No. 3045

AIRFLOW CHARACTERISTICS IN THE OCCUPIED ZONE OF VENTILATED SPACES

H. Hanzawa **A.K. Melikow, Ph.D.** **P.O. Fanger**
ASHRAE Fellow

ABSTRACT

Draft is one of the most common causes of complaint in ventilated or air-conditioned spaces. Therefore, knowing the turbulent airflow in these spaces and the impact of this flow on the sensation of draft is very important.

The characteristics of turbulent flow (turbulence intensity, length scales of turbulence, turbulence kinetic energy, etc.) were investigated in 20 typically ventilated spaces. Relationships between these characteristics and the mean velocity were found. The mean velocities and turbulence intensities of all ventilated spaces varied widely - the mean velocity from less than 0.05 m/s to 0.40 m/s and the turbulence intensity from 10% to 70%. The turbulence energy spectra are similar to those in a fully developed turbulent flow. The spectra reveal the major contribution to total turbulent energy made by the larger eddies in the low-wave number range. Some of the experimental results were compared with existing numerical predictions.

INTRODUCTION

Draft, defined as unwanted local cooling of the human body caused by air movement, is perhaps one of the most common causes of complaint in ventilated or air-conditioned spaces. Draft may cause people to stop ventilation systems and to plug up air diffusers. The occupants may also try to counteract the draft by elevating the air temperature, and during the winter this will normally increase energy consumption. Earlier draft criteria were based on climate chamber studies where subjects were exposed to laminar or low turbulent airflow (Houghton 1938; McIntyre 1979).

However, the airflow in ventilated spaces is not normally laminar. Typically the air velocity fluctuates and Fanger and Pedersen (1977) have shown that periodically fluctuating airflow is more uncomfortable than nonfluctuating (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. Later, 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.

In a field study, Thorshauge (1982) identified the velocity fluctuations that occurred in practice through measurements in several ventilated spaces. He found a linear relationship between the mean velocity and the standard deviation of the velocity fluctuations. But still there is lack of information about the actual airflow in ventilated rooms.

The purpose of this study is to identify, by means of modern measuring techniques, the characteristics of turbulent airflow occurring in the occupied zone of a wide range of ventilated

---

Hisashi Hanzawa worked on this study as visiting Research Associate at the Laboratory of Heating and Air Conditioning, Technical University of Denmark. His affiliation is Takenaka Komuten Co. Ltd., Environmental and Mechanical Engineering Unit, Technical Research Laboratory, 5-14, 2-Chome, Minamisuna, Koto-ku, Tokyo. Arsen K. Melikow is Research Associate and P.O. Fanger is Professor at the Laboratory of Heating and Air Conditioning, Technical University of Denmark, Building 402, DK-2800 Lyngby, Denmark.

spaces in practice. Such information is essential for assessing previous studies, for planning future studies on the impact of turbulent airflow on man's sensation of draft, and for modelling airflow in ventilated spaces. Several studies have applied two- or three-dimensional models for numerical calculation of airflow, using experimental data measured in reduced models (Nielsen 1974; Gosman et al. 1980; Unno et al. 1983; Sakamoto and Matsuo 1980). The predicted mean velocity distribution was in good agreement with measured data in reduced models, but there are discrepancies between the predicted turbulent characteristics of airflow and the experimental results of these characteristics (Sakamoto and Matsuo 1980). Moog (1981) discusses the complexity of the room airflow in connection with its prediction. To modify the numerical models, the present measurements of characteristics of room airflow on the scale 1:1 will be useful.

CHARACTERISTICS OF TURBULENT AIRFLOW IN SPACES

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

The instantaneous velocity - $V = \bar{V} + V'$ - which was 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

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

The dash denotes averaging of the time.

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

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

The energy spectrum of the velocity fluctuations

$$\int_0^\infty E(n) dn = \overline{V'^2} \qquad (3)$$

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 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

$$E(k) = \frac{\bar{V}}{2\pi} E(n) \qquad (4)$$

so that

$$\int_0^\infty E(k) dk = \overline{V'^2} \qquad (5)$$

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

The length scales of turbulence comprise the integral scale, L, and the microscale, 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 largest eddies, while the microscale, 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 microscale 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

$$q = \frac{1}{2}\rho(\overline{V'^2} + \overline{V'^2_1} + \overline{V'^2_2}) \tag{8}$$

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 omnidimensional probe is sensitive mainly to the velocity fluctuations, V'. In the present investigation, the airflow was almost isothermal and incompressible, i.e., ρ = constant, so the results for q are calculated as

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

The turbulence energy dissipation, ε, can be calculated from the turbulent energy, q, and the microscale, λ, by means of the formula (Launder and Spalding 1972)

$$\varepsilon = q^{3/2}\,.\,\lambda^{-1} \tag{9}$$

THE INVESTIGATED SPACES

The measurements were performed in 20 ventilated furnished spaces during normal operating conditions, with occupants in some of them. The spaces were selected to cover typical locations, types of outlets, and exhaust terminal devices encountered in Danish heating and ventilating practice. The main characteristics of the ventilated spaces are given in Table 1. Each ventilated space in Table 1 is marked by a symbol, which is used in the following figures.

In each space, velocity probes were placed in six or more locations within the occupied zone. At each location, measurements were taken at four heights: 0.1, 0.6, 1.1, and 1.7 m above floor level as recommended in the ISO Standard 7726. All measurements were taken during a 20-minute period. The air temperature differences between the four levels were less than 2°C. The field studies were performed from December 1984 to January 1985 in the Copenhagen area.

THE MEASURING EQUIPMENT

The measurements were performed using a multichannel flow analyzer and an indoor climate analyzer. The two instruments have omnidimensional temperature-compensated probes. Thirteen probes were calibrated by their respective manufacturers. The signals from the indoor climate analyzer probe and from some of the multichannel flow analyzer probes were recorded on a tape recorder and calculated by a microcomputer. Figure 1 shows a diagram of the measuring and calculating equipment used.

RESULTS

Measurements were taken from more than 500 points in the investigated spaces. Twenty percent of these measurements had a mean velocity of less than 0.05 m/s and therefore had to be discarded since the calibration of the probes does not apply at such low velocities.

The standard deviation as a function of the mean velocity in all the investigated places at ankle level (0.1 m) and head level for a seated person (1.1 m) is shown in Figures 2a and b respectively. It is obvious that there is considerable variability in the standard deviation recorded. In the figures, regression lines from the previous field studies of Thorshauge (1982) and Fanger and Christensen (1986) are shown for comparison. The slope of the regression line for head level in the current study is identical to that established by Fanger and Christensen. The regression equations for the relationship between standard deviation and mean velocity at each of the four heights are shown in Table 2. The correlation coefficient of the present study is somewhat lower close to the floor (r=0.668) and this agrees with the results of Thorshauge (r=0.6).

The turbulence intensity was found to be a function of the mean velocity; when the mean velocity increased, the turbulence intensity decreased. This relationship is most noticeable for ankle level (0.1 m). The same relationship between the turbulence intensity and mean velocity was registered by Fanger and Christensen (1986) and Thorshauge (1982). In Figure 3, a percentage distribution of the mean velocity and turbulence intensity for all the measurements ($\overline{V} > 0.05$ m/s) is shown. At the head level, the turbulence intensity was 10-60%, while at ankle level, it ranged from less than 10% to 70%.

Distribution of mean velocities and turbulence intensities in ventilated spaces depends on the type of ventilation system. In Figure 4 the average mean velocity and turbulence intensity measured at the same level as a function of the height from the floor for two spaces (No. 2 and No. 11 from Table 1) are shown. These two spaces had different air distribution systems, with airflow blowing tangentially and directly into the room.

Energy spectra of the velocity fluctuation measured at ankle and head level in ventilated spaces are shown in Figure 5. 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. The same spectra in a form $E(k)/\overline{V'^2} = f(k)$ are presented in Figure 6. The experimental results accord very well, particularly in the higher wave number range for $k > 5\ m^{-1}$.

From Figure 6 (a and b), the main differences in turbulent energy distribution at levels 0.1 m and 1.1 m are obvious. The spectrum curves for the points too close to the floor level 0.1 m (Figure 6a) contain a rather wide range where $E(k)/\overline{V'^2} \sim k^{-1}$ is closely followed, while the spectrum curves higher above the floor (Figure 6b) (level 1.1 m) followed the $k^{-5/3}$ law. The turbulent energy distribution is completely different in the case of turbulent and laminar flows. Two examples are shown in Figure 7. The spectrum for the laminar flow was measured in a clean room. In the case of the laminar flow, the energy distribution remains with a low but approximately constant value in a wide range of wave numbers.

The analysis of the data for the integral length scale L shows that it depended on the mean velocity but not on the standard deviation. Figure 8 (a and b) shows the integral length scale as a function of the mean velocity. It was found that the microscale λ of the turbulence depended on the mean velocity also, as shown in Figure 9 (a and b). When the mean velocity increases, the microscale increases as well. From Figures 8a, 8b, 9a and 9b, it is obvious that there is a wide variation in the integral scale and the microscale, especially at level 1.1 m. The relationships between L and λ and $\overline{V}$ were found by the least squared regression (Table 3).

The turbulent kinetic energy as a function of the mean velocity is presented in Figure 10 (a and b) for ankle and head levels respectively. The data are measured in spaces with the airflow directed tangentially into the room (Table 1). The relationships between q and $\overline{V}$ were found by least squared regression (Table 3).

DISCUSSION

The present study comprises measurements in a wide range of spaces ventilated in different ways. It provides comprehensive information on the most important characteristics of the airflow in the occupied zone of these spaces. The relationship between the standard deviation and the mean velocity was found (Figure 2a and b, Table 2). The correlation coefficient at level 0.1 m is not so high. It is obvious from Figure 2a and b that at the same level from the floor for the same mean velocities, large differences in the values of the standard deviation were recorded. The turbulence intensity increased when the mean velocity decreased. But in all investigated spaces and at all four investigated heights, the mean velocity and the turbulence intensity varied widely (Figure 3) - the mean velocity from less than 0.05 m/s to 0.4 m/s and the turbulence intensity from less than 10% to 70%.

The influence of the turbulent flow on the sensation of draft is shown in Figure 11. In this figure the results from two different sensation experiments are compared. The first, by Fanger and Pedersen (1977), presents the percentage of dissatisfied, i.e., those feeling draft at the neck region as a function of the local air velocity when the airflow is laminar, and the second by Fanger and Christensen (1986), when the airflow is turbulent ($Tu \approx 30$-60%). Although the conditions of the experiments were not identical, the impact of the turbulent flow on the draft sensation was obvious. The draft chart by Fanger and Christensen (1986) was based on studies in which subjects were exposed to a turbulent flow similar to the practical conditions identified in the present field study. Figure 3 shows that at level 1.1 m for most of the current field measurements the turbulence intensity was 10-60%, i.e., within the limits investigated by Fanger and Christensen. However, in the current field study values of turbulence intensity lower than 10% and higher than 50% at the same mean velocity were also encountered in the occupied zone. Therefore, it is recommended that further climate chamber studies be undertaken where subjects are exposed to turbulent flow with different turbulence intensities from less than 10% to 70% at the same mean velocities.

The air distribution in the investigated spaces may be separated roughly into two groups. The first group with the air supply directed tangentially into the space (cases 1,2,3,3',4,5,6, 7,10,13 from Table 1) and the second group (cases 9,11,12 from Table 1) where the air flows more directly toward the occupied zone. In the spaces of the first group, decrements of mean velocity and increments of turbulence intensity with increasing height above floor level were observed. However, the opposite trend was observed in the spaces from the second group: the mean velocity increased and the turbulence intensity decreased when the level from the floor increased (Figure 4a and b).

The turbulence intensity, which shows the magnitude of the velocity fluctuations in comparison with the mean velocity, is not sufficient to characterize the turbulent flow. It is quite possible to find two turbulent flows with the same mean velocity and turbulence intensity but with different frequencies of the velocity fluctuations. The previous experiments of Fanger and Pedersen (1977) have shown that the frequency of velocity fluctuations also affects people's feeling of draft. In their experiments, the subjects were exposed to periodically fluctuating airflows with the same mean velocity and turbulence intensity and different frequencies of the velocity fluctuations. They have found that discomfort was maximum at frequencies around 0.3 - 0.5 Hz. Madsen (1984) has checked this by means of a thermal simulation model of the human skin on an analogue computer. This shows that the heat flow just below the skin surface (where the thermoreceptors are situated) is maximum at a frequency similar to that causing the highest degree of discomfort. On the basis of these experiments, he hypothesized that the high subjective sensitivity was a result of periodically high outputs from the thermal receptors to the sensory cortex caused by a corresponding high heat flow through the receptors following the moments of highest air velocity.

In this connection, the integral length scale of turbulence seems to be an important characteristic of the turbulent flow, as it establishes a measure of the extent of the mass of air that moves as a unit. These eddies carry the major part of the turbulent energy, and they are responsible for the main fluctuations of velocity. In the current study it was found (Figures 8a and b) that the integral length scale increases when the mean velocity increases. But the regression coefficients were only moderate - 0.72 - 0.73 (Table 3). Figure 8 shows the values of the integral length scale published by Olesen (1979) from field measurements in three ventilated spaces. They are within the limits of the present measurements. The characteristic frequency of the largest eddies can be calculated by means of the formula

$$n_c = \frac{\bar{V}}{2\pi L} \tag{10}$$

but only approximately, since the relation $L = \bar{V}.\tau$ ($n_c = 1/2\pi\tau$) is correct when the flow field has a uniform mean velocity, $\bar{V}$, and when $\bar{V} >> V'$ (Hinze 1975). τ is an integral time scale defined from the autocorrelation (Hinze 1975). The results show that the characteristic frequencies change from 0.04 Hz to 0.15 Hz. The values defined by Olesen (1979) are also within these limits. But these values (0.04 Hz - 0.15 Hz) are quite different from the frequencies 0.3 - 0.5 Hz causing discomfort according to Fanger's and Pedersen's studies (1977). An attempt was made to evaluate how much of the turbulent energy was concentrated in the region of the frequencies between 0.3 and 0.5 Hz. The results show that it is no more than 3.5% of the total turbulent energy.

The turbulent energy distribution is similar to that in a fully developed turbulent flow (Figure 5a and b). The spectra in Figure 6 (a and b) show that the experimental results measured at the same level in different ventilated spaces are remarkably similar. The spectra in these figures also reveal the major contribution of total turbulent energy made by the larger eddies in the low-wave number range. Figure 6 (a and b) show also some differences in this respect. The spectrum curves for the points not so close to the floor, for example at level 1.1 m (Figure 6b) follow the -5/3 law rather closely in the wave number 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}, thus indicating strong interaction between mean and turbulent flow. At this point a strong production of turbulent energy takes place (Hinze 1975). These results are in good agreement with the experimental results presented in Hinze (1975), measured in different boundary layers.

The turbulent kinetic energy, q, and the microscale of turbulence, λ, depend on the mean velocity (Figure 10 (a and b), Figure 9 (a and b)). In Figure 10 (a and b) only the results from the ventilated spaces with tangentially directed airflow are presented. The correlation coefficients for the relationships between q, λ, and $\overline{V}$ were not high (Table 3). At the same level and for the same mean velocities, these parameters varied within quite wide limits. These characteristics, together with the turbulent energy dissipation, ε, are often used in the turbulence models for the numerical prediction of the turbulent flow in ventilated spaces. Few experimental results are available at present for comparison with these predictions. Most of them concern measurements of the mean velocity and turbulence intensity in models. The results from the numerical predictions are presented as curves of equal mean velocity, microscale, turbulent energy, and dissipation. But as the present and other investigations (Moog 1981; Rolloos 1977) show, because of the complexity of the airflow, only equal ranges of these parameters can be considered in real ventilated spaces. In Table 4, the results from the present experiment and numerical predictions in occupied zones show the order of magnitude of these parameters. The experimental results are from the ventilated spaces with approximately the same tangential flow to the occupied zone as in the numerical predictions. The predicted values for q in Gosman et al. (1980) are within the limits of those from the experiment, but large differences exist for the microscales. This is not so for the results from the predictions in Unno et al. (1983). The measured values of the microscale and the dissipation are in good agreement with those predicted, but differences exist with regard to the values of the turbulent kinetic energy. However, in order to improve the results from the numerical predictions and to understand the airflow in normal ventilated spaces, further detailed field measurements and laboratory experiments are essential.

CONCLUSIONS

Airflow characteristics were measured at 500 points in four heights of the occupied zone in 20 ventilated spaces.

A relationship between standard deviation and mean velocity was found (Table 2). It indicates slightly lower turbulence than that for which the draft chart of Fanger and Christensen (1986) was established. Mean velocities from 0.05 m/s to 0.4 m/s and turbulence intensities from 10% to 70% at ankle level, 0.1 m, and from 10% to 60% at head level, 1.1 m, were measured. Further studies on the impact of turbulence intensity on the sensation of draft are recommended.

The major part of turbulent energy is concentrated in the low-wave number range, $k<5$ m^{-1}, corresponding to eddies with dimensions 0.1 - 0.5 m. The spectra curves indicate that a significant production of turbulent energy takes place near the floor.

The integral scale of turbulence, the microscale of turbulence, and the turbulence kinetic energy were established to be functions of the mean velocity (Table 3).

Comparison with the numerical predictions shows that further more detailed field and laboratory studies at scale 1:1 are needed to obtain a clearer understanding of airflow in ventilated spaces and for developing turbulence models for numerical predictions.

REFERENCES

Fanger, P.O.; and Pedersen, C.J.K. 1977. "Discomfort due to air velocities in spaces." In: Proceedings of the Meeting of Commission B1, B2, E1 of the International Institute of Refrigeration, Beograd, p. 4.

Fanger, P.O.; and Christensen, N.K. 1986. "Perception of draught in ventilated spaces." Ergonomics, Vol. 29, No. 2, pp. 215-235.

Gosman, A.D.; Nielsen, P.V.; Restivo, A.; and Whitelaw, J.H. 1980. "The flow properties of rooms with small ventilation openings." Trans. of ASME, Vol. 102, pp. 316-323.

Hinze, J.O. 1975. Turbulence. New York: McGraw Hill.

Houghten, F.C. 1938. "Draft temperatures and velocities in relation to skin temperature and feeling of warmth." American Society of Heating and Ventilating Engineers Transactions, Vol. 44, p. 289.

ISO 7726. Thermal environments. Specifications relating to appliance and methods for measuring physical characteristics of the environment, Geneva.

Launder, B.E.; and Spalding, D.B. 1972. Mathematical models of turbulence. London and New York: Academic Press.

Madsen, T.L. 1984. "Why air velocities may cause thermal discomfort." Proceedings of Indoor Air '1984, August 20-24, 1984, Stockholm, Sweden.

McIntyre, D.A. 1979. "The effect of air movement on thermal comfort and sensation." In: Indoor climate (edited by P.O. Fanger and O. Valbjorn). Copenhagen, Danish Building Research Institute, pp. 541-560.

Moog, W. 1981. "Room flow tests in a reduced scale." ASHRAE Transactions, Vol. 87, pt. 1.

Nielsen, P.V. 1974. "Flow in air conditioned rooms." Ph.D. thesis. Technical University of Denmark, Lyngby, Denmark.

Olesen, B.W. 1979. "Draught and air velocity measurements." DISA Information, No. 27, May, pp. 30-35.

Rolloos, M. 1977. On the possibilities and limitations of modelling room air flow conditions. Report nr. K69, Laboratory for Refrigerating and Air Conditioning Engineering, Dept. of Mech. Engineering, Delft University of Technology, Netherlands.

Sakamoto, V.; and Matsuo, Y. 1980. "Numerical predictions of three-dimensional flow in a ventilated room using turbulence models." App. Math. Modelling, Vol. 4, pp. 67-72.

Thorshauge, J. 1982. "Air velocity fluctuations in the occupied zone of ventilated spaces." ASHRAE Transactions, Vol. 88, pt. 2.

Unno, K.; Nagasawa, Y.; Hanzawa, H.; Takahashi, N.; and Tajima, H. 1983. "A study of numerical analysis of room air distribution." Takenaka Technical Research Report, No. 29, pp. 19-37.

ACKNOWLEDGMENTS

The Danish firms Brüel & Kjær and DANTEC Elektronik are acknowledged for making their airflow instruments available for the present study.

TABLE 1

Main Characteristics of the Various Ventilated Spaces

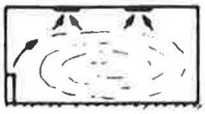
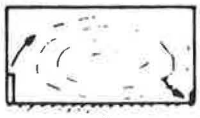
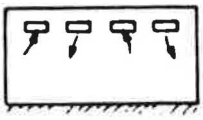
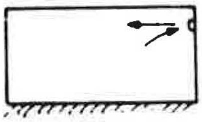
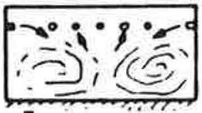
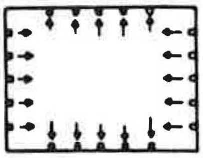
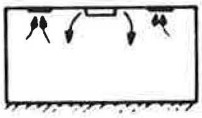
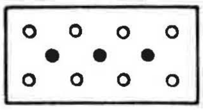
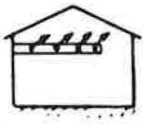
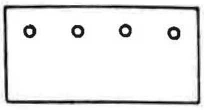
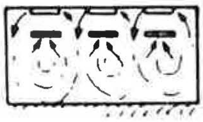
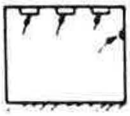
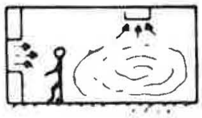
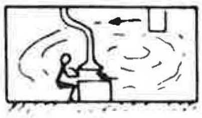
No. & Symbol	Type of Space	Floor Area (m^2)	Space Volume (m^3)	Air Change (1/h)	Type of Ventilation System Mean Velocity $\bar{V}_o$ and Turbulent Intensity Tu_o are given
1 ⧄	office	13	34	9.5	 1,2,3,3'  4  5 6 No 1 2 3 5 6 7 $\bar{V}_o$ m/s 1.5 1.8 1.3 2.4 1.8 1.8 Tu_o % 11 8 11 7 8 11
2 ⌖	office	29	76	6.4	
3 -○- 3' ◆	office with/ without nozzles	56	148	3.0	
4 ○	school room	62	155	7.4/ 3.3	
5 ■	school room	78	210	4.6	
6 ■	school room	78	225	2.3	
7 ◇	swimming hall	1650	15000	1.6	
8 ▲	school room	58	210	4.0	 
9 ▷	small auditorium	74	361		 9  10
10 ✶	large auditorium	187	850		
11 △	meeting room	108	324	7.4	 $\bar{V}_o$ = 3.8 m/s Tu_o = 7% 
12 ⌖	meeting room	39	109		  $\bar{V}_o$ = 3.5 m/s
13 ×	industrial hall	52	182		 
14 □	large industrial hall	144	504		 
15 ■	large industrial hall	223	771		
16 ▽	lecture room	50	150	12.5 / 15.0	 
17 ▼	lecture room	50	150		
18 ◆	lecture room	50	150		
19 ⊙	lecture room	50	150		
20 +	with thermal load	50	150		
21 ○	clean room with laminar flow	42	160	25.0	21  laminar flow 22  turbulent flow
22 ●	clean room with turbulent flow	148	378		

TABLE 2

Regression Equations Calculated for the Standard Deviation of the Velocity (RMS) as a Function of the Mean Velocity ($\overline{V}$)

Measuring height	Regression equation	Coefficient of correlation
0.1 m	$RMS = 0.191\ \overline{V} + 0.0078$	0.6680
0.6 m	$RMS = 0.330\ \overline{V} + 0.0021$	0.9122
1.1 m	$RMS = 0.328\ \overline{V} + 0.0021$	0.8372
1.7 m	$RMS = 0.266\ \overline{V} + 0.0032$	0.8199

TABLE 3

Regression Equations for the Turbulence Characteristics (L, λ, q) as a Function of the Mean Velocity ($\overline{V}$)

Measuring height	Regression equation	Coefficient of correlation
1.1 m	$L = 0.1389 + 1.1256\ \overline{V}$	0.721
	$\lambda = 0.0120 + 0.1336\ \overline{V}$	0.763
	$q^{1/2} = -0.00092 + 0.22918\ \overline{V}$	0.852
0.1 m	$L = 0.07186 + 1.174\ \overline{V}$	0.7849
	$\lambda = 0.01844 + 0.1196\ \overline{V}$	0.732
	$q^{1/2} = 0.00289 + 0.1720\ \overline{V}$	0.6471

TABLE 4

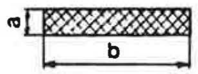
Comparison of the Turbulence Characteristics (λ, q, ε) Between the Present Experiment and Numerical Calculations

Results	$\lambda/_{H} = \lambda^{**}$	$\lambda/_{L_o} = \lambda^{*}$	$q/_{\overline{V}_o^2} = q^{*}$	$\varepsilon^{*} = \frac{q^{*3/2}}{\lambda^{*}}$
Present experiment	$(7-17)10^{-3}$	$(7-18)10^{-2}$	$(4.38-97)10^{-5}$	$(1.04-374)10^{-6}$
Numerical calculation, Gosman et al (1980)	0.1–0.3	1 – 3	$(5-10)10^{-5}$	
Numerical calculation, Unno et al (1983)	$(7.5-14)10^{-3}$	$(7.5-14)10^{-2}$	$(5.9-13)10^{-4}$	$(9.5-46)10^{-6}$

H - the height of the room

L_o - the equivalent diameter of the outlets

$L_o = \sqrt{a.b}$



$\overline{V}_o$ - the average outlet velocity

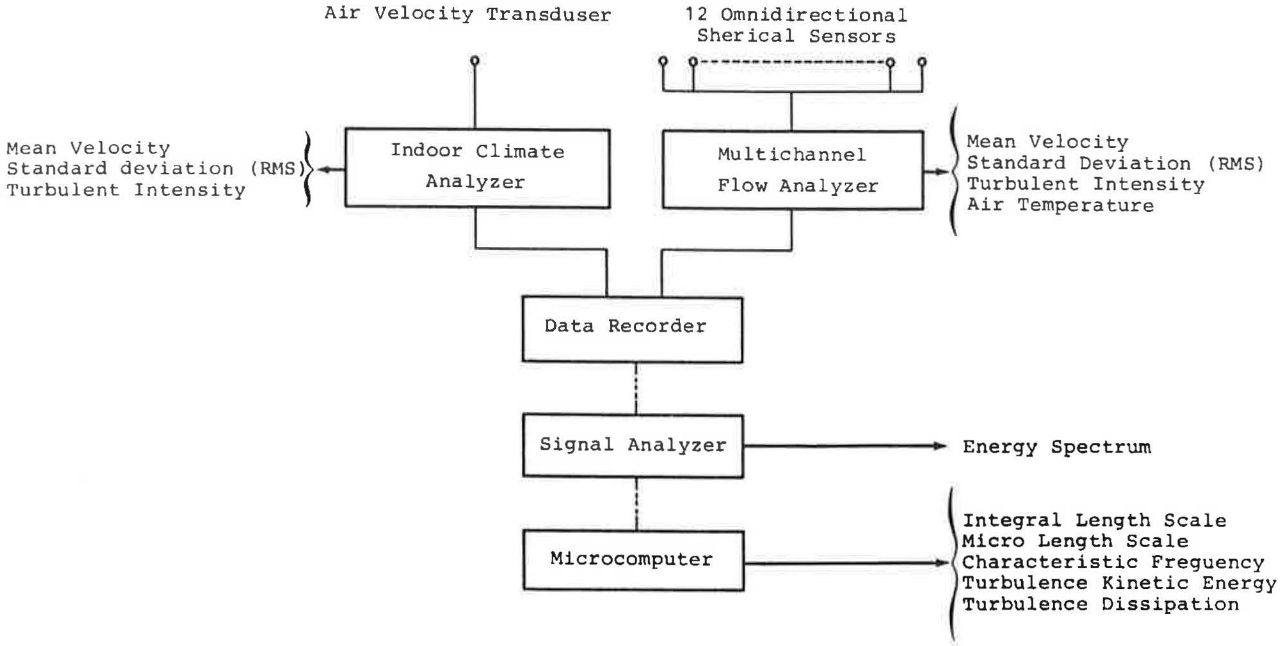


Figure 1. Measuring and analyzing system

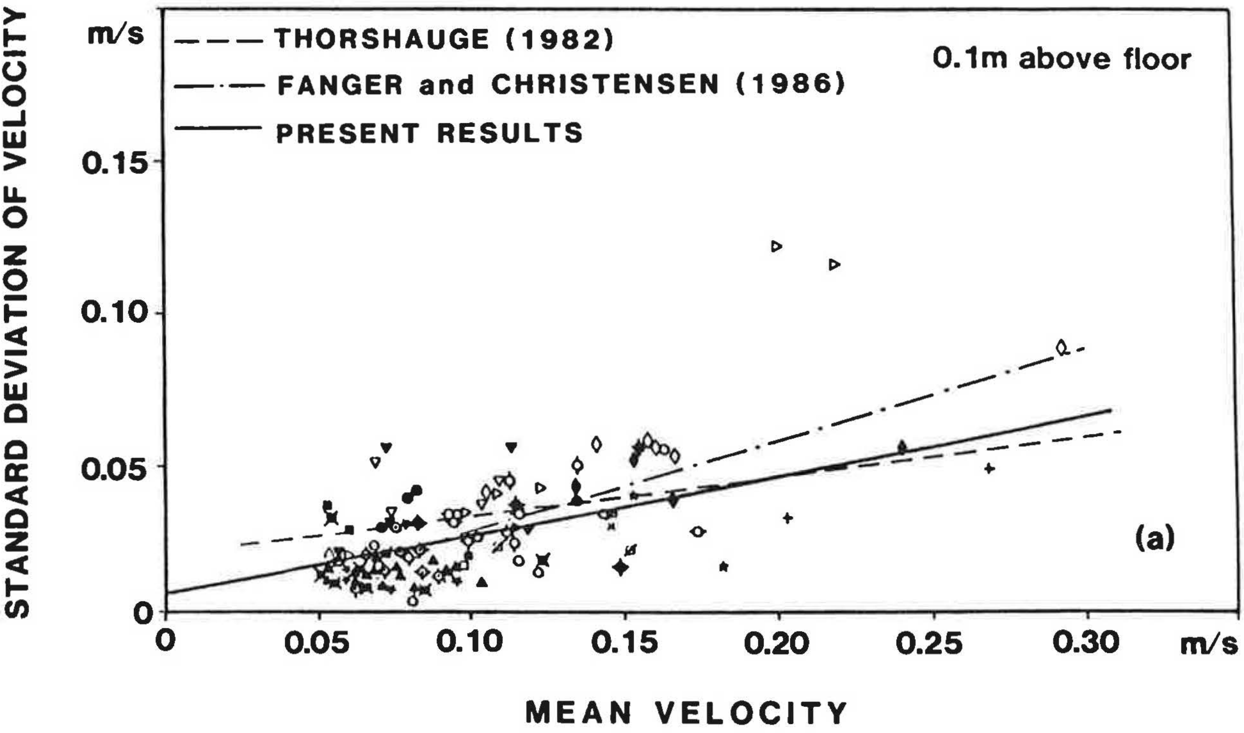


Figure 2a. Relationship between standard deviation and mean velocity (Table 2) at ankle level (0.1 m above the floor)

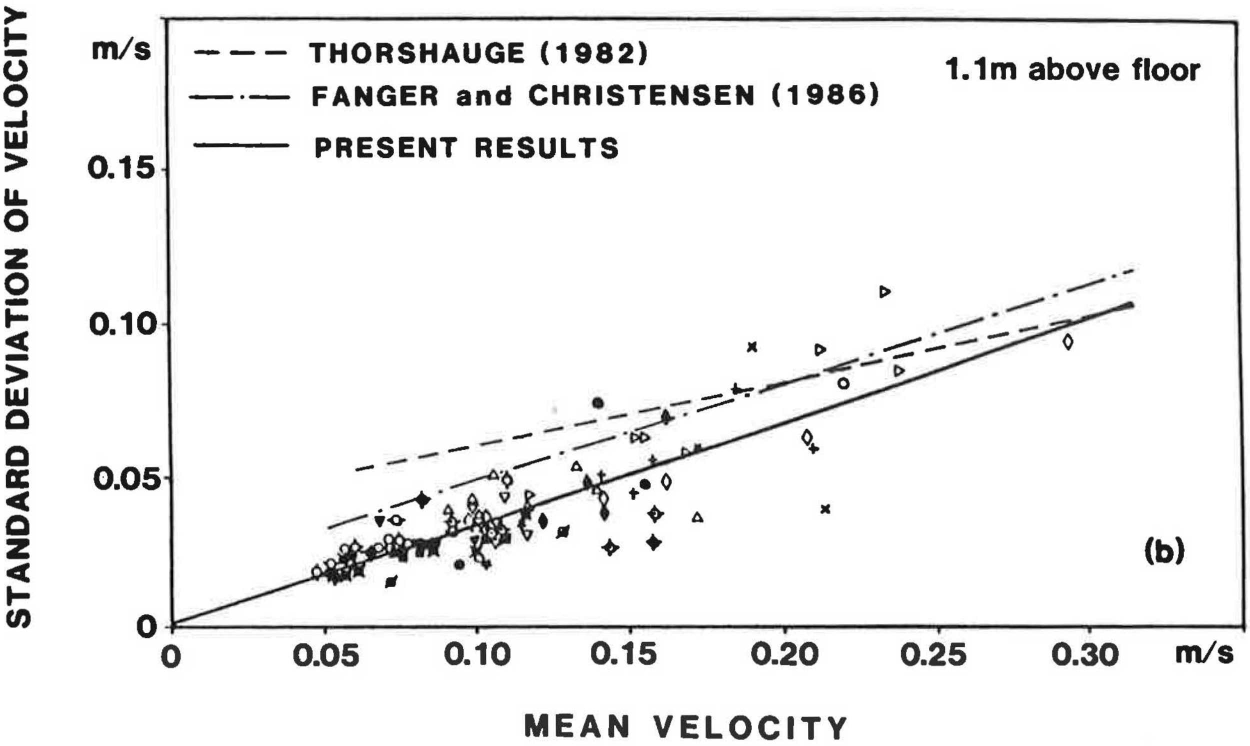


Figure 2b. *Relationship between standard deviation and mean velocity (Table 2) at head level (1.1 m above the floor)*

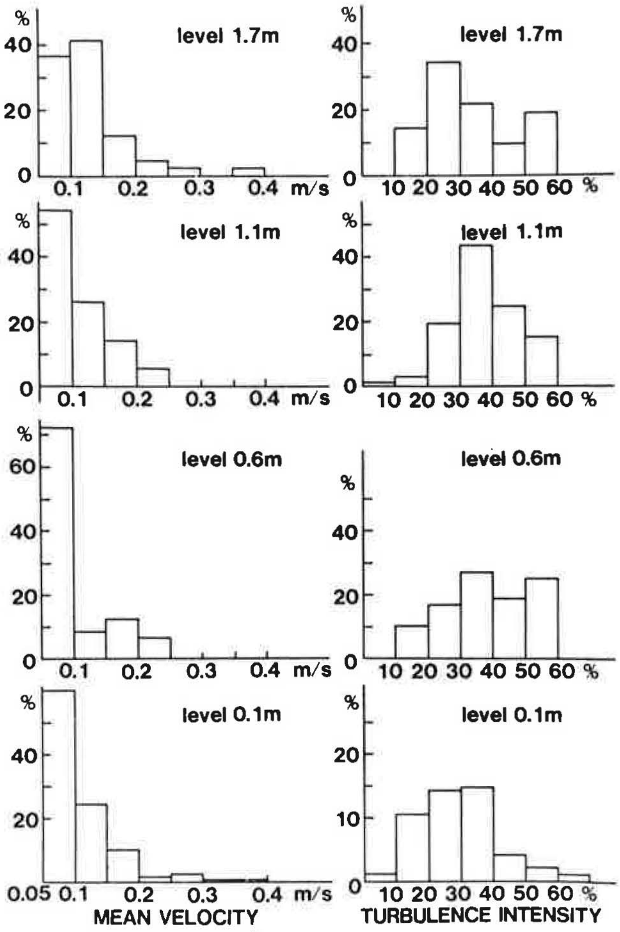


Figure 3. *Histograms of the mean velocity, $\overline{V}$, and the turbulence intensity, Tu, distribution at different heights (from all results)*

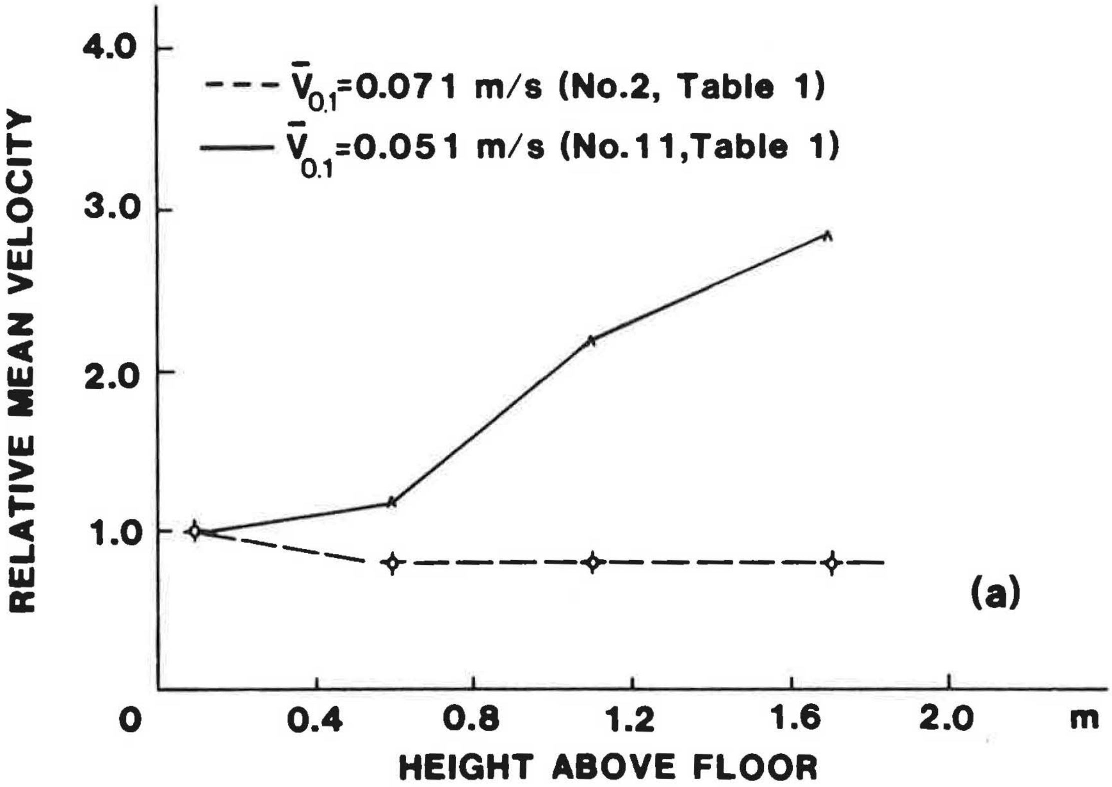


Figure 4a. Variation of the relative mean velocity, $\bar{V}/\bar{V}_{0.1}$, with the level from the floor for tangential flow (No. 2, Table 1) and direct flow (No. 11, Table 1). $\bar{V}_{0.1}$ is the mean velocity at level 0.1 m. $\bar{V}$ and $\bar{V}_{0.1}$ are averaged from all values measured at the same level

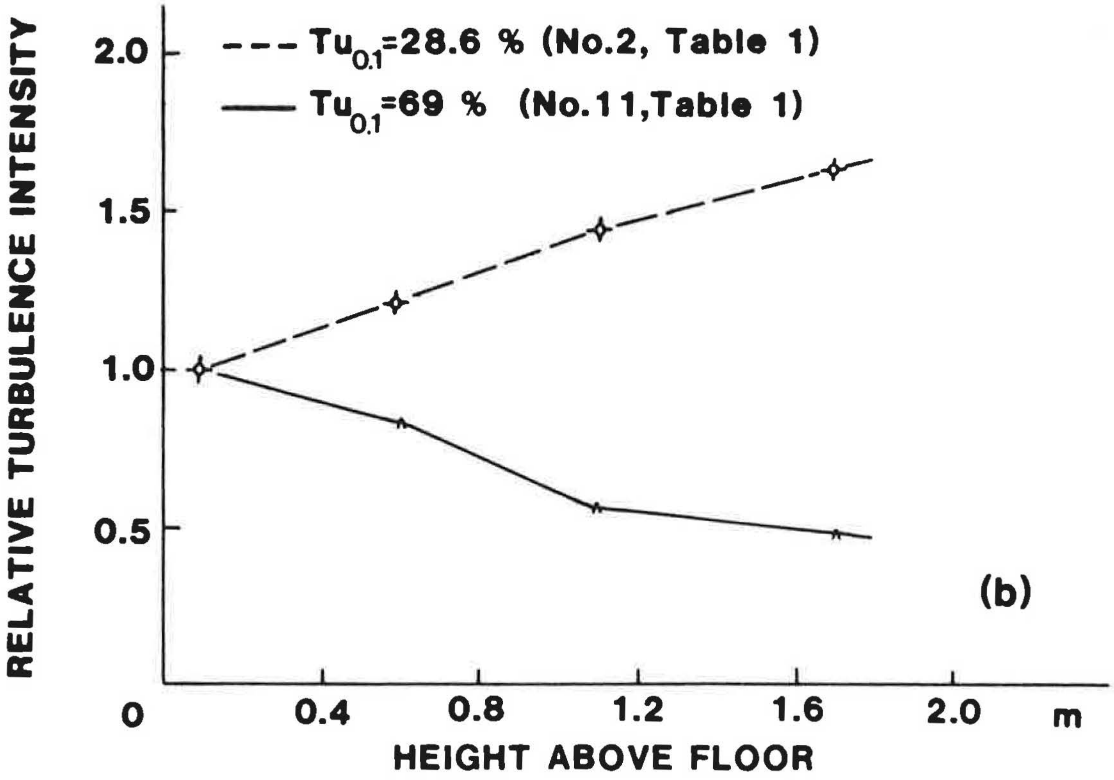


Figure 4b. Variation of the relative turbulence intensity, $Tu/Tu_{0.1}$ with the level from the floor for tangential flow (No. 2, Table 1) and direct flow (No. 11, Table 1). $Tu_{0.1}$ is the turbulence intensity at level 0.1 m. Tu and $Tu_{0.1}$ are averaged from all values measured at the same level

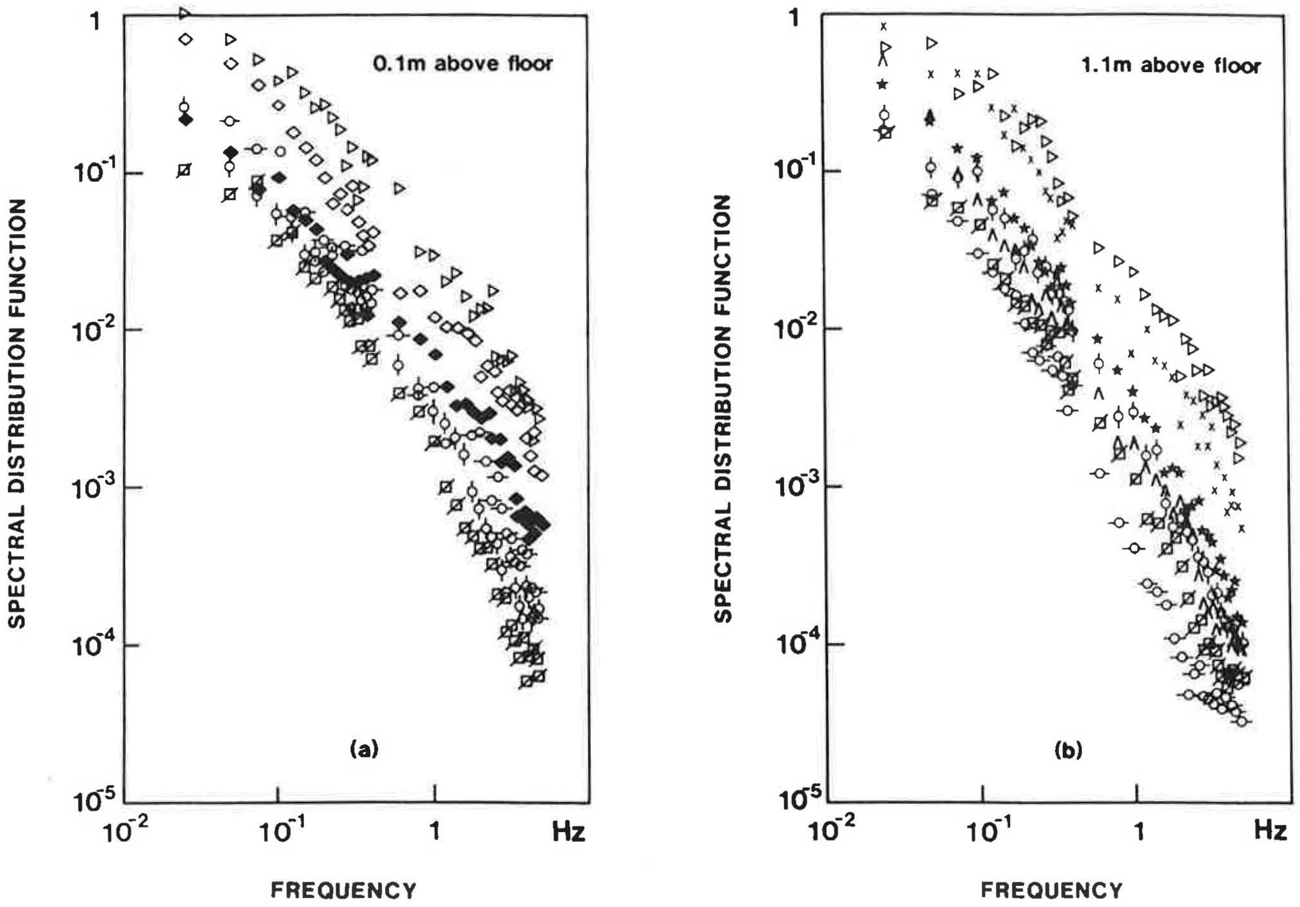


Figure 5. Energy spectra of the velocity fluctuations measured in different ventilated spaces (Table 1). Vertical axis represents distribution function E(n) divided by distribution function E1(n) for space No. 9 (Table 1) at frequency 0.025 Hz: (a) at ankle level, 0.1 m above the floor, (b) at head level, 1.1 m above the floor

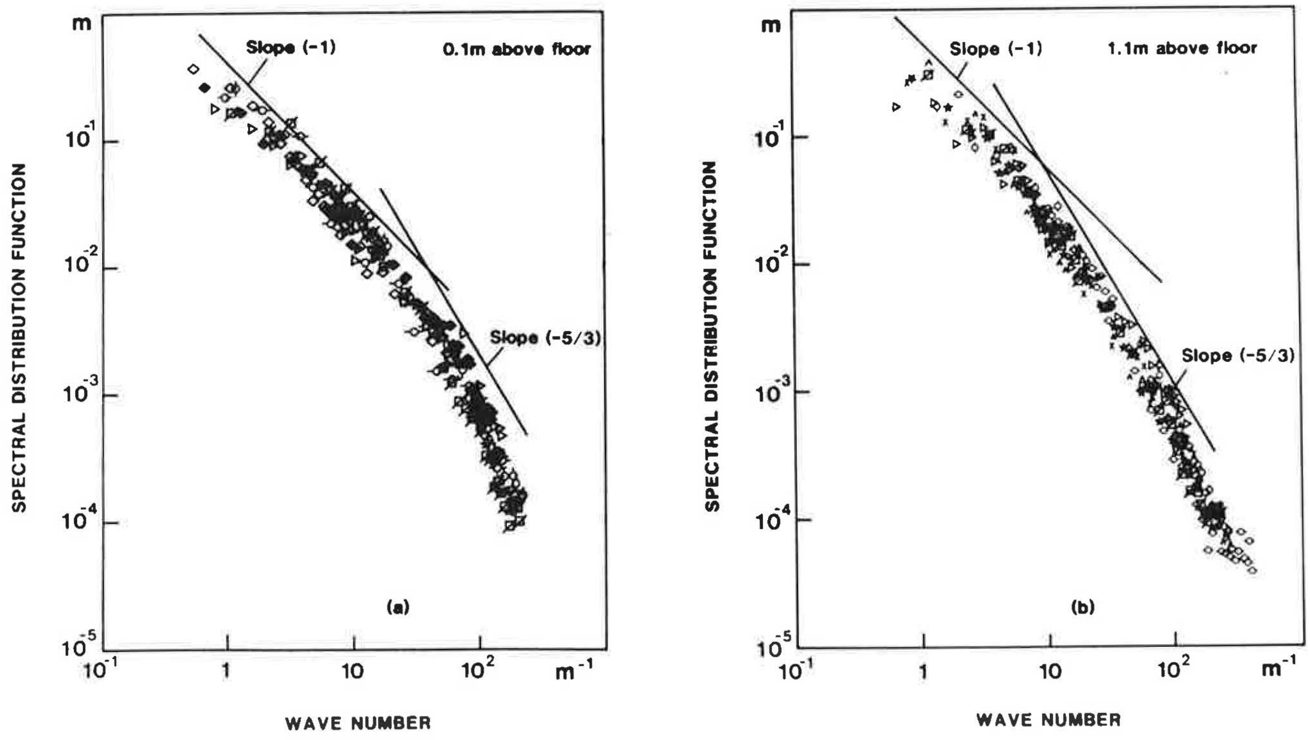


Figure 6. Energy spectra measured in different ventilated spaces (Table 1). Vertical axis represents $E(k)/\overline{V'^2}$: (a) at ankle level, 0.1 m above the floor, (b) at head level, 1.1 m above the floor

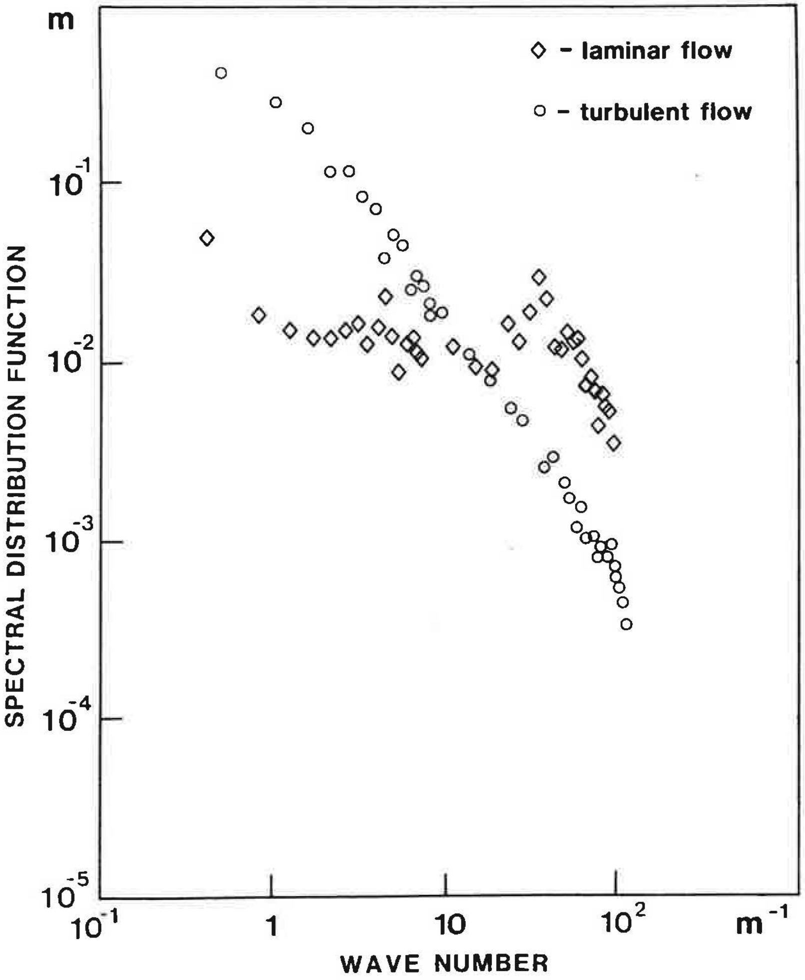


Figure 7. Energy spectra of the velocity fluctuations. Comparison between laminar and turbulent flow. Vertical axis represents $E(k)/\overline{V'^2}$

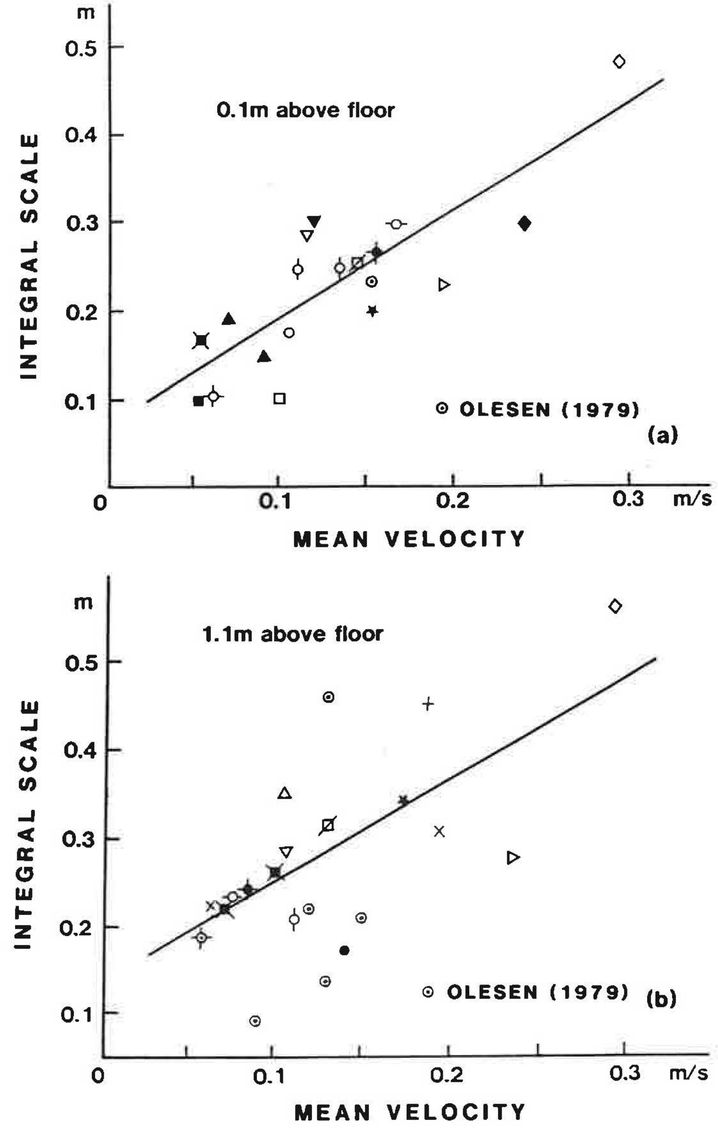


Figure 8. Relationship between integral scale, L, and mean mean velocity, $\overline{V}$: (a) at ankle level, 0.1 m above the floor, (b) at heat level, 1.1 m above the floor

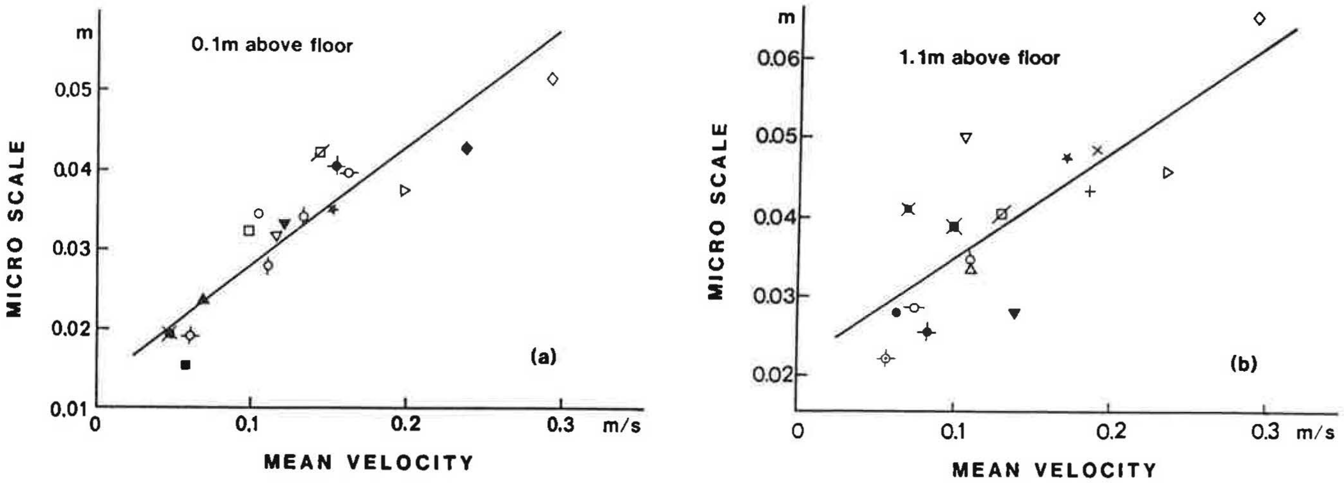


Figure 9. Relationship between microscale, λ, and mean velocity, $\overline{V}$: (a) at ankle level, 0.1 m above the floor, (b) at head level, 1.1 m above the floor

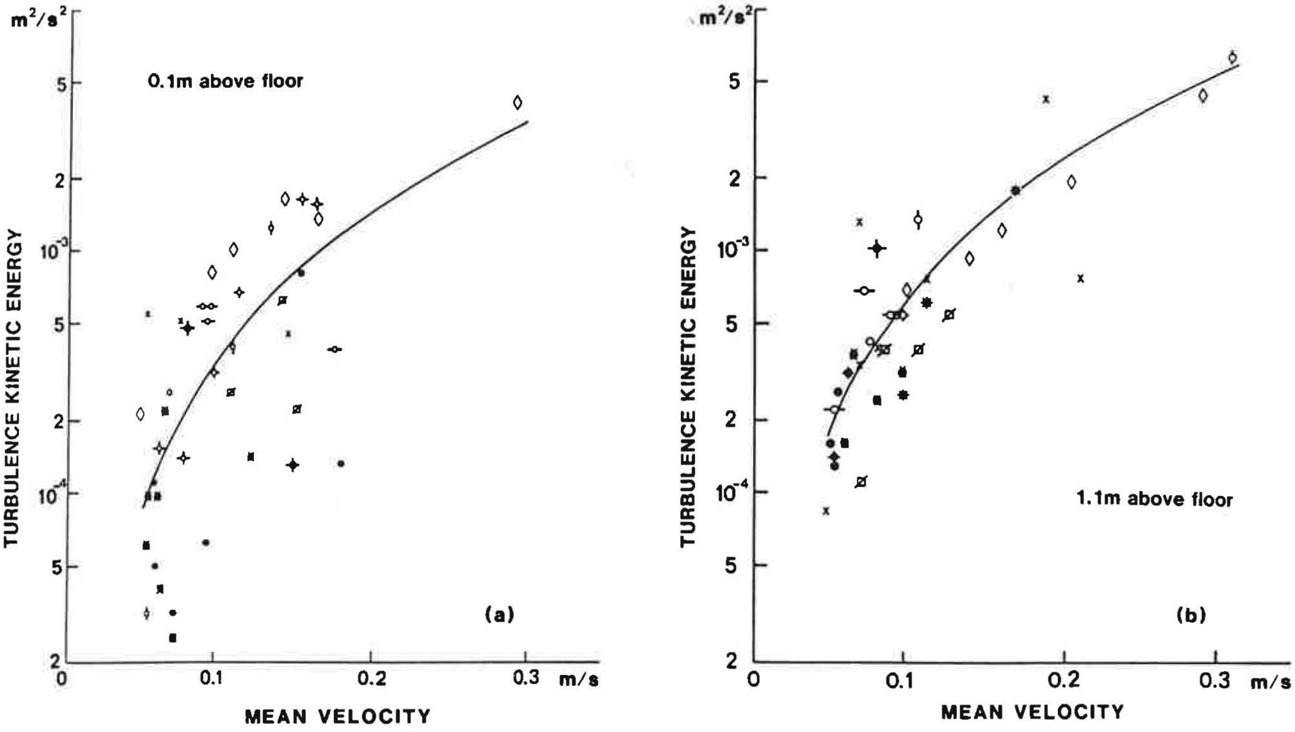


Figure 10. Turbulence kinetic energy, q, as a function of mean velocity, $\overline{V}$: (a) at ankle level, 0.1 m above the floor, (b) at head level, 1.1 m above the floor. The lines present the regression equations listed in Table 3

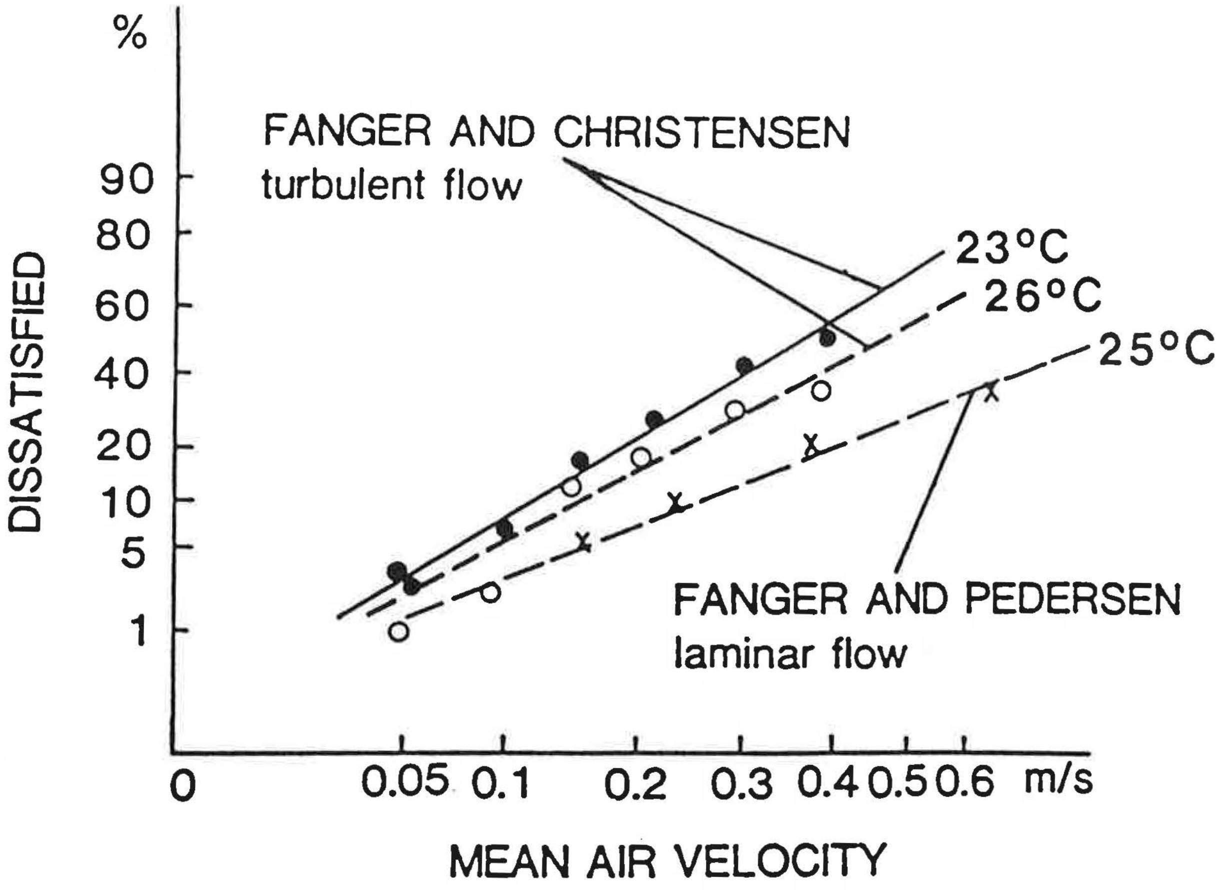


Figure 11. The percentage of dissatisfied, i.e., those feeling a draught at the head region, as a function of the mean velocity in case of laminar and turbulent flows . The horizontal axis presents the square root of the mean velocity