *Predicted percent dissatisfied due to draft, PD, and vertical temperature difference, $\Delta t_{1.1-0.1}$, at each measured location in the rooms*

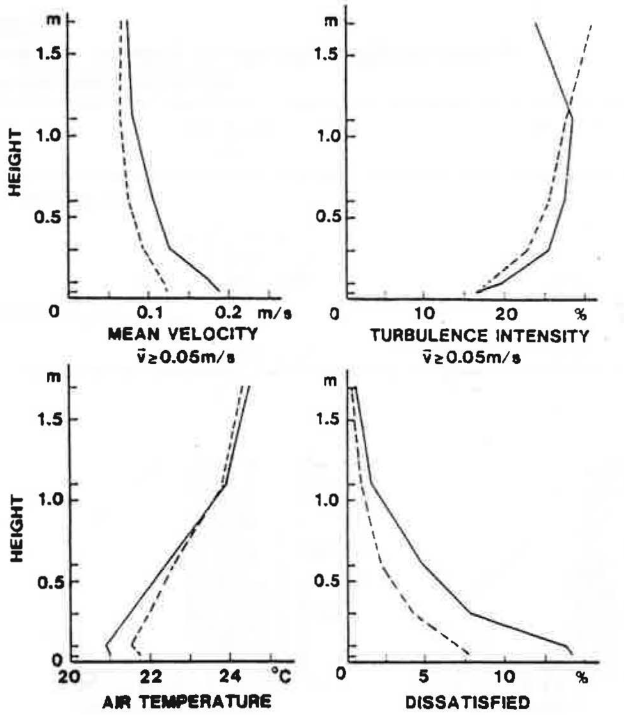


Figure 7 *Vertical profiles of average mean velocity, turbulence intensity, air temperature and percent dissatisfied due to draft in the two halves of the occupied zone: (———) the half near the outlets, (— — —) the half far from the outlets*

floor. The lowest air temperature was measured at 0.1 m above floor level (Figure 4c). The average PD was calculated to be highest near the floor as well, with a maximum value of less than 12%. However, the standard deviation of PD in Figure 4d reaches values of up to 19% dissatisfied.

The measured mean velocities, turbulence intensities, and air temperatures were used to quantify the percentage of persons dissatisfied due to draft (PD) by means of Equation 1. For each measured location in the occupied zone of the rooms, the PD was calculated for the six heights. For the analyses, however, it was decided to use only the highest calculated values of PD from the six heights at each location. This provides a more realistic result, because each location is considered a person who will be dissatisfied in some way if he feels discomfort due to draft on just one part of his body.

Figure 5a compares histograms of the PD for all investigated rooms based on the measurements taken at all six heights and only at the heights recommended in the standards (0.1, 0.6, 1.1, and 1.7 m). The PD is higher when the results from the six heights measured are used than when only the standard heights are considered.

The vertical temperature gradient in the occupied zone is an important parameter to be studied. According to the standards (ISO 1984; ASHRAE 1981) for light, mainly sedentary activity, the vertical air temperature difference between 1.1 and 0.1 m above floor level (level of head and ankles, respectively) should be less than 3°C. Figure 5b shows a histogram of the vertical temperature difference between 1.1 and 0.1 m in the investigated spaces. Quite a large percentage (40%) of the locations within the occupied zone had a temperature difference of more than 3°C, e.g., they do not comply with the standards. In the figure, a histogram of the temperature difference between 1.1 and 0.033 m above floor level, $\Delta t_{1.1-0.033}$, is shown as well. For these heights, 34% of the measurements showed a vertical temperature difference of more than 3°C. Therefore, the standard heights are used in the following analyses.

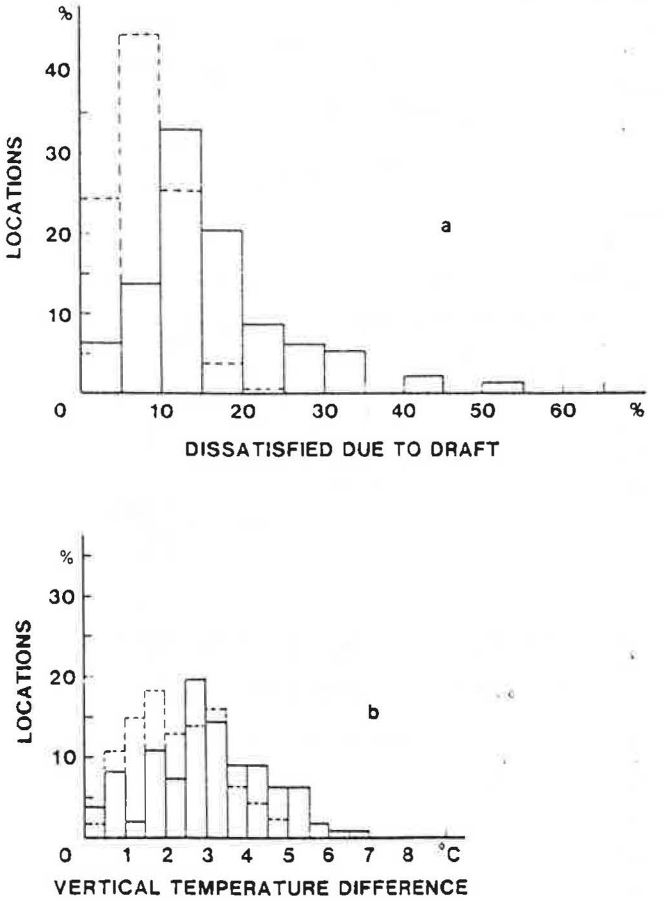
Figure 6 combines the two local discomforts. The points on the figure present maximum PD and the vertical temperature difference, $\Delta t_{1.1-0.1}$, at each measured location in the rooms. The limits of PD = 15% and $\Delta t_{1.1-0.1}$ = 3°C are indicated in the figure. The percentage dissatisfied due to vertical temperature difference found by Olesen et al. (1979) in subjective experiments is included in the top of the figure as well.

Non-uniformity of the occupied zone of rooms with displacement ventilation also was studied on a horizontal plane after dividing the rooms roughly into two halves—one near the outlets and the other far from them. Figure 7 compares vertical profiles for the average mean velocity, turbulence intensity, air temperature, and predicted PD in the two halves of the occupied zone. There are substantial differences on the horizontal plane of the occupied zone.

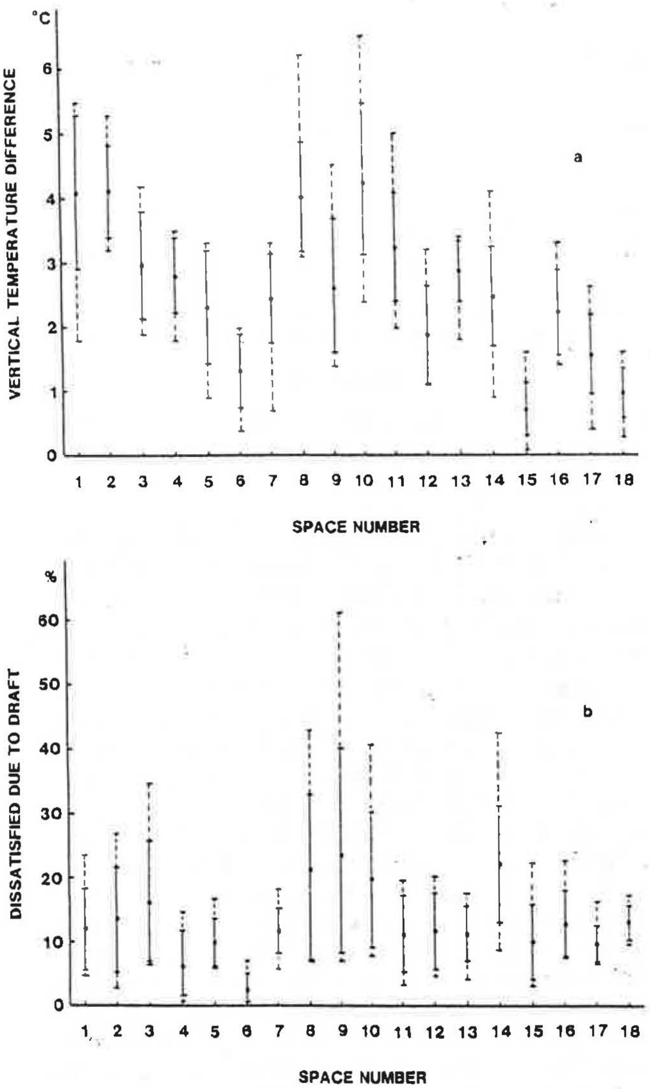
This also is obvious in Figure 8a, which compares histograms of PD for the two halves of the occupied zone. The histograms are based on the maximum value of PD among the four standard heights (0.1, 0.6, 1.1, and 1.7 m above floor level).

Figure 8b compares histograms of the vertical temperature difference, $\Delta t_{1.1-0.1}$, in the two halves of the occupied zone. The largest vertical temperature differences were measured in the half where the outlets were installed.

Figure 9 presents the vertical temperature difference and the predicted percent dissatisfied in the occupied zone of each room. The mean value, the standard deviation, and the maximum and minimum values in the figures



Figures 8a and 8b *Histograms of percent dissatisfied due to draft, PD, and vertical temperature difference $\Delta t_{1.1-0.1}$, in the occupied zone of rooms: (———) in the half near the outlets, (— — —) in the half far from the outlets*



Figures 9a and 9b *Predicted percent dissatisfied, PD, and measured vertical temperature difference $\Delta t_{1.1-0.1}$, in the investigated rooms. Mean value, standard deviation, maximum and minimum values for each room are included.*

are based on data for all locations in a room. For the PD the maximum calculated of the six heights at each measured location is used.

Percent locations where $\Delta t_{1.10.1}$ is larger than 3°C and PD is larger than 15% may indicate that part of the occupied zone where local thermal discomfort may be expected. Figure 10 indicates this part for each room separately for $\Delta t_{1.1\text{-}0.1}$ and PD.

Mean velocity, turbulence intensity, and air temperature distribution in rooms with displacement ventilation depend on several factors: type, location, and height of the outlet; exhaust and supply air temperature difference; airflow rate; etc. Figure 11 shows how mean velocity, turbulence intensity, and air temperature depend on exhaust and supply air temperature difference at two air change rates (4.2 and 7.7 per hour). The experiments were performed in one of the investigated rooms where the supply air temperature and the airflow rate were changed, but where the other conditions in the rooms remained unchanged. At each air change rate measurements were performed for six values of the exhaust and supply air temperature difference in the range from 3° to 9.5°C. For each height above the floor, mean velocity, turbulence intensity, and air temperature were measured at nine locations within the occupied zone and then averaged. In the same way the predicted percent dissatisfied due to draft and the vertical temperature difference were calculated for the 12 experiments. Figure 12 shows the percent dissatisfied due to draft and the vertical temperature difference as a function of the exhaust and supply air temperature difference for the two air change rates.

DISCUSSION

The present study evaluates the conditions for local thermal discomfort in 18 spaces with displacement ventilation in practice. The risk of local discomfort due to draft and vertical temperature differences are analyzed since they are the most critical for the displacement ventilation principle. Only spaces used by sedentary occupants were chosen, as these two types of discomfort exist mainly at low activity levels.

In thermal comfort standards (ISO 1984; ASHRAE 1981) 80% acceptable limits are specified. It is assumed that the limits for general thermal comfort should be based

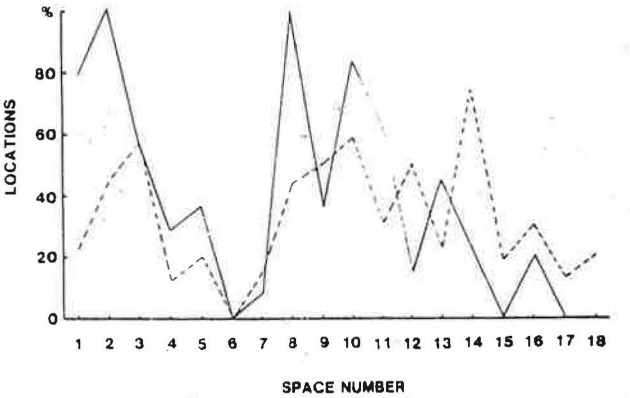


Figure 10 *Percent locations with PD > 15% and* $\Delta t_{1.1-0.1} > 3°C$ *in the occupied zone of the investigated rooms*

on a 10% dissatisfaction criterion. Next it is assumed that less than 10% are dissatisfied due to local thermal discomfort. The limits for the vertical temperature difference and radiant temperature asymmetry correspond to approximately 5% dissatisfied and the limits for floor temperature correspond to 10%. The draft is restricted by summer and winter limits for mean velocity and air temperature, but the significant impact of turbulence intensity is not considered. This should be included in the standards as well. Using the model of draft risk, the most realistic limit for local discomfort due to draft is probably 15% dissatisfied, since air movement (mean velocity and turbulence intensity) is most difficult to control in practice. Therefore, PD should not exceed 15% at any point within the occupied zone.

The histograms in Figure 5a show that at the heights recommended in the standards. 28% of the locations within the occupied zone where measurements were performed had a PD above 15%. If all the measured heights are considered, the percentage is 33%. A statistical test showed that PD calculated for all measured heights was significantly higher than PD calculated only for the heights recommended in the standards. Therefore, the standard heights are not sufficient in order to estimate the draft risk. This may be a serious problem during summer in rooms with displacement ventilation.

The vertical temperature difference is another local discomfort that should be considered in rooms with displacement ventilation. The results in Figure 5b show that for 40% of the locations within the occupied zone $\Delta t_{1.1\text{-}0.1}$ exceeded the maximum of 3°C recommended in the standards.

The limits of different local discomforts recommended in the standards are based on subjective experiments, in which each type of local discomfort was studied separately. It was then assumed that the individuals most sensitive to cold on the body in general would also be the ones most sensitive to different types of local discomfort, and consequently the percent dissatisfied is not additive. The question is whether there is any scientific evidence to support this assumption. Berglund and Fobelets (1987) studied the combined effect of local discomfort due to draft and radiant temperature asymmetry from cold vertical surfaces by subjective experiments. The perception of draft was found to be independent of radiant temperature asymmetry. The effects of velocity and radiant asymmetry were

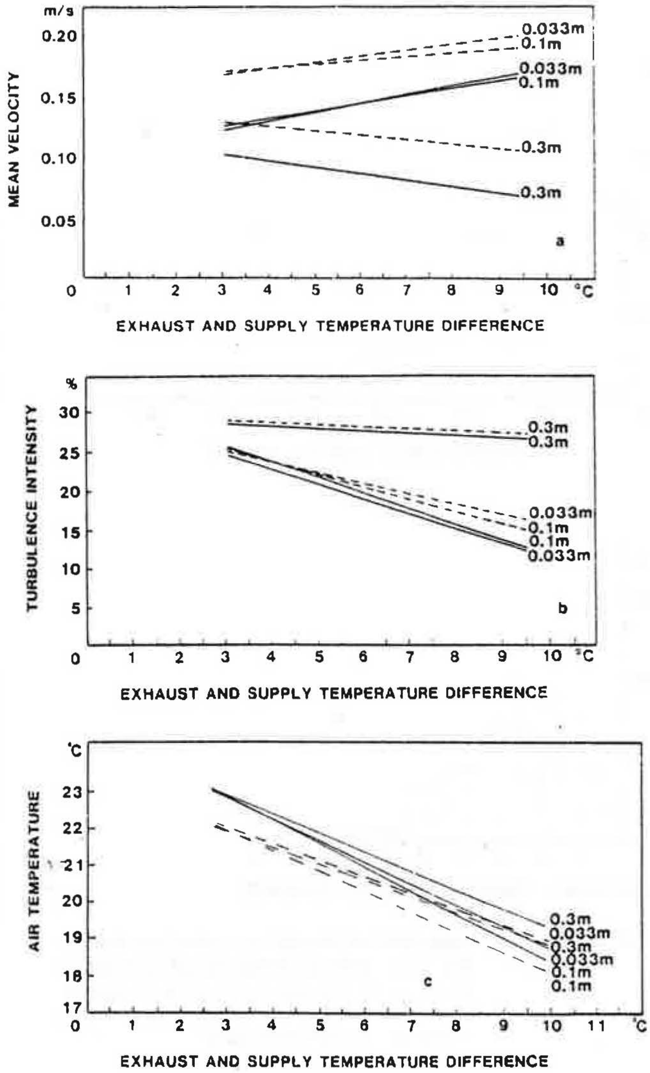


Figure 11 ***Mean velocity,*** $\bar{v}$, ***turbulence intensity, Tu, and air temperature,*** t_a, ***as a function of the exhaust and supply temperature difference and the airchange rate,*** n^{-1}, ***in one of the investigated rooms*** ——— $n = 4.2\,h^{-1}$; — — — $n = 7.7\,h^{-1}$

independent and additive. There are no available studies on the combined effect of draft and vertical temperature difference. The present results (Figure 6) indicate that this could be a serious problem in rooms with displacement ventilation. Only 52% of the locations in the investigated spaces have both local discomforts within the limits fixed in Figure 6. Approximately 18% of the locations have PD > 15% and $\Delta t_{1.1\text{-}0.1} > 3°C$. Some 43% of the locations have PD exceeding 10% and $\Delta t_{1.1\text{-}0.1}$ exceeding 2.5%. There is a need for subjective experiments where persons are exposed to airflows with different mean velocities, turbulence intensities, and air temperatures for a range of vertical temperature differences all at the same time.

In rooms with displacement ventilation, the supply air is usually introduced at one side of the occupied zone. Therefore, the uniformity of the occupied zone on a horizontal plane was studied. The results show substantial asymmetry on the horizontal plane (Figures 7, 8a, 8b). The mean velocities were higher and the air temperatures lower in the zone closest to the outlets (Figure 7). Some 46% of

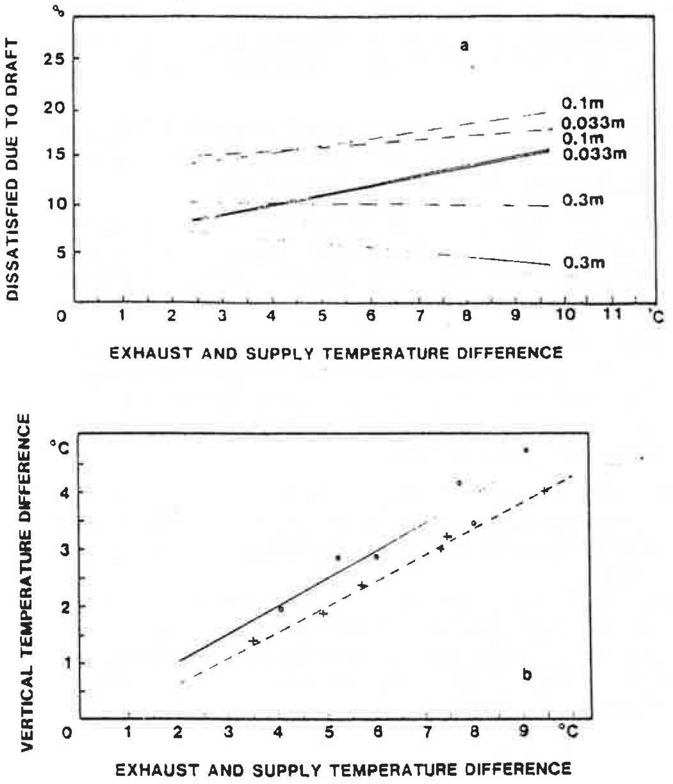


Figure 12 *Predicted percent dissatisfied due to draft, PD, and vertical temperature difference, $\Delta t_{1.1-0.1}$, as a function of the exhaust and supply air temperature difference at two air-change rates (——— 4.2 h^{-1}; — — — n = 7.7 h^{-1}) in one of the investigated rooms*

the calculated PD values (for the standard heights in Figure 8b) exceed 15% in the half of the occupied zone nearest the outlets. If all measured heights are considered, this percentage is 54%. A larger vertical temperature difference was measured in that half of the occupied zone closest to the outlets. Of the locations measured there, 49% showed $t_{1.1-0.1}$ exceeding 3°C.

Large deviations in the vertical temperature difference and the predicted percent dissatisfied due to draft were identified between the investigated spaces and within the occupied zone of each space (Figure 9). The results in Figure 9 show that in some of the rooms with displacement ventilation the average $\Delta t_{1.1-0.1}$ and PD and their standard deviations are equal to or less than 3°C and 15%, respectively; for example, spaces 5, 6, 7, 15, 17, and 18. Figure 10 illustrates that for these spaces the conditions for $\Delta t_{1.1-0.1}$ and PD were satisfied in quite a large part of the occupied zone. Therefore, the displacement ventilation may create acceptable thermal comfort conditions in the occupied zone of the room.

The results of this study (Figure 11) show that when the airflow rate increases, the mean velocity and turbulence intensity at levels near the floor increase and the air temperature decreases. When the exhaust and supply air temperature difference increases, the mean velocity increases and the turbulence intensity decreases, especially at 0.033 and 0.1 m above floor level. The air temperature decreases when the exhaust and supply air temperature increases.

The airflow rate has the opposite effect on the predicted percent dissatisfied due to draft and the vertical temperature difference in the room. Figure 12 shows that the draft risk (especially near the floor at the heights 0.033 and 0.1 m) increases and the vertical temperature difference decreases when the airflow rate increases. A similar result was also found by Palonen et al. (1988).

The results in Figures 11 and 12 present average values and, as mentioned before, rather large deviations of the discussed parameters were identified within the occupied zone.

The present study indicates a risk of local discomfort due to draft and vertical temperature difference in several rooms in practice ventilated by displacement ventilation. Substantial non-uniformity on a horizontal plane was registered. But in some of the rooms acceptable thermal comfort conditions were identified for a large part of the occupied zone. Therefore, when designed and considered with care, it is feasible to use the whole potential of the displacement ventilation principle and to create a good thermal climate in rooms.

CONCLUSIONS

In the present paper the risk of local discomfort due to draft and vertical temperature difference has been evaluated in rooms with displacement ventilation in practice. The following conclusions can be drawn:

— There was a significant risk of local discomfort due to draft, PD, at the low heights or vertical temperature difference, $\Delta t_{1.1-0.1}$. PD > 15% was identified for 33% of measured locations within the occupied zone and $\Delta t_{1.1-0.1}$ > 3°C for 40% of the locations.

— Predicted percent dissatisfied due to draft exceeded 15% for 46% of the measured locations in the half of the occupied zone closest to the outlets. In that half of the occupied zone, a vertical temperature difference exceeding 3°C was registered for 49% of the measured locations.

— For 18% of the measured locations within the occupied zone PD > 15% and $\Delta t_{1.1-0.1}$ > 3°C was registered. 43% of the locations had PD > 10% and $\Delta t_{1.1-0.1}$ > 2.5°C. The combined discomfort due to draft and vertical temperature difference should be studied by subjective experiments.

— Measurements at the heights recommended in the standards are insufficient to evaluate thermal comfort conditions in the occupied zone.

— The risk of local discomfort due to draft and vertical temperature difference was low in some of the investigated rooms. Therefore, when the displacement ventilation system is well designed, it is feasible to create good thermal comfort in rooms with displacement ventilation.

— Mean velocity increases and turbulence intensity and air temperature decrease when the exhaust and supply air temperature difference increases. When airflow rate increases, mean velocity and turbulence intensity increase and air temperature decreases.

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