SF-98-20-2

New Method for Testing Dynamic Characteristics of Low-Velocity Thermal Anemometers

Arsen K. Melikov, Ph.D., P.E.
Member ASHRAE

Zbigniew Popiolek, Ph.D., D.Sc., P.E.

Finn E. Jørgensen, P.E.

ABSTRACT

A comprehensive investigation was made of the dynamic behavior of five low-velocity thermal anemometers with omnidirectional sensors. Both the shape of the dynamic response curves of the instruments and their dynamic response were different. The dynamic response of the anemometers was mainly influenced by the frequency of the velocity fluctuations and only slightly by the mean velocity of the airflow and the amplitude of the velocity fluctuations. A main conclusion of this study is that the time constant, the response time, and the cut-off frequency recommended in the present standards and test methods, as well as the test methods for describing the dynamic response of low-velocity anemometers, cannot be applied to all anemometers available on the market. A concept of upper frequency, describing the dynamic response of anemometers, and a new method for testing the dynamic behavior of low-velocity anemometers are presented in the paper. The method applies to all low-velocity anemometers and is suggested for inclusion in future indoor climate standards.

INTRODUCTION

Accurate measurements of mean velocity and turbulence intensity of the airflow in rooms are required in order to assess thermal comfort conditions and air distribution in occupied zones (ISO 1985, 1996; ASHRAE 1992, 1990). At present, thermal anemometers with an omnidirectional type velocity sensor, designed to be insensitive to the velocity direction, are most used in practice due to their easy and convenient operation (in most cases the direction of the air velocity in the occupied zone of spaces is not known and is variable). Several factors, such as the calibration of the transducer, the dynamic behavior of the anemometer, the design of the transducer and its directional sensitivity, the measuring and sampling period, the correction of the velocity due to changes in the air temperature during measurements, the natural convection flow generated by the heated velocity sensor, etc., all have an impact on the accuracy of the velocity measurements.

Studies (Melikov and Sawachi 1992; Sawachi and Melikov 1993) have identified large differences (up to 100%) between thermal anemometers available on the market with regard to the mean velocity and turbulence intensity measured. The accuracy of the mean velocity measurements depends on the accuracy of the static calibration of the thermal anemometer, the impact of free convection, and the directional sensitivity of the velocity sensor. The turbulence intensity, Tu, is a ratio of the standard deviation of the velocity and the mean velocity. Therefore, the accuracy of the turbulence intensity measurements will not be affected by the calibration of the anemometer, assuming that its linearization (if any) is properly performed (the error introduced in the measured velocity due to linearization should be smaller than 0.05 m/s). However, it will be affected by the dynamic characteristics of the velocity sensor and the anemometer. Fast velocity changes will not be detected by a thermal anemometer with a long response time. As a result, the standard deviation of the velocity, as well as the turbulence intensity, will be measured smaller than in reality.

Comprehensive measurements of airflow characteristics in real-scale test rooms with numerous combinations of ventilation system, air supply device, airflow rate, and supply and return air temperature difference, performed by a three-dimensional laser doppler anemometer, have been reported in the literature (Finkelstein et al. 1996). Real field situations were simulated in the test rooms, which were furnished, arranged, and equipped as a real office. During the measurements, occupants performed typical office work. The frequency of the velocity fluctuations, which contribute up to

---

Arsen Melikov is an associate professor in the Laboratory of Indoor Environment and Energy, Department of Energy Engineering, Technical University of Denmark. **Zbigniew Popiolek** worked on this project as a visiting researcher at the Laboratory of Indoor Environment and Energy, Technical University of Denmark; at present he is a professor in the Department of Heating, Ventilation and Dust Removal Technology at Silesian Technical University, Poland. **Finn E. Jørgensen** is a senior research engineer at Dantec Measurement Technology, Denmark.

THIS PREPRINT IS FOR DISCUSSION PURPOSES ONLY, FOR INCLUSION IN ASHRAE TRANSACTIONS 1998, V. 104, Pt. 1. Not to be reprinted in whole or in part without written permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329. Opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ASHRAE. Written questions and comments regarding this paper should be received at ASHRAE no later than **February 6, 1998.**

90% of the standard deviation of the velocity, has been identified to be in the range 0.3 to 2 Hz. These velocity fluctuations can be measured by a hot-wire thermal anemometer; however, uncertainties in the measurements occur due to the impact of free convection and of the directional sensitivity of the sensor (Zhang et al. 1991). Low-velocity anemometers with an omnidirectional velocity sensor should be able to measure these velocity fluctuations.

The dynamic behavior of an anemometer defines how well it measures velocity amplitude as a function of the frequency of the velocity fluctuations. The dynamic response of a constant-temperature anemometer with a hot-wire velocity probe has been studied during the years and reported (Freymuth 1992; Bruun 1995). The dynamic response of an anemometer system can be determined by testing in flow with a perturbation (a step change of velocity, an oscillatory flow, or an imposed temperature variation) or by moving the probe to create velocity fluctuations. Another approach to determine the dynamic response of an anemometer system is to apply an electronic disturbance signal (for example, a square wave voltage) to the bridge. This method, however, cannot be applied to low-velocity anemometers, first, because the method only gives correct results for instruments (velocity transducers) the dynamic response of which can be described by only one time constant (it will be shown later in this paper that the dynamic response of some low-velocity anemometers cannot be described by one time constant) and, second, because for most of the low-velocity thermal anemometers, access to the bridge top, where the square wave voltage should be applied, is not possible.

The standards (ISO 1985, 1996; ASHRAE 1992, 1990) recommend that the dynamic response of low velocity anemometers be evaluated on the basis of the time for the output signal from the instrument to reach the 63% value (time constant) or the 90% value (response time) of the final change of the velocity. A well-known method to determine the time constant, *tc*, and the response time, *tr*, is to generate a step change of velocity and record the velocity measured by the instrument in the time. The method is recommended in the present standards (ASHRAE 1992, ISO 1985). The time constant is considered to be numerically equal to the time taken for the output of the instrument to reach 63% of its final change in steady-state value without overshoot. The response time (90% value) is then calculated as $tr = 2.3026 \cdot tc$.

Another method of determining the dynamic response of a low-velocity anemometer is to define the cut-off frequency of the instrument (Sandberg and Petersson 1990; Nordtest method 1991). Measurements are performed in well-defined periodically fluctuating airflows with identical amplitude (standard deviation) but different frequency, *fi*, of the velocity fluctuations. The standard deviation of the output signal from the anemometer is determined. The ratio of the standard deviation of the output signal and the true standard deviation of the airflow velocity is calculated and presented as a function of the frequency of the velocity fluctuations. The true standard deviation of the airflow velocity is measured by a reference anemometer. The cut-off frequency, *fc*, is defined as the frequency, *fi*, at which the standard deviation ratio is 0.707 (−3 dB), i.e., the measured standard deviation is 0.707 of the true standard deviation of the velocity. The relationship between the cut-off frequency and the time constant is $fc = 1/(2 \cdot \pi \cdot tc)$. It is used to calculate the time constant and the response time of the anemometer.

The cut-off frequency method (Nordtest 1991) and the step-change method recommended in the current standards (ASHRAE 1992, ISO 1985) require an analogue output of the tested anemometer. In order to find the relation between the response time, *tr*, and the time constant, *tc*, or the cut-off frequency, *fc*, one must assume a transfer function of the anemometer. The two methods assume that the low-velocity thermal anemometers have a dynamic behavior that can be evaluated as a first order internal system. Only in this case can $tr = 2.3026 \cdot tc$ and the ratio of the amplitude of the signal measured by the anemometer and the amplitude of the true fluctuations of the velocity in the flow be defined as equal to $(1 + (2 \cdot \pi \cdot Tc \cdot f)^2)^{-0.5}$. However, this is not always the case with low-velocity thermal anemometers. Many anemometers have a complicated sensor design, and their dynamic response cannot, therefore, be characterized by a single time constant. This makes it impossible in practice to apply the above-mentioned methods for testing the dynamic behavior of low-velocity anemometers.

In this study, five low-velocity thermal anemometers with an omnidirectional type sensor were selected from those available on the market, and their dynamic response was studied experimentally, compared, and evaluated according to requirements in the current international standards. The experiments comprised both tests under step change of the velocity and tests in a periodically fluctuating airflow. In this paper, only results obtained from the tests with periodically fluctuating airflow are reported. Based on the results, a new method for testing the dynamic behavior of anemometers is proposed. The method can be used to test anemometers regardless of their dynamic response. The results presented in this paper are part of a large and comprehensive study on the accuracy of low-velocity measurements made indoors using thermal anemometers with an omnidirectional (hot-sphere) type velocity sensor (Melikov 1997).

METHOD

Thermal Anemometers

Five thermal anemometers, A, B, C, D, and E, with an omnidirectional type velocity sensor were tested. The anemometers are available on the market. The velocity probes of the anemometers are shown schematically in Figure 1. All consist of heated (velocity) sensor and unheated sensor.

Anemometer A has a velocity sensor with an ellipsoid body made of a highly insulating thermal foam material,

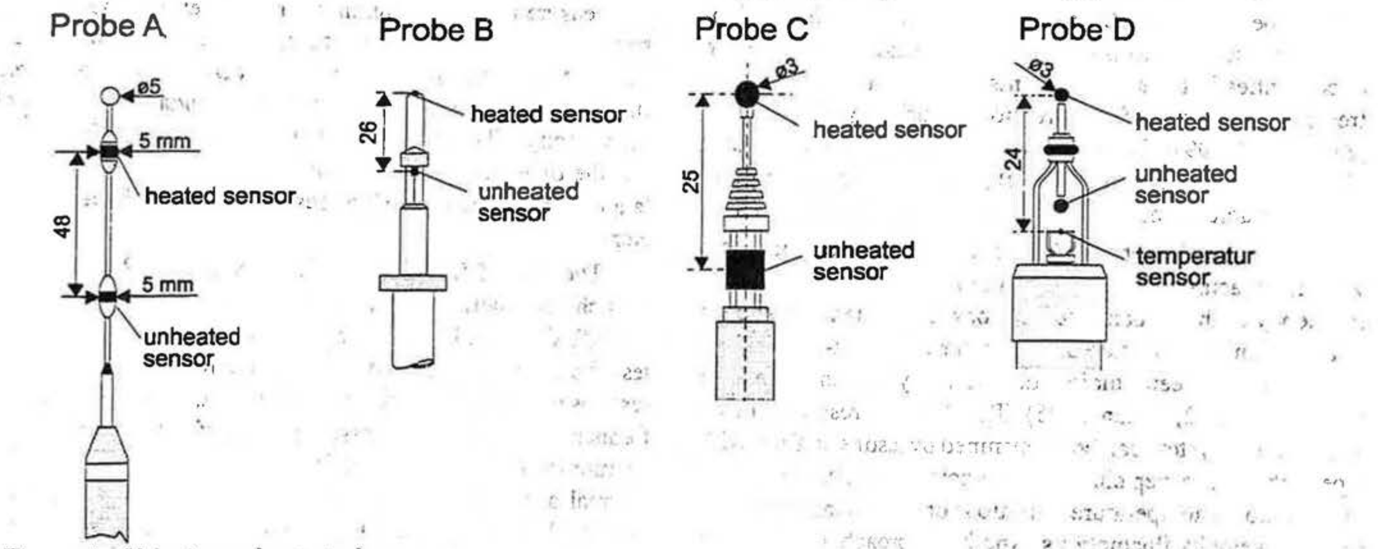

Figure 1 *Velocity probes tested.*

ground to shape and supported by a thin stainless steel tube. The ellipsoid carries three coils of electrically heated nickel wire. The coils are wound in a single layer without any space between the windings, and they are protected by a thin layer of white epoxy enamel. Thus, the diameter of the ellipsoid at the location of the heated wire is approximately 5 mm. The overheating temperature of the velocity sensor is 15°C (the overheating temperature is the difference in the temperature of the heated velocity sensor and the air).

The velocity sensor of anemometer B is a small thermistor with a diameter of less than 1 mm. The overheating temperature of the velocity sensor is 10°C. The design of anemometer B allows for the selection of different time constants of the velocity sensor in the range 0.1 s to 10 s.

The velocity sensor of anemometers D and E is designed as a spherical body with a diameter of 3 mm. The body of the sensor is made of quartz and coated with a heated nickel layer. The velocity probes also have a separate sensor for measuring the air temperature. The overheating temperature of velocity sensor D is 25°C. The design of anemometer E allows for the selection of different overheating temperatures for the velocity sensor. Anemometer C has a spherical velocity mass sensor of 3 mm diameter made of enameled copper wire molded into a sphere and an overheating temperature of 25°C.

The unheated sensor of the tested velocity probes is used to correct the measured velocity when the air temperature is different from the air temperature of the calibration. The response time of the unheated sensor is typically longer than the response time of the heated (velocity) sensor and is different for the anemometers available on the market. This response time is not provided by the manufacturers. Information concerning the method of performing the temperature correction is also not provided by the manufacturers. The five anemometers measure the mean velocity and the standard deviation of the velocity.

A hot-wire thermal anemometer 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 μk. 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. The tested anemometers and the reference anemometer were calibrated before the tests.

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 3 mm thick. A specially designed supporting structure makes it possible to position the wind tunnel at various angles against the horizontal level. The dynamic tests reported below were performed when the wind tunnel (also the airflow in it) was positioned horizontally. The air enters the wind tunnel through a filter and honeycomb straighteners. The cross section of this part of the tunnel is 300 x 300 mm^2. The air flows through two sections with reduced sizes. The first section (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 x 33 mm^2. The tunnel allows the static pressure to be measured in the three sections. 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

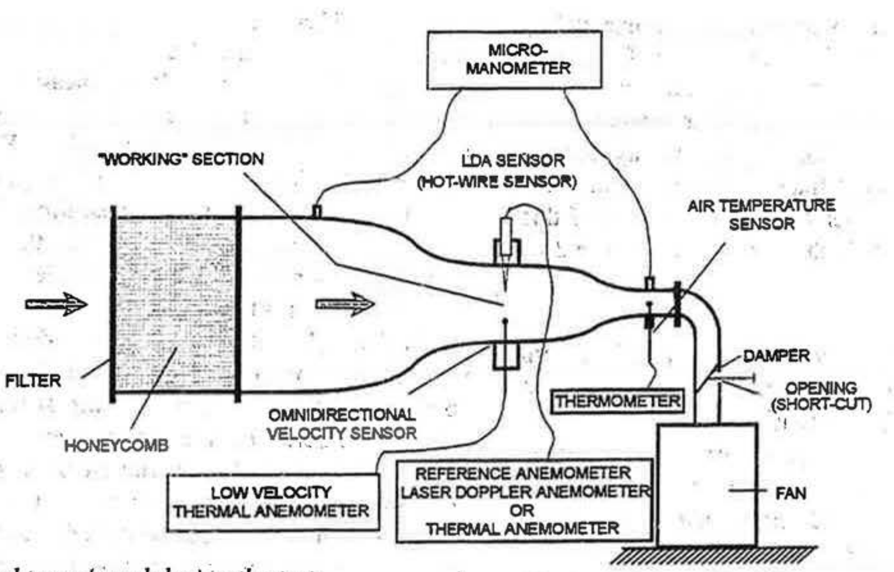

Figure 2 *The wind tunnel used during the tests.*

opens and closes the valve at different frequencies and at different levels. A short-cut 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 (short-cut) 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. Figure 3 shows typical records of generated airflow at different frequencies and amplitudes of velocity fluctuations. The corresponding frequency spectra of the velocity fluctuations are shown as well. The generated velocity fluctuations were not perfectly sinusoidal. This, however, has an insignificant impact on the accuracy of the experiments because it can be seen from the spectra that the most important third harmonic does not exceed 10% of the basic harmonic.

Uncertainties of the Measurements

In a flow with a constant velocity in the range 0.02 – 0.6 m/s, the uncertainty of the velocity measured by the reference anemometer was estimated to be ±0.005 m/s and of the velocity measured by the tested anemometers to be less than ±0.01 m/s.

The hot-wire anemometer used as a reference has a bandwidth in the kHz range of frequencies. Therefore, the uncertainties of the velocity measurements in a periodically fluctuating flow due to the reference anemometer 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

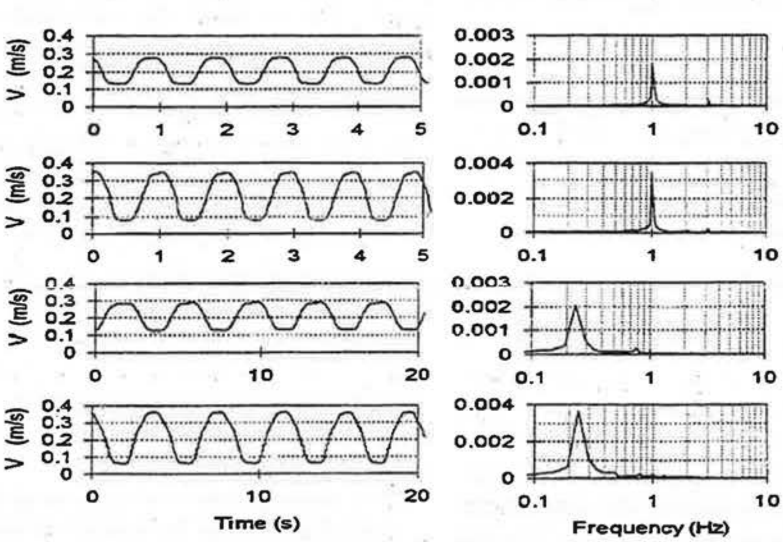

Figure 3 *Examples of velocity records with different frequencies (0.25 Hz and 1 Hz) and amplitudes (Tu = 30% and 52%). On the right side, corresponding frequency spectra of velocity fluctuations are presented.*

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 indicated 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%.

Experimental Conditions

The tests were performed in a horizontal airflow with periodically fluctuating velocity. The air temperature was kept constant (air temperature fluctuations were less than 0.2°C).

The impact of the mean velocity, the turbulence intensity, and the frequency of the velocity fluctuations on the dynamic response of anemometers A, B, C, and D were studied under 20 combinations of mean velocity of the airflow (0.1, 0.2, 0.4, and 0.6 m/s) and frequency of the velocity fluctuations (approximately 0.25, 0.5, 0.8, 1.8, and 3.2 Hz). The amplitude of the velocity fluctuations during these tests was kept constant, selected to provide an airflow with a turbulence intensity of 30% (±2%). In fact, the generated flow was a pseudo turbulent flow with a regular velocity pattern in the time unlike a real turbulent flow with a velocity pattern that may change its shape and magnitude in time. However, the pseudo turbulent velocity field is often used to simulate real turbulent flow as it is more accessible to theoretical treatment (Hinze 1975).

Experiments were performed with anemometer B to identify the impact of the time constant of a low-velocity anemometer on the dynamic response of the instrument. Tests were performed with three time constants of the instrument, 0.1, 0.25, and 1.0 s, under the following combinations of the airflow characteristics: mean velocity equal to 0.2 m/s; three levels of turbulence intensity, 10%, 30%, and 50%; and periodical velocity fluctuations with five different frequencies within the range 0.25 to 3.2 Hz.

The impact of the overheating temperature of the velocity sensor on the dynamic response of anemometer E was studied under the following combinations: overheating temperature, 11.5°C, 15.4°C, 21.8°C, 26°C, and 32.4°C; mean velocity, 0.1, 0.2, 0.4, and 0.6 m/s; turbulence intensity of 30%; and frequency of velocity fluctuation, 0.25, 0.5, 0.8, 1.8, and 3.2 Hz.

RESULTS

Figures 4a, 4b, 4c, and 4d show the dynamic response of the four anemometers, A, B, C, and D, at different mean velocities of the flow. The standard deviation ratio as a function of the frequency of the velocity fluctuations (standard deviation damping curves) is presented in the figures. The standard deviation ratio is defined as the standard deviation of the velocity measured by the tested anemometers divided by the standard deviation of the velocity measured by the hot-wire anemometer used as a reference.

Large differences in the shape of the standard deviation damping curves of the anemometers were identified. The standard deviation of the velocity measured by anemometer A was higher than that measured by the reference anemometer for the frequency range up to 1.5 - 2 Hz. Therefore, the standard deviation ratio as shown in Figure 4a was higher than 1 in that range of frequencies. Most probably this was caused by electrical filters built into the instrument. This effect was observed for the whole range of tested velocities, 0.1 m/s - 0.6 m/s. At frequencies of the velocity fluctuations higher than 0.7 - 0.8 Hz, the standard deviation ratio started to decrease, and its value became 1 at a frequency of approximately 1.5 - 2 Hz, i.e., the standard deviation of velocity measured by the tested anemometer was almost identical to the standard deviation measured by the reference anemometer. For frequencies of the velocity fluctuations higher than 2 Hz, the standard deviation of the velocity measured by this anemometer was lower than the standard deviation of the velocity in the flow, i.e., the standard deviation ratio was smaller than 1.

Anemometers B and C had a rather similar dynamic response (Figures 4b and 4c). For anemometer B, the standard deviation ratio already started to decrease at a frequency of the velocity fluctuations of approximately 0.2 - 0.3 Hz, i.e., this anemometer measured the standard deviation of the velocity lower than it was in reality when the frequency of the velocity fluctuations of the airflow was higher than 0.3 Hz. The dynamic response of anemometer B was faster than the response of anemometer C due to the difference in the size and the design of the sensors already described in the section "Thermal Anemometers."

The dynamic response of anemometer D followed a rather complicated curve: the standard deviation ratio initially decreased and became approximately 0.6 at about 1 Hz after which it remained almost constant for a range of frequencies up to almost 8 Hz and was then followed by a decrease. The sensor of this anemometer is designed as a quartz ball covered by a thin layer of nickel film. These two elements of the sensor, the quartz ball and the thin nickel film, have different time constants. The nickel film responds much faster to velocity changes than does the quartz body, which has a large mass. This results in the complicated dynamic response curve of the transducer.

The experimental results showed a tendency for improvement of the dynamic response of the anemometers when the mean velocity of the flow increased, i.e., with all other conditions being identical. A small increase of the standard deviation ratio was observed when the mean velocity was 0.4 and 0.6 m/s. This effect was more clearly pronounced at low frequencies of the velocity fluctuations. It was difficult to make an accurate assessment of the impact of the mean velocity on the dynamic response of the anemometers because the effect was comparable with the accuracy of the experiment, which was assessed to be ±0.05 of the value of the standard deviation ratio.

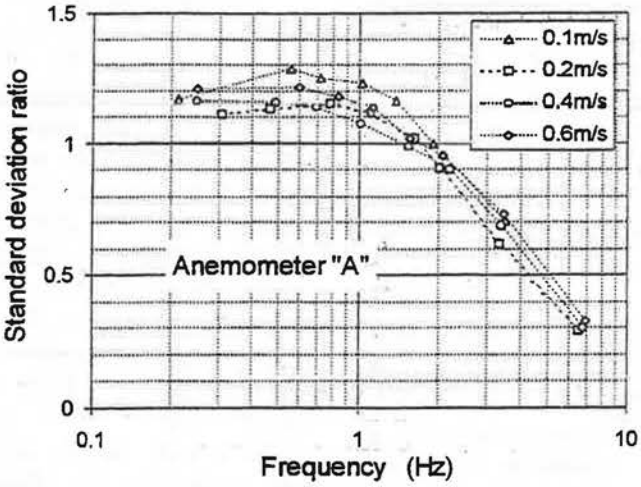

Figure 4a *Standard deviation ratio as a function of the frequency of the velocity fluctuation. Results from tests by anemometer A at different mean velocities are compared.*

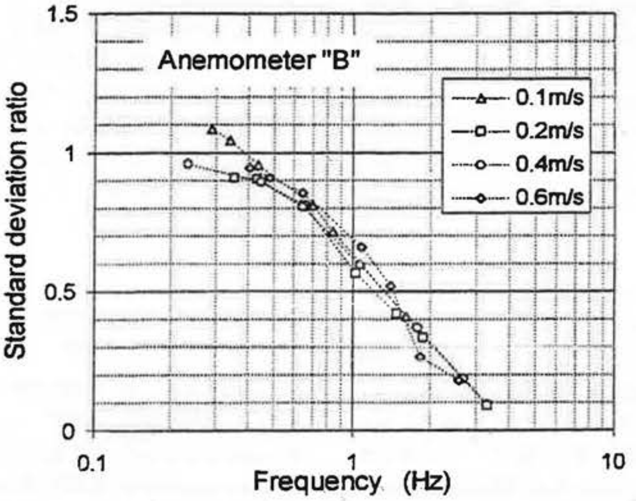

Figure 4b *Standard deviation ratio as a function of the frequency of the velocity fluctuation. Results from tests by anemometer B at different mean velocities are compared.*

Tests were performed with anemometer B to study the impact of the time constant of the anemometer on its dynamic response. Figure 5 shows the standard deviation ratio as a function of the frequency of the velocity fluctuations at time constants of 0.1, 0.25, and 1.0 s. Tests were performed at a constant mean velocity of 0.2 m/s. As expected, the results showed a significant improvement of the dynamic response of the anemometer when the time constant of the instrument decreased. The standard deviation ratio increased when the selected time constant decreased, especially at high frequencies of the velocity fluctuations. However, it should be noted that the improvement of the dynamic response of the instrument at a small time constant was not as expected. For example, at a frequency of the velocity fluctuations of 1 Hz and a time constant of 0.1 s, the anemometer measured the standard deviation of the velocity as much smaller than the true standard deviation measured by the reference anemometer, i.e., the standard deviation ratio was only 0.7. The dynamic response of this anemometer can be described by a first order transfer function and, therefore, the response time should be 2.3 times the time constant, i.e., the response time will be 0.23 s when the time constant is 0.1 s. With this response time, the standard deviation of the velocity fluctuations with a frequency of 1 Hz measured by the tested anemometer has to be very similar to the standard deviation measured by the reference anemometer.

The impact of the amplitude of the velocity fluctuations on the dynamic response of low-velocity anemometers was studied using anemometers B and D. The mean velocity ratio (defined as the mean velocity measured by the tested anemometers divided by the mean velocity measured by the reference anemometer) and the standard deviation ratio were determined from experiments in a periodically fluctuating airflow with a mean velocity of 0.2 m/s. Three amplitudes of the veloc-

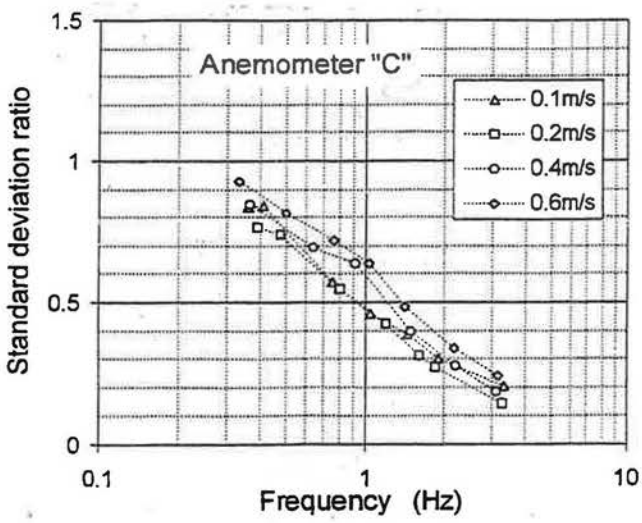

***Figure 4c** Standard deviation ratio as a function of the frequency of the velocity fluctuation. Results from tests by anemometer C at different mean velocities are compared.*

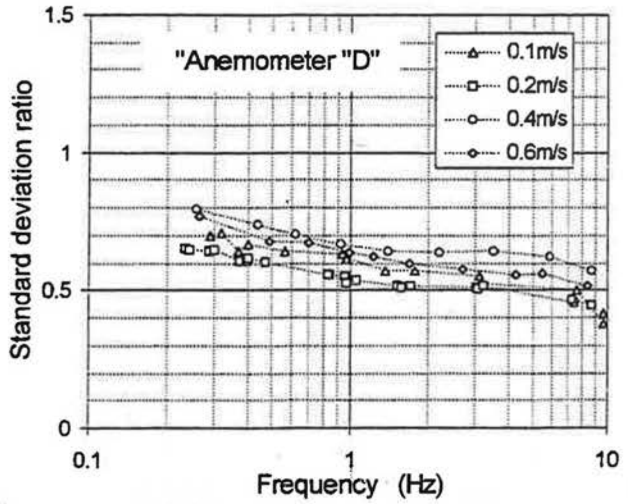

***Figure 4d** Standard deviation ratio as a function of the frequency of the velocity fluctuation. Results from tests by anemometer D at different mean velocities are compared.*

ity fluctuations were generated to correspond to three levels of turbulence intensity, namely, 10%, 30%, and 50%. At each level of turbulence intensity, four frequencies of the velocity fluctuations were generated in the range 0.25 Hz to 2 Hz. The mean velocity ratio and the standard deviation ratio, determined for the two anemometers at a turbulence intensity of 10% and frequency of velocity fluctuations of 0.25 Hz, were used as a reference value to divide, respectively, the mean velocity ratio and the standard deviation ratio determined by the two anemometers during the test. Thus, a relative mean velocity ratio and a relative standard deviation ratio were calculated and are presented as a function of the frequency of the velocity fluctuations in Figure 6 (a and b) and Figure 7 (a and b). The experiments with anemometer B were performed at two time constants of the instrument, 0.1 and 0.25 s.

The results in Figure 6a show that the mean velocity ratio for anemometer D decreased when the amplitude of the velocity fluctuations increased. The decrease was close to 10% when the turbulence intensity of the airflow increased from 10% to 50%. The frequency of the velocity fluctuations had almost no impact on the mean velocity ratio when the turbulence intensity of the flow increased up to 30%. Further increase of the turbulence intensity up to 50% caused a small decrease of the mean velocity ratio with the increase of the frequency of the velocity fluctuations. A similar effect, but less pronounced, was identified also for anemometer B (Figure 6b). For this instrument, a small decrease of the mean velocity ratio was observed only at frequencies of velocity fluctuations higher than 1 Hz and a turbulence intensity of 50%. The tests showed no significant impact of the time constant of anemometer B on the measured mean velocity

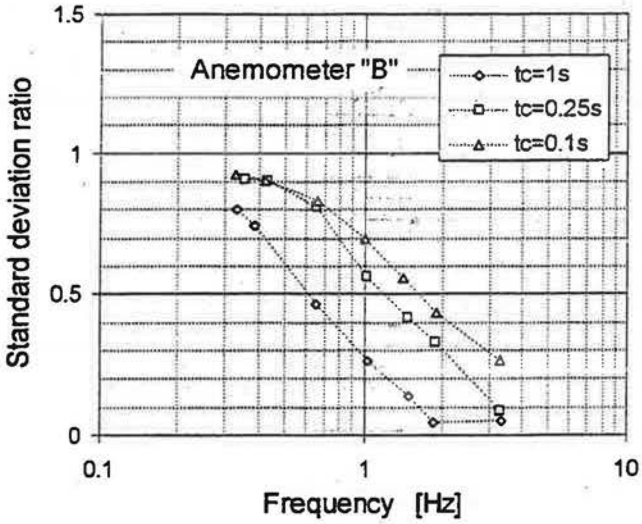

Figure 5 *Standard deviation ratio as a function of the frequency of the velocity fluctuation. Results from tests by the anemometer B at different time constants of the instrument are compared at a mean velocity of the airflow of 0.2 m/s.*

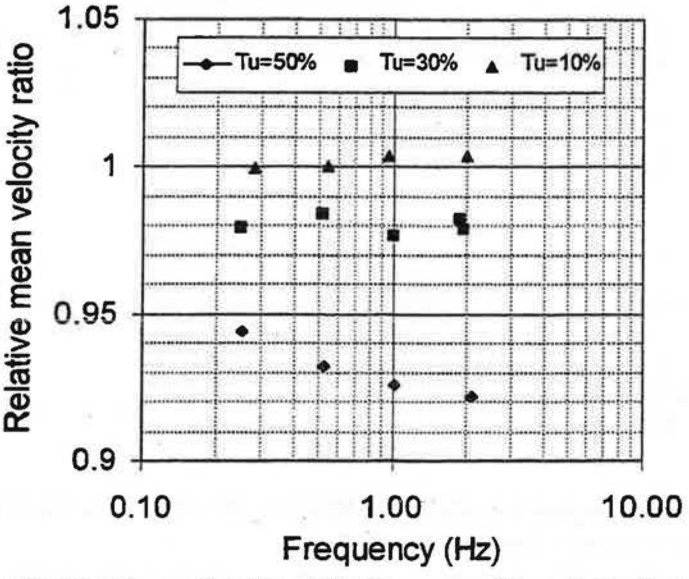

Figure 6a *Relative mean velocity ratio as a function of the frequency of the velocity fluctuations at different amplitudes of the velocity fluctuations is compared. Tests by anemometer D at a mean airflow velocity of 0.2 m/s.*

ratio (Figure 6b). The standard deviation ratio for the two anemometers was almost not influenced by the amplitude of the velocity fluctuations (Figures 7a and 7b). The response of the instruments was as already identified during the frequency tests described above.

The overheating temperatures of the velocity sensors for most of the low-velocity anemometers available on the market, including four of the tested anemometers, namely, A, B, C, and D, are selected by the manufacturers during the design of the instruments and cannot be changed by the user. Anemometer E, used in the present tests, allows for selection of the overheating temperature of the velocity sensor. The overheating temperature is the difference between the temperature of the velocity sensor and the air temperature of the flow where measurements are performed. The static calibration of the low-velocity anemometers is performed at a fixed temperature, typically 20°C. However, very often the instruments are used to perform measurements in rooms with an air temperature lower or higher than the temperature of the calibration. Most of the anemometers are designed to compensate for the air temperature difference from the calibration and the time of the measurements. If this compensation is not made, the air velocity will be measured incorrectly. The mistake in the measured velocity will increase when the overheating temperature of the velocity sensor decreases.

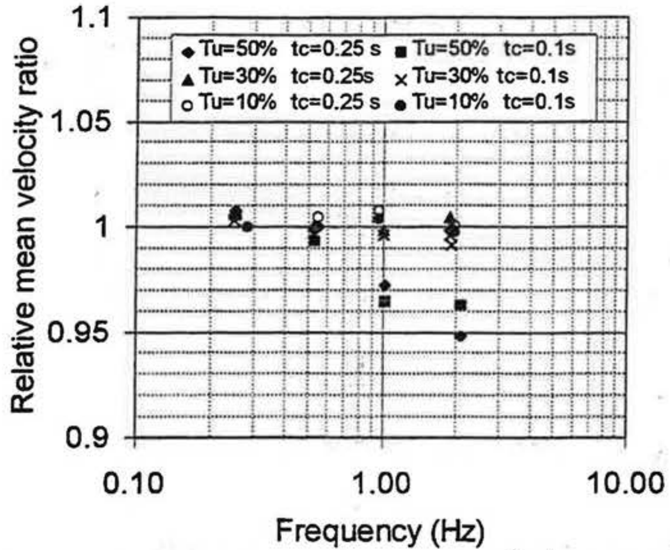

Figure 6b *Relative mean velocity ratio as a function of the frequency of the velocity fluctuations at different amplitudes of the velocity fluctuations is compared. Tests by anemometer B at a mean airflow velocity of 0.2 m/s and two time constants of the instrument.*

The impact of the temperature compensation on the accuracy of the velocity measurements was studied by anemometer E. The instrument was calibrated at five overheating temperatures of the velocity sensor: 11.5°C, 15.4°C, 21.8°C, 26°C, and 32.4°C above the air temperature. The calibration was performed at 20°C. The results were used to calculate the necessary correction of the velocity if measurements are performed at an air temperature different from that of the static calibration. For this purpose, the calibration data for the five overheating temperatures were approximated by the following equation:

$$\sqrt{V} = k_0 + k_1\left(\frac{U^2}{t_s - t_a}\right) + k_2\left(\frac{U^2}{t_s - t_a}\right)^2 \tag{1}$$

where t_s is the temperature of the sensor; t_a is the air temperature; U is the output voltage; V is the velocity; and $k_0 = -0.3962$, $k_1 = 6.4761$, $k_2 = 15.0328$ are coefficients from the calibration of the sensor. The above equation was used to calculate the necessary correction of the velocity when measurements were performed at an air temperature different from that of the static calibration. The results from the calculations are shown in Figure 8. The necessary correction of the measured velocity as a function of the velocity of the flow is shown in the figure only for 1 K difference between the air temperature of calibration and the air temperature of measurement. The overheating temperature is a parameter in the figure. The results show that the lower the overheating

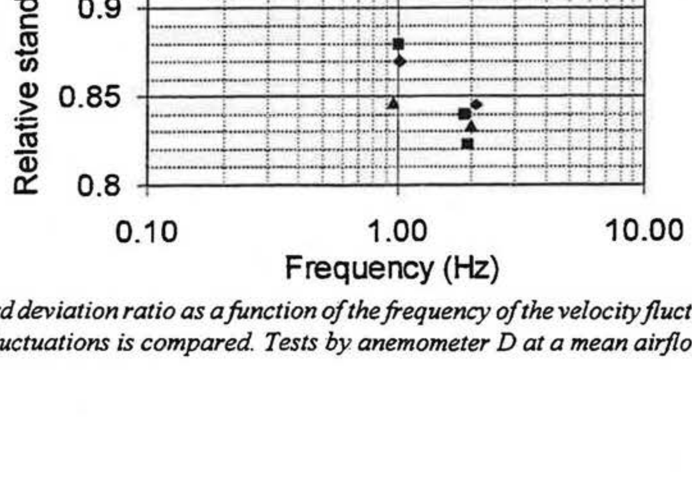

Figure 7a *Relative standard deviation ratio as a function of the frequency of the velocity fluctuations at different amplitudes of the velocity fluctuations is compared. Tests by anemometer D at a mean airflow velocity airflow of 0.2 m/s.*

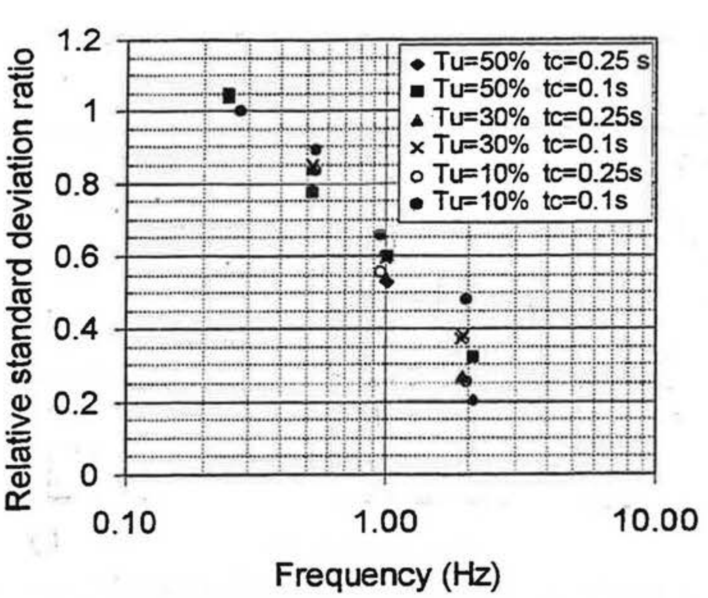

Figure 7b *Relative standard deviation ratio as a function of the frequency of the velocity fluctuations at different amplitudes of the velocity fluctuations is compared. Tests are performed by anemometer B at a mean velocity of the airflow of 0.2 m/s and two time constants of the instrument.*

temperature of the velocity sensor, the greater the impact of the air temperature changes on the accuracy of the velocity measurements; therefore, the overheating temperature of the velocity sensor should be as high as possible.

Anemometer E was also tested to identify the impact of the overheating ratio on the dynamic response of the anemometer. Tests were performed in a periodically fluctuating airflow at 60 different combinations of mean velocity, overheating temperature of the sensor, and period of fluctuations, as already identified in the section "Experimental Conditions." For 12 combinations of mean velocity and overheating temperature, experiments were performed at five frequencies of the velocity fluctuations in the range 0.25 to 3.2 Hz. The results of these tests are shown in Figure 9 (a, b, and c). The standard deviation ratio as a function of the frequency of the velocity fluctuations is shown in the figures. The standard deviation ratio at different velocities and overheating temperatures are compared. The standard deviation ratio decreased when the mean velocity of the flow decreased and the frequency of the velocity fluctuations increased. The standard deviation ratio increased when the overheating ratio of the sensor increased. These results confirm that the dynamic

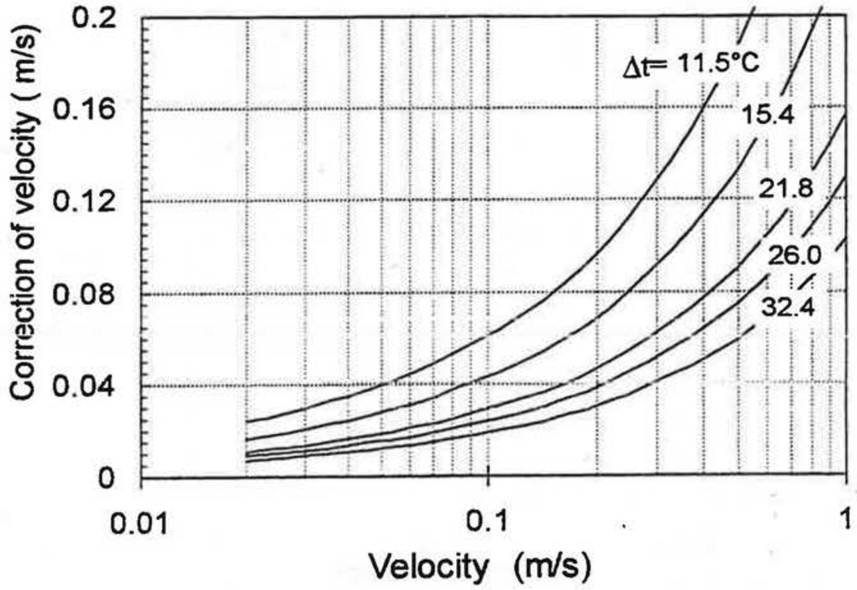

Figure 8 *Necessary corrections of the measured velocity due to changes of the air temperature by 1 K at different overheating temperatures, Δt, of the velocity sensor.*

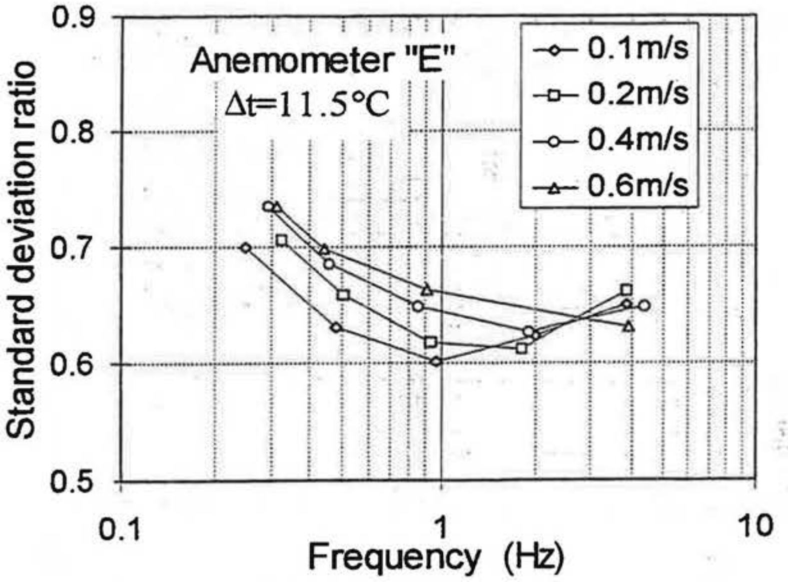

Figure 9a *Standard deviation ratio as a function of the frequency of the velocity fluctuations measured by anemometer E at different mean airflow velocities and at an overheating temperature of the velocity sensor of 11.5°C.*

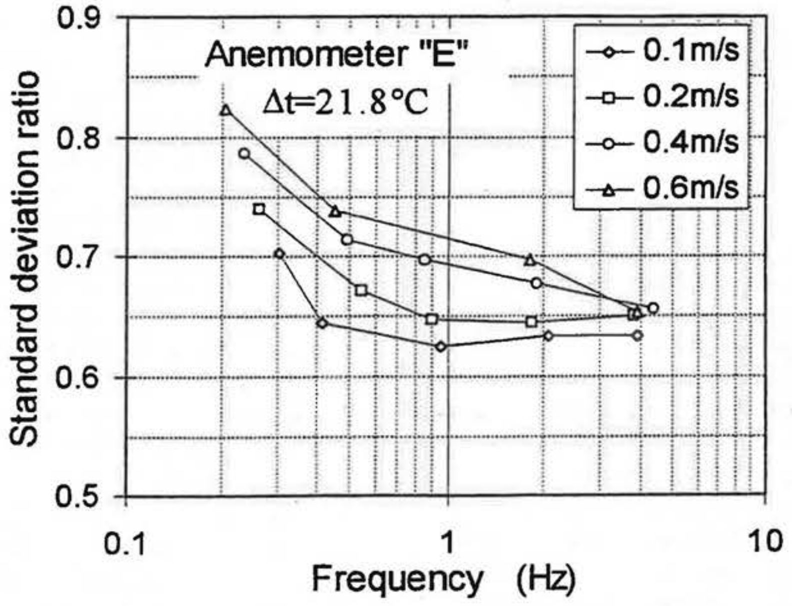

Figure 9b *Standard deviation ratio as a function of the frequency of the velocity fluctuations measured by anemometer E at different mean velocities of the airflow and at an overheating temperature of the velocity sensor of 21.8°C.*

response of the sensors improves at a high velocity and a high overheating temperature.

A high overheating temperature will improve the dynamic response of the anemometer and will decrease the impact of the air temperature changes on the accuracy of the velocity measurements. However, the high overheating temperatures of the velocity sensor will cause a strong free convective upward airflow that can introduce a significant error in the measured mean velocity and turbulence intensity, especially when the measurements are performed in downward flow (Melikov 1997; Popiolek et al. 1997). Therefore, the selection of the overheating temperature of the hot-sphere-type sensors is a result of a compromise between the antagonistic impact of these two factors on the accuracy of the measurements.

The accuracy of measuring the standard deviation of the velocity and, therefore, of the turbulence intensity depends on the dynamic response of the anemometer as well as on several other factors, such as the directional sensitivity of the velocity sensor, the impact of free convection due to the heated sensor,

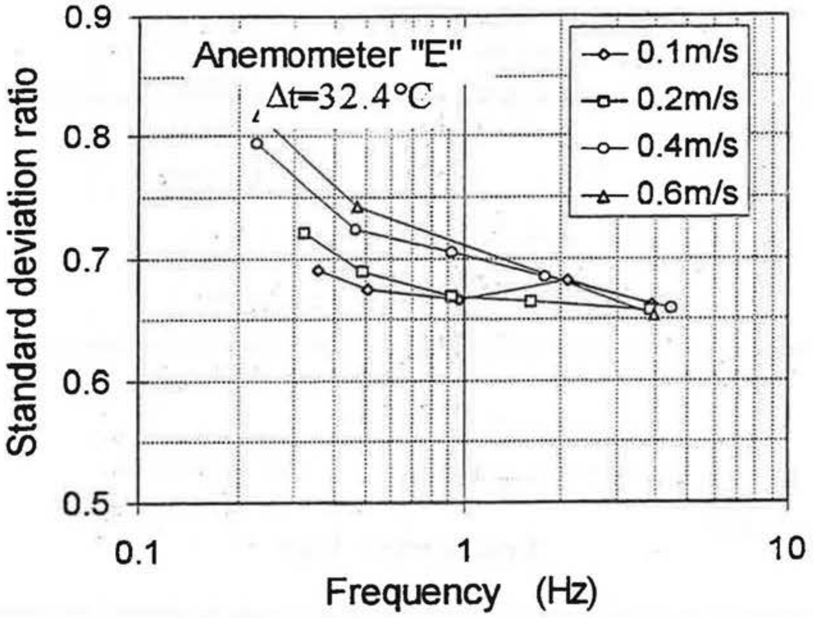

Figure 9c *Standard deviation ratio as a function of the frequency of the velocity fluctuations measured by anemometer E at different mean airflow velocities and at an overheating temperature of the velocity sensor of 32.4°C.*

and the ability of the instrument to correct the measured velocity when air temperature fluctuations occur in the flow. This has been studied and reported (Stannov et al. 1997; Popiolek et al. 1997; Melikov et al. 1997a, 1997b).

DISCUSSION

The current standards require measuring ranges, measuring accuracy, and 90% response time of the velocity sensors (to be understood as the anemometer as a whole). ISO Standard 7726 (ISO 1985) specifies a required response time of 1 s and a desirable response time of 0.5 s (in the new draft of the standard, ISO 7726 1996, the required response time is 0.5 s and the desired response time is 0.2 s). ASHRAE Standard 55 (ASHRAE 1992) requires a response time from 1 s to 10 s and a desirable response time of 0.2 s when indoor measurements of turbulence intensity are to be performed. ASHRAE Standard 55 and the draft of ISO Standard 7726 assume that the dynamic behavior of the anemometer is of the first order and, therefore, the 90% response time is 2.3 times the time constant of the anemometer (ISO Standard 7726 assumes that the response time is 3.1 times the time constant; this assumption is probably a mistake). The Nordtest method (1991) is also based on the assumption that low-velocity thermal anemometers have a dynamic response that can be described by a first order transfer function. In Figure 10, the dynamic response of anemometers A, B, C, and D is compared with the dynamic response of the low-velocity anemometers with a first order transfer function and a 90% response time of 0.5 s as assumed in ISO Standard 7726 (desired response) and in the draft ISO Standard 7726 (required response). The dynamic response of anemometers B and C is rather close to the requirements in the standards, i.e., almost a first order transfer function and a response time of 0.5 s. However, the dynamic response of anemometers A and D is different. The shape of the standard deviation damping curves did not follow the shape of a first order transfer function, and this makes it impossible to determine the response time of the instruments according to the recommendations in the standards (ASHRAE Standard 55, ISO Standard 7726, and the draft ISO Standard 7726).

According to the above standards, the time constant should be defined as a response of the instrument to a step change of the velocity. This requires an analog output from the instrument. The determination of the cut-off frequency in the Nordtest method (1991) also requires recording of the instantaneous velocity measured by the anemometer from an analog output of the instrument.

The methods for testing the dynamic response of low-velocity anemometers recommended in the standards (ASHRAE 55, ISO 7726, draft ISO 7726) and in the Nordtest method (1991) have the following disadvantages:

- An analog output for the thermal anemometers is required; however, an analog output is not present for many of the existing instruments. Furthermore, most often the analog output of the low-velocity thermal anemometers is modified (the analog signal from the sensor is initially converted into a digital signal, statistically analyzed, and then provided to the analog output by a digital-analog conversion) and is not as fast as the response of the velocity sensor (for example, anemometers B and D in the present study).
- The assumption that the dynamic response of low-velocity anemometers can be described by a first order transfer function is not true for all anemometers available on the market;

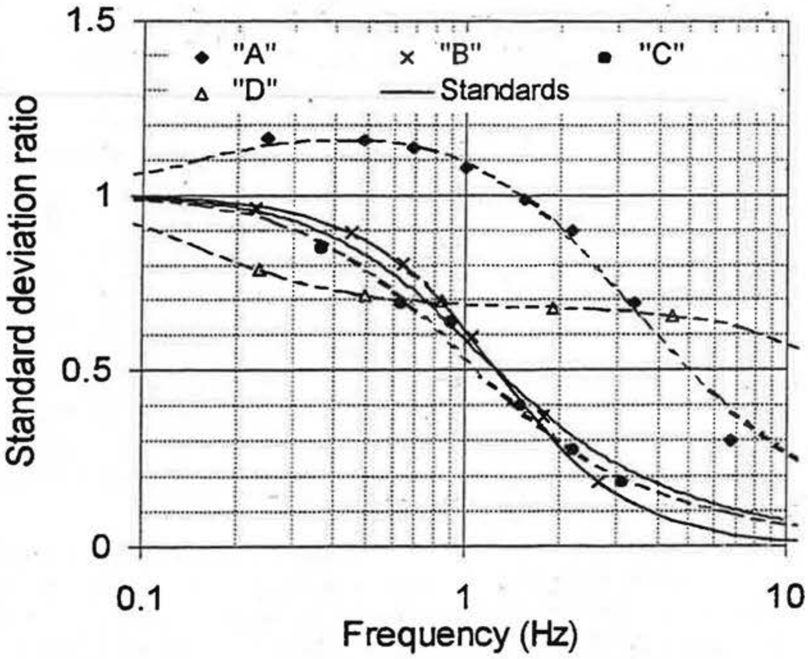

Figure 10 *Comparison of the dynamic response of anemometers A, B, C, and D at 0.4 m/s with the dynamic response of a low-velocity anemometer with a response time of 0.5 s, as assumed in the standards (ASHRAE 55 and ISO 7726).*

therefore, the time constant cannot always be used to define the response time of the velocity sensor.

- The time constant and the response time, introduced in the thermal anemometry, do not clearly relate the characteristics of the thermal anemometer with the measured parameter, which is the air velocity fluctuating with a changeable amplitude and a random frequency.

It is unrealistic to expect and to require that low-velocity anemometers have a dynamic response that can be described by a first order transfer function or a rapid analog output. Therefore, the use of the time constant, the response time, and the cut-off frequency to describe the dynamic behavior of low-velocity anemometers, as suggested in the current standards and test methods (ISO 1985, 1996; ASHRAE 1992, 1990; Nordtest 1991), has rather limited application in practice. This research suggests using the upper frequency, f_{up}, to describe the dynamic behavior of low-velocity anemometers. The definition of the upper frequency is:

The upper frequency defines the highest frequency of sinusoidal velocity fluctuations up to which the low-velocity anemometer should be able to measure the standard deviation of the velocity with a defined accuracy.

In other words, the upper frequency defines the highest frequency of sinusoidal velocity fluctuations up to which the determined standard deviation ratio should be not more than a certain percent different than 1 (for example, a limit can be ±10%, i.e., the determined standard deviation ratio should be in the range 0.9 to 1.1). The limit has to be defined after careful analysis of the impact of the standard deviation of the velocity on the assessment of risk of draft in rooms as well as the design limitations of the low-velocity anemometers.

The upper frequency can be used to define the dynamic response of any anemometer. This approach is clear and without any assumption concerning the dynamic response curve of the thermal anemometer. It does not require a fast analog output from the anemometer, as required in the method of 90% response time and the cut-off frequency method. The method can be applied for anemometers both with and without analog output.

The upper frequency method requires testing of the anemometers in a periodically fluctuating airflow with different frequencies (similar to the tests described in this study) and reading (or calculating) only the standard deviation of the velocity measured by the tested anemometer. Tests on dynamic characteristics in airflows with sinusoidal fluctuations of the velocity require determination of the frequency transmittance, defined as the ratio of the amplitude of the output signal to the amplitude of the input signal of the instrument (the amplitude can be calculated as 1.4142 times the standard deviation of the signals). It is rather difficult, however, to generate ideal sinusoidal velocity fluctuations. Therefore, the standard deviation ratio can be used. Tests were performed to study the extent to which nonideal sinusoidal velocity fluctuations will affect the accuracy of determination of the standard deviation ratio used to define the upper frequency. Airflows with different types of velocity fluctuation (rectangular, triangular, etc.) were generated. First results of the tests are reported by Kierat and Popiolek (1997). The results showed that the accuracy of determination of the standard deviation ratio was insignificantly (<2%) affected by the fact that dynamic tests were performed in airflows with sinusoidal velocity fluctuations that are not ideal. The standard deviation ratio appears to be a rather convenient parameter for use in practice, as most of the thermal anemometers available on the market display the standard deviation of the measured velocity.

The results of this study show that the upper frequency of the five thermal anemometers tested was very different; for anemometer A, it was less than 0.2 Hz; for anemometer B, the upper frequency was 0.4 Hz; and for anemometers C and D, it was, respectively, less than 0.3 and 0.2 Hz.

Tests with two of the anemometers, B and D, were performed to investigate whether it was possible to relate the upper frequency with the 90% response time. The response of the anemometers to a velocity step-change up and a velocity step-change down was studied. This part of the study will be reported in a separate paper. An important result of the tests was that the 90% response time for the velocity step-change down was approximately 10% smaller than the 90% response time for the step-change up, i.e., the response of the anemometers was faster with a velocity decrease than with a velocity increase. The standards (ASHRAE 55 and ISO 7726) require that the 90% response time be determined under a step change of velocity, but they do not specify whether the velocity change should be a step up or a step down.

It is suggested that the upper frequency be used in the standards instead of the response time and the time constant. The required and the desired upper frequency included in future standards have to be defined after analysis of the velocity fluctuations that occur in rooms in practice. Several studies on airflow characteristics in rooms have been reported in the literature (Thorshauge 1982; Hanzawa et al. 1987; Sandberg 1987; Kovanen et al. 1987; Melikov et al. 1990; Heber and Boon 1991). Low-velocity thermal anemometers with an omnidirectional velocity transducer have been used during the measurements. The results of the present study indicate a high risk of inaccurate measurements of the velocity fluctuations by these instruments due to slow or complicated response time.

Recent comprehensive measurements by a three-dimensional laser doppler anemometer (LDA) have been reported (Finkelstein et. al. 1996). The LDA can measure all velocity fluctuations that occur in rooms independent of the flow direction and its mean velocity, turbulence intensity, and frequency of velocity fluctuation. Therefore, the LDA measurements can be considered as more reliable than the measurements by low-velocity thermal anemometers. The measurements reported by Finkelstein et. al. (1996) reveal that velocity in rooms can fluctuate with a frequency of more than 5 Hz. However, within the occupied zone of rooms, most of the velocity fluctuations have a frequency of below 2 Hz and even below 1 Hz. Therefore, it may be suggested that a required upper frequency of 1 Hz and desirable upper frequency of 2 Hz be recommended in future standards for low-velocity anemometers.

There are only a few studies on human response to frequency of velocity fluctuations. Fanger and Pedersen (1977) found that at a comfortable air temperature of 26°C, a periodically fluctuating airflow with a frequency of velocity fluctuation of 0.5 - 0.6 Hz was felt most uncomfortable by the subjects participating in the experiments. Asakai and Sakai (1974) performed experiments with human subjects in warm environments (air temperature of 31°C). The subjects were exposed to a periodically fluctuating flow and could select the frequency of the velocity fluctuations. The tests showed that with all other conditions being equal, velocity fluctuations with a frequency of 1.2 Hz were preferred by most subjects and resulted in the greatest improvement in their thermal comfort. Human response to the frequency of velocity fluctuations remains to be studied in detail. However, these first results support the required and desirable upper frequencies defined above.

The suggested concept of the upper frequency has been used to develop a test method for describing the dynamic response of anemometers for low-velocity measurements indoors. The test method is outlined below.

Test Method for Describing the Dynamic Characteristics of Thermal Anemometers for Low-Velocity Measurements

This method is to be used to determine the dynamic response of anemometers for measurements in an airflow with velocity fluctuation frequencies in the range 0.25 - 5 Hz, such as in rooms, vehicles, animal houses, industry, HVAC systems, etc. The method determines the upper frequency taken as a single measure of the dynamic response of the anemometer and can be used to compare the dynamic response of different anemometers.

A horizontal one-dimensional airflow with a uniform cross-sectional distribution of the velocity has to be used. The wind tunnel used for the dynamic tests described in this paper or a wind tunnel with a different design, such as, for example, the test rig described in the Nordtest method (1991), can be employed. It should be possible to change the instantaneous velocity of the flow periodically with a desired amplitude and frequency of the longitudinal velocity fluctuations. The turbulence intensity of the flow should be in the range of 40% to 50%; it should be possible to change the frequency of the velocity fluctuations in the range 0.25 - 5 Hz.

The mean velocity, the standard deviation, and the frequency of velocity fluctuations of the airflow generated in the wind tunnel should be known. If these characteristics of the airflow cannot be described accurately in advance by a mathematical function, then the instantaneous air velocity should be measured during the tests by a reference instrument located in the cross section of the flow and recorded. These records should be used to define accurately the mean velocity of the flow, the standard deviation of the velocity, and the frequency of the velocity fluctuations. The temperature fluctuations in the generated airflow should be small, with a standard deviation below 0.2°C.

The tested instrument should be able to measure the mean velocity and the standard deviation of the velocity. If this is not built into the instrument, then an analog signal of the instantaneous velocity should be recorded and used to calculate the mean velocity and the standard deviation of the velocity.

The tested velocity transducer should be placed in a point of the flow where the velocity is known from measurement by a reference anemometer. The transducer should be aligned with the mean airflow direction in the same way, as specified and calibrated by the manufacturer. The tested transducer and the reference transducer should not disturb each other. The sensor used for temperature compensation, if any, should be located in the flow as well. The measurements should be performed with a minimum of five samples per second.

Measurements of the mean velocity and the standard deviation should be performed by the tested anemometer at the combinations of mean velocity, amplitude of the velocity fluctuations, and frequency of the velocity fluctuations similar to the following: mean velocity of 0.2 and 0.4 m/s; turbulence intensity in the range 40% to 50%; and frequency of velocity fluctuations of 0.25, 0.5, 1.0, and 2.0 Hz. A hot-wire thermal anemometer is commonly used for velocity measurements in practice and may be used as a reference. This instrument has a low sensitivity at air velocities below 0.1 m/s. Therefore, a mean velocity of 0.2 m/s is suggested for the tests. The measurement time should be sufficient to obtain reliable results for the mean velocity and the standard deviation. During the tests, the variations of the air temperature and pressure should be small enough not to influence the accuracy of the tests.

The results of the measurements should be used to define the upper frequency of the anemometer in the following way. The standard deviation ratio should be calculated and presented in a figure as a function of the frequency of the velocity fluctuations. The figure produced should have two curves from the tests at mean velocities of 0.2 m/s and 0.4 m/s. The upper frequency is defined as the highest frequency up to which the standard deviation ratio remains, for example, in the limits of 0.9 to 1.1 (1 ±10%). The determination of the upper frequency is shown in Figure 11. The standard deviation ratio as a function of the frequency is presented in the figure from tests with a low-velocity anemometer at two mean velocities of the flow, 0.2 and 0.4 m/s. The upper frequency, f_{up} = 0.3 Hz, is the lowest defined from the tests at the two velocities.

CONCLUSIONS

Dynamic behavior of five low-velocity thermal anemometers with an omnidirectional sensor have been studied in a periodically fluctuating horizontal airflow under numerous combinations of mean velocity and amplitude and frequency of velocity fluctuations. The impact of the time constant of the instrument and the overheating temperature of the velocity sensor on the accuracy of measuring the mean velocity and the standard deviation of the velocity have been identified.

The results showed that the dynamic responses of the anemometers tested were different. With all other conditions identical, the standard deviation of the velocity measured by the instruments decreased when the frequency of the velocity fluctuations increased. This response was only slightly influenced by the mean velocity of the flow. The impact of the amplitude on the mean velocity and the standard deviation of the velocity measured by the instruments was small and

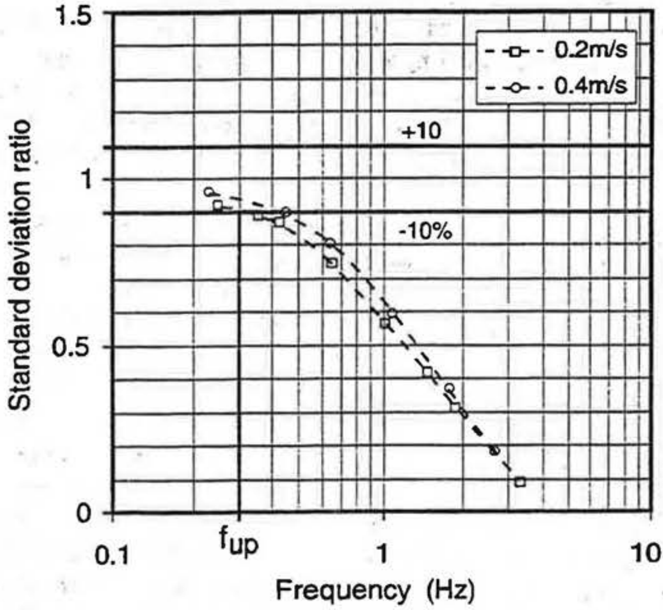

Figure 11 *Dynamic response curves at mean velocities of 0.2 and 0.4 m/s are used to define the upper frequency of a low velocity anemometer,* f_{up} = *0.3Hz.*

mainly when the turbulence intensity was above 30%. Large differences in the shape of the dynamic response curves of the anemometers were identified. The dynamic response curves for three of the five anemometers tested could not be described by a first order transfer function.

As expected, the results showed that the standard deviation of the velocity fluctuations was measured close to the true standard deviation of the velocity when the time constant of the instruments decreased and the overheating temperature of the velocity sensor increased.

This study showed that the test method of step change of the velocity recommended in the current standards (ASHRAE Standard 55 and ISO Standard 7726) and the method of cut-off frequency recommended in the Nordtest method NT VVS 089 for studying the dynamic response of low-velocity anemometers cannot always be applied because they assume that the anemometer behaves as a measuring system with one exponential time constant and has an analog output for the measured velocity, which is not the case in practice.

A concept of the upper frequency is proposed in this study to describe the dynamic response of low-velocity anemometers.

A new test method for describing the dynamic behavior of low-velocity anemometers is outlined and suggested for inclusion in future indoor climate standards. The method is based on the upper frequency and can be applied to any anemometer.

ACKNOWLEDGMENTS

The results presented in this paper are part of research project MAT1-CT93-0039 sponsored by the European Community, Directorate for Research and Development, Programme "Standards, Measurements and Testing."

REFERENCES

Asakai, M., and K. Sakai. 1974. Cooling effect of car ventilators. *Bulletin of JSAE*, 6: 75-82.

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

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

Bruun, H.H. 1995. *Hot-wire anemometry: Principles and signal analysis.* New York: Oxford University Press, Inc.

Fanger, P.O., and C.J.K. Pedersen. 1977. Discomfort due to air velocities in spaces. *Proc. of the Meeting of Commission B1, B2, E1 of the International Institute of Refrigeration*, 4, pp. 289-296.

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.

Freymuth, P. 1992. *Bibliography of thermal anemometery.* TSI Inc.

Hanzawa, H., A.K. Melikov, and P.O. Fanger. 1987. Airflow characteristics in the occupied zone of ventilated spaces. *ASHRAE Transactions* 93 (1): 524-539.

Heber, A.J., and C.R. Boon. 1991. Air velocity and turbulence with non-isothermal jet ventilation. *Proc. of ASAE Winter Meeting, December 17-20*, Paper No. 91-4549, pp. 1-24.

Hinze, J.O. 1975. *Turbulence.* New York: McGraw-Hill.

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

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.

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).

Kovanen, K., D. Seppanen, U. Serien, and A. Majanen. 1987. Air velocity, turbulence intensity and fluctuation frequency in ventilated spaces. *Proceedings of ROOMVENT '87*, Session 4, Stockholm.

Melikov, A.K., G. Langkilde, and B. Derbiszewski. 1990. Airflow characteristics in the occupied zone of rooms with displacement ventilation. *ASHRAE Transactions* 96, (1): 555-563.

Melikov, A., and T. Sawachi. 1992. Low velocity measurements: Comparative study of different anemometers. *Proceedings of ROOMVENT '92*. Aalborg. Denmark, Vol. 3, pp. 291-306.

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., U. Krüger, G. Zhou, T.L. Madsen, and G. Langkilde. 1997a. Air temperature fluctuations in rooms. *Building and Envirionment* 32 (2): 101-104.

Melikov, A.K., G. Langkilde, and T.L. Madsen. 1997b. Impact of velocity and temperature fluctuations on the accuracy of low velocity measurements indoors by thermal anemometers. *ASHRAE Transactions* 104 (1).

Nordtest method. 1991. Nordtest method, *NT VVS 089, Thermal anemometers low velocities: Frequency response and time-constant or cut-off frequency*. Espoo, Finland.

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

Sandberg, M. 1987. Velocity characteristics in mechanically ventilated office rooms. *Proc. of ROOMVENT '87, Air distribution in ventilated spaces*, Stockholm, 10-12 June, 1987, Session 2a.

Sandberg, M., and I. Petersson. 1990. A method for the determination of the time constant of low velocity anemometers. *Proceedings of ROOMVENT '90*, Oslo, Norway, Session B2, Paper No.40, pp. 1-10.

Sawachi, T., and A.K. Melikov. 1993. Air velocity measurements indoors using thermal anemometers with hot-sphere type sensors. *Thermal Anemometry, 1993*. D.E. Stock, S.A. Sherif, A.J. Smits, and J. Davidson, eds. ASME, FED-Vol. 167, pp. 27-3.

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).

Thorshauge, J. 1982. Air velocity fluctuations in the occupied zone of ventilated spaces. *ASHRAE Transactions* 88 (2): 753-763.

Zhang, J.S., G.J. Wu, and L.L. Christianson. 1991. Hot wire/film anemometry for room air motion studies. *Proc. of 12th AIVC Conference, Ottava, Canada, 24-27 September*, Poster 53, pp. 277-287.