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Air Turbulence and Sensation of Draught

P. O. FANGER, A. K. MELIKOV, H. HANZAWA* and J. RING**

Laboratory of Heating and Air Conditioning, Technical University of Denmark, DK-2800 Lyngby (Denmark)

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SUMMARY

The impact of turbulence intensity (Tu) on sensation of draught has been investigated. Fifty subjects, dressed to obtain a neutral thermal sensation, were in three experiments exposed to air flow with low (Tu<12%), medium (20%<Tu<35%) and high (Tu>55%) turbulence intensity. In each experiment the sedentary subjects were exposed to six mean air velocities ranging from 0.05 m/s to 0.40 m/s. The air temperature was kept constant at 23 °C. They were asked whether and where they could feel air movement and whether or not it felt uncomfortable. The turbulence intensity had a significant impact on the occurrence of draught sensation. A model is presented which predicts the percentage of people dissatisfied because of draught as a function of air temperature, mean velocity and turbulence intensity. The model can be a useful tool for quantifying the draught risk in spaces and for developing air distribution systems with a low draught risk.

1. INTRODUCTION

Draught is defined as an unwanted local cooling of the human body caused by air movement. It is one of the most common causes of complaint in ventilated or air-conditioned buildings, automobiles, trains and airplanes. Draught may cause people to stop ventilation systems or to plug up air diffusers. The occupants may also try to counteract the draught by elevating the air temperature, and during the winter this will normally increase energy consumption. Serious draught complaints occur often, although measured velocities are lower than prescribed in existing standards. This is frustrating for the ventilation engineer and a threat to the image of the ventilation and air-conditioning industry in general. To improve conditions it is essential to establish a better understanding of the human response to air movement and to improve the methods for designing air distribution in spaces. This paper deals with the human response.

There are only a few specific draught studies available. Houghten [1] studied ten male subjects exposed to a non-fluctuating, local velocity at the back of the neck and at the ankles. McIntyre [2] used a similar method where he exposed the head region of subjects to a nearly laminar air flow. Berglund and Fobelets [3] have recently reported studies of the responses of 50 subjects exposed to air currents at low levels of turbulence intensity or nearly laminar flow. However, the air flow in ventilated spaces is not normally laminar. Typically the air velocity fluctuates, and Fanger and Pedersen [4] have shown that periodically fluctuating air flow is more uncomfortable than non-fluctuating (laminar) air flow. Exposing subjects to well-defined periodic velocity fluctuations in a climate chamber, they found that the discomfort was at a maximum at velocity frequencies around 0.3 - 0.5 Hz. In real spaces the occupants are not exposed to a well-defined periodically fluctuating air flow. The velocity fluctuates in the random manner characteristic of turbulent flow. Characteristics of turbulent air flow in spaces are defined in Appendix 1. Fanger and Christensen [5] exposed 100 subjects to air velocities with fluctuations believed to be typical for ventilated spaces in practice. During their experiments the mean velocity was varied from 0.05 m/s to 0.40 m/s at air

*Present address: Takenaka Komuten Co. Ltd., Environmental and Mechanical Engineering Unit, Technical Research Laboratory, 5-14, 2-Chome, Minamisuna, Koto-ku, Tokyo, Japan.

**Present address: Department of Physics, Hamilton College, Clinton, New York 13323, U.S.A.

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temperatures of 20, 23 and 26 °C. They presented the results in a draught chart predicting the percentage of dissatisfied occupants as a function of mean velocity and air temperature. Thorshauge [6] and Hanzawa *et al.* [7] have identified the velocity fluctuations occurring in practice through measurements in numerous spaces ventilated in different ways. Similar studies were later performed in unventilated spaces heated by different methods by Melikov *et al.* [8]. They found a wide range of turbulence intensities between 10% and 70% occurring in the field.

The purpose of the present study is to investigate the impact of turbulence intensity on the sensation of draught. It should be seen as an extension of the previous study by Fanger and Christensen [5] where one level of turbulence was investigated. The present research studies whether turbulence intensity should be considered along with mean velocity and temperature when assessing the risk of draught.

2. EXPERIMENTAL PLAN

The idea in the experiments was to use the same protocol as Fanger and Christensen [5], varying the turbulence intensity instead of the air temperature.

In the experiments 50 subjects were exposed to air flow with three different levels of turbulence intensity. The air temperature was maintained at 23 °C. The subjects were exposed to an increasing mean velocity up to 0.40 m/s. Each subject was studied during three experiments at low turbulence ($Tu<12\%$), at medium turbulence ($20\%<Tu<35\%$) and at high turbulence ($Tu>55\%$). The aim in all three experiments was to keep the subject's body as a whole thermally neutral by modifying clothing. Some adaption of clothing will probably also take place in many cases in practice. During the first hour of each experiment the subject was therefore encouraged to modify his clothing so that he felt thermally neutral. During the remaining 1.5 hours clothing was constant and the subject was exposed to six different levels of the mean velocity as shown in Fig. 1. The order in which each subject was exposed to six velocity levels (see Fig. 1) was selected to avoid having

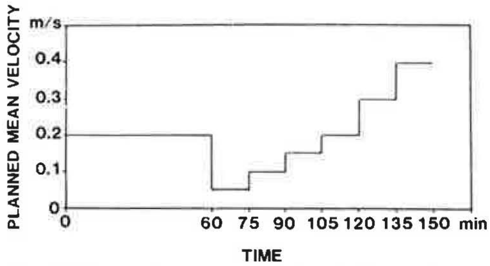

Fig. 1. Planned mean velocity during each experiment.

exposure to high and maybe rather unusual air velocities first, perhaps influencing the assessment of succeeding lower velocities. Thus the sequence established the level at which discomfort was first sensed.

3. FACILITIES

The same laboratory space used by Fanger and Christensen [5] was modified to function as a draught chamber in the present experiments. Figure 2 shows a plan of the room, 6 m × 6 m × 3 m, which had one outside wall with no windows. The other three walls were light indoor partitions. The ceiling was suspended, the lighting fixtures being placed level with the ceiling. The floor was concrete, covered with linoleum.

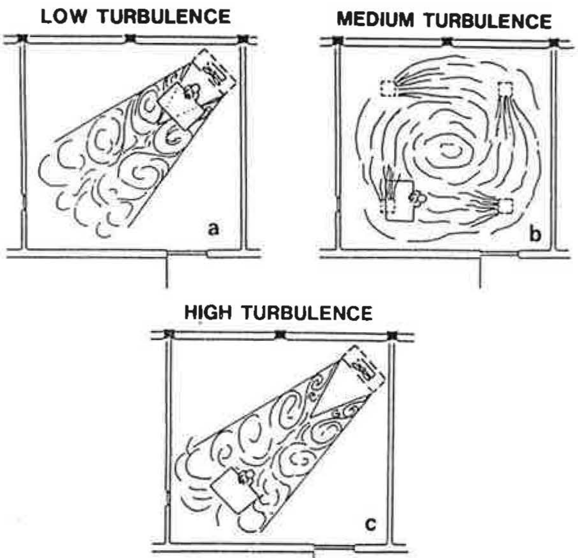

Fig. 2. The experimental set-up in the draught chamber when a subject was exposed to: (a) low turbulent, (b) medium turbulent, and (c) high turbulent air flow.

During the three experiments with different levels of turbulence intensity the subject was seated at the locations shown in Fig. 2(a, b, c). In an adjacent control room the observer could watch the subject through a small observation window and communicate with him/her by means of an intercom. All instruments were situated in the control room.

As in the studies by Fanger and Christensen [5] a flow direction from behind the subject was provided. This seems to be the direction at which humans are most sensitive [9]. The low and high turbulence was established by a jet from an air box (1×1.8 m^2) with two axial fans and several perforated plates to make the air flow uniform. By seating the subject in the core of the jet close to the air box, he or she was exposed to low turbulent air flow (Fig. 2(a)). To establish the high turbulence the subject was seated 5 m from the box (Fig. 2(c)) where the air flow was naturally turbulent with an intensity around 40 - 50%. To increase the turbulence intensity further to above 55%, the speed of the fan wheel was changed randomly by modifying the voltage to the electromotors. The medium turbulence intensity in the space was established by the ventilation system similar to the system described by Fanger and Christensen [5]. For this purpose, four plane, quadratic diffusers were situated at the ceiling. Three sides of each diffuser were covered by tape so that the air was supplied to the space as shown in Fig. 2(b). In this way the subject was exposed to a mainly horizontal airflow from behind. The direction of the flow was checked by smoke experiments.

The mean velocity at the position of the subject at the neck level was controlled. The air temperature in the room around the subject was kept constant at 23 °C by means of two small electric convectors placed at the walls. During spring conditions it was necessary in some cases to cool the room by supplying cooled air from the air-conditioning system.

The air velocity, turbulence intensity and air temperature were measured at points 0.1 m, 0.6 m and 1.1 m above the floor in a vertical line 0.15 m behind the neck of the subject. At this distance the temperature and the velocity field were undisturbed by free convection currents from the human body [10]. At these locations the airflow characteristics were measured by a Brüel & Kjær (B&K) indoor climate analyser type 1213 and a DANTEC Multichannel flow analyser type 54N10. The two instruments have omnidirectional temperature-compensated probes with a time constant of 0.1 s. The analog signal from the B&K probe located at level 1.1 m was recorded on a tape recorder (B&K-7005) and later analysed by B&K dual channel signal analyser type 2332. The air temperature at the three levels was measured by DANTEC probes. During all the experiments the analog signals for the instant velocity from the two instruments were recorded on a pen recorder. By observing the pen recorder, the mean velocity was manually controlled to maintain the planned value shown in Fig. 1. The two instruments were connected with a microcomputer for collecting the data from the measurements. Figure 3 shows a diagram of the measuring and calculating equipment used.

To mask changes in the aerodynamic noise level, when the mean velocity was changed, fan noise was generated over four loudspeakers in the draught chamber. The subject was thus exposed to a constant noise level independent of the air flow and velocity.

The mean radiant temperature was approximately equal to the air temperature during the experiments. The air humidity was not controlled. The humidity ratio varied with the season and was between 7 and 9 g/kg corresponding to a range of 40 - 60% relative humidity.

4. SUBJECTS

Fifty persons (25 males and 25 females) served as subjects in the experiments, most of them being university students. Only persons in good health were allowed to participate. All subjects were volunteers who were paid for taking part in the experiments. Each subject participated in three 2.5-h experiments on three different days. The three experiments took place at the same time of the day, either at 8:45 - 11:15, 11:45 - 2:15, 2:45 - 5:15 or 5:45 - 8:15. The 375 experimental hours took place during the winter and the spring of 1986.

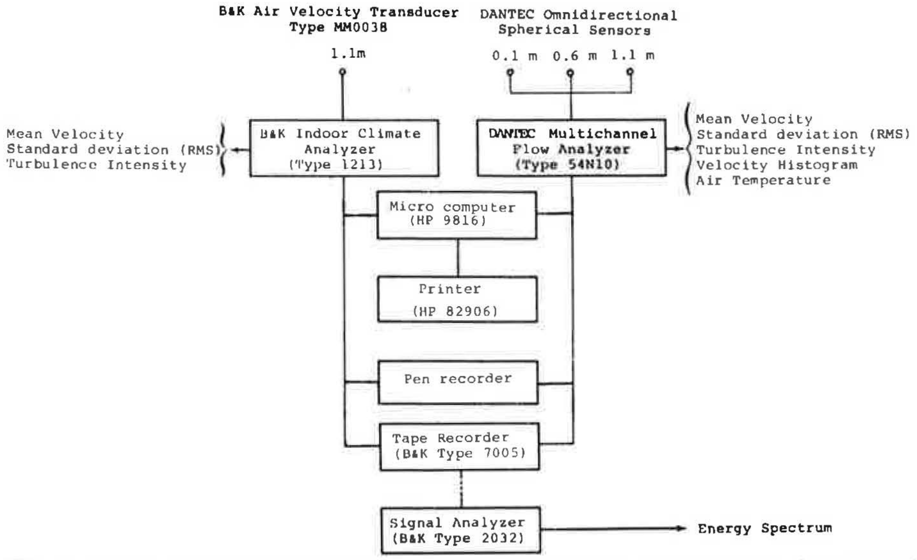

Fig. 3. System of instruments for registration and analysis of the airflow characteristics.

TABLE 1

Anthropometric data for the subjects

Sex	No. of subjects	Age (years)	Height (m)	Weight (kg)	Skin area (m^2)
Females	25	21 ± 3	1.69 ± 0.07	60.4 ± 7.8	1.69 ± 0.13
Males	25	22 ± 2	1.81 ± 0.06	71.4 ± 8.4	1.90 ± 0.12
Females and males	50	22 ± 2	1.75 ± 0.09	65.9 ± 9.8	1.79 ± 0.17

The subjects were instructed to eat normally before arrival at the laboratory and to have had a good night's sleep. No intake of alcohol or drugs were allowed during the 24 hours prior to each experiment. The subjects were asked to wear normal clothing, but they were not permitted to wear boots, gloves, a sweater or a blouse with a high collar or a scarf that would protect the neck from draught.

Anthropometric data for the subjects are listed in Table 1.

5. EXPERIMENTAL PROCEDURE

The subjects reported 15 min prior to the commencement of the experiment, and it was ascertained that they did not feel sick. They were informed about the experimental procedure, and the questionnaires that had to be filled in during the experiment were explained. During the experiment the subjects were allowed to read, write or engage in some form of handwork. No eating was allowed.

During the experiment the mean velocities shown in Fig. 1 were aimed for. During the first hour the mean velocity was kept at 0.20 m/s, which is approximately the average of the velocities maintained during the last 1.5 h of the experiment. During the first hour the subject was encouraged every 10 min to modify his or her clothing if he or she felt warm or cool. Extra clothing was available in the draught chamber. During the last 1.5 h of the experiment no modification of clothing was allowed. The subject was then exposed to six 15-min periods with increasing mean velocities as shown in Fig. 1, and the turbulence intensity was kept at one of the investigated three levels. At each velocity level the subject was asked at 5, 10 and 15 min after the beginning of the period whether he or she had felt an air movement during the previous 5 min, whether it was uncomfortable, and where it was felt (questionnaire B, Fig. 4). At the end of each velocity period and every

QUESTIONNAIRE A

Time: ....

Name: ....

I feel:

- *cold*
- *cool*
- *slightly cool*
- *neutral*
- *slightly warm*
- *warm*
- *hot*

Please mark on the scale

QUESTIONNAIRE B

Time: ....

Name: ....

During the past 5 min. have you noticed any movement of air (since you last completed this questionnaire)? *no* ☐ *yes* ☐

If yes, do you find the air movement uncomfortable? *no* ☐ *yes* ☐

Where do you notice the air movement? *face* ☐ *neck* ☐ *hands* ☐ *feet* ☐

other places ....

Fig. 4. Questionnaire A concerning thermal sensation and questionnaire B concerning perception of air movement.

Time min	Mean Vel. m/s	Questionnaire A	Questionnaire B	Modify Clothing
10		×		×
20		×		×
30	0.20	×		×
40		×		×
50		×		×
60				
	<0.05		× ×	
75		×	×	
	0.10		× ×	
90		×	×	
	0.15		× ×	
105		×	×	
	0.20		× ×	
120		×	×	
	0.30		× ×	
135		×	×	
	0.40		× ×	
150		×	×	

Fig. 5. Schedule of each experiment.

10 min during the first hour, the subject was asked about general thermal sensation (questionnaire A, Fig. 4), and for the previous velocity period the mean velocity, the velocity histogram, the standard deviation of the velocity fluctuations, the turbulence intensity and the mean temperature of the air were determined. At the end of the experiment the subject was asked to list the garments he or she was wearing. The schedule for the experiment is shown in Fig. 5.

6. RESULTS

The mean velocity and the turbulence intensity during each of the six 15-min velocity periods were determined for the 150 experiments. The mean velocities at head level were then divided into classes as listed in Table 2. The mean values of each velocity class for the three levels of turbulence

TABLE 2

Velocity classes and measured mean velocities within each class at three levels of turbulence. Standard deviation of the mean velocity is listed also

Velocity class (m/s)	Measured mean velocity (m/s)		
	Low turbulence	Medium turbulence	High turbulence
$\bar{v}<0.075$			
$0.075<\bar{v}<0.125$	0.100 ± 0.004	0.103 ± 0.004	0.104 ± 0.010
$0.125<\bar{v}<0.175$	0.150 ± 0.003	0.147 ± 0.004	0.154 ± 0.011
$0.175<\bar{v}<0.25$	0.200 ± 0.003	0.203 ± 0.007	0.208 ± 0.013
$0.25<\bar{v}<0.35$	0.302 ± 0.002	0.304 ± 0.005	0.298 ± 0.020
$0.35<\bar{v}$	0.404 ± 0.004	0.400 ± 0.009	0.396 ± 0.021

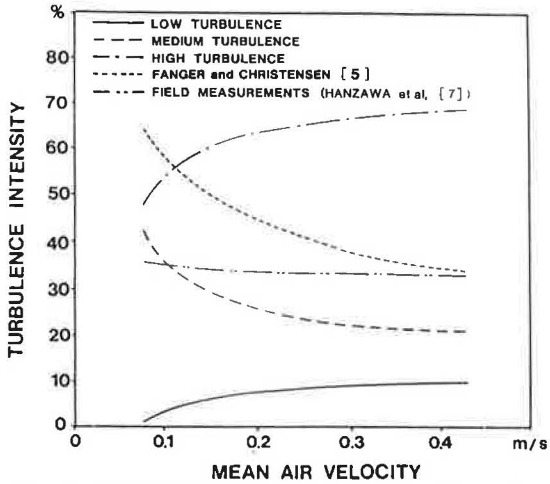

Fig. 6. Turbulence intensity as a function of mean velocity at head level during the experiments. Results from previous draught experiments and from field measurements in typically ventilated spaces are plotted as well.

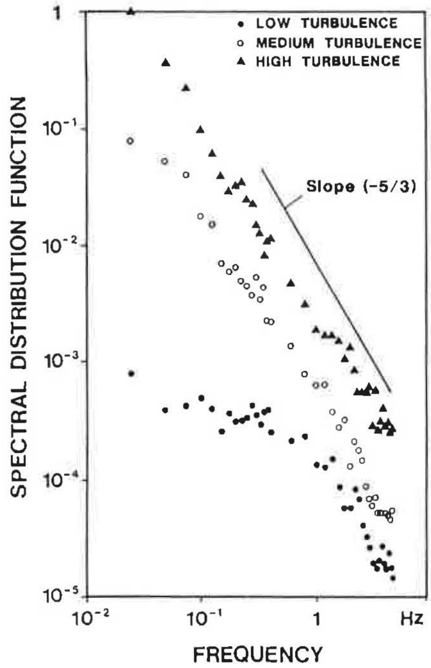

Fig. 8. Typical spectra of the velocity fluctuations during the three experiments. Vertical axis is made dimensionless by dividing by the turbulence energy measured in the case with high turbulence at 0.025 Hz.

intensity were close to the planned values shown in Figs. 1 and 5. In Table 2 the standard deviation of the mean velocity during the experiments with all 50 subjects is listed as well. During the three experiments, the subjects were exposed to the same mean velocity at three levels of turbulence intensity.

In Fig. 6 the turbulence intensity has been plotted as a function of the mean velocity. Earlier results from Fanger and Christensen's [5] draught study and the field measurements of Hanzawa *et al.* [7] are presented in Fig. 6 as well. The turbulence intensity was not independent of the mean velocity. It increased with velocity at high and low turbulence intensity while it decreased at medium turbulence intensity. Figure 7 shows typical samples of instantaneous velocity. Energy spectra of the velocity fluctuations with three levels of turbulence intensity are shown in Fig. 8. In the case of low turbulence, the energy distribution remained at a low but approximately constant value over a wide

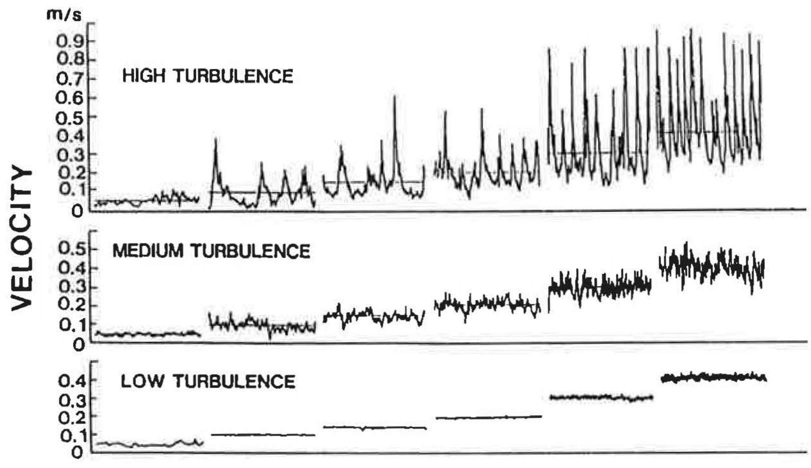

Fig. 7. Samples of velocity fluctuations at six mean velocities and three different turbulences. Each sample is taken during a period of 5.5 min.

range of frequencies. The shape of the energy spectra curve for high turbulence is similar to a fully developed turbulent flow with a −5/3 power law dependence on frequency. Most of the turbulent energy was concentrated at low frequencies.

During the present experiments the subjects were exposed to air flow at three levels of the turbulence intensity. The airflow conditions were the same for all subjects. A comparison of the air flow during the present experiments and in ventilated spaces in practice is discussed in Appendix 2, which also discusses the reproducibility of the air flow in the experiments.

The main question to each subject was whether and where he or she had felt any air movement, and if yes, whether this air movement was uncomfortable. This question was asked three times during the 15-min period, at each velocity level. We required at least two answers out of three as "uncomfortable" to classify the velocity as draught, i.e., to classify the subject as "dissatisfied" at that particular condition.

Figure 9 shows the percentage of subjects who felt draught at the head region as a function of the mean velocity at the neck. The head region comprises the head, the neck and the shoulders. The results from Fanger and Christensen's [5] draught study are plotted as well. The lines in Fig. 9 are based on a probit analysis [11] of the percentage of subjects feeling draught versus the square root of the mean velocity. The square root was selected since heat transfer by forced convection is approximately proportional to the square root of the mean velocity. There was a significant influence of the turbulence intensity on the percentage feeling draught.

The responses at the head region were analysed to identify a possible impact on draught sensitivity of sex, length of hair, or of the subjects' self-estimation of his/her draught sensitivity.

In Fig. 10 the responses for men and women are compared. Women seem to be slightly more draught-sensitive than men at lower velocities, while this difference disappears at higher velocities.

The hair may provide some protection from the air velocity, especially at the back of the neck. The length of the hair of each subject was categorized as long, short or medium. The draught percentages for each of these three categories are shown in Fig. 11. The results do not show any impact of the length of the hair on the percentage of dissatisfied.

All subjects who participated in the experiments were asked to categorize themselves into three groups: more sensitive to draught than others, equally sensitive to draught as others, and less sensitive to draught than others. The number of subjects classified in these three categories is listed in Table 3.

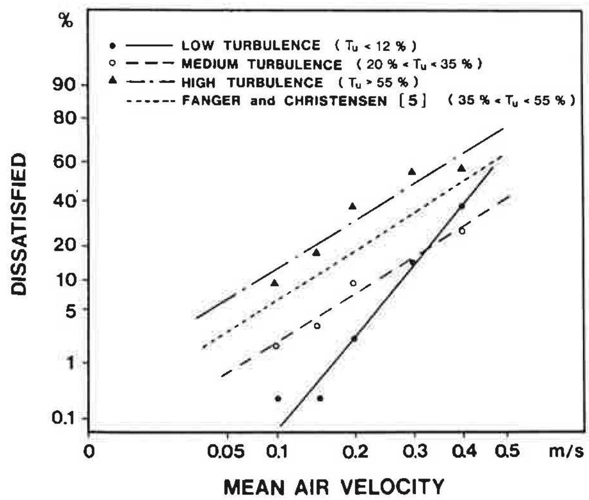

Fig. 9. The percentage of dissatisfied subjects, i.e., those feeling a draught at the head region, as a function of the mean air velocity at the three levels of turbulence intensity. The points with 0% dissatisfied have been plotted at 0.2%.

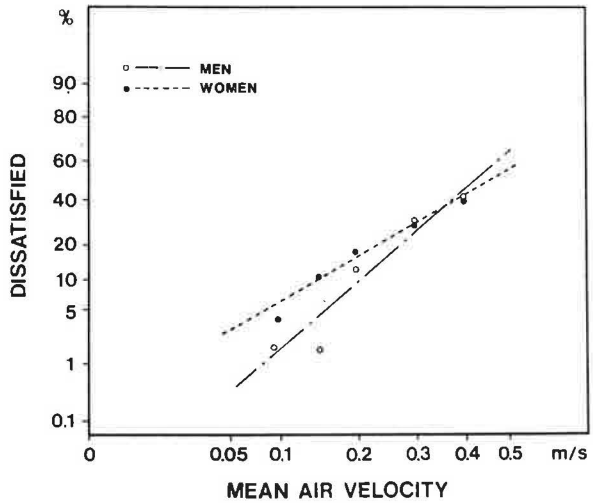

Fig. 10. The percentage of dissatisfied subjects, i.e., those feeling a draught at the head region, as a function of the mean air velocity. Men and women are shown separately. Data at low, medium and high turbulence are pooled.

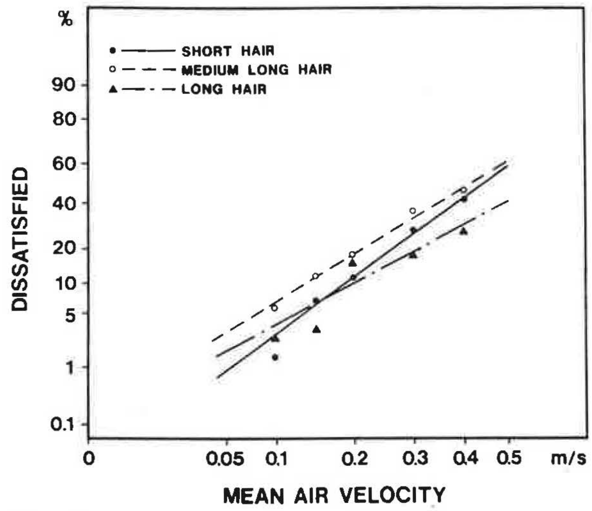

Fig. 11. The percentage of dissatisfied subjects, i.e., those feeling a draught at the head region, as a function of the mean air velocity. Subjects with short, medium and long hair are shown separately. Data at low, medium and high turbulence are pooled.

TABLE 3

Number of subjects within different categories

Subjects assessing themselves	Number of subjects
More sensitive to draught than others	8
Equally sensitive to draught as others	29
Less sensitive to draught than others	13

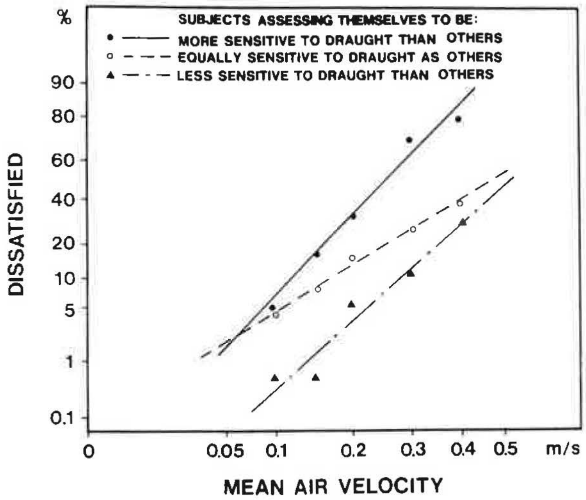

Fig. 12. The percentage of dissatisfied subjects, i.e., those feeling a draught at the head region as a function of the mean air velocity. Subjects assessing themselves to be more sensitive to draught than others, equally sensitive to draught as others, and less sensitive to draught than others are shown separately. Data at low, medium and high turbulence are pooled.

Figure 12 presents the percentage feeling draught for these three groups of people. There is a good agreement between the subjects' self-estimation of their draught sensitivity and their real sensitivity.

At each velocity and turbulence intensity level the subject was asked whether he or she could sense any air movement. Figures 13 - 16 show the percentage sensing air movement as a function of the mean velocity. There was no significant impact of the sex, the length of the hair or the self-estimated draught

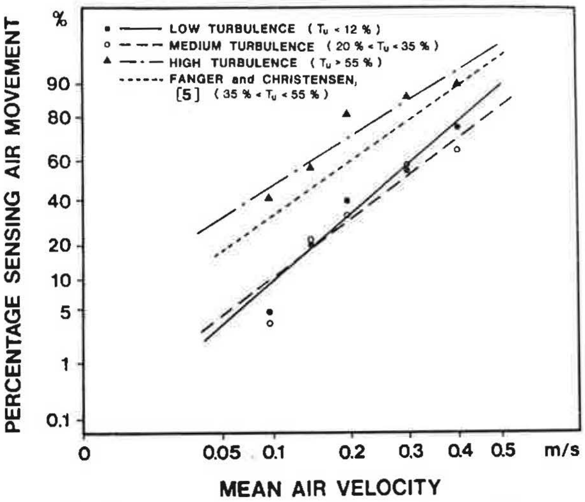

Fig. 13. The percentage of subjects who could sense an air movement at the head region as a function of the mean air velocity, at low, medium and high turbulence. Results from previous draught experiments are shown as well.

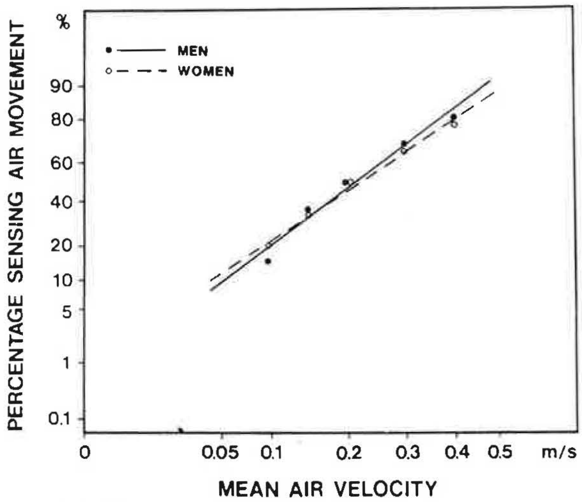

Fig. 14. The percentage of subjects who could sense an air movement at the head region as a function of the mean air velocity. Men and women are shown separately. Data at low, medium and high turbulence intensity are pooled.

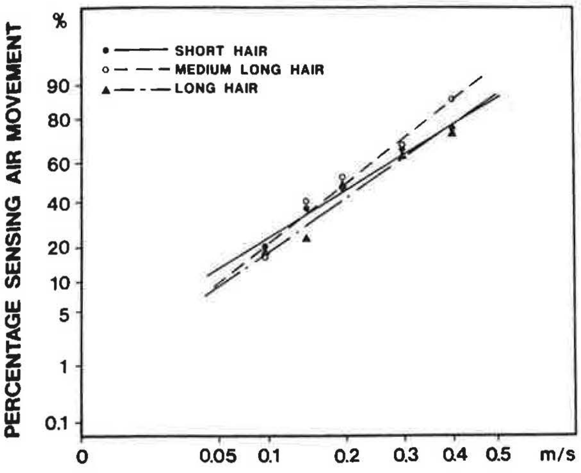

Fig. 15. The percentage of subjects who could sense an air movement at the head region as a function of the mean air velocity. Subjects with short, medium and long hair are shown separately. Data at low, medium and high turbulence are pooled.

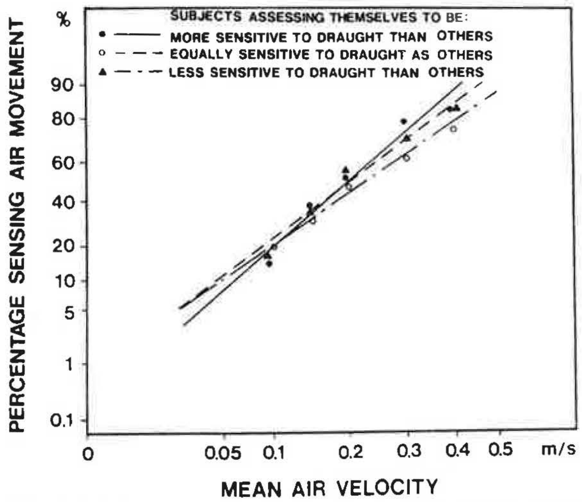

Fig. 16. The percentage of subjects who could sense an air movement at the head region, as a function of the mean air velocity. Subjects assessing themselves to be more sensitive to draught than the others, equally sensitive to draught as others, and less sensitive to draught than others are shown separately. Data at low, medium and high turbulence are pooled.

sensitivity of the subject on the sensing of the air movement.

Complaints at other parts of the body than the head region were also registered. Next to the head region, the arms (including hands) and the feet (including ankles) were the regions with most complaints. But the corresponding mean velocities were also lower than, and the turbulence intensity different from the head level. In Table 4 the percentage

TABLE 4

Mean air velocity, $\bar{v}$, turbulence intensity, Tu, air temperature, t_a, and percentage of dissatisfied people, PD, due to draught felt at the head. $\bar{v}$ and Tu are measured at 1.1 m. The results given below the line are from Fanger and Christensen [5]

HEAD			
Mean air velocity (m/s)	Turbulence intensity (%)	Air temperature (°C)	Percentage dissatisfied (%)
0.100	3	23	0
0.150	5	23	0
0.200	8	23	2
0.302	9	23	16
0.404	10	23	32
0.103	35	23	0
0.147	30	23	4
0.203	26	23	10
0.304	23	23	17
0.400	21	23	27
0.104	55	23	9
0.154	61	23	18
0.202	64	23	39
0.298	66	23	56
0.396	68	23	58
0.096	58	23	5
0.150	50	23	12
0.201	44	23	21
0.299	38	23	33
0.393	34	23	51
0.096	43	26	2
0.150	40	26	11
0.204	38	26	16
0.299	33	26	26
0.393	30	26	30
0.096	51	20	16
0.150	44	20	24
0.207	40	20	35
0.299	35	20	55
0.393	32	20	65

of dissatisfied among the 50 subjects is listed at the mean velocities and mean turbulence intensities they were exposed to at the head. In Table 5 the same information is given for the arms and feet.

The thermal sensation votes for the entire body during the experiments are shown in Fig. 17. The aim was to maintain a neutral thermal sensation by modifying clothing during the first hour of the experiment. This was fulfilled during the experiments with three levels of turbulence intensity. During the last hour of the experiments there was a slight decrease of the thermal vote when exposed to higher velocities. The results agree

TABLE 5

Mean air velocity, $\bar{v}$, turbulence intensity, Tu and percentage of dissatisfied people, PD, due to draught at arms and feet at 23 °C air temperature. $\bar{v}$ and Tu were measured at 0.6 m for the arms and 0.1 m for the feet

ARMS			FEET		
Mean air velocity (m/s)	Turbulence intensity (%)	Percentage dissatisfied (%)	Mean air velocity (m/s)	Turbulence intensity (%)	Percentage dissatisfied (%)
0.012	18.1	4	0.058	44	4
0.156	7.83	8	0.078	41.6	2
0.199	6.8	8	0.098	41.3	4
0.271	7.6	14	0.121	37	14
0.352	8.4	20	0.150	34.6	16
0.113	33.9	8	0.101	44	2
0.162	20.7	4	0.150	24.7	4
0.202	17.5	2	0.185	18.9	4
0.264	17.8	14	0.231	18.1	10
0.345	18.9	24	0.287	17.8	14
0.113	62.7	4	0.109	51.5	6
0.156	62.5	8	0.138	54.6	4
0.201	63	20	0.181	55.9	14
0.271	61.1	32	0.225	54.6	24
0.334	57.3	32	0.258	52.1	20

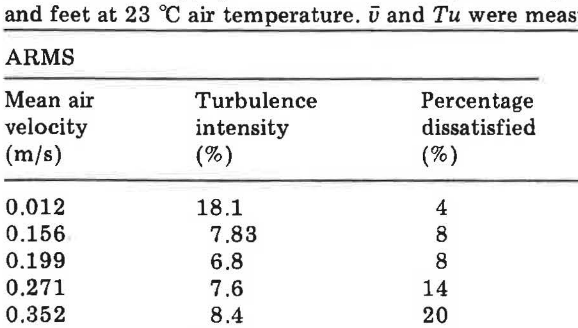

Fig. 17. Mean thermal sensation vote observed during the experiments at low, medium and high turbulence. The dotted line shows the thermal vote during the previous draught experiments.

TABLE 6

Estimated average insulation of the clothing worn by the subjects during the final 1.5 h of the experiments

Turbulence	Females (clo)	Males (clo)	Females and males (clo)
Low turbulence	0.72	0.76	0.74
Medium turbulence	0.72	0.77	0.75
High turbulence	0.73	0.77	0.75

with the previous results from Fanger and Christensen's draught study [5]. The estimated clo values of the clothing worn are shown in Table 6.

7. DISCUSSION

Figure 9 shows the importance of turbulence for the sensation of draught. An air flow with high turbulence is felt as a draught by more people than a low turbulent air flow with the same mean velocity and temperature. For a given percentage of people feeling draught, a significantly higher mean velocity can be allowed when the air flow has a low turbulence intensity.

Fanger and Pedersen [4] had found in 1977 that a fluctuating air velocity is felt more uncomfortable than a constant velocity. This was demonstrated in experiments where subjects were exposed to periodic fluctuations of the velocity with different amplitudes and frequencies. The present results confirm that humans seem to dislike velocity fluctuations whether periodic or occurring in the random manner typical for a turbulent flow. The turbulence to which our subjects were exposed had a nature similar to the turbulence actually occurring in ventilated, occupied spaces. This is documented by comparison with the field studies by Hanzawa *et al.* [7] who measured characteristics of the turbulence occurring in ventilated spaces in a wide variety of buildings (displacement ventilation not included). The observed turbulence intensities were in the same range as investigated here, and the spectral frequency distributions of the velocity fluctuations in the field were similar to the observations in the present laboratory study (see Appendix 2).

Why is high turbulence more uncomfortable than low turbulence? One suggestion made by Mayer [12, 13] is that the convective heat transfer grows with increasing turbulence. Madsen [14] suggested that the heat flux as sensed by the thermal receptors in the skin could cause the difference, since the heat flux was shown to increase with growing turbulence. Similarly, we believe that the reason for the discomfort caused by high turbulence could be the fluctuations of the skin temperature. The mean level of the skin temperature will not change significantly during the fluctuations, but the rate of change of the skin temperature with time will be greater at high turbulence. According to Hensel [15] the rate of change of skin temperature with the time initiates signals to the brain. They are probably warning signals, meant to provide an early modification of human behaviour and of the regulatory mechanisms of the body to counteract a cooling process, which in the long run might be a threat to life. During exposure to velocity fluctuations no warning is required but the warning signals will still occur and may explain the draught sensation.

In the present experiments the turbulence was varied while maintaining a constant air temperature of 23 °C. In the previous study by Fanger and Christensen [5] the air temperature was varied from 20 to 26 °C while the turbulence was maintained between the medium and high turbulence level of the present study. The previous study resulted in a draught chart predicting the percentage of people feeling draught as a function of air temperature and mean velocity.

In order to extend this treatment to our new data, we have developed a model which incorporates the convective heat transfer process to link turbulence to skin temperature fluctuations and Hensel's account of thermoreceptors [15] to link thermal sensation to these temperature fluctuations. This theory is then applied to all of the data at 20, 23 and 26 °C from the present and the previous study by Fanger and Christensen [5] as given in Table 4 and the best fit is found. The details of this semi-empirical model are thus determined by the best fit to the data but the general form is determined by physical and physiological principles.

To begin with we assume Hensel's two kinds of thermoreceptor responses, the static and the dynamic. The dynamic depends on the rate of change of skin temperature while the static depends on the level of the skin temperature.

The static response corresponds to laminar air flow which Fanger and Pedersen [4] have shown can cause discomfort. We also know that, in still air, free convective flow exists along the warm human body, so that only if the air velocity is above 0.04 - 0.05 m/s will this layer be penetrated [5].

Thus the static part is:

$$PD_s = a(t_s - t_a)(\bar{v} - 0.05)^b$$

PD is the predicted percentage of dissatisfied caused by draught, a and b are adjustable constants, t_s is the mean skin temperature (°C), t_a is the air temperature (°C) and $\bar{v}$ is the mean air velocity (m/s). The exponent b according to empirical data [16] is in the range 0.4 to 0.7.

The dynamic part ought also to be proportional to $(t_s - t_a)(\bar{v} - 0.05)^b$ as the heat flow from the skin depends on this convective term. Air velocity fluctuations will cause changes in the heat transfer which in turn will cause fluctuations of the skin temperature about its mean value.

We assume for the dynamic part

$$PD_d = c\bar{v}Tu(t_s - t_a)(\bar{v} - 0.05)^b$$

where c is adjustable and $\bar{v}Tu$ is a dependence which is simple and suitable for our data. Note that $PD_d = 0$ if $Tu = 0$ which is the case for laminar flow. Combining the static and dynamic part and assuming a skin temperature of 34 °C for subjects feeling thermally neutral, the mathematical expression of the model is

$$PD = a(34 - t_a)(\bar{v} - 0.05)^b + c\bar{v}Tu(34 - t_a)(\bar{v} - 0.05)^b$$

We then used the experimental data of Table 4 comprising 30 sets of PD and corresponding values of t_a, $\bar{v}$ and Tu. The best fit was found for a = 3.143, b = 0.6223 and

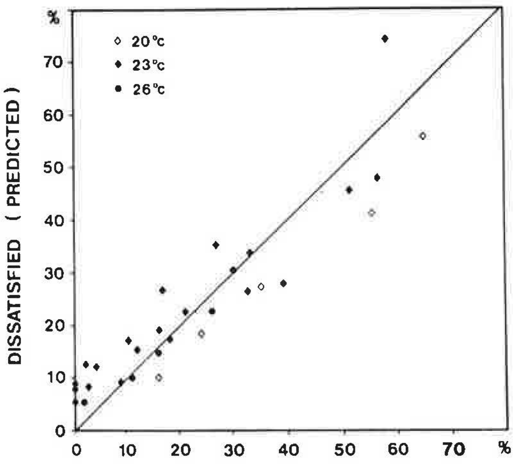

Fig. 18. Comparison of percent dissatisfied predicted by the model with the experimentally measured percent dissatisfied. The line illustrates perfect correlation ($r = 1.00$). The sample correlation coefficient for this scatter plot is $r = 0.96$.

$c = 0.3696$ with a sample correlation coefficient of 0.96. Predicted and observed percentages of dissatisfied are shown in Fig. 18 and the line of perfect correlation ($r = 1.00$) is given for comparison.

The model is thus

$$PD = 3.143(34 - t_a)(\bar{v} - 0.05)^{0.6223} + 0.3696\bar{v}Tu(34 - t_a)(\bar{v} - 0.05)^{0.6223}$$

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

The model is an extension of the Fanger and Christensen [5] draught chart model to include turbulence intensity. In this previous study Tu decreased when $\bar{v}$ was increased. This meant that the impact of $\bar{v}$ was less than in the present new model.

The ranges of the three parameters for the experimental data to which the model was fitted are: $20<t_a<26$ °C, $0.05<\bar{v}<0.4$ m/s and $0<Tu<70\%$. It should also be noted that any $\bar{v}<0.05$ counts as $\bar{v} = 0.05$ and although values of PD>100% are mathematically possible, they are not meaningful and should be counted as 100%.

The main features of the model are shown in Fig. 19 which is a three-dimensional drawing of surfaces of constant percentage dissatisfied (10%, 15% and 20%) with the axes being turbulence intensity, mean velocity and air temperature. Higher percentages of dissatisfied can be seen to be associated with higher Tu, higher $\bar{v}$ and lower t_a. The ranges of these parameters shown are mainly those for which we had experimental data. The exception to this rule is air temperature where a larger range is allowed to show better the shape of the surface.

Figures 20 and 21 give more precisely the curves which result from intersections between planes of constant Tu and the surfaces of PD = 10% and 20% respectively.

We have stressed above, e.g., in the discussion of Fig. 9, the impact of turbulence on dissatisfaction. For the five different mean velocities of the experiment, Fig. 22 exhibits the way in which PD depends on Tu at $t_a = 23$ °C. It is obvious that the effect of

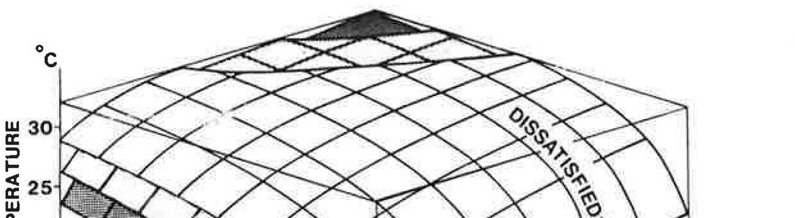

Fig. 19. A three-dimensional representation of the draught-risk model. The surfaces shown correspond to 10%, 15% and 20% dissatisfied respectively. The axes are turbulence intensity, mean air velocity and air temperature.

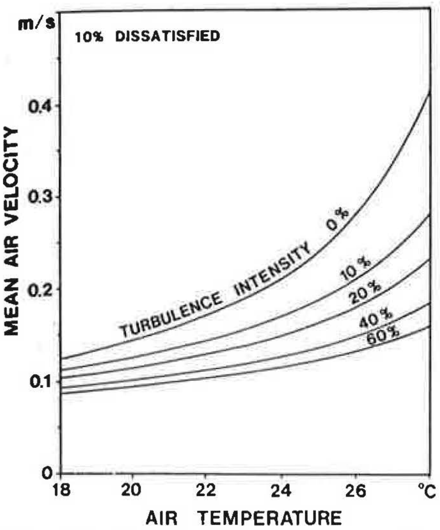

Fig. 20. Combinations of mean air velocity, air temperature and turbulence intensity which will cause 10% dissatisfied. Calculated from the model of draught risk.

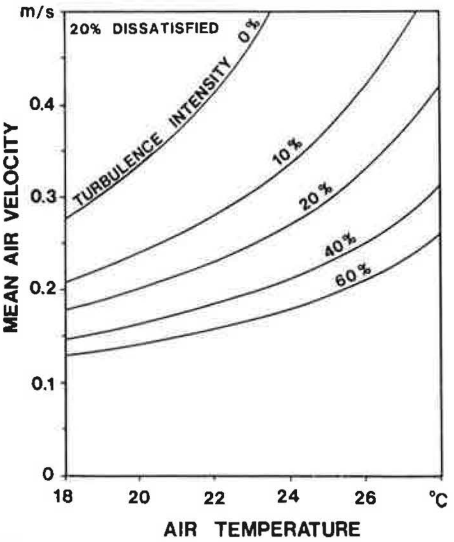

Fig. 21. Combinations of mean air velocity, air temperature and turbulence intensity which will cause 20% dissatisfied. Calculated from the model of draught risk.

turbulence is significant and increases with the mean velocity.

The model developed for the head region was applied to the data observed at the arms and the feet (Table 5). Figure 23 shows the comparison between the predicted and observed percentages of dissatisfied. It is obvious that people were less draught-sensitive at these regions than the head. A higher physiological sensitivity of the head may contribute to this difference but it is obvious that the clothing has played an

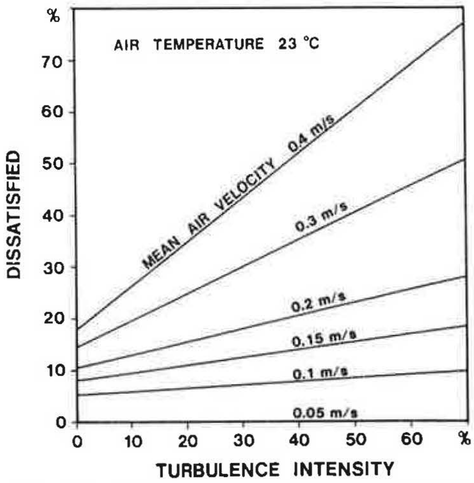

Fig. 22. Percent dissatisfied as a function of turbulence intensity and mean air velocity at the head. Calculated from the model of draught risk. The diagram applies for an air temperature of 23 °C.

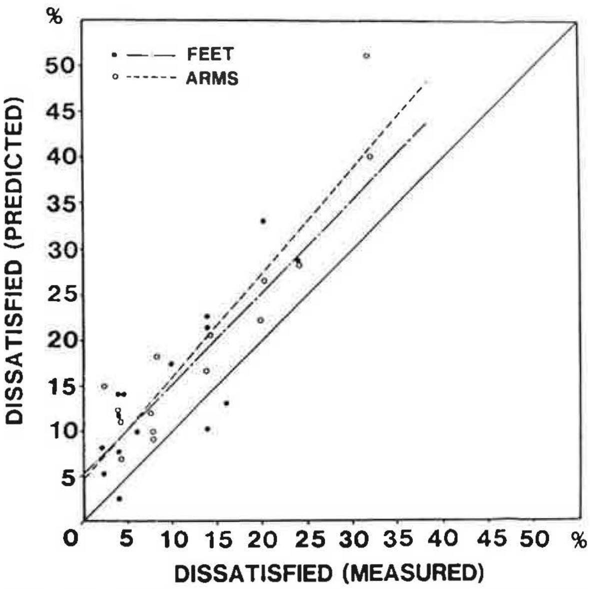

Fig. 23. Comparison of predicted and measured percentages of draught risk for arms and feet. The prediction was done by the draught risk model using measured mean velocities and turbulence intensities at the arms and feet. The solid line represents perfect correlation. The broken lines give the best fits for arms and feet. The correlation coefficient is 0.92 for the arms and 0.82 for the feet. The intercepts are about +5% in both cases.

important role. At the arms, 81% were wearing clothing with long sleeves; 93% had their feet and ankles covered. A clothing layer will damp the thermal impact on the skin of velocity fluctuations and thus decrease the impact of turbulence on draught.

The model predicts the percentage of people dissatisfied due to draught as a function of air temperature, mean velocity and turbulence intensity. For practical applications the model would be useful for predicting the draught risk in spaces for human occupancy. The draught risk may be calculated from measurements of the three variables in the occupied zone. The model may be used for all heights in the occupied zone, although it may tend to overestimate the draught risk at arms and feet level. For people with bare arms and ankles or with nylon stockings, it may be a reasonable approximation to use the model for the head throughout the occupied zone.

The model may also be used to estimate the draught risk from computer calculations of temperature, velocity and turbulence in ventilated spaces. For rating the performance of air distribution systems in spaces, the Air Diffusion Performance Index (ADPI) has frequently been used [24]. The new model offers an updated method of rating the performance of air distribution systems by predicting the draught risk. Systems should be compared at fixed air temperature in the occupied zone, e.g., 22 °C at 0.6 m above the floor.

The strong impact of turbulence on draught risk would obviously provide an incentive to develop air distribution systems which produce low turbulence in the occupied zone. Traditionally, ventilation systems have been designed to establish a good mixing between supply air and room air and high turbulence was an efficient way of promoting mixing. High turbulence could be provided by selecting air jets with high velocity and small outlets. To decrease the draught risk the idea was to situate the outlets far from the occupied zone, so there was sufficient time and distance for the mean air velocity to decrease before reaching the occupants. The effort was concentrated on the mean velocity while nobody considered the significance of turbulence on the sensation of draught.

To decrease turbulence in the occupied zone it seems promising to decrease the velocity of the supply air. Larger outlets and lower velocity mean a lower Reynold's number for the same air supply. This has already been utilized to a certain extent in the new displacement ventilation systems [17]. By introducing the supply air with low velocity directly into the occupied zone, such systems also have a potential for increasing the ventilation efficiency compared to traditional ventilation systems which promote mixing [18]. Systematic studies of turbulence and ventilation efficiency for displacement ventilation and other systems are thus recommended. It would also be useful to study and develop the aerodynamic design of air diffusers to promote low turbulence in the occupied zone.

The present results confirm the high draught sensitivity identified already by Fanger and Christensen [5]. This may explain many complaints occurring in practice although the mean velocity may meet existing comfort standards (International Standards Organization (ISO) [19], American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [20], Deutsches Institut für Normung (DIN) [21]). There is a need to update these standards to include this new insight into the risk of draught.

Models predicting thermal sensation for the body as a whole like the PMV allow quite high velocities [19, 23]. Is this not in contrast to the present results which require low velocities to obtain a small draught risk? No, the present draught model presents an additional requirement to the PMV index. But it should be remembered that the draught phenomenon exists particularly at low human activities, e.g., sedentary. At higher activity levels, e.g., walking, complaints of draught are rare and the PMV index is sufficient to judge thermal comfort.

8. CONCLUSIONS

An air flow with high turbulence causes more complaints of draught than air flow with low turbulence at the same mean velocity and air temperature.

A model of draught risk is presented. It predicts the percentage of people dissatisfied due to draught as a function of air temperature, t_a, mean velocity, $\bar{v}$, and turbulence intensity, Tu (%). The percent dissatisfied, PD, is given by this equation:

$$PD = 3.143(34 - t_a)(\bar{v} - 0.05)^{0.6223} + 0.3696\bar{v}Tu(34 - t_a)(\bar{v} - 0.05)^{0.6223}$$

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

for PD>100% use PD = 100%

The model can be a useful tool for quantifying the draught risk in spaces and for development of air distribution systems with a low draught risk.

There is a need to update the existing standards to include the impact of turbulence intensity on the risk of draught.

ACKNOWLEDGEMENT

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APPENDIX 1

Characteristics of turbulent airflow in spaces

The turbulent air flow in spaces may be characterized by the following parameters.

The *instantaneous velocity*, $v = \bar{v} + v'$, 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

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

The bar denotes averaging over time.

The *standard deviation* of the velocity, equal to the root-mean-square (RMS) of the velocity fluctuation, $(\overline{v'^2})^{1/2}$, 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

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

The *energy spectrum* of the velocity fluctuations $E(n)$, where

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

and $E(n)$ is the density of distribution of $\overline{v'^2}$ in the whole range of frequencies, n. $E(n)$ is known as the spectral distribution function of $\overline{v'^2}$. It is often convenient [22] to consider the wave number $k = 2\pi n/\bar{v}$ instead of the frequency n and to introduce the energy spectrum function $E(k)$ instead of $E(n)$. It appears suitable to define $E(k)$ by

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

so that

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

which is similar to eqn. 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.

APPENDIX 2

The airflow during the experiments

Draught experiments (Fanger and Christensen [5]) have identified the head region as the most draught-sensitive part of the body for persons wearing normal indoor clothing. It was decided to control the mean velocity $\bar{v}$ at 1.1 m above the floor. Analysis of the results for the three levels of the turbulence intensity (50 experiments for each level) provided the regression equations for the standard deviation, $(\overline{v'^2})^{1/2}$ (m/s), of the velocity fluctuations as a function of the mean velocity. These equations are listed in Table 7. The regression equations from Fanger and Christensen's [5] draught study and the field measurements in ventilated spaces of Hanzawa *et al.* [7] are listed in the Table as well. Figure 24 shows these relationships. The line by Hanzawa *et al.* [7] is based

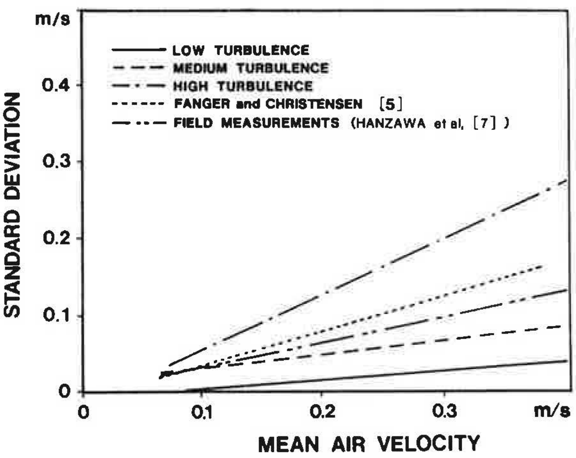


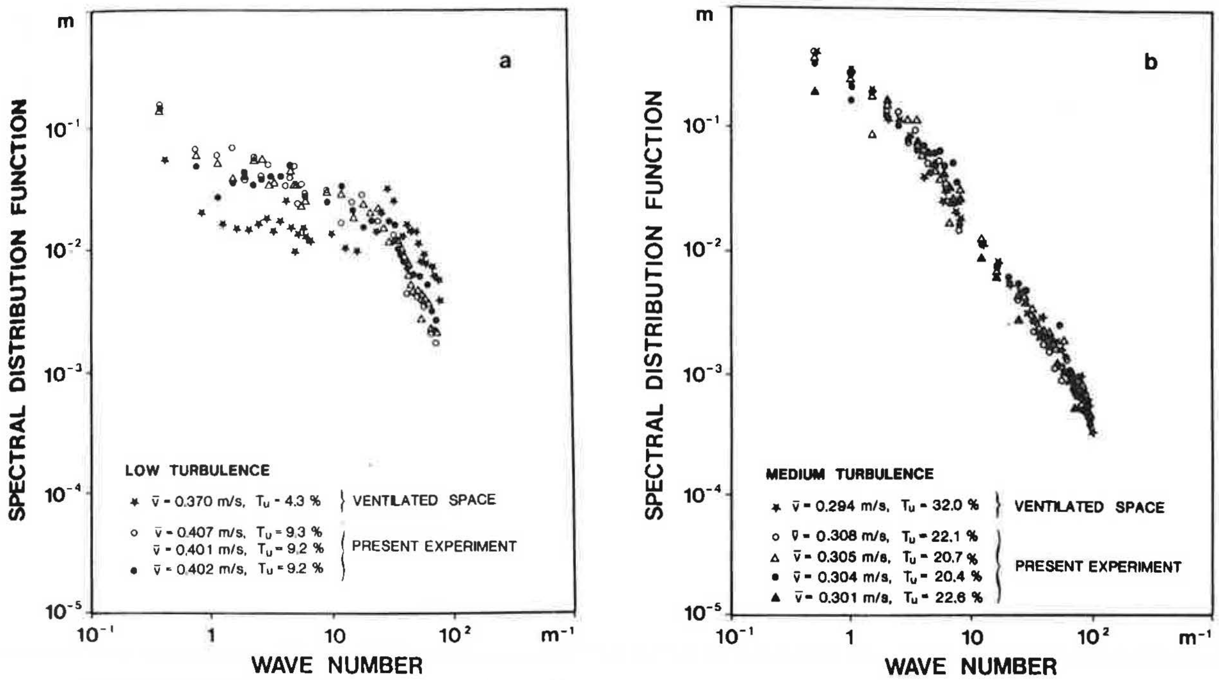
Fig. 24. Standard deviation of the velocity fluctuations as a function of the mean air velocity during the experiments. Results from previous draught experiments and from field measurements in typically ventilated spaces are plotted for comparison.

TABLE 7

Regression equations for the standard deviation of the velocity fluctuations as a function of the mean velocity

Experiment	Regression equation
Present experiments	
Low turbulence	RMS = $0.1218\bar{v} - 0.00846$
Medium turbulence	RMS = $0.1661\bar{v} + 0.01863$
High turbulence	RMS = $0.7278\bar{v} - 0.0185$
Fanger and Christensen [5]	RMS = $0.4029\bar{v} - 0.2764\bar{v}^2 + 0.0175$
Hanzawa, Melikov, Fanger [7]	RMS = $0.328\bar{v} - 0.002$

SPECTRAL DISTRIBUTION FUNCTION



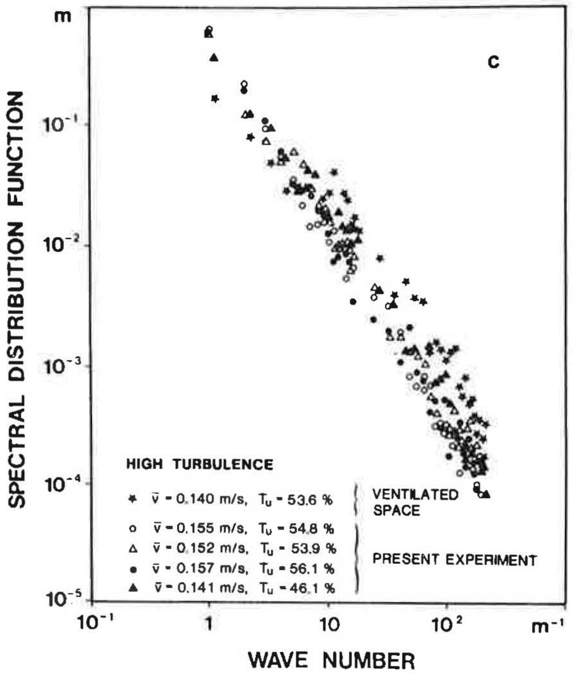
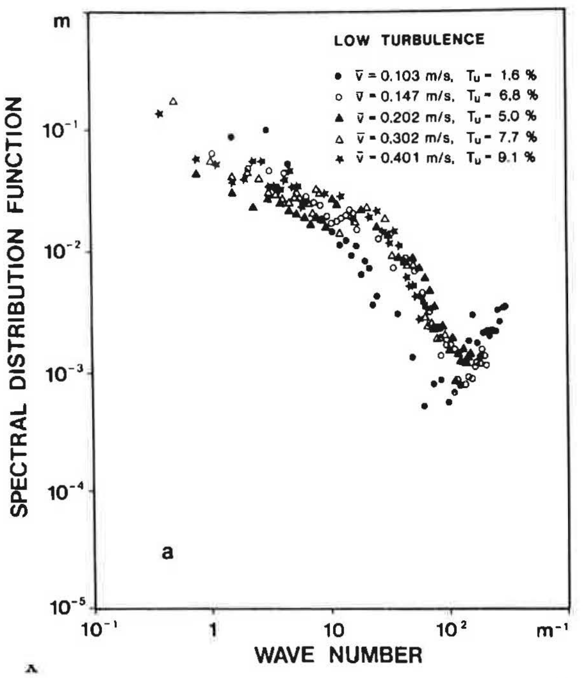
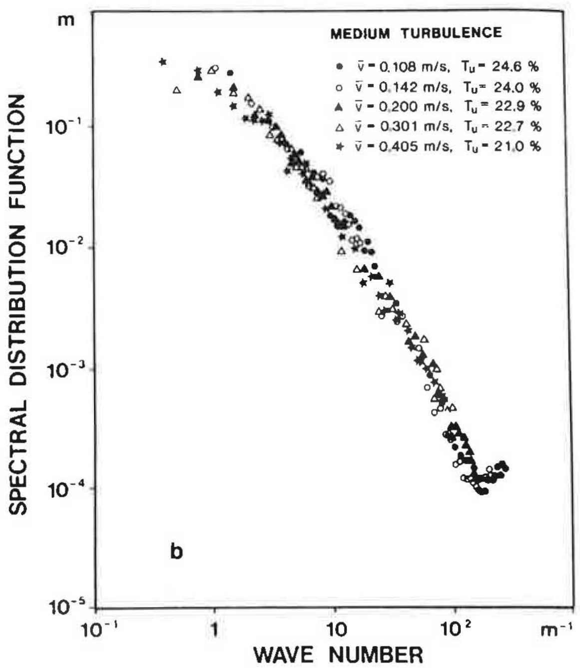


Fig. 25. Comparison of spectra of the velocity fluctuations measured during the present experiments and in ventilated spaces in the field [7]. (a) For low turbulence; (b) for medium turbulence; and (c) for high turbulence.

on the measurements in more than 20 different ventilated spaces. During the field measurement the mean velocity varied from less than 0.05 m/s to 0.40 m/s and the turbulence intensity from 10% to 70%. The present draught experiments and the previous draught experiments by Fanger and Christensen [5] cover the same region of the mean velocity and the turbulence intensity as measured in the field.

During the present draught experiments, with a few exceptions, the planned mean velocities and turbulence intensities were established. 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 turbulent intensity but different frequencies





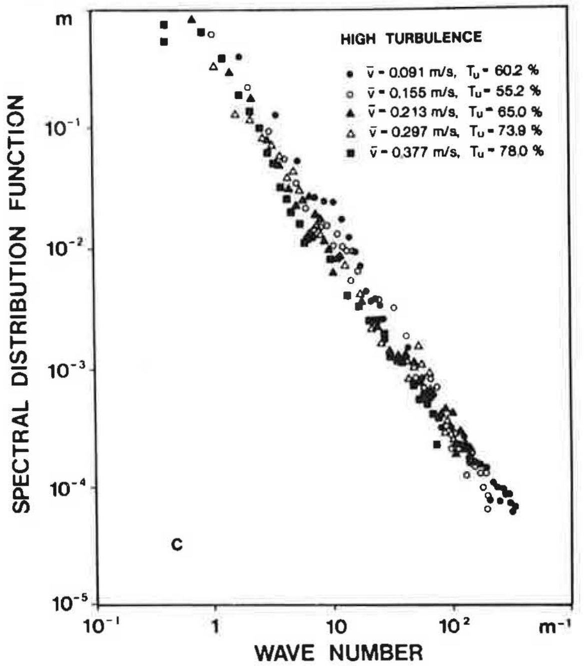
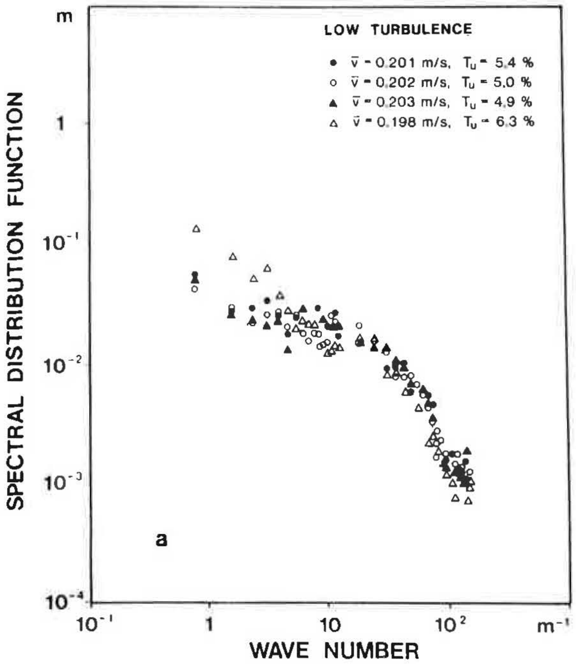
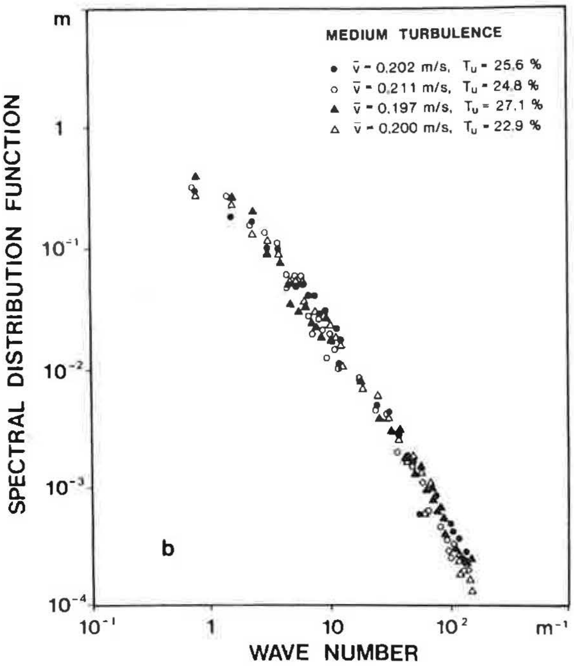


Fig. 26. Comparison of spectra of the velocity fluctuations at different mean velocities during the experiments with: (a) low turbulence; (b) medium turbulence; and (c) high turbulence.

of the velocity fluctuations. The previous experiments by Fanger and Pedersen [4] have shown that the frequency of the velocity fluctuations also affects people's feeling of draught. That is why an important aim was to make the air flow fluctuate in a way typical of that occurring in practice. This we were able to do. Figure 25(a, b, c) shows a comparison of the spectra of the velocity fluctuations from present experiments and field measurements for the three levels of turbulence intensity — low, medium and high. The Figures show the same density of distribution of the velocity fluctuations.

The reproducibility of the airflow characteristics (the mean velocity, the turbulence intensity and the spectral distribution of the velocity fluctuations) during the experiments with all 50 subjects was important as well. As pointed out before, these conditions were reproducible. In Figs. 26(a, b, c) and 27(a, b, c) spectra of the velocity fluctuations





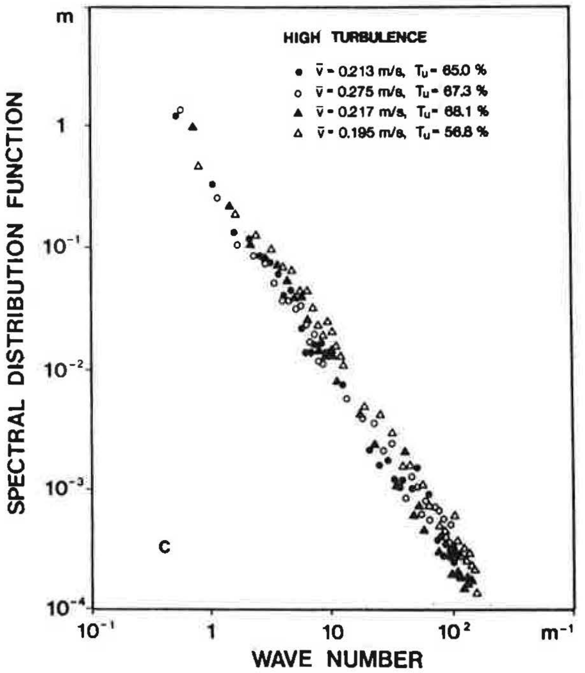


Fig. 27. Comparison of spectra of the velocity fluctuations from experiments with four randomly selected subjects. During the experiments with the four subjects, a mean velocity of 0.20 m/s was intended at three levels of turbulence intensity: (a) low; (b) medium; and (c) high.

for different mean velocities and from different experiments are compared in the cases of low, medium and high turbulent flow. Within each level of turbulence intensity the density of distribution of the velocity fluctuations is the same. In the case of low turbulence it remained with a low but approximately constant value in a wide range of wave numbers. For medium and high turbulence intensity it is similar to a fully developed turbulent flow with highest values at low wave numbers.