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Impact of Natural Convection on the Accuracy of Low-Velocity Measurements by Thermal Anemometers with Omnidirectional Sensor

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ABSTRACT

Thermal anemometers with heated velocity sensors are mostly 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. Tests were performed with four anemometers available on the market to identify this impact in an airflow with a constant velocity and in an airflow with a periodically fluctuating velocity. The free convection flow had a significant impact on the accuracy of the velocity measurements, especially at flow velocities below 0.15 m/s and for sensors of a large size and with high overheating temperature. The mechanism of the interaction between the free convection flow and the downward flow was revealed. The impact of free convection has to be considered carefully when measurements are performed to assess room air movement or to validate CFD calculations. The results show that it is possible to model and predict the impact of free convection on the accuracy of the velocity measurements under non-steady-state conditions by simple tests performed under steady-state conditions.

INTRODUCTION

Thermal anemometers with an omnidirectional velocity sensor are the instruments most commonly used for low-velocity measurement indoors. Depending on design, the sensor has a diameter of less than 1 mm to 5 mm and an overheating temperature of 10°C to 40°C. The overheating temperature is the difference between the temperature of the heated sensor and the air temperature. The heated velocity sensor creates an upward free convection flow. The larger the sensor and the higher the temperature difference between the sensor and the airflow, the stronger the free convection flow. Therefore, the free convection flow can be quite different for different velocity transducers. The free convection flow will interact with the airflow where measurements are to be performed, and this will have an impact on the accuracy of the low-velocity measurements.

Several studies on the impact of free convection on the velocity measurements by hot-wire anemometers have been performed and reported in the literature. A comprehensive review of these studies was made by Bruun (1995). Studies with omnidirectional low-velocity sensors have been performed and reported as well (Jørgensen 1978; Gierczycka and Popiolek 1994). However, the studies are limited to tests performed in an airflow with a constant velocity. The interaction of free convection with fluctuating flow, as is typical in practice, has not been studied. Furthermore, the studies reported have been performed with a single velocity probe or with velocity probes made under laboratory conditions.

This paper reports results from experiments performed to identify the impact of free convection flow on the accuracy of the velocity measurements in an airflow with a constant velocity and in an airflow with a periodically fluctuating velocity. Four thermal anemometers with omnidirectional velocity sensors of different design were tested. The anemometers are available on the market. The mechanism of the interaction between the free convection flow and the downward flow was investigated in order to identify whether it is possible to model and predict the impact of free convection on the accuracy of the velocity measurements. The results presented in this paper are part of a large and comprehensive study on the accuracy of low-velocity measurements by thermal anemometers with an omnidirectional (hot-sphere) type velocity sensor (Melikov 1997).

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EXPERIMENTAL METHOD

Tested and Reference Anemometers

Four low-velocity thermal anemometers, B, C, D, and E, available on the market were used during the tests. Each anemometer has an omnidirectional velocity sensor. The velocity sensor of anemometer B is a small thermistor with a diameter of less than 1 mm. The overheating temperature of the sensor is 10°C. Anemometer C has a spherical velocity mass sensor of 3 mm diameter made of enamelled copper wire molded into a sphere; the overheating temperature is 25°C. The velocity sensors of anemometers D and E are designed as a quartz ball with a diameter of 3 mm; the quartz ball is coated with a heated nickel layer. The overheating temperature of the sensor in anemometer D is set by the manufacturer at 25°C. The velocity probes of anemometers B, C, and D have an unheated sensor that measures the air temperature. The air temperature measurements are used to correct the velocity when the air temperature of the airflow is different from the air temperature of calibration. The velocity sensors are shown schematically in Figure 1.

The dynamic characteristics of the anemometers with regard to their shape and frequency range are different. The dynamic response of anemometers B and C can be described by a first order transfer function, e.g., the dynamic characteristics of the instruments include only one exponential time constant function as assumed in ANSI/ASHRAE Standard 55-1992 (ASHRAE 1992). Anemometers D and E have rather complicated dynamic characteristics that cannot be described by a first order transfer function but include two time constant functions. The dynamic response of the anemometers was carefully studied and is described in detail by Melikov et al. (1997) and Popiolek et al. (1996).

Anemometers B, C, and D display the mean velocity and the standard deviation of velocity. During the experiments, these two flow characteristics were recorded and used for the analyses. The sampling time was as designed by the manufacturers of the instruments. Anemometer E consists of a velocity probe and a constant-temperature bridge controlled by a computer. The overheating temperature of sensor E can be adjusted at the different levels. An analog signal was recorded only during the experiments with anemometer E. In this case, the signal was sampled with a frequency of 100 Hz.

A one-dimensional laser doppler anemometer (LDA) with a fiber-optic system was used as a reference anemometer during the tests. During some of the tests in a horizontal flow with a periodically fluctuating velocity, a thermal anemometer with a hot-wire velocity probe was used as a reference. This velocity sensor was made with a platinum-plated tungsten wire 1.2 mm long and with a diameter of 5 μm. The overheating ratio of the sensor was 0.8 (wire temperature of 220°C). The frequency response of the hot-wire anemometer was more than 10 kHz in the range of the velocities studied. A fog generator that is available on the market was used to introduce a seeding in the flow. The seeding was an evaporated inside fog fluid that was nonirritating, nonflammable, innocuous, and sweet-scented and that leaves no residues. The size of the particles was in the normal range for these type of applications, between 3 μm and 20 μm. The seeding was tested and recommended by the manufacturer to be used for LDA measurements in a low-velocity airflow.

In order to avoid the impact of factors other than natural convection on the accuracy of the measurements, the tested anemometers were recalibrated (static calibration) in a horizontal flow according to the readings of the reference anemometers.

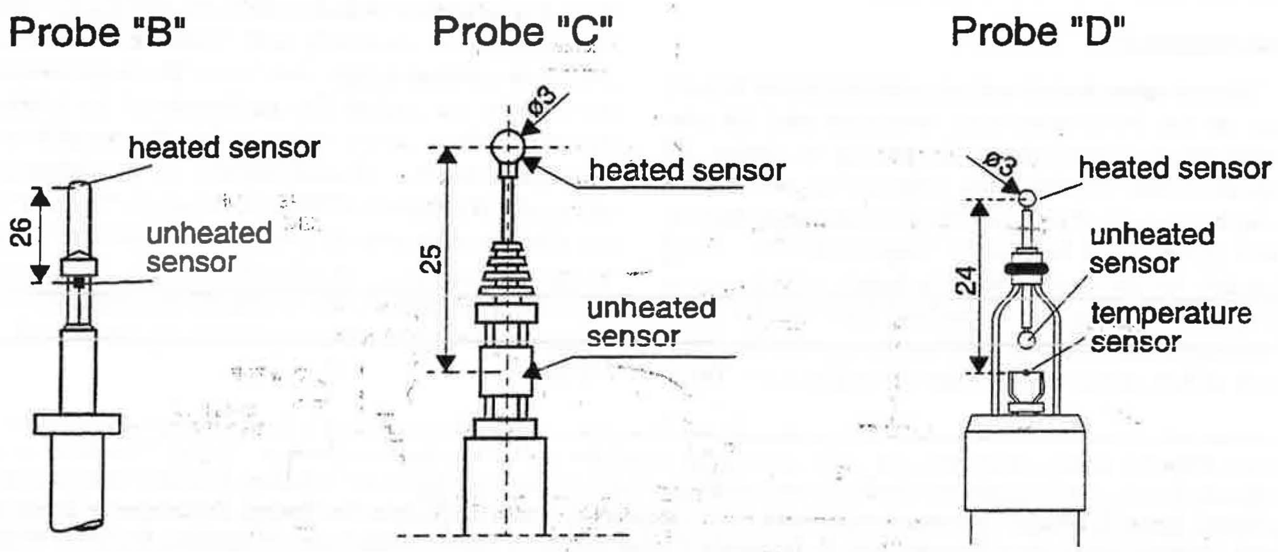

Figure 1 *Velocity probes tested.*

Experimental Facilities

The tests were carried out using a closed wind tunnel with a square cross section. The wind tunnel is shown in Figure 2. It is made of plexiglass. A specially designed supporting structure makes it possible to position the wind tunnel at various angles against the horizontal level. The working section, where the tested hot-sphere sensors and the hot-wire sensor (used as a reference) are positioned, has a cross section with dimensions of 104 x 104 mm^2. Tests showed that in this section a uniform velocity distribution exists in a cross area of 80 × 80 mm^2. The velocity range that can be achieved in the working section is from 0 m/s to 2 m/s. The air temperature was measured in the next section of the wind tunnel with a cross area of 33 × 33 mm^2. The tunnel allows the static pressure to be measured in the two sections, as shown in Figure 2. It is used to calibrate the wind tunnel and to adjust the air velocity needed in the working section. The velocity of the airflow in the working section is regulated by changing the rotational speed of an exhaust fan sucking air through the wind tunnel. The velocity fluctuations were generated by a valve moved by a specially designed pneumatic system. A piston opens and closes the valve at different frequencies and at different levels. A shortcut is introduced in the system by opening and closing the valve. The fan sucks the air through the wind tunnel when the valve is open and directly from the surroundings (the shortcut) when the valve is closed. In this way, an airflow with a periodically fluctuating velocity at different frequencies and amplitudes, rather similar to a sine type fluctuation, was generated. A more detailed description of the wind tunnel is presented in Melikov et al. (1997).

The reference measurements by an LDA or a hot-wire anemometer were performed in the measuring section on the same plane with the tested sensor but 3 mm apart in the transverse direction. During some of the tests, defined below, the LDA measurements were performed at a point located upstream in the downward flow at a distance of 3 mm from the tested sensor.

A static calibration of the wind tunnel makes it possible to calculate the velocity in the measuring section, based on differences in the static pressure measured in the two cross sections, the measuring section, and a larger cross section before the measuring section. An LDA was used as a reference during the calibration of the wind tunnel. A set of electronic micromanometers with a resolution of 0.01 Pa is used to measure the pressure difference between the two sections. Density of the air was calculated on the bases of the barometric pressure and air temperature (relative humidity was assumed to be 50%). The calibration characteristic of the wind tunnel, i.e., the velocity in the wind tunnel as a function of the pressure difference and the density of the air, was approximated by a polynomial equation. The accuracy of the velocity approximation was better than ±0.003 m/s. The calibration of the wind tunnel was performed in a horizontal position. The repeatability of the calibration was better than ±0.005 m/s.

Experimental Conditions

The four anemometers, B, C, D, and E, were tested in horizontal airflow (0°), downward airflow (90°), and upward airflow (-90°) with a constant velocity. The experiments were performed at different mean velocities ranging from 0.05 to 0.30 m/s.

The tests in an airflow with periodically fluctuating velocity were performed with two anemometers, B and D. A periodically fluctuating downward airflow was used in the

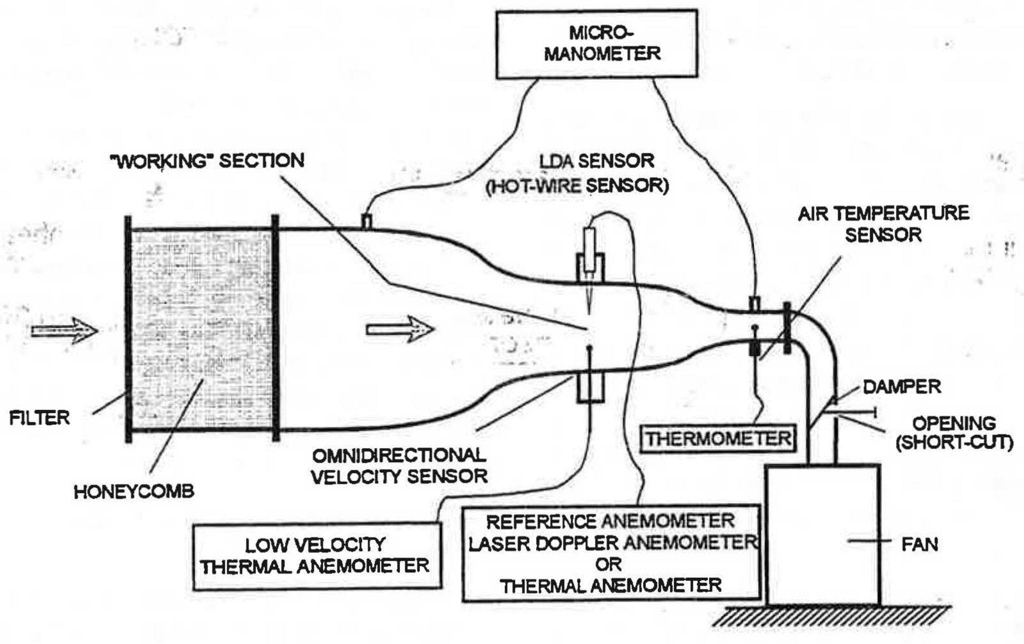

Figure 2 *The wind tunnel used during the tests.*

tests. These tests were performed using 14 combinations of mean velocity, standard deviation of the velocity (turbulence intensity), and frequency of the velocity fluctuations as follows: mean velocity in the range 0.05 - 0.30 m/s, standard deviation of velocity in the range 0.03 - 0.15 m/s (*Tu* in the range 5% - 65%), and frequency of the velocity fluctuations in the range 0.25 - 2 Hz. The airflow during the tests was isothermal.

The results from the tests in a downward flow were compared with results from previous tests in a horizontal flow performed to study the dynamic response of the anemometers and reported by Melikov et al. (1997). However, a limited number of tests in a horizontal flow were performed during the present investigation in order to test the repeatability of the measurements. A comparison of the results from the present tests and the previous tests performed in a horizontal flow showed that the repeatability of mean velocity ratio and standard deviation ratio measurements was within ±0.03.

Uncertainties of the Measurements

The uncertainty of the reference velocity measured by the LDA or calculated on the basis of the airflow volume flux in the wind tunnel was estimated at ±0.005 m/s within the velocity range 0.02 ÷ 0.4 m/s. For measurements by the tested anemometers, the uncertainty due to signal processing (linearization, averaging, A/D conversion) was estimated to be less than ±0.005 m/s within the velocity range 0.02 ÷ 0.4 m/s. The uncertainty of the velocity measurements in the tests with an airflow with a constant velocity did not exceed ±0.01 m/s within the velocity range 0.02 ÷ 0.4 m/s. This uncertainty represents the most conservative estimate. Normally, contributions to the uncertainty from the reference anemometer and the tested anemometer would have been added geometrically, providing an uncertainty of ±0.007 m/s instead of ±0.01 m/s.

Both the LDA and the hot-wire anemometer used as a reference have a bandwidth in the kHz range of frequencies. Therefore, the uncertainties of the velocity measurements in a periodically fluctuating flow due to the reference anemometers can be considered to be the same as in a flow with a constant velocity. The uncertainty of the velocity measurements in a periodically fluctuating flow due to the tested anemometers varies for the different instruments as it depends on a number of factors, such as dynamic response, static calibration, etc., and is rather difficult to determine. The best way to estimate the uncertainty of the velocity measurements in a periodically fluctuating flow is to evaluate the scatter from repeated measurements. This is identified in the "Results" section of this paper.

The error caused by deviations of the velocity fluctuations from an ideal sinusoidal fluctuation was studied and reported by Kierat and Popiolek (1997). The impact of this error on the results presented in this paper was less than 2%.

RESULTS

Tests in an Airflow with Constant Velocity

Results of the experiments in an airflow with a constant velocity are shown in Figures 3a, 3b, 3c, and 3d. The deviation in the velocity measured by the anemometers due to the impact of free convection for the sensor from the reference velocity, as a function of the reference velocity, is shown in the figures. The uncertainties of the velocity measurements are indicated in the figures. In Figures 3a and 3b, the reference velocity was measured by the LDA on the same plane, 3 mm from the sensor. The results from the tests by anemometer C are presented in Figure 3c. During these tests, the reference velocity was calculated on the basis of the measured pressure difference between two cross sections of the wind tunnel. The tunnel was calibrated by the LDA in a horizontal position.

As expected, the impact of free convection on the accuracy of the velocity measurements was different for the four anemometers. The greatest impact was observed for anemometer D and the smallest for anemometer B. The velocity sensor of anemometer B has the smallest diameter and its overheating temperature is 10°C. Therefore, sensor B generates a rather weak free convection upward flow. Anemometer D has a larger sensor with an overheating temperature of 25°C and, therefore, generates a stronger free convection flow that counteracts the flow in the wind tunnel.

The impact of the free convection flow generated by sensor C on the mean velocity measured by the instrument was between that of anemometers B and D. The free convection flow had a significant impact on the velocity measured by anemometers C and D, especially at flow velocities below 0.2 m/s. The error in the measured velocity due to the impact of free convection decreased with the increase of the velocity.

Figure 3d presents the results of the velocity deviation measured by anemometer E, adjusted to an overheating temperature of 22.7°C. The velocity in the wind tunnel was kept constant, equal to 0.074 m/s. The wind tunnel was rotated, and the mean velocity measured by anemometer E was recorded every 15°. It can be seen from the results in the figure that the impact of free convection can be observed within the range of angles ±60° from the vertical position.

These tests showed that the interaction between the free convection flow from the heated velocity sensor and the airflow in the wind tunnel was strongest in the case of downward flow; therefore, in this case, the impact of the free convection flow on the accuracy of the velocity measurements was strongest. This impact will increase when the overheating temperature of the sensor increases.

Tests in an Airflow with Periodically Fluctuating Velocity

In practice, the airflow in rooms fluctuates. Therefore, the interaction between the fluctuating downward airflow and the free convection flow from the velocity sensor is not in a steady-state condition. The impact of free convection on the

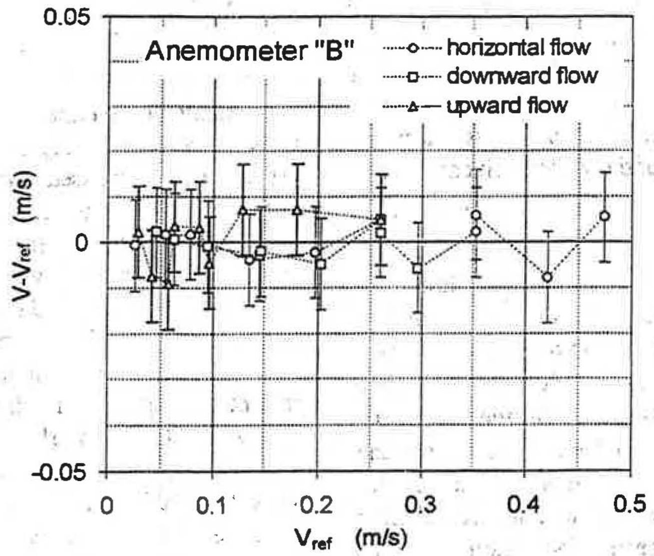

Figure 3a *Deviation of the mean velocity, V, measured by anemometer B due to the free convection. Reference mean velocity,* V_{ref}*, is measured by LDA.*

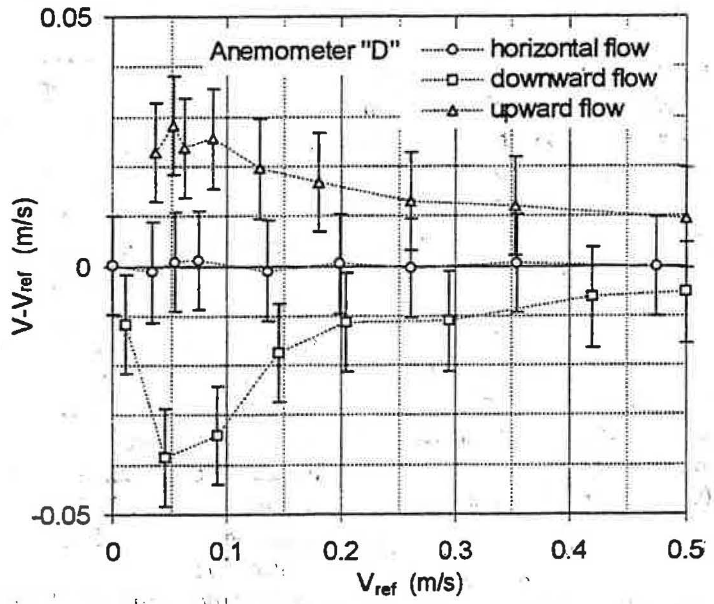

Figure 3b *Deviation of the mean velocity, V, measured by anemometer D due to the free convection. Reference mean velocity,* V_{ref}*, is measured by LDA.*

accuracy of the velocity measurements may, therefore, be different in practice than that identified during the tests with a constant velocity of the airflow. This impact was studied by two thermal anemometers, B and D, under several experimental conditions as described in the section "Experimental Conditions."

The experimental results of the tests in a downward airflow with periodically fluctuating velocity are shown in Figures 4a, 4b, 5a, 5b, 6a, and 6b. Figures 4a, 5a, and 6a present the mean velocity ratio and the standard deviation ratio as a function of the mean velocity, the turbulence intensity, and the frequency of the velocity fluctuations from the experiments with anemometer B. Similar results are presented in Figures 4b, 5b, and 6b from the tests with anemometer D. The mean velocity ratio and the standard deviation ratio are defined by dividing the mean velocity and the standard deviation measured by the tested anemometer by the mean velocity and the standard deviation measured by the reference anemometer. The results of the tests in a downward flow are compared with previous results in a horizontal flow shown in the figures as solid lines reported by Melikov et al. (1997). Experimental results from a limited number of tests in a horizontal flow performed during the present investigation are shown in the figures as well.

The results of the study indicate that anemometers B and D behaved differently due to a difference in their dynamic

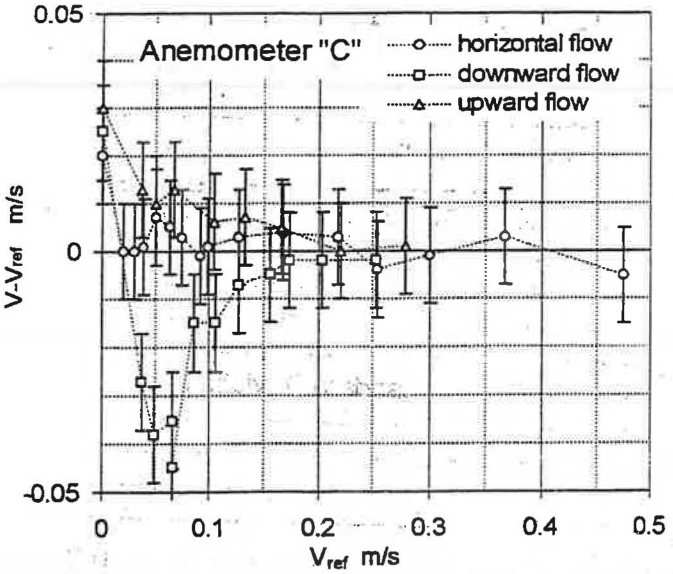

Figure 3c *Deviation of the mean velocity, V, measured by anemometer C due to the free convection. Reference mean velocity, V_{ref}, is calculated on the basis of the airflow volume flux in the wind channel.*

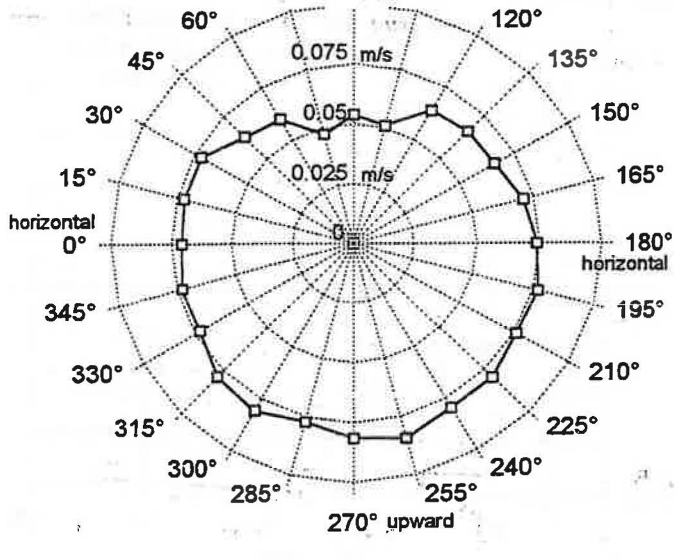

Figure 3d *Mean velocity, V, measured by anemometer E in airflow from different directions and a reference mean velocity of 0.074 m/s. The overheating temperature of the velocity sensor $\Delta t = 22.7°C$. Reference mean velocity (0.074 m/s) is calculated on the basis of the airflow volume flux in the wind tunnel.*

response and the generated free convection flow. As already discussed, the tests with a constant velocity showed that the impact of free convection on the velocity measurements by anemometer B was insignificant due to a rather weak free convection generated by velocity sensor B. The comparison in Figures 4a, 5a,and 6a showed that the results from the tests with a periodically fluctuating downward flow were identical to the results from the test in a periodically fluctuating horizontal flow because the impact of free convection was insignificant.

The results of these tests showed that the mean velocity ratio for anemometer B remained almost unchanged when the mean velocity, the turbulence intensity, or the frequency of the velocity fluctuations in the flow increased. The standard deviation ratio decreased slightly when the mean velocity of the downward flow decreased and when its turbulence intensity increased. The frequency of the velocity fluctuations caused a large decrease in the standard deviation ratio. The standard deviation ratio decreased from 1 to almost 0.1 when the frequency of the velocity fluctuations increased from 0 to 2 Hz. The decrease was due to the dynamic response of the anemometer studied and reported by Popiolek et al. (1996) and Melikov et al. (1997). It may be concluded that the impact of free convection on the accuracy of the measurements by anemometer B was insignificant.

The scatter of the results is interpreted as a combination of the uncertainties of the measurements due to the tested anemometer and the reference anemometer as discussed in the

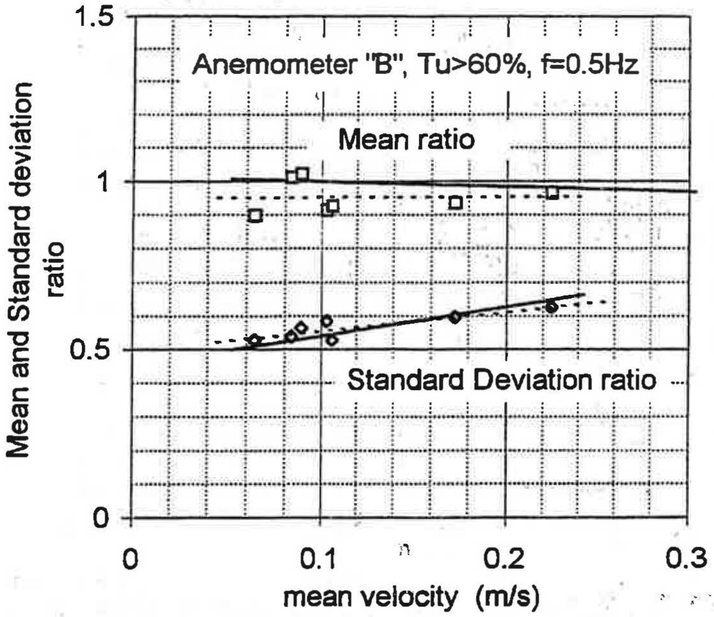

Figure 4a *Mean velocity ratio □ and standard deviation ratio ◊ as a function of the mean velocity of the flow. LDA used as a reference anemometer. ——— average results obtained in horizontal flow, ----- trend lines in downward flow. Experiments with anemometer B.*

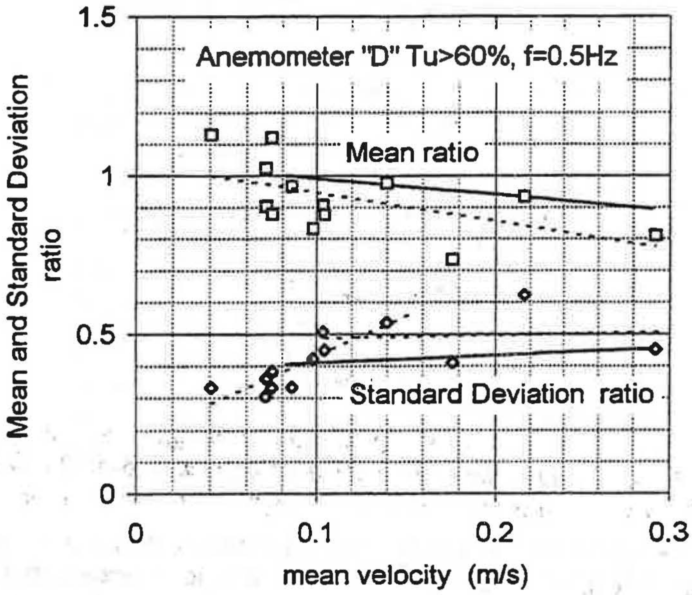

Figure 4b *Mean velocity ratio□ and standard deviation ratio ◊ as a function of the mean velocity of the flow. LDA used as a reference anemometer. ——— average results obtained in horizontal flow, ---------- trend lines in downward flow. Experiments with anemometer D.*

section "Uncertainties of the Measurements." For anemometer B the scatter of the mean velocity ratio and the standard deviation ratio was in the range ±0.05.

The tests in an airflow with a constant velocity, as described in the previous section, identified a strong free convection flow generated by sensor D. The results from the tests in periodically fluctuating flow showed that the mean velocity ratio and the standard deviation ratio measured by this anemometer in a horizontal flow and in a downward flow were rather similar and almost not influenced by the free convection flow when the mean velocity of the flow was higher than approximately 0.15 m/s (Figure 4b). An increase of the mean velocity of the fluctuating flow above 0.15 m/s caused only a small decrease in the mean velocity ratio and had almost no effect on the standard deviation ratio, even at very high turbulence intensity of the flow in the wind tunnel.

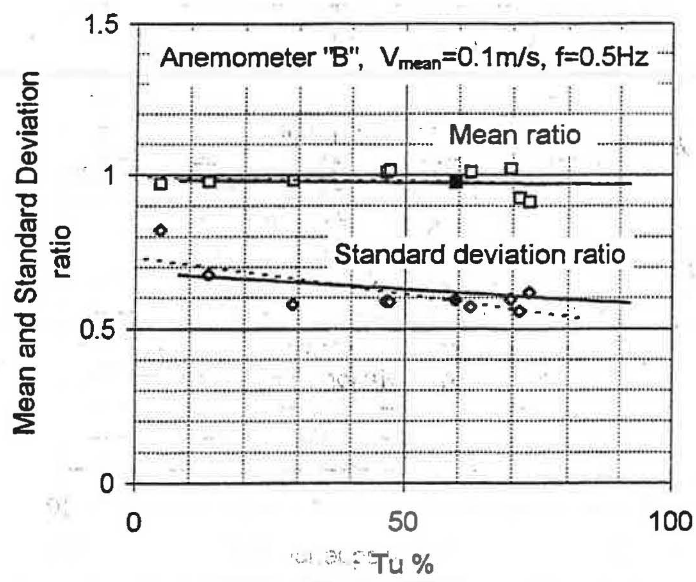

Figure 5a *Mean velocity ratio □ and standard deviation ratio ◊ as a function of the turbulence intensity of the flow. —— trend lines in downward flow, ■ mean ratio in horizontal flow with LDA as reference anemometer, ◆ standard deviation ratio in horizontal flow with LDA as reference anemometer, —— average results obtained in horizontal flow with hot wire as reference anemometer. Experiments with anemometer B.*

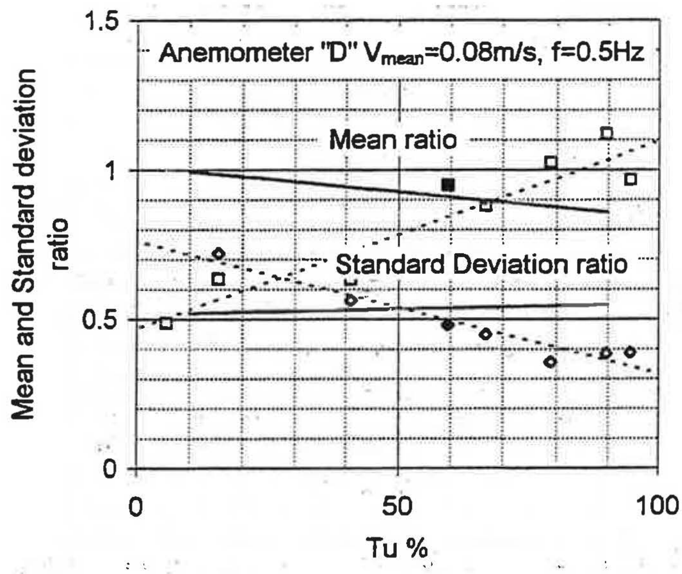

Figure 5b *Mean velocity ratio □ and standard deviation ratio ◊ as a function of the turbulence intensity of the flow, —— trend lines in downward flow, ■ mean ratio in horizontal flow with LDA as reference anemometer, ◆ standard deviation ratio in horizontal flow with LDA as reference anemometer, ——— average results obtained in horizontal flow with hot wire as reference anemometer. Experiments with anemometer D.*

The free convection flow had a significant impact on the measurements by anemometer D in a periodically fluctuating downward flow with a mean velocity lower than 0.15 m/s (Figure 5b). The impact of the free convection flow on the accuracy of the measurements was influenced by the turbulence intensity of the downward flow. The mean velocity ratio decreased and the standard deviation ratio increased when the turbulence intensity of the downward flow decreased. At a low turbulence intensity, the free convection flow had a strong counteracting effect on the airflow at the measuring location. Therefore, the mean velocity measured by the anemometer was much lower than the mean velocity measured by the reference anemometer when the omnidirectional velocity sensor was not heated (anemometer was switched off) or was absent in the flow. When the turbulence intensity of the downward flow increased, the large velocity fluctuations were able to penetrate the upward free convection flow. This caused an increase in the mean velocity measured by the anemometer.

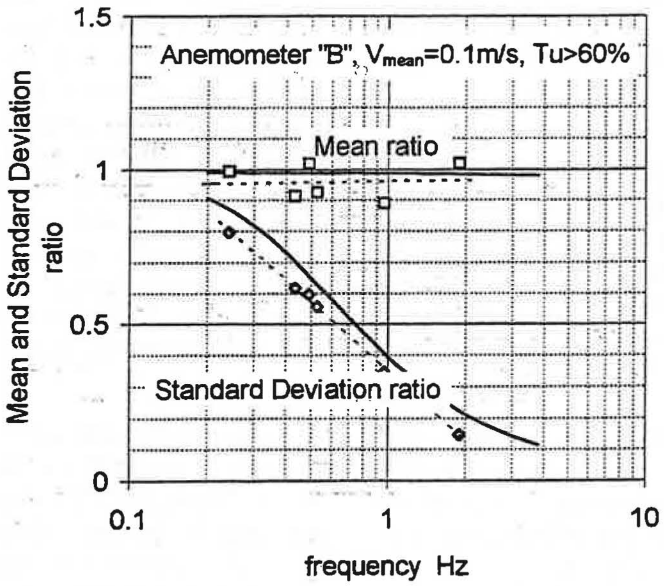

Figure 6a *Mean velocity ratio □ and standard deviation ratio ◊ as a function of the frequency of the velocity fluctuations. ---- trend lines in downward flow, —— average results of mean and standard deviation ratio in horizontal flow with LDA as reference anemometer. Experiments with anemometer A.*

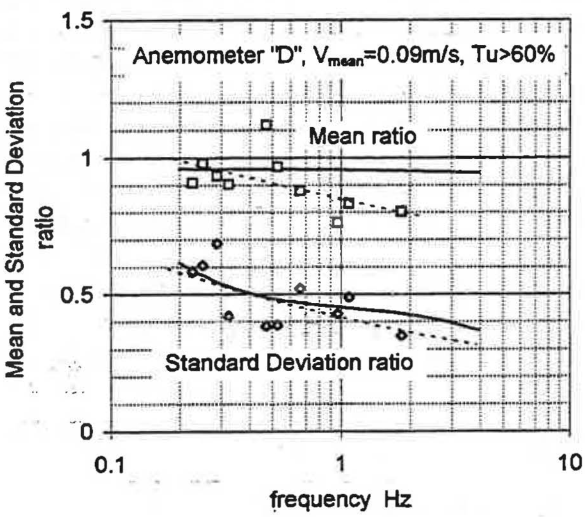

Figure 6b *Mean velocity ratio □ and standard deviation ratio ◊ as a function of the frequency of the velocity fluctuations. ----trend lines in downward flow, ——— average results of mean and standard deviation ratio in horizontal flow with LDA as reference anemometer. Experiments with anemometer D.*

The decrease of the standard deviation ratio with the increase of the turbulence intensity of the downward flow was due to the large velocity fluctuations being partly damped by the upward free convection flow. This effect was investigated closely and is described later in this paper.

The impact of free convection on the standard deviation ratio identified by anemometer D was not influenced by the frequency of the velocity fluctuations (Figure 6b). Therefore, the impacts of the frequency of the velocity fluctuations on the standard deviation ratio identified in a horizontal flow and in a downward flow were similar. In this respect, the results by anemometers D and B were identical. The frequency of the velocity fluctuations had an impact on the mean velocity ratio identified by anemometer D in downward flow but had no impact in a horizontal flow. The mean velocity ratio decreased when the frequency of the velocity fluctuations increased (Figure 6b). The decrease was due to the interaction of the free convection flow and the flow in the wind tunnel.

It should be noted that the scatter in the results is larger for anemometer D than for anemometer B. The scatter of the mean velocity ratio and the standard deviation ratio for anemometer D was less than ±0.15. This indicates a larger uncertainty of the measurements by anemometer D than by anemometer B. However, despite the larger uncertainty, the results discussed seem to show clear tendencies.

DISCUSSION

The results from the tests performed in this study indicate that free convection from a heated omnidirectional velocity sensor may have a significant impact on the mean velocity and the standard deviation (i.e., turbulence intensity) measured by low-velocity thermal anemometers. The accuracy of the measurement depends on the interaction of the free convection flow with the flow at the point where measurements are to be performed.

Several tests in a periodically fluctuating downward airflow were performed to reveal in detail the interaction of the free convection flow from the heated velocity sensor with the flow in the wind tunnel. An airflow with different amplitude and frequency was employed during the tests, and the measurements were performed by anemometer E as well as by the LDA. The LDA was adjusted to measure at a point located 3 mm above the omnidirectional sensor. Continuous measurements were performed by the LDA, starting first with the thermal anemometer switched off and, after approximately 32 seconds, continuing with the anemometer switched on. Records of the instantaneous velocity measured by anemometer E and the LDA during the tests are shown in Figure 7. Figure 8 compares only part of the records made simultaneously by the LDA when the anemometer was switched on with a record from measurements performed by the LDA when the anemometer was switched off. The records are arranged in phases.

At the beginning, when anemometer E was switched off, the measured velocity fluctuations by the LDA were close to sinusoidal type changes with a mean velocity of 0.071 m/s and a turbulence intensity of 70.2%. Thirty-two seconds later, the thermal anemometer was switched on and, as can be seen from Figure 7, after a transition period of approximately ten seconds, the interaction between the free convection flow from the hot-sphere sensor and the downward flow reached a steady-state condition. At this point, the LDA measured the mean velocity as 0.040 m/s and the turbulence intensity as 189.3% while the thermal anemometer measured the mean velocity as 0.069 m/s and the turbulence intensity as 26.1% (Figure 8). Under these conditions, anemometer E measured the mean velocity of the flow to be 0.069 m/s, which was rather close to the mean velocity of 0.071 m/s measured by the reference LDA.

The instantaneous records in Figures 7 and 8 reveal that the free convection flow from the heated sensor interacted with the fluctuating flow in the wind tunnel. The effect from the interaction between the free convection flow and the fluctuating flow increased when the instantaneous velocity of the flow started to decrease. For the particular test condition shown in Figures 7 and 8, the strength of the free convection flow became comparable with the strength of the downward flow in the wind tunnel at an instantaneous velocity of approximately 0.05 m/s. A further decrease of the velocity of the downward flow caused a reversal of the flow in the wind tunnel in the upward direction. The LDA is sensitive to the flow direction, and it measured the upward flow as a further decrease of the velocity below 0 m/s. Consequently, the velocity fluctuations identified by the LDA had increased amplitude, which caused a decrease of the mean velocity and an increase of the turbulence intensity measured. Therefore, the turbulence intensity measured by the LDA increased almost three times (up to 189.3%) compared to the turbulence intensity measured when the anemometer was switched off (70.2%), i.e., when the free convection was not present.

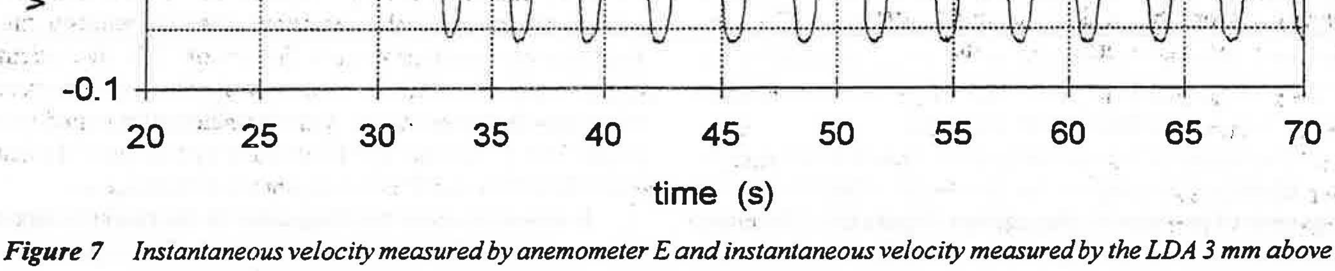

Figure 7 *Instantaneous velocity measured by anemometer E and instantaneous velocity measured by the LDA 3 mm above the omnidirectional sensor. During the first 32 seconds of the measurements, anemometer E was switched off, and after 32 seconds, it was switched on.*

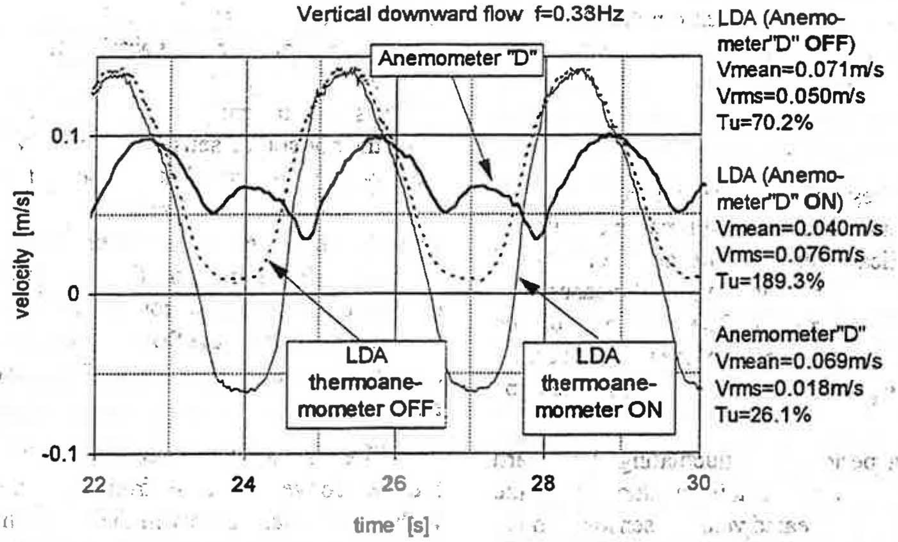

Figure 8 *Comparison of instantaneous velocity record measured by anemometer E with instantaneous velocity records measured by the LDA at 3 mm above the omnidirectional sensor in periodically fluctuating downward airflow when anemometer E is switched off and when it is switched on.*

Unlike the LDA, the heated velocity sensor does not sense the flow direction but only the magnitude of the velocity. Therefore, for a short period of time, when the velocity of the flow generated by the wind tunnel was lower than 0.05 m/s, the anemometer measured the velocity as a result of the upward free convection flow. The following increase of the instantaneous velocity of the downward flow started to damp the free convection flow and, thus, caused a decrease of the velocity measured by the anemometer. At velocities higher than 0.05 m/s, the downward flow started to dominate. A further increase in the velocity of the downward flow caused an increase in the velocity measured by the omnidirectional sensor. As a result of the interaction of the free convection flow and the downward flow, the mean velocity measured by the anemometer was 0.069 m/s and the turbulence intensity only 26.1%, i.e., very different from the turbulence intensity of the flow, 70.2%, measured by the LDA when the anemometer was switched off.

The interaction of a downward fluctuating flow and a free convection flow was studied at different combinations of mean velocity, turbulence intensity, and frequency of the downward flow. It is important to note that the identified mechanism of interaction between the free convection flow and the downward flow is similar for all omnidirectional velocity sensors, but it depends on the strength of the free convection flow generated by the sensor.

For the anemometers tested in this study, the impact of free convection on the velocity measurements was identified as below 0.15 m/s and for velocity sensors with high overheating temperature and relatively large dimensions. Tests on the dynamic response of the anemometers performed in a horizontal flow showed that both the mean velocity and the standard deviation of the velocity measured by the low-velocity anemometers were almost unaffected by the amplitude of the velocity fluctuations, i.e., the turbulence intensity of flow had no impact on the accuracy of the measurements (Melikov et al. 1997). On the contrary, the present tests identified that the turbulence intensity had a strong impact on the velocity measurements by the anemometers in a downward flow with a low mean velocity and presence of a free convection flow from the heated velocity sensor. Under these conditions, the accuracy of the mean velocity measurements increased and the accuracy of the measured standard deviation of the velocity decreased when the turbulence intensity of the flow increased. For example, with all other conditions identical, the mean velocity measured by anemometer D at low turbulence intensity (<10%) was 50% lower than the mean velocity of the fluctuating flow in the wind tunnel, while at a high turbulence intensity, it was almost equal to the mean velocity of the flow. At low turbulence intensity, the standard deviation of the fluctuating velocity was measured 30% lower and at a high turbulence intensity of the flow, 60% lower.

Low-velocity measurements are required in the current standards both for assessment of the indoor environment (ASHRAE 1992; ISO 1985) and for detailed identification of the room air distribution (ASHRAE 1990). The impact of free convection identified in the present study has to be considered in order to perform reliable measurements. The results of this study are also important when validation of CFD calculations of room air movement are made. Very often results from measurements by low-velocity anemometers with omnidirectional sensors are used to validate CFD calculations of room air movement. The findings of the present study are important for carefully analyzing the accuracy of the measured velocity characteristics before they are compared with results from computations.

The impact of free convection on the accuracy of the velocity measurements was not affected by the frequency of the velocity fluctuations of the downward flow. As in a horizontal flow, the ability of the anemometer to measure the velocity fluctuations in the downward flow was a result of its dynamic behavior. The results of the present tests show that it is possible to model and to predict the impact of free convection on the accuracy of the velocity measurements only by tests in downward flow with a constant velocity and only if the dynamic response of the anemometer is known.

The dynamic response of low-velocity thermal anemometers improves, along with the accuracy of the velocity measurements, when the overheating temperature of the omnidirectional sensor increases (Popiolek et al. 1996; Melikov et al. 1997). However, the high overheating temperature of the sensor generates a strong upward free convection flow that has the opposite effect on the accuracy of the measurements, especially in downward flow. The antagonistic effect of several factors on the accuracy of the measurements as reported in this and other studies (Stannov et al. 1997; Melikov et al. 1997) has to be considered carefully by the manufacturers of low-velocity anemometers.

CONCLUSIONS

Comprehensive tests were performed using four low-velocity thermal anemometers with an omnidirectional sensor to study the impact of free convection on the accuracy of the velocity measurements in downward flow, both with constant and with periodically fluctuating velocity. The interaction of a free convection flow from a heated velocity sensor with a periodically fluctuating downward flow was studied in detail.

The impact of free convection on the accuracy of the mean velocity measurements and the standard deviation of velocity (turbulence intensity) measurements was significant for velocity sensors with a high overheating temperature and of a large size, especially at downward velocities below 0.15 m/s. The impact was strongly affected by the turbulence intensity of the flow. The accuracy of the measured mean velocity increased and that of the standard deviation of the velocity decreased when the amplitude of the velocity fluctuations in the flow (turbulence intensity) increased.

The impact of free convection on the accuracy of the velocity measurements was not affected by the frequency of the velocity fluctuations of the downward flow.

The results show that it is possible to model and predict the impact of free convection on the accuracy of the velocity measurements in a periodically fluctuating downward airflow by simple tests performed in a downward airflow with a constant velocity.

The impact of free convection on the accuracy of the velocity decreases when the overheating temperature of the velocity sensor is low. This, however, will have a negative impact on the dynamic response of the low-velocity thermal anemometer. This antagonistic impact of the overheating temperature has to be very carefully considered during the design of the instrument.

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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.

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

Bruun, H.H. 1995. *Hot-wire anemometry: Principles and signal analysis,* p. 507. Oxford University Press.

Gierczycka, E., and Z. Popiolek. 1994. Tests of omnidirectional thermoanemometric sensors. *Proc. of ROOMVENT '94,* Vol. 2, pp. 347-361.

Jørgensen, F.E. 1978. An omnidirectional thin-film probe for indoor climate research. *DISA Information,* pp. 24-29.

Kierat, W., and Z. Popiolek. 1997. Impact of the method of linearization and excitation shape on the accuracy of measurement of the dynamic characteristics of thermal anemometers with omnidirectional sensors. *Proc. of 5th Symposium, Application of Fluid Mechanics in Environmental Engineering, Gliwice-Wisla, April 1997.* Silesian Technical University of Gliwice, Dept. of Heating, Ventilation and Dust Removal Technology, Gliwice, Poland (in Polish).

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, Technical University of Denmark, Department of Energy Engineering, 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.

Stannov, T., A.K. Melikov, Z. Popiolek, and F.E. Jørgensen. 1997. Test method for describing directional sensitivity of anemometers for low velocity measurements indoors. *ASHRAE Transactions* 104 (1).