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Appraisal of a hot-wire temperature compensation technique for velocity measurements in non-isothermal flows

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Abstract

The development and evaluation of a data acquisition system employing a hot/cold-wire probe for the simultaneous measurement of instantaneous velocity and temperature in the boundary layer of a non-isothermal turbulent flow is described. The performance of an analytical expression for compensating the velocity reading of a hot-wire for varying fluid temperature has been assessed using a simple, low cost, high performance thermal calibration unit. The effectiveness of the expression for compensation of a temperature contaminated hot-wire velocity reading in flows ranging from 0.75 to 8.5 m/s and temperatures between 20 and 60°C has been demonstrated. For velocities in excess of 3 m/s the applied correction proved accurate to within ±2.2% over the 20–60°C temperature range.

1. Introduction

The constant temperature hot-wire anemometer is used extensively to measure velocity and turbulence quantities. Its output signal is related directly to the convective cooling effect of an air stream passing over the sensing element. In non-isothermal flows the response of a hot-wire to changes in velocity and temperature are indistinguishable. As a result, temperature contamination of the sensor leads to large errors in the measured velocity. For example, at 3 m/s the relative error introduced into the velocity measurement is approximately 1.5% per degree Celsius [1]. One method to overcome the problem of temperature contamination is to calibrate the probes separately at all the flow temperatures under investigation. However, when a large number of measurements are required over a range of different fluid temperatures ($\Delta T_f \approx 40°C$), the process of recalibration becomes time-consuming. A practical method to overcome this problem is to use a cold-wire probe placed in close proximity to the hot-wire for sensing instantaneous flow temperature. With this arrangement the response of the hot-wire can be broken down into the respective velocity and temperature components and corrections to the output signal can be applied before conversion to a true velocity.

There are a number of experimental heat transfer correlations describing forced convection around hot-

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Nomenclature

E	corrected voltage [V]
E_m	measured hot-wire voltage [V]
f_c	cut-off frequency [Hz]
T_f	fluid temperature [°C]
ΔT_f	fluid temperature change [°C]
T_r	reference temperature [°C]
T_w	hot-wire sensor temperature [°C]
u'	axial turbulence [m/s]
U_c	corrected axial velocity [m/s]
U_{CL}	axial jet exit centreline velocity [m/s]
U_0	actual axial velocity [m/s]

wire probes, the earliest example of which is given by [2]. The empirical relationship proposed by [3] has proved popular and indeed forms the basis of many temperature compensation schemes. Correction procedures for temperature contaminated hot-wire signals in non-isothermal flows are summarised by [4]. Analogue compensation techniques employing electronic circuits have been used, for example by [5] and [6]. The compensating circuitry, however, is often quite complicated and does not offer much in the way of flexibility [7]. On the other hand, computer-orientated digital techniques are flexible and can be implemented quickly with a suitable data acquisition and probe arrangement.

The basic correlations of [3] have been used with various modifications, for temperature compensation, with varying degrees of success. In particular, different reference temperatures at which to evaluate the fluid properties have been suggested. In a series of controlled experiments [8], compensation techniques based on the equations of [3] were compared. In all instances the temperature compensation according to the original formulation [3] proved to be the most accurate. For computer based experiments simplified versions of these relationships are desirable. For the case of small fluid temperature changes ($\Delta T_f \approx 40°C$) simple analytical interpretations of the influence of varying temperature on hot-wire readings have been suggested [9,10]. By assuming little or no change in the values of the fluid properties the following temperature correction was proposed [10]:

$$E^2 = E_m^2 \frac{(T_w - T_r)}{(T_w - T_f)} \quad (1)$$

where E is the corrected voltage, E_m is the measured hot-wire voltage, T_w is the wire temperature, T_r is the reference temperature at which the hot-wire was calibrated and T_f is the fluid temperature. Recent use of this expression has yielded an uncertainty in the mean streamwise velocity of 3.5% [11,12].

Work by the authors to date into impingement heat transfer has involved near wall measurements using laser-Doppler anemometry and hot-wire anemometry in isothermal flows complemented by heat transfer data [13]. In order to increase the understanding of the heat transfer process, detailed information within the hydrodynamic and thermal boundary layers of a non-isothermal flow is desirable. To ensure reliable experimental data it is always advisable, and good practice, to calibrate each individual probe arrangement. This paper describes the development and evaluation of a data acquisition system employing a hot/cold-wire probe for measuring velocity and temperature characteristics in non-isothermal flows. To facilitate the investigation a simple, low cost, high performance thermal calibration unit has been developed. The velocity and temperature characteristics of the air stream can both be controlled allowing evaluation of the temperature correction proposed by [10] when applied to the current probe configuration.

2. Experimental arrangement

2.1. Probe design

To separate the effects of velocity and temperature, when using hot-wire anemometry in a non-isothermal flow, an additional fine 'thermometer' wire (cold-wire) can be mounted close to the hot-wire to monitor temperature changes giving a dual probe. To allow positioning against a solid boundary the configuration of the dual probe was similar to that of a standard boundary layer probe (Dantec 55P05) with the prongs being offset from the main body by a distance of approximately 3 mm. The velocity sensing element consisted of a 5 μm diameter platinum plated tungsten wire, gold plated at the ends to provide an active sen-

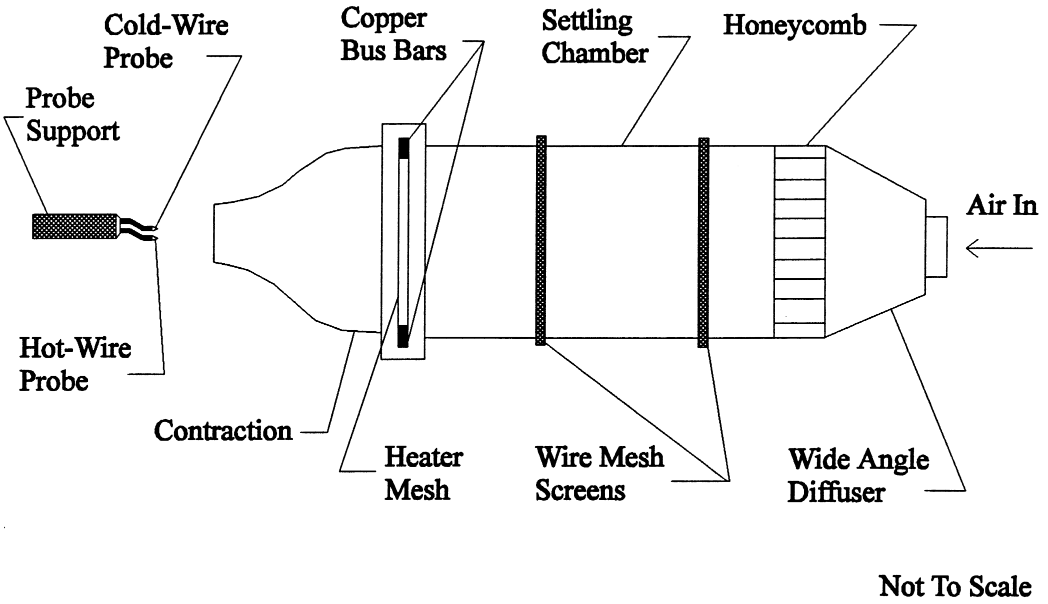

Fig. 1. Schematic plan view of the thermal wind tunnel and relative probe orientation.

sor length of 1.25 mm. The temperature sensor, also gold plated at the ends with an active length of 1.25 mm, was made from a 2.5 μm diameter unplated platinum wire. The frequency limit up to which the cold-wire followed fluctuating fluid temperatures, referred to as the cut-off frequency, f_c, or the point at which the attenuation of the signal reached −3 decibels was estimated using theoretical techniques [14,15]. This yielded a cut-off frequency of approximately 1000 Hz which falls within the range of experimentally determined values reported by [14].

The relative physical positions of the wires in space becomes critical when they are mounted extremely close together due to wake interference. Probe orientation tests were performed by [6] to identify the region of negligible wake interference when two wires were separated in the horizontal up/downstream plane. They demonstrated that the fluid velocity measured by the downstream hot-wire started to deviate significantly from the true velocity when the distance separating the two wires became less than 150 wire diameters. For a 2.5 μm diameter upstream cold-wire, this would unacceptably increase the spatial resolution. It is for this reason that the wires were not orientated in this manner. Instead, to avoid any mutual interference, the two wires were separated in the vertical direction by a distance of 200 μm. This separation was considered negligible when compared to the size of the calibration jet outlet (1%) and so essentially the probe sensed simultaneously the temperature and velocity fluctuations at the same point in the flow.

2.2. Calibration wind tunnel unit

A schematic diagram showing a plan view of the small Perspex thermal wind tunnel and relative probe orientation is given in Fig. 1. Air for the rig was supplied via a centrifugal fan (Airflow Developments Ltd type BC 1507 B) which was driven through a variable transformer by a 0.5 A motor. This arrangement enabled 0–100% control of the fluid flow.

The contraction to the 20 mm diameter jet exit was designed with a 16:1 area ratio using a BASIC computer program according to [16]. The heater, similar to that described by [17], comprised a fine wire (40 μm diameter) stainless steel mesh in a woven arrangement yielding 37% open area. A Perspex framework was used to secure the heater in position and keep the mesh taut during experiments. A variable DC power supply (0–10 V, 0–100 A) was used to deliver electrical energy to the mesh via two copper bus bars. The wind tunnel was thermally insulated using polystyrene and pipe lagging. The jet exit air temperature was measured to within 0.1°C using a calibrated type K thermocouple placed in close proximity to the cold-wire element of the probe. The axial flow velocity of the jet was monitored using a 2.3 mm diameter 90° bend, pitot-static tube manufactured according to [18]. The pitot-static tube was connected to an analogue micromanometer (Perflow Instruments Ltd) that allowed measurement of the fluid displacement to within 0.01 mm. From this reading the dynamic pressure and axial flow velocity were calculated based on ambient

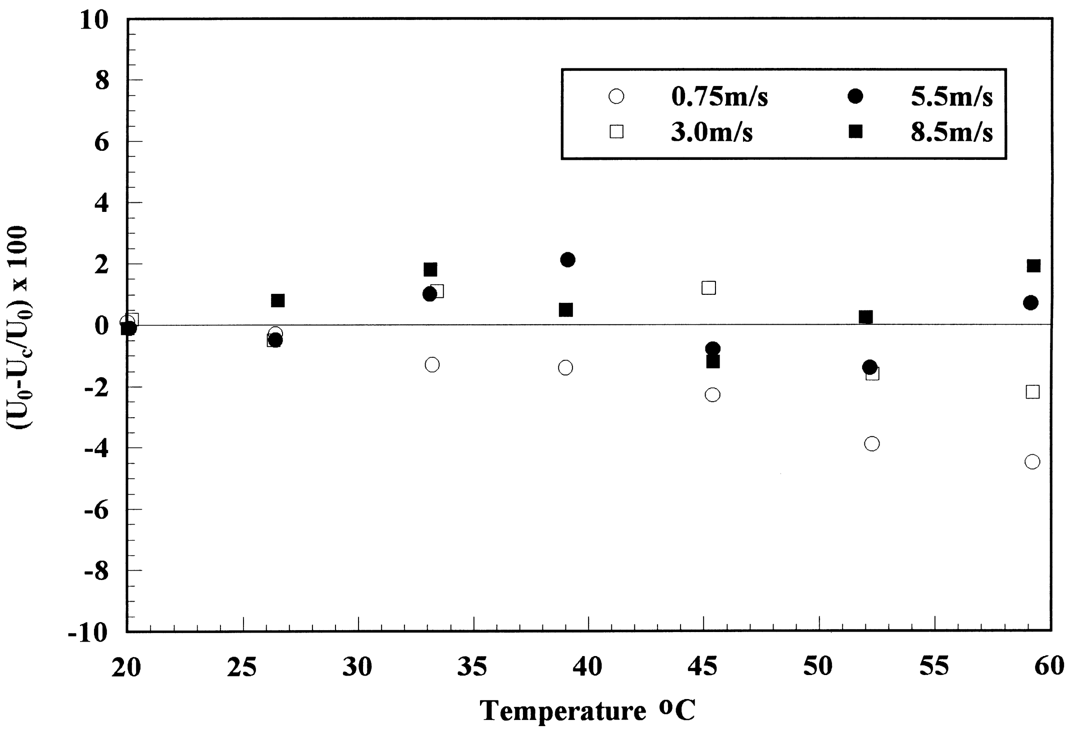

Fig. 2. Percentage difference between actual velocity and corrected velocity.

and local conditions respectively. The thermal wind tunnel provided control of the jet air temperature and velocity to within 0.1°C and 0.5% respectively, over the entire range investigated.

The jet exit characteristics of the calibration facility were determined using a single sensor hot-wire probe (Dantec 55P11). For a mean flow speed of 4 m/s the velocity distribution across the jet exit plane was uniform to within ±1%. The turbulence level, u'/U_{CL}, was also consistent at $0.007 \pm 4\%$ across the central region of the flow where calibrations were to be performed.

2.3. Data acquisition and control

A TSI-IFA-100 Intelligent Flow Analyser was used to operate the hot-wire sensor in constant temperature mode. An integral TSI model 157 signal conditioner enabled the offset, filtering and amplification of the signal as required. The cold-wire probe was operated in constant current mode using a purpose built cold-wire bridge circuit assembled in the laboratory. The circuit was very similar to the one described and extensively tested by [19] which had a frequency response of 13.5 kHz.

The dual probe was positioned in the outlet plane of the wind tunnel along the jet centreline using a computer controlled three-dimensional traverse mechanism with a spatial resolution of 2.5 μm. Data collection and analysis was performed by a two-channel Spectral Dynamics SD380 signal analyser in conjunction with an interfaced personal computer. The signal analyser had an input range of 0.01–20 V and was fitted with a 16-bit 100 kHz A/D card. A total of 6000 samples per channel were taken for each measurement.

3. Experimental results

The hot-wire probe was calibrated in the thermal wind tunnel over the velocity range of interest (0.7–9.0 m/s) at a constant reference temperature of 18.5°C. The sensor was operated at 250°C yielding an overheat ratio of approximately 1.8. Calibration of the cold-wire was performed across the temperature range 18.5–60°C with a constant heating current through the wire of 0.5 mA. The performance of Eq. (1) for compensating the velocity reading of a hot-wire due to varying fluid temperature was assessed for the present configuration. This involved specifying four flow velocities (0.75, 3.0, 5.5 and 8.5 m/s) and maintaining those constant whilst altering the temperature characteristics of the fluid. At all times, the temperature effects on the properties of air were accounted for. A total of seven different air flow temperatures, approximately equi-spaced, in the range 20–60°C were investigated for each given velocity.

In order to compare the results, the corrected flow velocity, U_c, was calculated as a percentage difference of the actual velocity, U_0. The percentage difference is presented in Fig. 2 as a function of flow temperature for the four velocities under consideration. It can be seen that applying correction (1) to the contaminated hot-wire readings for $U_0 \geqslant 3$ m/s results in errors scattered around the true velocity. In the range $3 \leqslant U_0 \leqslant 8.5$ m/s and $20 \leqslant T_f \leqslant 60$°C the corrected velocities lie within ±2.2% of the actual velocities. This is in reasonable agreement with the findings of [8] who used a similar linear correction formula. For the case of $U_0 = 0.75$ m/s the magnitude in velocity error, although small below 40°C, shows a steady rise with increasing air stream temperature culminating in a maximum discrepancy of −4.5% at approximately 60°C. The compensation Eq. (1) has overcorrected for the temperature contamination of the wire resulting in velocities that are too high. This is a common occurrence at low flow rates where the influence of natural convection and conduction of heat to the prongs makes a greater contribution to the overall heat transfer from the wire [10]. The maximum observed error of −4.5% is not, however, as significant as that reported by [8] for similar operating conditions. An explanation for this could be in the design of the probe itself. The present configuration consists of a platinum plated tungsten wire that is gold plated at the ends as opposed to an unplated hot-wire used by [8]. The gold plating serves to reduce the amount of heat dissipated by the prongs and thus reduce in magnitude the overcorrection experienced at the lower velocity end.

4. Conclusions

The performance of a common/popular analytical expression, proposed by [10] for correcting hot-wire velocity readings due to temperature contamination has been assessed. For velocities in excess of 3 m/s, the correction formula has shown consistent accuracy to within ±2.2% over the entire temperature range under investigation. A 4.5% overcorrection in velocity was the highest discrepancy observed at a flow rate of 0.75 m/s and a temperature approaching 60°C. The carefully controlled experiments were performed in a simple, low cost, high performance calibration unit employing a fine wire mesh heating arrangement. The computer controlled data acquisition system and probe arrangement described are particularly suited to non-isothermal experiments where measurements at a large number of locations are required.

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