Hot Wire Anemometry

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The Hot-Wire Anemometer (HWA) is the most well known thermal anemometer, and measures a fluid velocity by noting the heat convected away by the fluid. The core of the anemometer is an exposed hot wire either heated up by a constant current or maintained at a constant temperature (refer to the schematic below). In either case, the heat lost to fluid convection is a function of the fluid velocity.

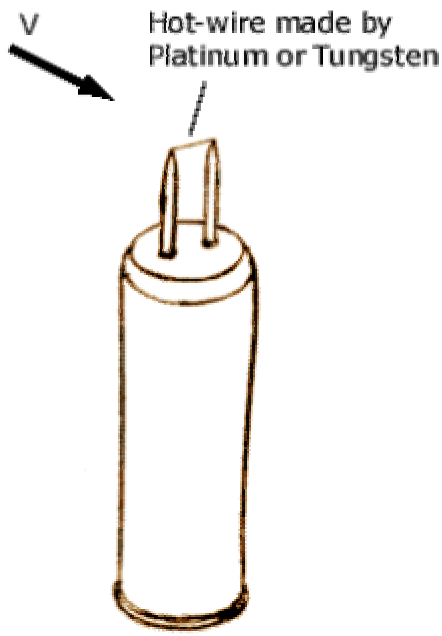


Figure 1: A typical hot-wire probe

By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity in accordance with convective theory.

Typically, the anemometer wire is made of platinum or tungsten and is 4 ~ 10 µm (158 ~ 393 µin) in diameter and 1 mm (0.04 in) in length. Typical commercially available hot-wire anemometers have a flat frequency response (< 3 dB) up to 17 kHz at the average velocity of 9.1 m/s (30 ft/s), 30 kHz at 30.5 m/s (100 ft/s), or 50 kHz at 91 m/s (300 ft/s).

1. Basic Principle of Hot-Wire Anemometry

When sensing wire of the hot-wire probe is heated and kept in a flow, it is cooled by the flowing fluid, causing the temperature to drop, and consequently the electric resistance of the wire to diminish. For turbulence measurements in gases, wires of 5μm diameter are generally used. The usual materials are platinum, platinum-iridium, and tungsten.

The total amount of heat transferred depend on

1. The flow velocity
2. The difference in temperature between the wire and the fluid
3. The physical properties of the fluid
4. The dimensions and the physical properties of the wire

Generally, (2) and (4) are known. If (3) is known or kept constant, the value of (1) can be measured.

The wire is cooled by heat conduction, free and forced convection, and radiation. Usually, the sensing element radiates only a small amount of energy to its surroundings. Under normal operating conditions, the radiation losses are much less than 0.1% of the convection losses and hence will be neglected.

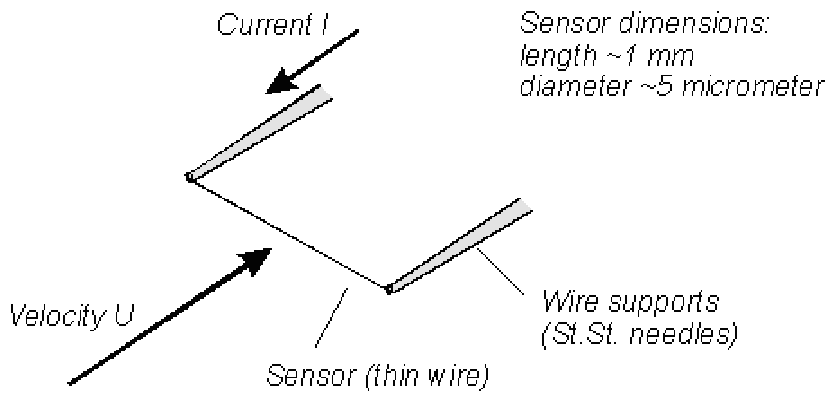


Figure 2: A typical hot-wire sensor exposed to flow

Most hot-wire anemometers operate in the forced convection regime in order to maximize their sensitivity to the velocity. However, at low Reynolds number (Re), free convection is important. Collins and Williums (JFM 6, 357, 1959) have shown that if

$$\mathrm{Re} < G_r^{1/3}, \qquad \mathrm{Gr} = \text{Grashof number}$$

effect of free convection can be neglected. For a hot-wire probe with 2.5μm diameter at 300^0 K in air, the Grashof number is about 6 $\times 10^{-7}$.

Therefore, for Re > 0.01 (i.e. U > 10 cm/sec) effect of free convection can be neglected. In addition, conduction loss through the support can also be neglected. Thus, the rate of heat transferred by forced convection from hot wires depends primarily upon the velocity and fluid temperature.

The heat transferred per unit time to the ambient fluid from a wire is

$$Q_s = hp\, dl\left(T_w - T_f\right)$$

where, *h* is the heat transfer coefficient, *d* is the diameter of the wire, *l* is the length of the wire, T_w is the wire temperature, and T_f is the fluid temperature.

For thermal-equilibrium conditions, this heat loss per unit time must be equal to the heat supplied per unit time by Joule heating.

$$Q_s = I^2 R_w = hp\, dl\left(T_w - T_f\right) \tag{1}$$

where *I* is the electric heating current and *Rw* is the wire resistance.

Introducing a dimensionless group Nusselt number

$$Nu = \frac{Q_{conv}}{Q_{cond}} = \frac{hp\, dl\left(T_w - T_f\right)}{K_f * \text{temp gradient} * \text{area}}$$

$$= \frac{hp\, dl\left(T_w - T_f\right)}{K_f * \dfrac{\left(T_w - T_f\right)}{d} * p\, dl} = \frac{h\, d}{k_f}$$

where K_f is the heat conductivity of the fluid. Now equation (1) can be written as

$$I^2 R_w = p\, k_f l\left(T_w - T_f\right) Nu \tag{2}$$

The wire temperature T_w is related to the heated wire resistance *Rw* by the empirical relation

$$R_w = R_f\left[1 + a\left(T_w - T_f\right)\right]$$

where a is the thermal coefficient of resistance.

Equation (2) can now be written as

$$\frac{I^2 R_w R_f a}{p\, k_f l\left(R_w - R_f\right)} = Nu \tag{3}$$

The heat transfer coefficient, and so the Nusselt number, depend on a large number of geometrical and physical parameters, which may conveniently be included in dimensionless groups. In non-dimensional terms, Corrsin (1949) suggested that

$$N_u = f\left(\mathrm{Re},\ \mathrm{Pr}, M, Gr, Kn, l/d, a_T, g, q\right) \tag{4}$$

where Re is the Reynolds number, *Pr* is the Prandtl number, *M* is the Mach number, *Gr* is the Grashof number, *ß* is the coefficient of thermal expansion of the fluid, *Kn* is the Knudsen number, *l/d* is the aspect ratio of the probe, a_T is the overheat ratio, g is the ratio of specific heat and *?* is the angle between the axis of the sensing element and the velocity vector.

It is impossible to consider all of these independent variables simultaneously. This is avoided in the following analysis by making some appropriate approximations.

1. The buoyancy, i.e. Grashop effect, will be negligible for most velocities of interest.
2. Knudsen number will not effect heat transfer as the wire diameter is much greater that the mean free path at the molecules.
3. The effect of compressibility can be neglected when M < 0.3.
4. The role of the aspect ratio l/d is minimized by assuming that it is large enough (usually > 200) so that the heat loss is essentially two-dimensional.

By assuming that ? and g are constant for the present analysis, equation (4) reduces to

$$N_u = f\left(\mathrm{Re},\ \mathrm{Pr},\ a_T\right) \tag{5}$$

This is the functional form of the convective heat transfer that is valid for incompressible fluids under the above restrictions. Even after the restrictions imposed in the previous paragraph have been made, there is still a lack of agreement in the literature concerning the exact form of the relationship expressed in equation (5). Many authors have sought an explicit form for the convective heat loss, and there is considerable evidence that

$$N_u = A(\mathrm{Pr},\ a_T) + B(\mathrm{Pr},\ a_T)\mathrm{Re}^n \tag{6}$$

correlate most of the available data, where A, B, and n are functions of the Prandtl number for a given wire.

Heat transferred is not a strong function of the overheat ratio in subsonic flows. Thus, for air, equation (6) can be written as

$$N_u = A + B * \mathrm{Re}^n \tag{7}$$

King was the first to recognize that the convection losses be written in the form equation (7), with n = 0.5.

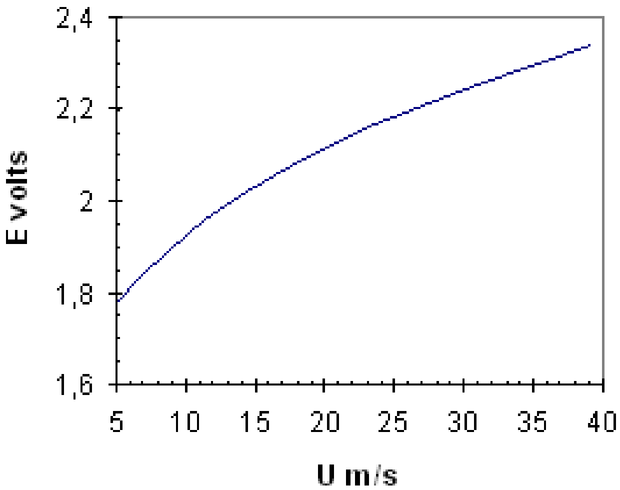


Figure 3: A typical variation of hot-wire output with flow velocity

For the purpose of the hot-wire anemometry, it is convenient to write equation (3) in the following form using equation (7)

$$\frac{I^2 R_w}{R_w - R_f} = A_1 + B_1 U \quad \text{or} \qquad (8)$$
$$I^2 R_w^2 = E^2 = (T_w - T_a)(A + BU^n)$$

and to determine the values of A_1, B_1, and n by a suitable calibration method under the operating conditions just before and also just after a series of measurements. The reason for this is that these constants, and in particular the exponent n, is rather sensitive to slight changes in the condition of the hot wire. A typical variation of hot-wire output voltage with flow velocity is shown in figure 3.

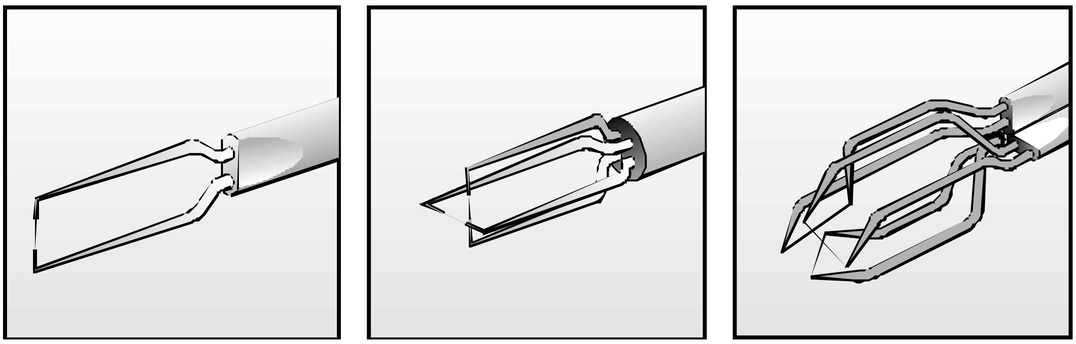
2. Hot-Wire Probes

The primary role of *HWA* is as a research tool for turbulent flow studies. It is therefore important that the sensing element and its associated electronic circuit should provide a virtually instantaneous response to the fastest occurring flow changes. Also, to obtain accurate turbulence measurements, the dimensions of the hot-wire sensor should not be much larger than the Kolmogorov length scale of the smallest eddies.

The single component of a single hot wire probes are two fine thin sewing needles or jeweler's broaches acting as the two prongs. These prongs are embedded in the ceramic which is electrically insulated. The two prong ends embedded in the ceramic tube are soldered to two rubber sheathed metal wires which are extended by means of a shielded cable to terminate on a BNC connector. The active part of the wire element may extend to the prongs, or it may be restricted to a central part by using plated wire ends near the prongs. Typical diameter of the wire is $5\mu m$. This means the sensor is not visible in a normal manner. The micro dimensions of the sensor wire enables hot-wire to posses the characteristic of high frequency response suitable for turbulence measurements. The wire material should have the following properties:

1. It should be strong so that it does not break easily. And yet the wire breakage is frequent unless the probe is handled very carefully and delicately.
2. It should also posses high temperature coefficient of resistivity to make the sensor more sensitive to velocity fluctuations.

For most practical *HWA* applications, the wire materials are tungsten, platinum or platinum alloys e.g., platinum-rhodium or platinum-iridium, other conductors, e.g. nickel, silver, and copper, can be used; however they are less desirable because they cannot be drawn into such small diameters, their resistivity is nonlinear, their melting point is too low , etc. For very fine wires, platinum and its alloys are usually selected since it is available with diameters as small as 0.25µm in the form of Wollaston wires.



Single wire X-wire Triple wire

Figure 4: Hot-wire probes

Tungsten is presently the most popular hot-wire material. When coated with a thin platinum layer, it becomes more resistant to oxidation and soldering to the support needles is eased. Its temperature coefficient ($0.0032/{}^{0}C$) does not differ too much from that of pure platinum.

Hot-wire probes are normally used in gas flows when accurate turbulence results are required due to their small size and well-defined calibration characteristics.

3. Modes of *HWA* Operation

There are two main modes of operating a hot-wire probe:

1. The Constant-Current (CC) mode, in which the probe temperature varies but the current is maintained constant.
2. The Constant-Temperature *(CT)* mode, in which the probe resistance (and thereby its temperature) is kept constant by varying the current.

3.1 Constant current operation:

In constant current operation, the heating current in the hot-wire sensor is constant. Forced convection changes the wire resistance resulting in voltage fluctuations. A typical CC circuit incorporating a Wheatstone bridge is shown in Figure below.

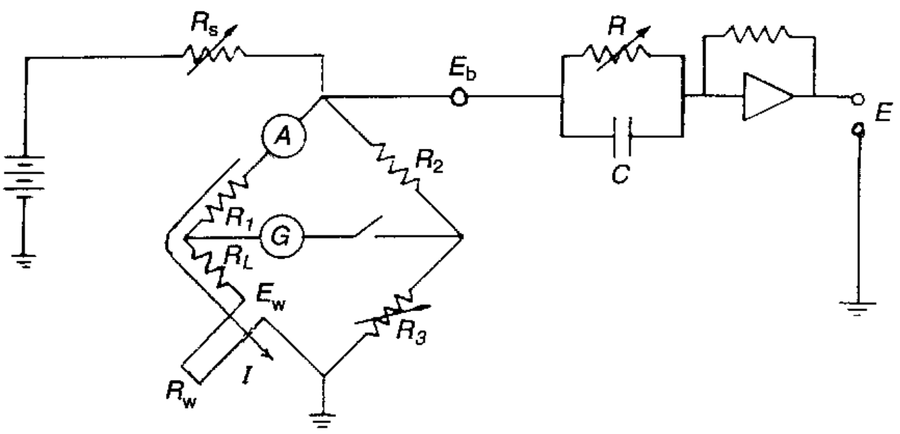


Figure 5: A typical CC circuit incorporating a Wheatstone bridge

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

$$\frac{R_w + R_L}{R_1} = \frac{R_3}{R_2}$$

which applies when the bridge is in balance. This condition is achieved by adjusting the resistance R_s, and the corresponding current, I, through the wire. 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 the above equation. This procedure makes CC anemometers laborious to use. Knowing the value of I and assuming that n = 0.5, a least-squares curve-fitting technique can be applied to the calibration data to determine the calibration constants *A* and *B*.

3.2 Constant temperature operation:

There are major advantages in maintaining the hot-wire probe at a constant operational temperature, since the thermal inertia of the sensor element is automatically adjusted when the flow conditions vary. This mode of operation is achieved by incorporating a feedback differential amplifier into the HWA circuit to obtain a rapid variation in the heating current to compensate for instantaneous changes in flow velocity.

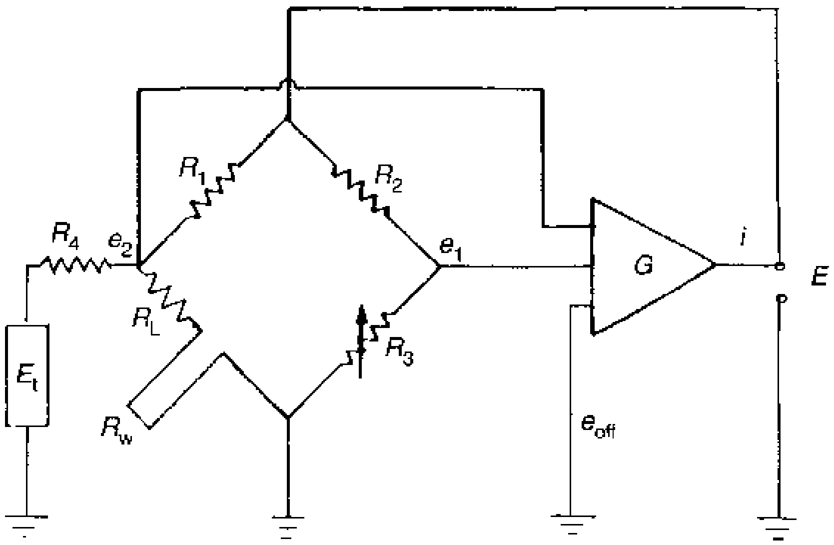


Figure 6: A sketch of a typical CT circuit containing a Wheatstone bridge and a feedback amplifier.

The principle of a *CT* circuit is illustrated in the figure below. In constant temperature operation, the hot-wire sensor forms one arm of a Wheatstone bridge. However, the bridge unbalance due to forced convection induces changes in the sensor resistance (or temperature). As the flow conditions vary the error voltage ($e_2 - e_1$) will be a measure of the corresponding change in the wire resistance. These two voltages form the input to the operational amplifier. The selected amplifier has an output current, i, which is inversely proportional to the resistance change of the hot-wire sensor. Feeding this current back to the top of the bridge will restore the sensor's resistance to its original value. Modern amplifiers have a very fast response, and in the *CT* mode the sensor can be maintained at a constant temperature except for very-high-frequency fluctuations.