01 Dec 1981

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J. Phys. E: Sci. Instrum., Vol. 14, 1981. Printed in Great Britain

RESEARCH PAPERS

Hot-wire anemometer behaviour in low velocity air flow

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Received 16 July 1979, in final form 3 July 1980

Abstract The behaviour characteristics of a commercially available hot-wire anemometer have been examined in the presence of low velocities, less than 0·1 m/s for the most part, and in both horizontal and vertical air flows. The orientation of the probe in a horizontal flow has been found to have a definite effect on velocity measurements, and a lower limit to the reliable application of hot-wire anemometry has been evaluated for a particular type of probe.

Vertical flow measurements have resulted in the discovery of the magnitude of natural convective velocity, and a possible method for determining the dimensions of the temperature jump distance has been developed indirectly from the description of the shape of the calibration curve.

List of symbols

a cross sectional area
c_p specific heat at constant pressure
d diameter
g acceleration due to gravity
h height
k heat conductivity
r radius
t time
u velocity
α wire temperature resistance coefficient
μ dynamic viscosity
ν kinetic viscosity
ρ air density
H heat transfer per unit length
L probe length
R sensor electrical resistance
R_0 sensor electrical resistance at zero flow velocity
T temperature
T_w wire temperature
T_0 temperature of the environmental air
T_f 'air film' temperature $\frac{1}{2}(T_w+T_0)$
Gr Grashof number $gd^3(T_w-T_0)/(\nu^2 T_0)$
Nu Nusselt number $H/[\pi k(T_w-T_0)]$
OHR wire overheating ratio $(R-R_0)/R_0$
Pr Prandtl number $c_p\mu/k$
Re Reynolds number dw/ν
Ra Rayleigh number $Gr \times Pr$

Subscripts
0 evaluated at ambient conditions
20 evaluated at 20°C

1 Introduction

Measurements of the hot-wire anemometer are based upon the convective heat loss from the electrically heated sensor caused by flow of fluid about the sensor. This cooling causes a change in the probe resistance, which results in an increase in amplifier output current. In this manner, due to the temperature coefficient of resistance of the sensor, the operating resistance (and thus the temperature) of the probe is maintained. Therefore, it may be assumed that the instantaneous value of electric power applied to the sensor is equal to the instantaneous thermal loss of the sensor to its surroundings.

The thermal loss is dependent upon the nature, pressure, temperature and velocity of the medium being measured (and also upon the probe used), so that, if only velocity is allowed to vary, the probe current becomes a direct measure of the velocity. In this respect, a thin heated wire has two distinct advantages: its small size introduces only a very small disturbance to the flow field and its low thermal inertia allows a reasonably high frequency response.

Reliable, accurate determination of extremely small velocities would be a valuable tool in the measurement of aerosols and their transport mechanisms and in the investigations of particulate deposition within the respiratory tract. Further uses would include ventilation studies in buildings and in mine shafts. Therefore, as a preliminary step in the development of the hot-wire anemometer as a low velocity measuring device, this investigation has attempted to shed some new light upon the behaviour of a hot-wire probe in the presence of low velocities, and upon the effect – if any – of the orientation of the probe on that behaviour. In this context the article completes the investigations made by several authors which are mentioned in the review articles on hot-wire anemometry (e.g. Corrsin 1963, Comte-Bellot 1976).

2 Methodology of low velocity control

The forced velocity imposed upon the hot-wire probe is generated by draining water at a controlled rate from an air-tight tank connected to the calibration nozzle, in which the probe is mounted. (A schematic diagram shows the relative

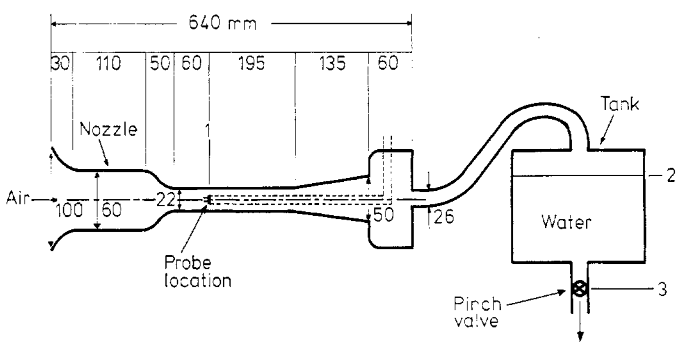

Figure 1 Equipment schematic. The nozzle which is used either in the horizontal or vertical position is part of a set of DISA 55D41/42 calibration equipment. Straight-wire probe DISA 55P11 has the stem length of 30 mm and stem diameter of 2 mm. Its prongs are 5 mm long. The probe is always oriented parallel and the wire perpendicular to the incident flow. All dimensions in mm.

locations in figure 1.) Location 1 is that of the probe within the calibration nozzle. Location 2 is the water surface within the tank, and location 3 is the water exit control. These location numbers will be used as subscripts where appropriate in the following discussion.

As water drains from 3, the water level, 2, falls from $h=A$ to $h=B$ in time $t=\tau$. The rate at which water exists at 3 is determined from Bernoulli's equation. Assuming constant water density and using location 3 as a reference level, one can calculate the velocity at the point 3 in the simple form $u_3=\sqrt{2gh}$ if the cross section $a_3 \ll a_2$. (In this case $a_3=a_2/278$.) Continuity allows the velocity at 2 to be stated in terms of u_3 as

$$u_2=Dh^{0\cdot5} \qquad D=Ca_3(2g)^{0\cdot5}/a_2. \tag{1}$$

The constant D has been introduced because of the coefficient of discharge, C, to allow for friction. The velocity at 2 may also be expressed by

$$u_2=-\mathrm{d}h/\mathrm{d}t=-D^2t/2+DA^{0\cdot5}. \tag{2}$$

In order to determine D experimentally, it is necessary to find an expression for it in terms of measured values. This can be accomplished by taking the average value of u_2 between A and B, using (2) above:

$$\tau^{-1}\int_A^B -\mathrm{d}h=\tau^{-1}\int_0^\tau [-D^2t/2+D(A)^{0\cdot5}]\mathrm{d}t \tag{3}$$

which leads to the expression

$$D_{1,2}=2[(A)^{0\cdot5}\pm(B)^{0\cdot5}]/\tau. \tag{4}$$

Comparison with actual data shows the proper root to be

$$D=D_2=2[(A)^{0\cdot5}-(B)^{0\cdot5}]/\tau, \tag{5}$$

so that (2) now becomes

$$u_2=2[(A)^{0\cdot5}-(B)^{0\cdot5}](h)^{0\cdot5}/\tau. \tag{6}$$

The flow at 1 (250 mm from the tube entrance) is laminar and has a parabolic velocity profile for all velocities smaller than 200 mm s^{-1}. Therefore, the velocity actually seen by the hot-wire probe, u, is twice the average (or volumetric) flow velocity, so that

$$u=2u_1=2(d_2/d_1)^2u_2. \tag{7}$$

For flow Re > 280 in the test section with a diameter of 22 mm the correction for nonparabolic profile can be estimated from the velocity profile measurement in the tube. For Re = 560 the difference in $u_{\max}$ is less than 4%.

The air velocity at the probe is now a function of time, τ, required for the water tank to drain from A to B, and of h at the point where a measurement is performed. For the sake of simplicity, measurements were made at $\bar{h}$, the mean value of A and B, so that

$$u=K/\tau \qquad K=4(d_2/d_1)^2[(A)^{0\cdot5}-(B)^{0\cdot5}](\bar{h})^{0\cdot5}. \tag{8}$$

3 Experimental equipment

Equipment used in this experiment consisted of a hot-wire anemometer, a digital voltmeter, a calibrating nozzle, a low velocity generator and electronic control panel, a tele-thermometer, and a mercury barometer.

(i) The hot-wire anemometer is a DISA type 55D01 constant temperature anemometer, used with a DISA type 55P11 straight-wire probe as a transducer. A bridge ratio of 1:20 was used on the anemometer and the built in decade resistance was adjusted for an overheating ratio of 1·8. With the gain adjust set at 3, the low frequency gain was set at high, and the high frequency filter was set at 2. During operation the meter switch was set at 10. The straight-wire probe was made of platinum-plated tungsten wire, usually 5 μm in diameter and 1·25 mm in length – a length-to-diameter ratio of 250.

(ii) A FLUKE Model 8200A Digital Voltmeter was used to read the DC voltages with 100 μV resolution. Its accuracy is ±(0·02% of input + 0·03% of range) and input impedance is 10 MΩ ± 0·2%.

(iii) The calibrating nozzle is part of a set of DISA type 55D41/42 calibration equipment, and was modified for connection to the low velocity generator. (Its motor-driven fan, capable of flow velocities of 1 to 200 m/s, was replaced by an adaptor plate.)

(iv) The low velocity generator is a glass cylinder (140 mm in height with an inner diameter of 160 mm) mounted vertically between two sheets of heavy plexiglas. The top is connected via PVC tubing to the adaptor plate on the nozzle. The bottom is connected to a water supply tap via copper tubing, and also to a drain via rubber tubing through a screw-type pinch valve. Inside the cylinder, mounted to the top, are three wire tank probes that, when connected to the control panel, activate the timer for measurement of the mean water surface velocity. In this manner, velocities from less than 10 to over 400 mm/s can be obtained.

(v) The electronic control panel comprises of two digital 110 V AC timers – one which measures in seconds and the other which measures in minutes. They are activated by a set of relays which are powered by a 16·5 V DC source and switched by the water in the cylinder making and breaking contact with the wire tank probes.

(vi) Temperatures were measured with a YSI Model 47 Tele-Thermometer which has an accuracy of 1% of the scale span at an ambient temperature of 25°C (the approximate value for most of the experiments in this report). The thermometer probe was mounted close to the opening of the inlet to the calibration nozzle.

(vii) Ambient air pressures were determined with a Central Scientific Company mercury barometer with a vernier slide attachment.

4 Method of measurement

Water levels in the tank of the low velocity generator were measured from the top surface of the lab bench to the point at which the timer switched on, A, and to the point at which the timer switched off, B, the midpoint of these heights being $\bar{h}$. (For ease of computation, the height of the pinch valve was used as a reference level, and its value subtracted from all height measurements.) The values of A and B may be varied by the installation of tank probes of different lengths, thus allowing lower velocities to be measured in shorter times. (Of course, each set of tank probes has a unique value of K, according to (8).)

Since ambient temperature drifts could cause corresponding voltage drifts across the anemometer bridge (including the probe) as well as drifts in the display of the DVM, both the anemometer and the DVM were enclosed in an insulated cardboard box.

In order to eliminate a much more direct influence of the air conditioner drafts – namely, that across the inlet of the nozzle itself – the inlet was enclosed in a flexible tube which had its other end near the floor, out of all drafts.

Measurements were performed by filling the tank with water to A and then allowing it to empty at a rate determined by the pinch valve. As the water level passed $\bar{h}$, the bridge voltage, V_B, was read from the DVM and recorded. At the end of each run the time was recorded and the timer reset. In this manner, V_B was directly related to u, a function of time as shown by (8).

The accuracy of (8) was tested by computing the largest possible degree of error obtainable in each direction from the zero-error value. All measured distances were considered to be accurate within ±0·5 mm, and time was considered accurate within ±0·05 s. To maximise the influence of error in measurements, the smallest values of A and B were used (i.e., the heights of the shortest tank probes), together with a fictive τ corresponding roughly to 10 mm/s. In the highly unlikely event that all the measurements were in error by their respective maximum amounts, the measured $u = 10$ mm/s could be off by as much as +22% or −18%.

5 Results and discussion

Initially, the entire range of the velocity generator was traversed (0 to over 400 mm s^{-1}), but subsequent trials focussed attention on the lower end of this range and speeds in excess of 10 m s^{-1} were seldom encountered.

All the data collected appear to follow the same general shape curve (figure 2) which is expressed by the formula

$$\mathrm{Nu} = A + B\,\mathrm{Ra}^n \qquad (9)$$

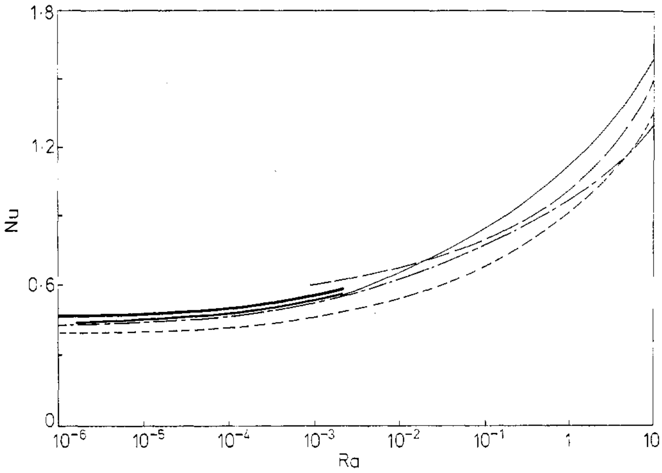

Figure 2 Comparison of the curves for natural and forced convection from horizontal cylinders (heated wires). Results: ———, Mikheyev (1956)[a]; — — —, Hatton *et al* (1970); — – — –, Van der Hegge Zijnen (1956); – – – –, Tsubouchi and Masuda (1966)[a]; data reported in this article are plotted as two thick curves indicating the uncertainty due mainly to the assumed air temperature around the wire and other data plotted from Hatton *et al* (1970).

[a] References given in Hatton *et al* (1970).

or in the form introduced by Hatton *et al* (1970)

$$\mathrm{Nu} = [T_f/T_0]^m [A_1 + B_1\,\mathrm{Ra}^n]. \qquad (10)$$

The parameters in equation (10) have the values deduced from the experiments of Hatton *et al* (1970): $m = 0{\cdot}154$; $A_1 = 0{\cdot}384$; $B_1 = 0{\cdot}590$. A formula similar to (10) was also used for mixed flow regime where both the natural and forced convection are effective in the heat transfer from the wire. Hatton *et al* (1970) suggested the relationship

$$\mathrm{Nu}[T_f/T_0]^{-m} = A_2 + B_2\,\mathrm{Re}^n, \qquad (11)$$

with the parameters $m = 0{\cdot}154$; $A_2 = 0{\cdot}384$; $B_2 = 0{\cdot}581$. The last formula is based on the assumption that the same Nu number is obtained from both forced and natural convections when

$$\mathrm{Re} = 1{\cdot}03\,\mathrm{Ra}^{0{\cdot}418}. \qquad (12)$$

This is analogous to the relationship deduced for sole natural convective regime

$$\mathrm{Re} = 2{\cdot}00\,\mathrm{Gr}^{0{\cdot}50}, \qquad (13)$$

which expresses the equality between a buoyancy force acting on a fluid element and its gain of kinetic energy. Relationships (10) to (13) were applied in this study.

All calibration curves are plotted in terms of Nu, Ra or Re numbers in spite of the fact that the authors are very aware of the divergence of opinion among the scientists on the usefulness and possibility of a universal comparison of hot wire anemometers (e.g. Bradshaw 1971, p 116). The dimensionless parameters depend to a large extent on the properties of the probe and on the physical state of the gaseous medium. This state, however, depends on the temperature around the heated wire. For convenience, one assumes a steady and uniform temperature close to the wire. Most of the authors are using the 'film' temperature $T_f = \frac{1}{2}(T_w + T_0)$, which was applied in this work when calculating the dimensionless parameters. During the course of experimental work several DISA Pt-coated tungsten probes were used. Their wire diameters were 5 μm and their lengths varied around 1·25 mm. The temperature resistance coefficient at 20°C was $\alpha_{20} = 0{\cdot}00362$ and the wire resistance in still air between 2·75 and 3·00 Ω. During the calibration a standard overheating ratio of OHR = 1·8 was maintained. These wire characteristics combined with the measured electrical magnitudes while exposing the wire to the air flow of known velocity enabled finally the calculation of Nu, Ra and Re numbers. The T_f usually varied around 130°C depending on the probe manufacturing. This enabled the estimation of air density and kinematic viscosity close to the wire ($\rho \cong 8{\cdot}753 \times 10^{-4}$ g cm^3, $\nu \cong 26{\cdot}448$ mm^2 s^{-1}) and the coefficient of thermal conductivity of the air ($k = 2{\cdot}72 \times 10^{-5}$ W mm^{-1} s^{-1} grad^{-1}) in the vicinity of the wire.

Radiative effects have not been included in the calculation because they are considered to be negligible (e.g. Comte-Bellot 1976). The heat conduction to the supports was also neglected despite the considerable distortion of the heat transfer from relatively short wires (Bradshaw 1971, p 111). The main reason for these assumptions was that the presented study focuses on the calibration of commercially available probes which are supposed to have a high degree of comparability. This comparability should be frequently checked because the authors found deviations from the 'ideal' probe–amounting to 20% heat transfer difference – depending upon the probe use and condition. For this reason the measurements with different probes yielding the same calibration curve but shifted on the Nu numbers axis were 'homogenised' (figure 3 was matched to figures 4–7 obtained by different probes).

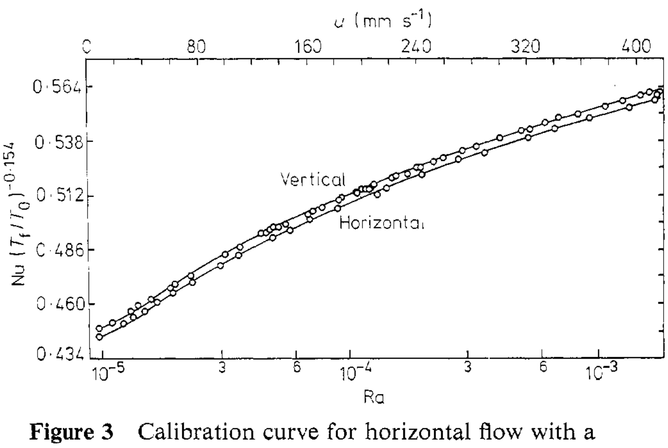

Figure 3 Calibration curve for horizontal flow with a probe wire in the vertical and horizontal position.

In figure 2 are plotted data of other investigations with the results of this experiment (full line) for $10^{-6} < \mathrm{Ra} < 3 \times 10^{-3}$. The correspondence of the data might depend, however, to a certain extent on the definition and assumed values of the effective wire temperature. The estimated limits of uncertainty are marked by two full lines in figure 2. On the other hand all data presented in this work have the right functional dependence and are very consistent and reproducible. This is documented in figure 3 where the individual measurements are plotted as a function of Ra (or u).

Also evident in figure 3 is a permanent difference in the quantity of power dissipated by the probe wire with respect to its orientation in the horizontal flow. The same probe (oriented parallel to the incident flow) lost 0·87% less heat if its wire was in the horizontal position than it did in the vertical position. This represents a difference of up to 10% for air speeds below 200 mm/s. In the neighbourhood of 50 mm/s (the region predicted by Collis and Williams (1959) for the full onset of buoyancy forces) the difference in air speed amounts to over 20%. For this reason it is important that the probe be mounted in the same orientation during measurement as during calibration.

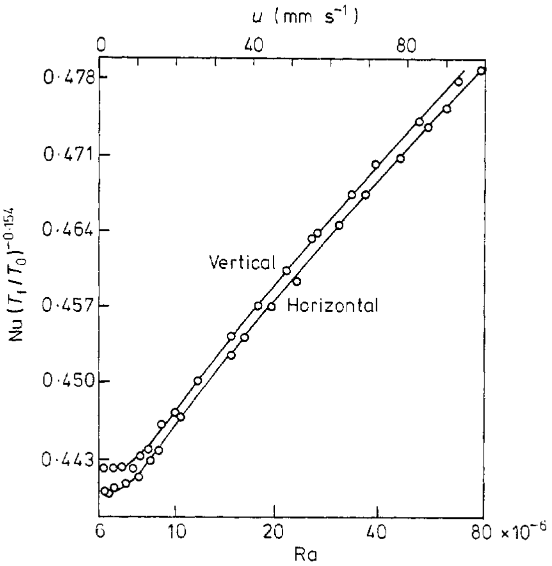

Figure 4 Calibration curves for horizontal flow with a probe wire in the horizontal and vertical position.

Figures 4 and 5 indicate 3 to 7 mm/s (corresponding to $\mathrm{Ra} \simeq 7 \times 10^{-6}$) to be the vicinity of the limit of applicability of a hot-wire anemometer of the type used in this investigation. Due to multivalent readings, it becomes impossible for the anemometer to distinguish air speeds below this value. For all practical purposes, it would seem safe to accept 10 mm/s as the lower reliable limit (for this type of probe) to the application of hot-wire anemometry in horizontal flows.

Comparison of figures 4 and 5, for mixed vertical flow in the upward and downward directions, respectively, shows an average difference in velocity of 13·5 mm/s at the same rate of heat loss for the same probe on the same day (so as to eliminate any ageing effects). If f and n represent forced and natural convection velocities respectively, then

$$(f+n)-(f-n)=1{\cdot}35,$$

which shows that $n = 6{\cdot}75$ mm/s is the magnitude of the natural convective velocity for the particular OHR used. This

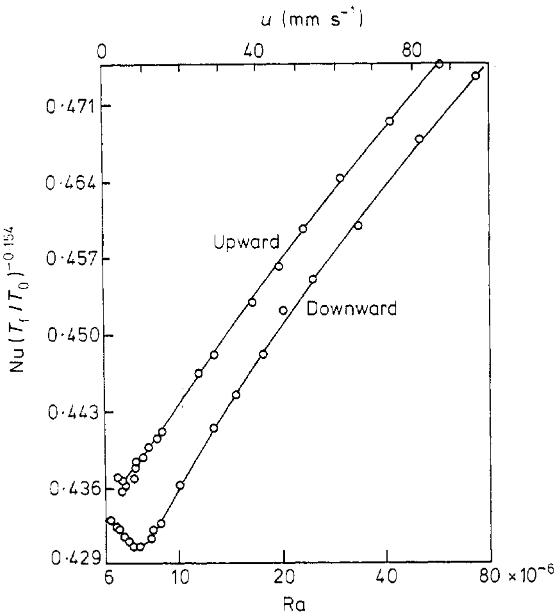

Figure 5 Calibration curves for an upward and downward oriented air flow (the nozzle was in a vertical position with the inlet pointing downward or upward).

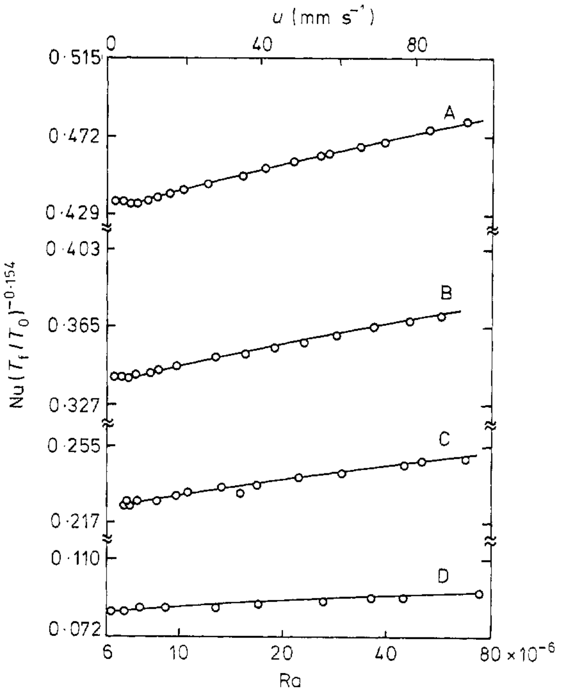

Figure 6 Calibration curves for horizontal flow with horizontal probe wire at different OHRS: A, 1·8; B, 1·6; C, 1·4; D, 1·2.

is practically the same as the critical value mentioned in the preceding paragraph.

In figures 6 and 7, it is demonstrated that the slope of the calibration curve increases with the OHR. No appreciable difference in slope can be found as a result of different orientation. Since the slope determines the overall sensitivity of the anemometer, the highest possible OHR should be used. The limiting value depends upon the probe sensor characteristics, and for most commercial probes of the size and type used in this investigation a maximum OHR of 1·8 is recommended.

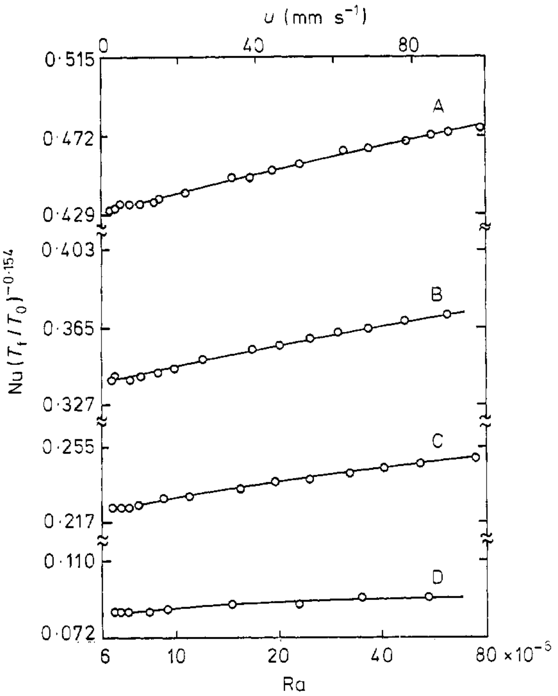

Figure 7 Calibration curves for horizontal flow with vertical probe wire at different OHRS: A, 1·8; B, 1·6; C, 1·4; D, 1·2.

An interesting observation is illustrated in figure 8. It appears that, for some probes, the amount of slope changes with age of the probe (age being determined by hours of energisation). Although this may be partially attributed to a changing of the material constants of the wire due to annealing, there must be a further explanation since the changes continue until failure occurs. Several authors suggested that the change in probe sensitivity is caused by deposited dust on the heated wire (Bradshaw 1971, pp 123–6; Collis, 1952).

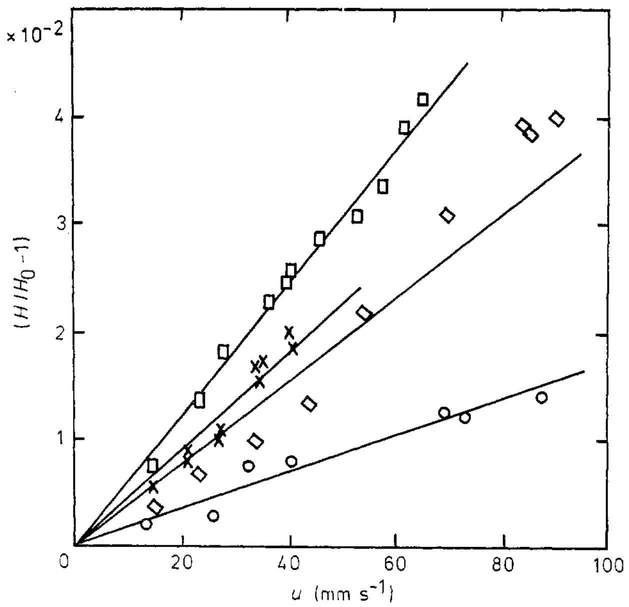

Figure 8 Demonstration of ageing effects. All probes were operated at a maximum recommended OHR of 1·8. ○, 14 h; ◇, 15 h; □, 16 h; ×, 17 h.

Although the authors found dust deposited on the hot wire, they feel that in the case of very low air flow velocities with the existence of 'dust free' space around the heated wire, there might be another reason for the relatively fast change of the hot wire anemometer calibration curve. A closer examination of the evidence yields some illuminating clues.

First, the particular type of probe used in this study has an unusually short lifespan, the longest being less than 50 h. Second, the lifespan and rate of decay are inconsistent from probe to probe. The shortest-lasting probe survived for 2 h; some probes changed their slope much more quickly and to a greater degree than did others, which hardly changed at all. Third, something that is consistent is the type of failure. All the probes experienced a break in the sensor near one of its supports. Each of these breaks appeared to be the result of a 'burn-out', i.e., a melting through of the sensor.

6 Conclusions

So far as can be determined from literature, the lower limit of applicability of commercially produced hot-wire anemometer has rarely been determined, but only predicted by extrapolation from experimental data or estimated by dimensional arguments. This investigation has demonstrated the existence of the lower limit to be about 10 mm/s for the particular type of probe used. The suggested volumetric measurement of air velocity is inexpensive and competitive with the more sophisticated rotating arm and probe traversal techniques.

The equipment employed in this investigation has been especially designed so that air speeds as low as 1 mm/s could be repeatedly and accurately induced. By superimposing such well-controlled forced velocities onto those stemming from free convective forces, the actual magnitude of the velocity of natural convection has been determined for a commercially available probe. The primary advantage of the described method is that the nozzle can be mounted with its axis in the horizontal or vertical position.

This method which was used for obtaining the calibration curve of a probe is accurate enough to prove the consistency of the results of these measurements with those of other authors (Van der Hegge Zijnen 1956, Collis and Williams 1959, Hatton *et al* 1970). The method applied extended further the calibration in air into the domain of Ra (or Re) where only two other authors worked with different experimental arrangement. One of the most detailed studies of a hot-wire anemometer at very low air speeds was that by Baille (1973) obtained with a carriage mounted probe which travelled within a square duct (0·7×0·8 m), 10 m long. There is qualitative agreement between his curves and figures 3 and 4 for very low steady air speeds, however, an exact comparison is difficult. The main problem seems to be the use of pure platinum wire by Baille, contrasting the platinum plated tungsten wires of a common DISA probe used in this study and the relatively low number of data points taken by Baille at velocities below 100 mm/s.

An important discovery is that some hot-wire probes suffer from ageing effects which cause the slope of the calibration curve to change with time. Although most probes stabilise quite rapidly and are very reliable after only a few hours of use, others change their characteristics continually until failure. Therefore, to ensure reliability of measurements, all probes should be periodically checked against their calibration curves – at least until stabilisation has been verified. (Such a check would only involve the testing of two or three points to compare the slope to that of the calibration curve.)

The results of this study indicate that the hot-wire anemometer is an instrument very suitable for the measurement of extremely low velocities, provided that it is properly calibrated and that its limits are not exceeded.

Acknowledgments
The authors would like to express their gratitude for the partial support of this study by the United States Department of Transportation, Grant RC 82009.

References

Baille A 1973 Lois de refroidissement des fils chauds aux faibles vitesses
Bull. de la Dir. des Etudes et Rech., Electricité de France S.A. No 3 4–201

Bradshaw P 1971 *An Introduction to Turbulence and its Measurement* (Oxford: Pergamon)

Collis D C 1952 The dust problem in hot-wire anemometry
Aeronaut. Quart. **IV** 93–102

Collis D C and Williams M J 1959 Two-dimensional convection from heated wires at low Reynolds numbers
J. Fluid Mech. **6** 357–84

Comte-Bellot G 1976 Hot-wire anemometry
Ann. Rev. Fluid Mech. **8** 209–31

Corrsin S 1963 *Turbulence: Experimental Methods Handb. Phys.* (Berlin: Springer) **812** 523–9

Hatton A P, James D D and Swire H W 1970 Combined forced and natural convection with low-speed air flow over horizontal cylinders
J. Fluid Mech. **42** 17–31

Van der Hegge Zijnen B G 1956 Modified correlation formulae for heat transfer by natural and forced convection from horizontal cylinders
Appl. Sci. Res. **A6** 129–40