Modified anemometers for indoor climate research

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Abstract An anemometer which was developed for indoor climate research has been modified in order to get the same shape of calibration curve for each anemometer. Experiments in a wind tunnel showed that this was the case for more than 80% of a test series of the modified anemometers. The time constant has increased but is still acceptable. Calibration curves and time constants could be predicted by calculation with reasonable accuracy. Some influence of dust particles on the instrument was noticed.

List of symbols

c	specific heat (J kg^{-1} °C^{-1})
D	diameter of the sphere (mm)
E	thermovoltage (μV)
Gr	Grashof number ($Gr = \Delta TD^3g/T\nu^2$)
K	see equation (8)
Nu	Nusselt number ($Nu = \alpha D/\lambda$)
n	see equation (5)
q	heat production (W)
R	radius of a sphere (mm)
Re	Reynolds number ($Re = vD/\nu$)
T	temperature (°C or K)
v	velocity (m s^{-1} or cm s^{-1})
α	heat transfer coefficient (W m^{-2} °C^{-1})
Δ_0	see equation (5)
ϵ	radiation emission coefficient
λ	coefficient of thermal conductivity (W m^{-1} °C^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
τ	time constant (s)

Subscripts

a	air
rad	radiation
s	sphere

Introduction

ndoor climate research requires anemometers for measuring ir velocities between 0·1 and 2 m s^{-1}. The instrument should e insensitive to the direction of flow and must have compenation for air temperature and radiation from the surroundings avoid time-consuming corrections of the measured values.

An anemometer meeting the requirements of compensation for air temperature and radiation and having an accuracy of 10% has been developed by the TNO Research Institute for Environmental Hygiene (den Ouden 1958). Insensitivity to direction of flow however could be only partly attained. The instrument works as a thermocouple with each weld being surrounded by a small grey sphere. One of the spheres is electrically heated. Figure 1 shows the principle.

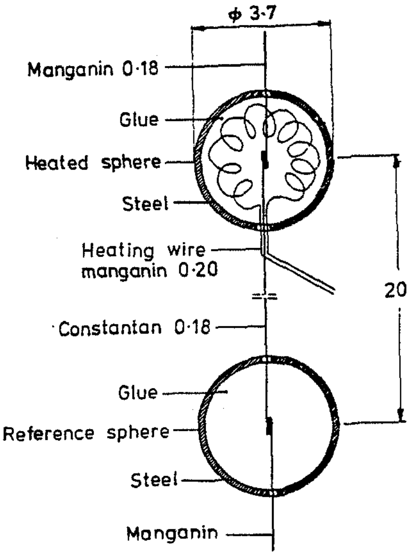

Figure 1 Existing anemometer element. Both spheres are filled with glue. Dimensions in mm

Because of this construction the thermovoltage is influenced by the air velocity but not by the air temperature and the radiation of the surroundings. The emission coefficient for radiation is about 0·8 and because of this high value no influence by settling of dust particles has been noticed. Experiments indicated that errors in the measurements of more than 10% occur if the support is in front of the spheres at an angle less than 30° while the axis between the spheres is perpendicular to the flow. This is caused by the wake of the support. Errors of more than 10% also occur if the axis between the spheres makes an angle less than 60° with the direction of the flow (van Laar 1961a). In order to prevent errors of more than 10% being caused by these wake interferences, the direction of the flow should be more or less known. Because a rough estimation of the flow is very easy this has never been felt to be a problem.

The shape of the calibration curve is different for each anemometer because in the heated sphere strong temperature gradients will exist between the weld and the surface of the sphere. This is caused by the irregular shape of the heating wire and the low thermal conductivity of the glue in the sphere. All anemometers will be different in this respect. Usually series of anemometers with nearly identical calibration curves are required because they allow the use of only one electrical system transforming the thermovoltage into the value of the velocity. In that case a large number must be produced from which only a small number can be selected for use. Therefore the demand arose for a type of anemometer which will always have the same calibration curve. In this report the construction of such a type will be described and the calculated and measured calibration curves of a test series will be compared.

2 Construction of the heated sphere

The differences in shape of the calibration curves can be avoided by having a homogeneous temperature field inside the heated sphere. This could be realized by mounting heating wires at the surface and by using a material with high thermal conductivity. Mounting of the heating wire over a sufficient part of the surface however was impossible for practical reasons. Instead a construction has been chosen consisting of a core and a jacket, each made from metal. The heating wire is wound around the core and together with the jacket they have the shape of a sphere. The weld is inside the core which will have a homogeneous temperature field in the centre. A preliminary version of this type was made using copper for both core and jacket. The diameter was 6 mm.

Because of the slow response at sudden changes in the velocity (large time constant) we tried to minimize the diameter and the ρc value of the material, which had to be a metal because of its high conductivity. The best material from this point of view was lead which was chosen for the jacket. Because of the poor mechanical properties of lead, aluminium was preferred for the core for reasons of manufacturing.

The values of λ and ρc for these metals are:

	ρc (kJ m^{-3} °C^{-1})	λ (W m^{-1} °C^{-1})
Copper	3480	370
Lead	1325	35
Aluminium	2460	165.

For glue the λ value is about 0·18 W m^{-1} °C^{-1}. The smallest diameter which could be realized proved to be 5 mm. A test series of 22 anemometers with this construction of the heated sphere was investigated in a small wind tunnel for a velocity range of 0–2 m s^{-1}. Figures 2 and 3 show the construction of the heated sphere and the new version of the anemometer. The reference sphere is made from lead only.

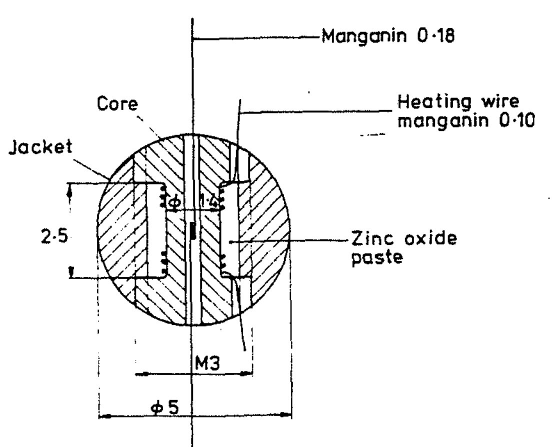

Figure 2 Heated anemometer element (test series). Diameter of sphere $D=5$ mm. The core is of aluminium and the sphere is of lead. Dimensions in mm

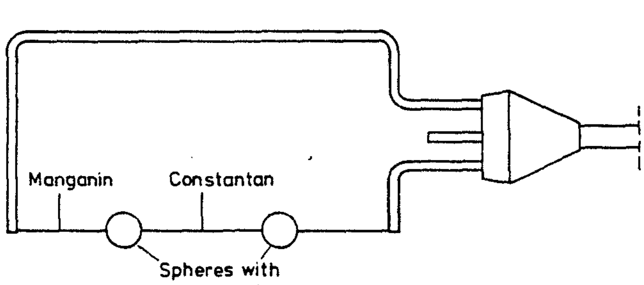

Figure 3 Support with spheres

In the heated sphere a temperature gradient can now exist only in the jacket and the ends of the core. To minimize this gradient the space between the core and the jacket was filled with a paste of zinc oxide with a λ value of 12 W m^{-1} °C^{-1}. The heat production is about 0·09 W which would give a temperature difference between centre and surface of about 0·04°C in the case of homogeneous heat production. This corresponds to a thermovoltage of 1·6 μV which cannot be read from the calibration graphs.

For a sphere made of glue this temperature difference would be about 8°C. So the new construction has nearly eliminated temperature gradients in the heated sphere. Measurements showed that the directional sensitivity is the same as for the existing anemometer.

3 Calculation of the calibration curves

From a test series of 22 anemometers as described above, calibration curves have been determined by calculation and by experiments in a small wind tunnel. In the calculations it has been assumed that there are no temperature gradients in the heated sphere. The heat produced in the sphere is transferred to the air by convection and to its surroundings by radiation. For forced convection of spheres to air Yuge (1960) gives the equations

$$Nu=2+0{\cdot}493Re^{0\cdot5} \qquad \text{if } 10<Re<1800 \tag{1}$$

$$Nu=2+0{\cdot}300Re^{0\cdot5664} \qquad \text{if } 1800<Re<1{\cdot}5\times10^5. \tag{2}$$

In these equations the Prandtl number is taken as 0·715. The heat production will cause free convection at low velocities. Yuge gives the following equation for free convection only:

$$Nu=2+0{\cdot}392Gr^{0\cdot25} \qquad \text{if } 1<Gr<10^5. \tag{3}$$

For combined convection he gives two empirical formulae. In our case, with velocities not below 6 cm s^{-1} the value of $0{\cdot}493Re^{0\cdot5}$ is always larger than the value of $0{\cdot}392Gr^{0\cdot25}$. Then the following formula should be used:

$$Nu=2+0{\cdot}493Re^{0\cdot5}+\Delta_0\exp\left[-n(0{\cdot}493Re^{0\cdot5}-0{\cdot}392Gr^{0\cdot25})\right]. \tag{4}$$

In the case of horizontal flow Yuge gives for Δ_0 and n, if $0{\cdot}392Gr^{0\cdot25}<2{\cdot}56$:

$$\begin{aligned}\Delta_0&=3{\cdot}636\times10^{-4}Gr\\ n&=762{\cdot}3Gr^{-1}.\end{aligned} \tag{5}$$

The heat loss due to radiation is given by the equation

$$q_{rad}=5{\cdot}775\times10^{-8}\epsilon(T_s^4-T_a^4)4\pi R^2 \tag{6}$$

where T is in degrees Kelvin.

This may be rewritten as (Gröber *et al* 1963)

$$q_{rad}=5{\cdot}775\epsilon K(T_s-T_a)4\pi R^2. \tag{7}$$

In this equation

$$K=(T_s^3+T_s^2T_a+T_sT_a^2+T_a^3)\times10^{-8}. \tag{8}$$

At air temperatures of 20°C (293 K) and temperature differences of between 10 and 40°C the value of K will vary between 1·06 and 1·25. The temperature difference between the sphere and the air is then calculated from the equation

$$T_s-T_a=q/4\pi R^2(\alpha+5{\cdot}775K\epsilon). \tag{9}$$

K is dependent on the temperature of the surface of the sphere but in fact the Re and Nu numbers are also dependent on this temperature because in the boundary layer at the sphere the air temperature increases relative to the surface temperature.

Therefore the calculations for the viscosity and thermal conductivity of the air have been carried out by assuming both a temperature of 20°C and a film temperature

$$T_{film} = 0{\cdot}5(T_s + 20)\,°C.$$

The emission coefficient ϵ is still unknown. In order to determine its value an anemometer was selected which had been used in a dusty factory hall. This anemometer was heated to different temperatures by changing the electrical current while the air velocity in the wind tunnel was kept constant at 40 cm s^{-1}. The whole range of temperatures used in calibration was covered in this way by choosing eight different values for the heating current. Then the anemometer was cleaned and the procedure was repeated with the same values for the heating current and the same air velocity. Finally the spheres were painted black and the procedure was again repeated. The emission coefficient of this paint was determined experimentally. Its value is 0·93 at 40°C and 0·94 at 80°C with an accuracy of 1%. In this temperature range a linear relationship for ϵ has been assumed. For each value of the current ϵ could now be calculated with equation (9) from the measurement with the painted anemometer by putting

$$(T_s - T_a)(\alpha + 5{\cdot}775K\epsilon) = \text{constant}.$$

In the case of the painted anemometer this value could be calculated and in the other cases ϵ was the only unknown variable.

4 Results of the calculations and measurements

In the calculations the thermovoltage is taken as 1000 μV at 40 cm s^{-1} just as in the experiments. The value of α at this velocity was calculated from equation (1) and ϵ was determined as described in §3. For both the clean and dirty anemometers, eight values for ϵ were found from which the average value was determined, while the standard deviation gave an idea of the scatter. A systematic temperature dependence of ϵ was not observed and therefore the average value has been used in the calculations. Then q was calculated from equation (9) by assuming both $T = 20$°C and $T = T_{film}$ in calculating α. From equations (1) and (9) the thermovoltage at other velocities could now be calculated.

Tables 1 and 2 show the results.

Finally the effect of free convection was taken into account by using equations (4) and (5). This effect was only noticeable at velocities below 20 cm s^{-1}. Table 3 gives some calculated values at 6 and 10 cm s^{-1}. In the calculations T is taken as T_{film}.

Table 3 Calculated temperatures and thermovoltages at combined convection

	v (cm s^{-1})	Gr	$T_s - T_a$ (°C)	E (μV)
Clean anemometer	6	553	40·61	1665
	10	505	37·11	1514
Dirty anemometer	6	540	39·63	1619
	10	495	36·33	1481

Figure 4 shows the calculated calibration curves and the curve averaged from the experimental curves of the test series. In the experiments the heating current was 175 mA. The thermovoltage was set at 1000 μV by a shunt at a velocity of

Table 1 Calculated temperatures and thermovoltages for the clean anemometer

	$T=20$°C, $q=0{\cdot}08249$ W; $\epsilon=0{\cdot}43$ (standard deviation: 0·03)				$T=T_{film}$, $q=0{\cdot}08307$ W; $\epsilon=0{\cdot}43$ (standard deviation: 0·03)			
v (cm s^{-1})	Re	α (W m^{-2} °C^{-1})	$T_s - T_a$ (°C)	E (μV)	Re	α (W m^{-2} °C^{-1})	$T_s - T_a$ (°C)	E (μV)
6	19·9	21·60	42·58	1750	17·5	22·05	42·11	1728
10	33·1	24·85	37·72	1540	29·7	25·2	37·51	1530
20	66·2	30·95	31·10	1256	60·5	30·95	31·32	1266
40	132	39·4	24·90	1000	123	39·7	24·90	1000
80	265	51·5	19·37	767	249	51·7	19·43	770
120	397	60·8	16·54	650	379	61·0	16·61	652
180	596	72·2	14·03	550	571	72·3	14·11	553

Table 2 Calculated temperatures and thermovoltages for the dirty anemometer

	$T=20$°C, $q=0{\cdot}08591$ W; $\epsilon=0{\cdot}69$ (standard deviation: 0·04)				$T=T_{film}$, $q=0{\cdot}08649$ W; $\epsilon=0{\cdot}69$ (standard deviation: 0·04)			
v (cm s^{-1})	Re	α (W m^{-2} °C^{-1})	$T_s - T_a$ (°C)	E (μV)	Re	α (W m^{-2} °C^{-1})	$T_s - T_a$ (°C)	E (μV)
6	19·9	21·60	41·22	1688	17·5	22·05	40·81	1675
10	33·1	24·85	36·90	1504	29·7	25·2	36·68	1495
20	66·2	30·95	30·81	1244	60·5	30·95	31·02	1253
40	132	39·4	24·90	1000	123	39·7	24·90	1000
80	265	51·5	19·57	775	249	51·7	19·63	777
120	397	60·8	16·80	661	379	61·0	16·86	665
180	596	72·2	14·31	560	571	72·3	14·38	564

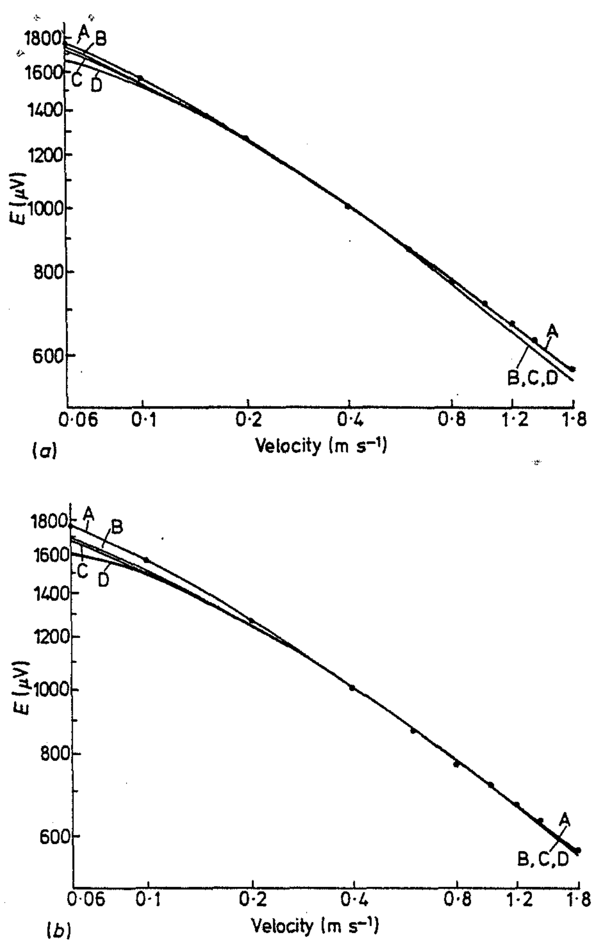

Figure 4 Calculated and experimental calibration curves for the test series. Heating current 175 mA. (*a*) Clean anemometer; (*b*) dirty anemometer. A, average calibration curve of the test series and three selected anemometers (experimental); B, calculated calibration curve (equation (9)), T=20°C; C, as B, $T=T_{\rm film}$; D, as C, corrected for free convection

40 cm s^{-1} in the wind tunnel. Then the thermovoltages were measured at 10 cm s^{-1}, 1 m s^{-1} and 1·80 m s^{-1}. In this way the series of 22 anemometers has been tested. Three of them having very nearly the same thermovoltages as the average from the series were selected for further measurements. Figure 4 shows the results.

It appeared that one anemometer showed deviations in velocity of more than 10% from the average values while six showed deviations of more than 5%, but three of these only at 10 cm s^{-1} where the calibration curve has flattened out and therefore accuracy may be expected to decrease. The most realistic criterion however is an accuracy of 5% at velocities above, say, 40 cm s^{-1} and of 10% below 40 cm s^{-1}. Then only the three other anemometers (14%) are unacceptable. In the old version only 27% could be used for a series with one electrical system.

5 Time constants

It is clear that the time constant of the anemometer should be as small as possible and hence must be investigated. Therefore the time constants of a preliminary version (§2) and of an anemometer of the test series were determined by measurements and calculations. In the calculation for the new type of anemometer both the clean and dirty conditions have been considered. The air temperature is 20°C and $T=T_{\rm film}$.

The time constant of a heated sphere without temperature gradients can be calculated from the equation

$$\tau=\tfrac{4}{3}\pi R^3\rho c/4\pi R^2(\alpha+5{\cdot}775K\epsilon). \qquad (10)$$

Equation (10) indicates that τ is dependent on the velocity. The time constants have also been determined from records of the thermovoltage at sudden changes in the velocity in the wind tunnel from 25 to 70 cm s^{-1} and the reverse. Figure 5 shows the measured and calculated time constants. For the existing type the time constant is 19 s at 25 cm s^{-1} and 17 s at 70 cm s^{-1}. The test version shows a decrease with a factor 3–3·5 compared with the preliminary version. The values for the test series are higher than for the existing type but are still considered as acceptable for measurements of average velocities in climate research. It is seen that dust particles have a slight influence on the time constant.

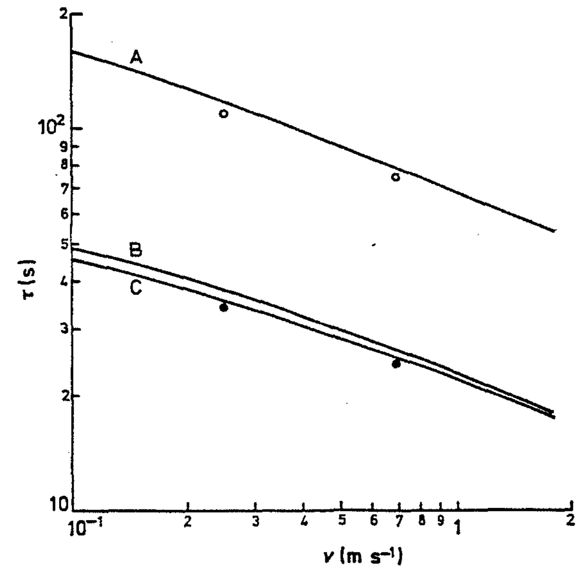

Figure 5 Time constants. A, copper sphere, calculated, D=6 mm ($T=T_{\rm film}$); ○ copper sphere, experimental; B, lead jacket with aluminium core, calculated for clean conditions, D=5 mm; C, as B, but for dirty conditions; ● lead jacket with aluminium core, experimental

6 Discussion

The calculated calibration curves show the influence of dust particles because of an increase in the emission coefficient. In the experiments with the test series the anemometers can be considered as clean and it appears that the calculations and measurements show the best agreement under this condition. Tables 1 and 2 show that for dirty conditions the q values have to be increased by 4% to get the same thermovoltage at 40 cm s^{-1}. In practice a constant heating current is required and this means adjustment of the shunt resistance of the anemometer after some time. If this were not done the thermovoltage in this case would drop from 1000 μV to 960 μV at 40 cm s^{-1} indicating an increase in velocity of about 12%. It is known that the existing type of anemometer should also be calibrated from time to time.

From tables 1 and 2 and figure 4 it is clear that dust particles also change the shape of the curve. Using the thermovoltages at 6 cm s^{-1} of table 2 in the curve of the clean anemometer, a velocity of 7 cm s^{-1} would be found which means an error of 16%. In order to minimize errors in the measurements it is therefore necessary first to clean the anemometer and afterwards if necessary to adjust the thermovoltage at 40 cm s^{-1} from time to time.

7 Conclusions

(i) According to the most realistic requirements for indoor climate research more than 80% of the anemometers can be used in one series with one electrical functional system. It is expected that experience in construction will increase this percentage.
(ii) The anemometers must be cleaned and calibrated from time to time because the radiation emission coefficient may have changed. The old type also needs calibration from time to time.
(iii) Calibration curves and time constants can be calculated with reasonable accuracy.
(iv) The calculated influence of free convection at low velocities was not observed in the experiments.

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A simple two-component laser Doppler anemometer using a rotating radial diffraction grating

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Abstract A direction-sensitive two-component laser Doppler anemometer is described. The basic element in this system is a rotating radial diffraction grating functioning both as a beam splitter and as a frequency shifter. Two different arrangements are discussed. One arrangement gives two non-orthogonal velocity components from which the on-axis velocity component could be derived. The second arrangement directly gives two orthogonal velocity components perpendicular to the optical axis. Experimental results are reported from measurements of the orbital velocities below artificially generated surface waves in a water flume.

1 Introduction

In the field of laser Doppler anemometry the need has become apparent for a two-component system for the simultaneous measurement of two orthogonal velocity components. The major problem in a two-component system is the separation of the Doppler frequency shift into two non-interfering channels. The full potential of a two-component system is achieved if optical frequency shifting is applied for both velocity components to be measured.

Several two-component systems have been proposed in the literature. Most of these systems operate in the fringe mode and the channel separation has been accomplished by applying cross polarization (Blake 1972), two colours (Grant and Orloff 1973) or optical frequency shifting at different frequencies (Adrian 1975, Farmer and Hornkohl 1973). In this paper we consider two-component systems that operate in the reference beam mode. The basic element in these arrangements is the rotating radial diffraction grating which functions both as a beam splitter and as a frequency shifter. The advantage of such a system is that no special provisions have to be made to achieve channel separation. The optical system is simple to set up and easy to align.

2 The rotating diffraction grating

The rotating grating used in the optical system consists of a glass disc (diameter 35 mm) which is mounted on the shaft of a small electronic motor. The disc is provided with a track of

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