TO-82-5 No. 1

Air-Velocity Fluctuations in the Occupied Zone of Ventilated Spaces

J. Thorshauge

INTRODUCTION

Draft can be defined as an undesirable, local, convective cooling of the body. For many years, draft criteria have been based on Houghton's investigations from the 1930s in which ten male subjects were exposed to an air current with a constant (nonfluctuating) velocity directed toward the neck or ankles.[1] In practice, however, velocity is not constant but fluctuating, and Pedersen has shown that it is the fluctuations that cause discomfort and result in people feeling draft at far lower velocities than the constant velocities in Houghten's investigations.[2,3] Pedersen exposed his subjects to well-defined periodic velocity fluctuations and found that frequency and amplitude also were important factors.

In practice, however, velocity fluctuations are not periodic but intermittent. Therefore, in order to establish realistic draft criteria, it is necessary to perform supplementary experiments, exposing subjects to intermittent velocity fluctuations as they occur in practice. In order to do this, it is first essential to identify the velocity fluctuations that can actually occur. The purpose of the present project is to identify these velocity fluctuations through measurements in several typically ventilated spaces.

THE VENTILATED SPACES

The air velocity measurements were made in 12 different ventilated spaces, which were offices, open-plan offices, a meeting room, lecture rooms, small and large auditoriums with an air volume of 30-930 m^3 and an air change designed for 4-8 h^{-1}. The outlets in these spaces were ceiling diffusors, induction units, and wall grilles (Tab. 1). It is estimated that the places chosen, with their particular ventilations systems, are typical of modern ventilated spaces.

MEASURING METHOD AND MEASURING EQUIPMENT

The measurements were made in unused, furnished spaces, with the ventilation system functioning normally. The supply air had a temperature 1-3 K below room temperature. One of the three measuring locations in the space was chosen by means of a smoke experiment, so that it was positioned at a location where the highest air velocity was estimated to occur. The other two measuring locations were chosen at random in the occupied zone, where it was expected people would sit when the space was in use. All three measuring locations were placed in the occupied zone of the space (i.e., at least 0.6 m from the walls). At each location, measurements were taken at three heights: 0.1 m (ankle height), 0.6 m (center of gravity of a seated person), and 1.1 m (neck of a seated person) above floor level. Measurements were thus made at nine points in each space.

A commercially available, omnidirectional, temperature-compensated probe (Fig. 1) was used to measure the air velocities. This probe consists of two small quartz spheres (diameter 2.6 mm) covered with a thin nickel film.[4] One of the quartz spheres is electrically heated and maintained

Jørgen Thorshauge, Laboratory of Heating & Air Conditioning, Technical University of Denmark, DK-2800 Lyngby. Present affiliation: Crone & Koch, Consulting Engineers, International Aps, Ordrupvej 60, DK-2920 Charlottenlund, Denmark.

CONTENTS

CONTENTS

at a constant temperature. The necessary current is a measure of the sphere's heat loss, which depends on the air velocity and the temperature. The other sphere measures the air temperature by resistance measuring and compensates for the influence of temperature on the heat loss of the first sphere. These measurements and compensations are performed electronically, so the combined time constant of the system is less than 0.8 s. The measuring and calibrating uncertainty of the probe and the combined system in the measuring range of the probe are shown in Tab. 2.

An outline of the measuring and calculating equipment used is given in Fig. 2. With this equipment, the air velocity was measured approximately 4½ times per second over a measuring period that varied from 10 to 60 minutes.

CHARACTERISTICS OF VELOCITY FLUCTUATIONS

Fig. 3 shows a typical example of the air velocity variation at a measuring point during part of the measuring period. This strongly fluctuating air movement can be described by the following characteristic parameters, divided into two main groups:

1. Velocity:
   - Mean velocity (average over time), $\bar{V}$
   - Standard deviation, SD_v
   - Maximum velocity, V_{max}
   - Minimum velocity, V_{min}
   - Turbulence intensity, $f' = \frac{SD_v}{\bar{V}}$
   - Relationship between maximum and mean velocity, $\frac{V_{max}}{\bar{V}}$
   - Histogram and normal probability plot
   - Frequency spectrum of the velocity variation
2. Acceleration:
   - Mean acceleration, $\bar{g}$
   - Standard deviation, SD_g
   - Maximum acceleration, g_{max}
   - Minimum acceleration, g_{min}
   - Histogram of acceleration distribution
   - Frequency spectrum of the acceleration

Figs. 4 and 5 show the characteristic parameter values of the velocity at a typical measuring point (same measuring point as in Fig. 3).

As the measuring period is divided into time intervals within which the velocity has been constantly rising or falling, the acceleration within a time interval is defined as the slope of the line that connects the first and the last measured air velocity in the particular time interval (see Fig. 6, which is a part of Fig. 3). So defined, acceleration in an interval is therefore the average acceleration in the particular interval. These accelerations have been divided into two groups: positive acceleration (positive slope) and negative acceleration (negative slope). Fig. 7 shows the characteristic parameter values for these two groups at the same measuring point as in Figs. 3-5.

Pedersen demonstrated that of the characteristic parameters describing fluctuation of an air movement, it is the mean velocity, the relationship $V_{max}/\bar{V}$, and the frequency of the velocity variations that are significant for man's subjective evaluation of draft.[2,3] Based on calculations made on an electrical analog computer and on Hensel's physiological studies,[5] Madsen claims that man's subjective evaluation can be explained by the heat flow through the thermoreceptors of the skin.[6]

Therefore, the cause of draft is considered to be linked to the velocity variation, but, as acceleration is always present in air movement and as acceleration is closely linked to velocity, it seems reasonable to assume that the characteristic parameters for acceleration can also have an influence on the subjective evaluation of draft.

MEASURING DURATION

In 6 of the 12 typically ventilated spaces, a measuring period of 60 minutes was used. Fig. 8 shows, for a typical measuring point, the manner in which the mean velocity, $\bar{V}$, and the standard deviation, SD_v, develop throughout the measuring period. As can be seen from Fig. 8, after a 3-minute measuring period, the mean velocity has much the same value as after the full measuring period (60 minutes), while for SD_v, this occurs first after approximately 5 minutes. In order to study closer the influence of the measuring period, various other periods (1, 2, 4, 10, and 20 minutes) were simulated on the basis of the measurements already obtained, using a 60-minute measuring period, and $\bar{V}$ and SD_v were calculated. These measuring periods were staggered at an interval of 30 seconds over the whole measuring period (60 minutes). This corresponds to the mean value, $\bar{V}$, and the standard deviation, SD_v, at the measuring point being determined (e.g., 137 times with a simulated measuring period of 2 minutes). Figs. 9 and 10 show the influence of the measuring period on the accuracy of the mean velocity and the standard deviation calculated. With a measuring period of 10 minutes there is more than 80 percent probability that mean velocity and standard deviation will differ less than 10 percent from the values that would be obtained with an "infinitely" long measuring period (60 minutes). This degree of accuracy is sufficient in the present investigation, considering the measuring and calibrating uncertainty of the probe. Therefore, data for the first 10 minutes of the measuring time at each measuring point were used in the following analysis of the results.

RESULTS

The statistical analysis covers only those measuring points where $\bar{V} \geq 0.05$ m/s (60 points), as it was not possible with certainty to calibrate the probe below this value.

Velocity

The air velocities measured are normally distributed (a typical example is given in Figs. 4 and 5); thus, the distribution is established by the two parameters, $\bar{V}$ and SD_v. By means of linear regression analysis with the model $y = a + b \cdot \bar{V}$, the relationship between $\bar{V}$ and each of the parameters, SD_v, V_{max}, and V_{min}, is estimated. The regression equations are given in Tab. 3. Tab. 4 gives the calculated relation between $\bar{V}$ and f' and $V_{max}/\bar{V}$, respectively. A frequency analysis of the velocity variations revealed that practically all the energy lies in the interval 0 - 0.2 Hz.

Acceleration

Numerically, there was no difference between the groups (positive and negative acceleration). By means of linear regression analysis with the model $y = a + b \cdot \bar{V}$, the relation between $\bar{V}$ and the mean value of acceleration ($\bar{g}$), the standard deviation on acceleration (SD_g), and the maximum acceleration (g_{max}) are estimated. Tab. 5 gives the estimated regression equations. A frequency analysis revealed no predominant frequency in the spectrum investigated (i.e., 0 - 2 Hz).

DISCUSSION

Considering the irregular nature of the fluctuations, it is surprising that it was possible nevertheless to establish a reasonably good relation between mean velocity and the characteristic values of the fluctuations, i.e., standard deviation of the velocity, maximum and minimum velocity, mean acceleration, standard deviation of acceleration, and maximum acceleration. Determination of the relation between SD_v and $\bar{V}$ at a height of 0.1 m above floor level is nevertheless uncertain ($r = 0.6$).

At all the measuring points, the velocities measured are normally distributed. From the mean velocity ($\bar{V}$) and the standard deviation (SD_v), it is thus possible to calculate the percentage of the measuring time that the velocity has exceeded any velocity level.

Therefore, for practical measurements in ventilated spaces, it would seem sufficient to measure the mean velocity, since the other parameters that characterize the velocity fluctuations are dependent on this. This relation is less certain for measurements close to the floor, especially for standard deviation. Therefore, when measuring near the floor, it is recommended that the standard deviation of the velocity be determined.

Contrary to expectations, a multiple linear regression analysis of the measuring points, where $\bar{V} \geq 0.05$ m/s, revealed no significant (5% level) influence of the size of the space, the supply air flow, or the type of outlets on the estimated relations. The results obtained show good agreement with Pedersen's measurements in ventilated spaces; he found $V_{max}/\bar{V}$ values between 2 and 4 and the frequency of the velocity variations in the spectrum 0 - 0.2 Hz.[2]

Pedersen set up a model giving the number of persons that could be expected to experience draft as a function of the mean velocity frequency, amplitude, and temperature, when these persons were exposed to a periodically fluctuating air velocity. In Pedersen's experiment, the relation $V_{max}/\bar{V}$ varied between 1 and 2, with a periodic frequency of velocity fluctuations between 0 and 1 Hz. Compared to the air velocities measured in practice, Pedersen's test conditions were unrealistic. First, velocity fluctuations are not periodic, and second, the frequency and the relationship $V_{max}/\bar{V}$ do not occur in practice in the intervals investigated.

There is a need for further draft experiments in which people are exposed to velocity fluctuations of the same irregular nature as actually take place in typically ventilated spaces and as identified in the present investigation. Consequently, the experiments should be performed with a mean velocity ($\bar{V}$) of between 0.05 m/s and 0.50 m/s, $V_{max}/\bar{V}$ between 1.5 and 6, turbulence intensity (f') between 0.2 and 1.0, mean acceleration ($\bar{g}$) between 0.02 and 0.25 m/s^2, and with a frequency of velocity fluctuations of between 0 and 0.2 Hz.

CONCLUSIONS

By measuring with an omnidirectional probe at 60 points in the occupied zone of 12 typically ventilated spaces, a linear relationship was found between mean velocity and each of the following parameters that indicate the characteristics of velocity fluctuations: standard deviation of the velocity, maximum velocity, mean acceleration, and standard deviation of the acceleration. Neither the space volume, the supply airflow, nor the type of outlets had any significant influence on this relationship.

In practice, the measurement of the mean velocity at a point is usually sufficient to characterize the velocity fluctuations at a certain point in a ventilated space. With measurements near the floor, it is recommended that the standard deviation be determined as well.

The draft limit should be studied by exposing subjects to velocity fluctuations similar to those found in the present investigation.

REFERENCES

1. F.C.Houghten, "Draft temperatures and velocities in relation to skin temperature and feeling of warmth", ASHVE Transactions 44 (1939), p.289.

2. C.J.K.Pedersen, "Komfortkrav til luftbevægelser i rum (Comfort requirements to air movements in spaces)" (thesis submitted for Ph.D. [in Danish], Laboratory of Heating & Air Conditioning, Technical University of Denmark, 1977).

3. P.O.Fanger and C.J.K.Pedersen, "Discomfort due to air velocities in spaces", Proceedings of the meeting of Commissions B1, B2, E1 of the IIR, Belgrade, 1977/4, pp.289-296.

4. F.Jørgensen, "An omnidirectional thinfilm probe for indoor climate research", DISA-Information, No. 24, 1979.

5. H.Hensen, "Thermoreception and human comfort", P.O.Fanger and O.Valbjørn, eds., Indoor Climate (Copenhagen 1979), Danish Building Research Institute, pp.425-440.

6. T.Lund-Madsen, "Limits for draught and asymmetric radiation in relation to human thermal well-being", Proceedings of the meeting of Commissions B1, B2, E1 of the IIR, Belgrade, 1977/4, pp.297-306.

TABLE 1. Data of the various Spaces

Type of space	Floor area m^2	Air volume m^3	Air change h^{-1}	Type of outlet
office	11	30	4	Air diffusor mounted in the ceiling
office	19	60	4	Grilles mounted in the wall
office	19	60	4	Grilles mounted in the wall
meeting room	32	95	8	Air diffusors mounted in the ceiling
lecture room	50	150	8	Air diffusors mounted in the ceiling
lecture room	50	150	4	Air diffusors mounted in the ceiling
open plan office	100	300	4	Air diffusors mounted in the ceiling
auditoria	100	330	8	Air diffusors mounted in the ceiling
auditoria	150	475	8	Air diffusors mounted in the ceiling
auditoria	150	475	4	Air diffusors mounted in the ceiling
auditoria	230	930	8	Air diffusors mounted in the ceiling
open plan office	250	750	4	Induction units at the frontage

TABLE 2. Probable Error of the Measuring Equipment at Various Velocity Levels

Air velocity m/s	Probable error of the probe	Calibration error	Probable error of the equipment
0.05	± 16 %	± 10 %	± 19 %
0.10	± 7 %	± 10 %	± 12 %
0.20	± 6 %	± 5 %	± 8 %
0.50	± 6 %	± 5 %	± 8 %
1.00	± 6 %	± 5 %	± 8 %

TABLE 3. Regression Equation for Standard Deviation (SD_V), Maximum Value (V_{max}) and Minimum Value (V_{min}) as a Function of Mean Velocity for Each of the Three Measuring Levels

Measuring level m	Regression equation m/s	Correlation cofficient r	Number of measuring points
1.1	$SD_V = 0.04 + 0.21\ \bar{V}$	0.94	14
0.6	$SD_V = 0.02 + 0.20\ \bar{V}$	0.84	18
0.1	$SD_V = 0.02 + 0.13\ \bar{V}$	0.60	28
1.1	$V_{max} = 0.23 + 1.39\ \bar{V}$	0.94	14
0.6	$V_{max} = 0.12 + 1.52\ \bar{V}$	0.90	18
0.1	$V_{max} = 0.10 + 1.30\ \bar{V}$	0.88	28
1.1	$V_{min} = -0.02 + 0.22\ \bar{V}$	0.93	14
0.6	$V_{min} = 0 + 0.12\ \bar{V}$	0.84	18
0.1	$V_{min} = -0.02 + 0.37\ \bar{V}$	0.82	28

TABLE 4. Equations Calculated for Turbulence Intensity (f') and the Relationship $V_{max}/\bar{V}$ as a Function of the Mean Velocity ($\bar{V}$) for Each of the Three Measuring Levels

MEASURING LEVEL m	CALCULATED EQUATION
1.1	$f' = 0.21 + \frac{0.04}{\bar{V}}$
0.6	$f' = 0.20 + \frac{0.02}{\bar{V}}$
0.1	$f' = 0.13 + \frac{0.02}{\bar{V}}$
1.1	$\frac{V_{max}}{\bar{V}} = 1.39 + \frac{0.23}{\bar{V}}$
0.6	$\frac{V_{max}}{\bar{V}} = 1.52 + \frac{0.12}{\bar{V}}$
0.1	$\frac{V_{max}}{\bar{V}} = 1.30 + \frac{0.10}{\bar{V}}$

TABLE 5. Regression Equations for the Mean Value ($\bar{g}$), the Standard Deviation (SD_g) and the Maximum Value (g_{max}) of the Numerical Acceleration as a Function of Mean Velocity ($\bar{V}$) for Each of the Three Levels

Measuring level m	Regression equation m/s^2	Correlation coefficient r
1.1	$\bar{g} = 0.62\ \bar{V}$	1.00
0.6	$\bar{g} = 0.51\ \bar{V}$	0.99
0.1	$\bar{g} = 0.49\ \bar{V}$	0.95
1.1	$SD_g = 0.02 + 0.38\ \bar{V}$	0.98
0.6	$SD_g = 0.01 + 0.31\ \bar{V}$	0.95
0.1	$SD_g = 0.02 + 0.14\ \bar{V}$	0.70
1.1	$g_{max} = 0.11 + 2.25\ \bar{V}$	0.96
0.6	$g_{max} = 0.11 + 1.45\ \bar{V}$	0.93
0.1	$g_{max} = 0.09 + 0.95\ \bar{V}$	0.75

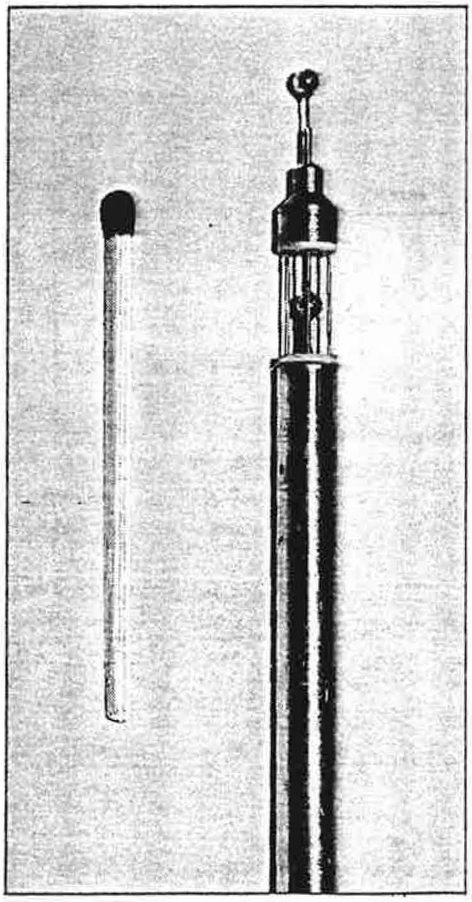


Figure 1. A commercially available, omnidirectional, temperature-compensated probe

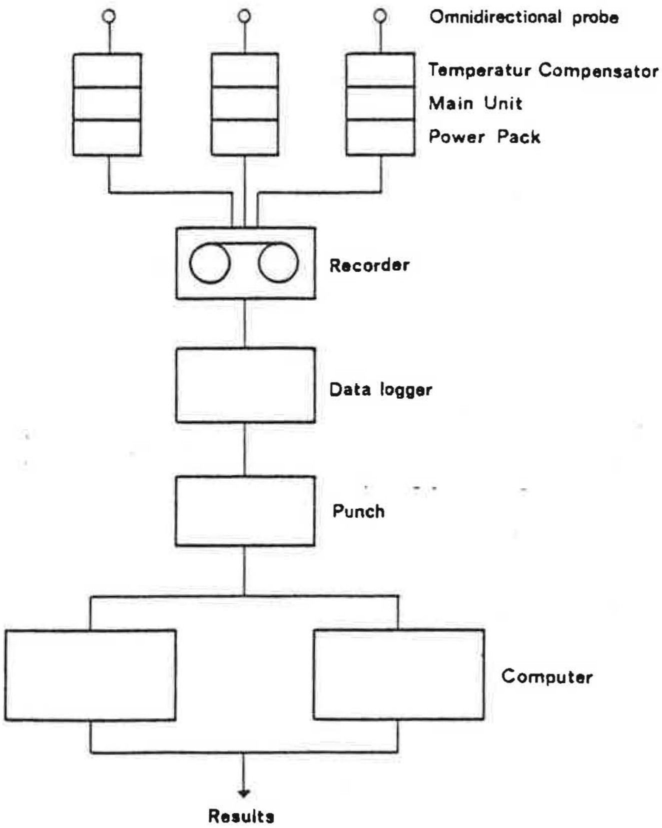


Figure 2. Chart showing the measuring and calculating equipment used

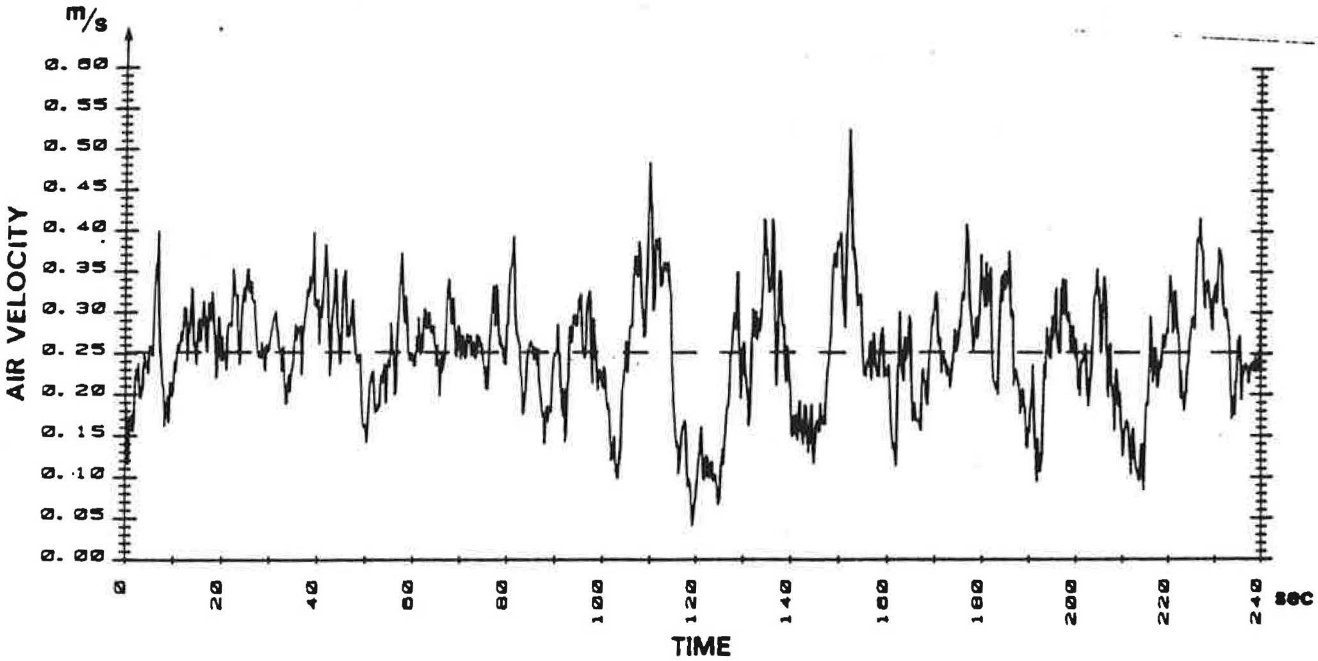


Figure 3. Example of air velocity variations. The broken line indi- indicates the mean velocity ($\bar{V}$)

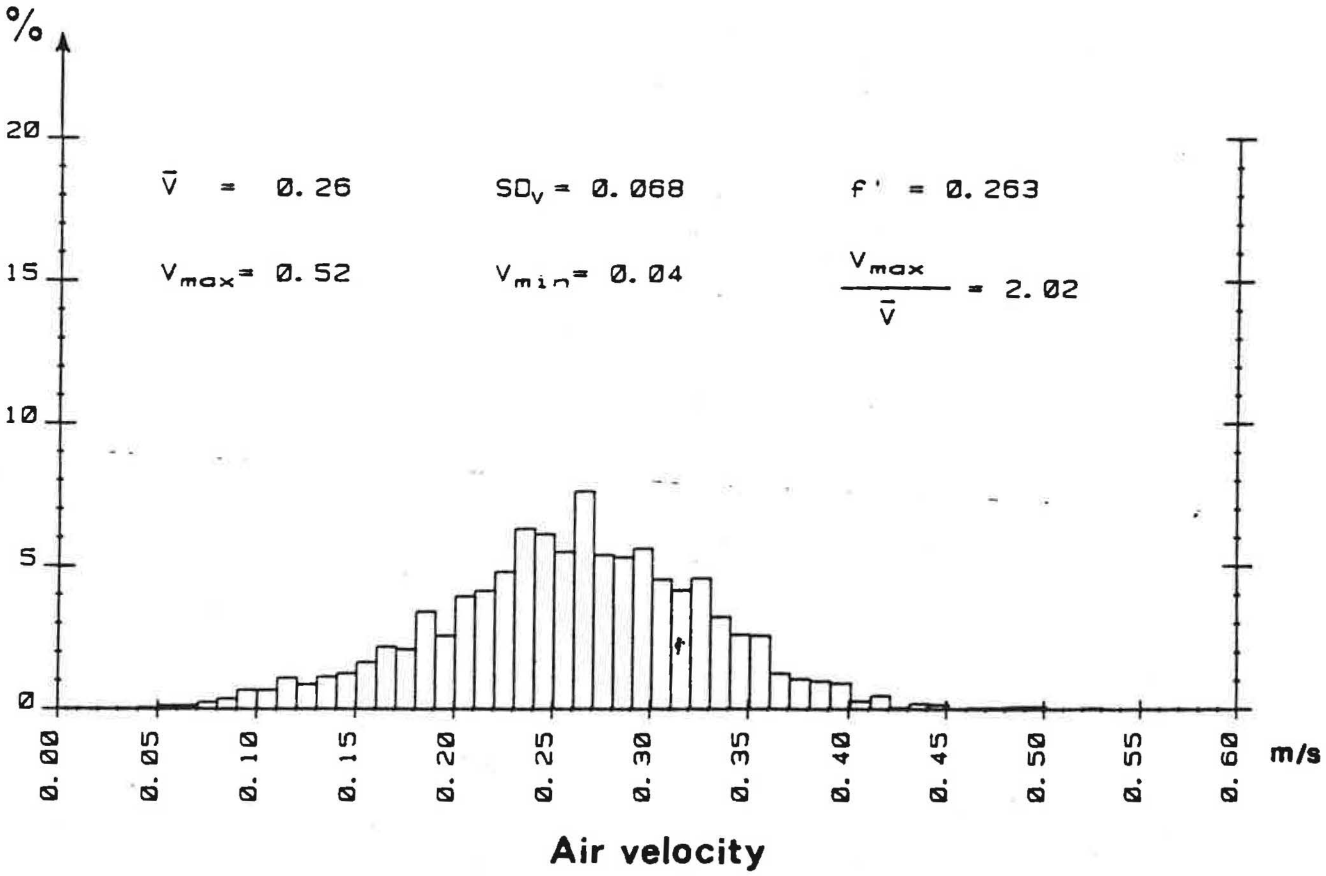


Figure 4. Histogram of velocity distribution at typical measuring point (same as Fig. 3), and the characteristic parameters $\bar{V}$, SD_V, f', V_{max}, V_{min} and $V_{max}/\bar{V}$ *over a measuring period of 10 minutes*

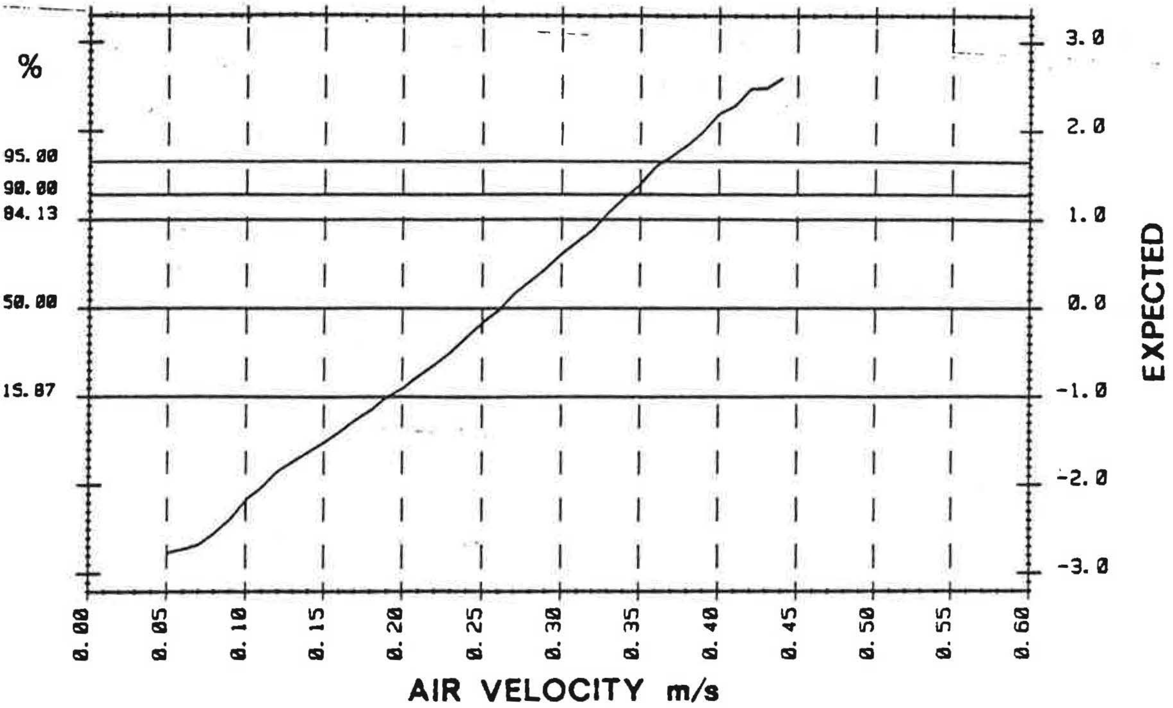


Figure 5. The velocity distribution from Fig. 4 on probability paper

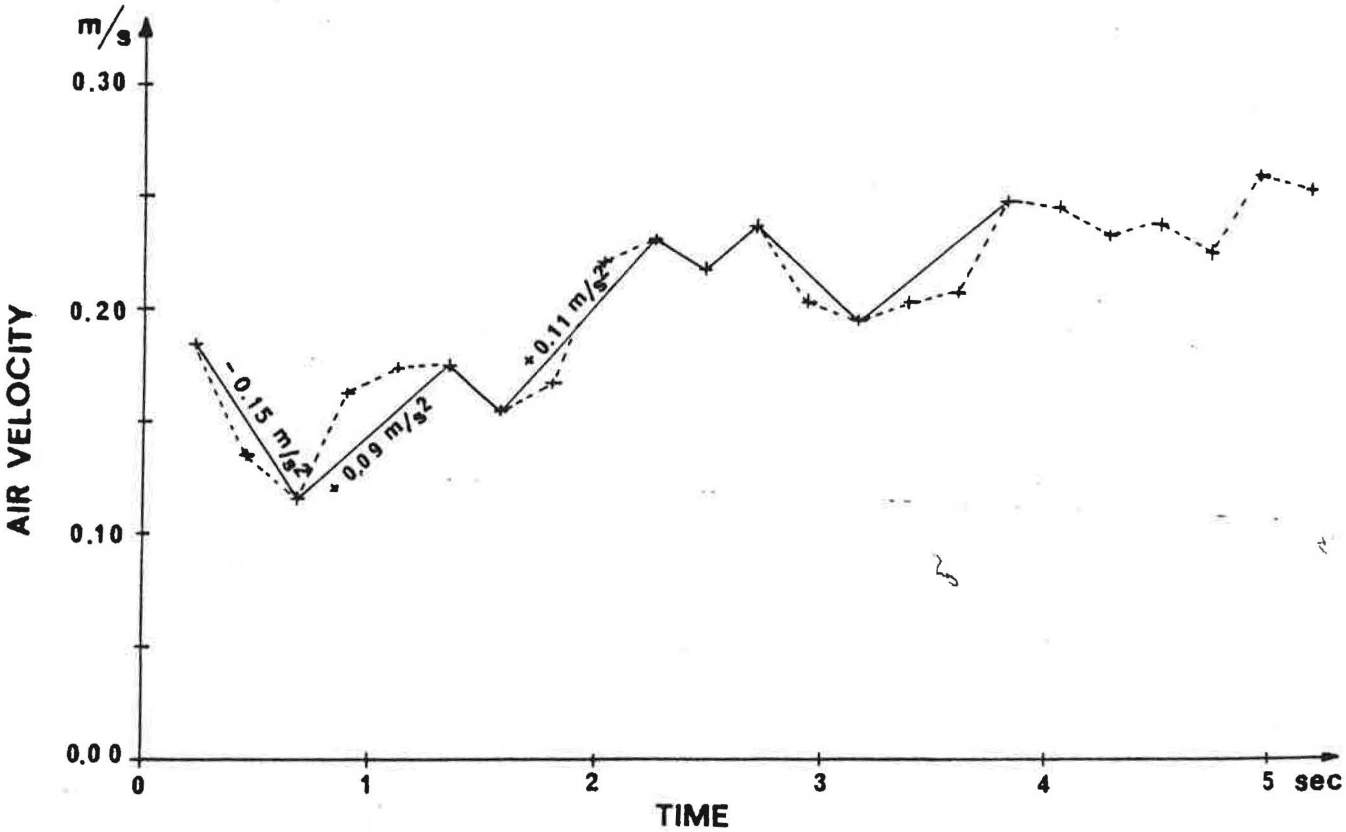
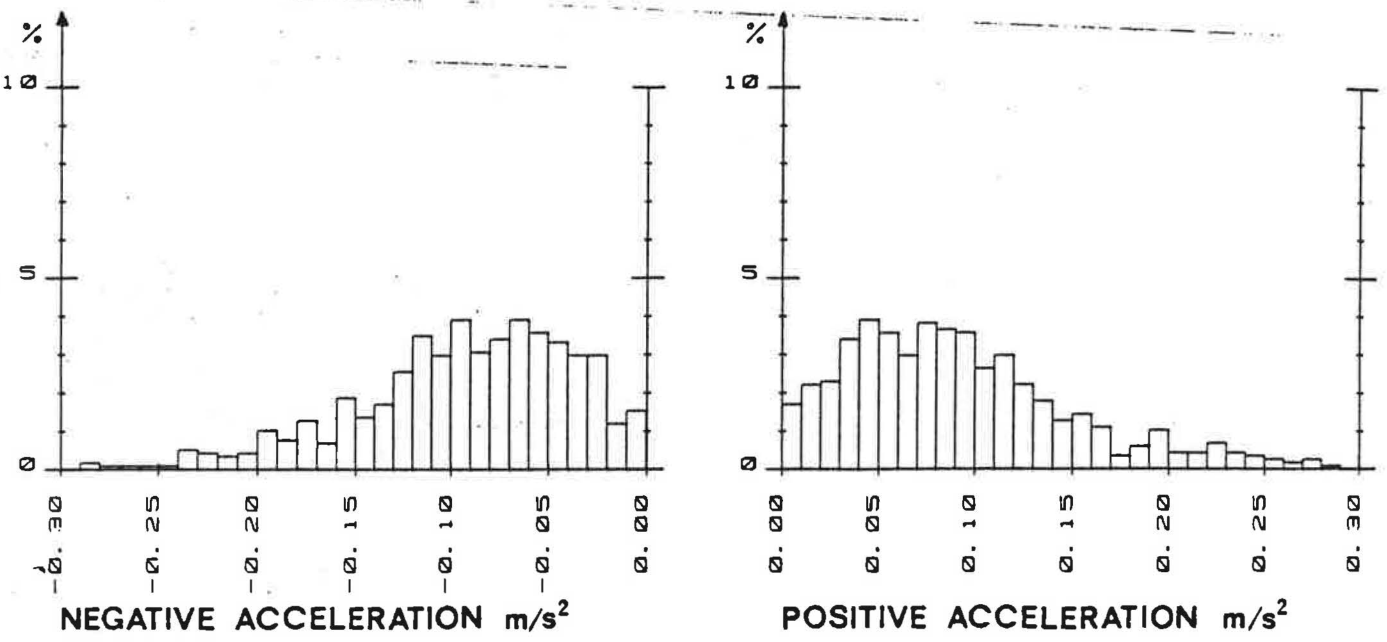


Figure 6. Calculation of acceleration: the broken line indicates the velocity variations measured at a point (part of Fig. 3); the slope of the solid line indicates the accelerations



$\bar{g}$ = -0.10 SDg = 0.060

g_{min} = - 0.46

$\bar{g}$ = 0.09 SDg = 0.061

g_{max} = 0.35

Figure 7. The distribution of positive and negative acceleration at a measuring point; same measuring point as in Figs. 3-5

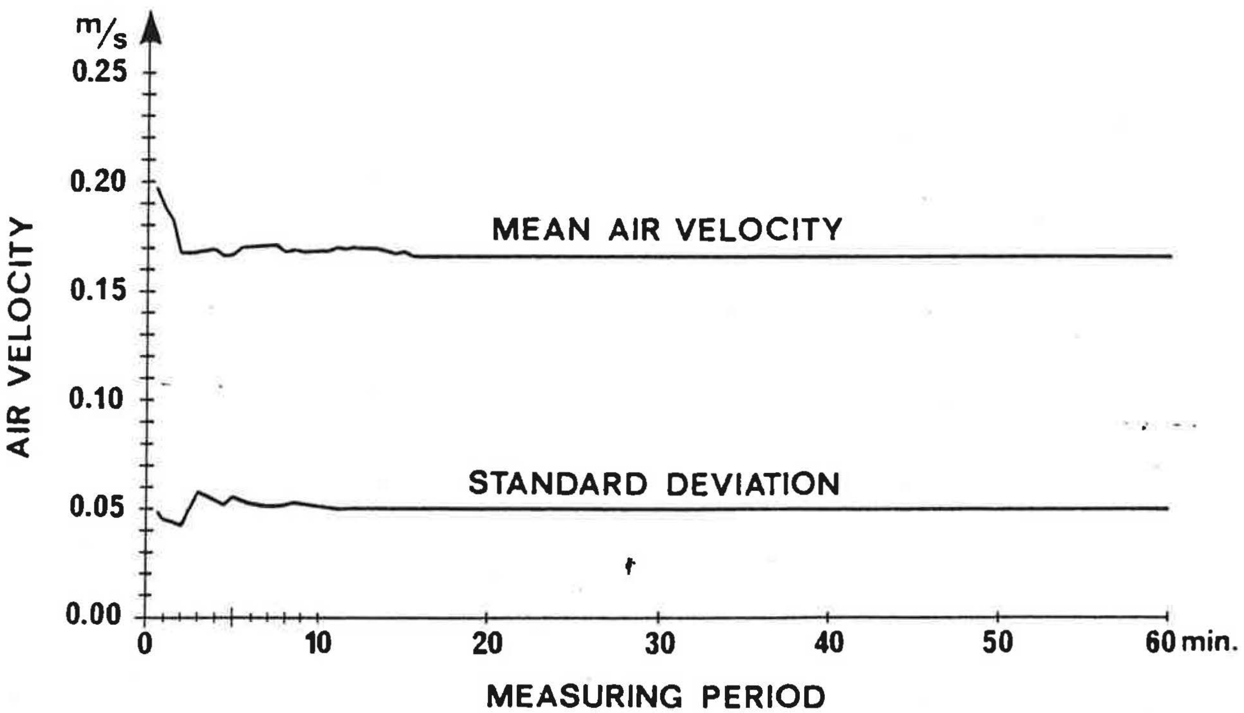


Figure 8. The influence of the length of the measuring period on the mean velocity ($\bar{V}$) and the standard deviation (SD_V) at a measuring point. Each point (t, $\bar{V}$) and (t, SD_V) respectively on the two curves indicates the mean velocity ($\bar{V}$) or the standard deviation (SD_V) in the period 0 - t

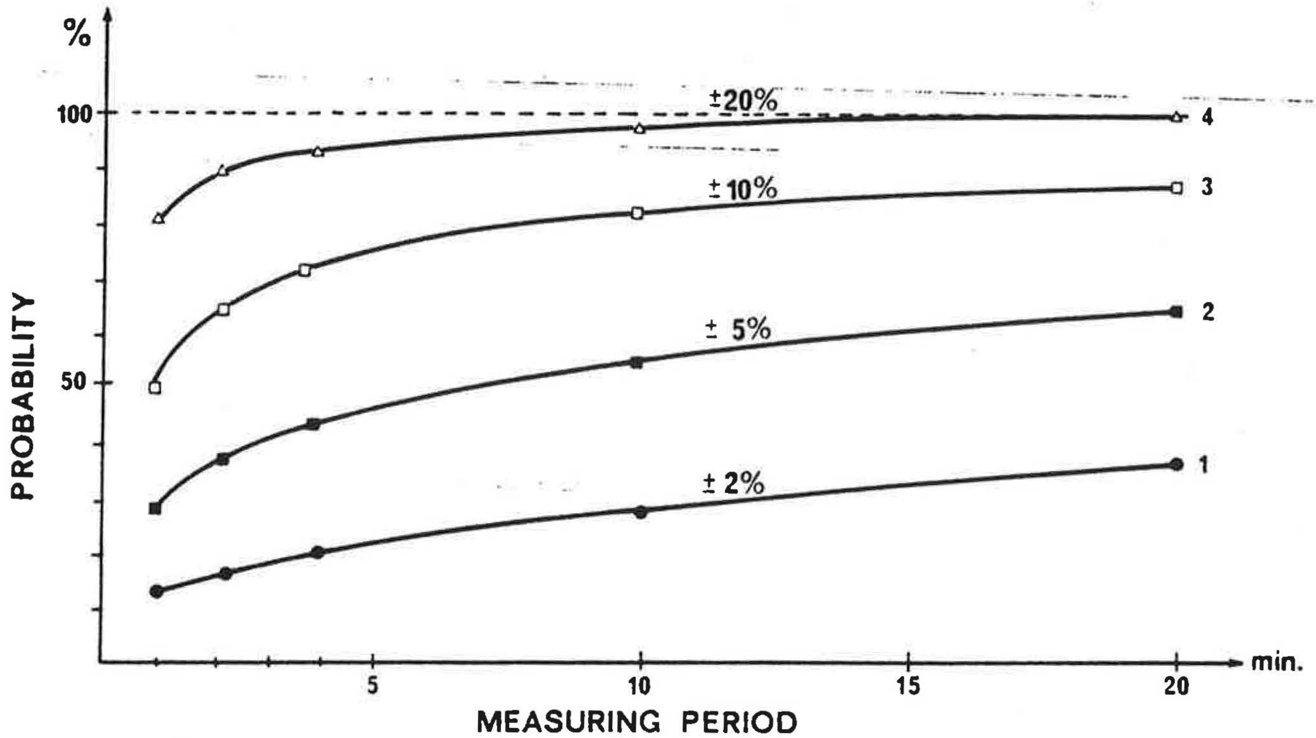


Figure 9. The influence of the measuring period on the accuracy of the mean velocity calculated. Curves 1-4 indicate the probability of the mean velocity determined in a certain measuring period deviating less than ±2%, ±5%, ±10%, or ±20%, respectively, from the mean velocity determined during an "infinitely" long measuring period (60 minutes)

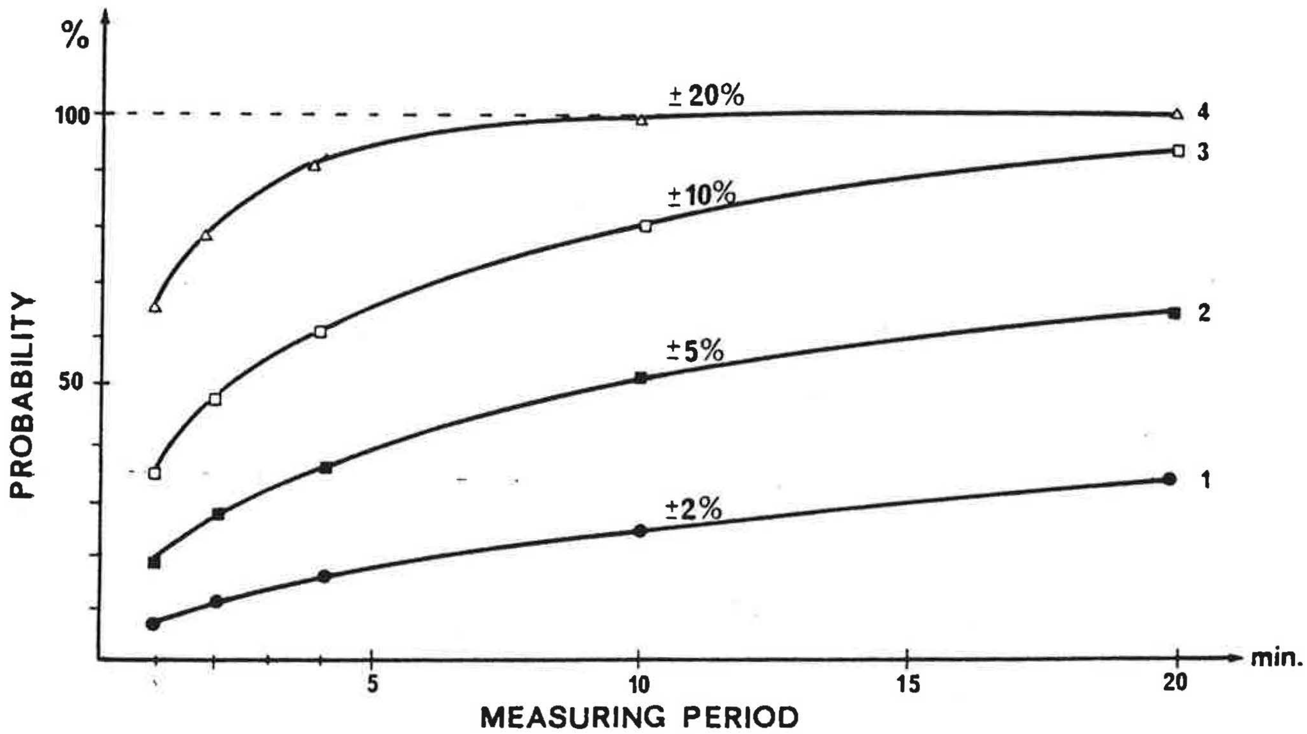


Figure 10. The influence of the measuring period on the accuracy of the standard deviation on velocity calculated. Curves 1-4 indicate the probability of the standard deviation determined in a certian measuring period deviating less than ±2%, ±5%, ±10%, or ±20% from the standard deviation determined during an "infinitely" long measuring period (60 minutes)

DISCUSSION

P.L. MILLER, Mech. Eng. Dept., Kansas State Univ., Manhattan: Did you state that there was a linear relationship between SD and mean velocity? What was that relationship? Over what range of mean velocities were your tests made?

J. THORSHAUGE: By means of linear regression analysis, the relationship between SD and mean velocity was estimated. The regression equations are given in Tab. 3. The mean velocities in the ventilated spaces range from 0.05 m/s to 0.40 m/s.

R.L. HICKS, Ontario Hydro, Tononto, Canada: Is the measuring instrument specially built or commercially available? Was the probe oriented for maximum reading?

THORSHAUGE: The measuring instrument is commercially available. The probes were not oriented for maximum reading but always placed horizontal 0.1 m, 0.6 m, and 1.1 m above floor level.

N. BUCKLEY, Broan Manufacturing, Hartford, WI: What is the response time of the velocity measuring device? Over what time cycle were readings taken?

THORSHAUGE: The response time for the velocity measuring device is 0.03 sec, and the readings were taken approximately four and one half times per second.

G.Y. ACHAKJI, National Resch. Council of Canada, Ottawa: During the air velocity measurements, were there any measurements taken for air temperature and humidity in the different ventilated spaces?

THORSHAUGE: During the air velocity measurements, the room temperature and the relative humidity were only measured once. The room temperature rnaged from 20°C to 24°C and the relative humidity ranged from 35 percent to 45 percent.