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Review

Issues and temperature compensation techniques for hot wire thermal flow sensor: A review

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The hot-wire anemometer is used extensively to measure velocity and turbulence quantities. Hot-wire measurement of non-isothermal flows necessitate the use of thermal compensation or error correction. This paper focus of issues and techniques for thermal compensation and error correction in industrial application was studied. Firstly, comprehensive review on the theory of several types of the most commonly used hot-wires anemometry in the field. Secondly, it considered the compensation techniques both in CTA and CCA hot-wire anemometry. Results of compensating techniques are presented for both CTA and CCA and were compare with different techniques. Finally, computational intelligent can be suitable for those systems where it is very complex or impossible to obtain the model by means of classical methods.

Key words: Hot wire, thermal flow sensor, temperature compensation.

INTRODUCTION

Thermal anemometry is still a widely used method for air velocities measurement in research and industry, in spite of the appearance of modern tools in recent decades (Bruun, 1995). In thermal anemometry the heat transfer from a heated wire placed in a fluid flow, measures the air velocity. If only the fluid velocity varies, then the heat loss can be interpreted as a measure of that variable. Typical representatives of this subclass of thermal flow sensors are hot-wire and hot-film anemometers, (Perry, 1982; Lomas, 1986). These sensors operated under constant temperature or constant current conditions and also working for flow-rate measurements in a wide range of applications, (Bradshaw, 1971; Hinze, 1975; Emrich, 1981; Cheremisinoff, 1988). In hot-wire anemometry, the sensor consists of a very fine metallic element, whose diameter is typically about 5 lm, supported by two prongs at the end of a slender probe body. The wire is heated by an electric current and simultaneously cooled by convective heat transfer induced by the lower temperature incident flow. The wire response depends on both the velocity and the temperature of the flow (Ashhab and Al-Salaymeh, 2006). Its major applications are in moderate to high velocities under isothermal conditions such as wind tunnel measurements, but thermal anemometry can be adapted to a variety of applications in different fields. In hot film anemometry, the sensor consists of a thin layer of conducting material that has been deposited on a non-conducting substrate. Hot-film may also be cylindrical or in other forms. In the field of indoor climate, the measured velocities are low and usually accompanied by a varying air temperature, which places different demands on the performance of the anemometer as compared to the high velocity isothermal case (Sandberg, 1994). As the heat transfer process is sensitive both to the velocity and temperature of the air, any changes in temperature must be compensated for in order to achieve accurate velocity measurements.

The schemes for temperature compensation proposed so far show large differences in the results, probably mainly due to difficulties in identifying the mechanisms involved in the heat transfer process (Lundstrom and Sandberg, 2007). This review will discuss the basic theory of several types of the most commonly used hot-wire anemometry in the field and provide an update on the

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error compensation techniques for the hot-wire anemometry measurement.

BACKGROUND

Hot-wire anemometers have been used since the late 1800s. The specific origin of hot-wire anemometry cannot be accurately determined but it seems to go back to the beginning of the last century. Indeed, according to King (1915), preliminary experiments on the use of a platinum wire heated by an electric current for the measurement of wind velocity were carried out by Shakespear, at Birmingham, they were discontinued for lack of facilities for the erection of a suitable whirling table for calibration of the wires. One of the earlier studies of heat transfer from a heated wire was made by Boussinesq (1905) and extended by King (1914) and he attempted to experimentally verify his theoretical results. These earlier investigations of hot-wire anemometry considered only the mean heat transfer characteristics from heated wires and it was important both for the design of hot-wire anemometers and for the theory of the convection of heat from cylinders immersed in a stream of fluid. As far as their basic principles are concerned, thermal heat loss sensors can be taken as being fully developed. The first quantitative measurements of fluctuations in subsonic incompressible flows were made in 1929 by Dryden and Kuethe (1929) using constant current anemometry where the frequency response of the wire was extended by the use of a compensating amplifier. Ziegler (1934) developed a constant temperature anemometer for measuring fluctuations by using a feedback amplifier to maintain a constant wire temperature up to a given frequency.

In the 1950's, Kovasznay (1950, 1953) extended hotwire anemometry to compressible flows where it was found experimentally that in supersonic flow, the heated wire was sensitive only to mass flow and total temperature and developed a graphical technique to obtain these fluctuations, which is mostly used in supersonic flow. Insubsonic compressible flows the heat transfer from a wire is a function of velocity, density, total temperature, and wire temperature. Because of this complexity, these flow regimes were largely bypassed until the 1970's and 1980's when attempts were made to develop methods applicable (Rose and McDaid, 1976) for these flows. The available publications concerning early electrical anemometry therefore appear to be, first, Kennelly and Wright (1909) and then, independently (Morris, 1912).In recent years there were several new developments in hot-wire anemometry that can be attributed to advances in electronics, data acquisition/reduction methods and new developments in basic anemometry techniques. Previous reviews, survey reports, and conference proceedings on hot-wire anemometry are included in references (Badwin and Sandborn, 1960; Sandborn, 1974; Laufer, 1975; Vagt, 1979; Blackwelder, 1981; Goodstein, 1983).

THEORY OF OPERATION

Fundamentally, a hot wire makes use of the principle of heat transfer from a heated surface being dependent upon the flow conditions passing over it. Hot wire anemometer consists of a thin wire mounted to supports and exposed to a velocity U as in Figure 1. When a current is passed through wire, heat is generated. In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings. If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium. The most common wire materials are tungsten, platinum and a platinum-irridium alloy. A thin platinum coating is usually applied to improve bond with the plated ends and the support needles. The needles should be thin but strong and have high thermal resistance (low thermal conductivity) to the probe body (Fraden, 2010).

As the fluid passes over the hot wire, it carries away heat. The heat loss depends on the flow rate, the heat capacity of the fluid, and the temperature difference between the wire and the fluid. Since the heat capacity of the fluid is known and the temperatures are monitored in real-time, the flow rate can be determined from the heat loss (related to the electrical resistance of the wire via Ohm’s law and the temperature coefficient of the wire (Melani and Bertini, 2008).

The differential equation that describes the temperature of the single wire is realized as:

$$\rho_w c_w A_w \frac{\delta T_w}{\delta t} = \frac{I^2 \chi_w}{A_w} - \pi d_w h (T_w - T_a) \quad (1)$$

Where: ρ_w is the density of the wire material, c_w the specific heat of the wire material, A_w the cross-sectional area of the wire, T_w the wire temperature, t the time, I the heating current, χ_w the resistivity of the wire material, d_w the wire diameter, h the coefficient of convective heat transfer, T_a the temperature of the fluid.

The resistance of the sensor element can be approximated as a linear function of temperature, that is:

$$R_w = R_a [1 + \alpha_a (T_w - T_a)] \quad (2)$$

Where: R_w wire resistance, R_a, the heater resistance at reference temperature, T_a (ambient).

Implementing constant temperature operating mode the temperature of the heated wire (T_w) relative to the ambient temperature (T_a) is kept constant by a Wheatstone bridge (Rasmussen and Zaghloul, 1998).

The current I (or voltage U) which is needed therefore, is proportional to the mass flow. However, there are

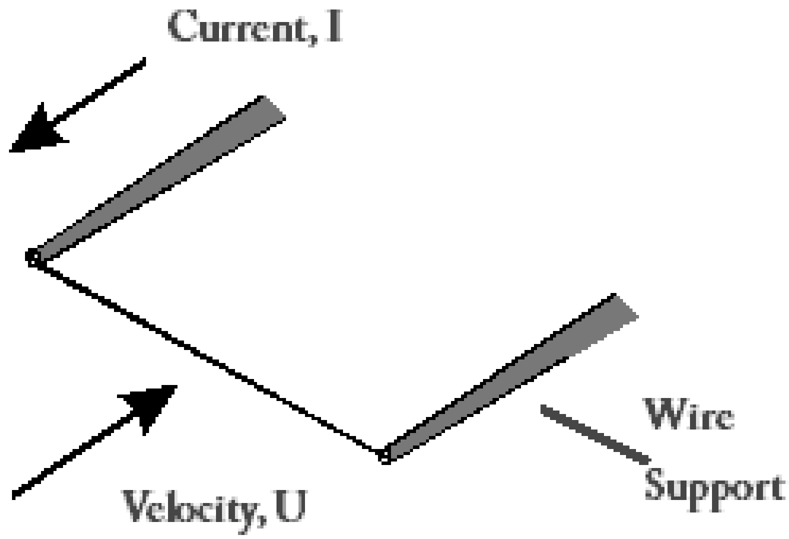

Figure 1. Hot wire anemometer.

deviations from a linear dependence according to the Kings law. The King's law takes account for the different contributions to the heat transfer through the boundary layer by convection and conduction with flow and is empirically described in Equation (3).

$$I^2 R_w{}^2 = U^2 = (T_w - T_a)(A + Bv^n) \quad (3)$$

The voltage drop (U) is used as a measure of velocity (v). The constants A, B and the exponent n are empirically determined and ambient specific.

CONSTANT TEMPERATURE ANEMOMETER (CTA)

The temperature is constantly maintained at any reasonable flow rate by the increase in supplied electric power. That power is the measure of the flow rate. In a hot wire anemometry, the wire has a positive temperature coefficient and thus is used for a dual purpose; to elevate temperature above the media temperature (so it will be a cooling effect) and also to measure that temperature because the wire resistance goes down when the wire cools (Fraden, 2010). Figure 2 shows a simplified bridge circuit for the constant temperature method.

The feedback from a servo amplifier keeps the bridge in a balanced state. Resistor R_1-R_3 are constant, while R_w represents resistance of the hot wire and is temperature dependent. Drop in the wire temperature T_w causes temporary drop in R_w and a subsequent reduction in the bridge voltage –e that is applied to the negative input of the servo amplifier. This leads to increase in Vout, which is applied to the bridge as a feedback. When Vout goes up, current I through the wire increase, leading to increase in temperature. This restores the wire temperature when flowing media attempt to cool it, so T_w remains constant over the entire flow rate range. The feedback voltage Vout is the output signal of the circuit and the measure of the mass flow rate. The output voltage becomes higher according to the flow. Under a steady flow rate, the electric power Q_e supplied to the wire is balanced by the out-flowing thermal power Q_T carried by the flowing media due to a convective heat transfer. That is:

$$Q_e = Q_T \quad (4)$$

Considering the heating current I, the wire temperature T_w, temperature of the fluid T_a, the wire surface area A_w, and the heat transfer coefficient h, the balance equation is:

$$I^2 R_w = hA_w (T_w - T_a) \quad (5)$$

King (1914) developed a solution of a heat loss from an infinite cylindrical body in an incompressible low Reynolds number flow:

$$h = a + bv_f^c \quad (6)$$

Where a and b are constant and c = 0.5. This equation is known as King's Law. Combining the above three equations allows to eliminate the heat transfer coefficient h:

$$a + bv_f^c = \frac{I^2 R_w}{A_w (T_w - T_a)} \quad (7)$$

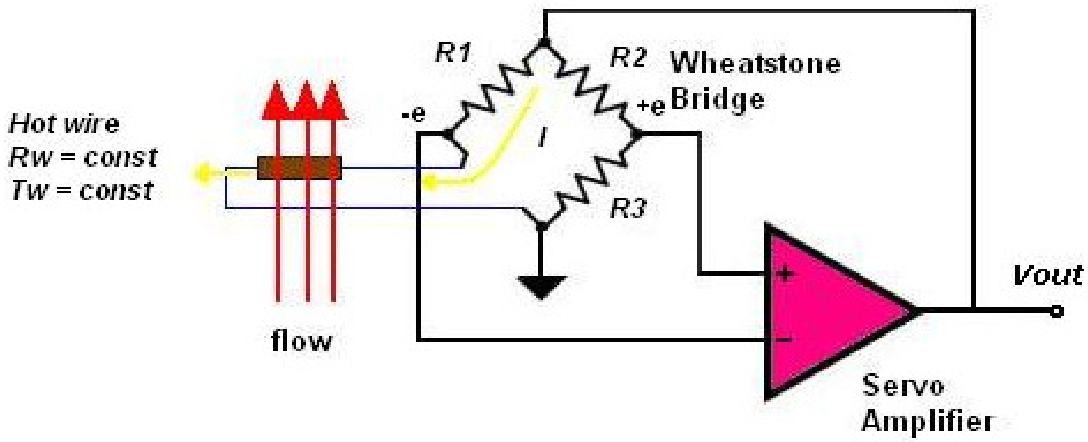

Figure 2. CTA hot wire anemometer with bridge.

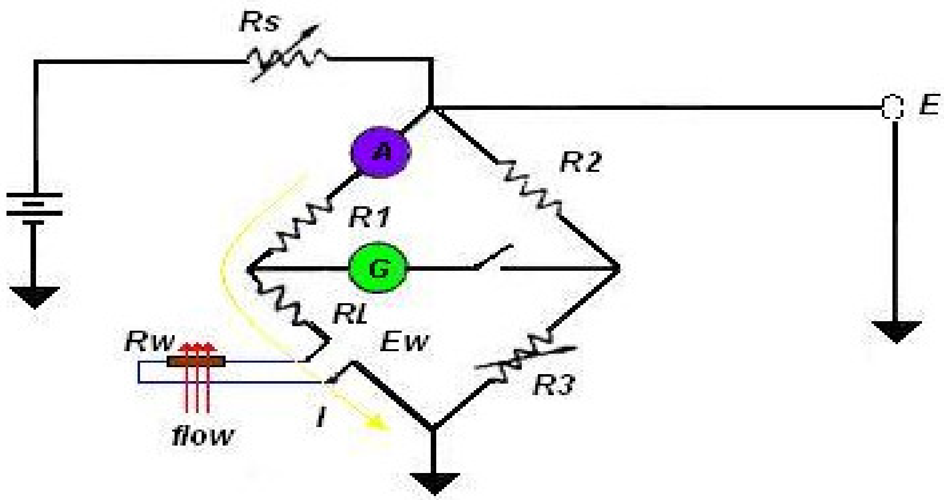

Figure 3. CCA hot wire anemometer with bridge.

Considering that:

$$Vout = i(R_w + R_1) \quad (8)$$

Then, the equation for the output voltage as function of the fluid velocity is:

$$Vout = (R_w + R_1)\sqrt{\frac{A_w(a + b\sqrt{v})(T_w - T_a)}{R_w}} \quad (9)$$

CONSTANT CURRENT ANEMOMETER (CCA)

A typical CCA circuit with wheatstone bridge (Bruun, 1995) is shown in Figure 3. Selecting, at a specified velocity, an overheat ratio R_w/R_a, the calculated value of R_w is first set by adjusting R_3 using the relationship:

$$\frac{R_W + R_L}{R_1} = \frac{R_3}{R_2} \quad (10)$$

which applies when the bridge is balance, as observed with the galvanometer, G. This condition is achieved by adjusting the resistance Rs, and the corresponding current, I, through the wire is measured by the ammeter, A. During calibration, the current, I, is kept constant for each velocity setting. The bridge is balanced by adjusting the resistances R_3 and R_s and the corresponding value of R_w is determined from Equation (10).

PULSED WIRE ANEMOMETER

Three types of probe that have been used in pulsed wire anemometry are the crossed wire velocity probe, the parallel wire wall shear stress probe and the parallel wire

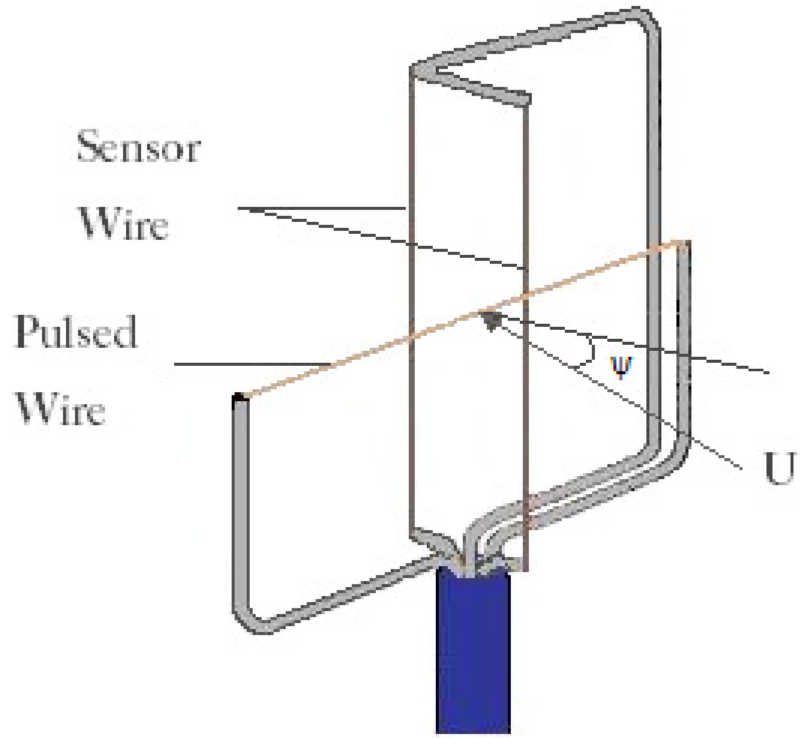

Figure 4. Pulsed wire anemometer.

velocity probe (Bradbury, 2000). These are concerned with a type of time-of-flight pulsed-wire anemometers that uses two wires mounted perpendicular to the flow to carry out "time-of-flight measurements'' which yield velocity information, (Bradbury and Castro, 1971; Bradbury, 1976; Handford and Bradshaw, 1989). The pulsed wire probe consists of three fine wires as shown in Figure 4. The central wire is the pulsed wire and on either side of this are the sensor wires with their axes perpendicular to the pulsed wire. The central wire, typically a 9 µ Tungsten wire of about 4 mm in length is pulsed with a short duration voltage pulse of a few microseconds duration. The amplitude of the voltage pulsed is chosen to raise the temperature of the wire to several hundred degrees centigrade. This causes a tracer of heated air to be released into the flow which is convection away with the velocity of the airstream passing the probe at that moment. The two sensors Tungsten wire are operated as simple resistance thermometers and they are used to measure the time of arrival of the heat tracer at one or other of the two sensor wires. In an ideal situation, the time taken for the tracer to reach a sensor wire would be:

$$t_c = \frac{s}{\left|\overline{U}\right| \cos \Psi} \tag{10}$$

s is the spacing between the pulsed wire and the sensor wire, $\left|\overline{U}\right|$ is the magnitude of the velocity vector and ψ is the angle between the direction normal to the plane of the probe and the instantaneous velocity vector .

The plane of the probe is defined as the plane parallel to the axes of all three wires in the probe. Thus, from the time of flight t_c the magnitude of the velocity vector resolved at right angles to the plane of the probe can be obtained. Some examples of pulsed-wire application are the measurements of mean-velocity vectors, velocity and wall shear stress probability distributions (Eaton and Westphal, 1981), reverse flow intermittency (Westphal et al., 1981), velocity auto and spatial correlation (Gaster and Bradbury, 1976), mean and fluctuating surface shear stress (Jaroch, 1985), Reynolds stress (Castro and Cheun, 1985) and nearwall measurements (Schober and Hancock ,1998).

HOT-WIRE ANEMOMETER TEMPERATURE COMPENSATION TECHNIQUES

The basic compensation system comprises a constant-temperature bridge circuit that was proposed by Takagi (1986). Tan-atichat et al. (1977) analyzed a scheme utilizing a temperature probe immersed in the working fluid to compensate for the dependence of hot wire and hot film velocity calibration on ambient temperature variations. To achieve compensation, only properties of the anemometer bridge, the velocity and temperature probes need to be known. The scheme provides means for incorporating the temperature compensation *a priori* to conducting the experiments, without the need for temperature calibration. Experiments were conducted, using tungsten hot wire in air, to check the performance of the analysis and to verify some of the assumptions that were made. For typical probes, with an ambient temperature increase of 20°C, maximum error in the indicated velocity of 1% or less can be achieved. In Takagi (1986), a simple system for compensating a hot-wire anemometer for ambient temperature variations was proposed. In addition to the hot-wire probe, this system requires a temperature probe for sensing the working flow temperature. It is found that the empirical heat-loss equation for plated wire probes is less susceptible to variations in both flow temperature and hot-wires operating temperature than that for welded wire probes. For an ambient temperature increase of 25°C, the output drift of the system using the plated probe is within 1% of the indicated velocity. In the overcompensation mode of the system, compensation with 1% accuracy is achieved for a temperature rise of up to 35°C and for a limited velocity range. In non-isothermal flows the response of 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, in Ball and Ashforth-Frost (1999) 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 was 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 also been demonstrated. For velocities in excess of 3 m/s the applied correction proved accurate to within ±2.2% over the 20 to 60°C temperature range. The thermal air-flow sensor, which is heated to a temperature with a constant degree of difference (Δt) from that of the gas, provides power consumption according to the flow rates. The flow signal output of the sensor decreases depending on the rise in ambient temperature. This effect is easily compensated (Toda and Sanernasa, 1996) by inserting two identical compensation resistors (R_{com}) in the Wheatstone bridge circuit without (Δt) change. This compensation is accomplished based on the influential change of ambient temperature on the sensor power consumption in proportion to the ratio of R_{com} to the bridge resistor.

A basic method of temperature compensation in a constant temperature anemometric bridge circuit involves an additional compensating sensor being connected into the bridge. The resistance of the temperature-compensating sensor must be several times bigger than that of the anemometric sensor. That is one of the major limitations of those sensors. A modified compensation system for a constant-temperature hot-wire anemometer that is based on a bridge circuit allows for the use of a temperature compensation sensor of any resistance. Ligeza (1998) presents some modification to the constant-temperature bridge system with temperature compensation. A compensating sensor of any resistance may be applied there. As a result, a wider group of measuring sensors may be used, which, in certain applications, may optimize measuring processes. This modification consists of transformation of the voltage supplying the compensating branch of the anemometric bridge. Schematic diagrams of the measurement circuits as well as one selected application of the new system for a low-frequency case also been presented. Another approach for temperature compensation is based on incorporating into the bridge circuit an electronic element the resistance of which is controlled by a signal from the separate temperature measurement circuitry (Lee Kim, 1995). In contrast to the available compensation techniques, a photoconductive cell is introduced here as a variable resistor in the bridge. The major advantage of adopting an active component such as photoconductive cell is that temperature compensation can be achieved by using any kind of temperature sensors, once the output of temperature sensor is given as a voltage. Validation experiments was done using a photoconductive cell with a thermocouple-thermometer are conducted in the temperature range from 30 to 50°C and the velocity ranges from 3 to 18 m/s. For precise anemometric measurements, Ligęza (2003a, b) developed an original non-bridge constant-temperature circuit with four-point measurement of the sensor resistance. The temperature compensation was done to the circuit by adding a temperature compensation sensor with an appropriate circuit which allows for temperature compensation (Ligęza, 2001). Temperature-correction of the output signal is based on the conversion of the signal generated by the constant-temperature system (without compensation) into the temperature-compensated signal is proposed (Sherif, 1998). The objective of this research is to describe the use of a systematic procedure which compensates for ambient temperature drift in constant-temperature anemometer operation. The procedure was demonstrated for a normal (90°) sensor probe. Constant-current anemometers operating as resistance thermometers are ideally suited for measurement of stream temperature fluctuations. In order to extend their limited frequency response due to the thermal inertia of the wire, open-loop compensation using a zero-pole network is often used. This method becomes unsatisfactory for unsteady flows with large velocity changes as the time constant of the wire changes significantly from instant to instant. An instantaneous velocity-dependent compensation method (Bremhorst and Graham, 1990) was described for use with a velocity-temperature probe. Once set, the compensator time constant matches the wire time constant at all times. Limits for good compensation were also presented. Another solution to the temperature correction problem is a system that incorporates two hot-wire anemometers (Sakao, 1973; Ligęza, 2004). Importantly, both sensors operate in constant-temperature circuits, thereby allowing for the transmission of a wide range of frequencies for both velocity and temperature measurements. An interesting modification of the two-anemometer system is the two-state hot-wire anemometer, which operates on the basis of a periodically changing heating level from a single measurement sensor (Fiedler, 1978; Ligęza, 1994). The fluid temperature compensation technique for constant temperature anemometer employing only one sensor operating periodically at two alternate temperatures was proposed in Ferreira and Freire (2001). This technique gives satisfactory result only for constant fluid velocity. The effectiveness of this method has been evaluated for a time varying velocity. The errors in the two consecutives samples were shown to alternate between positive and negative values. The use of a digital filter to attenuate these errors also been qualitatively demonstrated.

Nam and Kim (2004) had suggests two compensation methods that maintain the gap constant in response to the temperature change of fluid by pointing out the error of temperature compensation that resulted from the Wheatstone-bridge equilibrium. The first method is by changing the slope of Rh (the resistance of heating temperature) in the calculating method. Changing the slope of Rh is needed to measure it in a circuit and to calculate the compensated Rh. It needs to know voltage and current within a circuit in real time. The experiment result represents that the gap is maintained at a constant value, when temperature compensation was input. The experiment results of changing the slope in a calculating method have maximum errors 3.5% over entire the velocity range (0 to 35 m/s). The calculating method needs to measure the voltage and current in a circuit in real time, and to calculate compensated Rh, so the maximum 3.5% errors is supposed to come from measuring the voltage and current in the circuit in a real time. The second method is by changing the slope of Rf (the resistance of fluid temperature) in adjusting the ratio of the resistances. The experiment results of changing the slope in adjusting the ratio of resistances method have almost no error. The adjusting method does not need to measure the current in a circuit in real time in order to calculate. Its compensated results can be acquired in a circuit and it is an easy compensation method.

For determining the air mass flow in the intake pipe of an internal combustion engine by means of an electrical bridge, normally the current flowing through the current measurement resistor when balancing the bridge is evaluated as an indirect measure of the air mass flow. The primary measured quantity for the air mass flow is, however, the power converted at the air flow measurement resistor around which the air flows so that the indirect measurement always includes an error. Bennohr and Daetz (1997) introduce a new invention that utilizes the evaluation of the sum of the voltage across the current measurement resistor and the voltage or a partial-voltage across the air flow measurement resistor as a measure of the air flow to reduce this measurement error. Sosna and Buchne (2010) present a new temperature compensation technique for thermal flow sensors that are operated in a constant-temperature-difference (CTD) mode. The resistive heater of a thermal flow sensor is maintained at a constant temperature some tens of Kelvins above fluid temperature with the help of a Wheatstone bridge circuit. In case of a change in media temperature, an adjustment of the heater temperature is necessary; otherwise, the temperature difference falls/rises with respect to the temperature change, and the sensor output signal deviates from its calibration. Temperature compensation can be performed by the use of an additional resistive temperature sensor. The circuit design presented includes a potentiometer that is capable of changing the resistance of the temperature sensor and its temperature coefficient of resistance (TCR) for an easy adjustment for temperature compensation. This gives the freedom to use any material such as platinum, aluminum, or, in this case, an alloy of tungsten and titanium for the temperature sensor, regardless of its resistance value and TCR with respect to the heater of a thermal flow sensor. Heat transfer from a fine wire to air has been experimentally investigated (Lundströma and Sandberga, 2007). High accuracy measurements, where both the air temperature and wire temperature have been varied systematically and independently have made it possible to map the behaviour of the heat transfer process for different velocities, air temperatures, and wire temperatures. Based on these results, a compensation method is proposed which makes it possible for temperature to compensate hot wires of large aspect ratio and at low Reynolds numbers for anemometry measurements with velocity calibration only at one air temperature. Three correction methods that account for differences between the test and calibration temperatures were compared (Bowers and Willits, 1988). Anemometer mass flux data were taken at 23.4 and 40.0°C. The 40.0°C data was corrected to a predicted mass flux at 23.4°C by using the three methods. The Bremhorst procedure, which linearly related the square of the anemometer voltage to the test temperature, was more accurate than either the method recommended by manufacturers, involving temperature difference only, or another method that included both temperature differences and property temperature dependence. For mass fluxes from 1 to 6 kg/ms, the percent error of the Bremhorst procedure ranged from 8.8 to 2.7% while the latter two methods ranged between 56.1

and 9.1%. The Bremhorst procedure corrected the 40.0°C data to 23.4°C data with resulting mass fluxes being within the 5% accuracy of the anemometer for mass fluxes of 2 kg/m or greater.

CONCLUSION AND FUTURE WORK

This paper presents an overview of the temperature compensation techniques of hot wire thermal flow sensor to present examples of past work done in the field and to describe some of the recent and important developments in this field in recent years. The most relevant methods for temperature correction in CTA and CCA anemometer are presented. The percentages of correction errors for the methods are also discussed. This overview is intended to be a guide for researchers working on temperature compensation, in the design and application of this sensor. For the future work, researchers can used the temperature compensation methods based on computational intelligence which are able to scan a vast solution set and are not as sensitive to bad initial values as classical methods. These methods can be suitable for those systems where it is very complex or impossible to obtain the model by means of classical methods.

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