Technical Review

No. 2 · 1988

Quantifying Draught Risk

Brüel & Kjær

Previously issued numbers of Brüel & Kjær Technical Review

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Contents

Quantifying Draught Risk

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Abstract

Draught, defined as an unwanted local cooling of the human body caused by air movement, is one of the most common causes of complaints in ventilated or air-conditioned spaces. The high ventilation rate required to establish acceptable air quality, often leads to uncomfortably high air velocities.

Because of the high level of pollution in modern buildings, caused by increased internal loads from office machines (computers, printers, etc.), there will be an ever increasing demand for higher ventilation rates.

In most existing standards the requirements for the air velocity in a room are based on the mean air velocity limit, which depends on the existing air temperature. New draught studies show, however, that high turbulent air flow causes more complaints of draught than low turbulent air flow at the same mean air velocity and temperature. Many field studies show that turbulence intensity in rooms varies from 10–70%, indicating that it should be taken into account during revision of the existing standards. This paper discusses how to deal with the draught problem, and describes the measurements necessary for estimating draught risk.

Sommaire

Les refroidissements localisés et indésirés du corps par mouvement d'air sont l'une des plus fréquentes causes de plainte dans les locaux ventilés ou avec air conditionné. Le taux de renouvellement de l'air, qui doit être élevé pour maintenir une atmosphère de qualité suffisante, se traduit souvent par une vitesse de l'air trop élevée pour être confortable.

De nos jours, les sources de pollution (ordinateurs, imprimantes, etc.) sont de plus en plus nombreuses dans les bureaux et le taux de renouvellement de l'air ne peut qu'aller en s'accroissant.

La plupart des normes actuelles portant sur la vitesse de l'air dans un local définissent sa vitesse moyenne limite en fonction de la température ambiante. Cependant, des études ont maintenant montré que pour une même température et vitesse moyenne de l'air, un flux d'air très turbulent provoque plus de plaintes qu'un flux d'air peu turbulent. L'étude de nombreux cas pratiques montre que l'intensité de la turbulence dans des locaux varie de 10 à 70%, et que celle-ci devrait donc être prise en compte lors de la révision des normes existantes. Cet article indique comment traiter le problème des courants d'air, et décrit les mesures nécessaires pour estimer le risque de courant d'air.

Zusammenfassung

Zugluft, d.h. die unbeabsichtigte Auskühlung des menschlichen Körpers an einzelnen Körperteilen durch Bewegung der Luft, führt häufig zu Beschwerden in Räumen mit Ventilation oder Klimaanlagen. Um eine akzeptable Luftqualität zu erreichen ist eine hohe Ventilationsrate erforderlich, die wiederum oft unangenehm hohe Luftgeschwindigkeiten bewirkt.

Die Luft in modernen Gebäuden wird immer stärker durch Büromaschinen wie Rechner, Drucker usw. belastet, so daß immer höhere Ventilationsraten notwendig werden.

In den meisten gegenwärtig vorhandenen Richtlinien und Normen basieren die Anforderungen an die Luftgeschwindigkeit in einem Raum auf einem gemittelten Luftgeschwindigkeitsgrenzwert, der von der Raumtemperatur abhängt. Untersuchungen zur Zugluft haben nun gezeigt, daß bei gleicher mittlerer Luftgeschwindigkeit und Temperatur Luftströme mit hohen Turbulenzen eher als Zugluft empfunden werden als Luftströme mit geringen Turbulenzen. In Untersuchungen vor Ort ist festgestellt worden, daß die Intensität von Turbulenzen in Räumen zwischen 10–70% variiert. Diese Intensität von Turbulenzen sollte daher auch schon bei den existierenden Richtwerten beachtet werden. Dieser Artikel untersucht, wie mit dem Problem der Zugluft umzugehen ist, und beschreibt, mit welchen Meßmethoden die Wahrscheinlichkeit von Zugluft eingeschätzt wird.

Introduction

Draught is defined as unwanted local cooling of the human body caused by air movement. It is a serious problem in ventilated or air-conditioned buildings, automobiles, trains and airplanes. Draught has been identified as one of the two most annoying environmental factors in workplaces and the most annoying factor in offices (Bolinder et al [1], Arbejdsmiljøgruppen [2]). It may even cause people to stop ventilation systems or to plug up air diffusers. Serious draught complaints often occur despite measured velocities being within limits 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. In heated rooms without mechanical ventilation, draught may be caused by convective air currents along windows and other cold surfaces providing air-movement in the occupied zone. In rooms where there are draught problems the occupants may increase the air temperature to counteract the draught, normally during the winter, and this will increase the energy consumption. Only one degree higher air temperature costs typically 5 – 15% more energy.

The general thermal comfort concept and the local thermal discomfort has been discussed by Fanger [3, 4, 5, 6] and in earlier Technical Reviews by Olesen [7, 8]. In the following only the local discomfort caused by local convective cooling, namely draught, and how to measure and estimate the draught risk in spaces will be discussed.

Air flow in the occupied zone of rooms

Typically the airflow in rooms is turbulent, e.g. velocity fluctuates randomly (Fig. 1). The turbulent airflow in the spaces may be characterized by the following magnitudes:

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

$$\bar{v} = \frac{1}{t_1} \int_{t_0}^{t_0 + t_1} v dt \qquad \text{m/s} \qquad (1)$$

The bar denotes averaging over time.

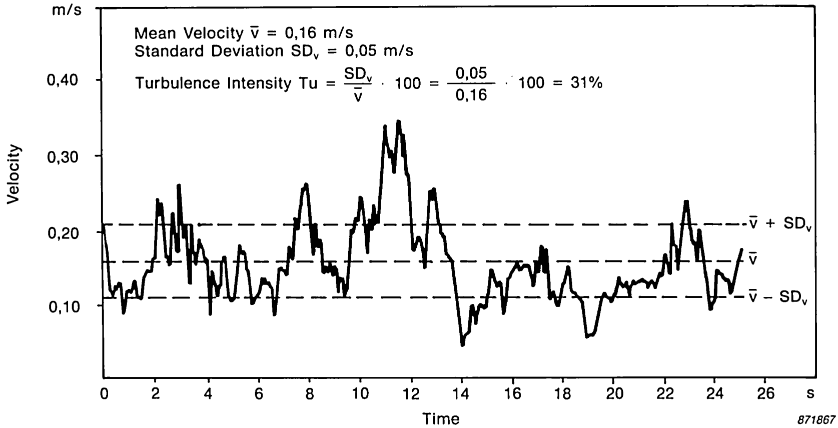


Fig. 1. Record of instantaneous velocity in the occupied zone

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

$$Tu = \frac{\sqrt{\overline{v'^2}}}{\bar{v}} \cdot 100\% \tag{2}$$

The **energy spectrum** of the velocity fluctuations

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

shows the density of distribution of $\overline{v'^2}$ in the range of frequencies, n. $E(n)$ is known as the spectral distribution function of $\overline{v'^2}$. It is often convenient (Hinze [9]) to consider the wave number $k = 2\pi n/\bar{v}$ instead of the frequency n and to introduce the energy spectrum function $E(k)$ instead of $E(n)$. It appears suitable to define $E(k)$ by

$$E(k) = \frac{\bar{v}}{2\pi} E(n) \qquad m^3/s^2 \tag{4}$$

so that

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

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 eulerian integral time scale, T_E, measures the longest connection of the turbulent behaviour of v'. It may be calculated from $E(n)$ when n approaches zero (Hinze [9]):

$$T_E = \frac{E(n)}{4\ \overline{v'^2}} \quad s \tag{6}$$

Air flow in the occupied zone of rooms has been examined in several field studies [10, 11, 12, 13, 14, 15, 16, 17]. During some of the field studies [11, 12, 13, 16] and the draught study [25, 26] Brüel & Kjær Indoor Climate Analyzer 1213 was used extensively together with other instruments for measuring mean air velocity, standard deviation of the velocity, air temperature and radiant temperature asymmetry. Air velocity transducer MM 0038, temperature transducer MM 0034 and radiant temperature asymmetry transducer MM 0036 were used. The instrument and the sensors are described and discussed in [42, 43].

The Indoor Climate Analyzer Type 1213 and the Velocity Sensor MM 0038 were used for energy spectra measurements (Figs. 5, 6, 15). During the measurements [12, 16, 26] the analog signal from the Indoor Climate Analyzer was recorded on a tape recorder (B & K Type 7005) and later analyzed by B & K Dual Channel Signal Analyzer Type 2032. The energy spectra were used to calculate the integral time constant (Fig. 7) and some other turbulent characteristics of the airflow described in [12, 16]. Fig. 2 shows a diagram of the measuring and calculating equipment used.

A wide range of typical ventilated spaces [10, 11, 12, 13, 14, 15] and heated rooms without mechanical ventilation [13, 16, 17] were included in these

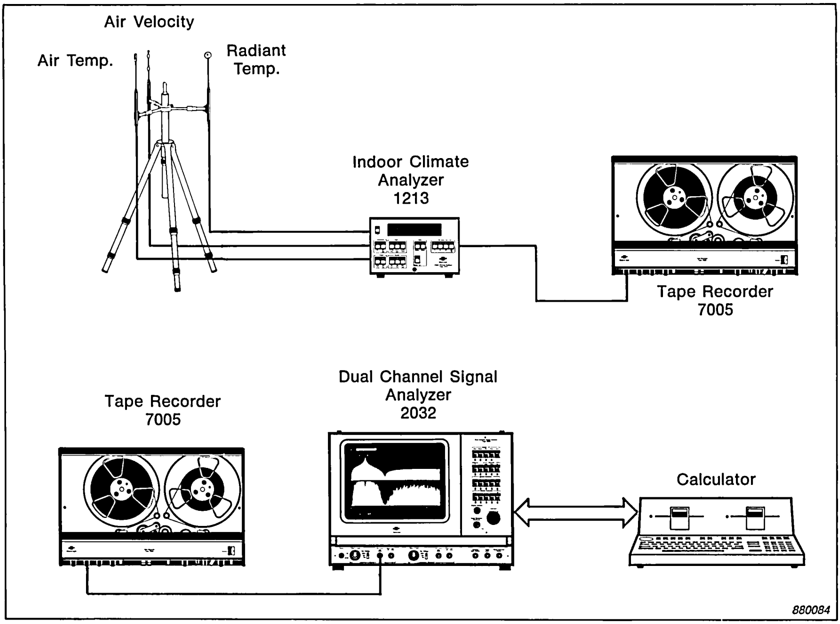
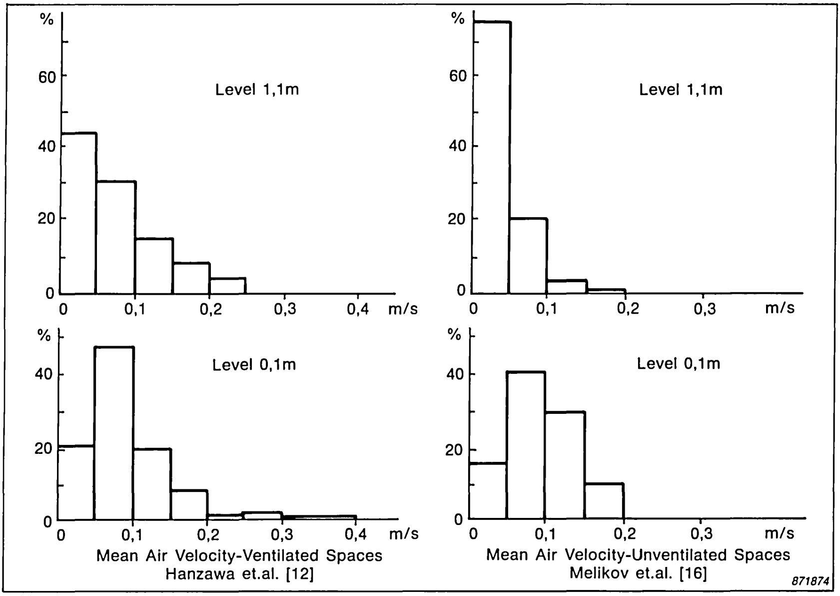


Fig. 2. B & K instruments used for registration and analysis of the airflow characteristics during field studied [12, 16] and draught study [26]

field studies. The ventilated spaces were selected to cover typical locations, types of outlets and exhaust devices. The heated rooms without mechanical ventilation had different heating methods — floor and ceiling heating, as well as heating by radiators, convectors and skirting board. Rooms with a variery of window areas were investigated. This parameter is important because during the winter natural convective air currents down windows may create considerable velocities in the occupied zone. Mean velocity up to 0,4 m/s and turbulence intensity from less than 10% to 70% were measured. Some results from the field study [12,16] are shown in Fig. 3 (a and b). The figure compares a percentage distribution of the mean velocity and the turbulence intensity measured at two heights — 0,1 m and 1,1 m above the floor in spaces with and without mechanical ventilation. According to the ISO Standard 7726 [18] for sedentary person these two heights correspond to the feet and head level. Both the mean velocity and the turbulence intensity were lower in heated rooms without mechanical ventilation than in ventilated spaces. Relatively high veloci-



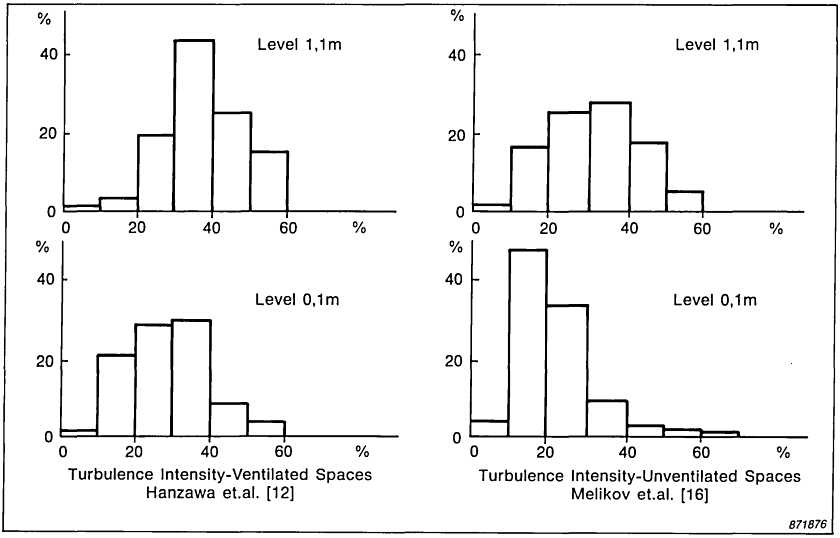


Fig. 3. a) Histograms of the mean velocity ($\bar{v}$) and b) turbulence intensity (T_u) in ventilated spaces and heated rooms without mechanical ventilation (unventilated spaces)

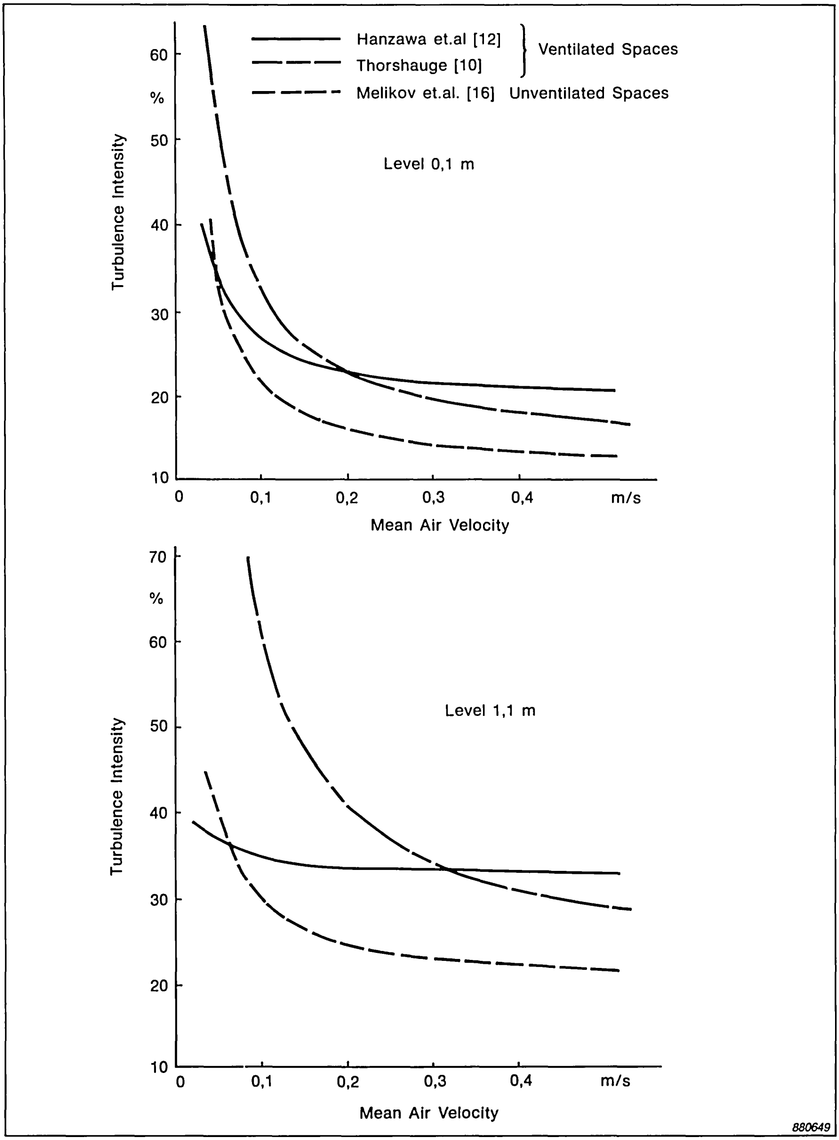


Fig. 4. Relationship between turbulence intensity (Tu) and mean velocity ($\bar{v}$) in ventilated spaces and heated rooms without mechanical ventilation (unventilated spaces)

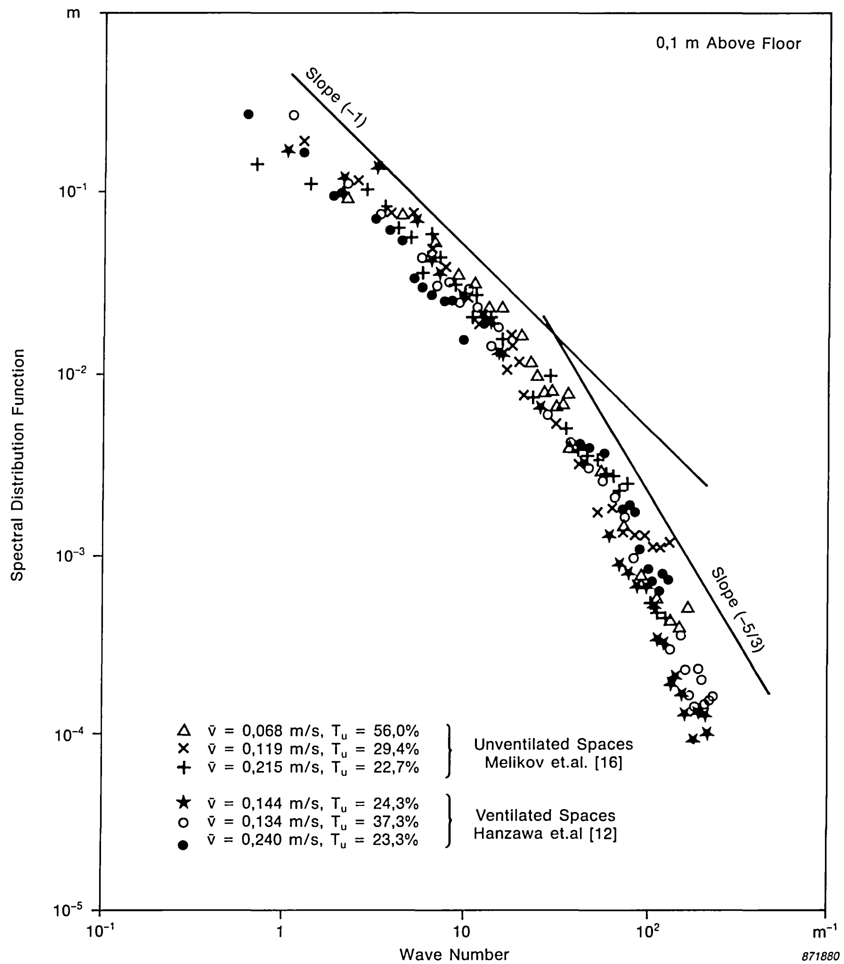


Fig. 5. a. Energy spectra measured at ankle level (0,1 m above floor). Vertical axis represents $E(k)/\overline{v'^2}$

ties (up to 0,25 m/s) were measured near to the floor (0,1 m) in heated rooms with large windows and insufficient heat sources under the windows.

Although the turbulence intensity varied in wide ranges, it was found to decrease when the mean velocity increased. Fig. 4 compares this relation-

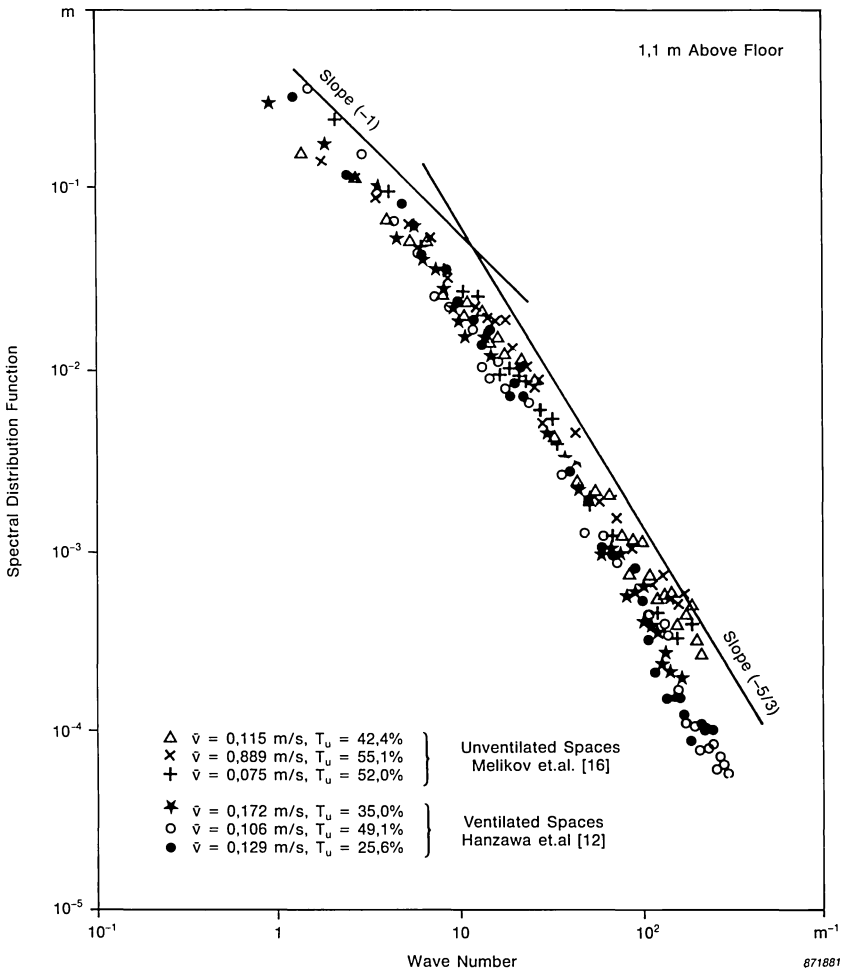


Fig. 5. b. Energy spectra measured at head level (1,1 m above floor). Vertical axis represents $E(k)/\overline{v'^2}$

ship measured in ventilated spaces and heated rooms without mechanical ventilation at two heights — 0,1 m and 1,1 m above the floor. The results are from [12,16].

The mean velocity and the turbulence intensity are not sufficient to characterize the nature of the air flow in the spaces. It is possible to find

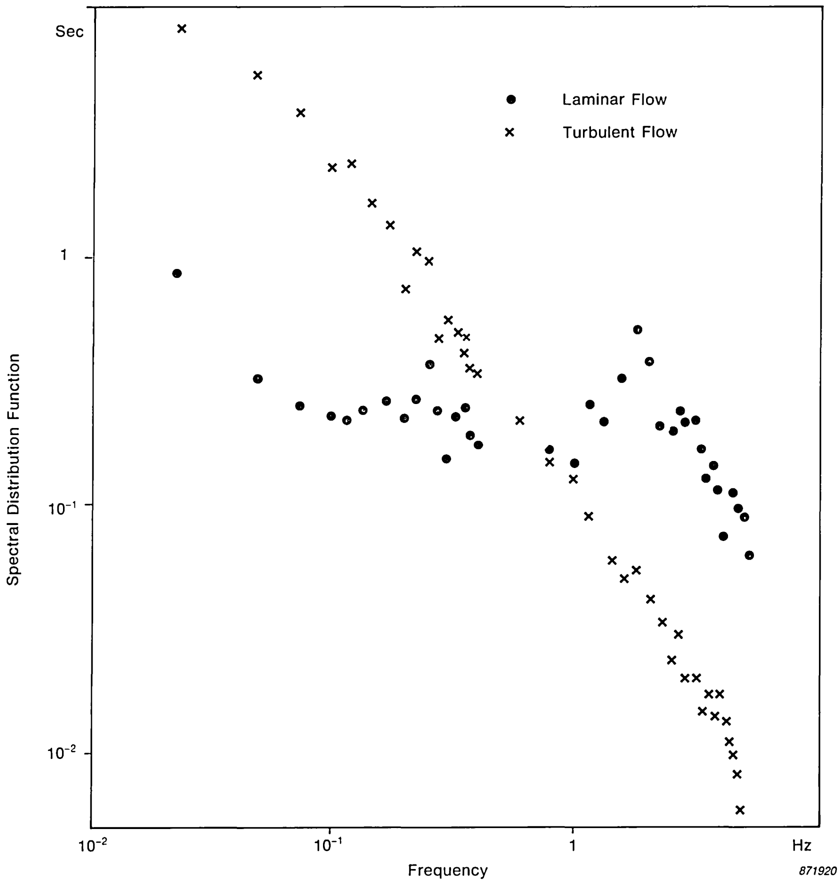


Fig. 6. Comparison of energy spectra measured in laminar and turbulent flow. Vertical axis represents $E(n)/\overline{v'^2}$

two turbulent flows with the same mean velocity and turbulence intensity but with different frequencies of the velocity fluctuations. Therefore it is important to know the energy spectra of the velocity fluctuations. The energy spectra measured in ventilated rooms and heated rooms without mechanical ventilation are shown in Fig. 5 (a and b). The spectra curves do not indicate an energy concentration at any specific region of the spectra. The spectrum curves for the points 1,1 m above the floor follow "–5/3" law rather closely, while near the floor (Fig. 5 a) turbulent energy varies al-

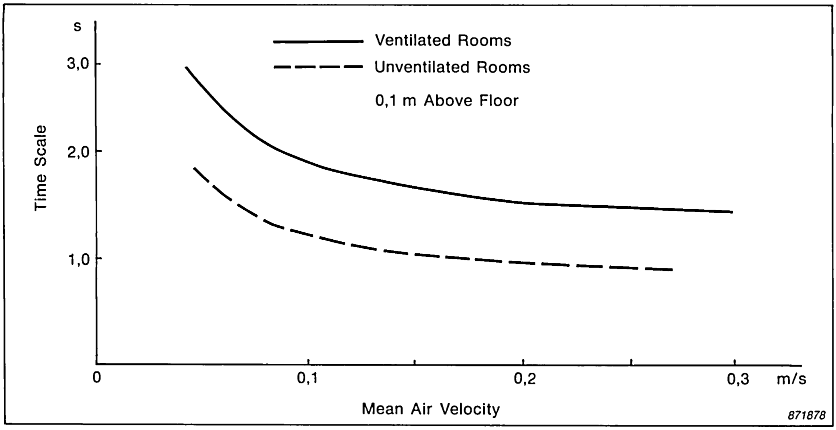


Fig. 7. Eulerian integral time scale as a function of the mean velocity

most according to k^{-1}, thus indicating strong interaction between mean and turbulent flow [9]. Fig. 6 shows how different the spectral distribution of the turbulent energy is in the case of turbulent and laminar flows. The spectrum for the laminar flow was measured in a clean room. In the case of the laminar flow, the energy distribution remains at a low but approximately constant value over a wide range of frequencies.

The integral time scale was found to be bigger in ventilated rooms than in heated rooms without mechanical ventilation (Fig. 7). It decreases as mean velocity increases.

Draught Studies

There are a few draught studies available. Houghten [19] studied ten male subjects exposed to a non-fluctuating, local velocity at the back of the neck and at the ankles. He found less than 10% dissatisfied at mean velocity 0,3 m/s. McIntyre [20] used a similar method where he exposed the head region of subjects to a nearly laminar airflow. At an air temperature of 21°C and velocities up to 0,2 m/s no discomfort was registered. However, as discussed previously, the airflow in ventilated spaces typically is not laminar but turbulent, i.e. velocity fluctuates. Fanger and Pedersen [21] have shown that periodically fluctuating airflow is more uncomfortable than non-fluctuating (laminar) airflow. In a climate chamber sixteen sedentary subjects (8 females and 8 males) were exposed at the back of the neck to a horizontal airflow with well defined periodic velocity fluctua-

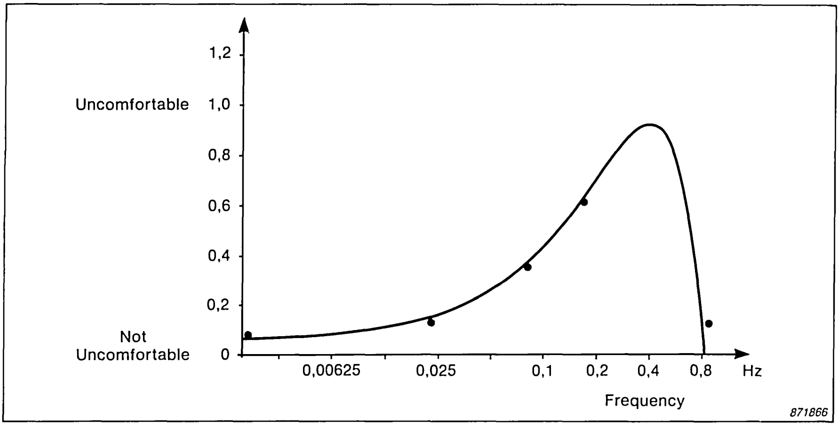


Fig. 8. Mean values of the degree of discomfort expressed by 16 subjects being exposed to a fluctuating airflow as a function of the frequency. Mean velocity: 0,3 m/s. Constant standard deviation 0,23 m/s

tions. The mean velocity and the amplitude of the velocity fluctuations were kept constant (i.e. the turbulence intensity) but the frequency of the velocity fluctuations was changed. The temperature of the airflow was close to the air temperature in the climate chamber which was kept at a level preferred by each individual subject (determined in a pre-test). They found that discomfort had a maximum at velocity frequencies around 0,3 – 0,5 Hz (Fig. 8).

Fanger and Christensen [22] 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 0,4 m/s at air 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 (Fig. 9). The percentage may either be determined graphically from the draught chart or calculated by the regression equation:

$$PD = 13800 \left[\left(\frac{\bar{v}-0{,}04}{t_a-13{,}7} + 0{,}0293 \right)^2 - 0{,}000857 \right] \qquad (7)$$

The head region was found to be the most draught-sensitive part of the body for persons wearing normal indoor clothing. No significant differences were found between the draught sensitivity of men and women.

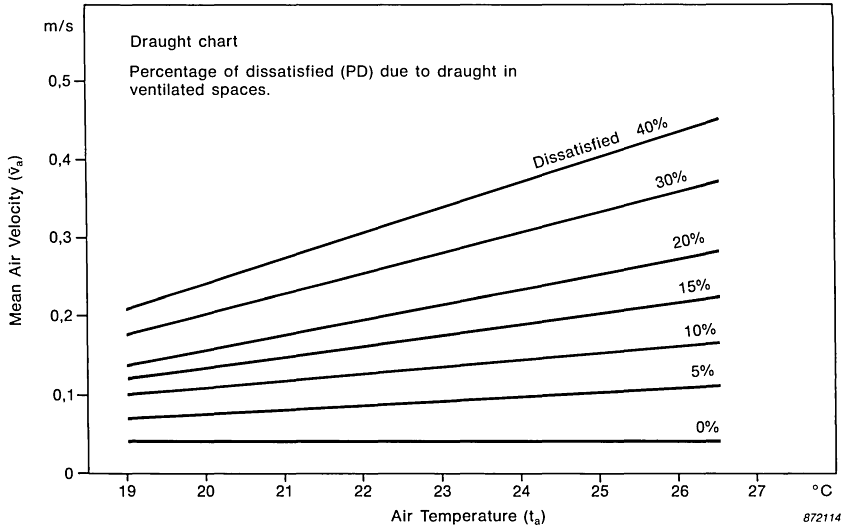


Fig. 9. Percentage of dissatisfied due to draught as a function of mean velocity and air temperature, Fanger and Christensen [22]

Berglund and Fobelets [23] made a study with 50 subjects. In their experiments the subjects were exposed to turbulent airflow approximately in the same range of mean velocities (0,05 – 0,5 m/s) as in Fanger's and Christensen's study. Fig. 10 shows the results from this study. The percentage experiencing draught is given by the equation:

$$PED = 113\,(\bar{v} - 0{,}05) - 2{,}15\,t_a + 46 \qquad (8)$$

The comparison between the two studies (Fig. 11) shows higher percentage of dissatisfaction in Fanger's and Christensen's study. The questionaires and procedures were different in the two studies. An important difference was the turbulence intensity. In both experiments the turbulence intensity was decreasing when the mean velocity was increasing, but in Fanger's and Christensen's study it was between 65% and 30% while in the study of Berglund and Fobelets it was approximately from 40% down to 5%. Fig. 11 also shows the results from a draught study performed by Tanabe [24]. They register a significantly lower percentage of dissatisfied.

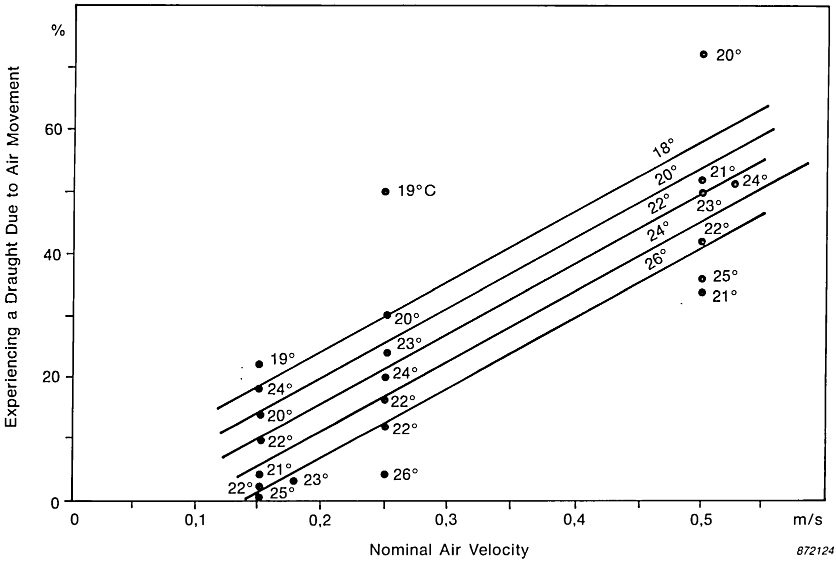


Fig. 10. Percentage of subjects experiencing draught (dissatisfied) as a function of nominal air speed (mean velocity) and temperature, Berglund and Fobelets [23]

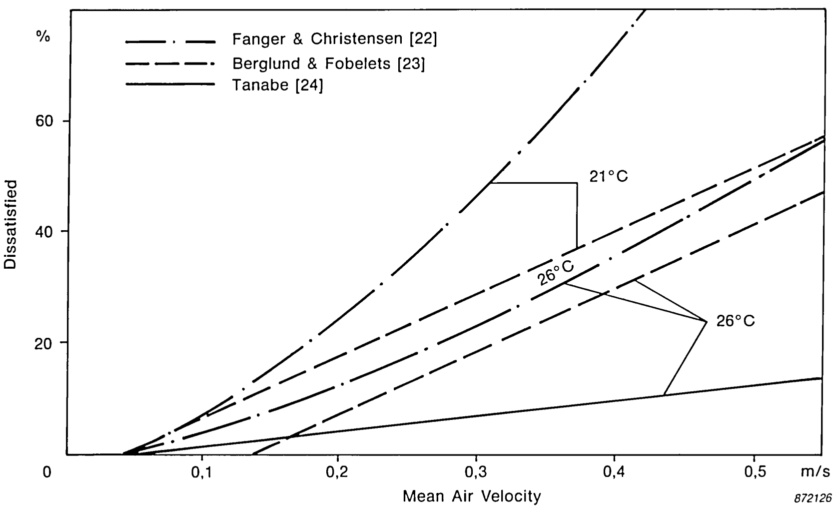


Fig. 11. Comparison of dissatisfied due to draught from different draught studies

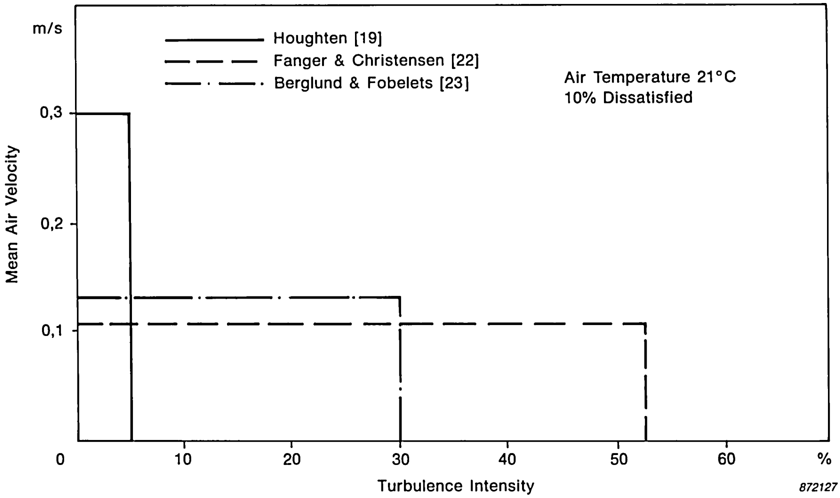


Fig. 12. Mean air velocity limits for 10% dissatisfied due to draught/constant air temperature 21°C) from different draught studies

The turbulence intensity during Fanger's and Christensen's and Tanabe's experiments (air temperature 26°C) was in the same range 55–30%. The clo value of the subjects' clothing was almost the same 0,58 and 0,6 respectively.

Fanger and Christensen [22] and Berglund and Fobelets [23] identified a much higher rate of dissatisfaction than previous draught studies of Houghten [19] and McIntyre [20] (Fig. 12). The reason is most likely the differences in the turbulence intensity. In Houghten's and McIntyre's studies the subjects were exposed to a low-turbulent airflow from a jet. McIntyre measured the turbulence intensity to be 3%. As previously discussed, the turbulence intensity is much higher in ventilated spaces.

The impact of the turbulence intensity on the sensation of draught has been investigated recently by Fanger et al. [25, 26]. Fifty subjects, dressed to obtain a neutral thermal sensation, were exposed to airflows with three different levels of turbulence intensity. The subjects were exposed to increasing mean velocity ranging from 0,05 m/s 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 turbulence intensity range was selected to be the same

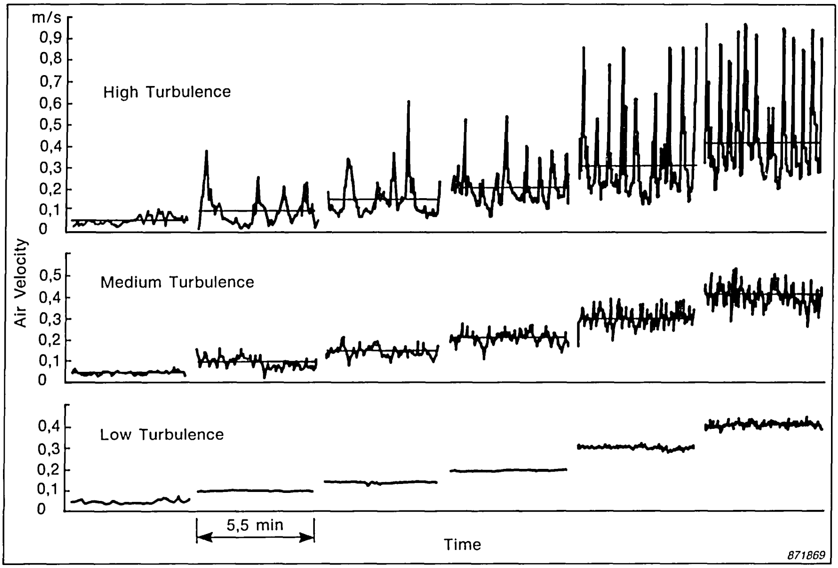


Fig. 13. Samples of velocity fluctuations at six mean air velocities and three different turbulences

as measured in a normal office situation (Fig. 3b). Fig. 13 shows typical samples of instantaneous velocity recorded during the draught study.

An important aim of these experiments was to expose the subjects to an airflow with the same nature as encountered in daily life. Instantaneous velocity recorded during the field measurements [12] and the draught experiments [26] are compared in Fig. 14. The samples are chosen from measurements with approximately the same mean velocity and turbulence intensity. Energy spectra of the velocity fluctuations for the three levels of turbulence intensity are compared in Fig. 15 (a, b, c). The comparisons indicate that the nature of the airflow during the draught experiments was the same as those found in practice. The air temperature was kept constant at 23°C. The subjects were asked whether and where they could feel air movement and whether or not it felt uncomfortable. As in [22] the head region which comprises the head, the neck and the shoulders was found to be the most draught sensitive part of the body.

Fig. 16 shows the percentage of subjects who felt draught at the head region as a function of the mean velocity at the neck. The results from

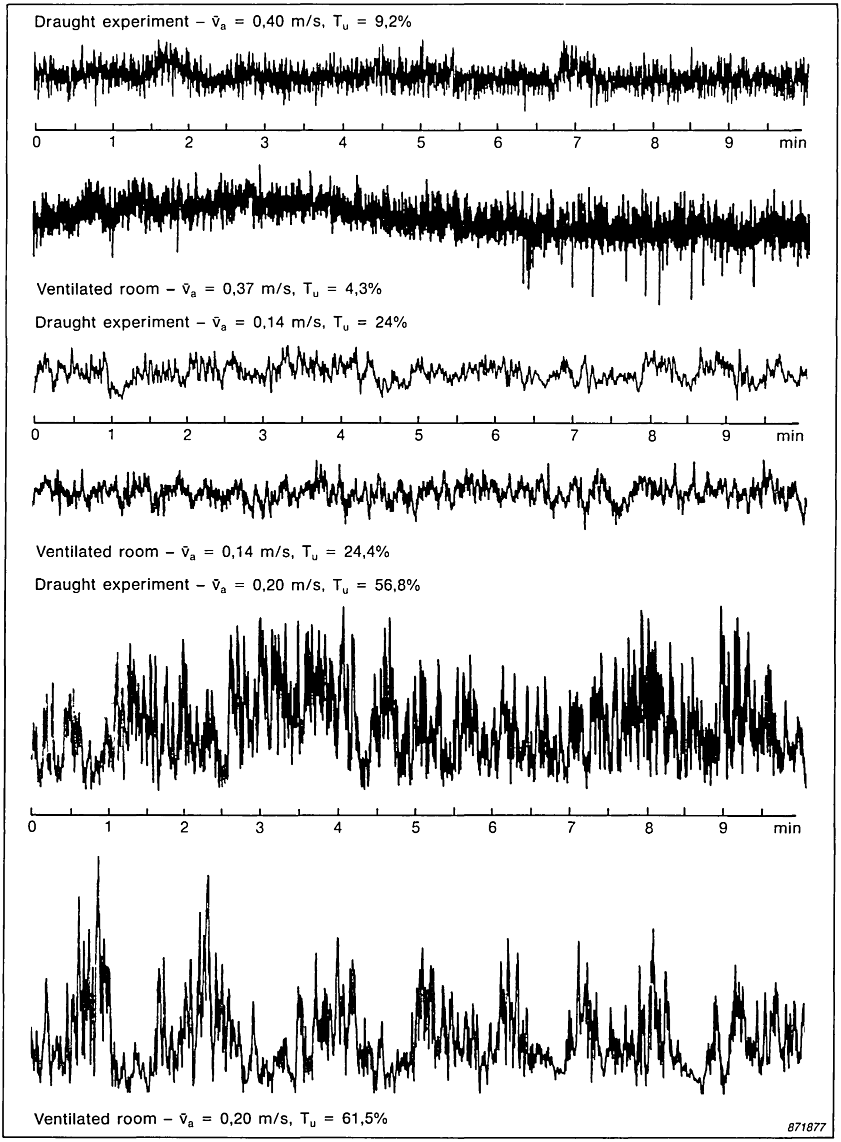


Fig. 14. Records of instantaneous velocity at three levels of turbulence intensity. Figure compares records in ventilated spaces and draught study [26] at the same mean air velocity

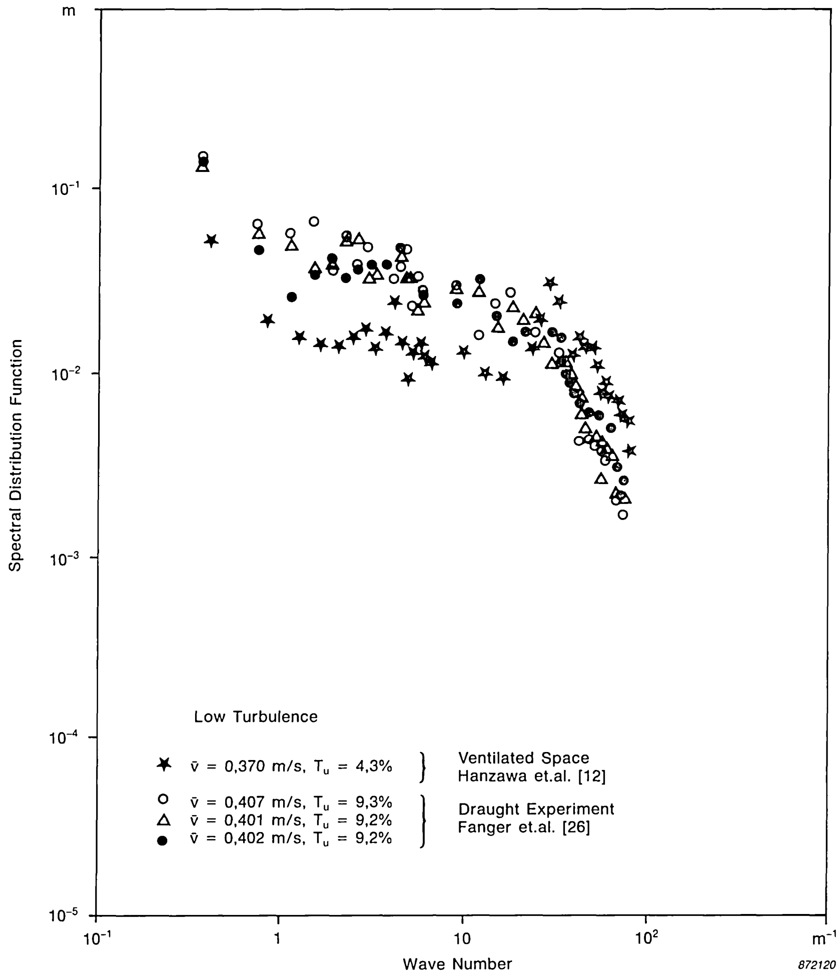


Fig. 15. a. Low turbulence airflow. Comparison of spectra of the velocity fluctuations measured by Fanger et. al. [26] during their draught study and in ventilated spaces measured by Hanzawa et. al. [12]. (See Fig. 15.a)

Fanger's and Christensen's draught study [22] are plotted as well. The lines in Fig. 16 are based on a probit analysis [27] of the percentage of subjects feeling draught versus the square root of the mean velocity. The

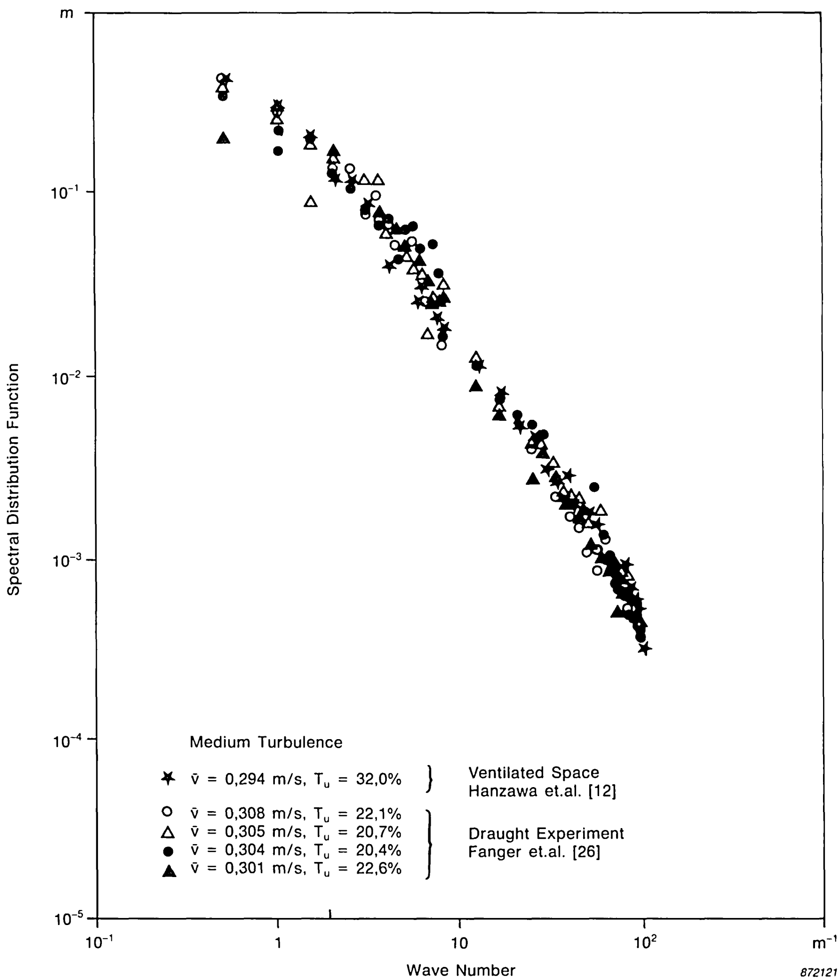


Fig. 15. b. Medium turbulence airflow. Comparison of spectra of the velocity fluctuations measured by Fanger et. al. [26] during their draught study and in ventilated spaces measured by Hanzawa et. al. [12]. (See Fig. 15.a.)

square root was selected since heat transfer by forced convection is approximately proportional to the square root of the mean velocity. The turbulence intensity had a significant impact on the occurrence of draught sensation.

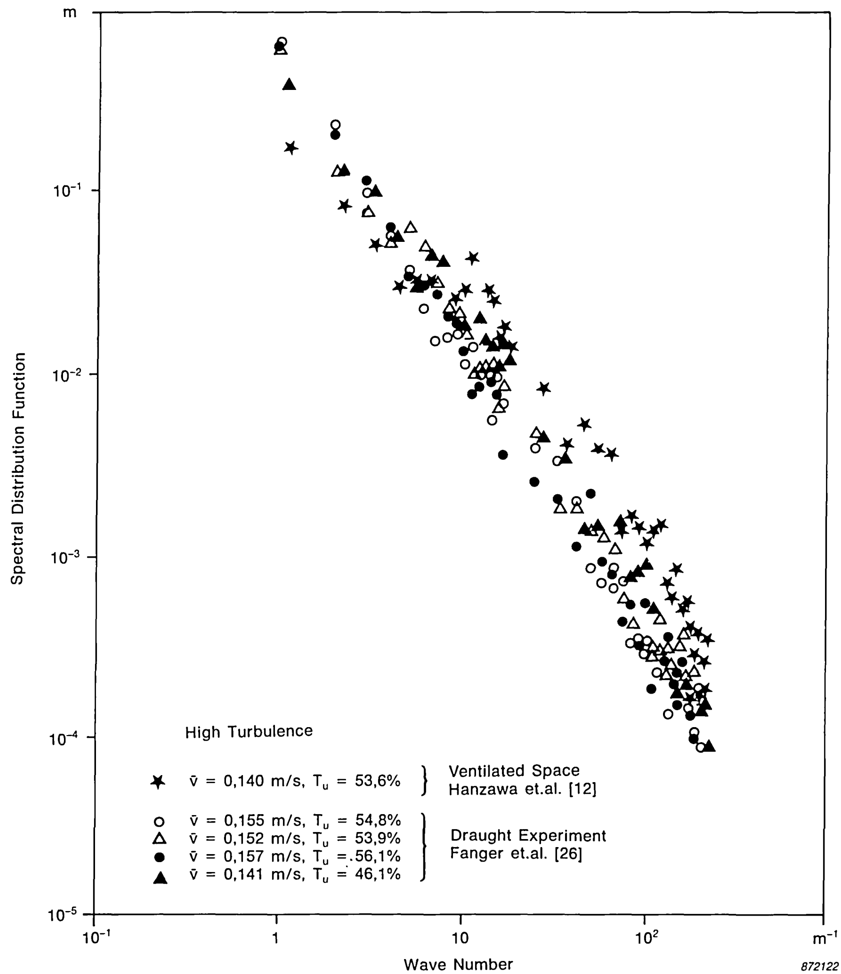


Fig. 15. c. High turbulence airflow. Comparison of spectra of the velocity fluctuations measured by Fanger et. al. [26] during their draught study and in ventilated spaces measured by Hanzawa et. al. [12]. (See Fig. 15.a.)

Many subjects were able to sense air movements even at low velocities. As expected, the number of subjects sensing air movement increased with the mean velocity but surprisingly in [22] there was no influence from the air temperature. On the contrary the turbulence intensity was found to

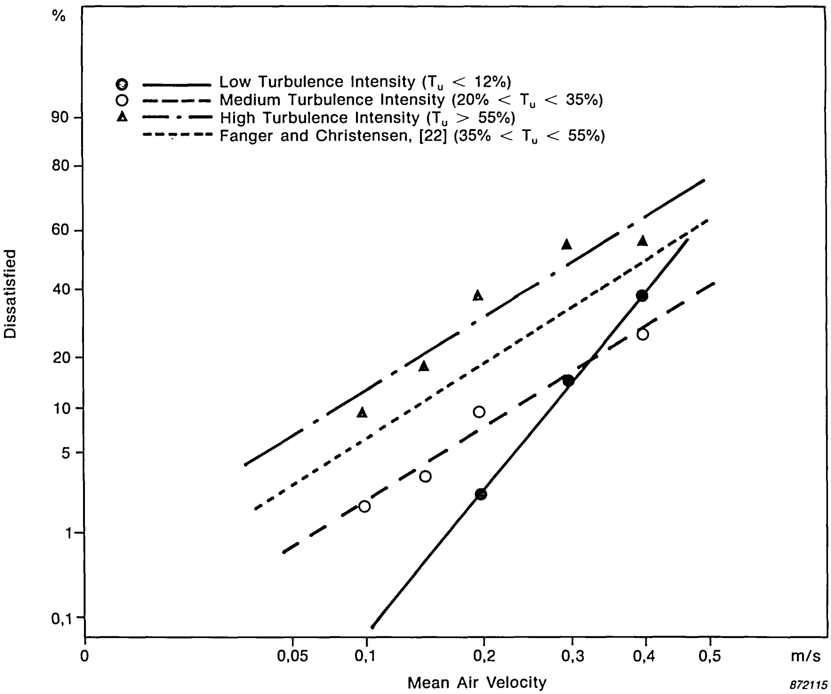


Fig. 16. Percentage of dissatisfied people due to draught at the head region as a function of the mean air velocity at three levels of turbulence intensity

have significant impact on the percentage of people sensing air movement [26]. Airflow with high turbulence intensity was sensed by more people than airflow with low turbulence intensity. Fig. 17 shows a relationship between percentage dissatisfied due to draught and percentage sensing the air movement at the same mean velocity, turbulence intensity and temperature.

More airflow fluctuations: more draught complaints – why?

Fanger and Pedersen [21] found that periodically fluctuating airflow with frequencies 0,3 – 0,5 Hz are the most undesirable for the draught feeling (Fig. 8). The impact of a periodically fluctuating airflow on human being's cooling sensation was also registered by Assakai and Sakai [28].

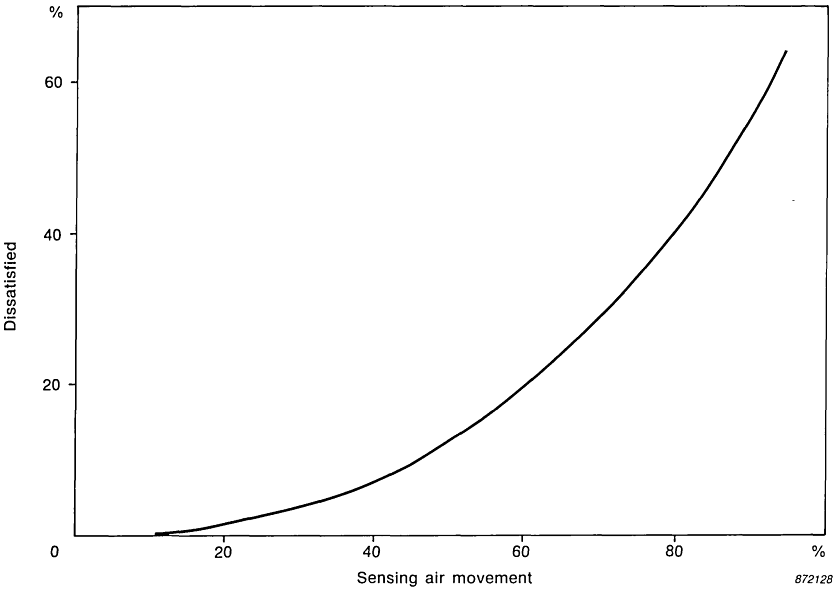


Fig. 17. Relationship between percentage dissatisfied due to draught and percentage sensing air movement at the same mean air velocity and turbulence intensity

In a test chamber human beings were exposed to a constant airflow with the velocity at which they felt most comfortable. At the beginning the cooling sensation was evaluated as 3 on a 5 point scale. After five minutes the evaluation showed that the cooling sensation decreased to 2,6 due to adaptability of the human body with time. After that the subjects were exposed at the same airflow but pulsating. They could choose the most agreeable pulsating cycle. Evaluation at the beginning and after five minutes indicated that the cooling effect increased with time up to 3,3. The pulsation cycle determined to be most comfortable was about 1,2 Hz. Fig. 18 demonstrates these results. The impact of periodically and randomly fluctuating air movement on man's thermal sensation and feeling of draught at different thermal conditions has been studied recently by Tanabe [24]. As in previous studies it was found that fluctuating airflow had stronger impact on subjective thermal sensation and feeling of draught than non-fluctuating airflow.

Hensel [29] has studied and described the reaction of the skin and the thermoreceptors located at different layers below the skin surface to dif-

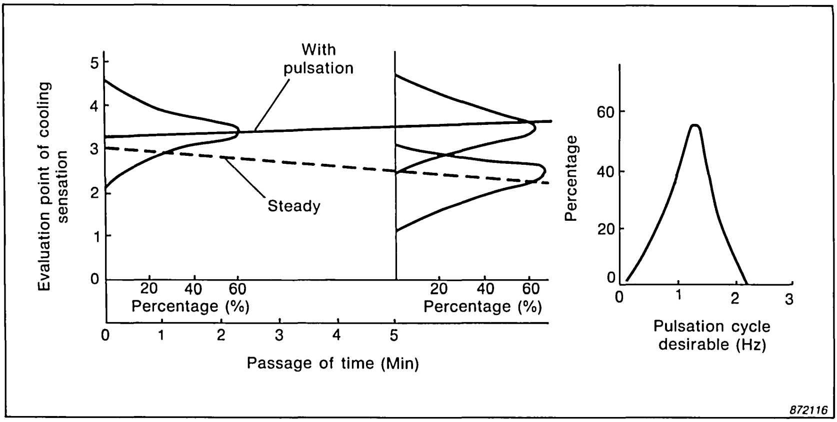


Fig. 18. Changes in cooling effect with time. 1,2 Hz is the most comfortable pulsation. Asakai and Sakai [28]

ferent thermal influences. The thermoreceptors can be divided into the class of warm and cold receptors. The thermoreceptors have a static sensitivity to constant temperature (t) and a dynamic sensitivity to temperature changes ($dt/d\tau$), with a positive temperature coefficient for warm receptors and a negative coefficient for cold receptors. Irrespective of the initial temperature, a warm receptor will always show a transient increase in frequency on sudden warming and a transient inhibition of its discharge on sudden cooling, whereas a cold receptor will respond in the opposite way, namely, with an overshoot on cooling and an inhibition on warming. Besides this dynamic behaviour there are also typical differences in the static sensitivity curves of both types of thermoreceptors, in that the temperature of the maximum discharge is much lower for cold receptors than it is for warm receptors. The draught sensation, e.g. undesirable local cooling of the body, should be connected with the response of the cold receptors, as the receptors register the temperature changes at the skin surface.

Why is fluctuating airflow more uncomfortable than non-fluctuating airflow at the same conditions, e.g. mean air velocity and temperature? One suggestion made by Mayer [30, 31] is that the convective heat transfer increases with increasing turbulence intensity. This has certainly an impact but may not be sufficient to explain the dramatic effect of turbulence shown in Fig. 16. The velocity fluctuations will cause skin temperature fluctuations which will be reigstered by the receptors. The temperature changes will have an impact on the dynamic sensitivity of the receptors.

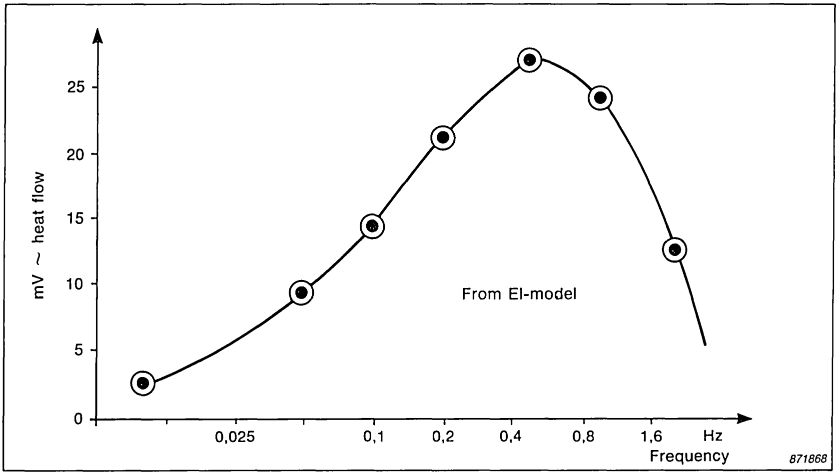


Fig. 19. Maximum heat flow through thermal receptors simulated by an electrical analog model as a frequency of the input signals (from Madsen [34])

This theory has been studied by Madsen [32, 33, 34]. He simulated the human skin including thermoreceptors by electrical model. In the model, temperature was simulated by voltage, heat flow by current, thermal capacity corresponds to electrical capacitance and thermal resistance corresponds to electrical resistance. On the electrical model the maximum heat flow through the receptors was determined when the skin was exposed to a number of sine-shaped velocity changes, with constant amplitude, but with different frequencies. Fig. 19 shows the relationship between the heat flow and frequency from this experiment. The form of the curve is almost identical to the curve from Fanger and Pedersen's subjective study [21], Fig. 8. Both curves have a maximum around 0,5 Hz. Madsen hypothesised that for fluctuating airflow high sensitivity is a result of periodically high outputs from the cold receptors to the brain. This is caused by a corresponding high heat flow through the receptors following the moments of highest air velocity. The dynamic response of the thermoreceptors to the rate of change of the skin temperature is not simple. Although a non-zero $dt/d\tau$ is necessary as a stimulus, it by itself does not account for many of the characteristics of the receptors discussed by Hensel [29]. Magnitude (size of temperature step) and frequency of the stimulus may play a role in the response of the receptors and in sensation. The fluctuation of the skin temperature with time, activates the receptors to initiate 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 the human body. During exposure to velocity fluctuations this information is not useful and therefore undesired, but it may explain the nuisance called draught.

Model of draught risk

Fanger and Christensen [22] studied the impact of the mean velocity and air temperature on the sensation of draught. They measured the turbulence intensity but did not control it. Fanger et al [25, 26] studied the impact of the mean velocity and the turbulence intensity on man's sensation of draught. They kept the air temperature constant.

The results of these two studies were used and a model of draught risk was developed by Fanger et al [26]. The model predicts the percentage of people dissatisfied due to draught as a function of air temperature, t_a (°C), mean velocity, $\bar{v}$ (m/s), and turbulence intensity, Tu (%). The percent dissatisfied, PD, is given by the equation:

$$\mathrm{PD} = (34 - t_a)\,(\bar{v} - 0{,}05)^{0{,}6223}\,(0{,}3696 \cdot \bar{v} \cdot Tu + 3{,}143) \qquad (9)$$

for $\bar{v} < 0{,}05$ insert $\bar{v} = 0{,}05$ m/s
for PD $>$ 100% use PD = 100%.

The model incorporates the convective heat transfer process to link turbulence to skin temperature fluctuations and Hensel's account of thermoreceptors to link thermal sensation to these temperature fluctuations. The two kinds of thermoreceptor responses, the static and the dynamic were assumed. As it was pointed the dynamic response depends on the rate of change of skin temperature while the static depends on the level of the skin temperature. Due to the free convection airflow along the warm human body [35, 36], it was assumed that only velocities above 0,05 m/s would penetrate this layer. The exponent 0,6223 for the convective term in the model corresponds to the values in the literature [37]. The skin temperature was assumed to be 34°C. The ranges of the three parameters for the experimental data to which the model was fitted are:

$20 < t_a < 26$°C, $\quad 0{,}05 < \bar{v} < 0{,}4$ m/s and $0 < Tu < 70$%.

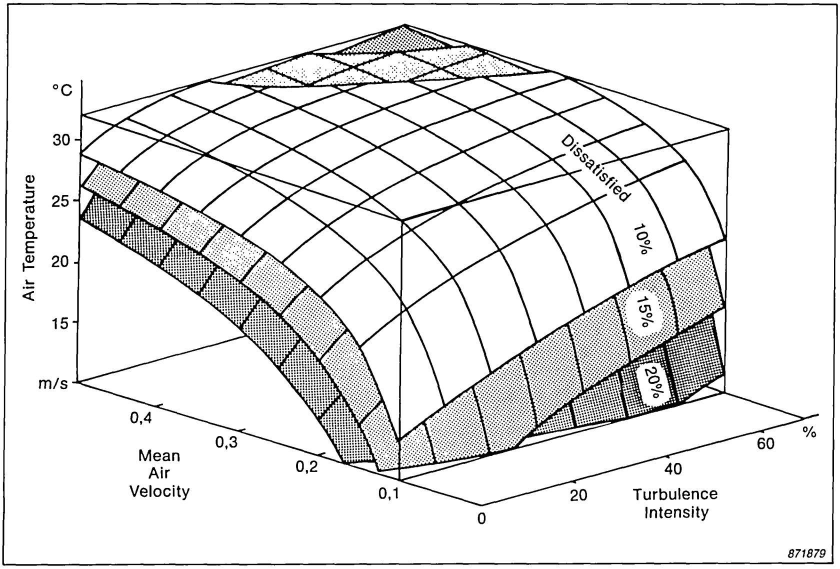


Fig. 20. A 3-dimensional representation of the draught risk model. The surfaces shown correspond to 10, 15 and 20% dissatisfied. The axes are turbulence intensity, mean air velocity and air temperature

It should also be noted that any $\bar{v} < 0{,}05$ m/s counts as $\bar{v} = 0{,}05$ m/s and although PD's bigger than 100% are mathematically possible they are not meaningful and should be counted as 100%.

Another way of presenting the model of draught risk is:

$$PD = 3{,}143\,(34-t_a)\;(\bar{v}-0{,}05)^{0{,}6223} + 0{,}3696\,(34-t_a)\;(\bar{v}-0{,}05)^{0{,}6223}\;\bar{v}\,Tu \qquad (9a)$$

$$PD = (34-t_a)\;(\bar{v}-0{,}05)^{0{,}6223}\;(3{,}143 + 0{,}3696 \cdot SD) \qquad (9b)$$

Equation (9b) can also be useful since some airflow instruments measure the standard deviation of the velocity fluctuations (SD) and not the turbulence intensity.

The main features of the model are shown in Fig. 20 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.

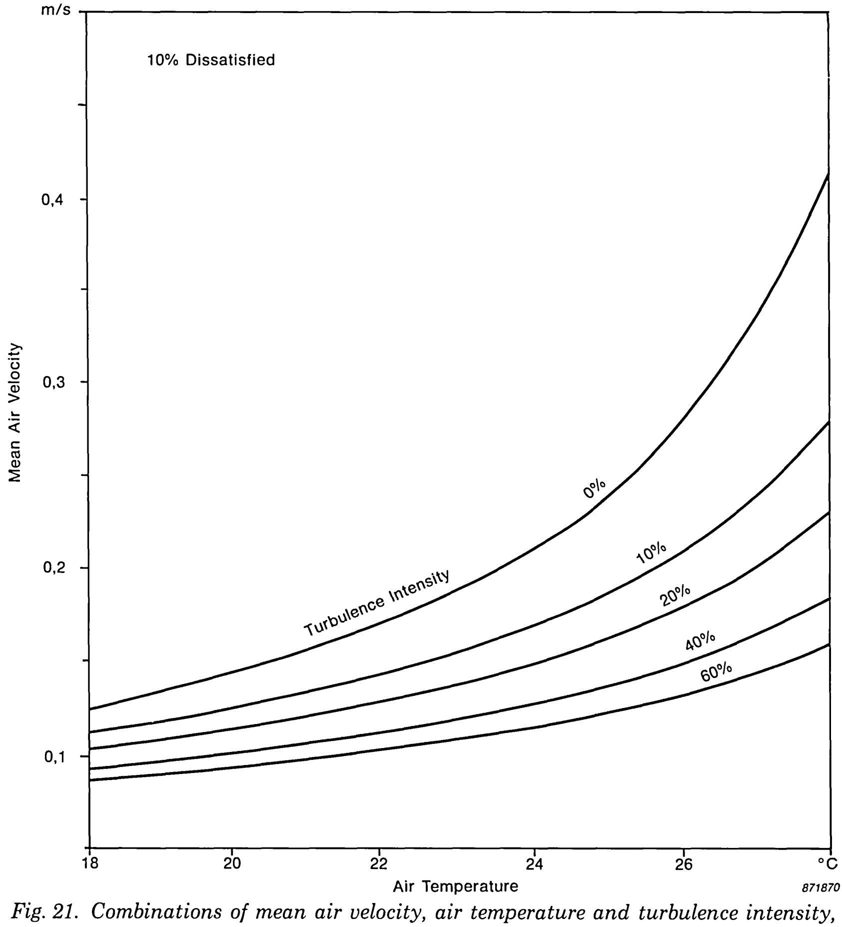


Fig. 21. Combinations of mean air velocity, air temperature and turbulence intensity, which will cause 10% dissatisfied. Calculated from the model of draught risk, Fanger et. al. [26]

Figures 21 and 22 give more precisely the curves which result from intersections between planes of constant *Tu* and the surfaces of PD = 10% and 20% respectively. It can be seen from Fig. 21 that at the same air temperature 23°C airflow with *Tu* = 60% will cause 10% dissatisfied at almost twice lower mean velocity ($\bar{v}$ = 0,11 m/s) than airflow with *Tu* = 0 %

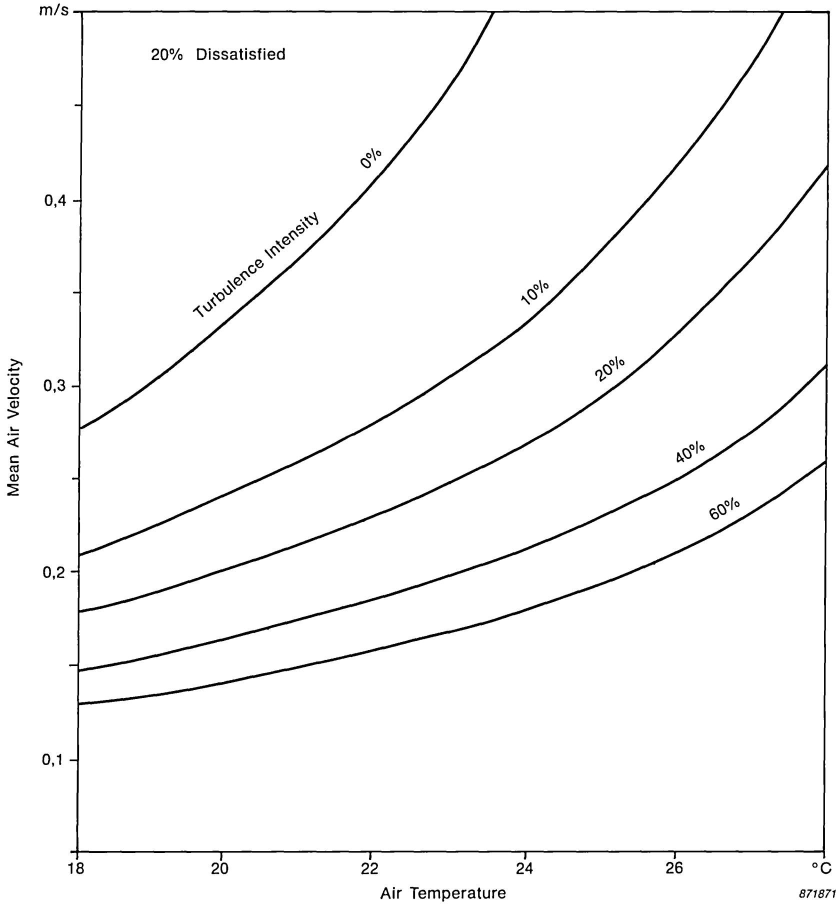


Fig. 22. Combinations of mean air velocity, air temperature and turbulence intensity, which will cause 20% dissatisfied. Calculated from the model of draught risk, Fanger et al. [26]

($\bar{v}$ = 0,19 m/s). Figs. 23 and 24 exhibit the way in which PD depends on *Tu* and $\bar{v}$ at t_a = 23°C. It is obvious that the effect of the turbulence is significant and it increases with the mean velocity. It is possible, using the model of draught risk, to calculate the uniform (non-fluctuating) air velocity which will cause the same percentage of dissatisfied due to draught as a

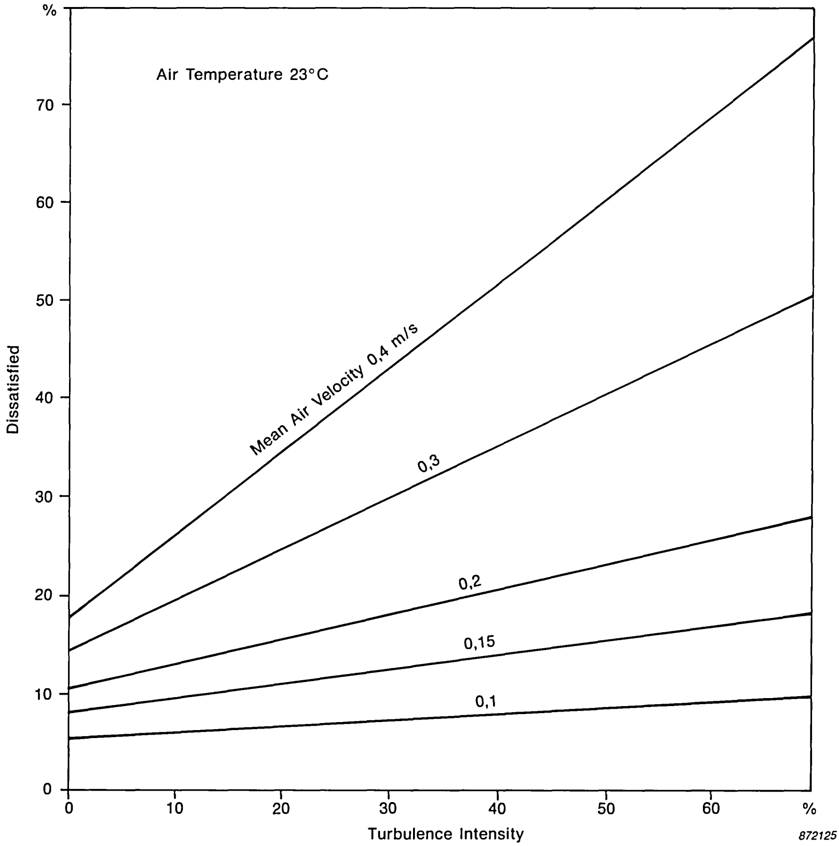


Fig. 23. Percent dissatisfied as a function of turbulence intensity and mean air velocity calculated from the model of draught risk [26]. The diagram applies for an air temperature 23°C

fluctuating airflow with the same mean velocity and temperature but different turbulence intensity. Fig. 25 shows this relationship.

The feet and arms were found to be sensitive to draught as well. Normally these parts of the body are covered by some clothing. The clothing layer will damp the thermal impact of velocity fluctuations on the risk and thus decrease the impact of turbulence on draught. The model of draught risk may be used for all heights in the occupied zone, although it may tend to

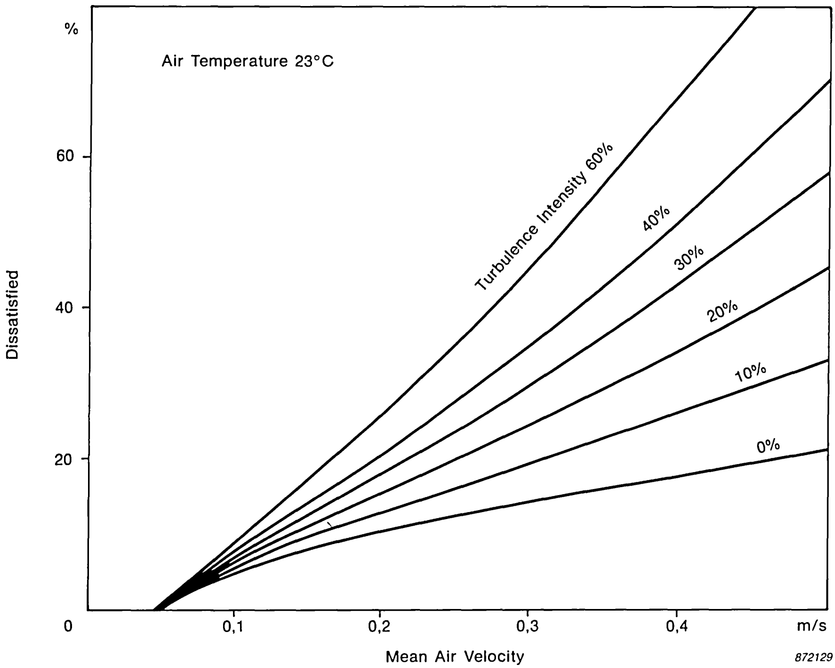


Fig. 24. Percent dissatisfied as a function of mean air velocity and turbulence intensity calculated from the model of draught risk [26]. The diagram applies for an air temperature 23°C

overestimate the draught risk at arms and feet level. For people with bare arms and ankles or with nylon stocking it is reasonable to use the model for the head.

Prediction of draught risk in rooms

Draught risk in spaces for human occupancy may be quantified by the model of draught risk. Measurements of three variables are necessary:

	MEAN AIR VELOCITY	– $\bar{v}$ (m/s)
	STANDARD DEVIATION	– SD (m/s)
or	TURBULENCE INTENSITY	– Tu (%)
	AIR TEMPERATURE	– t_a (°C)

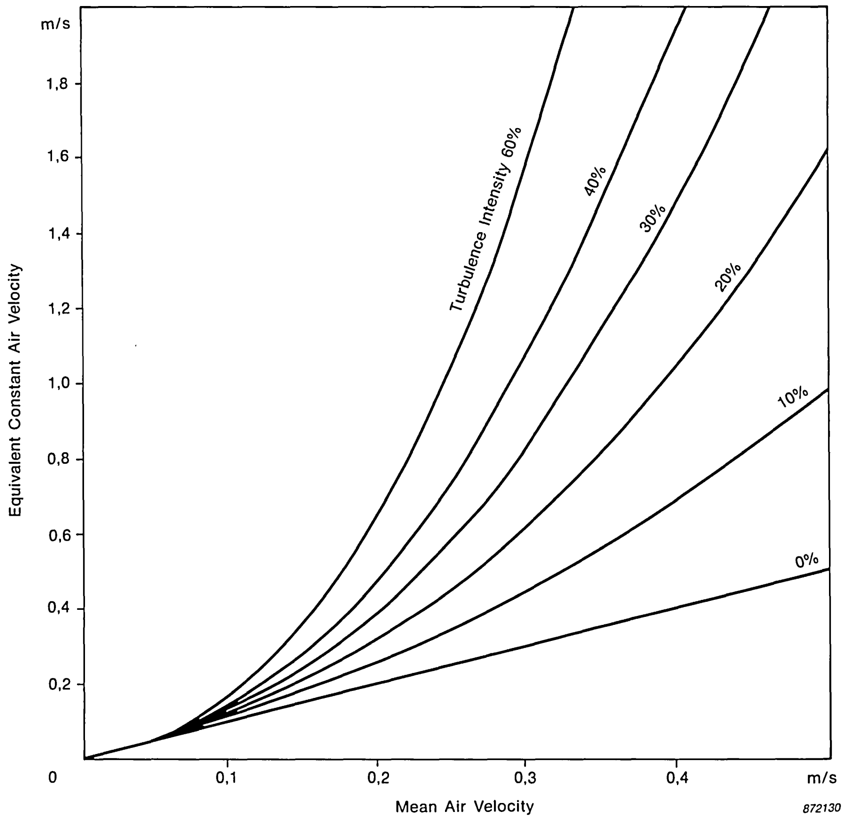


Fig. 25. Equivalent constant air velocity which will cause the same percentage of dissatisfied due to draught as actual airflow with different mean velocity and turbulence intensity. Calculated from the model of draught risk [26]

The three airflow characteristics should be measured at 0,1 m, 0,6 m, 1,1 m and 1,7 m above the floor in the occupied zone of the spaces. The heights are recommended in the standards (ISO 7726 [18], ASHRAE, 55–81 [39]). For sedentary persons, 0,1 m, 0,6 m and 1,1 m correspond to the feet, the arms and the head. The height corresponding to the head region for standing person is 1,7 m above the floor.

Model of draught risk, standards and practice

In the existing standards limits for the mean air velocity are recommended. ISO 7730 [38], ASHRAE 55–8 [39], and NKB–guidelines [40] have agreed on the same limits:

WINTER SITUATION – operative temperature between 20 and 24°C, mean air velocity less than 0,15 m/s

SUMMER SITUATION – operative temperature between 23 and 26°C, mean air velocity less than 0,25 m/s

Limits for turbulence intensity are not included in the standards. The values for the maximum mean velocity and minimum temperature recommended in the standards may be used to calculate maximum percentage of dissatisfied by the model of draught risk. This is shown on Fig. 26 for turbulence intensity up to 60% as it was measured in the field studies [10,12,14,15,16]. The maximum percentage of dissatisfied calculated with the limits for mean air velocity and temperature according to the German Standard DIN 1946 [41], are shown on Fig. 26 as well. The horizontal line

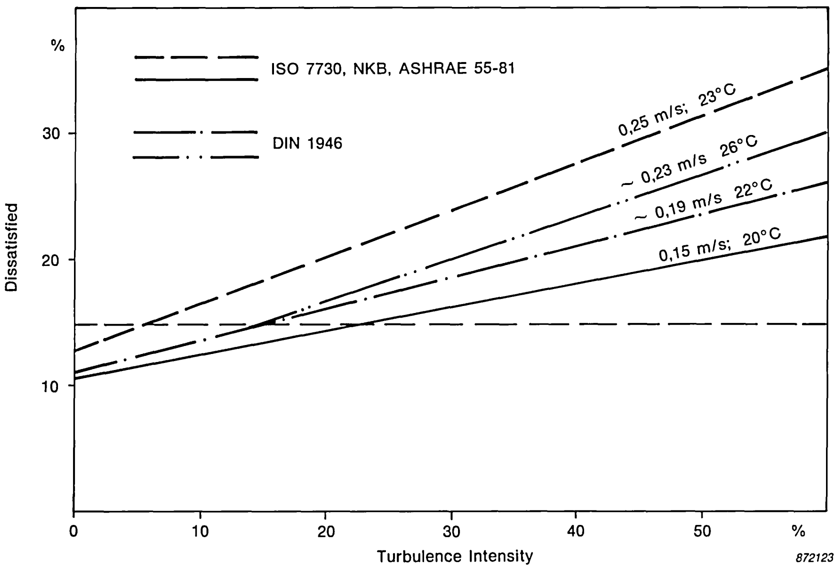


Fig. 26. Maximum percentage dissatisfied, based on the limits for the maximum mean air-velocity and minimum temperature recommended in the standards, as a function of the turbulence intensity. Calculated from the model of draught risk, Fanger et.al. [26]

on the figure determines the values of the turbulence intensity up to which 15% or less of the occupants will be dissatisfied due to draught. For ISO, ASHRAE and NKB summer limits (0,25 m/s and 23°C) airflow with $Tu > 7\%$ will cause more than 15% dissatisfied occupants. For the winter limits (0,15 m/s and 20°C) this value of Tu is 25%. For DIN standard turbulence intensity is between them, $Tu \approx 17\%$.

Thus, the frequent complaints of draught occurring in practice, although mean velocity and air temperature may meet existing standards, may be explained by the significant impact of turbulence intensity on man's draught sensitivity. Values for the mean velocity and the air temperature are recommended in the standards but the turbulence intensity is not considered. Therefore there is a need to update the standards to include this new insight in the draught risk.

What are the practical consequences of the velocity fluctuations' impact on man's draught sensitivity? Traditionally, ventilation systems are designed to establish good mixing of the supply air with the air in the room and low mean air velocity in the occupied zone. In order to fulfil these conditions, the outlets are located far from the occupied zone. The air comes into the space with relatively high velocity and creates high turbulent air flow.

But 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. This has already been utilised to certain extent in the new displacement ventilation system (44,45). The main idea behind the displacement ventilation is that the contaminents are displaced out of, the occupied zone without any mixing. The clean air is supplied directly into the occupied zone from large outlets with low velocity. In order to promote an undirectional displacing flow of the air through the room the turbulence intensity must be as low as possible. For the supply air to cover all floor area and then rise to the ceiling its temperature should be lower than the room air temperature.

Discussion of Results

The air flow in ventilated rooms is very complex and it should be investigated more. Air velocity measurements from different studies with different instruments have to be compared or analyzed together in order to understand the nature of the airflow and to assess the indoor climate in the rooms. Because of these the accuracy of the velocity measurements becomes an important factor.

The ISO Standard 7726 [18] requirements for measuring the velocity are specified (see also previous issue of B & K Technical Review [8]). The measuring instrument should be able to measure air velocity as low as 0,05 m/s, to measure velocity fluctuations as fast as 1 Hz, to give a mean air velocity based on 3 min. measurement and to give the equivalent standard deviation. A further requirement is that the velocity sensor should be omnidirectional, i.e. the air velocity should be measured correctly independent of the velocity direction relative to the sensor (except of course for a small angle around the support of the sensor).

Now the following questions about the accuracy of the velocity measurements connected with the calibration of the probes and their characteristics (static and dynamic) arise:

- Is the period of 3 minutes integration time enough? Very often high velocities occur in periods of more than 3 minutes.
- Is the recommended 1 Hz in the standard enough to register mean velocity and standard deviation with acceptable accuracy? Velocity fluctuations with frequency higher than 1 Hz were registered in rooms and in some cases these fluctuations can contribute a lot to the high frequency range in the energy spectra;
- How far may the calibration of the probes typically made in nearly laminar flow be used in high turbulent flow where velocity changes its direction and has fluctuating frequency?
- How much does the calibration of the probes made in different ways for different instruments affects the accuracy of the velocity measurements?

The above questions regarding the low velocity measuring technique, in general, need answering and they should be studied.

Conclusions

Airflow in rooms is turbulent with turbulence intensity from less than 10 to 70%. Velocity fluctuations with frequency higher than 1 Hz have been measured [12, 14, 15, 16].

A high turbulent airflow is felt as a draught by more people than low turbulent airflow with the same mean velocity and temperature [22, 25, 26].

A model of draught risk has been developed which predicts the percentage of dissatisfied people due to draught as a function of air temperature, mean air velocity and turbulence intensity [26].

The model of draught risk may be used to estimate draught risk in rooms, by measuring mean air velocity, turbulence intensity and air temperature. B & K Indoor Climate Analyzer measures these three airflow characteristics.

Air distribution systems which create low turbulent airflow should be developed to diminish draught complaints.

There is a need to update existing standards to include the turbulence intensity in draught risk.

More investigations on the accuracy of velocity measuring technique, in general, are required.

The airflow in rooms has been investigated in several studies and more has to be done to understand its nature. Quite a few researchers are involved in this problem. Results from different studies must be compared and analyzed together. Air velocity measurements are important for estimation of draught risk in rooms. Therefore the problems with the low velocity measuring technique, in general, should be studied.

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ISSN 007-2621

BV 0034-11

Printed in Denmark by Nærum Offset