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AIRFLOW CHARACTERISTICS IN THE OCCUPIED ZONE OF ROOMS WITH DISPLACEMENT VENTILATION

A.K. Melikov, Ph.D. **G. Langkilde** **B. Derbiszewski, Ph.D.**

ABSTRACT

This paper comprises measurements of airflow characteristics in the occupied zone of 12 spaces with displacement ventilation. Relationships between mean velocity and turbulence intensity, and maximum velocity and length scales of turbulence are found. Turbulent energy spectra were identified to be different within the occupied zone. Near the outlets they have a well-defined concentration of turbulence energy in the frequency range of 0.1 to 0.3 Hz. Far from the outlets, the energy spectra are similar to those in a fully developed turbulent flow and they reveal the major contribution to total turbulent energy made by the larger eddies in the low-wave number range.

Serious risk of local discomfort due to draft and vertical temperature difference was identified. The near zone around the outlet, within which predicted percent dissatisfied due to draft exceeded 15%, was found to penetrate deep into the occupied zone.

The results are compared with results from field studies in rooms with mixed ventilation and heated rooms without mechanical ventilation.

INTRODUCTION

Displacement ventilation has primarily been used in industrial environments but, during the last few years, has been common for spaces like offices, conference rooms, lecture rooms, and computer rooms. The main idea behind displacement ventilation (ASHRAE 1989) is that supply air should displace the polluted room air of the occupied zone without mixing. The air is supplied directly into the occupied zone with low velocity from large outlets located at the wall near the floor. The supply air, with a temperature of 2°C to 4°C below room air temperature, spreads near the floor and subsequently rises to the ceiling.

In rooms with displacement ventilation it is relatively easy to satisfy the general thermal comfort requirements described in the present standards (ISO 1984; ASHRAE 1981). It is more difficult to avoid local thermal discomfort due to draft and vertical temperature difference because of relatively high velocities and low air temperatures near the floor.

Draft—defined as an unwanted local cooling of the human body caused by air movement—is often a serious problem in practice. In several subjective experiments it has been shown that the feeling of draft depends on the following airflow characteristics: air velocity, air temperature, and velocity fluctuations (standard deviation and frequency of the fluctuations).

Typically, the air flow in rooms is turbulent and fluctuates randomly with frequencies up to 5 Hz. There are several models available that may be used to estimate draft risk, but most of them consider only the impact of mean velocity and air temperature on the sensation of draft. Only the recently developed model of draft risk (Fanger et al. 1988) takes into account the impact of turbulence intensity. The model predicts the percentage of people dissatisfied due to draft, *PD*, as a function of air temperature, *ta* (°C); mean velocity, $\bar{v}$ (m/s); and turbulence intensity, *Tu* (%):

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

for $\bar{v} < 0.05$ m/s insert $\bar{v} = 0.05$ m/s;
for $PD > 100\%$ use $PD = 100\%$.

The model of draft risk is a useful tool to predict the risk of draft in rooms by measuring mean air velocity, turbulence intensity, and air temperature. The model is based on results from subjective experiments where subjects were exposed to an air flow of the same nature as the air flow in rooms with traditional ("mixed") ventilation (Fanger et al. 1988; Melikov 1988).

There is only limited information about the air flow in practice in rooms with displacement ventilation. Mean velocity and air temperature have been studied in laboratory experiments by Palonen et al. (1988) and Sandberg (1988). Palonen et al. also measured the turbulence intensity. Mean velocity, air temperature, and turbulence intensity were measured by Nielsen (1988) in a preliminary field study in six rooms with displacement ventilation.

This paper presents results from a large field study performed by Melikov et al. (1989). The purpose was to investigate the airflow characteristics in the occupied zone of rooms with displacement ventilation. Such information is important for further development

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A.K. Melikov is a Research Associate and **G. Langkilde** is an Associate Professor at the Laboratory of Heating and Air Conditioning, Technical University of Denmark. **B. Derbiszewski** worked on this study as a Visiting Research Associate at the Laboratory of Heating and Air Conditioning, Technical University of Denmark. He is affiliated with the Technical University of Wrozlaw, Poland.

of the displacement ventilation principle. An important aim of the study is to identify the nature of the air flow. This is essential to assess the use of the model of draft risk when predicting thermal comfort conditions in rooms with displacement ventilation. Comparisons are performed between different ventilation principles (displacement ventilation, mixed ventilation, and natural ventilation).

AIRFLOW CHARACTERISTICS

The instantaneous velocity, $v = \bar{v} + v'$, is assumed to be the sum of the mean velocity, $\bar{v}$, and the velocity fluctuations, v', in the main direction of the flow. The mean velocity, $\bar{v}$, is the average of the instantaneous velocity, v, over an interval of time, t_1:

$$\bar{v} = \frac{1}{t_1}\int_{t_0}^{t_0+t_1} v\,dt \qquad (2)$$

The maximum velocity, v_{max}, is the highest instantaneous velocity registered during the measuring interval of time, t_1.

The standard deviation of the velocity, equal to the root-mean-square (RMS) of the velocity fluctuation, $\overline{v'^2}$, provides information about the average magnitude of the velocity fluctuation over an interval of time.

The turbulence intensity, Tu, is the standard deviation divided by the mean velocity:

$$Tu = \frac{\sqrt{\overline{v'^2}}}{\bar{v}} \qquad (3)$$

The energy spectrum of the velocity fluctuations,

$$\int_0^\infty E(n)\,dn = \overline{v'^2} \qquad (4)$$

shows the density of distribution of $\overline{v'^2}$ in the range of frequencies, n. $E(n)$ is known as the spectral distribution function of $\overline{v'^2}$. It is more convenient (Hinze 1975) to consider the wave number, $k = 2\pi n/\bar{v}$, instead of the frequency, n, and to introduce the energy spectrum function, $E(k)$, instead of $E(n)$. It appears suitable to define $E(k)$ by

$$E(k) = \frac{\bar{v}}{2\pi}E(n) \qquad (5)$$

so that

$$\int_0^\infty E(k)\,dk = \overline{v'^2} \qquad (6)$$

which is similar to Equation 3. It is possible to present the energy spectra in the form of $E(k)/\overline{v'^2} = f(k)$, as they are relatively independent of the mean velocity.

The length scales of turbulence are the integral scale, L, and the micro scale, ℓ, which are measures of the average size of the largest eddies and the smallest eddies mainly responsible for dissipation, respectively.

The integral scale can be calculated from $E(n)$ when n approaches 0 (Hinze 1975),

$$L = \frac{\bar{v}\cdot E(n)}{4\,\overline{v'^2}} \qquad (7)$$

while the micro scale can be calculated by means of the following formula (Hinze 1975):

$$\ell = \sqrt{\frac{\bar{v}^2\cdot\overline{v'^2}}{2\pi^2\int_0^\infty n^2E(n)\,dn}} \qquad (8)$$

The air temperature in different points of the occupied zone, t_a, was used to calculate the vertical temperature differences, $tvd = t_{1.1-0.1}$.

INVESTIGATED SPACES

Twelve rooms with displacement ventilation were investigated. Only rooms used by people with a sedentary activity (~1.2 met) were studied (offices, meeting rooms, computer rooms, etc.), as the risk of draft is higher at low activity levels. The spaces were selected to cover typical locations and types of outlets with different shapes, and flat and semicylindrical cross sections (Figure 1) encountered in the Scandinavian ventilating practice. The exhaust air outlets

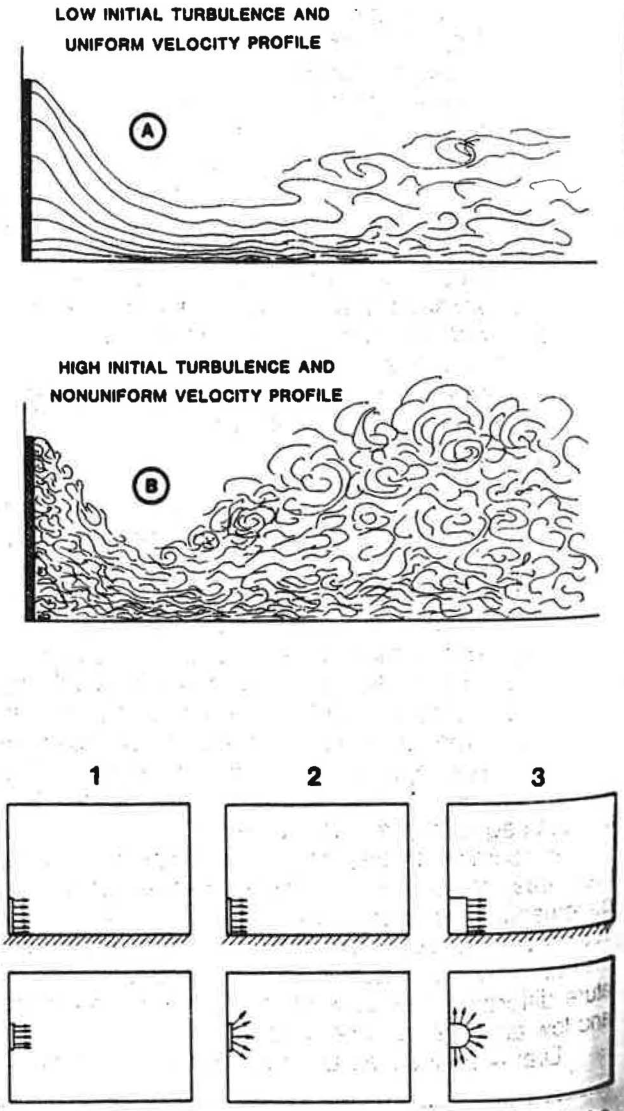

Figure 1 Different types of outlets and ways of introduc supply air into the occupied zone

were located at ceiling level. The spaces were furnished and the measurements were performed during normal operating conditions in the summer without heating. At least two persons—those taking the measurements—were in the room. For larger spaces, the normal number of occupants was simulated by laminated cylinders heated by 75 W electric lamps. The measurements began at least two hours after setting the experimental conditions. The main characteristics of the investigated spaces are given in Table 1.

EXPERIMENTAL CONDITIONS

In each space comprehensive measurements of mean velocity, standard deviation, and air temperature were performed at nine or more locations equally distributed and covering the occupied zone. At each location, measurements were taken at six heights: 0.033, 0.1, 0.3, 0.6, 1.1, and 1.7 m above floor level. The heights 0.1, 0.6, 1.1, and 1.7 m are recommended in the standards (ISO 1982; ASHRAE 1981). Energy spectra of the velocity fluctuations were analyzed for some points.

Radiant temperature asymmetry in three directions of the room—floor/ceiling, window/back wall, and right/left walls facing the window—was measured at 0.6 m, as recommended in the standards (ISO 1982; ASHRAE 1981) for a sedentary person. The measured radiant temperature asymmetry was within the limits prescribed in the standards. Supply and exhaust air temperatures were registered. They are listed in Table 1, together with the heat production in the rooms.

MEASURING EQUIPMENT

The measurements were performed using a multichannel flow analyzer and an indoor climate analyzer. For velocity measurements, the two instruments had omnidirectional temperature-compensated probes with time constants of 0.5 and 0.1 s, respectively. Analog signals from the fastest probe were recorded on a tape recorder and later analyzed by signal analyzer and computer in order to get energy spectra and some other airflow characteristics. Nineteen probes were calibrated by their respective manufacturers. The integration time was 10 minutes. Figure 2 shows a diagram of the measuring and calculating equipment used.

The investigated spaces, the experimental conditions, and the measuring equipment are described in detail by Melikov et al. (1989).

RESULTS

Measurements of airflow characteristics were taken at 1117 points in the investigated spaces, and 910 of them were taken in the occupied zone.

A percentage distribution of the mean velocity from all the measurements for the six heights is shown in Figure 3a. The results are compared with field measurements in rooms with mixed ventilation (Hanzawa et al. 1987) and heated rooms without mechanical ventilation (Melikov et al. 1988). In rooms with displacement ventilation, highest mean velocities were measured near the floor: 0.033 and 0.1 m. Above 0.3 m, most of the measured velocities were below 0.1 m/s.

For 37% of the points, mean velocities of less than 0.05 m/s were measured, and they were discarded since the calibration of the probes does not apply at such low velocities. This percentage was higher than in rooms with mixed ventilation (20%) registered by Hanzawa et al. (1987) and lower than in heated rooms without mechanical ventilation (70%) registered by Melikov et al. (1988). Figure 3b compares histograms of the turbulence intensity from these field studies. The histograms are based only on the points where mean velocity was measured to be higher than 0.05 m/s.

The standard deviation of the velocity as a function of the mean velocity at 0.033, 0.1, and 0.3 m above the floor is shown in Figure 4a. In Figure 4b, turbulence intensity as a function of the mean velocity at 0.1 m above the floor is shown and compared with results from previous field studies. The regression equation for the relationships in Figure 4b is listed in Table 2.

Figure 5a shows the maximum velocity as a function of the mean velocity at 0.033, 0.1, and 0.3 m above the floor. Figure 5b compares the relationships be-

TABLE 1
Main Characteristics of the Investigated Spaces and Measured Temperatures during the Experiments

NO.	FLOOR AREA m²	SPACE HEIGHT m	OUTLETS NUMBER —	HEIGHT m	TYPE (according to Figure 1)	HEAT PRODUCTION IN THE ROOM W/m²	SUPPLY AIR TEMPERATURE °C	EXHAUST AND SUPPLY AIR TEMP. DIFFERENCE °C
1	38	3.2	1	1.1	1-A	12.0	25.4	1.8
2	31	2.6	2	0.7	1-B	18.9	20.5	5.9
3	18	2.6	1	0.7	1-B	23.5	18.7	7.0
4	26	2.6	2	0.7	1-B	11.4	18.5	4.7
5	7	2.6	1	0.5	2-A	27.0	20.4	5.1
6	64	2.6	2	0.7	3-A	26.8	19.7	3.3
7	19	2.6	1	0.5	2-A	10.5	21.0	2.0
8	49	2.6	3	0.7	3-A	47.4	20.8	2.5
9	69	2.6	1	1.4	3-B	23.1	18.3	6.6
10	69	2.6	1	1.4	3-B	23.1	17.7	7.2
11	45	2.6	1	1.4	3-B	51.1	19.0	8.0
12	49	2.6	1	0.9	3-B	17.1	18.7	6.3

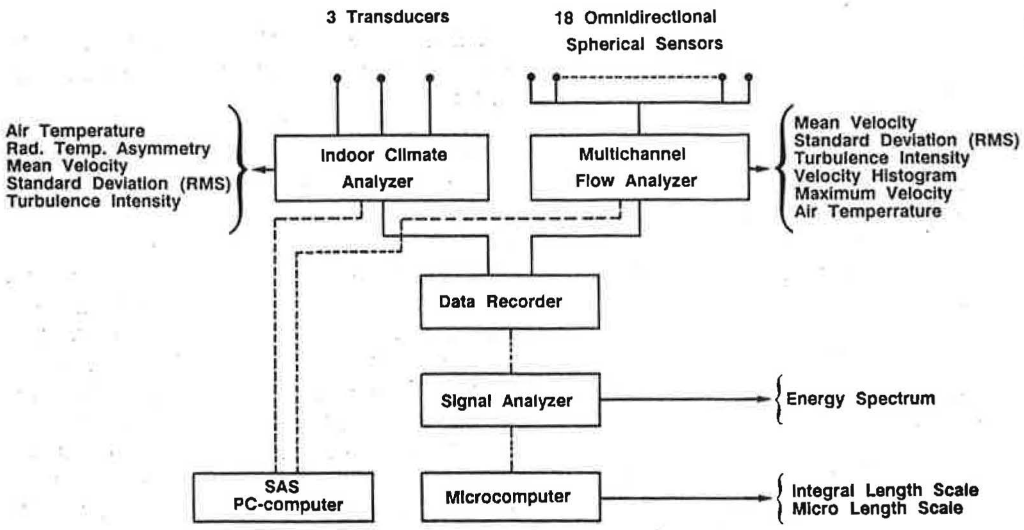

Figure 2 *Measuring and analyzing systems*

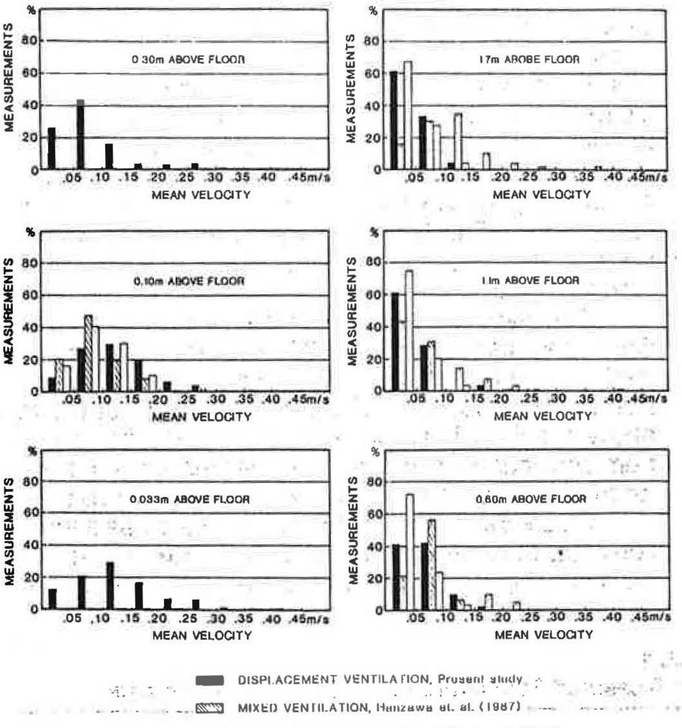

Figure 3a *Histograms of the mean velocity, $\bar{v}'$; distribution at different heights in rooms with displacement and mixed ventilation and heated rooms without mechanical ventilation*

tween maximum and mean velocity in the present study and in previous field studies in rooms with mixed ventilation and heated rooms without mechanical ventilation (Thorshauge 1982; Melikov 1989). The regression equations are listed in Table 3.

The spectral distribution of the turbulent energy was found to depend on the distance from the outlet and height above the floor. Figure 6 shows energy spectra in the near zone of outlets at different heights above the floor and different distances from the outlets. A concentration of turbulent energy at a narrow frequency band is obvious. A comparison of energy spectra measured in the present study far from the

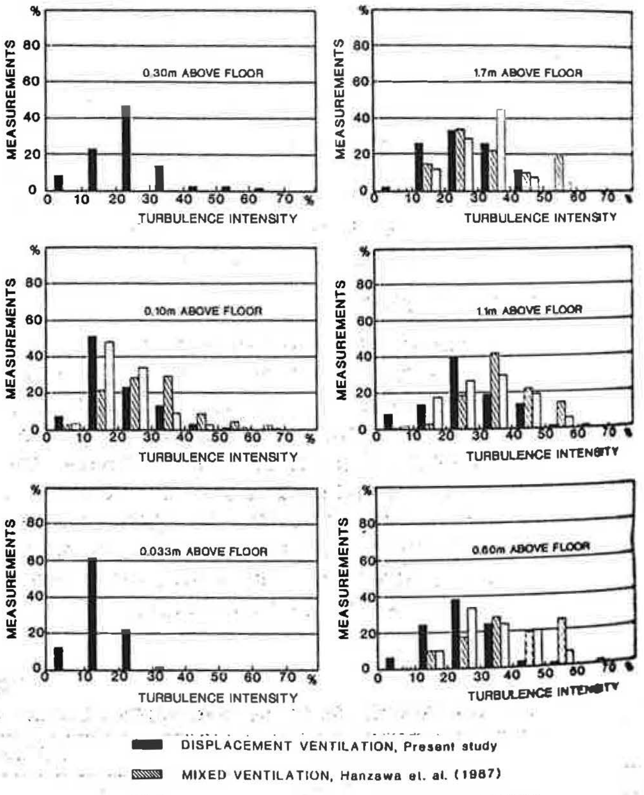

Figure 3b *Histograms of the turbulence intensity, Tu, distribution at different heights in rooms with displacement and mixed ventilation and heated rooms without mechanical ventilation; only measurements with $\bar{v} \geq 0.05$ m/s are included*

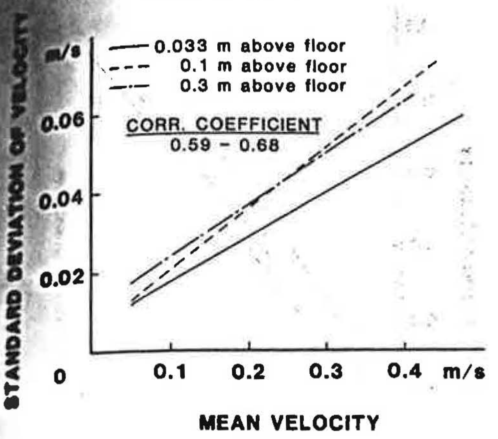

Figure 4a *Relationship between standard deviation, SD, and mean velocity, $\bar{v}$, at 0.1 m above floor. Only measurements with $\bar{v} \geq 0.05$ m/s are included.*

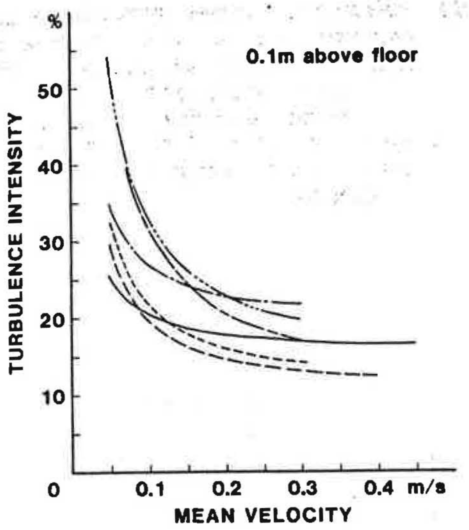

Figure 4b *Relationship between turbulence intensity,* Tu, *and mean velocity, $\bar{v}$, at different heights; only measurements with $\bar{v} \geq 0.05$ m/s are included. Presentstudy; Nielsen(1988); Hanzawa et al. (1987); Thorshauge (1982); Melikov et al. (1988); Kovanen et al. (1987).*

TABLE 2
Regression Equations for Turbulence Intensity, *Tu*, as a Function of Mean Velocity, $\bar{v}$, at Different Heights in the Occupied Zone

Height m	Reference	Equation %	Correl. Coeff. *r*	Number of Obs. *n*
	Displ. ventil.			
0.033	Present study	$Tu = 0.63/\bar{v} + 11.2$	0.68	126
0.10	Present study	$Tu = 0.52/\bar{v} + 15.3$	0.64	149
0.10	Nielsen (1988)	$Tu = 0.99/\bar{v} + 9.9$	0.69	82
	Mixed ventil.			
0.10	Hanzawa et al. (1987)	$Tu = 0.78/\bar{v} + 19.1$	0.67	275
0.10	Thorshauge (1982)	$Tu = 2.00/\bar{v} + 13.0$	0.60	28
0.15	Kovanen et al. (1987)	$Tu = 2.20/\bar{v} + 9.8$	0.39	229
	Heated rooms without mech. vent.			
0.10	Melikov et al. (1988)	$Tu = 1.14/\bar{v} + 10.4$	0.43	100
	Displ. ventil.			
0.30	Present study	$Tu = 1.02/\bar{v} + 13.1$	0.59	107
	Mixed ventil.			
1.10	Hanzawa et al. (1987)	$Tu = 0.21/\bar{v} + 32.8$	0.84	70

outlets with energy spectra from field studies in rooms with mixed ventilation (Hanzawa et al. 1987) and heated rooms without mechanical ventilation (Melikov et al. 1988) is shown in Figure 7. The energy distribution for the different field studies is the same, similar to a fully developed turbulent flow with most of the energy concentrated at low-wave numbers.

Figure 8 shows the integral length scale and the micro scale as a function of the mean velocity (at level 0.1 m). When the mean velocity increases, the integral length scale and the micro scale also increase. In Figure 8, the regression lines between the length scale and the mean velocity from other field studies are plotted. The regression equations for the lines in Figure 8 are listed in Table 4. The integral scale in rooms with displacement ventilation is lowest, but the micro scale is almost equal to this in rooms with mixed ventilation.

The lowest air temperature in rooms with displacement ventilation was identified at 0.1 m above floor. The average vertical temperature profile for all the spaces investigated is shown in Figure 9. The standard deviation, and minimum and maximum temperatures are shown in Figure 9.

DISCUSSION

Airflow characteristics in spaces with mixed ventilation were identified in several field studies (Hanzawa et al. 1987; Thorshauge 1982; Kovanen et al. 1987). Comprehensive field measurements of airflow characteristics in heated rooms without mechanical ventilation were performed by Melikov et al. (1988). The present paper comprises measurements in spaces with displacement ventilation. It reveals the most important characteristics of the air flow in the occupied zone of these spaces.

The most critical heights from a draft point of view are the heights near the floor (up to 0.3 m above the floor), where the highest air velocity—up to 0.48 m/s, and the lowest air temperature, 18.2°C—were measured (Figures 3 and 9). The relationship between the standard deviation of the velocity and the mean velocity was found for the heights near the floor—0.033, 0.1, and 0.3 m (Figure 4a). The lines on the figure show that the standard deviation increases with the height above the floor.

Turbulence intensity was found to be a function of the mean velocity; as in previous field studies, when the mean velocity increased, the turbulence intensity decreased. Figure 4b compares relationships between the turbulence intensity and the mean velocity identified in different field studies. The turbulence intensity in rooms with displacement ventilation is lower than in rooms with mixed ventilation.

The thermal comfort conditions in the occupied

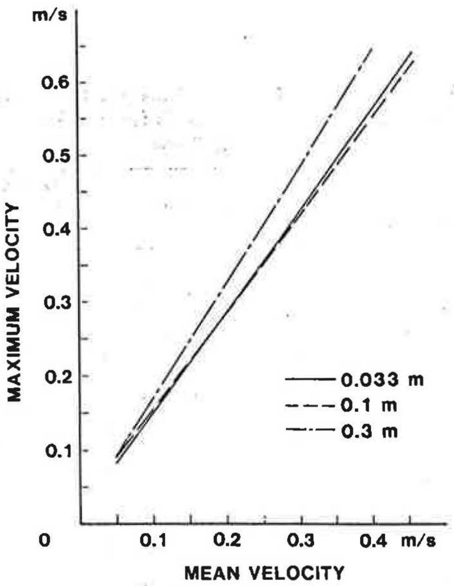

Figure 5a *Relationship between maximum velocity, v_{max}, and mean velocity, v'^2, at different heights*

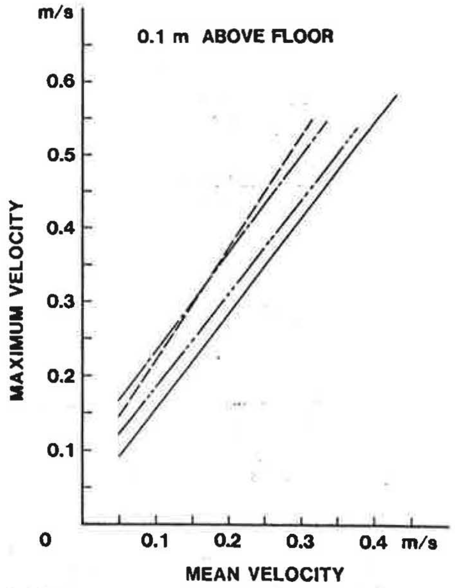

Figure 5b *Relationship between maximum velocity, v_{max}, and mean velocity, $\bar{v}$, at 0.1 m above floor. Results from different field studies are compared. , displacement ventilation (present study); , mixed ventilation (Melikov 1989); mixed ventilation (Thorshauge 1982); , heated rooms without mechanical ventilation (Melikov 1989).*

TABLE 3
Regression Equations for the Maximum Velocity, v_{max}, as a Function of the Mean Velocity, $\bar{v}$, in the Occupied Zone of Rooms in Practice

Height m	Reference	Equation m/s	Correl. Coeff. r	Number of Obs. n
	Displacement ventilation			
0.033	Present study	$v_{max} = 1.34\,\bar{v} + 0.02$	0.96	127
0.10	Present study	$v_{max} = 1.34\,\bar{v} + 0.02$	0.94	128
	Mixed ventil.			
0.10	Melikov (1989)	$v_{max} = 1.49\,\bar{v} + 0.07$	0.82	106
0.10	Thorshauge (1982)	$v_{max} = 1.30\,\bar{v} + 0.10$	0.88	28
	Heated rooms without mech. ventilation			
0.10	Melikov (1989)	$v_{max} = 1.25\,\bar{v} + 0.06$	0.83	228
	Displacement ventilation			
0.30	Present study	$v_{max} = 1.53\,\bar{v} + 0.02$	0.93	101

zone of rooms with displacement ventilation were analyzed by Melikov and Nielsen (1989). The regression equations between turbulence intensity and mean velocity identified in the present study and those by Hanzawa et al. (1987) from Table 2 were used to compare mixed and displacement ventilation at their most "drafty" heights by means of the model of draft risk. The comparison in Figure 10 shows that at the same mean velocity, displacement ventilation has a slightly lower risk of draft than mixed ventilation, especially at high velocities. 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 comparison in Figure 10 shows that both displacement and mixed ventilation have the limit of 15% dissatisfied at the same mean velocity, approximately 0.17 m/s. The expected effect of the lower turbulence intensity on *PD* in rooms with displacement ventilation is counteracted by the lower air temperature near the floor.

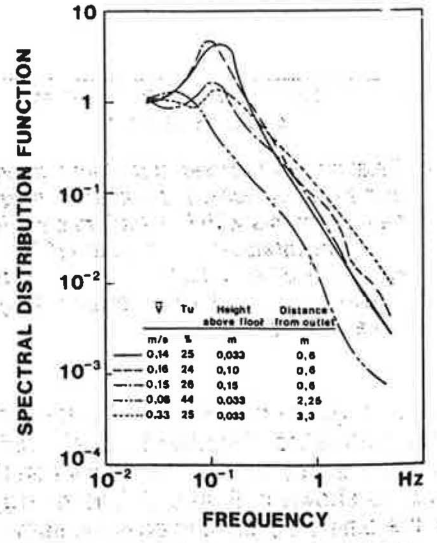

Figure 6 *Energy spectra of the velocity fluctuations measured at different heights in the occupied zone near the outlets. Vertical axis represents* E(n) *divided by* E1(n) *at 0.025 Hz.*

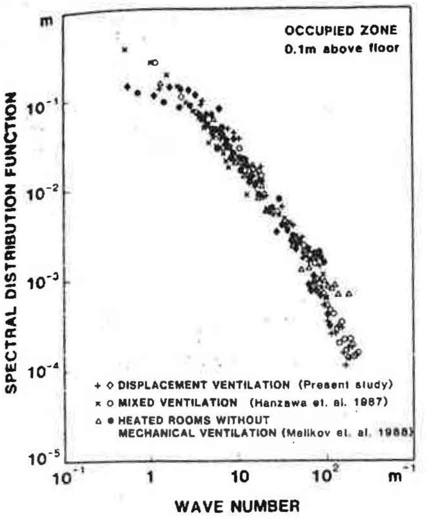

Figure 7 *Energy spectra of the velocity fluctuations measured in the occupied zone far from the outlets. Vertical axis represents* $E(k)/\bar{v}$. *Only measurements with* $\bar{v} \geq 0.1$ *m/s are included.*

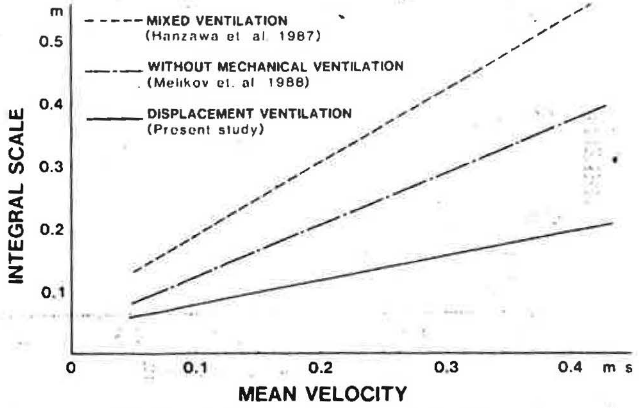

Figure 8a *Relationship between the integral scale, L, and the mean velocity,* $\bar{v}$ ($\bar{v} \geq 0.05$ *m/s) at ankle level, 0.1 m above floor. Results from different field studies are compared.*

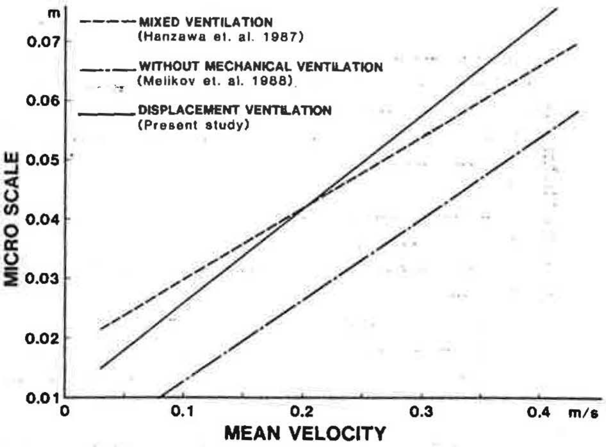

Figure 8b *Relationship between the micro scale,* ℓ, *and the mean velocity,* $\bar{v}$ ($\bar{v} \geq 0.05$ *m/s) at ankle level, 0.1 m above floor. Results from different field studies are compared.*

TABLE 4
Regression Equations for the Integral Scale, *L*, and the Micro Scale, ℓ, as a Function of the Mean Velocity, $\bar{v}$, at 0.1 m above Floor in Different Types of Rooms

Type of Ventilation	Equation m	Correl. Coeff. *r*
Displacement Present study	$L = 0.04 + 0.39\,\bar{v}$ $\ell = 0.01 + 0.16\,\bar{v}$	0.54 0.81
Mixed Hanzawa et al. (1987)	$L = 0.07 + 1.17\,\bar{v}$ $\ell = 0.02 + 0.12\,\bar{v}$	0.79 0.73
Heated rooms without mechanical ventil. Melikov et al. (1988)	$L = 0.05 + 0.68\,\bar{v}$ $\ell = 0.00 + 0.14\,\bar{v}$	0.80 0.80

In rooms with displacement ventilation, the outlets are located near the floor and therefore create nonuniformity in the velocity and temperature fields of the occupied zone on a horizontal plane. The zone around the outlet within which *PD* is larger than 15% may be defined as a near zone. Because of the location of outlets, arrangement of the furniture in the room, etc., the near zone is not necessarily equally distributed around the outlets. Figure 11 shows the maximum dimension of the near zone in each of the investigated rooms. The horizontal axis is the maximum distance from the outlet with *PD* > 15% divided by the distance from the outlet to the farthest point in the occupied zone. From the results in the figure, it is obvious that for many of the spaces the near zone penetrates deep into the occupied zone.

The vertical temperature difference is another local discomfort that also should be considered in rooms with displacement ventilation. According to the standards (ASHRAE 1981; ISO 1984), the vertical temperature difference, *tvd*, for sedentary activity between 1.1 and 0.1 m above the floor should be less than 3°C. Figure 12 shows the percent of the occupied zone for each of the investigated spaces with *PD* > 15%, *tvd* > 3°C, and with both *PD* > 15% and *tvd* > 3°C. In a large part of the room's occupied zone, at least one of the two local discomforts may cause serious complaints. Also quite serious is the risk of combined discomfort due to draft and vertical temperature difference. The limits in the standards are based on studies where each local discomfort was investigated separately. There is no evidence that these limits will remain the same if man is exposed at the same time to draft and vertical temperature difference. Therefore, the combined discomfort due to draft and vertical temperature difference should be studied.

Mean velocity and turbulence intensity are not enough to characterize the nature of the air flow in the spaces. It is possible to find two turbulent flows with

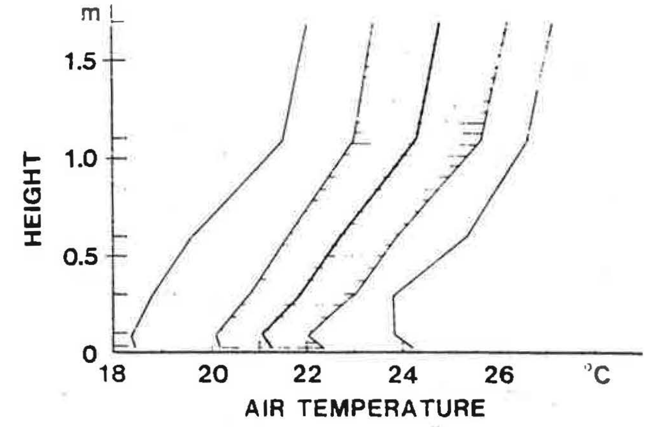

Figure 9 *Vertical profile of the average air temperature in the occupied zone of rooms with displacement ventilation. Standard deviation and minimum and maximum values are presented in the figure as well.*

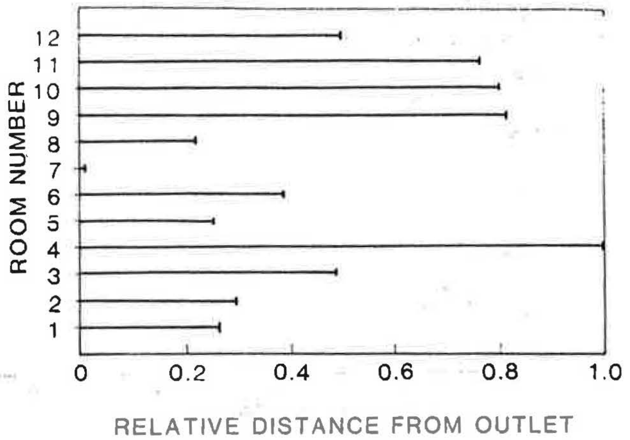

Figure 11 *Near zone identified in the investigated rooms. The relative distance presents the maximum distance from the outlets, where PD > 15% was calculated, divided by the longest distance from the outlet to the end of the occupied zone.*

the same mean velocity and turbulence intensity but with a different frequency of velocity fluctuations. The energy spectra measured in the occupied zone far from the outlets (Figure 7) show that the air flow there was of the same type as the one in rooms with mixed ventilation and heated rooms without mechanical ventilation. The spectra curves reveal that the major contribution to the total turbulent energy is made by the larger eddies in the low-wave number range. The air flow had the same nature as the air flow used when the model of draft risk was developed (Fanger et al. 1988; Melikov 1988). The spectra measured in the near zone have different distribution of the turbulent energy (Figure 6). Some spectra show strong energy concentration, defined as a peak. The frequencies at which the peak appears depend on the distance from the outlet, height above the floor, mean velocity, etc. In the present study, the peak was identified between 0.15 and 0.3 Hz. Fanger and Pedersen (1977) found that periodically fluctuating air flow with frequencies from 0.3 to 0.5 Hz was the most undesirable for people. In some of the spectra identified in the present study, turbulent energy in the peak was calculated to be up to 68% of the total turbulent energy. This energy concentration within a narrow range of frequencies is combined with a random turbulent field. This gives continuous distribution of the spectral density function in the spectra of frequencies, which is different from the one in Fanger and Pedersen's experiments. Therefore, it is not clear how much the energy concentration in the peak will contribute to the feeling of discomfort. It probably will not be as much as identified by Fanger and Pedersen and this requires further study.

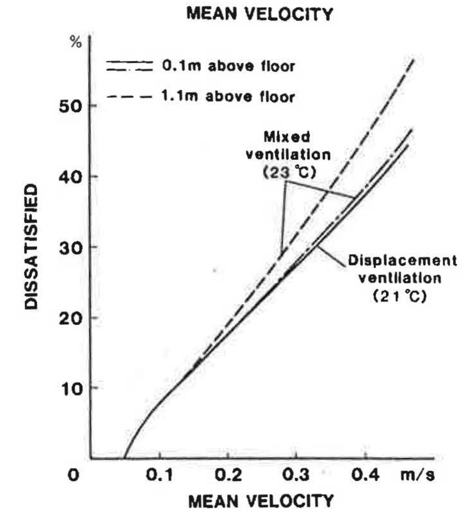

Figure 10 *Comparison of draft risk in rooms with displacement and mixed ventilation, evaluated by the model of draft risk (Equation 1) and the regression equations in Table 2*

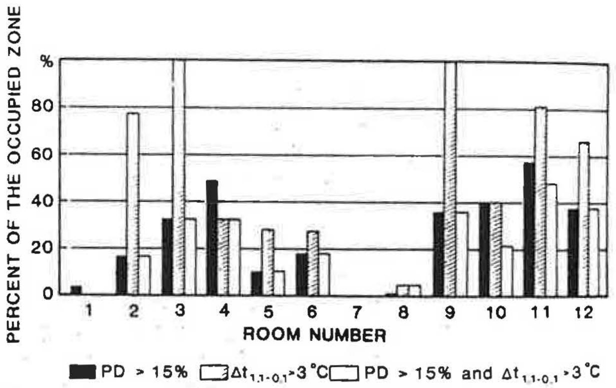

Figure 12 *Percent of the occupied zone of the rooms where* PD > 15%, tvd > 3°C *or* PD > 15% *and* tvd > 3°C *was identified*

CONCLUSIONS

Airflow characteristics were measured at 910 points at six heights of the occupied zone of 12 spaces with displacement ventilation.

- Highest mean air velocity, lowest turbulence intensity, and lowest air temperature were identified near the floor. Near the floor, turbulence intensity was lower than in rooms with mixed ventilation.
- Relationships between turbulence intensity, maximum velocity, scales of turbulence, and mean velocity were found and compared with those in rooms with mixed ventilation and heated rooms without mechanical ventilation.
- The near zone to the outlets, within which percent dissatisfied due to draft was larger than 15%, was found to penetrate deep into the occupied zone. In some rooms, risk of draft was identified all over the occupied zone.
- Serious risk of local discomfort due to vertical temperature difference was measured in the large part of the occupied zone of the rooms. In most cases, it was combined with risk of draft. This combined effect should be studied.
- In the near zone, concentration of turbulent energy (in some cases up to 68% of the total turbulent energy) was identified in the energy spectra at a narrow frequency range (0.1 to 0.3 Hz). It may contribute significantly to the sensation of draft. In the rest of the occupied zone the major part of turbulent energy is concentrated in the low-wave number range, $k > 5\ \mathrm{m}^{-1}$.
- Draft risk in rooms with displacement ventilation was almost the same as in rooms with mixed ventilation.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Danish Technical Research Council, which has supported this research project under contract no. 16-4320 M.

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DISCUSSION

W.S. Apple, Group Leader, Philip Morris USA, Richmond, VA: You tested three different types of displacement ventilation diffusers. Did you find that one type gave better results (smaller areas with predicted dissatisfaction > 15%) than the other types of diffusers?

G. Langkilde: Some differences were found between the different types of diffusers; however, no conclusions should be drawn since the data are insufficient, and other factors (e.g., difference between inlet and outlet air temperature) could also account for the difference. The sample of diffusers covers typical systems used in practice. Further investigations are necessary to establish possible differences.