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AIRFLOW CHARACTERISTICS IN THE OCCUPIED ZONE OF HEATED SPACES WITHOUT MECHANICAL VENTILATION

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ABSTRACT

Draft is one of the most common complaints in the indoor environment. It may be caused by convective air currents along windows and other cold surfaces providing air movement in the occupied zone of heated spaces.

The present paper comprises measurements of airflow characteristics (mean velocity, turbulence intensity, energy spectra of the velocity fluctuations, etc.) in a wide range of spaces in the field with different heating systems and without mechanical ventilation. The mean velocity and turbulence intensity in the occupied zone were lower than in mechanically ventilated spaces. The turbulence energy spectra were similar to those in a fully developed turbulent flow with the major part of the turbulent energy concentrated in the low-wave number range less than 5 m^{-1}. The highest velocity was measured close to the floor in rooms with a large window area and no heat source under the window.

INTRODUCTION

One of the most common complaints in indoor environments is draft, defined as an undesirable local cooling of the body caused by air movement.

Fanger and Pedersen (1977) have shown that periodically fluctuating airflow is more uncomfortable than non-fluctuating (laminar) airflow. Exposing subjects to well-defined periodic velocity fluctuations in a climate chamber, they found that the discomfort had a maximum at velocity frequencies around 0.3-0.5 Hz. The airflow in ventilated rooms is turbulent and it fluctuates randomly. Fanger and Christensen (1986) exposed 100 subjects to turbulent airflow and presented the results in a draft chart predicting the percentage of dissatisfied occupants as a function of mean velocity and temperature. They identified a higher rate of dissatisfaction than in previous studies by Houghten (1938) and McIntyre (1979) and explained this by the differences in turbulence intensity of the airflow. In Houghten's and McIntyre's studies the subjects were exposed to a low-turbulent airflow. McIntyre measured the turbulence intensity to be as low as 0.03. During Fanger's and Christensen's experiments, the airflow had a turbulence intensity of 0.3-0.6.

In a field study, Hanzawa et al. (1987) and Thorshauge (1982) identified the velocity fluctuations that occurred in practice through measurements in numerous ventilated spaces. They found a linear relationship between the standard deviation of the velocity fluctuations

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and the mean velocity. Hanzawa et al. (1987) identified also the other characteristics of turbulent flow, comprising turbulence intensity, energy spectrum of the velocity fluctuations, characteristic frequency of the velocity fluctuations, and length scales of turbulence.

No comprehensive information is available about the turbulent airflow occurring in heated spaces without mechanical ventilation. Natural convective air currents along windows and other cold surfaces may create considerable velocities in the occupied zone. The number of outside walls, the amount of insulation, the size of the windows, and the outdoor temperature may also influence the temperature and air velocity distribution in heated spaces. Olesen et al. (1980) investigated in an experimental test chamber different heating methods at the same space conditions. They measured the highest mean air velocities in the tests with floor heating systems.

The purpose of this field study is to investigate the airflow characteristics in the occupied zone of a wide range of unventilated rooms heated by different methods. Such information is essential to make an assessment of the potential risk of draft in such spaces.

Another aim was to study whether the nature of the turbulence occurring in such spaces is different from the turbulence in typical ventilated spaces. This is essential for judging whether the draft chart by Fanger and Christensen (1986) could also be used for unventilated spaces.

THE INVESTIGATED SPACES

The measurements were performed in 17 different types of unventilated, furnished spaces in Copenhagen during the heating season period between December 1985 and February 1986. Five different heating methods were investigated. These are floor and ceiling heating as well as heating by radiators, convectors, and skirting board. In some of the spaces the measurements were performed also when the heating system was not operating. The spaces were chosen to cover different sizes of window area. Relatively new buildings were chosen for the measurements, so the rooms were well insulated, with double-glazed windows and small infiltration. The characteristics of the investigated spaces are shown in Table 1.

Measurements were performed also in a test room in a laboratory. The test room was built for testing different heating systems. It simulated a space in a dwelling or a small office. The test room (4.8x3.6x2.5 m) was equipped with facilities to simulate a steady-state temperature down to $-10^{\circ}C$ outside one wall. This wall (the frontage) included a window, and air infiltration could be simulated around the window. The internal walls, floor, and ceiling were well insulated.

In each space, air velocity and temperature probes were placed in nine or more locations within the occupied zone. At each location, measurements were taken at four heights recommended in ISO Standard 7726, which are 0.1 m, 0.6 m, 1.1 m and 1.7 m above the floor. Measurements were taken during a period of 15-20 minutes.

THE CHARACTERISTICS OF TURBULENT AIRFLOW

The turbulent airflow in spaces may be characterized by the following magnitudes.

The instantaneous velocity, $v = \bar{v} + v'$, is assumed to be a 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

$$\bar{v} = \frac{1}{t_1} \int_{t_0}^{t_0+t_1} v \, dt \tag{1}$$

The standard deviation of the velocity, equal to the root-mean-square (RMS) of the velocity fluctuation, $\sqrt{\overline{v'^2}}$, 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

$$Tu = \frac{\sqrt{\overline{v'^2}}}{\bar{v}} \tag{2}$$

The energy spectrum of the velocity fluctuations

$$\int_0^\infty E(n)\,dn = \overline{v'^2} \tag{3}$$

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, $k = \frac{2\pi n}{\bar{v}}$, 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

$$E(k) = \frac{\bar{v}}{2\pi} E(n) \tag{4}$$

so that

$$\int_0^\infty E(k)\,dk = \overline{v'^2} \tag{5}$$

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 comprise the integral scale, L, and the micro scale, λ. It is assumed that the turbulent motion consists of the superposition of eddies of various sizes. The integral scale, L, identifies the average size of the biggest eddies, while the micro scale, λ, is a measure of the smallest eddies mainly responsible for dissipation.

The integral scale can be calculated from E(n) when n approaches zero (Hinze 1975)

$$L = \frac{\bar{v}.E(n)}{4\,\overline{v'^2}} \tag{6}$$

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

$$\lambda = \sqrt{\frac{\bar{v}^2.\,\overline{v'^2}}{2\pi^2 \int_0^\infty n^2\,E(n)\,dn}} \tag{7}$$

The turbulent kinetic energy per unit volume can be calculated from

$$q = \frac{1}{2}\,\rho\,(\overline{v'^2} + \overline{v_1'^2} + \overline{v_2'^2}) \tag{8}$$

where v'_1 and v'_2 are the components of the velocity fluctuation perpendicular to the main direction and ρ is the density of the air. It can be accepted that the omnidirectional probe is sensitive mainly to the velocity fluctuations, v'. In the present investigation, the airflow was almost isothermal and incompressible, i.e., ρ = const., so the results for q are calculated as

$$q = \frac{1}{2} \rho \overline{v'^2} \tag{8a}$$

THE MEASURING EQUIPMENT

The measurements of the air velocity were performed using a multichannel flow analyzer and an indoor climate analyzer. The two instruments have omnidirectional temperature-compensated probes. Thirteen probes were calibrated by their respective manufacturers. The analog signals for the velocity from some of the probes were recorded on a tape recorder and analyzed by a signal analyzer. Later, some of the turbulence characteristics were calculated by a microcomputer.

The outdoor air temperature, t_{out}, and the air temperature in the rooms, t_a were measured by the same velocity probes. t_a, was used to calculate the vertical air temperature differences, Δt, in each space. The radiant temperature asymmetry, Δt_{pr}, was measured at level 0.6 m (as it is recommended in ISO Standard 7726, 1982, for a sendentary person) in the three main directions of the room: floor - ceiling (Δt_{pr_1}), window - back wall (Δt_{pr_2}), and right-left walls facing the window (Δt_{pr_3}). For this measurement, the indoor climate analyzer was used. Figure 1 shows a diagram of the measuring and calculating equipment used.

RESULTS

The measurements of the air velocity and the air temperature were taken at about 1300 points in the investigated spaces.

Velocity

A percentage distribution of the mean velocity from all the measurements at four heights is shown in Figure 2. The highest velocities were measured at ankle level (0.1 m). At the other heights, more than 70% of the measured mean velocities were less than 0.05 m/s. The results are compared with the measurements in ventilated spaces (Hanzawa et al. 1987). The comparison shows that the mean velocity was lower in unventilated spaces than in ventilated spaces.

The following results for the velocity characteristics include only the measurements with mean velocity equal to or higher than 0.05 m/s, since the calibration of the probes does not apply at lower velocities. The analyses are based on those measurements only.

The standard deviation of the velocity fluctuations as a function of the mean velocity in all the investigated spaces at ankle level (0.1 m) and head level (1.1 m for a sitting person) are shown in Figures 3a and 3b. It is obvious that there is considerable variability in the standard deviation of the velocity fluctuations. At the same mean velocities, the standard deviation varies widely from space to space. Though regression lines of relationship between the standard deviation and the mean velocity are shown in the figures, the coefficients of correlation are low (Table 2). In the figures, regression lines from the previous field study of Hanzawa et al. (1987), in ventilated spaces, are shown for comparison. The regression equations for the relationship between the standard deviation and the mean velocity at 0.1 m and 1.1 m from that field study are shown in Table 2 as well. The lines from Figures 3a and 3b indicate smaller standard deviation of the velocity fluctuations (also smaller coefficients of correlation) in unventilated spaces than in ventilated spaces.

In Figure 4, percentage distribution of the turbulence intensity is shown and compared with the results measured by Hanzawa et al. (1987) in ventilated spaces. The comparison shows that the turbulence intensity was lower in unventilated spaces than in ventilated spaces.

The turbulence intensity varied from 10% to 70%. At ankle level (0.1 m), more than 95% of the measured turbulence intensities (for $\bar{v} \geq 0.05$ m/s) were less than 40%. At head level (1.1 m), turbulence intensity was measured from 10% to 60%, and 75% of the values were less than 40%.

Figure 5 compares the percentage distribution of the mean velocity and the turbulence intensity for two groups of unventilated spaces, with and without heat source under the window. In spaces without heat source below the window, the mean velocities were higher and the turbulence intensities were lower.

Figure 6 shows the importance of the heat source location and the window area for the downdraft. The radiator beneath the window decreases the maximum mean velocity from 0.145 m/s to below 0.075 m/s (Figure 6, comparison No. 1). In the case of floor heating, this is different. Comparison 2 in Figure 6 shows that higher velocities were measured when the floor heating system was switched on than when it was switched off. The velocity at ankle level in rooms with floor heating still remained rather high when outside temperature increased from $-10^{\circ}C$ up to $0^{\circ}C$ (Figure 6, comparison 3). The large windows increase velocities at ankle level in rooms with floor heating (Figure 6, comparison 4).

Energy spectra of the velocity fluctuations measured at ankle and head level are shown in Figure 7 (a and b). The shape of the energy spectra curves is similar to a fully developed turbulent flow. Most of the turbulent energy is concentrated at low frequencies (less than 0.1 Hz). The same spectra in a form $E(k)/\overline{v'^2} = f(k)$ are presented in Figure 8 (a and b). The experimental results fit better in the higher wave number range for $k > 5\ m^{-1}$. The spectrum curves for the points not so close to the floor (1.1 m), measured in the spaces with a radiator beneath the window, Figure 8b, follow the -5/3 law closely in the wave range k = 5.0 to 100 m^{-1}. The spectra taken at level 0.1 m, i.e., close to the floor, show a range where E(k) varies almost according to k^{-1}, which indicates strong interaction between mean and turbulent flow. At this height, a strong production of turbulence energy takes place (Hinze 1975), but compared with ventilated spaces (Hanzawa et al. 1987), these tendencies are not so strong.

The analysis of the data for the integral length scale, L, and the micro scale, λ, shows that they depend on the mean velocity. Figure 9 (a and b) shows these turbulent characteristics 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 increase as well. The regression equations of the relationship between L and λ and $\bar{v}$ are listed in Table 2. In Figure 9 the regression lines between length scales and the mean velocity from the field study of Hanzawa et al. (1987) are plotted as well, and the regression equations are listed in Table 2. The length scales in ventilated spaces are larger. In Figure 9a the two values of the integral scale measured by Olesen (1979) in unventilated spaces are shown as well. They are within the range of the present measurements.

The turbulence kinetic energy was also calculated (Equation 8a). It was inside the range of values measured in ventilated spaces (Hanzawa et al. 1987), but the correlation with the mean velocity was rather poor.

Temperature

The vertical air temperature profiles were measured at all investigated locations in the spaces. Figure 10 shows the average temperature differences pooled for each type of heating system. The temperature at 0.6 m was chosen to be the reference point, as it is the height of the center of gravity for a sedentary person. The vertical air temperature differences, $\Delta t_{1.1-.1}$ and $\Delta t_{1.7-.1}$, between head level (1.1 m above floor for a sedentary and 1.7 m above floor for a standing person) and ankle level (0.1 m above floor) are listed in Table 3. The area of the occupied zone close to the window is a common place for the occupant to be seated. The maximum vertical air temperature differences, Δt_w, between head level and ankle level near the window are listed in Table 3. Also listed in Table 3 are the maximum air temperature differences, Δt_m, measured in each space.

In each space, the radiant temperature asymmetry (in the three main directions of the room) was measured at least in one point (in some large rooms at two or three locations). The maximum radiant temperature asymmetry in each space in each of the three main directions is shown in Table 3.

In some of the spaces, the measurements were taken with normal heating during the day and without heating, for comparison. These results are also listed in Table 3.

DISCUSSION

Airflow characteristics in mechanically ventilated spaces were identified by Hanzawa et al. (1987) in a field study. The present paper comprises measurements in a wide range of spaces with different heating systems and without mechanical ventilation. It reveals the main characteristics of the airflow in the occupied zone, viz., mean velocity, turbulence intensity, energy spectrum of the velocity fluctuations, and length scales of turbulence.

The present results are compared with the results from the measurements in ventilated spaces (Hanzawa et al. 1987). Lower mean velocities and turbulence intensities were measured in unventilated spaces than in ventilated spaces (Figure 2, Figure 4). The highest velocities in the present study were measured at level 0.1 m above the floor (ankle level) in the spaces without heat source below the window to counteract the downdraft of the cold air (Figure 5). A comprehensive downdraft was measured in rooms with large windows and floor heating (Figure 6, comparison 4). The comparison of the spaces with and without a heat source below the window shows that, contrary to the mean velocity, the turbulence intensity in spaces with a heat source below the window was higher than in spaces without a heat source below the window (Figure 5). Fanger and Christensen (1986) found that the head region is the most draft-sensitive part of the body. The feet, although often covered by socks, shoes, and trousers, were also found to be rather sensitive to local draft. The percentage of dissatisfied people due to draft in Fanger's and Christensen's study (1986) was higher than in previous studies by Houghten (1938) and McIntyre (1979). The reason is most likely the differences in turbulence intensity. In contrast to previous draft studies, Fanger and Christensen (1986) exposed their subjects to turbulent airflow as it typically occurs in ventilated spaces (Hanzawa et al. 1987). The airflow in unventilated spaces was also measured to be turbulent, with highest velocities at ankle level 0.1 m above the floor. However, at this level more than 60% of the measurements ($\bar{v} \geqslant 0.05$ m/s) indicate turbulence intensity less than 20% (Figure 4), which is different from the turbulence intensity during Fanger's and Christensen's draft experiments. Further studies on the human sensation of draft at turbulence intensities occurring in unventilated spaces are recommended.

The present measurements in unventilated spaces showed that the airflow was turbulent and had the same nature as in ventilated spaces. The turbulent energy distribution was similar to that in a fully developed turbulent flow (Figures 7a and 7b). The spectra measured at the same level were similar (Figures 8a and 8b). The spectra curves reveal that the major contribution to the total turbulent energy were made by the larger eddies in the low-wave number range. Fanger's and Pedersen's subjective experiments (1977) show that the frequency of the velocity fluctuation had an impact on the sensation of draft. They have found that discomfort was maximum at frequencies around 0.3-0.5 Hz.

In this connection, the characteristic frequency of the largest eddies seems to be important. The largest eddies in turbulent flow carry the major part of the turbulent energy, and they are responsible for the main fluctuations of the velocity. They are defined by the integral scale (see Equation 6, Figure 9a). The characteristic frequency of the largest eddies can be calculated by means of the formula

$$n_c = \frac{\bar{v}}{2\pi L} \tag{9}$$

but only approximately, since it is correct when the flow field has a uniform mean velocity, $\bar{v}$, and when $\bar{v} >> v'$ (Hinze 1975). The calculated characteristic frequency for each of the investigated spaces was in the range from 0.05 to 0.25 Hz. These values are smaller than frequencies 0.3-0.5 Hz, causing the biggest discomfort according to Fanger's and Pedersen's study (1977). But still they are rather close to these limits, which show that the airflow in unventilated spaces may be rather unpleasant in terms of the frequency of the velocity fluctuations provided when the mean velocity is sufficiently high.

The draft results identified by Fanger and Christensen (1986) give the percentage of dissatisfied people due to draft as a function of the mean velocity and the air temperature. In the present study, the lowest temperatures were measured at ankle level (0.1 m above floor). This makes the risk from draft at ankle level higher in the rooms with floor heating and large windows, where the highest velocities were registered.

In ISO Standard 7730 and ASHRAE Standard 55-81 for light, mainly sedentary activity, the vertical air temperature difference between 1.1 m and 0.1 m above floor (head and ankle level) is recommended to be less than 3°C. The vertical air temperature profiles, averaged from all measurements in each room, show temperature differences less than 3°C (Figure 10). In rooms heated by a radiator at the back wall, the vertical air temperature differences were more than 3°C. Vertical air temperature differences more than 3°C were also measured close to the window in rooms with floor heating and a large window area and in rooms heated by a radiator beneath the window with a shelf above the radiator (Table 3, Δt_w).

The radiant temperature asymmetry measured in the present field study (Table 3) was always inside the comfort limits specified in the standards (ISO Standard 7730, 1984, and ASHRAE Standard 55-81).

CONCLUSIONS

Airflow characteristics were measured at 1300 points in four heights of the occupied zone in 17 spaces with different heating systems without mechanical ventilation.

Both the mean velocity and the turbulence intensity in the occupied zone were lower in unventilated spaces than in mechanically ventilated spaces.

Both in ventilated and unventilated spaces, the turbulence intensity was lower at ankle level than at head level.

The major part of turbulent energy is concentrated in the low-wave number range, $k < 5\ m^{-1}$, corresponding to eddies with dimensions 0.05-0.3 m.

The highest draft risk occurs close to the floor, where the mean velocity is highest and the air temperature is lowest. This applies especially to cases with large window areas and no or insufficient heat sources under the windows to counteract the downward free convection airflow.

Further studies on the human perception of draft at moderate turbulence intensities (10%-30%) occurring in unventilated spaces are recommended.

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TABLE 1

Main Characteristics of the Investigated Spaces

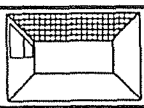
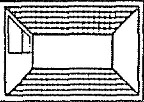
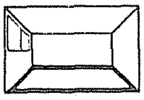
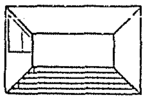
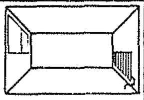
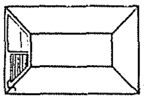
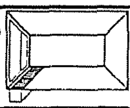
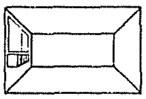
No.		SYMBOL	HEATING SYSTEM		TYPE OF SPACE	FLOOR AREA m^2	SPACE VOL. m^3
1		ϕ	CEILING HEATING		LIVING ROOM IN A PRIVATE HOUSE	36	82
2		∇	CEILING+FLOOR HEATING		DINING ROOM IN A PRIVATE HOUSE	19	44
3	1	¤	SKIRTING BOARD		SMALL MEETING ROOM	7	18
	2	◈			MIDDLE SIZE MEETING ROOM	30	76
	3	●			LIVING ROOM WITH LARGE WINDOWS	35	81
4	1	т	FLOOR HEATING		TEST ROOM - T_{out}=-10°C	17	43
	2	⊙			TEST ROOM - T_{out}= 0°C	17	43
	3	⊣			TEST ROOM with infiltration beneath window	17	43
	4	⫯			TEST ROOM without heating	17	43
	5	-o-			LIBRARY WITH LARGE WINDOWS	120	300
	6	⊢			LIBRARY WITH LARGE WINDOWS	120	300
	7	o			LIVING ROOM IN A PRIVATE HOUSE	34	78
	8	☼			LIVING ROOM IN A PRIVATE HOUSE	18	51
5		□	RADIATOR AT BACK WALL		LIVING ROOM IN A FLAT	15	38
6	1	△	RADIATOR BENEATH THE WINDOW		LIVING ROOM	54	125
	2	▲			LIVING ROOM without heating	54	125
	3	▷			TEST ROOM	17	43
	4	◁			TEST ROOM with infiltration beneath window	17	43
	5	∅			LIVING ROOM with shelf above radiators	15	37
	6	⊘			LIVING ROOM with shelf above radiators,without heating	15	37
	7	x			LARGE LIBRARY & ATRIUM		
	8	+			LARGE LIBRARY & ATRIUM		
7		★	CONVECTOR UNDER FLOOR LEVEL		LECTURE ROOM	61	214
8	1	◇	CONVECTOR BENEATH WINDOW		SMALL OFFICE	13	38
	2	⊥			SMALL OFFICE without heating	13	38
	3	■			OFFICE	56	169
	4	⌖			OFFICE without heating	56	169

TABLE 2

Regression Equations for Turbulence Characteristics (RMS, L, λ) as a Function of the Mean Velocity ($\bar{v}$)

Measuring Height	Regression Equation		Coefficient of Correlation
NON-VENTILATED SPACES, PRESENT STUDY			
0.1 m	RMS = 0.0114 + 0.104 $\bar{v}$	(m/s)	0.429
1.1 m	RMS = 0.010 + 0.197 $\bar{v}$	(m/s)	0.443
0.1 m	L = 0.0544 + 0.682 $\bar{v}$	(m)	0.796
0.1 m	λ = -0.001 + 0.139 $\bar{v}$	(m)	0.798
VENTILATED SPACES, HANZAWA et al (1987)			
0.1 m	RMS = 0.0078 + 0.191 $\bar{v}$	(m/s)	0.668
1.1 m	RMS = 0.0021 + 0.328 $\bar{v}$	(m/s)	0.837
0.1 m	L = 0.07186 + 1.174 $\bar{v}$	(m)	0.785
0.1 m	λ = 0.01844 + 0.1196 $\bar{v}$	(m)	0.732

Note: The equations are based on the measurements with $\bar{v} \geq 0.05$ m/s.

TABLE 3
Measured Temperatures During the Experiments*

No.		HEATING SYSTEM	t_{out}	$\Delta t_{.1-1.1}$ $\Delta t_{.1-1.7}$	Δt_w	Δt_m	Δt_{pr1}	Δt_{pr2}	Δt_{pr3}
			°C	°C	°C	°C	°C	°C	°C
1		CEILING HEATING (large windows)	2.4	1.55 (1.9)	2.5	2.5	-2.1	-2.8	0.1
2		CEILING+FLOOR HEATING (large windows)	2.4	2.1 (2.7)	2.4	2.4	-3.3	-1.6	-0.9
3	1	SKIRTING BOARD	0.6	0.75 (0.8)	1.3	1.3	1.9	-0.6	0.9
	2	SKIRTING BOARD	0.6	0.8 (0.9)	0.8	1.2	0.6	-1.2	1.1
	3	SKIRTING BOARD (large windows)	-5.1	0.9 (1.1)	1.5	1.5	1.6	-0.5	-1.1
4	1	FLOOR HEATING	-10	0.8 (0.9)	0.9	1.2	1.8	-3.4	0.3
	2	FLOOR HEATING	0	0.7 (0.7)	1.1	1.1	1.6	-2.6	0.2
	3	FLOOR HEATING (infiltration beneat window)	-10	1.0 (1.1)	1.8	1.8	2.9	-3.8	0.3
	4	FLOOR HEATING (without heating)	-10	1.2 (1.4)	1.0	1.4	1.0	-2.9	0.3
	5	FLOOR HEATING (large windows)	6.2	0.5 (0.4)	1.7	1.7	3.8	-5.6	-0.7
	6	FLOOR HEATING (large windows)	-8.1	1.2 (1.2)	3.2	3.2	4.5	-9.2	-0.7
	7	FLOOR HEATING	-4.3	0 (0)	1.7	1.7	4.0	-3.1	1.3
	8	FLOOR HEATING	-2.2	1.0 (1.0)	1.5	1.5	1.2	0.8	-0.7
5		RADIATOR AT BACK WALL	-4.5	4.9 (7.9)	3.8	5.9	-2.9	-5.5	1.2
6	1	RADIATOR BENEATH WINDOW	-7.7	2.1 (2.4)	1.6	3.8	-1.1	1.1	-1.0
	2	RADIATOR BENEATH WINDOW (without heating)	-6.6	0.9 (1.3)	1.6	1.6	-1.1	0.7	-1.0
	3	RADIATOR BENEATH WINDOW	-10	0.7 (0.8)	0.9	0.9	2.0	2.1	0.1
	4	RADIATOR BENEATH WINDOW (infiltration beneath window)	-10	0.75 (0.8)	1.1	1.2	2.0	2.1	0.1
	5	RADIATOR BENEATH WINDOW (shelf above radiators)	-1.3	3.8 (4.4)	4.0	4.5	-0.2	4.2	-0.3
	6	RADIATOR BENEATH WINDOW (without heating)	2.1	1.45 (1.55)	1.8	1.8	1.4	2.5	0.5
	7	RADIATOR BENEATH WINDOW (large area & atrium)	-4.1	0.3 (0.2)	0.2	1.0	-1.1	-2.1	2.7
	8	RADIATOR BENEATH WINDOW (large area & atrium)	-8.1	0.2 (0.2)	0.8	1.0	-0.9	-1.7	2.4
7		CONVECTOR UNDER FLOOR LEVEL (beneath large windows)	-4.3	1.4 (1.5)	0.6	0.8	-1.5	2.3	-0.6
8	1	CONVECTOR BENEATH WINDOW	-2.4	0.9 (1.1)	1.3	1.3	0.4	-1.6	0.2
	2	CONVECTOR BENEATH WINDOW (without heating)	-4.3	0.8 (0.8)	0.6	0.8	0.5	-1.3	0.3
	3	CONVECTOR BENEATH WINDOW	-2.9	1.45 (1.6)	1.2	1.8	-2.0	-1.9	-0.5
	4	CONVECTOR BENEATH WINDOW (without heating)	-4.5	0 (0.2)	0.6	0.6	1.4	-0.5	1.0

*t_{out}, outdoor temperature, $\Delta t_{1.1-.1}$ and ($\Delta t_{1.7-.1}$), vertical air temperature differences between head level (1.1 m above floor for sedentary and 1.7 m above floor for standing person) and ankle level (0.1 m above floor), Δt_w, vertical air temperature difference between head level (1.1 m) and ankle level (0.1 m) near the window, t_m, maximum vertical air temperature difference between head level (1.1 m) and ankle level (0.1 m) in each space, Δt_{pr1}, Δt_{pr2}, Δt_{pr3}, radiant temperature asymmetry in the three main directions of the room: floor-ceiling, window-back wall and right-left walls, facing the window.

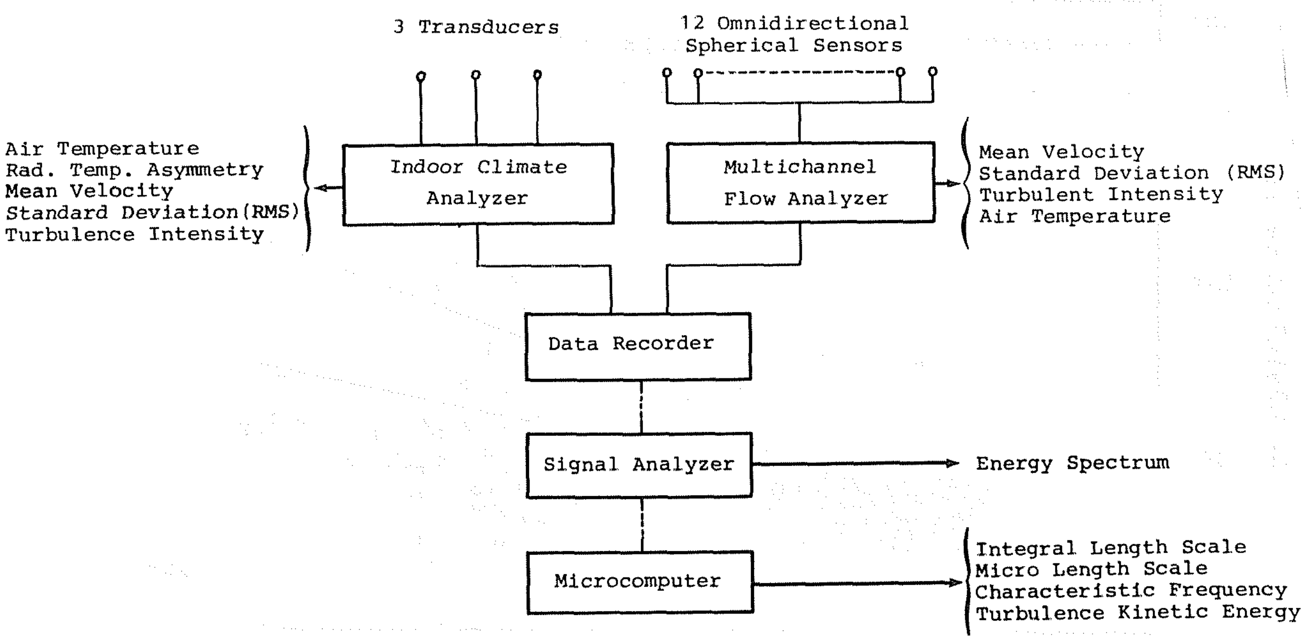


Figure 1 Measuring and analyzing systems

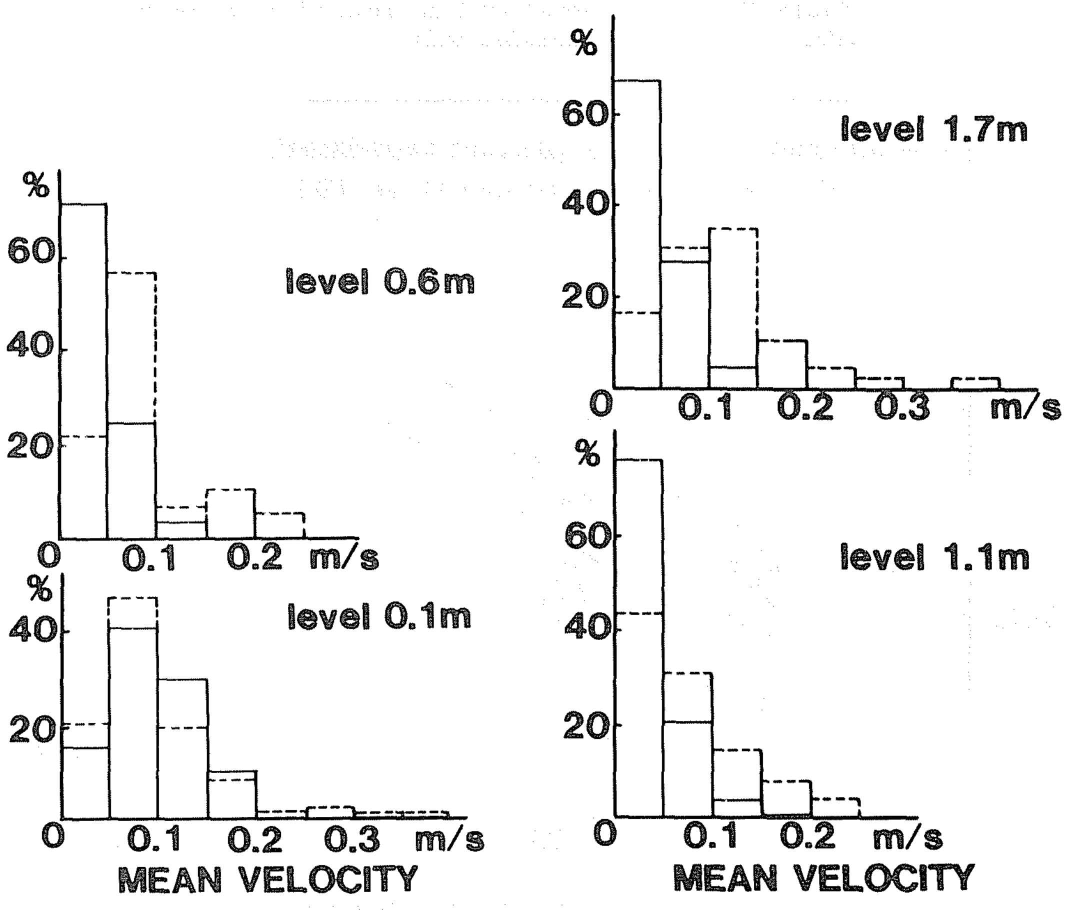


Figure 2 Histograms of the mean velocity, $\bar{v}$, at different heights; —— unventilated spaces, - - - - ventilated spaces, Hanzawa et al. 1987)

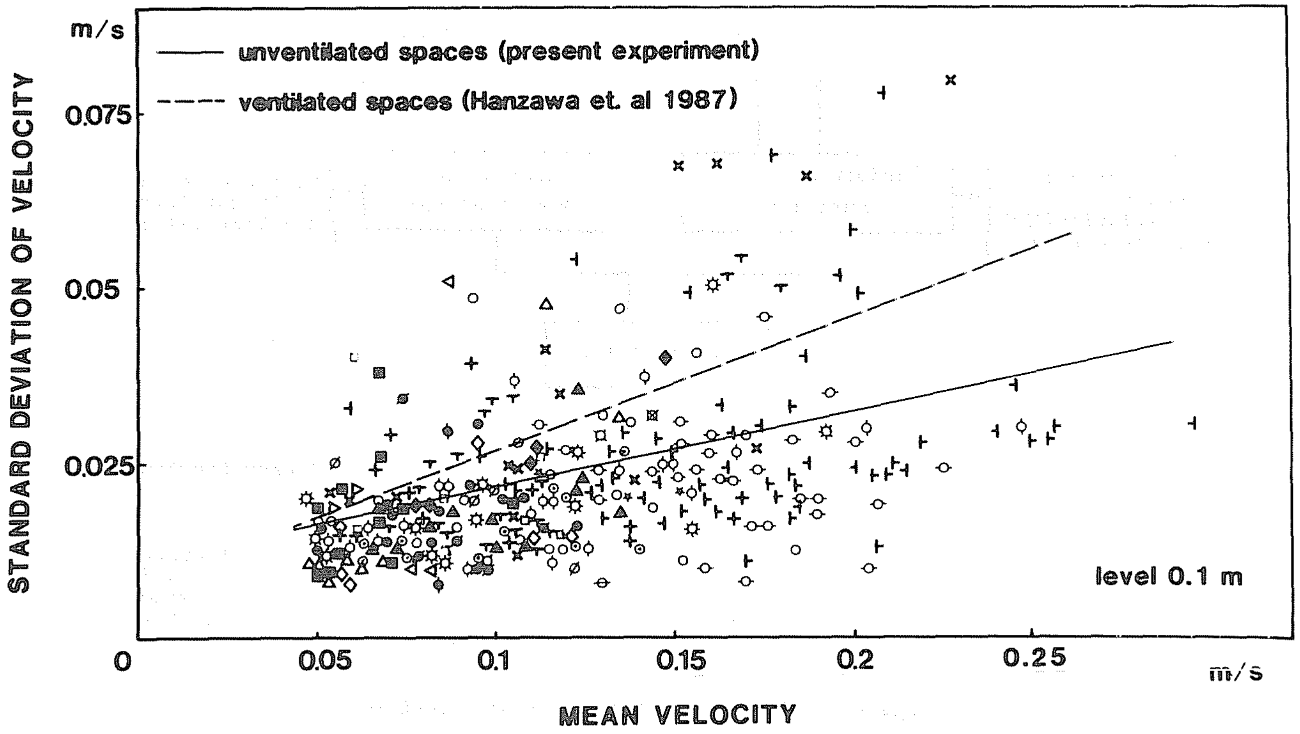


Figure 3a Relationship between standard deviation and mean velocity (Table 2) at ankle level (0.1 m above floor); measurements with $\bar{v} \geq 0.05$ are included only

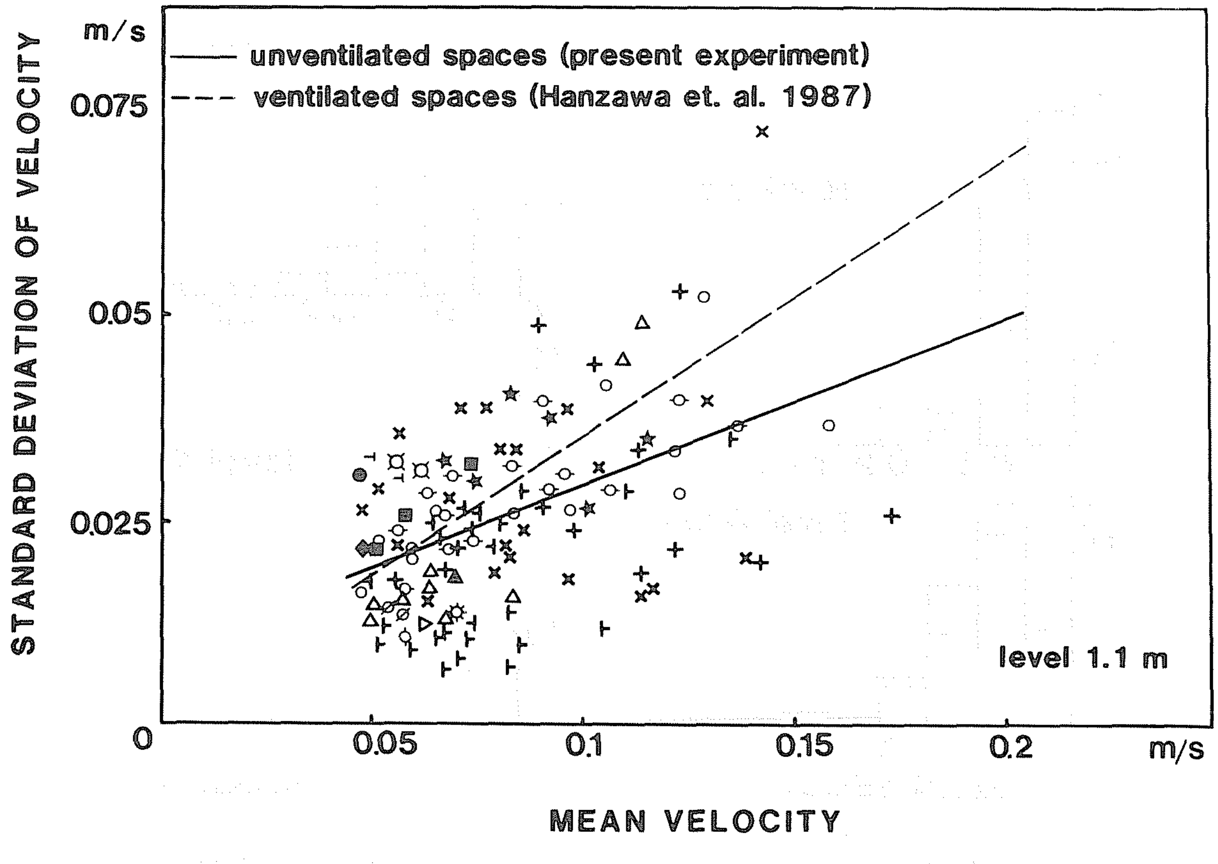


Figure 3b Relationship between standard deviation and mean velocity (Table 2) at head level (1.1 m above floor); measurements with $\bar{v} \geq 0.05$ m/s are included only

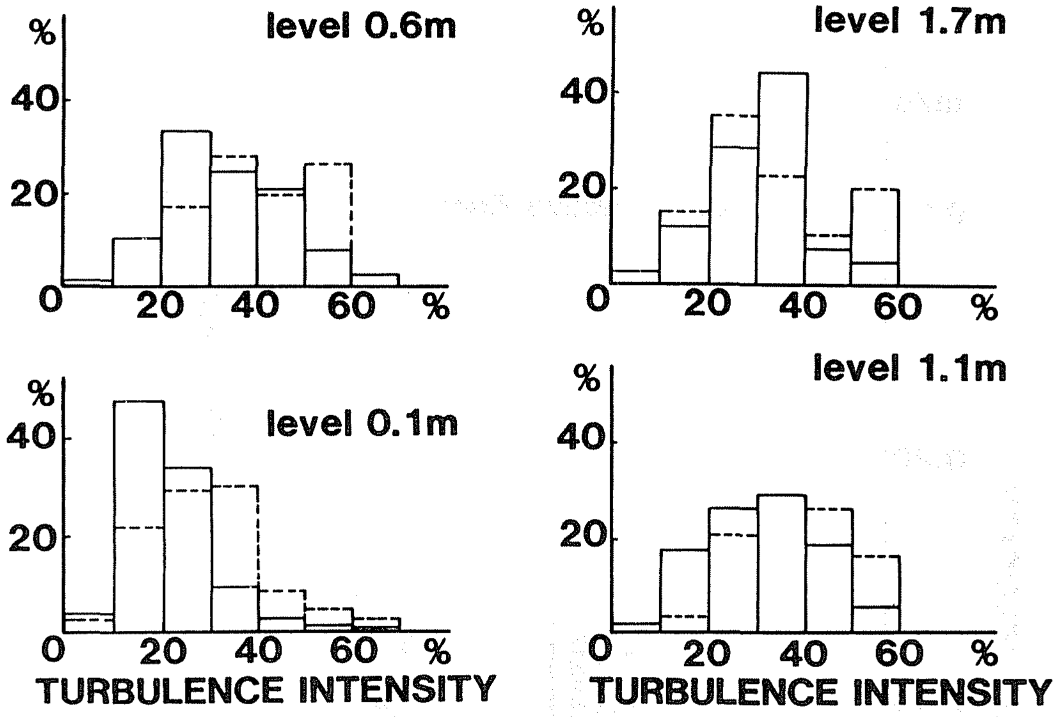


Figure 4 Histograms of the turbulence intensity, Tu, distribution at different heights; —— unventilated spaces, - - - - ventilated spaces (Hanzawa et al. 1987); measurements with $\bar{v} \geq 0.05$ are included only

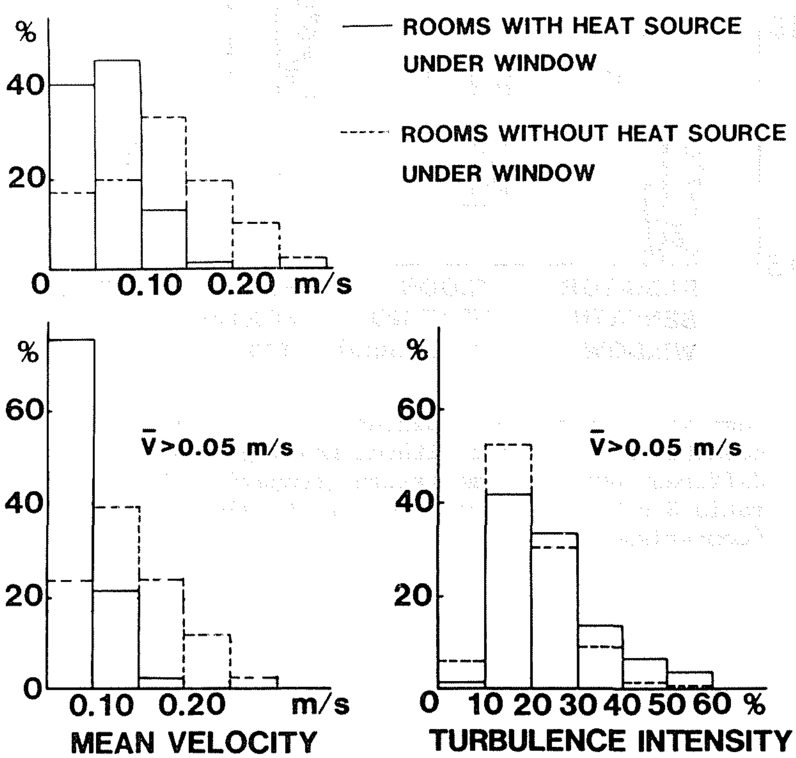


Figure 5 Histograms of the mean velocity, $\bar{v}$, and the turbulence intensity, Tu, ($\bar{v} \geq 0.05$ m/s), distribution at ankle level (0.1 m above floor) in rooms with and without heat source under the window. Histogram of the mean velocity from all measurements is included as well

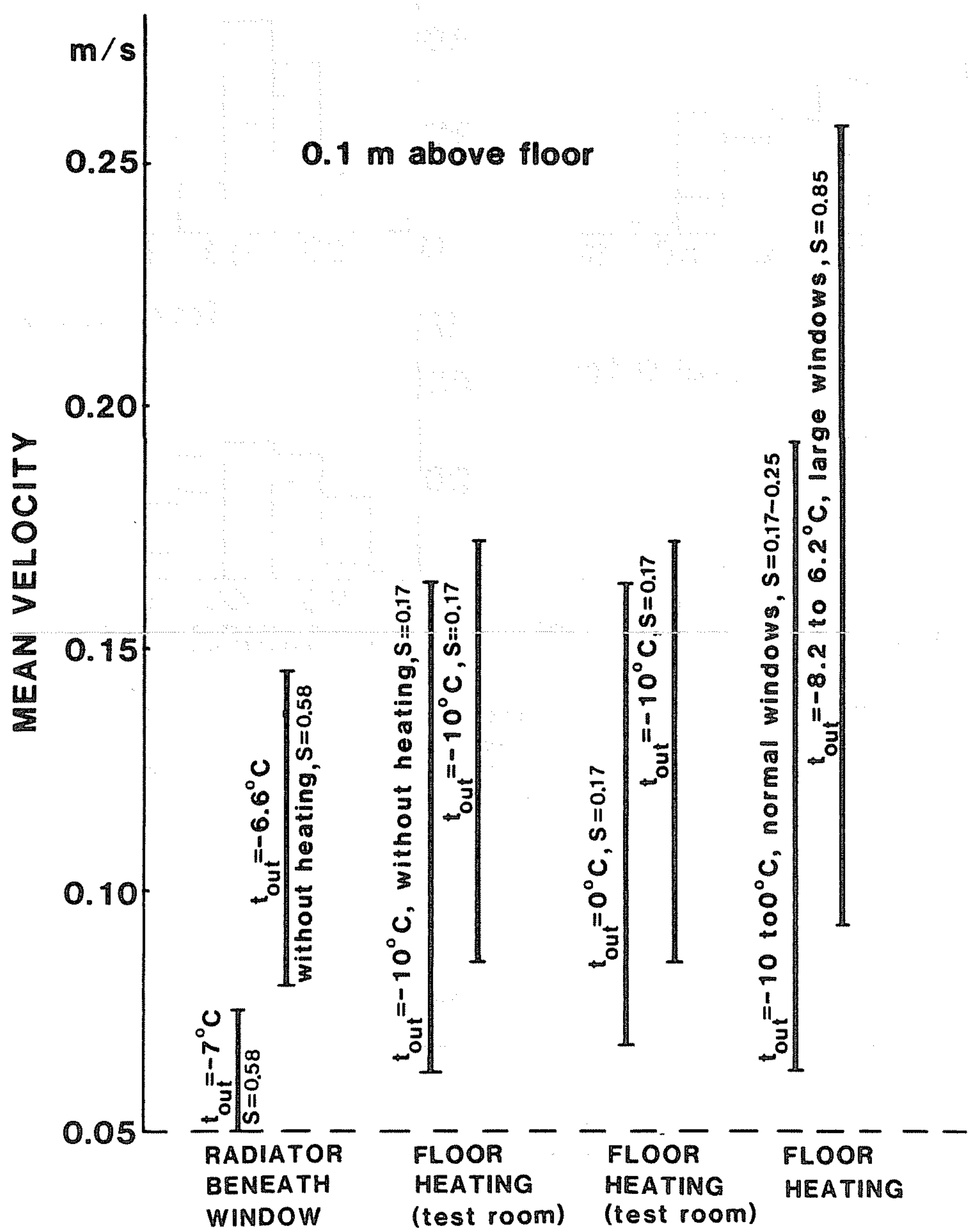


Figure 6 Mean velocity ranges measured in heated spaces with different conditions: with and without heating (comparisons 1 and 2), different outdoor temperature (comparison 3) and different ratio S between surface area of the window and the wall (comparison 4)

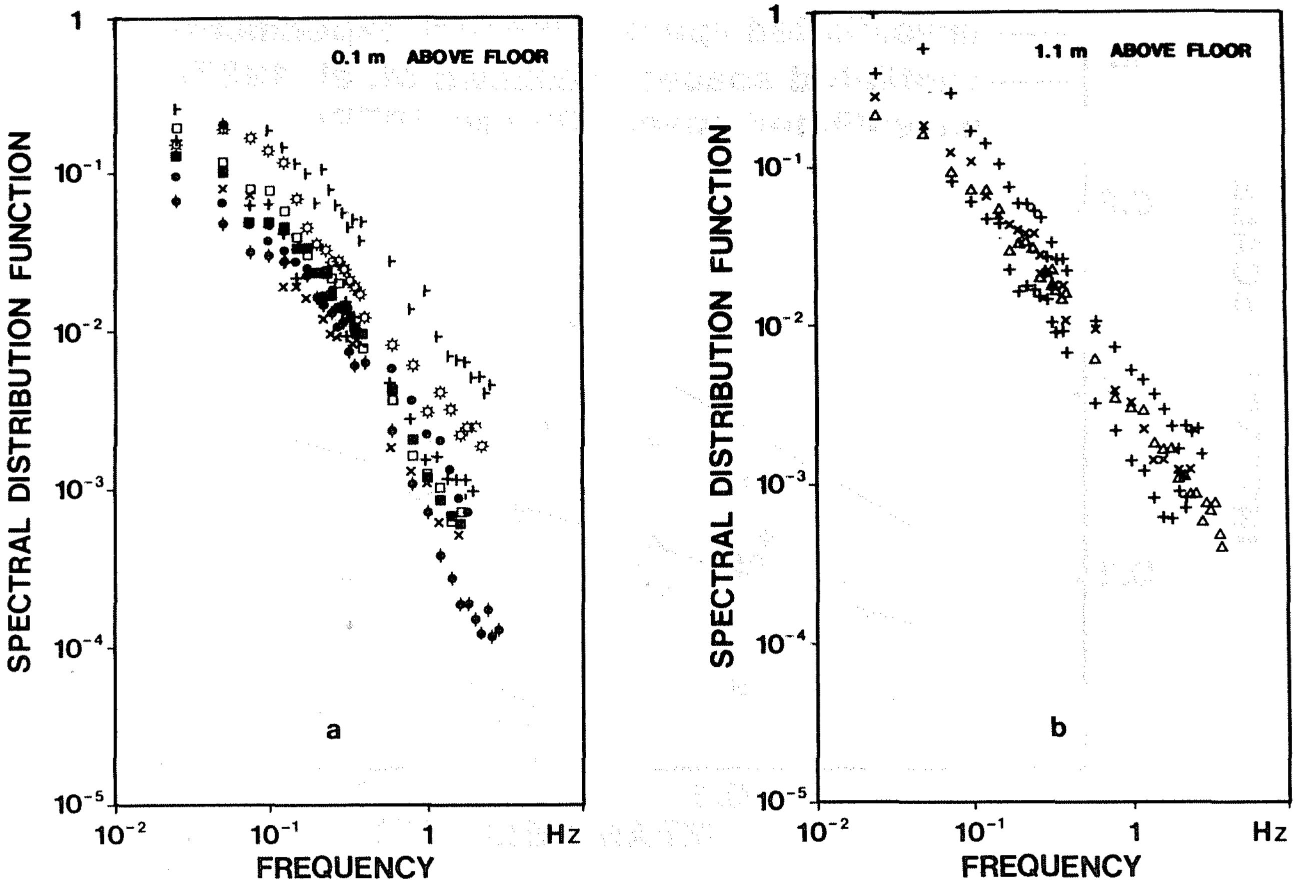


Figure 7 Energy spectra of the velocity fluctuations measured in spaces without mechanical ventilation (Table 1). Vertical axis represents distribution function E(n) divided by distribution function E1(n) for space No. 6-8 (Table 1) at frequency 0.025 Hz. (a) at ankle level, 0.1 m above the floor, (b) at head level 1.1 m above the floor. Only measurements with $\bar{v} \geq 0.05$ m/s are included

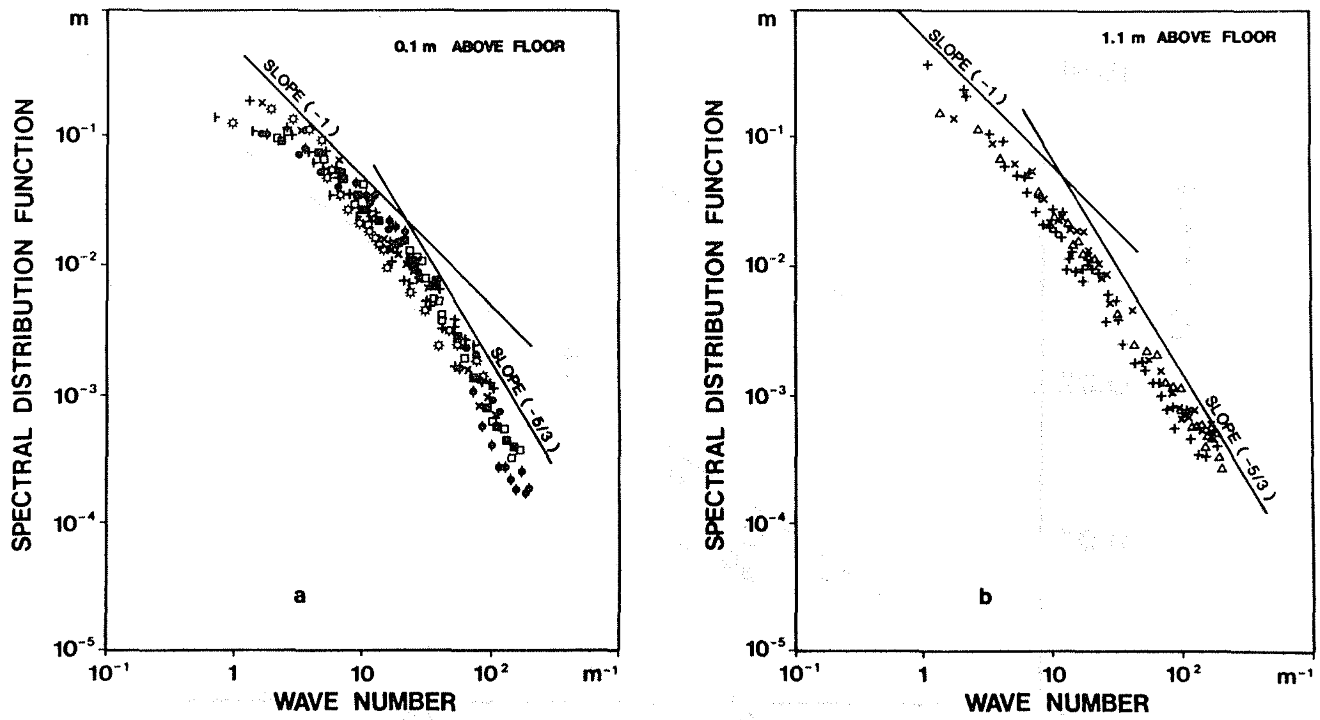


Figure 8 Energy spectra measured in spaces without mechanical ventilation (Table 1). Vertical axis represents $E(k)/v'^2$: (a) at ankle level, 0.1 m above the floor, (b) at head level, 1.1 m above the floor. Only measurements with $\bar{v} \geq .05$ m/s are included

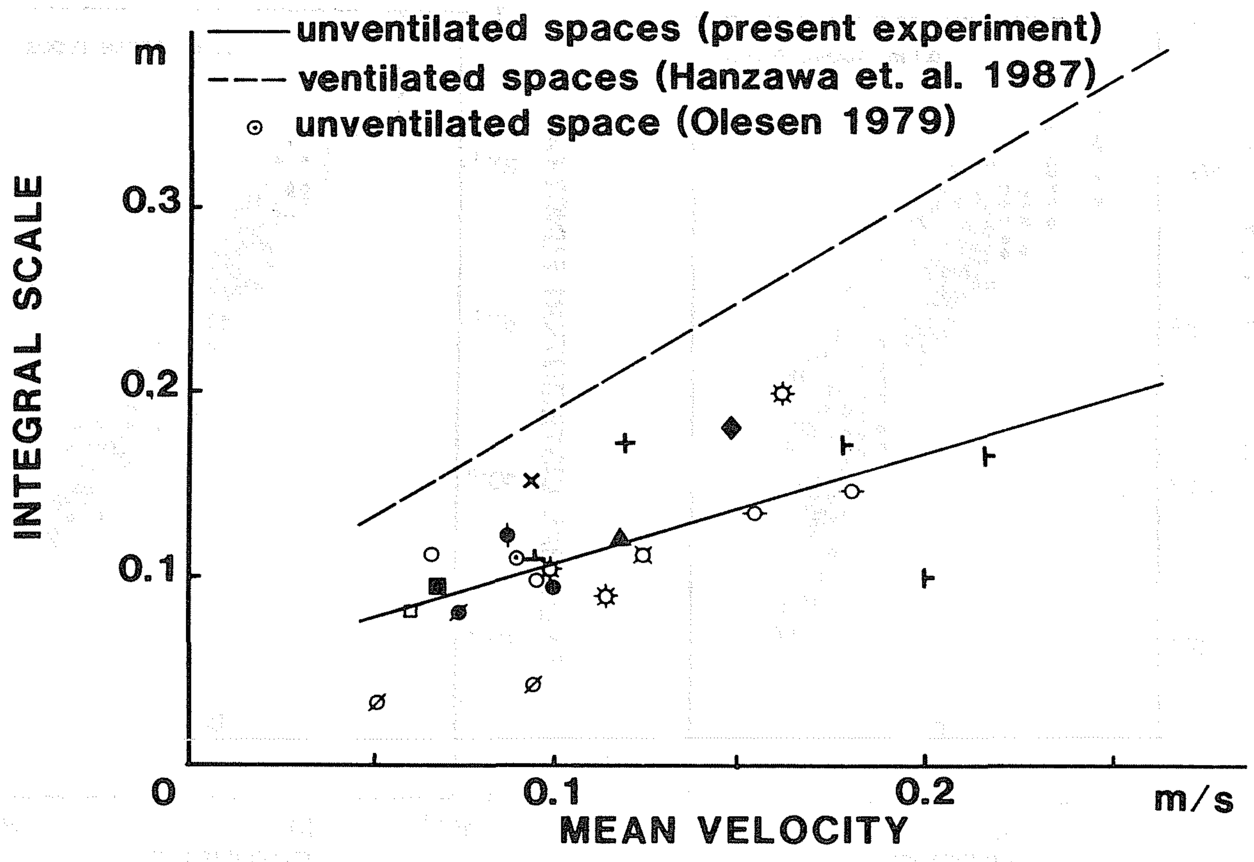


Figure 9a Relationship between integral scale, L, and mean velocity, $\bar{v}$, ($\bar{v} \geq 0.005$ m/s), at ankle level, 0.1 m above floor

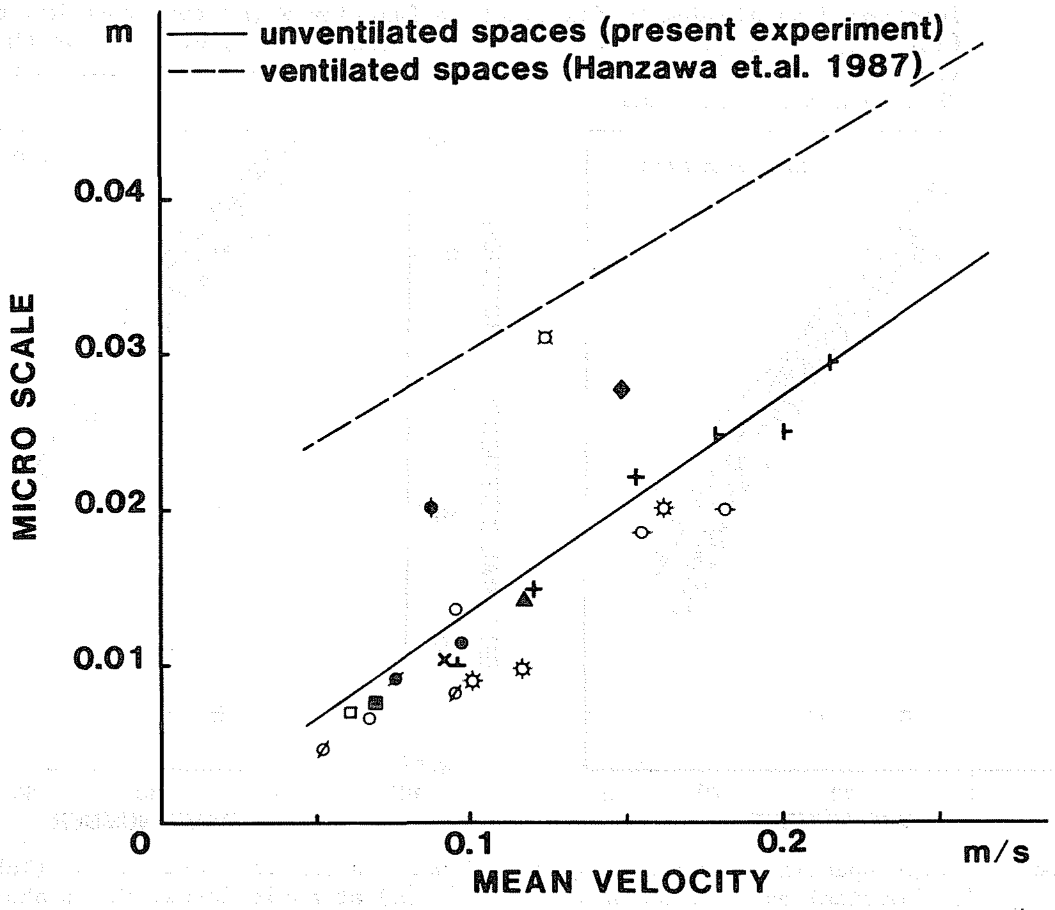


Figure 9b Relationship between micro scale, λ, and mean velocity, $\bar{v}$, ($\bar{v} \geq 0.05$ m/s), ankle level, 0.1 m above floor

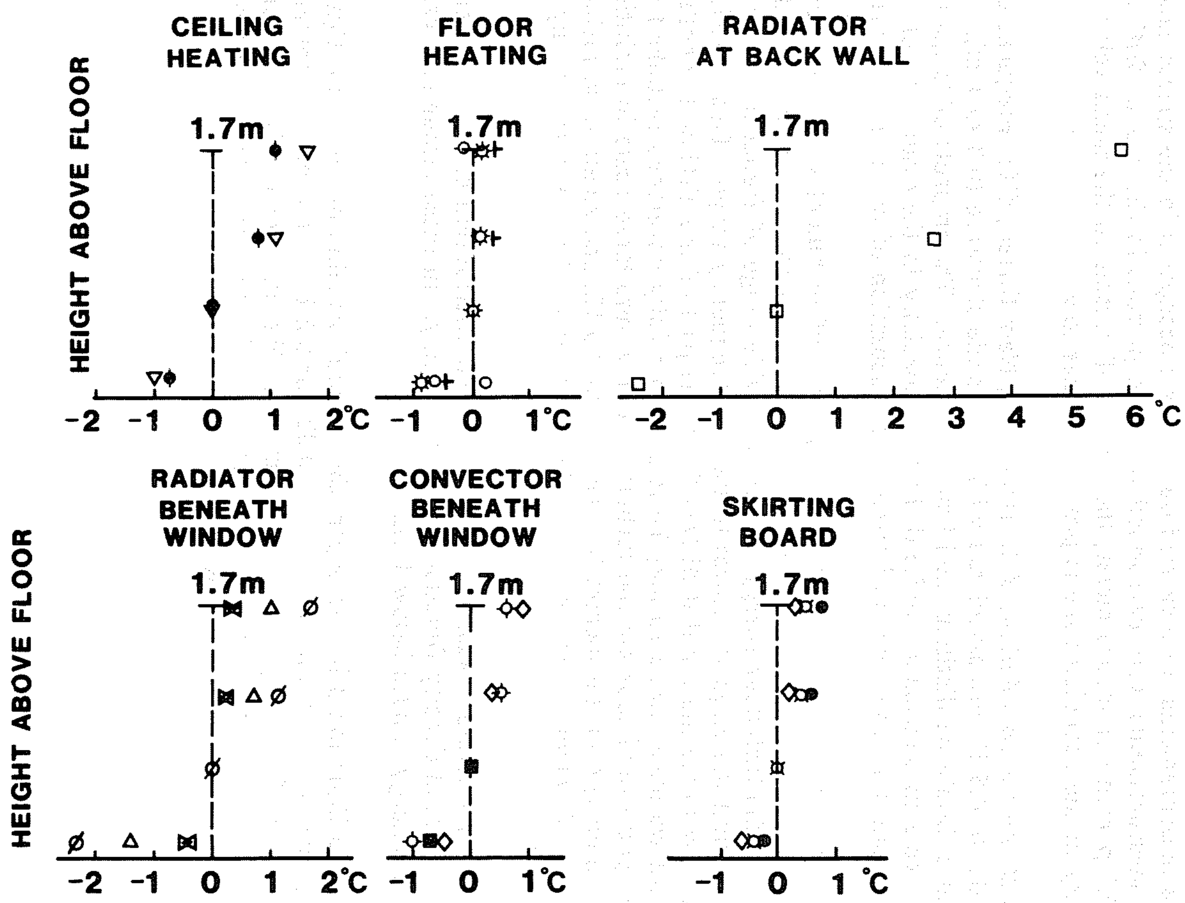


Figure 10 Vertical air temperature differences in spaces with different heating systems without mechanical ventilation. The air temperature at 0.6 m is the reference temperature

Discussion

H. HOMMA, Toyohashi (Japan) University of Technology: It is my understanding that air movement is very much changed between occupied and unoccupied conditions. Was this measurement carried out in occupied conditions?

A.K. MELIKOV: The measurements were carried out without occupants in the spaces except for a few rooms where the measurements were performed with two persons in the room. With a modest occupancy less than 0.1 person per square meter, the impact of person on the mean velocity and the turbulence intensity in the occupied zone is probably rather low.

A. FOBELETS, John B. Pierce Foundation, Yale University, New Haven, CT: Frequencies of turbulence energy of 0.2 to 0.5 Hz are associated with large-scale structure (0.3 to 1 m). These are flow instabilities and should be distinguished from turbulence. The impacts of large-scale instabilities and small-scale turbulence are quite different, especially in the evaluation of contaminant dispersion, but may also have an impact on the sensation of draft and thermal comfort.

MELIKOV: The turbulent airflow has wide continuous gamma of turbulent structures from very small scales up to large eddies. These structures play different roles for the processes in the flow. All of them contribute to the turbulent energy spectra in a wide range of frequencies, the small ones to high frequencies and the large structures to the low-frequency range. This contribution is different from one airflow to another, and it differs from one part of the airflow to another. The turbulent energy spectra we have measured may be related to a fully developed turbulent flow. It is not clear to me how you would separate the turbulent airflow into large-scale instabilities (0.3 to 1 m) associated with the energy in the spectra between 0.2 to 0.5 Hz and small-scale turbulence. The impact of frequency of velocity fluctuations on the sensation of draft was studied by Fanger and Pedersen in 1977 (see references).

S. LUXTON, University of Adelaide, Australia: To obtain the distribution of turbulent energy, it is necessary to weigh the spectral density function by the frequency. In these circumstances, are you sure that most turbulent energy resides below 1 Hz?

MELIKOV: According to Equation 3 in our paper, the spectral distribution function, E(n), should be multiplied by the frequency interval, dn (in our case, 0.025 or 0.2 Hz), in order to compare the turbulent energy at different frequency ranges of the spectra. We have done this and I can tell you roughly that the turbulence energy that resides below 1 Hz is more than 75%. We discussed this in one of our previous papers (see Hanzawa et al. 1987).