Test Method for Describing Directional Sensitivity of Anemometers for Low-Velocity Measurements Indoors

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ABSTRACT

Thermal anemometers with omnidirectional sensors are recommended in the standards to be used for low-velocity measurements indoors. Requirements for the directional sensitivity of the velocity sensor are prescribed. However, a method for testing the directional sensitivity of low-velocity anemometers does not exist. A simple test procedure is used in practice to identify the so-called "yaw" and "roll" directional sensitivity of an omnidirectional velocity sensor. However, this procedure cannot be used to assess the way in which the accuracy of the velocity measurements is influenced in practice by the directional sensitivity of the sensor.

In this paper, a test method for describing the directional sensitivity of omnidirectional velocity sensors is proposed and used experimentally. The test method can be used to define the impact of directional sensitivity on the accuracy of the velocity measurements. Further, the proposed method can be used to improve the accuracy of the velocity measurements by optimizing the static calibration of low-velocity anemometers and the positioning of the velocity probe during field measurements. The method is suggested for inclusion in future indoor climate standards.

INTRODUCTION

In order to assess the indoor environment as well as the air distribution in rooms, measurements of low velocity are needed (ASHRAE 1992, 1990; ISO 1995). Requirements for low-velocity measuring instruments are specified in ANSI/ASHRAE Standard 55-1992 (ASHRAE 1992), ANSI/ASHRAE Standard 113-1990 (ASHRAE 1990), and ISO Standard 7726 (ISO 1985) and its new draft (ISO 1996).

It is recognized that the air velocity in rooms changes magnitude and direction. Therefore, requirements regarding the directional sensitivity of low-velocity anemometers have been considered. The standards recommend using anemometers with omnidirectional sensors when the direction of the velocity vector at the measuring point in the flow is not known and changes in time. ISO Standard 7726 (ISO 1985, 1996) requires that the sensor measure the velocity with a defined accuracy, whatever the direction of the flow, within a solid angle of 3π st. Within the defined range of a special angle, ASHRAE Standard 55 requires the accuracy of the measured mean velocity (v) to be ±0.05 m/s, while according to ISO Standard 7726, the required accuracy should be ±(0.05 + 0.05 v) m/s and the desired accuracy should be ±(0.02 + 0.07 v) m/s.

PRESENT TEST PROCEDURE

At present there is no standard method for testing the directional sensitivity of omnidirectional anemometers. Low-velocity thermal anemometers with an omnidirectional type velocity sensor are recommended and are most used in practice for indoor measurements, especially within the occupied zone of a room. A common procedure for the manufacturers and users of these anemometers is to test the so-called "yaw" and "roll" sensitivity of the sensor. This test is performed by positioning the sensor at a point in a uniform isothermal laminary airflow with known velocity. Typically, the velocity probe is positioned so that its axis is perpendicular to the flow direction. Several measurements of the mean velocity are performed by rotating the probe at different "roll" angles, ω, and different "yaw" angles, φ. The two angles are defined in Figure 1. First, measurements are performed to define the roll sensitivity of the velocity sensor by rotating the probe around its axis at different angles ω in the range 0° ~ 360°. Then, at a roll angle equal to 0°, the probe is rotated at different yaw angles, φ, around an axis through the sensor's center and perpendicular to the axis of the probe, and measurements of the mean velocity are made. The mean velocity is defined as the instantaneous velocity integrated over an interval of time. The interval of time is recommended in the standards to be

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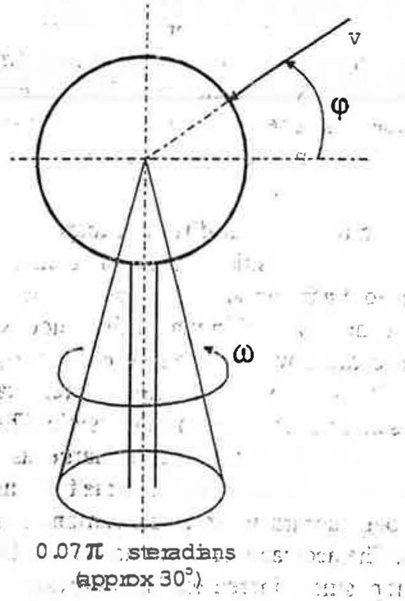

Figure 1 *Definition of the yaw angle, φ, and the roll angle, ω, for an omnidirectional probe in relation to the velocity, v. The solid angle Ω_s=0.07πst disregards the influence of the support of the sensor and the body of the probe.*

three minutes. The measured mean velocity as a function of the roll and yaw angles is then presented.

Most omnidirectional probes have acceptable roll characteristics, i.e., small deviations of the mean velocity measured at different roll angles from the reference velocity are observed. However, the yaw characteristic shows rather large deviations. Figure 2 shows an example of a yaw characteristic of a low-velocity anemometer with an omnidirectional velocity sensor. In the figure, the measured mean velocity as a function of the yaw angle is shown at a roll angle of 0°. The reference velocity, equal to 0.25 m/s, is the mean velocity measured by the instrument at roll and yaw angles equal to 0°. The example in Figure 2 shows that the accuracy of the measured mean velocity depends strongly on the yaw angle. The accuracy of the mean velocity measurements will comply with those recommended in ASHRAE Standard 55, i.e., ±0.05 m/s in the yaw angles range from −60° to 60° and from 130° to 240°. According to the required accuracy in ISO Standard 7726, the mean velocity measurements will be acceptable in the yaw angles range from −75° to 75° and from 105° to 250°. When the desirable accuracy recommended in this standard is considered, the ranges of acceptable yaw angles will be very limited (from −45° to 45° and from 140° to 220°). This means that an omnidirectional velocity sensor with directional characteristics, as shown in Figure 2, will not comply with the requirements for accurate velocity measurement within a solid angle of 3πst, as specified in both standards (ASHRAE 55 and ISO 7726).

The static calibration of the low-velocity probes is performed by the manufacturers always at a fixed positioning of the sensor according to the flow where it is calibrated. The roll and yaw angles of the static calibration are accepted as reference angles. These angles are used by the users to check the calibration of the anemometers after they have been used for a certain period of time. It is also recommended by the manufacturers that during field measurements, the velocity probe be positioned in the flow as close as possible to its positioning for static calibration.

Comprehensive measurements of the airflow in the occupied zone of rooms performed with a three-dimensional laser doppler anemometer (Finkelstein et al. 1996) indicate that the air velocity changes its magnitude and direction in a wide range. This means that during measurements in rooms the velocity vector will most often change its direction with respect to the probe orientation differently than the roll and yaw calibration of the sensor.

At present there is no method that makes it possible to assess the impact of the directional sensitivity of the omnidi-

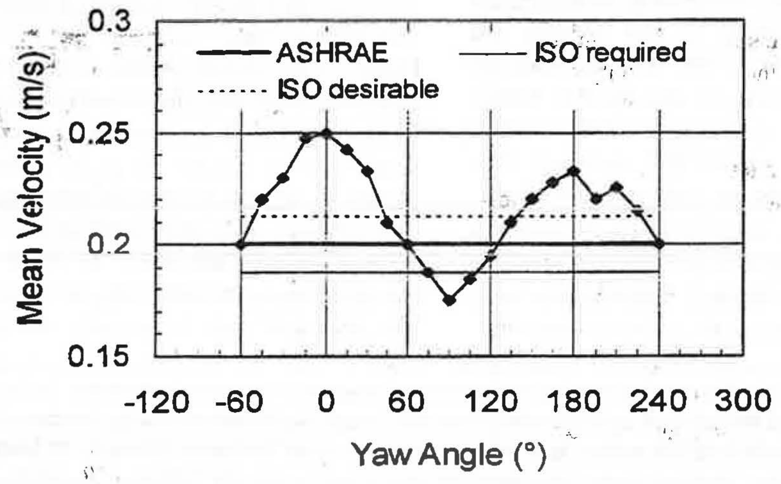

Figure 2 *Yaw characteristic of an omnidirectional velocity sensor. Reference mean velocity is 0.25 m/s measured at yaw angle equal to 0°.*

rectional probe on the accuracy of the velocity measurements. Such a method is proposed and developed in this paper. This research is part of a comprehensive recent study on the accuracy of low-velocity measurements by thermal anemometers with an omnidirectional type sensor (Melikov 1997).

THE TEST METHOD

It is suggested that this method be used for determining the directional sensitivity of omnidirectional velocity probes used for the measurement of mean velocity and turbulence intensity of airflow indoors. The low velocity range between 0.05 and 1 m/s is considered in the method.

Definitions

The directional sensitivity describes the behavior of the probe when the velocity changes its direction with respect to the probe orientation. The directional sensitivity affects both the mean velocity and the turbulence intensity calculated from samples of instantaneous velocity. It is, therefore, necessary to define two directional sensitivities: mean velocity directional sensitivity and turbulence intensity directional sensitivity.

Mean velocity directional sensitivity (MDS) is defined as the deviation in percent between the actual mean velocity and the mean velocity measured by the probe when it is exposed to a velocity with a constant magnitude, the direction of which varies as uniformly as possible over a solid angle of 3.93π steradian (Figure 1). The limitation of solid angle $\Omega_s = 0.07\pi$ steradian disregards the influence of the support of the sensor and the probe body.

Turbulence intensity directional sensitivity (TDS) is defined as a ratio in percent between the standard deviation created by the directionally induced velocity variations and the mean velocity.

The definitions of MDS and TDS are acceptable provided the probe is positioned so that the main flow direction remains within the defined solid angle and as close as possible to its positioning for static calibration.

The mean velocity directional sensitivity is a measure of the maximum error introduced in the mean velocity measured by the anemometer with an omnidirectional probe. The turbulence intensity directional sensitivity shows the maximum contribution to the turbulence intensity measured by the anemometer due to the directional sensitivity of the omnidirectional velocity probe.

Directional Sensitivity Calibration Procedure

The directional sensitivity is determined by placing the probe in a uniform laminar flow field with a constant air velocity of 0.2 m/s. The cross section of the flow should be large enough to allow the probe to rotate fully around two axes without any blocking effect.

The velocity output from the probe/anemometer is recorded. If the anemometer has an average function, the velocity should be measured over a suitable integration period, for example, 30 seconds or more, in order to diminish the impact of longitudinal velocity fluctuations (if any) on the accuracy of the measured velocity. The velocity measured with the probe positioned as during the static calibration is defined as actual mean velocity, v, i.e., it is the reference mean velocity.

By rotating the probe at different angles, φ_i and ω_i, as defined in Figure 3, its position in relation to the flow direction will be changed. Each measurement position, φ_i and ω_i, will define a solid angle Ω_i within which the velocity sensor will be sensitive to the flow. The angles φ_i and ω_i should be selected in order to achieve a solid angle representation around the velocity sensor that is as even as possible. The number of measurement positions should be as large as possible to achieve good representation of all possible flow directions and sufficient enough accuracy in the calculation of the MDS and TDS factors. The accuracy will increase when the number of measurement positions increases. The analyses show that for 50 measurement positions, the MDS will be estimated with an accuracy of ±2.6% (confidence level 0.95, test t-student) and the TDS with an accuracy of ±12% (confidence level 0.9, test chi-square). The number of measurement positions should be more than 50. Normally, the static calibration of the probe is carried out at fixed angles φ and ω, which should be accepted as equal to 0, i.e., $\varphi = 0°$, $\omega = 0°$ will define the reference position of the probe.

The solid angle Ω_i representing a particular positioning of the probe, defined in Figure 3 as $\varphi_i \pm \Delta\varphi_i$ and $\omega_i \pm \Delta\omega_i$, can be calculated by the following equation when $\varphi_i \pm \Delta\varphi_i \leq 90°$:

$$\Omega_i = 4\Delta\omega_i \cos\varphi_i \sin\Delta\varphi_i \quad (1)$$

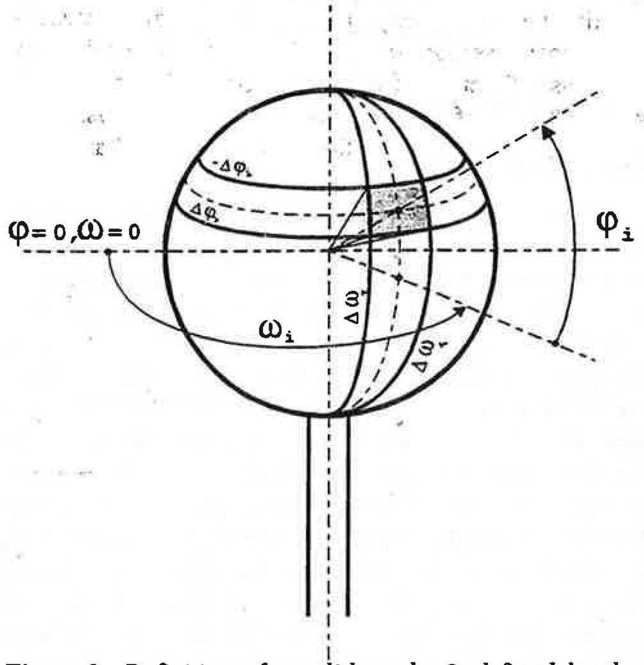

Figure 3 Definition of a solid angle Ω_i defined by the angles φ_i and ω_i and their deviations $\pm\Delta\varphi_i$ and $\pm\Delta\omega_i$.

It is recommended during the tests to position the probe so that similar solid angles are represented. One possible way to achieve even representation of solid angles is suggested in the following section. In case of uneven solid angle representation, a weighting of the velocity measurements should be made. The weighting factor, w, is defined as

$$w_i = \frac{\Omega_i}{4\pi - \Omega_s} \qquad (2)$$

As already discussed, the solid angle $\Omega_s = 0.07\pi$ steradian disregards the influence of the support of the sensor and the body of the probe (Figure 1).

Calculation of Directional Sensitivity

The mean velocity directional sensitivity (MDS) can be calculated as

$$\mathrm{MDS} = \frac{\sum_{i=1}^{n} w_i(v_i - v)}{v} \cdot 100 \qquad (3)$$

where

w_i = the weighting factor,

v_i = the mean velocity measured by the probe/anemometer at each particular position,

v = the reference mean velocity measured at $\varphi = 0°$, $\omega = 0°$.

The turbulence intensity directional sensitivity (TDS) can be calculated as

$$\mathrm{TDS} = \frac{\left[\sum_{i=1}^{n} w_i(v_i - v)^2\right]^{0.5}}{v} \cdot 100 \qquad (4)$$

VALIDATION OF THE METHOD

Anemometers Tested

Two thermal anemometers, B and D, with omnidirectional type velocity sensors were tested to validate the proposed test method. The anemometers are available on the market and were selected because their velocity sensors are of very different design. Anemometer D has a velocity sensor designed as a quartz ball with a diameter of 3 mm. The quartz ball is coated with a heated nickel layer; therefore, the heat is generated directly on the surface of the velocity sensor. The velocity sensor of anemometer B has an internal production of heat in a glass-encapsulated ellipsoidal thermistor bead with a diameter of less than 1 mm. It is foreseeable that deviations from the ideal picture of a uniform heat source may be less for the B than for the D probe because a possible nonuniform heat distribution is "smoothed out" when the heat is produced internally. Both anemometers have analog outputs. A special shield is designed to protect the sensors from damage during field measurements. The measurements reported below were performed without the protective shield. The velocity probes and the anemometers are described in detail by Popiolek et al. (1997) and Melikov et al. 1997.

Test Facilities

The tests were carried out in a free jet wind tunnel. The jet is circular with a diameter of 0.150 m. The wind tunnel generates a laminar steady-state airflow in the velocity range 0.10 to 30 m/s. The tunnel is calibrated by a reference anemometer. The tested probes were located in the center of a cross section of the jet with an even velocity distribution over a diameter of 0.1 m. A traversing mechanism was used to position the tested velocity probes at different roll and yaw angles, ω and φ, in the flow. The tested probe was positioned in the flow with its axis perpendicular to the velocity direction, as shown in Figure 4. At this position, the yaw angle was equal to zero, $\varphi = 0°$. At six yaw angles, as defined in Table 1, different roll angles, ω, were obtained by rotating the probe around its axis. A precision potentiometer connected with a voltmeter was used to adjust and to reproduce the roll angles accurately. Typically, the static calibration of omnidirectional velocity probes is performed at fixed roll and yaw angles, which are provided by the manufacturers. These angles were used in the tests as reference angles, $\varphi = 0°$, $\omega = 0°$.

The following experimental procedure was used. The tested probe was positioned in the flow with a mean velocity of 0.2 m/s. First, it was positioned at $\varphi = 0°$ and mean velocity measurements were performed at different roll angles, ω, as defined in Table 1. At the end, the probe was positioned at the reference position, $\varphi = 0°$, $\omega = 0°$, and measurement of the mean velocity was repeated. This was done to check the stability of the wind tunnel. The probe was then positioned at another yaw angle, and the procedure was repeated. During the experiments, the velocity of the generated flow changed less than ±0.002 m/s.

During the measurements, an analog signal from the tested anemometer was recorded for 100 seconds and then

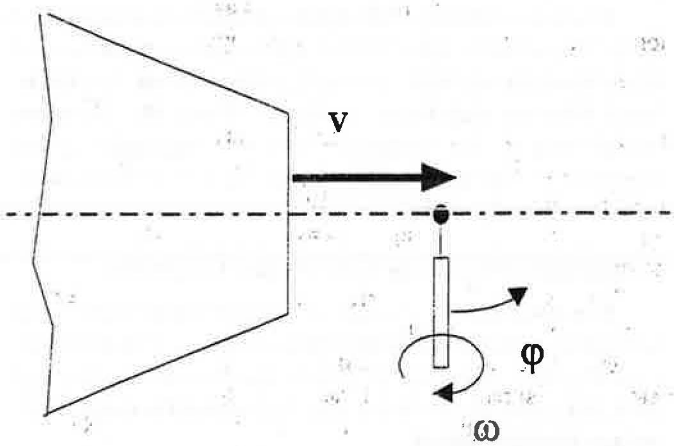

Figure 4 Location of the tested sensors in the jet during the experiments as seen from above.

TABLE 1

Values for the Yaw, φ, and Roll, ω, Angles Used for Testing the Directional Sensitivity of Omnidirectional Velocity Probes (Weighting Factors Used for Calculation of the Mean Velocity Directional Sensitivity are Also Listed)

φ	–60	–30	0	30	60	90
ω	0	0	0	0	0	1
	45	30	24	30	45	
	90	60	48	60	90	
	135	90	72	90	135	
	180	120	96	120	180	
	225	150	120	150	225	
	270	180	144	180	270	
	315	210	168	210	315	
		240	192	240		
		270	216	270		
		300	240	300		
		330	264	330		
			288			
			312			
			336			
No. of Points	8	12	15	12	8	1
Total No. of Points						56
Weighting Factors	0.0165	0.0190	0.0176	0.0190	0.0165	0.0173

used to calculate the mean velocity. This measuring time was sufficiently long, as the airflow had a low turbulence intensity (<2%), i.e., the velocity fluctuations in the flow were rather small. Often, recording of the analog output from the instrument is not needed because most of the anemometers available on the market read the mean velocity directly.

Results

An even solid-angle representation was achieved by positioning the probe at angles φ and ω, as suggested in Table 1. The probe was placed at six different yaw angles, φ, in steps of 30° from –60° to 90° as shown in Figure 5. For each yaw angle, the probe was rotated around its axis and measurements of mean velocity were performed at several roll angles, ω, as listed in Table 1. This provides 56 values of measured mean velocity. The reference angles, $\varphi = 0°$, $\omega = 0°$, were defined in the previous section.

Figures 6 and 7 present results from the tests with the two anemometers. The deviation (in percent) of the mean velocity measured at different roll and yaw angles from the mean velocity measured at the reference position ($\varphi = 0°$, $\omega = 0°$) is presented in the figures as a function of the angle ω. Results for six φ angles are shown. The results show that probe B measures the mean velocity higher than the reference velocity at yaw angles φ, between 0° and 90° and, on average, lower than the reference velocity at yaw angles between 0° and –60°.

The mean velocity deviation curves for yaw angles between 0° and –60° are quite wavy and with peak-to-peak values up to

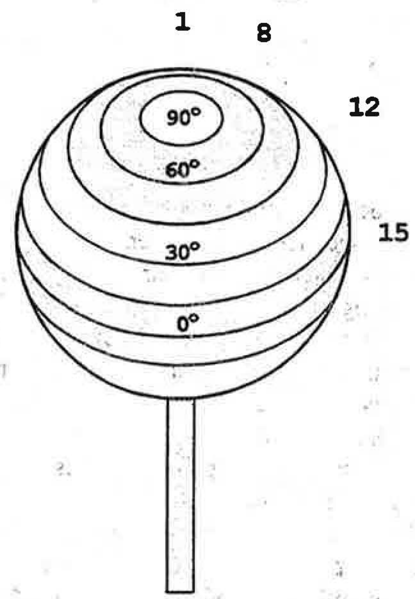

Figure 5 *Yaw angles used during the tests for validation of the method for describing the directional sensitivity of omnidirectional low-velocity probes.*

15% ($\varphi = -60°$ and $\omega = 90°$ and 270°). The results for probe D (Figure 7) show that it has relatively smooth roll characteristics. Unlike probe B, the nonuniformity in the directional sensitivity of probe D is not symmetrically distributed around the reference position $\varphi = 0°$. The probe measures the mean velocity lower than the reference velocity for almost the whole range of yaw and roll angles, with the highest deviation of 18% at $\varphi = -60°$ and $\omega = 90°$ and 270°. Another interesting feature of this probe is that at $\varphi = 60°$ it exhibits a drop that can be related to a lower production of heat in the ring-shaped strip in this area.

The observed directional sensitivity of the tested probes may be due to different reasons, such as heat loss through the support of the velocity sensor, uneven heat loss from the surface of the sensor, disturbances caused by the body of the probe, etc.

The collected data were used to describe the directional sensitivity of the two velocity probes by the method suggested in this paper. The weighting factors for each probe positioning during the tests was almost identical, equal to $w_i \cong 1/56$. Under these conditions, the mean velocity directional sensitivity (MDS) and the turbulence intensity directional sensitivity (TDS) were calculated by the following simplified equations:

$$\mathrm{MDS} = \frac{1}{56} \cdot \frac{\sum_{i=1}^{56} (v_i - v)}{v} \cdot 100 \tag{5}$$

$$\mathrm{TDS} = \frac{\left[\frac{1}{56} \sum_{i=1}^{56} (v_i - v)^2\right]^{0.5}}{v} \cdot 100 \tag{6}$$

The calculations identified MDS = −1.8% and TDS = 6.5% for probe B and MDS = −5.5% and TDS = 7.9% for probe D. The analyses of the results showed that it is possible to minimize MDS and TDS by selecting a reference position of the yaw and roll angles different from 0°. The results from the tests were used, and new reference angles that give smaller MDS and TDS values were identified. For probe B, MDS = 0% was possible to obtain at new reference angles of $\varphi = 0°$ and $\omega = 120°$. MDS = 0% was possible to obtain also for probe D at new reference angles of $\varphi = -30°$ and $\omega = 180°$. At these new reference angles, the TDS value for probe B was calculated to be 6.5% and for probe D, 6.1%. For other probes, the minimum MDS and TDS may be larger than 0%.

DISCUSSION

Human subject studies (Fanger et al. 1988; Mayer and Schwab 1990) have shown that the mean velocity and turbulence intensity of the room airflow have an impact on occupants' sensation of draft. Therefore, accurate measurements of these two airflow characteristics are required in the standards (ASHRAE 1992; ISO 1995; DSA 1995; DIN 1994). The impact of the airflow direction on occupants' thermal comfort (also perceived air quality) is not considered in the present standards, although research indicates that people are to some

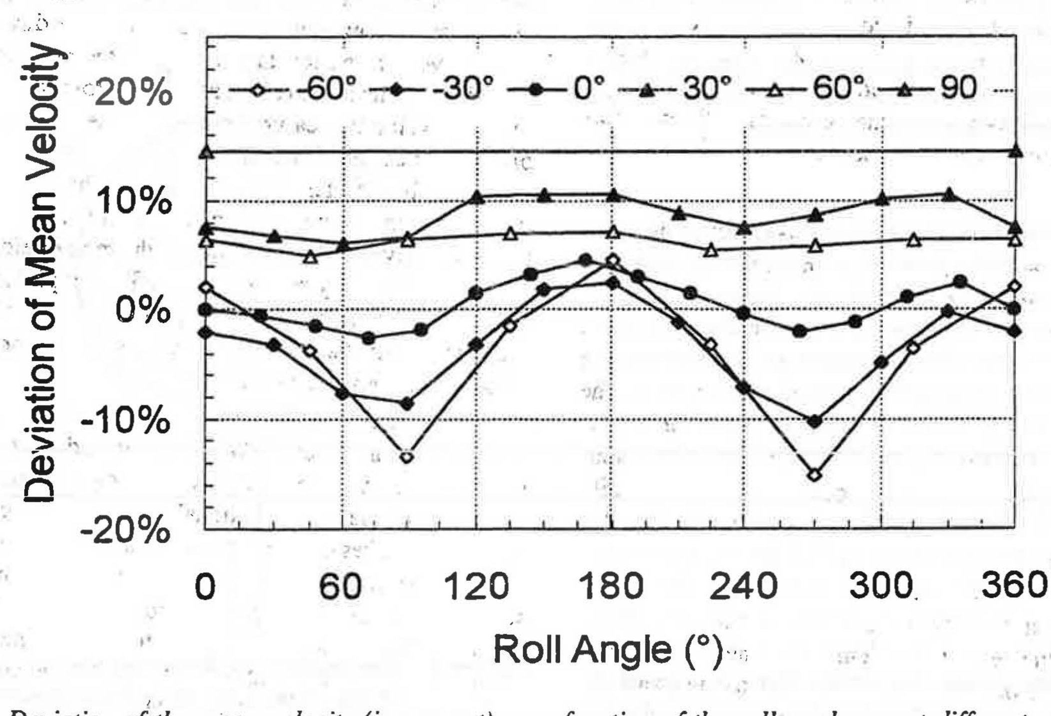

Figure 6 Deviation of the mean velocity (in percent) as a function of the roll angle, ω, at different yaw angles, φ. Measurements are performed with the anemometer B.

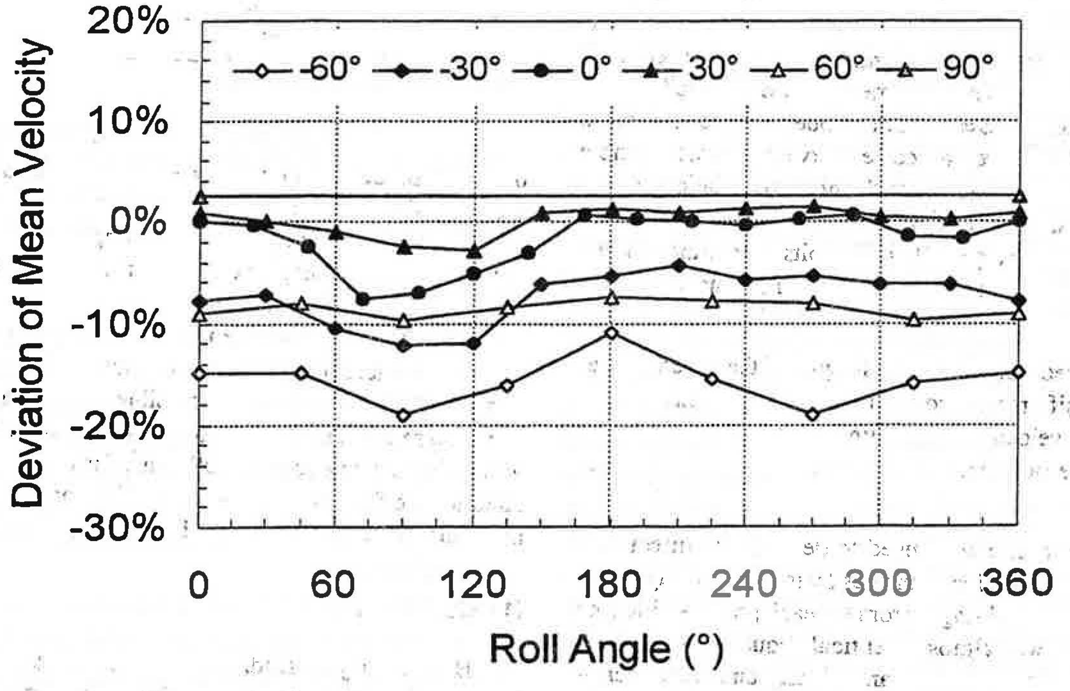

Figure 7 Deviation of the mean velocity (in percent) as a function of the roll angle, ω, at different yaw angles, φ. Measurements are performed with the anemometer D.

extent sensitive to flow direction (Mayer and Schwab 1988; Toftum et al. 1997).

Laser doppler measurements in the occupied zones of rooms have identified mean velocities from 0 m/s up to 0.6 m/s, turbulence intensity from less than 10% up to 70%, and changes of the direction of the instantaneous velocity vector in a wide range of yaw and roll angles (Finkelstein et al.1996). Therefore, it is recommended in the standards that low-velocity anemometers with an omnidirectional velocity probe be used for airflow measurements indoors.

An important requirement when low-velocity measurements are performed by means of omnidirectional velocity sensors is to position the probe in the flow as close as possible to the positioning during the static calibration. This is easy in low turbulent flow but rather difficult when the turbulence intensity of the flow is high. In a highly turbulent flow, the velocity vector will attack the sensor from different directions. The results of the present tests show that for various reasons the heat loss from omnidirectional probes is not evenly distributed over the surface of the sensor, which has an impact on the accuracy of the measured velocity. Therefore, it is not possible to describe the directional sensitivity of an omnidirectional probe from a knowledge of one roll characteristic and one yaw characteristic of the velocity probe in two planes, one through the center of the velocity sensor and the axis of the probe and the other on a perpendicular plane through the center of the velocity sensor, as is done according to the test procedure used at present.

When low-velocity measurements are performed in practice, it is important to assess the error introduced in the measured mean velocity and turbulence intensity due to the directional sensitivity of the sensor. The roll and yaw characteristics of omnidirectional sensors, as applied in present practice, can be used to assess the accuracy of the measurements only in an airflow with small changes of the direction of the velocity vector. In a low turbulent flow, the probe can be positioned as for the static calibration. Therefore, the accuracy of the mean velocity measurements will depend on the accuracy of the static calibration but not on the directional sensitivity of the probe. In turbulent flow, the roll and the yaw characteristics of the probe cannot be used to assess the impact of directional sensitivity on the accuracy of the mean velocity and the turbulence intensity measurements. This applies even if the mean direction of the flow for a period of time is known and it is assumed that a spatial symmetry exists in the directional response of the velocity sensor.

The method presented in this paper allows for the assessment of the largest error that can be introduced in the mean velocity and the turbulence intensity due to the directional sensitivity of the omnidirectional sensor by calculating MDS and TDS. It takes into account the nonuniform distribution of heat loss from the surface of an omnidirectional velocity sensor as well as the relative contribution of each segment on the surface of the sensor exposed to the instantaneous velocity of the flow. The error introduced during the measurements will be smaller than the calculated MDS and TDS values when the changes in the velocity direction are small. One should remember, however, that the accuracy of the velocity measurements also depends on the static calibration and the dynamic response of the instrument as well as on the impact of the free convection from the heated sensor (Melikov 1997; Melikov et al. 1997; Popiolek et al. 1996,1997).

It was discussed in the section on results that the MDS and TDS values depend on the selection of the reference position. It is, therefore, important that the proposed method be used when the velocity probe is positioned close to the positioning of the static calibration recommended by the manufacturer. The method can be adopted by users and manufacturers to decrease the error introduced in the measured mean velocity and turbulence intensity due to directional sensitivity of the probe by selecting a proper reference positioning of the probe.

It has been determined that the protective shield attached to some of the probes available on the market may cause a significant drop in the velocity read by the anemometers. This effect has been observed especially in low turbulent flow (Melikov 1997). The roll and yaw characteristics of an omnidirectional sensor with a shield will indicate larger changes of the velocity than the roll and yaw characteristics of the same sensor without a shield. Therefore, the directional sensitivity of a sensor with a shield may be incorrectly assessed as poor if the MDS and the TDS characteristics of the sensor are not known. This was clearly demonstrated by the experiments performed in this study with two velocity probes, although the probes were tested without a shield. However, the identification of MDS and TDS has to be performed with a shield if its use is recommended during field measurements.

Requirements for the directional sensitivity of low-velocity anemometers are prescribed in the standards (ASHRAE 1992; ISO 1985). However, a test method describing the directional response of omnidirectional probes does not exist. The analyses in this study show that knowledge of the roll and yaw characteristics of a probe is insufficient to describe the directional response of an omnidirectional probe. The method introduced in this paper for describing the directional sensitivity of omnidirectional probes can be included in the standards. The mean velocity directional sensitivity, MDS, and the turbulence intensity directional sensitivity, TDS, defined in this study can be used to assess the maximum error in the mean velocity and the turbulence intensity caused by the directional sensitivity of the omnidirectional sensor.

CONCLUSION

In this paper, a test method for describing the directional sensitivity of omnidirectional velocity sensors is proposed and used experimentally.

The test method can be used to define the impact of the directional sensitivity of an omnidirectional sensor on the accuracy of the mean velocity and the turbulence intensity measurements.

The proposed method can be used to improve the accuracy of the velocity measurements by optimizing the static calibration of low-velocity anemometers and the positioning of the velocity probe during field measurements.

It is suggested that the method be included in future indoor climate standards.

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REFERENCES

ASHRAE. 1992. *ANSI/ASHRAE Standard 55-1992, Thermal environmental conditions for human occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1990. *ANSI/ASHRAE Standard 113, Method of testing for room air diffusion.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

DIN. 1994. *DIN 1946, Raumlufttechnik. Gesundheitstechnishe Anforderungen* (VDI-Luftungsregeln).

DSA. 1995. *DS 474, Norm for specifikation af termisk indeklima.* Danish Standard Association.

Fanger, P.O., A.K. Melikov, H. Hanzawa, and J.W. Ring. 1988. Air turbulence and sensation of draught. *Energy and Buildings* 12 (1): 21-39.

Finkelstein, W., A. Melikov, T. Sefker, and G. Langkilde. 1996. Laser doppler measurements of airflow characteristics in rooms with mechanical ventilation. *Proc. of Indoor Air '96, July 21-26, 1996, Nagoya, Japan,* vol. 1, pp. 785-790.

ISO. 1996. ISO/TC 159/SC 5, Draft International Standard ISO/DIS/7726, Ergonomics of the thermal environment—Instruments for measuring physical quantities. Geneva: International Standard Organization.

ISO. 1995. *EN ISO 7730, Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.* Geneva: International Standard Organization.

ISO. 1985. *ISO Standard 7726, Thermal environments—Specifications relating to appliance and methods for measuring physical characteristics of the environment.* Geneva: International Standard Organization.

Mayer, E., and R. Schwab. 1988. Direction of low turbulent airflow and thermal comfort. *Proc. of Healthy Buildings '88,* Stockholm, Sweden, vol. 2, pp. 577-582.

Mayer, E., and R. Schwab. 1990. Untersuchung der physikalischen ursachen von zugluft. *Gesundheits-Ingenieur* 111 (H.1), pp. 17-30.

Melikov, A.K. 1997. Calibration and requirements for accuracy of thermal anemometers for indoor velocity measurement. Final report, EC research project, Contract No. MAT1 CT93 00 39, Department of Energy Engineering, Technical University of Denmark, p.175.

Melikov, A.K., Z. Popiolek, and F.E. Jørgensen. 1997. New method for testing dynamic characteristics of low-velocity thermal anemometers. *ASHRAE Transactions* 104 (1).

Popiolek, Z., A.K. Melikov, and F.E. Jørgensen. 1996. Dynamic response of thermal anemometers for low velocity measurements indoors. *Proc. of ROOMVENT '96*, July 17-19, Yokohama, Japan, vol. 1, pp. 477-484.

Popiolek, Z., A.K. Melikov, F.E. Jørgensen, W. Finkelstein, and T. Sefker. 1997. Impact of natural convection on the accuracy of low-velocity measurements by thermal anemometers with omnidirectional sensors. *ASHRAE Transactions* 104 (1).

Toftum, J., G. Zhou, and A.K. Melikov. 1997. Effect of airflow direction on human perception of draught. *Proc. of CLIMA 2000*, Brussels Aug. 30 - Sept. 2.