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LOW VELOCITY MEASUREMENTS: COMPARATIVE STUDY OF DIFFERENT ANEMOMETERS

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SUMMARY

Air velocity is an important indoor climate factor for man's thermal comfort. Reliable and accurate low velocity measurements have to be performed in order to assess the thermal comfort conditions in the occupied zone of rooms. Most often, the common user performing field measurements, rely on the calibration of the low velocity anemometers made by their manufacturers. Several factors important for the accuracy of the low velocity measurements, such as directional sensitivity of the sensor and its response time, type of measured airflow and its direction, etc., are not considered.

Five thermoanemometers and one ultrasonic anemometer, available on the market and calibrated by their manufacturers, were tested in an airflow with velocity fluctuations similar to the velocity fluctuations of the flow in ventilated rooms. During the tests the mean velocity of the airflow ranged from 0.12 to 0.5 m/s and the turbulence intensity ranged from 2 to 60%. The airflow was produced by a specially designed flow generator.

At equal conditions the anemometers measured different mean velocity (up to 100% difference) due to the different calibration they had. The different response time of the sensors and the instruments as a whole caused up to 100% difference in the measured turbulence intensity. In order to perform accurate measurements of the turbulence intensity a response time of 0.2 s has been recommended in the literature but this needs further studies. The design of the transducer (a special protection of the velocity sensor against damage) had an impact on the measured turbulence intensity as well. The omnidirectional sensors were sensitive to the direction of the velocity in a plane of the axis of the transducer (yaw sensitivity).

In order to perform accurate low velocity measurements the calibration and the directional sensitivity of the anemometers has to be checked. The main direction of the flow has to be known. There is a need for an international standard procedure for calibration of low velocity anemometers.

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INTRODUCTION

Air velocity is an important indoor environmental parameter for man's thermal comfort. Studies [1, 2, 3] have shown that velocity fluctuations have an impact on man's thermal comfort conditions. It has been found in [1] that at equal mean velocity and air temperature draught complaints increase when turbulence intensity, defined as the standard deviation of the velocity fluctuations divided by the mean velocity, increases. A model of draught risk has been developed in [1]. The model predicts the percent of people dissatisfied due to draught as a function of the air temperature, the mean velocity and the turbulence intensity. Therefore the draught risk in rooms can be quantified by measurements of these three physical parameters. The model of draught risk has been incorporated in the thermal comfort standards under revision [4,5]. This requires reliable measurements of the mean velocity and the turbulence intensity to be performed when estimating the thermal comfort conditions in rooms.

Accurate measurements of a low air velocity are difficult. Several methods, such as thermal anemometry, laser doppler anemometry, flow visualization, sonic anemometry, etc., may be used to measure the airflow velocity in rooms. At the present the thermal anemometer with an omnidirectional transducer is most used in the practice for low velocity measurements. The transducer (the probe) has to meet several requirements. It has to be sensitive enough to detect the lowest air velocity that can be perceived by human beings, it should be able to measure the velocity fluctuations, it should be sufficiently sturdy, so to be moved around from place to place without any risk of being damaged. Since the direction of the air velocity in the occupied zone of rooms is in most cases unknown and variable, the transducer should measure the air velocity correctly independent of its direction relative to the sensor (except for a small angle around the support of the sensor).

There are several anemometers for low velocity measurements available on the marked. The anemometers are calibrated by their manufacturers and most of the instruments are intended to be use for field and control measurements of the thermal comfort conditions in rooms and for measurements of installed ventilation systems. In such cases, the calibration of the anemometer is most often not checked by the user. In order to comply with the standards an important requirement is that at equal conditions the different anemometers should measure equal mean velocity and equal turbulence intensity (within the range of the accuracy of the instruments). Several factors, such as the personal experience, the type of the anemometer and the transducer, the measuring procedure, the evaluation method, etc., have an impact on the accuracy of the low velocity measurements.

This paper present some results from a study on the accuracy of low velocity measurements by thermoanemometers with omnidirectional sensors. Several anemometers, commercially available on the market, were compared regarding the mean velocity and the turbulence intensity they measured. The paper is addressed mainly to the engineers in the field of the heating, ventilating and air conditioning industry, who practice low velocity measurements.

EXPERIMENTAL FACILITIES

Five low velocity thermoanemometers and one ultrasonic anemometer were tested. Four of the thermoanemometers had transducers with omnidirectional sensors for the velocity measurements. One of the thermoanemometers had a transducer with a sensor designed as a hot-wire type probe. The five thermoanemometers are referred in this paper as anemometers "A", "B", "C", "D", "E" and the ultrasonic anemometer is referred as anemometer "U". The anemometers had an analog and display type of output (3 velocity components for the ultrasonic anemometer). All anemometers displayed the mean velocity. The anemometers "B" and "D" displayed also the standard deviation of the velocity and the anemometer "C" displayed the minimum and maximum velocity for the measuring period. A measuring period (integration time for calculation of the mean velocity and the turbulence intensity) between 1 second and 12 hours could be selected for the anemometer "D". The rest of the anemometers had fixed measuring periods below 3 minutes. Therefore analog signals from the anemometers, with an equal recording time, were treated in order to compare the anemometers. A limited information about the anemometers was given by the manufacturers. Table 1 lists the characteristics of the velocity sensors (given by the manufacturers) of the five thermoanemometers.

An airflow generator with a cross section 0.92 x 0.465 m was designed to produce an airflow with controlled mean velocity and turbulence intensity. Two fans were used to produced the airflow. An uniform outlet velocity distribution was achieved by filters fixed in the box. A honeycomb was used to make the airflow as laminar as possible. The turbulence intensity was generated by plates (wings) fixed at the outlet of the generator. Stepper motors were used to rotate the plates around their axis. The turbulence intensity was controlled by adjusting the rotation speed and the rotation angle of the wings. For this purpose a random function signal from a computer was used. Detail description of the airflow generator is given in [6].

ANEMO-METER	PROBE TYPE	RESPONSE TIME	DIRECTIONAL SENSITIVITY
"A"	heated sphere	< 0.4 s	omnidirectional
"B"	heated sphere	0.2 s (90% value)	omnidirectional
"C"	hot-wire type	0.2 s (90% value)	directional sensitive
"D"	heated sphere	0.1 s (63% value)	omnidirectional
"E"	heated sphere	-	omnidirectional

Table 1. Characteristics of the velocity sensors, given by the manufacturers.

A stable airflow with a mean velocity in the range from 0.1 to 1 m/s and with a turbulence intensity in the range from 5 to 60% could be provided by the airflow generator. Figure 1 shows instantaneous velocity records of different types of air flow produced by the airflow generator.

A special traversing device was used to positioned the transducers in the airflow. The devise allowed four rotations and two longitudinal movements of the transducer with an accuracy respectively 1 degree and 1 mm. In this way the velocity sensor could be positioned at the same point of the airflow but at different angles regarding the main flow direction.

The analog signal from the anemometer was sent to a datalogger and recorded on a diskette. A penrecorder was connected to the anemometer's analog output as well. This made possible a continuous observation of the instantaneous velocity measured during the experiment. The velocity of the generated flow was controlled by an additional thermoanemometer with a transducer fixed to the airflow generator. The air temperature was measured and it remained constant during the experiments.

RESULTS

Mean Velocity.

Figure 2 compares the mean velocity measured by the anemometer "B", chosen to be a reference anemometer, and the mean velocity measured by the rest of the

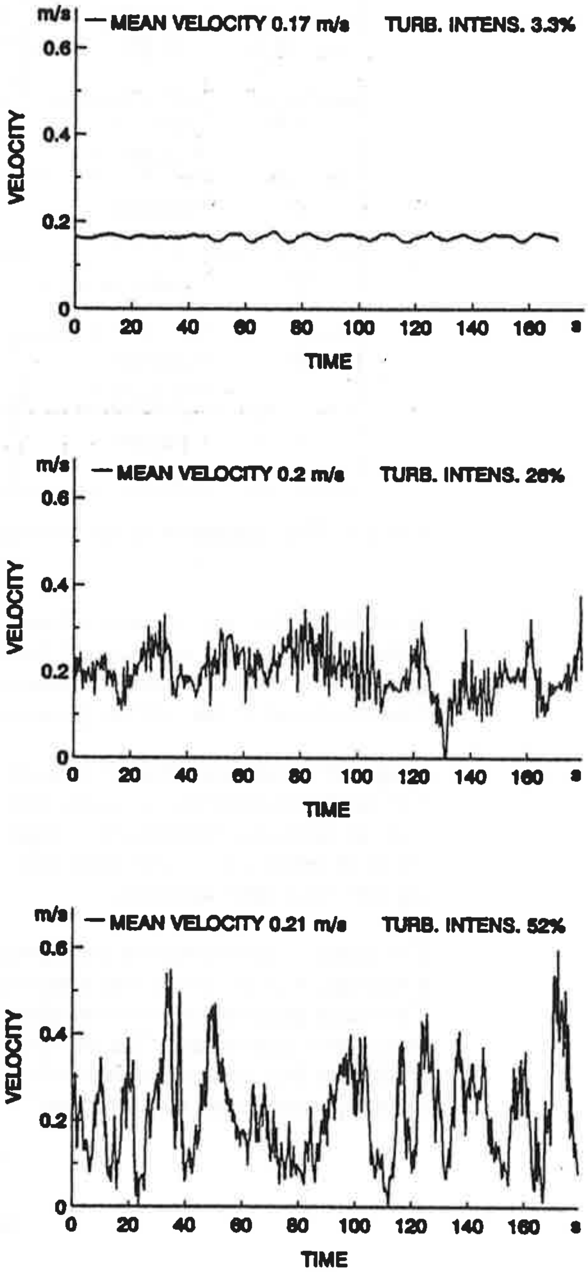


Figure 1. Velocity records of airflows with different turbulence intensity.

tested anemometers. The comparison was made at five mean velocities: 0.14, 0.22, 0.37, 0.42 and 0.47 m/s. The turbulence intensity of the flow was low, in the range from 2 to 8%. The measurements were done with a measuring period of 3 minutes. The straight line in the figure represents the perfect correlation. In Table 2 the difference (in percent) between the mean velocity measured by the reference anemometer and the five other anemometers is listed. Differences, larger than the limits for the accuracy of the anemometers given by the manufacturers, were observed. The mean velocity measured by the anemometer "D" was most similar to the mean velocity measured by the reference anemometer. The maximum difference in the velocity measured by these two instruments was 8%. The largest difference was observed between the reference anemometer and the anemometer "C". For the studied velocity range the anemometer "C" measured from 19 to 104% lower mean velocity than the reference anemometer. The reference anemometer and the anemometer "C" were calibrated by their respective manufactures shortly before the beginning of the experiment. The mean velocity measured by the anemometer "E" was from 34 to 67% higher than the mean velocity measured by the reference anemometer "B".

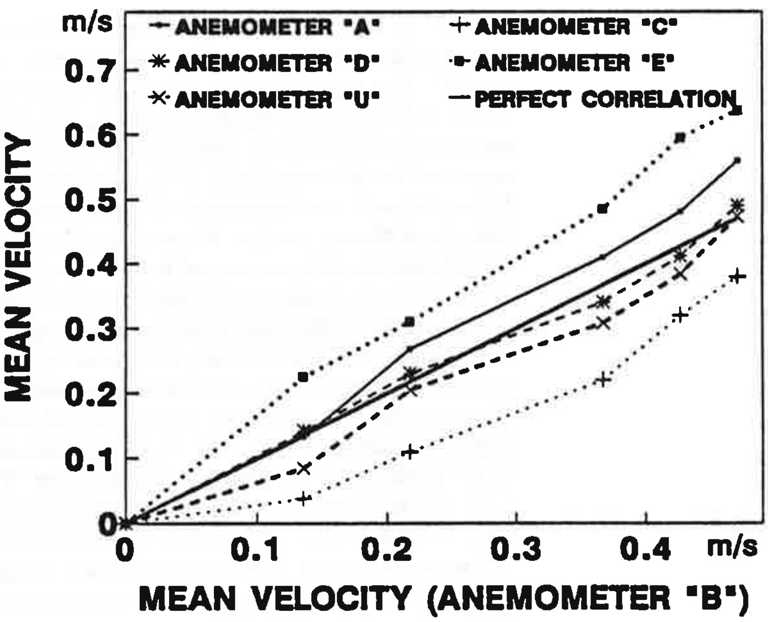


Figure 2. Comparison of the mean velocity measured by the different anemometers.

REFERENCE VELOCITY	ANEMOMETER				
ANEMOMETER "B"	"A"	"C"	"D"	"E"	"U"
0.14 m/s	-4%	-73%	7%	67%	-37%
0.22 m/s	20%	-104%	5%	41%	-5%
0.37 m/s	11%	-40%	-8%	32%	-16%
0.43 m/s	13%	-28%	-4%	39%	-11%
0.47 m/s	19%	-19%	4%	34%	0%

Table 2. Difference (in percent) in the mean velocity measured by the reference anemometer "B" and the other five tested anemometers.

Turbulence Intensity.

Figure 3 (a and b) shows the turbulence intensity measured by the tested anemometers as a function of the turbulence intensity measured by the reference anemometer "B". The regression equations of the relationships in the figures are listed in Table 3. The measuring period during this experiment was 15 min. The anemometers were compared at different turbulence intensity ranging from 2 to 60%. As expected the anemometers measured different turbulence intensity due to the different dynamic characteristics of the velocity sensors and the instruments as a whole and the different design of the transducers. Except for the anemometer "C", the turbulence intensity measured by the tested anemometers was lower than the turbulence intensity measured by the reference anemometer "B". The anemometer "E" measured the turbulence intensity in average 62% less than the reference anemometer. The turbulence intensity measured by the ultrasonic anemometer "U" was 17% lower than the turbulence intensity measured by the reference anemometer. The anemometer "C" measured turbulence intensity 42% higher than the turbulence intensity measured by the reference anemometer. The response time (time constant) of the sensors of the reference anemometer "B" and the anemometer "C" was equal, 0.2 s but the time constant of the anemometers was not given by the manufacturers. The reason for the higher turbulence intensity measured by the anemometer "C" compare to the turbulence intensity measured by the reference anemometer might be due to the smaller time constant of the anemometer "C" and the design of the transducer "C". This transducer had a special protection against damage, which probably generated vortices which increased the turbulence intensity around the velocity sensor. The probes "A" and "E" also had a protection (designed as a mesh) around the velocity sensor. In this case the protection might have damped the velocity fluctuations with relatively high frequency. The impact of the protection has to be considered in order to perform accurate low velocity measurements.

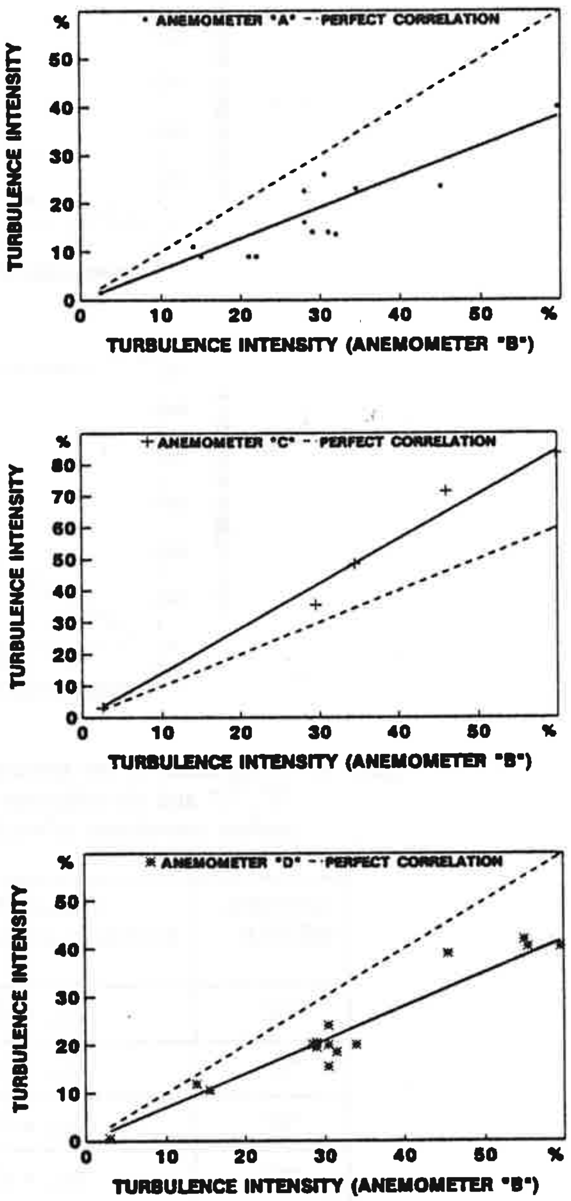
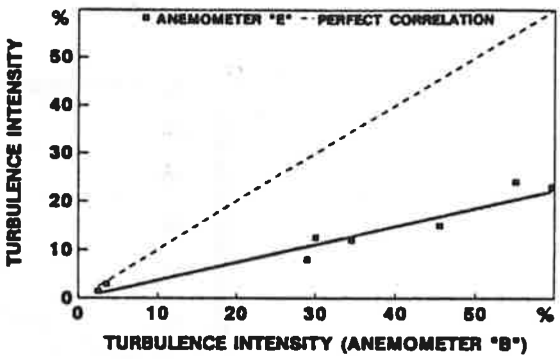


Figure 3a. Comparison of the turbulence intensity measured by the anemometers "A", "C", "D" and the reference anemometer "B". The broken line illustrates perfect correlation ($r^2 = 1.00$).



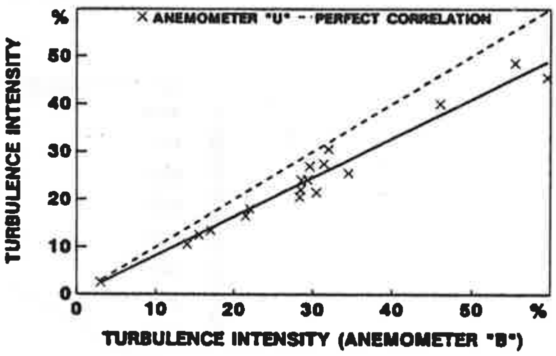


Figure 3b. Comparison of the turbulence intensity measured by the anemometers "E", "U" and the reference anemometer "B". The broken line illustrates perfect correlation ($r^2 = 1.00$).

ANEMO-METER	EQUATION Reference Anemometer is "B"	CORRELATION COEFFICIENT R^2
"A"	$Tu_A = 0.64\ Tu_B$	0.81
"C"	$Tu_C = 1.41\ Tu_B$	0.90
"D"	$Tu_C = 0.70\ Tu_B$	0.91
"E"	$Tu_E = 0.37\ Tu_E$	0.92
"U"	$Tu_U = 0.82\ Tu_B$	0.86

Table 3. Regression equations for the turbulence intensity measured by the tested anemometers as a function of the reference anemometer.

Directional Sensitivity

As done in [11], the directional sensitivity of the transducers was tested in two planes for different angles of attack of the velocity vector. Two tests were performed. The first test, on the roll-characteristic of the sensors, was performed by rotating the transducer around its axis, i.e. the velocity vector was all the time perpendicular to the axis of the probe. The second test studied the yaw-characteristic of the sensors and it was performed by rotating the transducer around an axis, through the velocity sensor, perpendicular to the axis of the transducer. In this case the angle between the velocity vector and the axis of the transducer was changed. In all tests the flow had a low turbulence intensity (less than 6%) and a constant direction. The measuring time was 3 min. Table 4 lists the results from this test performed at two mean velocities of the flow, 0.14 and 0.37 m/s. The formulas used for calculation of the listed results are given in the table as well. The roll sensitivity of the sensors was less than ±5%, with exception of transducer "A", which had increased roll sensitivity, 12%, at 90° and 270°. Due to its design (two side protection of the sensitive element) the transducer "C" very sensitive to the flow direction for roll angles in the range of 60°-120° and 240°-300°. The yaw characteristic of the sensors varied in a wide range of yaw angles between -45° and 225°. For some of the sensors the yaw sensitivity varied between 0 and -45%. Smallest yaw sensitivity, between 0 and 15%, was observed for the transducer "B".

DISCUSSION

Often serious draught complaints occur in ventilated rooms although measured velocities are lower than the summer and winter limits, resp. 0.25 and 0.15 m/s, recommended in the present standards [4,5]. One reason may be the accuracy of the velocity measurements. The calibration of the anemometers available on the market is made by the manufacturers and most often it is not checked by the common user. The comparison of the anemometers (Figure 2 and Table 2) showed that the mean velocity measured by the six tested anemometers was different. The difference ranged from less than 10% to more than 100%. Therefore when the anemometers are used for measurements in the same ventilated room different thermal comfort conditions will be identified. For example at the same location in the occupied zone of a ventilated room the mean velocity measured by the anemometer "C" will be 0.11 m/s, much below the recommended in the standards summer velocity limit of 0.25 m/s, while the mean velocity measured by the anemometer "E" will be 0.31 m/s, higher than the velocity limit recommended in the standards. The result of this test showed that the calibration of the anemometers available on the market may not be reliable and it has to be checked before measurements are performed. There is a need for an international standard procedure for calibration of low velocity thermoanemometers which has to be used by the manufactures and by the users of the instruments.

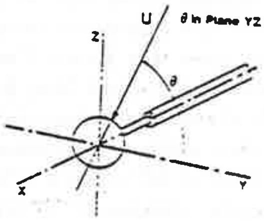
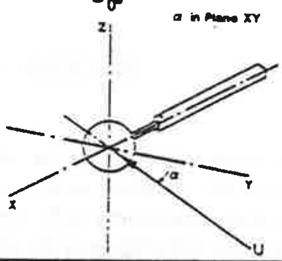
DIRECTIONAL SENSITIVITY	ANGLE	TRANSDUCER				
		A	B	C	D	E
ROLL CHARACTERISTIC: $\frac{U_{\theta}-U_{0^\circ}}{U_{0^\circ}}100\%$	0°	0 0	0 0	0 0	0 0	0 0
	45°	3.6 0.7	-1.5 0.3	- -3.2	0 0.9	-2.6 -0.6
	90°	-1.5 12	-2.2 -0.3	- -	2.7 0	-2.6 4.6
	180°	1.5 -2	-1.5 -0.8	- 3.7	0 1.5	-5.3 -2.1
	270°	19.7 12	-2.2 0.3	- -	-2 -0.6	-4 -0.6
YAW CHARACTERISTIC: $\frac{U_{\alpha}-U_{0^\circ}}{U_{0^\circ}}100\%$	0°	0 0	- 0	- 0	0 0	0 0
	45°	-18 -20	-3.7 -9.6	- -44	-12 -5.3	-12.4 -20.3
	90°	- -	- -15	- -	-8.7 30.6	- -
	-45°	-4.3 -37	-2.2 -9.6	- 20	-13.3 -10.6	-44 -3.7

Table 4. Directional sensitivity of the tested probes. The numbers (in percent) are calculated according to the formulas listed in the table. Results from testes at a mean velocity of 0.14 and 0.37 m/s are listed respectively below each other.

The different calibration of the anemometers results in measuring different mean velocity in the same flow. The turbulence intensity is a relation between the standard deviation of the velocity and its mean value, i.e. it is a dimentionless parameter, and therefore for a linearized anemometer (most commercially available low velocity anemometers are linearized) it should not be affected by the calibration of the probe. The accuracy of the turbulence intensity measurements will be influenced by the response time (time constant) of the sensor and the anemometer as a whole. Fast velocity changes will not be detected by "slow" anemometer (with a long response time). Only a limited information about the dynamic characteristics of the anemometers and the transducers were given by the manufactures of the tested anemometers, but obviously they had different dynamic characteristics. A separate investigation was necessary in order to determine the time constant of the anemometers, for example using the method suggested in [7]. But such investigation was not performed as it was not the purpose of the present study. A required 1 s and a desirable 0.5 s response time (90%) for the anemometer is specified in ISO Standard 7726 [8]. ASHRAE Standard 55-81R specifies a response time of the anemometer from 1 to 10 s, but for assessments of draughts or turbulence intensity a desirable response time of 0.2 s is recommended. Up to 100% difference in the turbulence intensity measured by some of the tested anemometers was observed (Figure 3, Table 3) in the present study. One reason was the different response time the anemometers had. In [12] transducers with different response time, from 50 to 1600 ms, were compared (time constant of the thermoanemometer was not given) in a flow with a turbulence intensity ranging from 5 to 70%. Up to 40% difference in the reading of the turbulence intensity was observed between the tested transducers. The way of generating the turbulence intensity and the frequency of the velocity fluctuations of the flow was not described. In order to recommend a response time for low velocity anemometers it is important to know the frequency of the velocity fluctuations of the airflow where the measurements will be performed. The airflow generated in the present experiments had velocity fluctuations very similar to the velocity fluctuations of airflows measured in ventilated rooms. Field measurements [9,10] revealed that large part of the turbulent energy of the airflow in rooms was associated with velocity fluctuations with low frequency, below 1-1.5 Hz, although velocity fluctuations with frequency above 5 Hz were identified as well. A response time of 0.2 s or even 0.1 s of the anemometer may be a realistic requirement for accurate measurements of the turbulence intensity in rooms. A response time of 0.2 s (preferably 0.05 s) has been suggested in [12]. There is a need for further studies in order to recommend an optimal response time for the low velocity anemometers.

As already discussed, the draught risk in rooms may be estimated by measurements of the air temperature, the mean velocity and the turbulence intensity. The observed differences between the anemometers, regarding the mean velocity and the turbulence intensity measured, may result in a wrong evaluation of the draught risk in rooms. Table 5 compares the draught risk estimated by measurements with the five thermoanemometers in a room with air temperature 25 °C (summer condition) and air temperature 21 °C (winter condition). The mean velocity and the turbulence intensity measured by the anemometer "B" are accepted as a reference values. The results in the parentheses are calculated when only the mean velocity measured by the anemometers has been considered and the turbulence intensity has been assumed to be 30% for the summer condition and 40% for the winter condition. If 15% dissatisfied due to draught is define as a realistic requirement for a ventilated room, then for the same room and conditions in it, the evaluated draught risk will be above or below the limit of 15% dissatisfied, depending on the anemometer used to measure the mean velocity and the turbulence intensity of the flow. So, the thermal comfort conditions in the same room will comply or will not comply with the standards depending the thermoanemometer used to perform the measurements.

ANEMO-METER	SUMMER CONDITION Ref. Velocity:0.22 m/s Ref. Turb. Intens: 30% Air Temperature 25 °C	WINTER CONDITIONS Ref. Velocity:0.13 m/s Ref. Turb. Intens: 40% Air Temperature 21 °C
"A"	17% (22%)	12% (13%)
"B"	17% (17%)	15% (15%)
"C"	8% (7%)	0% (0%)
"D"	15% (19%)	14% (14%)
"E"	17% (26%)	7% (28%)

Table 5. Draft risk estimated by measurements by the different anemometers. The model of draught risk developed in [1] was used.

Typically the airflow in rooms is turbulent, i.e. the velocity vector changes its magnitude and direction. Therefore it is important that the sensor is not sensitive to the changes of the velocity direction. The tested omnidirectional transducers complied with this requirement only when the velocity vector changed its direction in a plane perpendicular to the transducer's axis, i.e. the when the angle between the velocity vector and the axis of the probe remained 90°. The sensors became sensitive to the direction of the velocity vector when this angle was larger or smaller than 90°. The results of the test show that in order to perform accurate and reliable velocity measurements with an omnidirectional transducer the directional sensitivity of the sensor and the direction of the main flow has to be known. The design of the transducer has to be considered as well. Transducers with sensors designed as a hot-wire probe are very much directional sensitive and they have to be used for measurements only in flows with well known direction of the mean velocity vector and not high turbulence intensity. The impact of the protection around the velocity sensor, made against damages, on the accuracy of the measurements has to be considered as well.

CONCLUSIONS

Five thermoanemometers and one ultrasonic anemometer used for field measurements for low air velocity in rooms were compared in airflow with mean velocity ranging from approx. 0.12 to 0.5 m/s and turbulence intensity ranging from 2 to 60%. The anemometers, available on the market, were calibrated by their respective manufactures.

Large differences between the anemometers were observed (up to 100%) regarding the mean velocity and the turbulence intensity measured.

The sensors were sensitive to the direction of the velocity in the plane of the axis of the transducers (yaw sensitivity).

Draught risk assessed by measurements with the five thermoanemometers at equal room conditions was different.

In order to perform reliable measurements of the mean velocity the calibration and the directional sensitivity of the sensor has to be checked before use; in order to perform accurate measurements of the turbulence intensity an anemometer with a response time of 0.2 s has been recommended in the literature, but this needs further investigation; a protection around the sensor, made against damages, may damp the velocity fluctuations with relatively high frequency or it may generate additional turbulence in the flow.

There is a need for an international standard procedure for calibration of low velocity anemometers.

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