Introduction to Hotwire Anemometry

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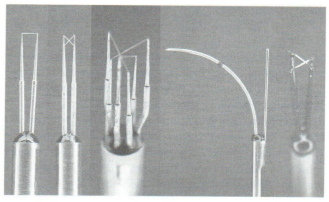
Introduction

• Basic principle – amount of cooling experienced by a heated wire can be related to the local flow velocity



Hot-wire and hot-film probes. (Photographs provided by and used with permission of TSI, Inc.)

• A small diameter metal wire sensor (made of tungsten, platinum or platinum alloy) is heated over flow temperature using an electric current

• Typically, diameter of wire = 0.5-5 μm, length = 0.15-1.5 mm, resistance ~ 4 ohms

• Similar to hot-wire, we can also have hot-film – consists of a thin metal film deposited over a quartz core

• Hot-wire mostly used with gases and hot-film with flow of liquids

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Principle of Hot-wire Anemometry

Resistance of a wire depends linearly on its temperature.

$R_s = R_f[1+\alpha(T_s-T_f)]$ … (1)

where R_s is electrical resistance at temperature T_s, R_f is resistance at T_f, and α is temperature-resistance coefficient (= 0.004 K^{-1} for tungsten and platinum)

From energy balance we have,

$dQ/dt = P - F$ … (2)

where Q is internal energy of sensor, P is electrical input power to sensor, and F is total rate of heat transferred from the sensor

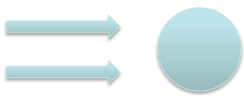
Now, $F = q_c + q_p + q_r + q_s$

where q_c is heat transfer rate due to convection from sensor to flow

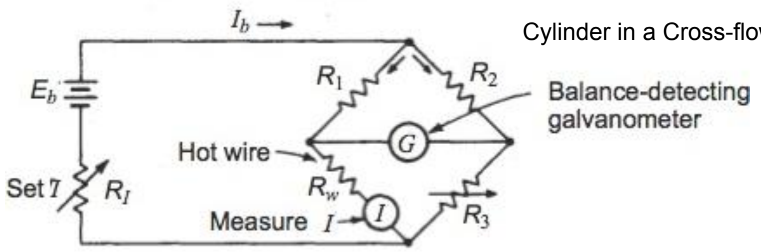
q_p is heat transfer due to conduction to supporting prongs

q_r is heat transfer due to radiation from sensor to surrounding

q_s is heat transfer to quartz substrate (relevant only in hot-film)



Cylinder in a Cross-flow



$q_{convection}$ = h (heat transfer coefficient) * A (surface area) * del_T (temperature difference between surface and fluid)

Heat transfer coefficient = f(geometry of surface, flow velocity, fluid properties)

For a fixed geometry: Heat transfer coefficient = h(flow velocity, fluid properties)
hd/k = g((rho*u*d/mu), (mu*Cp/k))
Nu (Nusselt number) = g(Re, Pr)

Principle of Hot-wire Anemometry (*contd.*)

Analyzing the factors contributing to heat loss, we get –

- Heat loss to the prong supports can be neglected if the aspect ratio (*l/d*) of the wire is large (> 200)
- Radiation heat transfer can usually be neglected with respect to convective heat transfer
- Note, heat transfer by convection be either be forced or free – their relative magnitudes will depend on the local flow velocity
- We want forced convection to dominate – for this $\mathbf{Re_d > Gr^{1/3}}$ where Re_d is Reynolds no. based on wire diameter and *Gr* is Grashof number
- For a circular cylinder in cross-flow, the average Nusselt number (Nu_d) is given by (Incropera and DeWitt, p 411) provided $Re_d\,Pr > 0.2$

$$Nu_d = 0.3 + \frac{0.62\,\mathrm{Re}_d^{1/2}\,\mathrm{Pr}^{1/3}}{[1+(0.4/\mathrm{Pr})^{2/3}]^{1/4}}\left[1+\left(\frac{\mathrm{Re}_d}{282000}\right)^{5/8}\right]^{4/5} \quad \text{where} \quad Nu_d = \frac{hd}{k}, \quad \mathrm{Re}_d = \frac{\rho U d}{\mu}$$

- For air (with *Pr* close to unity) and Re_d small (< 120), we get
  $h = C_0 + C_1$*sqrt(U) … (3)
  where *h* is heat transfer coefficient, C_0, C_1 are constants, *U* is local flow velocity, and *Pr* is Prandtl number

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Principle of Hot-wire Anemometry (*contd.*)

Zero order instrument: No derivative with respect to time is involved

First-order instrument: First order derivative

Second-order instrument: Second order derivative

- Electrical power input to sensor
  $P = E^2/R_s = I^2R_s$
  where *E* is voltage across wire
- Note that R_s can be related to T_s (using Eq (1))
- Therefore, Eq (2) can be written as

$$mC_p\, dT_s/dt = P(I, T_s) - F(U,T_s) \quad \ldots \quad (4)$$

where *m* is mass of wire, C_p is specific heat of wire material, T_s is wire (surface) temperature, *U* is component of velocity vector normal to the wire, and *I* is current supplied to the wire

- Want either *I* or T_s to be a constant, then *U* can be related to the other variable – called constant current and constant temperature modes of operation
- Constant temperature mode is preferred so that the thermal inertia ($mC_p\, dT_s/dt$ term) does not come into picture

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Principle of Hot-wire Anemometry (*contd.*)

• For constant temperature mode, Eq. (4) reduces to

$$E^2/R_s = hS(T_s-T_o) \quad \ldots \quad (5)$$

where *S* is surface area of wire and T_o is flow temperature

• Substituting Eq. (3) in Eq. (5), we get

$$E^2/R_s = (C_0 + C_1 * sqrt(U))\ S\ (T_s-T_o)$$

which is usually rewritten as

$$E^2 = A + B\ U^{1/n} \quad \ldots \quad (6)$$

A, B and 1/n are calibration constants.
1/n is expected to be close to 0.5 – comes in the range of 0.4-0.5
Eq (6) is referred to as the Kings law

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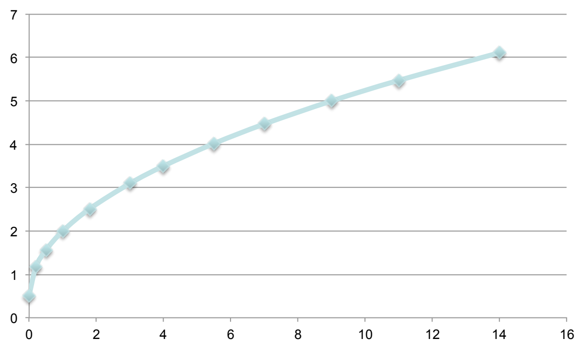
Typical calibration curve



Voltage (V) versus velocity (m/s)

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