Requirements and Guidelines for Low-Velocity Measurements

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ABSTRACT

In this paper, new requirements for the characteristics of anemometers used for low-velocity measurements indoors, as well as requirements for the signal processing, are presented. The static calibration, dynamic response, and temperature compensation of the anemometers, as well as the directional sensitivity and the design of the velocity transducer, are considered, together with the period and the sampling rate of the measurements. The requirements in ASHRAE Standard 55 (1992), ASHRAE Standard 113 (1990), and ISO Standard 7726 (1985) are modified, and new requirements not considered in the current standards are developed and suggested for inclusion in future standards.

INTRODUCTION

Draft and poor air quality are some of the most frequent complaints indoors. Studies (Fanger and Pedersen 1977; Fanger et al. 1988; Mayer and Schwab 1990) show that mean air velocity, turbulence intensity of the flow in rooms, and frequency of the velocity fluctuations are important parameters for a person's sensation of draft. Draft, defined as an unwanted local cooling caused by air movement, is considered in the present European, international, and national standards (ISO 1995; ASHRAE 1992; DIN 1994; DS 1995). The percentage of occupants in a space who may experience draft discomfort is assessed by a draft rating, DR (%), calculated by the following equation:

$$DR = (34 - t_a)(v - 0.05)^{0.62}(0.37vTu + 3.14) \qquad (1)$$

In this equation t_a (°C) is the air temperature, v (m/s) is the mean velocity, and Tu (%) is the turbulence intensity of the flow. The mean velocity is defined by the instantaneous velocity average over an interval of time, while the turbulence intensity is the standard deviation of the velocity divided by the mean velocity. This equation is based on results from human subject experiments (Fanger et al. 1988) and is included in EN ISO Standard 7730 (ISO 1995) and ANSI/ASHRAE Standard 55-1992 (ASHRAE 1992).

A draft rating below 15% is recommended in the standards. In the draft of the European pre-standard, pr ENV 1752 (1996), three quality classes, A, B, and C, for the indoor environment are considered. The spaces with an indoor environment of class A should be designed in such a way that the draft rating is less than 15%; for the spaces of class B, the draft rating should be between 15% and 20%; and for the spaces with the lowest quality environment, class C, the draft rating should be less than 25%. Any location within the occupied zone should comply with the definitions of these classes. The same requirements for three classes of indoor environment are under discussion for inclusion in the revision of ASHRAE Standard 55.

In order to perform accurate design and draft rating assessments of the indoor environment, accurate measurements of the air temperature, the mean velocity, and the turbulence intensity of the airflow in rooms are required.

Field measurements (Melikov et al. 1997a) reveal that the air temperature fluctuations in ventilated rooms are small, with a standard deviation of less than 0.5°C and with a frequency of less than 1 Hz. In ISO Standard 7726 (ISO 1985), the required accuracy for air temperature measurements is ±0.5°C and the desirable accuracy is ±0.2°C. ASHRAE Standard 55 requires an accuracy of ±0.2°C for air temperature measurements. Thus, the accuracy of the temperature measurements specified in the standards is sufficient for realistic draft assessment in practice.

The accuracy of the mean velocity and turbulence intensity measurements depends on several factors: the calibration of the instrument and its dynamic behavior, the directional sensitivity of the velocity sensor and the free convection flow

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it produces, the design of the transducer and the instrument, etc. Requirements for some of these factors are specified in the standards. Recent research reveals, however, that the requirements are not sufficient to perform accurate assessment of the thermal environment in rooms, and they need to be updated. Furthermore, several factors that have an impact on the accuracy of the velocity measurements are not considered in the standards, and they need to be defined. This paper discusses the existing requirements in the current standards for the characteristics of anemometers for low-velocity measurements. Updated requirements, as well as additional new requirements, are developed and suggested for inclusion in future standards.

UPDATING THE REQUIREMENTS SPECIFIED IN CURRENT STANDARDS

Requirements for the characteristics of instruments measuring low air velocity are given in the current standards, ISO Standard 7726 (ISO 1985) and its present revision, draft ISO/DIS 7726 (1996), and ASHRAE Standards 55 (ASHRAE 1992) and 113 (ASHRAE 1990). Most comprehensive are the requirements in ISO 7726 and ASHRAE 55. The requirements are listed in Tables 1 and 2 and are discussed in the following section.

Velocity Range

The range of velocities that can be measured by the low-velocity anemometers is specified between 0.05 and 0.5 m/s in ASHRAE Standard 55 (ASHRAE 1992) and between 0.05 and 1 m/s in ISO Standard 7726 (ISO 1985) (Table 1). Typically, the mean velocity in rooms is less than 0.5 m/s. However, the turbulence intensity may be as high as 60% or more (Finkelstein et al. 1996). This means that instantaneous velocities much higher than 0.5 m/s may occur in the flow. The instrument must be able to measure these velocities. Therefore, a velocity range from 0.05 m/s to 1 m/s should be specified in the standards.

Static Calibration of the Anemometer

The requirements for accuracy of low-velocity (air speed) measurements, as specified in the standards and listed in Table 1, are not sufficient to assess the thermal environment in rooms. Both EN ISO Standard 7730 (ISO 1985) and ASHRAE Standard 55 (ASHRAE 1992) specify that less than 15% of the occupants in rooms should complain of draft. The percentage of occupants that will complain of draft in a room can be assessed by Equation 1, which requires the measurement of air temperature, mean velocity, and turbulence intensity of the airflow in rooms. Accuracy of the velocity measurements, therefore, has a significant impact on draft assessment. For example, according to ISO Standard 7730, the draft rating in an environment (see Equation 1) with an air temperature of 20°C, turbulence intensity of 30%, and mean velocity of 0.17 m/s may be assessed as any value in the range between 11% and 29%. This is when the anemometer complies with the required accuracy for the velocity measurements specified in the standard, which for this particular mean velocity will be ±0.0585 m/s (calculated according to the requirements listed in Table 1). When the mean velocity measurements are performed with the desirable accuracy, ±0.0319 m/s, as specified in the standard, the draft rating may be assessed as any value in the range between 14% and 23%. Similar calculations performed according to the requirements for accuracy specified in ASHRAE Standard 55 show that the draft rating may be assessed as any value between 12% and 26%. This is because the required accuracy of the mean velocity measurement will be ±0.05 m/s. Thus, two anemometers, both measuring the mean velocity with an accuracy that complies with the requirements in the standards, will measure the environment as acceptable (DR<15%) and unacceptable (DR>15%). Tests performed by seven thermal anemometers (Melikov 1997) showed that, if carefully made, the accuracy of the static calibration of low-velocity thermal anemometers with an omnidirectional sensor may be as accurate as ±0.03 m/s. This is the desired accuracy specified in the draft ISO/DIS Standard 7726, which at present is under public review. In this way, the accuracy of the draft assessment in practice will be better than ±5%. Bearing in mind that this is an average prediction for occupants with differences in their thermal sensation, clothing, activity level, etc., this accuracy is considered acceptable.

Dynamic Response of the Anemometer

Present standards do not specify requirements for the accuracy of measuring the turbulence intensity; this accuracy depends on the dynamic characteristics of the anemometer as well as on its directional sensitivity and in some cases on free convection from the velocity sensor. In ISO Standard 7726 (ISO 1985) and ASHRAE Standard 55 (ASHRAE 1992), the dynamic characteristics of the anemometers are described by the response time and time constant of the instruments. It is assumed in ASHRAE Standard 55 that the 90% response time equals 2.3 times the time constant (63% value of the signal), while in ISO Standard 7726 the response time is assumed (most probably mistakenly) to be 3.1 times the time constant. The assumption for 2.3 times the time constant is valid if the measuring system includes only one exponential time-constant function. However, research performed recently identifies that this assumption is not valid for all anemometers available on the market (Popiolek et al. 1996; Melikov et al. 1997b). Four low-velocity thermal anemometers were tested, and it was found that they differed largely in the shape and the frequency range of their dynamic response. Two of the anemometers had a dynamic response that could not be described by only one exponential time-constant function. Further, it is specified in the standards that the response time (time constant) has to be determined in tests with a step change of the velocity. It is, therefore, essential that anemometers have an analogue output that is fast enough. However, most of the instruments available on the market do not have such an

TABLE 1
Requirements for the Characteristics of Low-Velocity Measuring Instruments

Parameter	ISO 7726 (1985) (Draft ISO 7726, 1996)	ASHRAE Standard 55 (1992)	NEW REQUIREMENTS
Measuring Range	0.05 to m/s	0.05 - 0.5 m/s (10 - 100 fpm)	0.05 to 1 m/s
Accuracy of Air Velocity Measurements as Calibrated	Required: ±(0.05 + 0.05 Va)m/s Desirable: ±(0.02 + 0.07 Va)m/s These levels shall be guaranteed whatever the direction of flow within a solid angle (Ω) = $3\pi st$.	±0.05 m/s (±10 fpm) It is important to consider the natural convection for the sensor.	Measuring range 0.05+1.0 m/s: ±0.03 m/s The readings in downward, horizontal, and upward flow with a velocity higher than 0.1 m/s shall be equal or differ less than 0.01 m/s.
Dynamic Behavior	Response time (90%): Required - 1s (0.5 s) Desirable - 0.5 s (0.2 s)	Response time (90%): Required - from 1 to 10 s Desirable - 0.2 s	Required upper frequency: 1 Hz[a] Desirable upper frequency: 2 Hz[a]
Directional Sensitivity	Except in the case of unidirectional current, the air velocity sensor shall measure the velocity whatever the direction of the air.	It shall be omnidirectional or must be carefully oriented.	The mean velocity directional sensitivity of the velocity sensor should be within the range of ±5%. The turbulence intensity directional sensitivity should be less than ±10%.[b] The placement of the sensor in regard of the mean flow direction shall be as close as possible to the placement of the sensor in the flow, where it was calibrated.[b]
Temperature Compensation	No requirement	No requirement	The temperature compensation shall be made in such a way that the change of the air temperature (from the temperature of calibration) will have an impact on the accuracy of the measured velocity of not more than 1% per K for the air temperature range 15-35°C.
Design of Transducer	No requirement	No requirement	Any protection against damages shall not influence the accuracy of the velocity measurements. The distance between the velocity sensor and the sensor used for temperature compensation shall be as close as possible but not more than 50 mm. The two sensors shall not influence each other.

a. The upper frequency can be determined by the test method suggested by Melikov et al. 1997b.
b. The mean velocity directional sensitivity and the turbulence intensity directional sensitivity of low-velocity probes can be determined by the test method suggested by Stannov et al. 1997.

output. It is, therefore, not always possible to describe the dynamic response of low-velocity anemometers by the response time or the time constant. Even if the anemometer has an analogue output, it is still not clear how to use the velocity step-change test procedure specified in the standards. This is because the response of the anemometers to a step-up change of the velocity is different from the response to a step-down change.

Instead of the velocity step-change test procedure specified in ISO Standard 7726 and ASHRAE Standard 55, the concept of the upper frequency, as introduced by Melikov et al. (1997b), can be used. The upper frequency is defined as the highest frequency of sinusoidal velocity fluctuations up to which the thermal anemometer should be able to measure the standard deviation of the velocity with a certain accuracy, for example, ±10%. The upper frequency approach is clear and without any assumption concerning the dynamic response curve of the anemometer and does not require a fast analog output from the instrument.

Human response to the frequency of velocity fluctuations has been studied over the years (Asakai and Sakai 1974; Fanger and Pedersen 1977; Tanabe and Kimura 1989). The results indicate that people are sensitive not only to the amplitude of the velocity fluctuations (turbulence intensity) but also to the frequency of the velocity fluctuations. In the experiments by Fanger and Pedersen (1977) performed at a comfortable air temperature, human subjects were most dissatisfied when exposed to periodically fluctuating airflow with a frequency of velocity fluctuations of approximately 0.5 Hz. In a warm environment (air temperature above 31°C), Asakai and Sakai (1974) enabled subjects to select the frequency of the periodic velocity fluctuations that decreased most the discomfort due to warmth. The mean velocity and the amplitude of the velocity fluctuations were unchanged. The results of this study showed that most of the subjects preferred velocity fluctuations with a frequency around 1.2 Hz. Human response to the frequency of the velocity fluctuations still needs to be studied.

Velocity measurements in full-scale rooms performed by a three-dimensional laser doppler anemometer (Finkelstein et al. 1996) reveal that the frequency of the velocity fluctuations in the occupied zone, which contribute up to 90% to the standard deviation of the velocity, have a frequency of 1 Hz or less. It is, therefore, realistic to require an upper frequency of 1 Hz with a desirable upper frequency of 2 Hz for low-velocity anemometers for measurements indoors.

Directional Sensitivity of the Transducer

ISO Standard 7726 (ISO 1985) specifies that the air velocity sensor shall measure the velocity whatever the direction of the air within a solid angle of 3 πst. However, the standards (ISO Standard 7726 and ASHRAE Standards 55 and 113) do not specify any method for testing the directional sensitivity of omnidirectional low-velocity sensors. A simple test procedure is used in practice to identify so-called "yaw" and "roll" directional sensitivity of an omnidirectional velocity sensor. The probe is located in a laminar flow, and mean velocity is measured by rotating the probe around its axes and also around an axis through the velocity sensor and perpendicular to the axes of the probe. However, research (Melikov 1997) shows that these two characteristics cannot be used to assess the way in which the accuracy of the velocity measurements in practice is influenced by the directional sensitivity of the sensor. This is because the heat loss over the entire surface on the velocity sensors is different from that identified by the yaw and roll characteristics. A test method that 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 has been proposed (Stannov et al. 1997). The method requires determination of two characteristics of the velocity transducer—mean velocity directional sensitivity (MDS) and turbulence intensity directional sensitivity (TDS). The 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 3.93 πst. The limitation of a solid angle of 0.07 πst disregards the influence of the support of the sensor and the probe body. The TDS is defined as a ratio in percent between the standard deviation created by the directionally induced velocity variations and the mean velocity. The analyses showed that it is realistic to require that MDS be no larger than ±5% and TDS be no larger than ±10%.

Measuring Time

Typically, air velocity in the occupied zone of a room fluctuates. The mean velocity and the standard deviation of the velocity are statistical parameters calculated from the instantaneous velocity measured by the anemometer over a period of time. Slow velocity fluctuations will not be measured if the measuring time is too short, and this will decrease the accuracy of the measured mean velocity and standard deviation of the velocity (also the turbulence intensity). The impact of the measuring time has been previously studied in laboratory tests and reported in the literature (Thorshauge 1982; Sawachi and Melikov 1993). Recently, comprehensive measurements in full-scale test rooms with different types of ventilation systems have been performed to identify the impact of the measuring period on the accuracy of the velocity measurements (Melikov 1997). Figure 1 shows results from these tests. The relative mean velocity and the relative turbulence intensity as a function of the measuring period are shown in the figure for measurements in different zones in a room with mixing ventilation and air supply devices located at the ceiling. The zones are defined as near the walls (zone 1), near the floor (zone 2), in the occupied part of the room at locations that are not directly exposed to the airflow from the air supply device (zone 3), and at locations directly exposed to the airflow from the air supply device. Results from measurements by two low-velocity thermal anemometers (TA) with omnidirectional velocity sensors and a three-dimensional laser doppler anemometer (LDA) are included. The thermal anemometers, available on the market, are described in detail by Popiolek et al. (1997), while the laser doppler anemometer is described by Melikov (1997). The relative mean velocity and the relative turbulence intensity are defined as the ratio of the mean velocity measured for a given period of time s_i, divided by the mean velocity measured for a period of 240 seconds (TA) and 300 seconds (LDA). The results show that when the measuring period was 180 seconds (3 minutes) the mean velocity and the turbulence intensity could be measured with an accuracy better than ±10%. Both ASHRAE Standard 55 and ISO Standard 7726 recommend that the mean velocity and the standard deviation of the velocity be calculated from records of

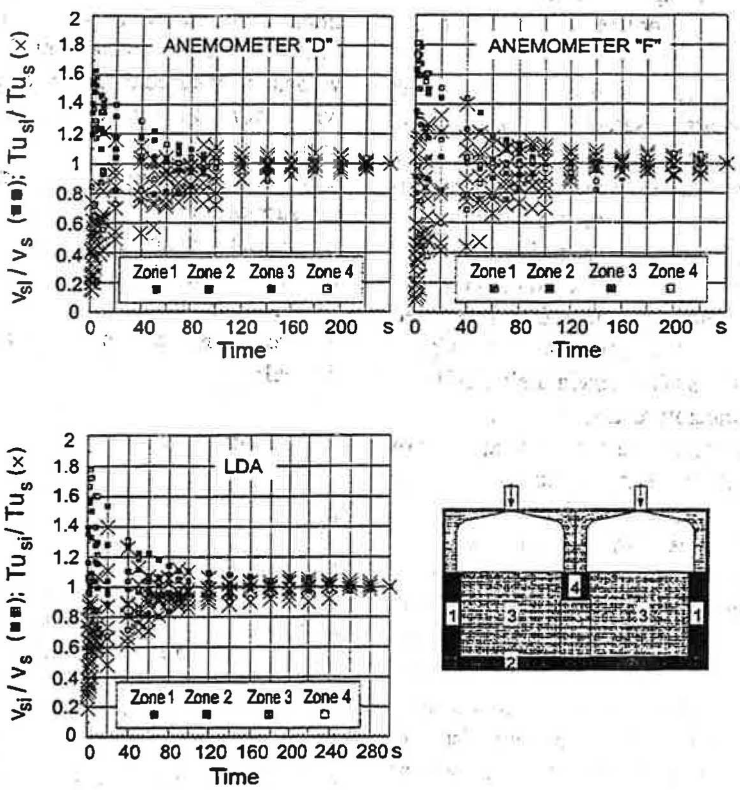

Figure 1 *Impact of the measuring time on the accuracy of the mean velocity and the turbulence intensity measured by two low-velocity thermal anemometers, D and F, and a laser doppler anemometer (LDA) in different zones of rooms—zone 1, near the walls; zone 2, near the floor; zone 3, occupied zone without direct exposure to supplied airflow; zone 4, zone with direct exposure to supplied airflow. Mean velocity,* V_{si}*, and turbulence intensity,* Tu_{si}*, determined for different periods of measuring time* s_i*, are divided by mean velocity,* v_s*, and turbulence intensity,* Tu_s*, determined for a measuring time of 240 seconds (anemometers D and F) and 300 seconds (LDA).*

the instantaneous velocity for a period of 3 minutes. However, slow velocity fluctuations with a period of more than 3 minutes (Table 2) may occur in the occupied zone as well. Thus, occupants may be exposed to a high velocity that may not be included in the 3-minute records used to calculate the mean velocity. Therefore, it is recommended that the mean velocity be calculated as an average value of three or more measurements when velocity fluctuations with a period longer than 60 seconds occur in rooms.

REQUIREMENTS NOT INCLUDED IN THE PRESENT STANDARDS

Impact of Natural Convection

Thermal anemometers with a heated velocity sensor are recommended in the standards to be used for low-velocity measurements in rooms. The heated velocity sensor generates an upward free convection flow that interacts with the airflow where measurements are to be performed and, thus, has an impact on the accuracy of the velocity measurements. A

TABLE 2
Requirements for Signal Processing

Parameter	ISO 7726 (1985)	ASHRAE Standard 55 (1992)	New Requirements
Measuring Period	Desirable: 3 min.	3 min. or 30 times the 90% response time of the instrument	Required: 3 min. Average value of three or more measurements are recommended when the period of the velocity fluctuations is more than 60 seconds.
Sampling Rate	No requirement	No requirement	5 or more samples per second

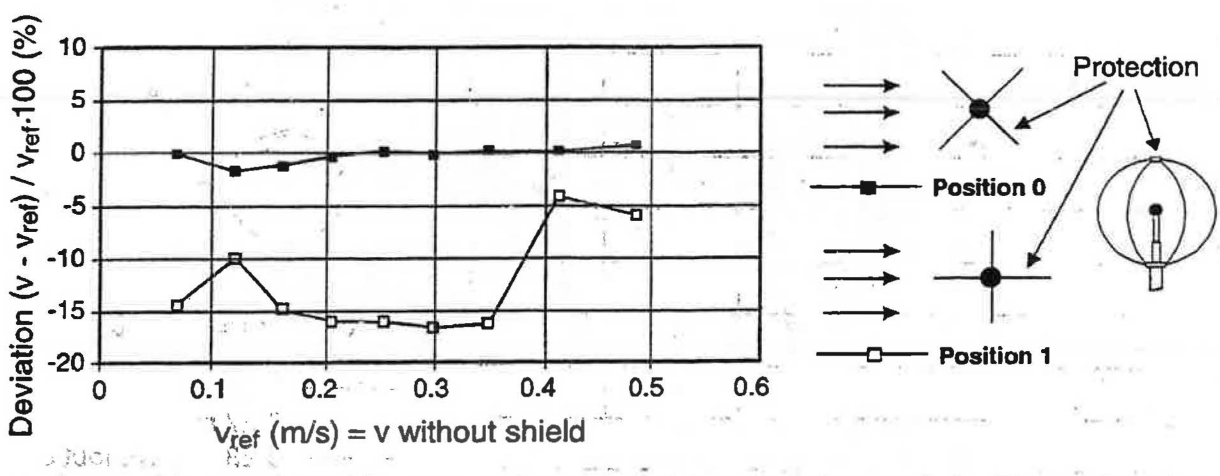

***Figure 2** Impact of the protection of the sensor on the accuracy of the measured mean velocity. The turbulence intensity of the airflow is below 1%.*

comprehensive recent study (Popiolek et al. 1997) shows that the free convection flow generated by the sensor has a significant impact on the accuracy of the velocity measurements, especially in downward flow with a velocity below 0.15 m/s and a high turbulence intensity, and for sensors of a large size and with a high overheating temperature. In such cases, the mean velocity can be measured up to 10% higher and the turbulence intensity up to two to three times lower than they are in the real flow. The overheating temperature is the difference between the temperature of the heated sensor and the air temperature.

Lowering of the overheating temperature of the velocity sensor will decrease the free convection flow from the sensor and will thus improve the accuracy of the measurements. However, this will have the opposite effect on the dynamic response of the anemometer. The anemometer will not respond to velocity fluctuations with a relatively high frequency; thus, the accuracy of the measurements will decrease. Furthermore, the low overheating temperature will increase the impact of the air temperature fluctuations on the accuracy of the measurements. These antagonistic effects are discussed in detail by Popiolek et al. (1997) and must be considered carefully by the manufacturers and users of low-velocity thermal anemometers. Mean velocities above 0.1 m/s are most important for occupants' thermal comfort. Research (Melikov 1997; Popiolek et al. 1997) indicates that it is possible to diminish the impact of free convection on the accuracy of the velocity measurements up to less than 0.01 m/s regardless of the direction of the airflow.

Positioning of the Velocity Transducer

Most accurate field measurements of velocity will be performed when the transducer is positioned in the flow as close as possible to its positioning in the flow where the static calibration was performed. It is not always easy to define the main direction of the flow in rooms as its direction changes. Comprehensive measurements performed by a three-dimensional laser doppler anemometer (Finkelstein et al. 1996) show that the airflow down the walls, along the floor, and in some parts of the occupied zone (depending on the location and the type of air supply device) is almost two-dimensional. It may be concluded that, in general, the accuracy of velocity measurements in rooms will improve if the transducer is positioned horizontally with its axis perpendicular to the main flow direction. However, in many cases, it will be necessary to identify the main flow direction (if any) before the start of the measurements.

Temperature Compensation

Thermal anemometers used at present correct automatically for changes of the air temperature during measurement. The air temperature is measured by an unheated sensor. The correction is needed because the static calibration of the transducers is performed at a constant air temperature, typically different from the air temperature during field measurements. Depending on its overheating temperature, the velocity sensor can measure the mean velocity with a difference of 15% to 30% from that of the real velocity of the flow if no correction is made for the difference between the air temperature of calibration and the air temperature of the measurement, even if only by 1 K. Most often, velocity measurements are performed in almost isothermal airflow with a temperature different from the air temperature of the static velocity calibration of the instrument. In this case, correction of the measured velocity for air temperature different from the temperature of calibration is rather simple. Analyses showed that low-velocity thermal anemometers can be designed in such a way that the impact of the temperature correction on the accuracy of the velocity measurements is less than 1% per K if the air temperature is in the range of 15°C to 35°C.

Air temperature fluctuations in rooms with mechanical ventilation are small, with a standard deviation less than 0.5°C and in many rooms even less than 0.25°C (Melikov et

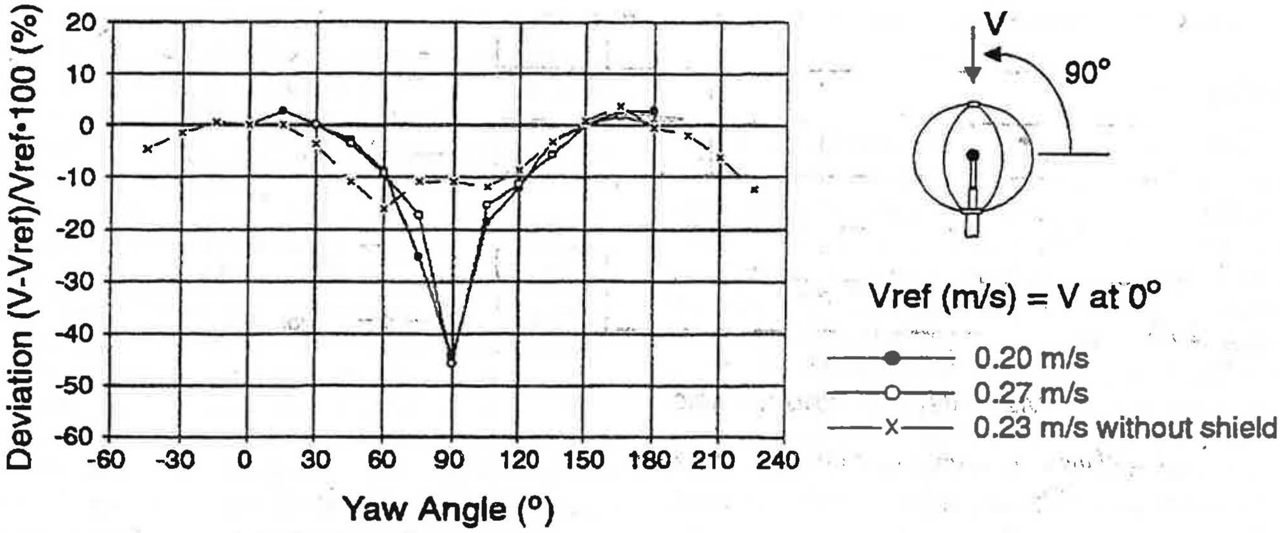

Figure 3 *Impact of the protection (shield) on the directional sensitivity of an omnidirectional velocity sensor.*

al. 1997a). However, in some rooms with exhaust type mechanical ventilation, large air temperature fluctuations with a standard deviation of up to 1°C may exist. The air temperature fluctuations may also be large in ventilated rooms where air is supplied directly into the occupied zone, such as with floor-mounted air supply devices, desk-mounted diffusors, etc. The response time of the sensor used to correct the measured velocity for changes of air temperature is not specified in current standards. Often it is chosen by the manufacturers to be much longer than the response time of the velocity-measuring sensor. Recent research (Melikov et al. 1997c) shows that the accuracy of the mean velocity measurements is not affected significantly by air temperature fluctuations. However, air temperature fluctuations may have a significant impact on the accuracy of the measured standard deviation of the velocity. The impact of temperature fluctuations on the accuracy of low-velocity measurements needs still to be studied.

Design of the Velocity Transducer

The design of the transducer is another important factor that may influence the accuracy of low-velocity measurements. The transducers often have special protection against damage for the velocity sensor, which may cause a drop in the mean velocity of up to 50% (Melikov 1997).

The impact of this protection on the mean velocity is shown in Figures 2 and 3. The protection in this case consists of four robust wires crossed around the omnidirectional (hot-sphere type) velocity sensor. In Figure 2, the deviation of the mean velocity from the reference velocity (reference velocity is defined accurately in advance) as a function of the mean velocity of the flow is shown. During this experiment, the velocity transducer was positioned horizontally with its axes perpendicular to the flow direction. The results in the figure show that a mean velocity of up to 15% lower than the actual mean velocity in the flow will be measured when the protection is fixed in front of the velocity sensor. The results in Figure 3 show that the protection has an impact on the directional sensitivity of the sensor. The mean velocity measured at a yaw angle of 90° was almost 50% lower than the reference velocity for a transducer with protection and only 10% lower than the reference velocity for a transducer without protection.

The tests revealed that the impact of the protection on the accuracy of the mean velocity measurement decreased when the turbulence intensity of the flow increased (Melikov 1997). Results from a comparative study of four anemometers (Sawachi and Melikov 1993) have identified a significant impact of the protection on the accuracy of the measured turbulence intensity. In the experiments, the protection, designed as a dense mesh around the sensor, damped the velocity fluctuations in the flow. Thus, the standard deviation was measured lower than it was in the flow.

The omnidirectional low-velocity transducers available on the market are designed to have a heated velocity sensor and an unheated temperature sensor used to compensate the measured velocity for temperature changes. The distance between the heated sensor and the unheated sensor of the transducer has to be great enough to avoid disturbances between the two sensors. However, a large distance may have an impact on the accuracy of the velocity measurements in airflow with temperature gradients because the velocity measurements will be corrected for an air temperature different from the air temperature at the velocity measuring point. Research (Melikov et al. 1997a) indicates that, in practice, a distance of 20 to 30 mm and even 50 mm between the two sensors will be sufficient to perform accurate velocity measurements in the occupied zone of rooms. However, for accurate measurements in airflow with large temperature gradients, the positioning of the transducer has to be considered very carefully in order to locate the two sensors in a region of the flow with equal temperatures.

Sampling Rate

Accurate measurements identify that significant velocity fluctuations, with a frequency up to 1 Hz and sometimes more (up to 2 Hz), occur in rooms (Finkelstein et al. 1996). It has already been noted that the required upper frequency of low-velocity anemometers should be 1 Hz (a desirable upper frequency of 2 Hz is recommended). Consequently, the anemometer will be able to detect the fastest velocity fluctuations in the flow. It has already been demonstrated that a measuring period of 3 minutes is needed to perform measurements of mean velocity and turbulence intensity (standard deviation of velocity) with an accuracy of ±10%. This observation was made for a fixed sampling rate of 5 Hz in all cases.

The mean velocity and the standard deviation of velocity (turbulence intensity) are statistical parameters. It is the combination of sampling rate and number of samples that determines the final accuracy of the statistics. In order to obtain the best accuracy of the mean and standard deviation of instantaneous velocity, i.e., a random stationary process, the optimum sampling rate should be twice the integral (Eulerian) time scale of turbulence (airflow characteristics in rooms are discussed in Hanzawa et al. [1987] and Sandberg [1987]). In this way, the individual samples will be statistically independent. For a desired confidence level of the mean velocity and the standard deviation of velocity, the minimum number of samples can be calculated. In order to obtain a certain accuracy, a larger number of samples is needed for the calculation of the standard deviation than for the calculation of the mean velocity.

Field measurements (Hanzawa et al. 1987; Sandberg 1987) reveal a wide range of time scales in room airflow, depending on the type of ventilation system and mean velocity. The results show that the integral time scale decreases when the mean velocity of the flow increases. For the range of mean velocity between 0.05 and 0.6 m/s identified in the occupied zone of rooms in practice (Hanzawa et al. 1987; Sandberg 1987; Finkelstein et al. 1996), the time scale changes from more than 1 second to 0.1 second. Based on the lowest time scale of 0.1 second, the optimum sampling rate will be 5 Hz. The optimum sampling rate at an integral time scale of 1 second will be 0.5 Hz. It is rather difficult, however, to design an anemometer with an adaptive sampling rate. Therefore, it is suggested that sampling be made with 5 Hz in all cases. It is possible to sample at evenly distributed intervals in thermal anemometers, as they always provide a continuous probe signal. At an integral time scale of turbulence greater than 0.1 second, not all samples will be statistically independent when the sampling rate is 5 Hz. However, this will not create greater uncertainties, provided the measuring time is long enough. The selected sampling rate of 5 Hz and 3 minutes measuring time provides 900 evenly distributed velocity samples, which appears to be enough for the cases shown in Figure 1.

Figure 4 shows mean velocity and turbulence intensity calculated on the basis of different numbers of samples extracted at different "sampling rates" from the same set of data acquired with a high frequency. The sampling was made at evenly distributed intervals. The relative mean velocity and the relative turbulence intensity as a function of the number of samples is shown in the figure for measurements in different zones in a room with mixing ventilation and air supply devices located at the ceiling. Results from four-minute measurements by two low-velocity thermal anemometers (TA) with omnidirectional velocity sensor, D and F, and five-minute measurements by a three-dimensional laser doppler anemometer (LDA) are included. The relative mean velocity and the relative turbulence intensity are defined as the ratio of the mean velocity and the turbulence intensity determined from four-minute measurements at a specific number of samples divided by the mean velocity and the turbulence intensity determined from four-minute TA measurements with 5,040 samples (21 samples per second) and five-minute LDA measurements with 7,500 samples (25 samples per second). The results confirm that the accuracy of mean velocity and turbulence intensity (standard deviation) measurements will be better than 1% when the number of samples is 900 and higher. Thus, the accuracy is not increased by increasing the number of samples for a fixed measuring time of four or five minutes. It may be concluded that 900 samples at evenly distributed intervals over a measuring time of three minutes will be sufficient to provide accurate statistics in low-velocity indoor flows.

NEW REQUIREMENTS FOR LOW-VELOCITY MEASUREMENTS INDOORS

New requirements that will improve the accuracy of low-velocity measurements indoors were developed both for the characteristics of the instruments and for the processing of the signal from the measurements. The requirements are based on the findings of recent research as described above. The new requirements for the characteristics of low-velocity measuring instruments are listed in Table 1 and for the signal processing in Table 2. It is suggested that the requirements developed be included in future standards.

Guidelines for Velocity Measurements in Rooms

The following guidelines will improve the accuracy of the velocity measurements in rooms. The recommendations in Tables 1 and 2 should be used.

The Instrument. Make sure that the anemometer has an omnidirectional velocity sensor and measures the mean velocity and the standard deviation of the velocity for a period of three minutes. It is possible also that an analog signal from a velocity transducer is directly converted into a digital signal and then processed. In this case, the resolution of the conversion should be high enough, corresponding to approximately

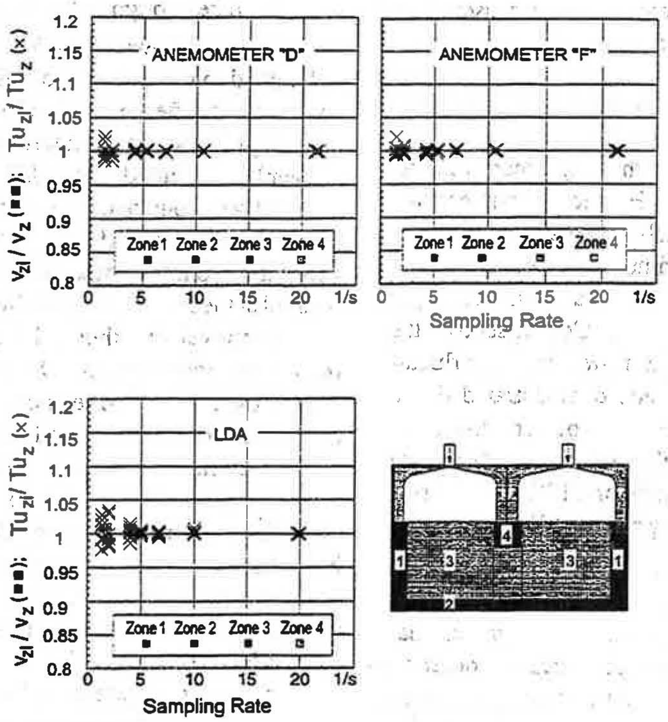

Figure 4 Impact of the number of samples (at evenly distributed intervals) on the accuracy of the mean velocity and the turbulence intensity measured by two low-velocity thermal anemometers (TA), D and F, and a laser doppler anemometer (LDA) in different zones of rooms—zone 1, near the walls; zone 2, near the floor; zone 3, occupied zone without direct exposure to supplied airflow; zone 4, zone with direct exposure to supplied airflow. Mean velocity, v_{zi}, and turbulence intensity, Tu_{zi}, determined from measurements with a different number of samples, zi, are divided, respectively, by the mean velocity, v_z, and the turbulence intensity, Tu_z, determined from measurements with 5,040 samples collected from four-minute measurements by TA (anemometers D and F) and 7,500 samples collected from five-minute measurements by LDA.

0.001 m/s. Check whether the characteristics of the instrument comply with the following requirements:

- Measuring range of velocity
- Accuracy of calibration
- Positioning of the probe during its static calibration
- Directional sensitivity of the transducer
- Accuracy of temperature compensation
- Impact of free convection from the sensor
- Upper frequency (if not provided, then 90% response time)
- Sampling rate
- Impact of the protection (if any)

Request this information from the manufacturer or perform tests yourself to establish it. Otherwise, the velocity measurements may not be reliable.

The Measurements.

- Identify (for example, by smoke experiments) the approximate direction of the airflow at the point of measurement.
- Identify whether there are large temperature gradients in the flow.
- Position the velocity transducer with regard to the main direction of the flow as close as possible to the positioning of its calibration.
- Make sure that the protection against damages (if any) does not disturb the flow.
- Make sure that the air temperature at the location of the heated velocity sensor and the unheated sensor used for temperature calibration is similar (difference should be less than 0.5°C).
- Make sure that the flow around the probe is not disturbed by its support.
- Make sure that the support provides a stable positioning of the probe without any vibrations.
- Repeat the measurements at least three times if slow velocity fluctuations occur at the point of measurement.

CONCLUSIONS

The impact of several characteristics of low-velocity anemometers on the accuracy of the measurements has been analyzed in this paper. The characteristics under discussion were static calibration, dynamic response, and temperature compensation of the instrument; directional sensitivity; design of the velocity transducer; and the measuring time and sampling rate.

The requirements in the current standards have been updated, and new requirements have been developed. It is suggested that the new requirements be included in future standards.

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