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Turbulence correction for thermal comfort calculation

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Abstract

Thermal comfort in ventilated spaces depends mainly on air temperature, air speed and turbulence intensity. Mean air speed is commonly measured with omnidirectional hot sphere sensors, whereas directionally sensitive measurement instruments and CFD-simulations normally give the mean velocity vector. The magnitude of the mean velocity vector in turbulent room air flows can be much lower than the mean air speed due to different time averaging processes. This paper studies the difference both experimentally and theoretically as a function of turbulence intensity. A correction method was developed for calculating estimates for omnidirectional mean air speed and turbulence intensity from directional air velocity data. The method can be applied to the calculation of draught risk and thermal comfort from CFD-simulation results. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Air speed; Air velocity; Turbulence intensity; Draught risk; Thermal comfort

1. Introduction

Thermal comfort in ventilated spaces depends mainly on air temperature and speed. The fluctuations of air speed, which are characterised by turbulence intensity, increase the sensation of draught and thus affect the thermal comfort [1]. For thermal comfort assessment, air speed is normally measured with omnidirectional hot sphere anemometers. The result is expressed as mean air speed and turbulence intensity calculated over the selected measurement period. Indexes for thermal comfort and draught risk are then calculated from these values together with air temperature and other affecting parameters.

Air flow can also be measured by using more advanced instruments with directional sensitivity, such as laser-doppler anemometers (LDA), particle image velocimeters (PIV) or ultrasonic anemometers. These instruments have also been applied to room air flow measurements in laboratory as well as in field applications [2–5]. The measurement result of a directionally sensitive instrument is the air velocity vector, which is described by its magnitude, defined as air speed, and direction. Time averaging of air velocity vectors gives the mean air velocity, which is always smaller than the corresponding mean air speed. This is due to the fact that air speed is always positive, but the velocity vector components can have both positive and negative values. In turbulent flows such as room air flows, the difference can be considerable. Therefore, the use of mean air velocity instead of mean air speed for thermal comfort assessment may lead to incorrect results.

The use of computational fluid dynamics (CFD) simulations for predicting room air flow patterns has been constantly increasing. The simulations have also been used for predicting thermal comfort and draught risk [6–10]. The results of the simulations typically include mean air velocity and turbulence kinetic energy. Thermal comfort and draught risk have nor-

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mally been calculated directly from air velocity results, as no general correction procedures for calculating omnidirectional values have been available.

The purpose of this paper is to study the difference between omnidirectional mean air speed and directional mean air velocity and the corresponding turbulence intensity values as well as the effect of the differences on the estimation of draught risk. The study is based on both theoretical calculations and measurements in a laboratory test room. A correction method is presented for calculating estimates for omnidirectional mean air speed and turbulence intensity from directional air velocity data.

2. Methods

2.1. Air speed and thermal comfort

Air velocity is a vector quantity described by its magnitude (speed), and direction. In most fluid dynamics applications, attention is focused to either instantaneous or averaged velocity vector field. For thermal comfort assessment, however, the air speed is the relevant parameter, because it is related to the cooling effect of the air flow on the skin. Therefore, the air speed is used for the determination of the PMV index which concerns the whole body thermal comfort in ISO 7730 standard [11]. In a turbulent flow, the fluctuation of air speed also has an effect on thermal comfort. The effect of fluctuations has so far been incorporated into the prediction of draught, which is defined as unwanted local body cooling because of air motion. Fanger et al. [1] have suggested Eq. (1) for calculating the draught rating (DR), i.e. percentage of people dissatisfied due to draught:

$$DR = (34 - T_a)(V_o - 0.05)^{0.62}(37 \cdot S_o + 3.14) \tag{1}$$

where: T_a is the air temperature; V_o is the mean air speed (≥ 0.05 m/s); and S_o is the standard deviation of air speed ($\leq V_o$).

The mean air speed and its standard deviation can be measured easily with an omnidirectional hot sphere anemometer. An averaging time of 3 min is normally used. The intensity of turbulence is described by the ratio of Eq. (2):

$$I_o = \frac{S_o}{V_o} \tag{2}$$

where the subscript refers to an omnidirectional value.

2.2. Air velocity and turbulence intensity

Instantaneous velocity vector V and its magnitude $|V|$, the air speed, as defined by Eqs. (3) and (4).

$$V = ui + vj + wk \tag{3}$$

$$|V| = \sqrt{u^2 + v^2 + w^2} \tag{4}$$

In a fluctuating velocity field, the vector can be presented as a sum of the mean velocity vector and a varying vector that has a zero mean value, as shown in Eq. (5).

$$V = \overline{V} + V' \tag{5}$$

The components of the velocity vector can be presented similarly (Eq. (6)).

$$u = \overline{u} + u', \quad v = \overline{v} + v' \quad \text{and} \quad w = \overline{w} + w' \tag{6}$$

The mean velocity vector can be calculated by averaging its components over a period T (Eq. (7)).

$$\overline{V} = \frac{1}{T}\int_0^T V\,dt = \overline{u}i + \overline{v}j + \overline{w}k \tag{7}$$

The mean velocity vector can be measured with directional sensors by sampling the three velocity components and calculating the mean values. The magnitude of the mean velocity vector V_V can be calculated from Eq. (8).

$$V_V = |\overline{V}| = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2} \tag{8}$$

However, the output of the omnidirectional sensor gives the magnitude of the instantaneous velocity vector. Averaging the output gives the mean air speed V_o (Eq. (9)), which always has a higher value than the magnitude of the mean velocity vector (Eq. (8)).

$$V_o = |\overline{V}| = \frac{1}{T}\int_0^T |V|\,dt \tag{9}$$

V_o can also be measured with directional sensors by calculating the magnitude of each sampled velocity vector and taking the average of the magnitudes.

The turbulence intensity in a 3-dimensional flow field is normally defined as the standard deviation or RMS-value of the velocity fluctuations divided by the magnitude of the mean velocity vector [12] (Eq. (10)).

$$I = \frac{S_V}{V_V} = \frac{\sqrt{\frac{1}{3}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})}}{V_V} \tag{10}$$

The kinetic energy of the fluctuating motion k is closely connected to turbulence intensity by Eq. (11).

$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) = \frac{3}{2}I^2V_V^2 \tag{11}$$

The turbulence intensity can be measured with directional sensors by calculating the standard deviations of the velocity components. However, this requires the sensor to be fast and small enough to follow the velocity fluctuations. The turbulence kinetic energy k is also normally calculated in CFD-simulations as a part of the turbulence modelling.

2.3. Laboratory measurements

The laboratory test arrangement is shown in Fig. 1. The dimensions of the test room are $10 \times 3 \times 6$ m and it is thermally insulated from the surrounding hall. Air was supplied into the room through two 3 m long Activent nozzle ducts located at 3 m height symmetrically in the room.

Three convective heaters with dimensions $1.2 \times 0.4 \times 0.1$ m were placed in the central plane, two with 600 W heating power 0.5 m from the walls, and one with 1200 W power in the middle of the room. The supply air flow rate was 0.35 m^3/s, which gave an air change rate of 7 l/h. Calculated temperature difference between supply and exhaust air was 5.7°C.

The air velocity was measured with two 3-dimensional Kaijo-Denki WA-390 ultrasonic anemometers, which have an accuracy of ± 0.02 m/s (Fig. 1). The ultrasonic anemometers measure air velocity with three pairs of ultrasonic sensors, each pair having a distance of 50 mm. Air temperature was measured with Craftemp thermistors, which were calibrated to give an accuracy of ± 0.1°C at room temperature.

Measurements were carried out by traversing the sensors in the central plane of the test room with an automatic traversing system (Fig. 1). The traversing was done in half of the central plane with a spacing of 0.1 m between measurement points. The averaging time in each point was 3 min and the sampling frequency was 1 Hz. The number of measurement points was ca 2000 and the number of samples in each point was 180 for each variable. The supply air flow rate and temperature were monitored and kept constant during the traversing.

The actual sampled variables were the three components of the velocity vector: u, v and w. From each sample, the air speed was calculated according to Eq. (4). In the end of the 3-min sampling period, the mean values and standard deviations of the velocity vector components and air speed were calculated. The turbulence intensities for air velocity and air speed were then calculated from Eqs. (10) and (2). Finally, the draught risk values were calculated according to Eq. (1) from both omnidirectional air speed data and from the directional velocity vector data.

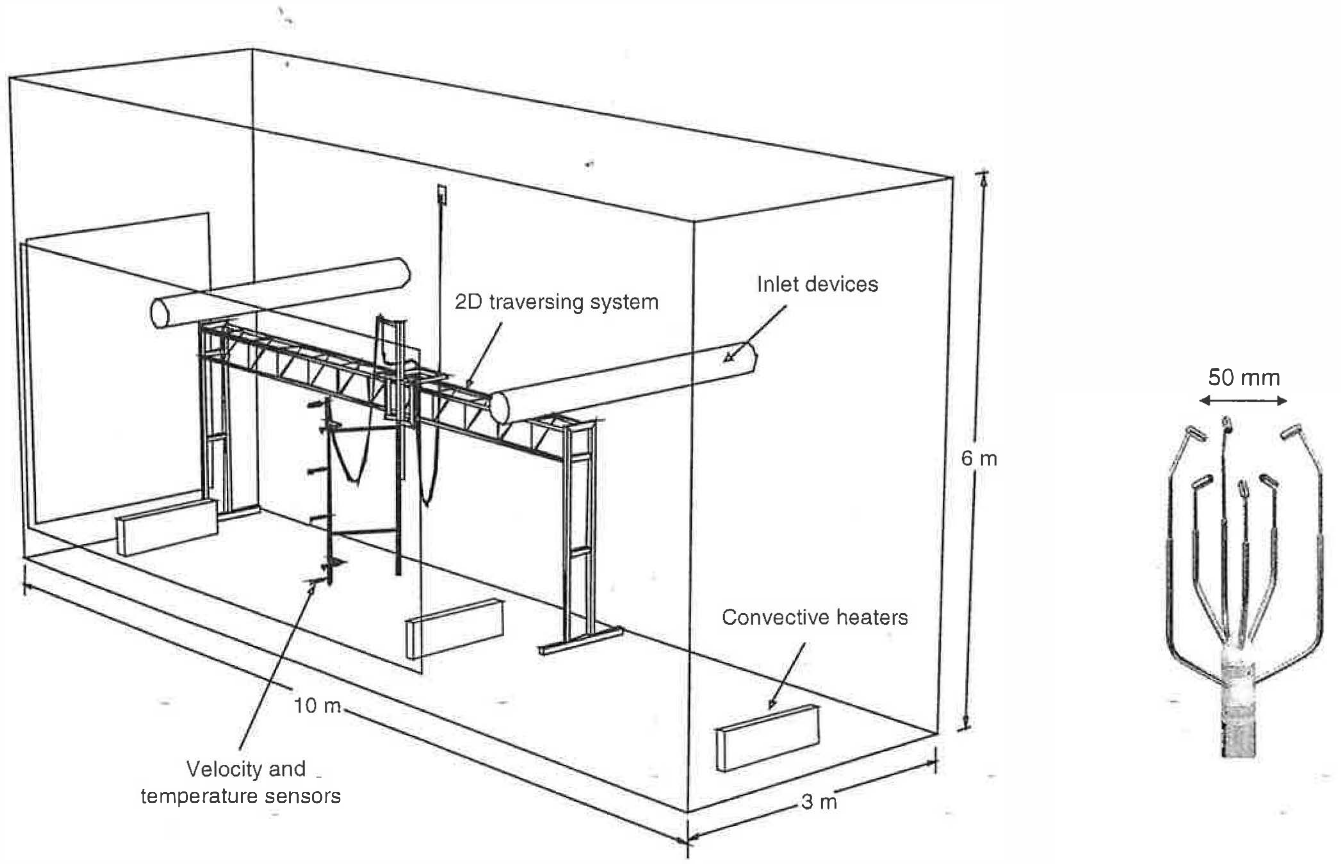
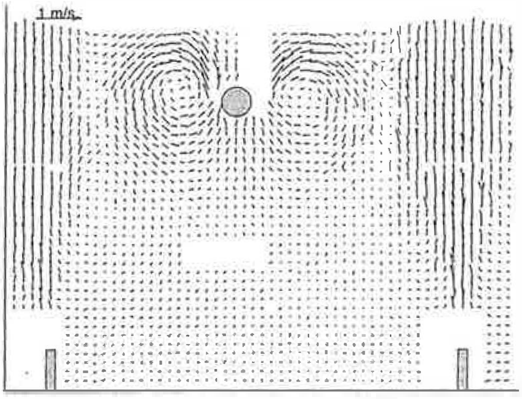


Fig. 1. Laboratory test room and the sensor of the ultrasonic anemometer.



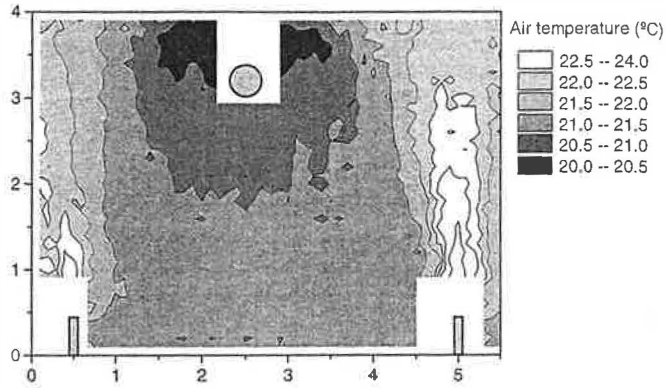


Fig. 2. Mean velocity vectors and temperature distribution in the measurement plane.

3. Results

3.1. Laboratory measurements

The flow pattern and temperature distribution in the measurement plane of the laboratory test room are shown in Fig. 2. The flow pattern is dominated by the plumes above the heaters and the eddies on both sides of the inlet device. The mean air velocity in the occupied zone between the plumes is low. The temperature differences in the occupied zone are small when the plumes are excluded.

The distributions of air speed and air velocity are shown in Fig. 3. The differences in the two variables are highest in the occupied zone and in the turbulent regions between the plumes and the supply air flow.

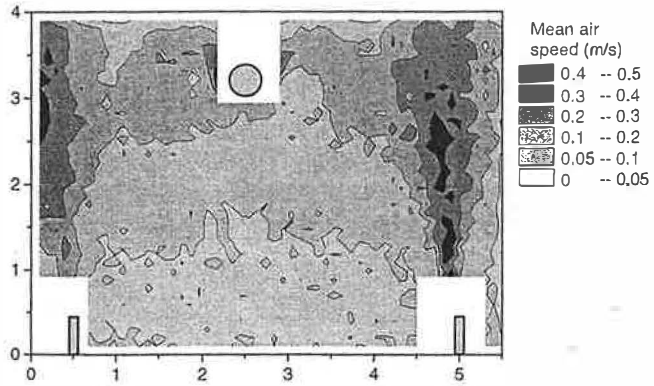
The standard deviations of air velocity and air speed are shown in Fig. 4. The difference of the values is smaller than that of the corresponding velocity and speed values, especially in the occupied zone.

The distributions of the turbulence intensities are shown in Fig. 5. The omnidirectional turbulence intensities are mainly between 40 and 60%, whereas there are large fluctuations in the directional turbulence intensity values. In the occupied zone, where the air velocity is low, the directional turbulence intensity is high. In the plumes, the difference between the two turbulence intensities is small.

The draught risk distributions calculated from omnidirectional and directional data are shown in Fig. 6. In the occupied zone, the draught risk calculated from the air velocity data is considerably lower than the omnidirectional one due to the difference between air speed and air velocity values. In the plume region the difference is smaller.

3.2. Theoretical difference between mean air speed and mean air velocity

The difference between the results of omnidirectional and directional velocity measurement was calculated as a function of turbulence intensity. The calculations are based on a turbulence model in which the three turbulent velocity components are uncorrelated and can be represented by normal distributions. The calculations were done with SAS 6.12 statistical software by first generating random velocity vectors with normally distributed velocity components and then calculating the mean air speed and turbulence intensity from the vec-



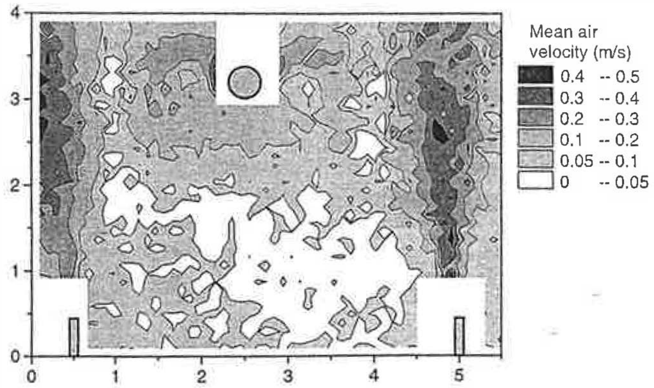


Fig. 3. Distribution of air speed and air velocity in the measurement plane.

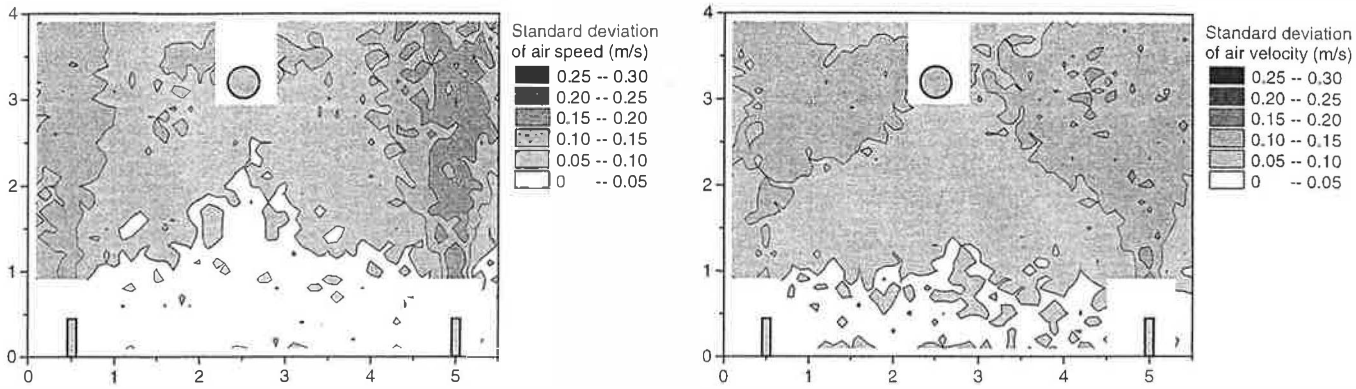


Fig. 4. Fluctuation of air speed and air velocity.

tors. The number of generated vectors was 10^7 for each turbulence intensity value.

The results are shown in Figs. 7 and 8, together with corresponding data points from laboratory measurements. The curves represent typical distributions of turbulent kinetic energy components in three flow types: isotropic turbulence ($S_y = S_x$, $S_z = S_x$); wall jet ($S_y = 0.6\ S_x$, $S_z = 0.8\ S_x$); and flow behind a plate ($S_y = 2S_x$, $S_z = S_x$). The main flow is in the x-direction.

Fig. 7 shows the influence of turbulence intensity on the mean value of air speed. With 50% turbulence intensity, the mean air speed is typically 15–25% higher than the mean air velocity. The measured differences were slightly lower than the calculated ones. Fig. 8 shows the correlation between the two turbulence intensities. The deviation of the measured values is large, but they support the trend of the calculated results.

3.3. Turbulence correction formulas

The curves presented above can be used as correction curves for estimating omnidirectional mean air speed and turbulence intensity when the corresponding vector quantities are known. Calculation formulas for the correction curves were developed for the case of isotropic turbulence. As the presented measurement results indicate, the corrections cannot be expected to be universally valid because of the varying characteristics of turbulence. However, such corrections can be useful for reducing the error of thermal comfort calculation. Similar curves have been used earlier for correcting hot-wire anemometer measurement results in turbulent flows [13,14]. The correction was applied with success to a recirculating flow behind a flat plate normal to the flow and to a free jet flow, but with less success to a boundary layer flow.

The correction formula needs to be developed only for either turbulence intensity or mean air speed because of the connection between the two variables. It can be shown that the mean values and standard deviations of air speed and air velocity are connected according to Eq. (12):

$$V_o^2 + S_o^2 = V_V^2 + 3S_V^2 = V_{mod}^2 \qquad (12)$$

where V_{mod} is called the 'modified air speed' [15], which can be useful when comparing CFD results with omnidirectional measurement results. From this connection, Eq. (13) for turbulence intensity can be writ-

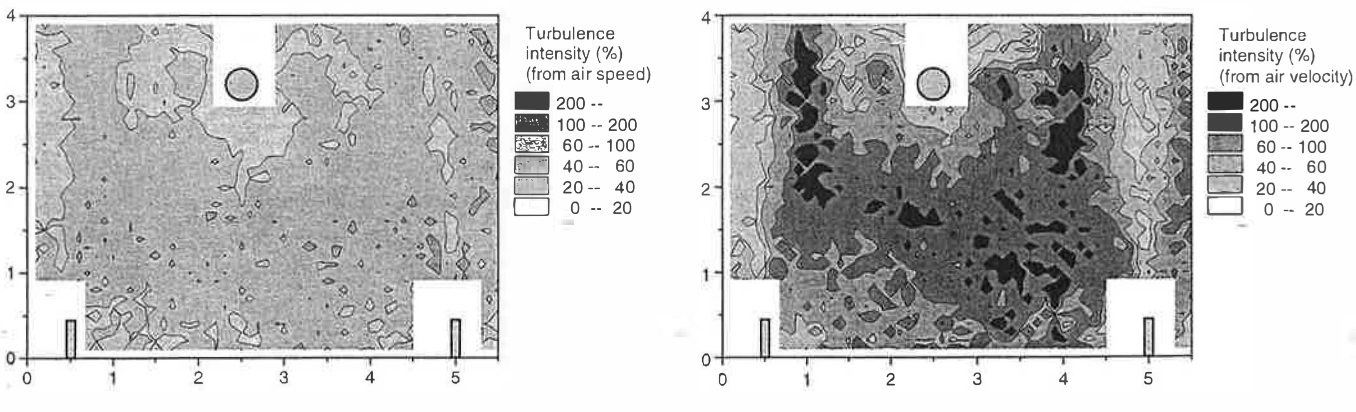


Fig. 5. Turbulence intensity based on air speed and air velocity.

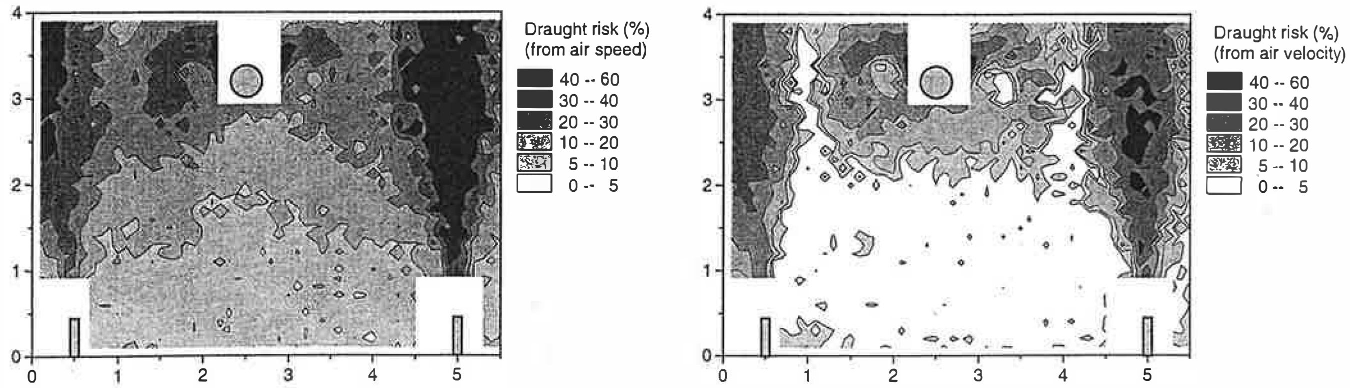


Fig. 6. Draught risk based on air speed (correct) and air velocity (incorrect).

ten:

$$I_o = \sqrt{(1 + 3I^2)\frac{V_V^2}{V_o^2} - 1}. \qquad (13)$$

This equation is valid for all turbulent flows. A correction formula for the velocity ratio V_o/V_V of isotropic turbulence was developed by non-linear least squares curve fitting. At low turbulence intensities, the statistically calculated V_o/V_V curve (Fig. 7) was found to follow a simple parabolic equation. At high turbulence intensities, the ratio was found to approach a linear relationship $V_o/V_V = 1.596 \cdot I$, where the constant 1.596 is the ratio 2·*Mean deviation/Standard deviation* for normal distribution. Therefore, the curve fitting was carried out in two pieces and Eqs. (14) and (15) were obtained for the correction formula of V_o/V_V.

$$\frac{V_o}{V_V} = 1 + I^2, \quad I \leq 0.45 \qquad (14)$$

$$\frac{V_o}{V_V} = \frac{1.596 \cdot I^2 + 0.266 \cdot I + 0.308}{0.173 + I}, \quad I > 0.45 \qquad (15)$$

The maximum relative error of the calculation formulas is 0.1% for V_o/V_V and 1.0% for I_o.

3.4. Testing of the correction formulas

The correction formulas were applied to the measurement results by calculating corrected values from the directional air velocity and turbulence intensity data. The obtained omnidirectional results are shown in Fig. 9. The distributions of the calculated omnidirectional values are close to the measured ones shown in Figs. 3, 5 and 6.

The mean values of the measured and calculated variables were computed for different zones of the test room. Three zones with different flow characteristics were selected as shown in Fig. 10; the occupied zone, the plume zone and the inlet zone near the inlet device. The spatial mean values are presented in Table 1.

The difference between the measured omnidirectional and directional mean values was remarkable in

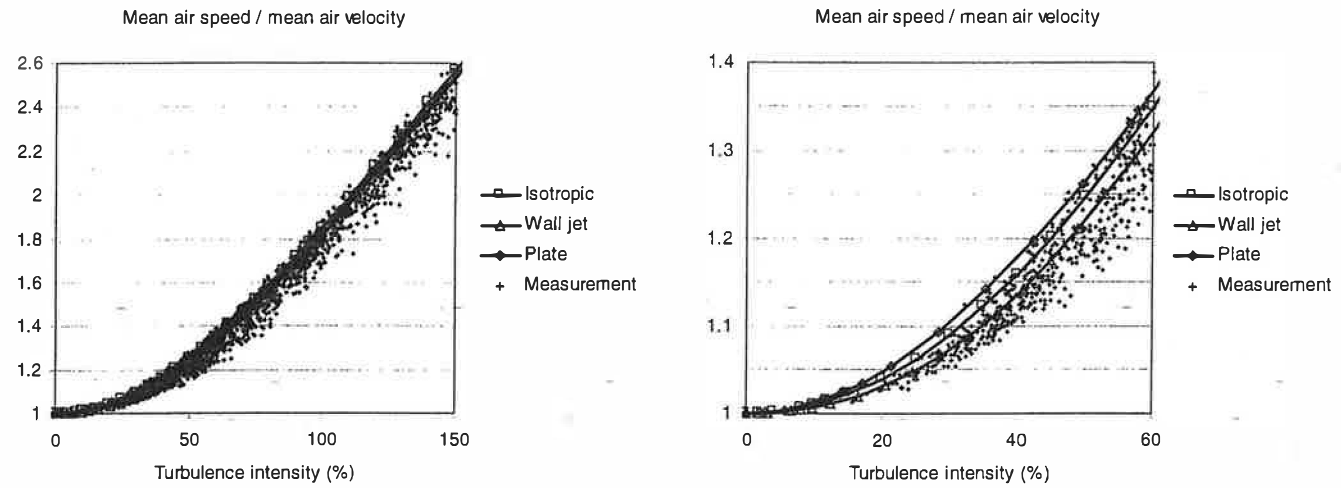


Fig. 7. The ratio of the time averaged values of air speed and air velocity as a function of turbulence intensity.

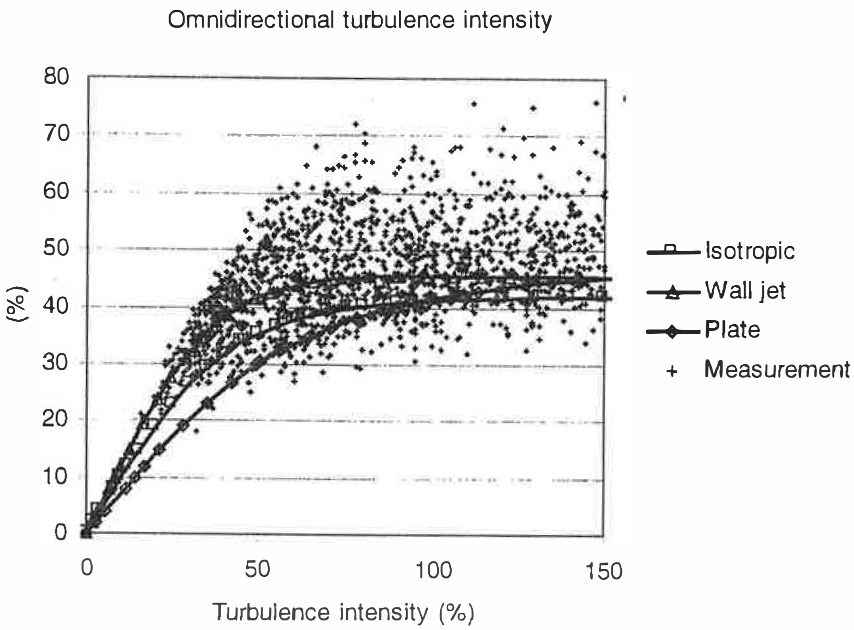


Fig. 8. The correlation between omnidirectional and directional turbulence intensities.

all zones. The directional data yielded 6–7 units lower draught risk values than the omnidirectional data and the mean air velocity was 5–7 cm/s lower than the mean air speed.

The omnidirectional results obtained with the correction formulas were close to the measured results. The formulas gave correct mean values for air speed in all zones and for draught risk in the occupied zone

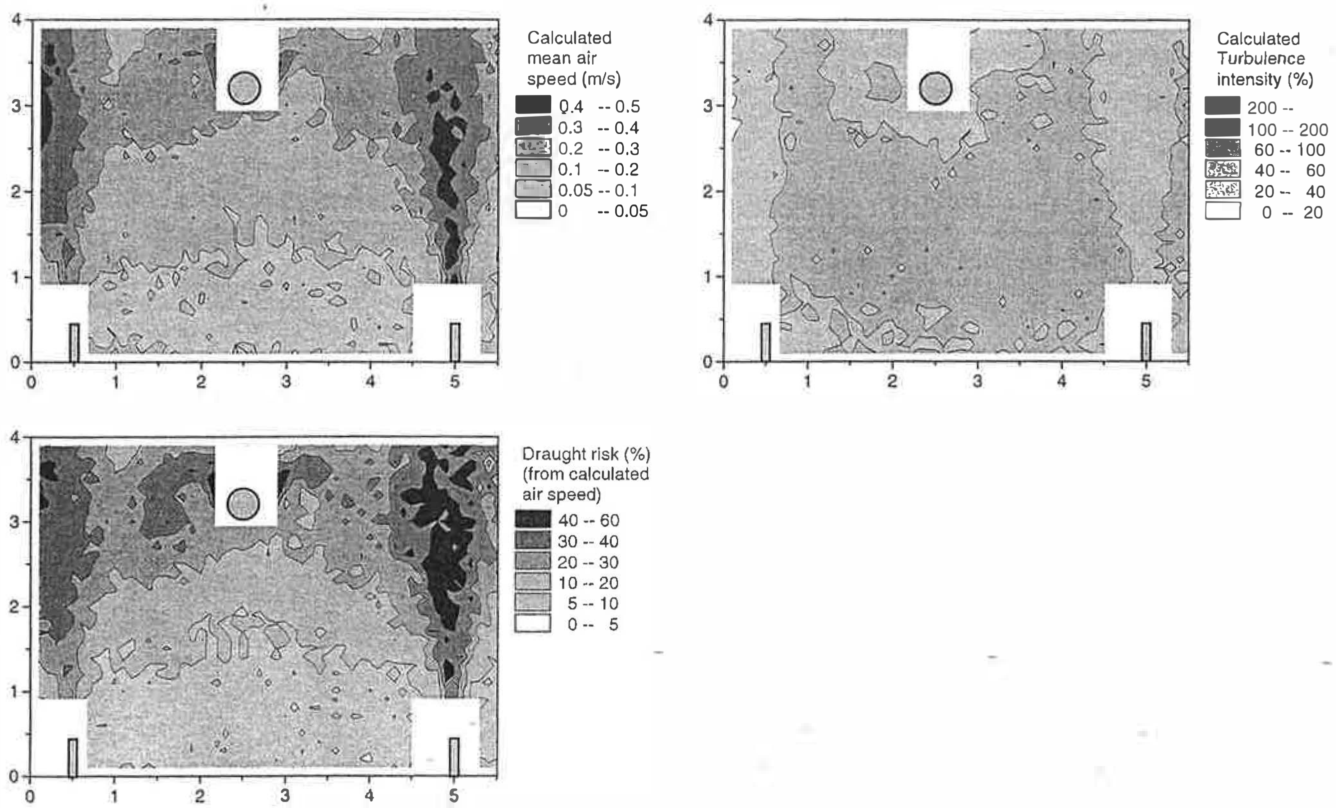


Fig. 9. Omnidirectional results obtained by using the correction formulas.

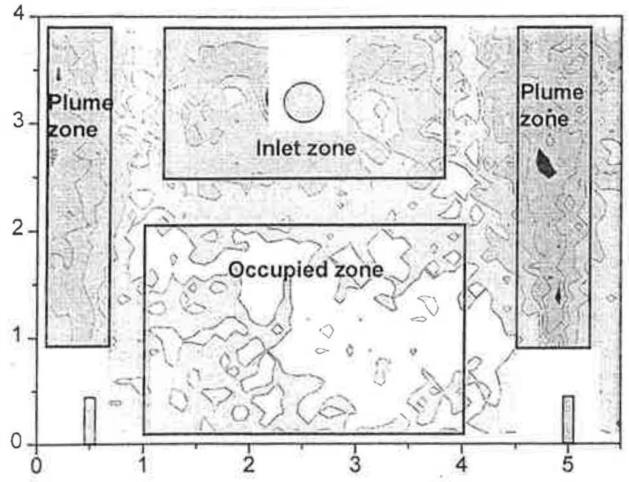


Fig. 10. Selected zones for spatial averaging of the variables.

and inlet zone. The corrected omnidirectional turbulence intensity was lower than the measured one in the occupied zone and the plume zone.

4. Discussion

The starting point of this study was that the definitions of mean air velocity and turbulence intensity normally used in thermal comfort studies are different from those adopted in fluid mechanics. Thermal comfort is commonly measured by using omnidirectional sensors yielding results as mean air speed. In contrast, the result of CFD-simulations or directional velocity measurements is normally the mean air velocity.

The correlation between directional and omnidirectional values was studied both theoretically and with measurements in a laboratory test case. The theoretical correlation was developed by statistical calculations with the assumption of normally distributed and uncorrelated turbulent velocity components. The correlation was calculated for three different turbulent flow types and compared to the measurement data. At high turbulence intensity values, the mean air speed grows linearly with increasing turbulence, whereas the omnidirectional turbulence intensity saturates at the 40–60% level.

The measurement data supported the trend of the calculated correlation curves, but the spread of measured values was large. The spread can be explained by variation in the statistical distribution of turbulent velocity components. The characteristics of turbulence depend on the local flow situation and can deviate substantially from isotropy and normal distribution.

The velocity measurements were done with an ultrasonic anemometer, which has a 50 mm spacing between the sensor elements. The size is larger than the smallest eddies in room air flows. Therefore, the sensor averages the velocity fluctuations spatially. The effect of this averaging on the capturing of the velocity fluctuations is not known. However, the turbulent kinetic energy of the larger eddies in room air flows is known to be dominant and therefore the effect may be small.

The difference between the omnidirectional mean air speed and the directional mean air velocity and the corresponding turbulence intensity values was found to be substantial in the measured laboratory test case. The mean air speed was even 20–100% higher than the mean air velocity depending on the flow type. Calculation of draught risk from directional air velocity and turbulence intensity instead of the omnidirectional values resulted in a notable underestimation of thermal discomfort. In the occupied zone, the draught risk was 9% when calculated from the omnidirectional data and 2% when calculated from the directional data. Therefore, the results of CFD-simulations or directional velocity measurements should be corrected in

Table 1
Spatial mean values of the variables in different zones of the flow field

	Velocity or speed (m/s)	Turbulence intensity (%)	Draught risk (%)
Occupied zone			
Directional	0.05	147	2
Omnidirectional	0.10	48	9
Calculated omnidirectional	0.10	41	9
Inlet zone			
Directional	0.17	77	23
Omnidirectional	0.24	39	29
Calculated omnidirectional	0.24	37	28
Plume zone			
Directional	0.25	57	29
Omnidirectional	0.30	45	36
Calculated omnidirectional	0.31	34	32

order to get unambiguous thermal comfort estimates at PMV and DR.

In this paper a proposal for correction formulas for isotropic turbulence was developed based on the calculated correlation curves. The developed analytical expressions followed the curves with 0.1% accuracy for air speed and 1.0% accuracy for turbulence intensity. The application of the correction formulas to the measured test case gave good results, especially in the occupied zone, where the mean values of draught risk and air speed were estimated correctly. Therefore, this procedure can be recommended for estimation of thermal comfort from CFD results.

The difference between the mean air speed and velocity as well as the corresponding turbulence values is notable in room air flows. This should be taken into account when using the results for thermal comfort studies. On the other hand, care should also be taken when using omnidirectional velocity measurement results for validation of CFD-simulations in turbulent flows.

Acknowledgements

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