Measuring flow velocity at elevated temperature with a hot wire anemometer calibrated in cold flow

Benjamin, S.F. and Roberts, C.A.

MEASURING FLOW VELOCITY AT ELEVATED TEMPERATURE
WITH A HOT WIRE ANEMOMETER CALIBRATED IN COLD FLOW

S. F. Benjamin and C. A. Roberts

School of Engineering, Coventry University, CV1 5FB, UK.

Abstract - Correction factors enable a hot wire anemometer calibrated at room temperature to be utilised at elevated temperature. This short paper reviews the equations on which those correction factors are based. The standard methods of correction, which work only over moderate temperature changes of a few degrees in the ambient, have been investigated over a greater temperature range. Modified correction factors are effective over a velocity range of 0 to 14 m/s and temperature range of 300 K to 500 K. The modified method of correction has been developed during research into the warm up of automotive catalysts and this has prescribed the range of velocity and temperature considered.

Nomenclature

A	Area of contact of wire with flow [m^2]
A_c, B_c	Constants
D	Diameter of hot wire (10 microns) [m]
h	Heat transfer coefficient [$W/(m^2\ K)$]
I	Current passing through wire [amps]
k	Thermal conductivity of air [W/(m K)]
M ,N	Constants
Nu	Nusselt number (hD/k)
Re	Reynolds number ($\rho UD/\mu$)
R_w	Operating resistance of wire (constant) [ohms]
T_w	Operating temperature of wire (constant) [K]
T_o	Temperature of cold flow calibration [K]
T_x	Elevated temperature of flow during experiment [K]
U	Velocity of air [m/s]
U_c	Velocity calculated using equation (7) [m/s]
U_m	Velocity obtained from mass flow [m/s]
V	Voltage [volts]
V_z	Voltage from anemometer under zero flow conditions [volts]
V_c	Corrected voltage used in cold flow calibration equation to find velocity [volts]
V_m	Voltage measured in hot flow experiment [volts]

Greek symbols

ρ Density of air [kg/m^3]

μ Viscosity of air [Pa s]

Introduction

Hot wire anemometers provide a useful means of measuring cold flow velocity. They have the advantages of small probe size and a frequency response which allows velocity fluctuations at high frequency to be detected. Traditionally they have been used to measure mean velocity and turbulence intensity. Recently computer processing of the signal from the hot wire anemometer bridge allows measurement of fluctuating velocity where the amplitude of the fluctuation is comparable in magnitude with the mean velocity. The anemometer has the disadvantage that it is calibrated in a constant temperature flow and must be operated in a flow of identical temperature. If the temperature of the flow drifts, or is intentionally changed, this is misinterpreted as a velocity change unless some allowance is made. There are standard methods for correcting for small temperature changes from ambient, see Bearman [1] and Lomas [2]. Manufacturers also quote formulae in their catalogues, for example T.S.I. [3]. Bruun [4] states that such correction methods are appropriate only for moderate elevations of temperature. A recent paper [5] has demonstrated acceptable accuracy over a limited velocity range for elevation as great as 40 degrees. There have been attempts previously to facilitate the use of hot wires at conditions further removed from those of the calibration, for example by Al -Daini et al. [6].

This work reported here was prompted because of the need to measure pulsating flow velocity during experiments on the early stages of warm up of automotive catalyst substrates. Clearly in experimental work of this type, the temperature elevations are much bigger than a few degrees of ambient drift because the temperature is intentionally ramped up. The velocities in the experiments are fairly low. Values up to 7 m/s in cold flow is typical with pulsating amplitudes also up to 7 m/s. The experimental conditions do not include flow reversal. The temperatures of the flow in the catalyst experiments rise typically from 293 K up to about 550 K maximum over about 60 seconds. These velocities and temperatures used in the catalyst experiments define the range of interest for this hot wire calibration investigation.

The ability of the existing correction methods, referred to above, to account for temperature change was explored. The methods were found to be unsatisfactory. An alternative correction method was found which gave improved agreement between calculated and measured velocity values at elevated temperature. The theoretical basis is explained below. Experimental measurements were made to provide data to test the modified correction factor. The results of the measurements are presented in this paper and show that improvement was achieved.

Theory

The analysis is based on the following assumptions:

i. The wire operates always at the same temperature T_w so that its resistance is always R_w

ii. The heat lost from the wire is equivalent to the supplied electrical power $I^2 R_w$

iii. The heat transfer coefficient can be determined from a constant value for Nu

In the following, the subscript o indicates cold flow (293 K) and the subscript x indicates hot flow (greater than 293 K but less than the wire temperature, which was about 793 K in the experiments). The following simple analysis reviews the origins of the correction factors.

In cold flow

$$I_o{}^2 R_w = h_o \, A \, (T_w - T_o)$$

In hot flow

$$I_x{}^2 R_w = h_x \, A \, (T_w - T_x)$$

In general terms for the cooling of a wire by a flow

$$Nu = hD/k = A_c + B_c \, Re^{0.5} = A_c + B_c \, (\rho U D/\mu)^{0.5}$$

Thus in cold flow

$$I_o{}^2 R_w{}^2 = (k_o/D)[\, A_c + B_c \, (\rho_o U D/\mu_o)^{0.5}] \, A \, R_w \, (T_w - T_o)$$

$$= (k_o/D) \, A_c \, A \, R_w \, (T_w - T_o) + (k_o/D) \, A \, R_w \, (T_w - T_o) \, B_c \, (\rho_o D/\mu_o)^{0.5} \, U^{0.5} \tag{1}$$

And in hot flow

$$I_x{}^2 R_w{}^2 = (k_x/D)[\, A_c + B_c \, (\rho_x U D/\mu_x)^{0.5}] \, A \, R_w \, (T_w - T_x)$$

$$= (k_x/D) \, A_c \, A \, R_w \, (T_w - T_x) + (k_x/D) \, A \, R_w \, (T_w - T_x) \, B_c \, (\rho_x D/\mu_x)^{0.5} \, U^{0.5} \tag{2}$$

King's Law [7] is used in the cold flow calibration and may be written

$$V^2 = M + N \, U^{0.5} = V_z{}^2 + N \, U^{0.5} \tag{3}$$

Thus comparing equation (1) with equation (3)

$$V_z{}^2 = (k_o/D) \, A_c \, A \, R_w \, (T_w - T_o)$$

$$N = (k_o/D) \, A \, R_w \, (T_w - T_o) \, B_c \, (\rho_o D/\mu_o)^{0.5}$$

Similar expressions would be obtained by comparing equation (2) with equation (3). Correction factors can be determined from this to enable application of a cold flow calibration equation of form (3) to operation of the wire in a flow at an elevated temperature. This assumes that a simultaneous measurement of temperature is available when velocity measurements are made.

The correction factor for the first term M or $V_z{}^2$ is CF1

$$CF1 = \frac{k_x \, (T_w - T_x)}{k_o (T_w - T_o)} \tag{4}$$

The correction factor for the calibration constant N is CF2

$$CF2 = \frac{k_x (T_w - T_x) (\rho_x \mu_o)^{0.5}}{k_o(T_w - T_o) (\rho_o \mu_x)^{0.5}} \tag{5}$$

Numerical values for gas properties from tables can be substituted into equation (5). Values for k, μ and ρ should be at the mean temperature of the gas and wire. Calculations show that

$$CF2 \approx \frac{(T_w - T_x)}{(T_w - T_o)} = CF$$

whereas CF1 values are different, being 10% greater than CF at 440 K and 20% greater than CF at 580 K. The experimental results below will show that using both CF1 and CF2 does not give effective correction. Thus it is convenient to neglect the difference between CF1 and CF2 and use only CF, i.e. neglect the variation in the values of the gas properties with temperature. Because the correction factor is then the same for both terms of the King's Law equation (3), it is more convenient to express the correction procedure as below.

$$V_c = V_m [(T_w - T_o)/(T_w - T_x)]^{0.5} \tag{6}$$

$$= V_m [1 - (T_o - T_x)/(T_w - T_x)]^{0.5} \tag{7}$$

This is quite useful as a correction factor for small drifts of temperature and is the equation quoted by T.S.I., [3]. It has been found to work over a wider temperature range if the index is increased from 0.5 to 0.55, as indicated later.

If $(T_o - T_x) < (T_w - T_x)$ then equation (7) can be approximated as

$$V_c \approx V_m [1 - 0.5 [(T_o - T_x)/(T_w - T_x)]] \tag{8}$$

Fortuitously, equation (8) performs better than equation (7) for the cases investigated in this paper. This equation is the best that has been found for correcting the data observed in practice at elevated temperature.

Equation (6) can alternatively be written

$$V_c = V_m [(T_w - T_x)/(T_w - T_o)]^{-0.5}$$

And can then be rewritten and approximated as follows:

$$V_c = V_m [1 + (T_o - T_x)/(T_w - T_o)]^{-0.5}$$

$$\approx V_m [1 - 0.5 [(T_o - T_x)/(T_w - T_o)]] \tag{9}$$

which is Bearman's equation, [1].

The three different factors set out in equations (7), (8) and (9) can be seen to have a common origin, but the method of approximation can influence how effective they are. Equation (8) has proved very good for the range of values in the experimental conditions tested here, whereas Bearman's correction method in equation (9) is poor for elevated temperatures. Fig. 1 shows numerical values of the different correction factors for the case T_o is 293 K, hot wire temperature T_w is 793 K and air temperature T_x is between 300 and 500 K. The factors can be seen to be very close at low temperatures but to diverge at higher temperatures.

Experimental method

For the experimental tests, the hot wire anemometer was a Dantec high temperature probe type 55A75 which has a 10 micron diameter Pt-Rhodium (90/10) wire which is 2.2 mm in length. This was operated at 793 K and was calibrated at 293 K. It was then used in hot air flow up to about 500 K. A description of the test rig can be found in a previous paper [8]. The anemometer was positioned in the hot flow between two 0.5 mm diameter K type thermocouples; the velocity profile was uniform. The mass flow rate was set. The temperature was raised from 293 K to about 500 K. The temperature and the voltage from the hot wire were recorded as the temperature rose. Because the mass flow rate was fixed, it was assumed that velocity rose in accordance with the temperature. This was verified with pitot tube measurements. The voltage from the anemometer was corrected using the correction factors and the velocity thus obtained was compared with that calculated from the measured cold flow velocity and the temperature assuming constant mass flow.

Results

The results are summarised by Fig. 2. It can be seen, as would be expected, that using the calibration equation uncorrected provides erroneous values except at the original calibration temperature. Using both CF1 and CF2 in full, equations (4) and (5), is not effective. Equation (7) with index 0.5 is better, but not acceptable. Equation (8) and Equation (7) with index 0.55 can both be seen to be good over the range of velocity and temperature investigated in this study. The velocities deduced from the hot wire voltage are close to the measured values for velocity in both cases.

An indication of error magnitude is provided by Fig. 3 which shows a plot of fractional difference between calculated and actual velocity as a function of $(T_w-T_o)/(T_w-T_x)$ for indices 0.5 and 0.55 applied to equation (7). The key of Fig. 3 shows a nominal cold flow velocity; it can be seen that accuracy is improved as velocity is increased. Fig. 3 also shows the advantageous effect of increasing the index from 0.5 to 0.55.

Conclusions

An exploration has been made of the theoretical basis for correction factors used to interpret hot wire anemometer voltage readings obtained for elevated flow temperatures. This has provided some useful insights. It has been found that a frequently used expression, equation (7), can be improved by raising its index from 0.5 to 0.55. A first approximation to equation (7) expressed as equation (8) also provides better correction than equation (7). Both equation (7) with index 0.55 and equation (8) have provided good correction at temperatures from 300 K to 500 K and at velocities up to 14 m/s.

Acknowledgements

References

[1] P. W. Bearman. Corrections for the effect of ambient temperature drift on hot wire measurements in incompressible flow. DISA Information 11 (1971) 25 – 30.

[2] C. G. Lomas. Fundamentals of Hot Wire Anemometry. Cambridge University Press 1986.

[3] T. S. I. Incorporated. Innovation in Thermal Anemometry. Product Catalogue. 1998.

[4] H. H. Bruun. Hot Wire Anemometry Principles and Signal Analysis. Oxford University Press. 1995.

[5] S. J. Ball. S. Ashforth-Frost. K. Jambunathan. C. F. Whitney. Appraisal of a hot-wire compensation technique for velocity measurements in non-isothermal flows. International Journal of Heat and Mass Transfer 42 (1999) 3097 – 3102

[6] A. J. Al-Daini. N. S. Girgis. R.G. Abdel-Gayed. S. N. Mawlwood. An empirical model for the use of a hot wire anemometer at elevated gas pressures and temperatures. Proceedings of International Conference on Computers in Machinery Industry, Chinese Mech Eng Society, Shanghai. 1992.

[7] L. V. King. On the convection of heat from small cylinders in a stream of fluid: determination of the convection constants of small platinum wires with applications to hot wire anemometry. Phil Trans Roy Soc A Vol. 214 (1914) 373 – 432

[8] S. F. Benjamin. C. A. Roberts. Warm up of automotive catalyst substrates: comparison of measurements with predictions. International Communications in Heat and Mass Transfer 25 (1) (1998) 19 – 32

<p style="text-align: center;">**<u>Figure Captions</u>**</p>

Fig.1

Numerical values for correction factors

Fig. 2

Velocity from hot wire anemometer plotted against true velocity from mass flow

Fig. 3

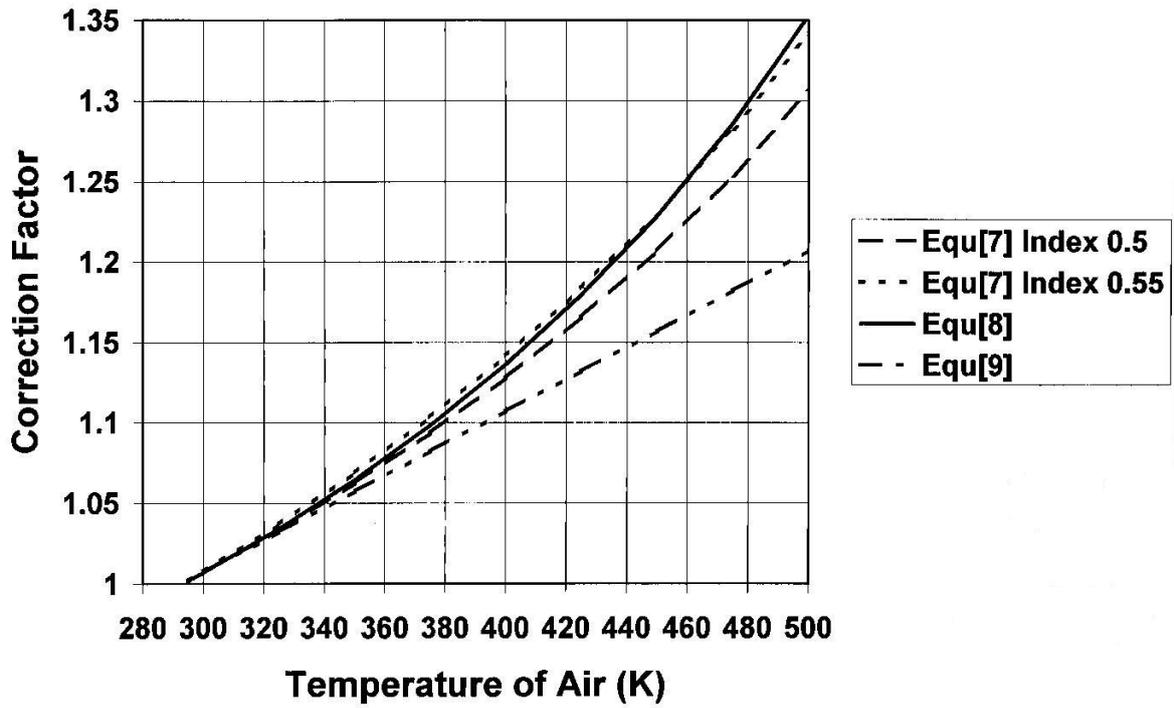Fractional difference between calculated and actual velocity as a function of $(T_w - T_o)/(T_w - T_x)$
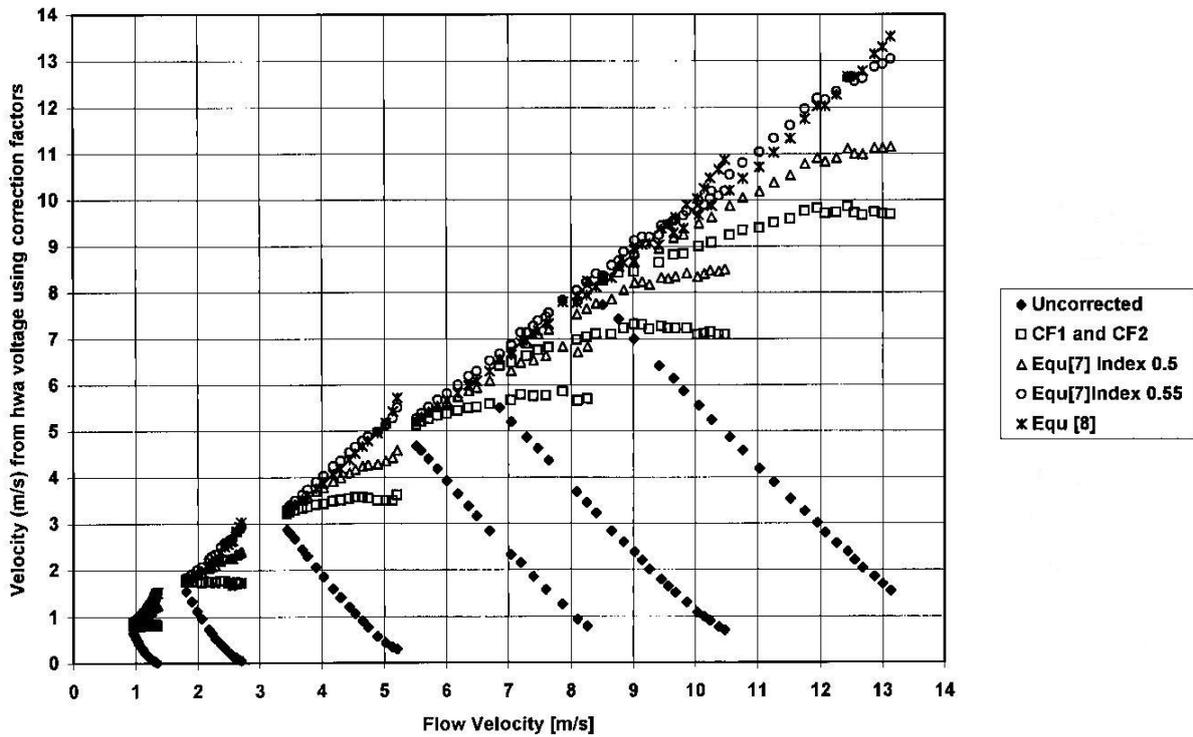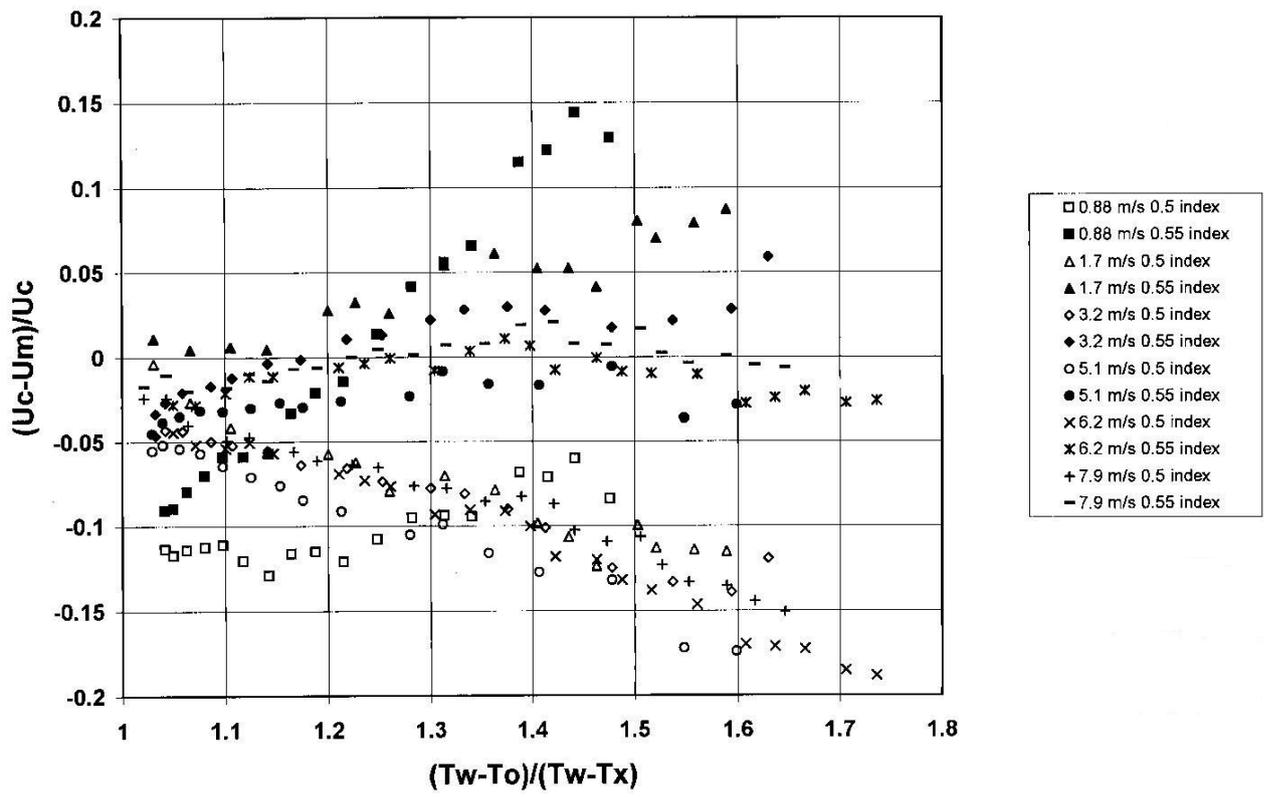
Figure 1

Figure 2

Figure 3