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# Temperature corrections for constant temperature and constant current hot-wire anemometers

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## Abstract

Changes in the ambient fluid temperature change the calibration curve for velocity measurements taken using hot-wire anemometry. New correction methods are proposed to account for the effects of relatively large temperature changes in the heat-transfer process and on the fluid properties. The corrections do not assume any particular heat-transfer correlation, and they do not require multiple calibrations over a range of temperatures. The corrections are derived for the constant temperature and constant current modes of operation.

**Keywords:** hot wire, anemometer, temperature correction

## 1. Introduction

One of the most important sources of error in measuring velocity using hot-wire anemometry is the change in the hot-wire calibration due to changes in the ambient temperature (Perry 1982). In order to minimize this error, an accurate correction technique is necessary, and many different correction techniques have been proposed for constant temperature anemometer (CTA) hot-wire systems. The most commonly used correction is that presented by Bruun (1995), where the output voltage  $E_w$  is corrected to a reference temperature  $T_r$  (usually the one corresponding to the temperature at which the calibration was performed). That is,

$$E_{w,r} = E_w \left[ \frac{T_w - T_r}{T_w - T_a} \right]^{1/2}. \quad (1)$$

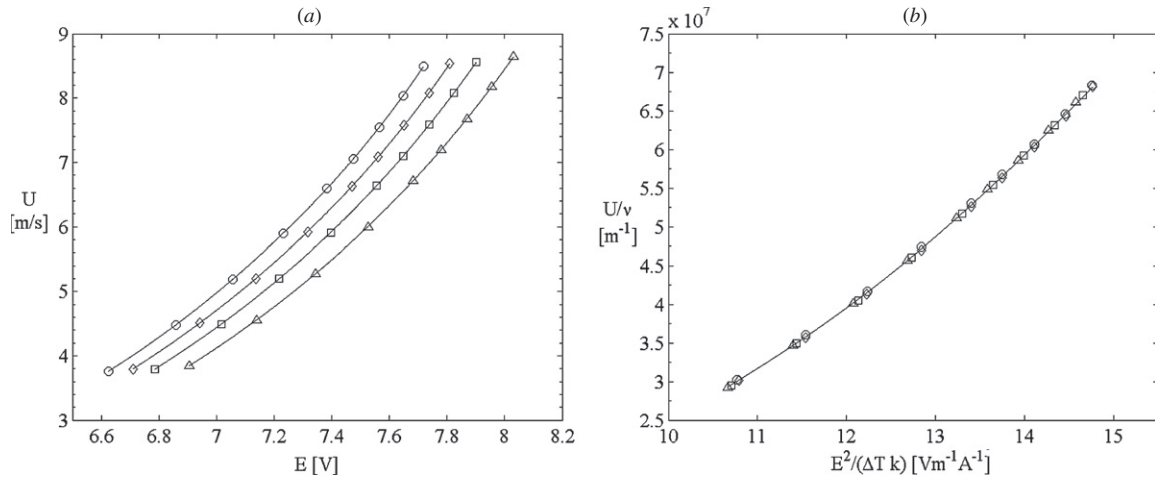
Here  $T_w$  and  $T_a$  are the wire and ambient temperatures, respectively, and the subscript  $r$  indicates that the value is taken at the reference temperature. This relationship assumes that the temperature changes are small enough so that the fluid properties remain constant. When performing experiments with larger temperature changes (typically more than two or three degrees), this assumption breaks down, leading to an over-correction. Other corrections have therefore been developed that incorporate the changes in fluid properties; see, for example, Collis and Williams (1959), Grant and Kronauer (1962), Bearman (1971), Abdel-Rahman and Strong (1987),

Benjamin and Roberts (2002), and the recent survey by Tropea *et al* (2007). All these corrections are based on an assumed heat transfer law such as King's law, and they are often cumbersome to incorporate in the data analysis.

For constant current anemometer (CCA) systems, it appears that no correction technique is presently extant. Recent developments in hot-wire technology that use wires with very small thermal mass make it possible to operate in constant current mode (CCA) with an inherently high frequency response (see Bailey *et al* (2010)), and CCA continue to find application in variable density flows. A correction for this mode of operation is therefore also of great interest.

To correct the data from CTA and CCA systems for temperature, a separate measurement of the fluid temperature is required. Sarma and Comte-Bellot (2002) showed that it is possible to eliminate the need for a separate temperature sensor, and automatically compensate for temperature drift in a constant voltage anemometer (CVA) by quickly changing the voltage over the wire to measure its cold resistance. However, this method can only be used in the CVA mode of operation.

Here we present new correction schemes for constant temperature and constant current hot-wire systems. The methods are not based on an assumed heat transfer law, they require a minimum of additional calibration and they are simple to implement in the data analysis. Furthermore, they



**Figure 1.** Calibration curves for constant temperature operation taken at different temperatures:  $\circ$ , 48 °C;  $\diamond$ , 45 °C;  $\square$ , 39 °C;  $\triangle$ , 33 °C. (a) Original calibrations and (b) calibrations replotted using the similarity variables given by equation (4).

appear to work well for relatively large temperature changes, and so they are particularly suitable for experiments in the atmospheric boundary layer, in heat transfer experiments and flows where there is inadequate control over the ambient temperature, such as that often experienced in high Reynolds number facilities.

## 2. Theory

The basic operating principle of constant temperature and constant current operation is that the resistance of the sensor material increases with increasing temperature. In the analysis presented here, we will assume a linear relationship between resistance  $R$  and temperature  $T$ , so that

$$R = R_r(1 + \alpha(T - T_r)), \quad (2)$$

where  $\alpha$  is the temperature coefficient of resistance, although our approach can easily be extended to include nonlinear terms.

In analyzing the heat transfer from the wire, we consider only heat transfer due to forced convection. We will assume that the wire has a large aspect ratio so that end-conduction effects can be neglected. According to Perry (1982) and Bruun (1995), we therefore require  $l/d > 200$ , where  $l$  is the length of the wire and  $d$  is its diameter. In order to neglect free convection effects, the Richardson number,  $Ri$ , that is, the ratio of natural to forced convection, needs to be less than about 0.1. For a conventional hot wire with a diameter around  $5 \mu\text{m}$ , this critical velocity is less than  $0.1 \text{ m s}^{-1}$ . In the analysis presented here, free convection effects will not be considered.

### 2.1. Constant temperature

In the constant temperature mode of operation, the wire resistance is held constant by the feedback circuit of the anemometer. The Joule heating is then balanced by the convective heat transfer, so that

$$\frac{E^2}{R} = h \Delta T A = \frac{k Nu}{d} A \Delta T, \quad (3)$$

where  $h$  the convective heat transfer coefficient,  $\Delta T = T_w - T_a$ ,  $A$  is the surface area of the wire,  $k$  is the thermal conductivity of the fluid and  $Nu = hd/k$  is the Nusselt number. For forced convection in subsonic flow, the Nusselt number depends on the Reynolds number  $Re$  and the Prandtl number  $Pr$  (see, for example, van Dijk and Nieuwstadt (2004)). Because the Prandtl number is only a weak function of temperature, we assume that  $Nu = f(Re)$ , where  $f$  denotes a functional dependence. Here  $Re = Ud/\nu$ , where  $\nu$  is the kinematic viscosity of the fluid, and  $\nu$  and  $k$  are evaluated at the film temperature  $T_f = \frac{1}{2}(T_w + T_a)$ . Hence,

$$E^2 = f(Re) \frac{k}{d} A \Delta T.$$

Since  $d$  and  $A$  are constant for a given wire,

$$E^2 = f_1(Re) k \Delta T,$$

which can be written as

$$Re = f_2\left(\frac{E^2}{k \Delta T}\right)$$

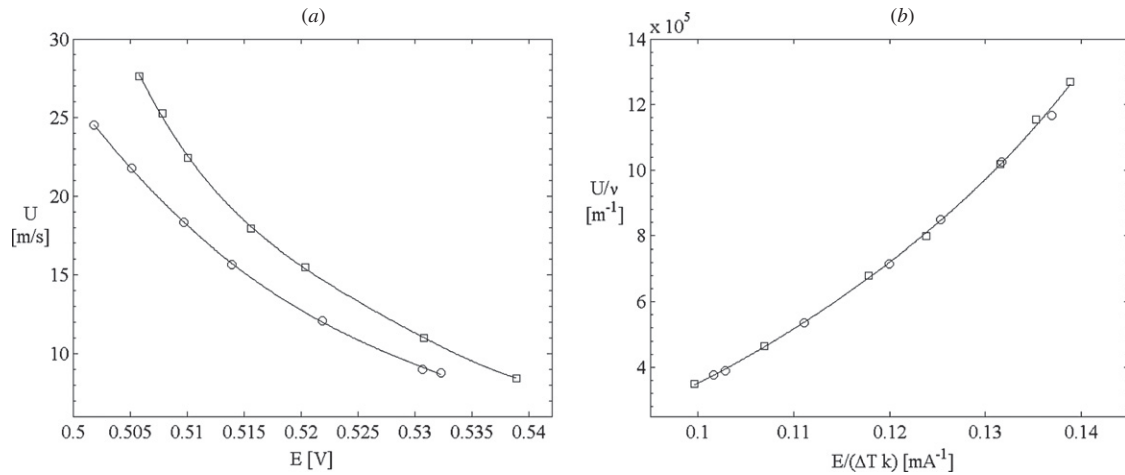
or

$$\frac{U}{\nu} = f_3\left(\frac{E^2}{k \Delta T}\right). \quad (4)$$

In the usual wire calibration procedure,  $U$  is found as a function of  $E$ . We see that if instead the calibration is done so that  $U/\nu$  is found as a function of  $E^2/k\Delta T$ , then it is possible to find  $U$ , the true velocity over the wire if  $\nu$  and  $k$  are known as a function of temperature. The viscosity can be found using the relationships given by, for example, Smits and Zagarola (2005), and the thermal conductivity of air can be found using the correlation given by Kannuliuk and Carman (1951), where

$$k = 418.4(5.75 \times 10^{-5}(1 + 0.00317T - 0.0000021T^2)). \quad (5)$$

In addition, it is necessary to know the temperature coefficient of resistance  $\alpha$  and the wire temperature  $T_w$ , which can be found from the resistance ratio  $R/R_r$  (see equation (2)).



**Figure 2.** Calibration curves for constant current operation taken at different temperatures:  $\circ$ , 19 °C;  $\square$ , 28 °C. (a) Original calibrations and (b) calibrations replotted using the similarity variables given by equation (7).

## 2.2. Constant current

A similar relationship can be found for the case of constant current operation, where  $I$  is the current through the wire. Equation (3) can then be rewritten as

$$EI = h\Delta T A = \frac{kNu}{d} A \Delta T. \quad (6)$$

Since  $I$ ,  $d$  and  $A$  are constant and  $Nu = f(Re)$ ,

$$E = g_1(Re)k\Delta T,$$

which can be written as

$$Re = g_2\left(\frac{E}{k\Delta T}\right)$$

or

$$\frac{U}{v} = g_3\left(\frac{E}{k\Delta T}\right). \quad (7)$$

This calibration relationship is very similar to that found for the constant temperature mode (equation (4)), but since  $T_w$  is no longer constant, one more step is needed to find  $\Delta T$ . Using equation (2), we have

$$T_w - T_r = \frac{1}{\alpha} \left( \frac{R}{R_r} - 1 \right),$$

where  $R$  is the wire resistance at the operating temperature. Now

$$\Delta T = (T_w - T_r) + (T_r - T_a).$$

That is,

$$\Delta T = \frac{1}{\alpha} \left( \frac{E}{IR_r} - 1 \right) + (T_r - T_a). \quad (8)$$

Equations (7) and (8) can now be used to find the true velocity over the wire.

It should be noted that for accurate results in either the constant temperature or constant current mode of operation, the value of  $\alpha$  needs to be known precisely. For the tungsten wire used to obtain the constant temperature data presented here, the average of the values given by van Dijk and Nieuwstadt (2004) was used ( $\alpha = 0.0044$ ). For the Wollaston wire (90% Pt, 10% Rh) used to obtain the constant current data presented here, the value given by Buzin and Wunderlich (2002) was used ( $\alpha = 0.00165$ ).

## 3. Experiment and discussion

To evaluate the method proposed for correcting constant temperature hot-wire data, the measurements obtained by Jiménez *et al* (2010a) in the Princeton High Reynolds number Test Facility (HRTF) were used. These data were taken using a tungsten wire of 5  $\mu\text{m}$  diameter and 1 mm length, operated by a Dantec Streamline CTA system at a wire temperature  $T_w$  of 195 °C. The wire was calibrated in the free stream of the wind tunnel using a Pitot-static tube. A first calibration was obtained at about 33 °C. By operating the tunnel without cooling, the air temperature increased, and three other calibrations were obtained, at 39 °C, 45 °C and 48 °C. More information on these measurements and the HRTF is given by Jiménez *et al* (2010a).

The calibration curves obtained at these temperatures are shown in figure 1(a). Each curve is fitted with a fourth-order polynomial, as suggested by Perry (1982), with an  $R^2$ -factor always better than 0.99999. The same curves plotted according to equation (4) are shown in figure 1(b). The data collapse to a single curve (a fourth-order polynomial) with an  $R^2$ -factor of 0.9998, demonstrating that the proposed correction technique accurately captures the effects of changing temperature on the calibration.

To evaluate the method proposed for correcting constant current hot-wire data, new measurements were obtained in the Princeton 2 ft by 3 ft (0.61 m by 0.91 m) recirculating wind tunnel (for more information, see Jiménez *et al* (2010b)). These data were taken using a Wollaston wire (90% Pt, 10% Rh) of 5  $\mu\text{m}$  diameter and 1 mm length, powered by an in-house circuit, in conjunction with a Krohn-Hite 3362 instrumentation amplifier. The wire was calibrated in the free stream of the wind tunnel using a Pitot-static tube. A first calibration was obtained at 19 °C. Then, by operating the tunnel without cooling, a new equilibrium temperature was reached at 28 °C, and a second calibration was obtained. During this second calibration, the cooling was manually adjusted in order to hold the temperature close to constant. The exact temperature was recorded for each calibration point and used in the later analysis.

The two calibration curves are shown in figure 2(a), and each curve is fitted with a fourth-order polynomial, with  $R^2$ -factor of 0.9998 and 0.9997, respectively. The same curves plotted according to equation (7) are shown in figure 2(b). The data collapse to a single curve (a fourth-order polynomial) with an  $R^2$ -factor of 0.9991, demonstrating that the correction method proposed for constant current operation works nearly as well as the one used for the constant temperature mode.

#### 4. Conclusions

The correction methods derived here for CTA and CCA operation appear to work remarkably well for relatively large temperature changes (15 °C and 9 °C, respectively). In addition, they do not require a different velocity calibration for each temperature (as many other methods do), and they are not based on an assumed heat transfer relationship. A single velocity calibration is all that is needed, in addition to knowing  $\Delta T$ , and the fluid properties  $k$  and  $\nu$  as a function of temperature. Note that all fluid properties are evaluated at the film temperature.

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