Temperature compensation and calibration of constant-temperature hot-wire anemometers

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Hot-wire probes can be used to infer the local fluid velocity over the wire from the heat transfer: if heat transfer is dominated by forced convection, then for a given electrical power dissipated through the wire, the wire temperature becomes a monotonic function of fluid speed. The resistance of the wire, in turn, is a monotonic function of the temperature and is easily measured. A simple feedback-control system is normally used to control the wire power output; in a constant-temperature anemometer, the wire resistance (and thereby temperature) is driven to a specific set-point [2].

Hot-wire anemometers are primarily used when high-bandwidth measurements are required, for example in the measurement of turbulence statistics. The very small measurement volumes of the wires themselves (which can be as small as 2 μm in diameter) are also well-suited for use in thin boundary layers. Hot-wire probes are, however, extremely fragile and will require frequent recalibration; they are not well-suited for use in industrial or field applications.

Semi-empirical model of a hot-wire

Because a hot-wire probe response is related to heat transfer, its signals are also necessarily sensitive to the local ambient fluid temperature T_a. Corrections are often employed in the calibration to extend the acceptable operational range, so that a two degree-of-freedom temperature-velocity calibration is not required.

For operation in air, a reasonable correction can be achieved from first principles. The rate of heat transfer from the wire to the fluid can be characterized in the form of the dimensionless Nusselt number $Nu = hd/k$, where h is the coefficient of convective heat transfer to the fluid, k is the fluid's thermal conductivity, and d is the wire's diameter. Since the rate of heat transfer to the fluid must match the electroresistive power lost through the wire, Nu for a hot-wire operated by a constant-temperature control circuit can be expressed as

$$Nu = C \frac{V_B^2}{2k\left(T_f - T_a\right)} \tag{1}$$

with

$$
\begin{aligned}
C &= \left(\pi\Omega R_0 L\left((1+n)\left(1+\frac{R_L}{\Omega R_0}\right)\right)^2\right)^{-1} \\
T_f &= \frac{1}{2}\left(T_0+\frac{\Omega-1}{\alpha_0}+T_a\right) \qquad (2)
\end{aligned}
$$

where V_B is the wire bridge supply voltage, C is a constant depending on the wire geometry and material characteristics, Ω is the overheat ratio, R_0 is the wire resistance at its reference temperature, L is the wire length, n is the bridge ratio, R_L is the resistance of the probe leads and any extension cable, T_f is the wire film temperature, T_0 is the reference temperature and α_0 is the wire temperature coefficient of resistance at T_0.

In air, the effects of fluid velocity and diffusion on heat transfer are approximately independent, so Nu can be expressed as

$$
Nu = A + Bf(Re)g(Pr) \qquad (3)
$$

where $Re = Ud/\nu$ is the Reynolds number (a dimensionless measure of speed), U is the fluid speed (assumed here to be the component of velocity normal to the wire axis), d is the wire diameter and ν is the kinematic viscosity; $Pr = C_p\mu/k$ is the Prandtl number (a dimensionless measure of heat diffusion), C_p is the specific heat at constant pressure and $\mu = \rho\nu$ is the dynamic viscosity; f and g are empirical functions, and A and B are dimensionless scaling constants. Combining eqs. (2) and (3),

$$
f(Re) = \left(C\frac{V_B^2}{2k(T_f-T_a)} - A\right)\left(Bg(Pr)\right)^{-1} \qquad (4)
$$

We can therefore define an independent dimensionless dependent variable $X = f(Re)$; this variable will be entirely independent of the temperature effects. Note, however, that Re remains a function of μ and ρ as well, which may each independently vary with temperature.

If the wire is modelled as a high aspect ratio circular cylinder, the constants in eq. (4) may be taken as [1]

$$
\begin{aligned}
A &= 0.3 \\
B &= 0.62 \\
g(Pr) &= Pr^{1/3}\left(1+0.54288Pr^{-2/3}\right)^{-1/4} \qquad (5)
\end{aligned}
$$

while Pr and the fluid properties (for dry air) may be approximated over the range $0^\circ\ \mathrm{C} \le T_a \le 100^\circ\ \mathrm{C}$ as [3]

$$
\begin{aligned}
k &= 2.447763\times10^{-2} + 7.399136\times10^{-5}T_f - 2.570032\times10^{-8}T_f^2 \\
\nu &= 1.339409\times10^{-5} + 9.152291\times10^{-8}T_f + 9.218673\times10^{-11}T_f^2 \\
Pr &= 0.7096338 - 1.268923\times10^{-4}T_f + 3.452048\times10^{-7}T_f^2 \qquad (6)
\end{aligned}
$$

where k is expressed in W/(mK), ν in m^2/s and T_f here in °C.

Characteristics specific to MUHW-series CTA

The overheat ratio of a conventional constant-temperature anemometer is given by

$$\Omega = \frac{R_{OH} - nR_L}{nR_0} \tag{7}$$

where R_{OH} is the overheat setting resistance, n is the bridge ratio, and both R_0 and R_L are usually provided by the probe manufacturer. For the Surrey Sensors Ltd. MUHW-series ultraminiature constant-temperature hot-wire anemometer [4], $n = 1$ and the Wheatstone bridge resistances have been fixed for best performance with hot-wire probes having nominal characteristics as shown in Table 1, and yield a fixed overheat ratio $\Omega = 1.7$.

Table 1: Nominal probe characteristics for use with the MUHW-series CTA.

Symbol	Description	Value
α_0	Temperature coefficient of resistance	0.0036 K^{-1}
d	Wire diameter	5 μm
L	Wire length	1.25 mm
R_L	Lead resistance	0.5 ohm
R_0	Wire resistance at T_0	3.5 ohm
T_0	Reference temperature	293.15 K

If the the signal conditioning (filter/amplifier) system is enabled, then the bridge voltage must be inferred from the factory-set gain and offset as

$$V_B = \frac{V_{out}}{10} + 0.512 \tag{8}$$

where V_{out} is the measured signal from the system, and both V_B and V_{out} are expressed in Volts. If the signal conditioning system is disabled, then $V_B = V_{out}$. The gain and offset have also been factory-set for best performance with probes having the nominal characteristics shown in Table 1, over the range 0 m/s $\leq U \leq$ 100 m/s in air.

Temperature-insensitive calibration

To calibrate a hot-wire probe in a way that the recovered speed is insensitive to temperature, a function $U(V_B, T_a)$ is ultimately required. From the model above, this can be constructed (for use in dry air) as follows:

(a) Expose the hot-wire probe to a flow of known speed U, and record both the fluid ambient temperature T_a and the output voltage V_{out}.

(b) From the measured T_a, the hot-wire probe's measured or supplied 'cold' resistance R_0, the reference temperature T_0 and lead resistance R_L from the supplier, determine the overheat ratio Ω from eq. (7), as well as the film temperature T_f and constant C from eq. (2).

(c) Using T_f, determine the fluid thermal conductivity k, kinematic viscosity ν and Prandtl number Pr from eq. (6). Be sure to express T_f in units of °C here.

(d) Using this value of Pr, determine the value of the dimensionless heat diffusion function g from eq. (5).

(e) Using V_B (obtained from the output voltage V_{out} using eq. 8), T_f, C, k, and g, determine the value of the dimensionless variable $X = f(Re)$ from eq. (4).

(f) From the set flow speed U, ν and the wire diameter d (from the manufacturer), determine the wire Reynolds number $Re = Ud/\nu$.

(g) Repeat this process for many known speeds U over the desired range of measurement, and construct a plot of Re vs X. This is the wire calibration curve. An example of this relationship is shown in Figure 1.

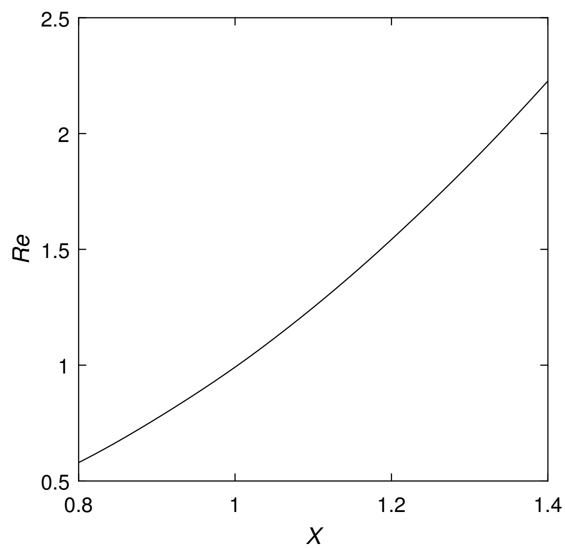

Figure 1: Typical calibration results for Re vs. X, measured using the MUHW-series CTA [4] driving a typical hot-wire probe with characteristics shown in Table 1.

Once the calibration function $Re(X)$ has been obtained, this can either be stored as a look-up table or approximated by a best-fit (a third- or fourth-order polynomial is usually sufficient, but any function may be used). During experimental measurement (when V_{out} and T_a are known but U is not), follow the same procedure (b) through (e) above to obtain a measured value of X. From the look-up table or functional approximation, obtain the value of Re corresponding to the 'measured' value of X. Then, the speed U may be computed as

$$U = Re\nu/d \tag{9}$$

In this formulation, the values of U obtained will be insensitive to the ambient fluid temperature over a reasonable range.

References

[1] Churchill, S. W. and Bernstein, M. (1977). A correlating equation for forced convection from gases and liquids to a circular cylinder in crossflow. *ASME J. Heat and Mass transfer*, **99**(2), 300–306.

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[3] Haynes, W. M. (2014). *CRC handbook of chemistry and physics*. CRC Press, Boca Raton, FL, 95th ed. edition.

[4] Surrey Sensors Ltd. (2025). Surrey Sensors Ltd. MUHW-series ultraminiature constant-temperature hot wire anemometry system. https://www.surreysensors.com/product/hot-wire/.