Lecture 05: Methods for local Flow Velocity Measurements: Hotwire – Anemometry Part #01

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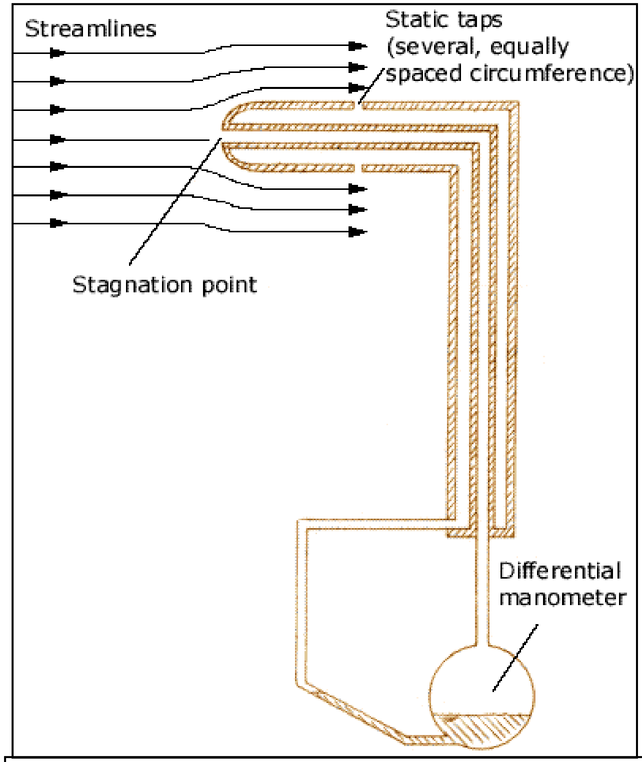
Methods to Measure Local Flow Velocity - 1

- ***Mechanical methods:***
  - Taking advantage of force and moments that a moving stream applies on immersed objects.
  - Vane anemometers
  - Propeller anemometers

❑ Methods to Measure Local Flow Velocity -2

- *Pressure difference methods:*
  - *Utilize analytical relationship between the local velocity and the static and total pressures.*
  - *Pressure taps sensing **static pressure** (also the reference pressure for this measurement) are placed radially on the probe stem and then combined into one tube leading to the differential manometer (p_{stat}).*
  - *The pressure tap located at the probe tip senses the **stagnation pressure** (p_0).*
  - *Use of the two measured pressures in the Bernoulli equation allows to determine one component of the **flow velocity** at the probe location.*
  - *Special arrangements of the pressure taps (Three-hole, Five-hole, seven-hole Pitot) in conjunction with special calibrations are used two measure all velocity components.*
  - *It is difficult to measure stagnation pressure in real, due to friction. The measured stagnation pressure is always less than the actual one. This is taken care of by an empirical factor C.*



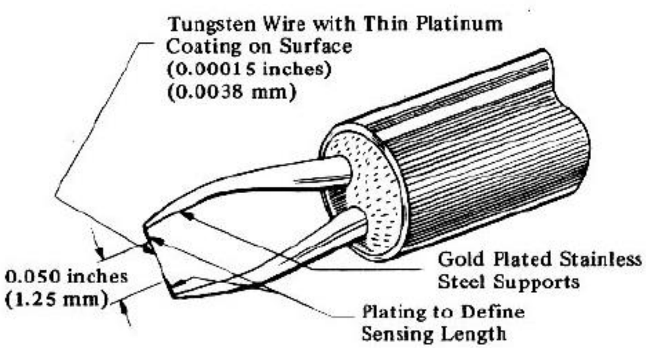
$$p_0 = p_{stat} + \frac{1}{2}\rho V^2, (Bernoulli)$$

$$V = \sqrt{2(p_0 - p_{stat})/\rho}$$

$$V = C\sqrt{2(p_0 - p_{stat})/\rho}$$

❑ Methods to Measure Local Flow Velocity -3

- ***Thermal methods:***
  - *Compute flow velocity from its relationship between local flow velocity and the convective heat transfer from heated elements.*



Hot wire anemometers

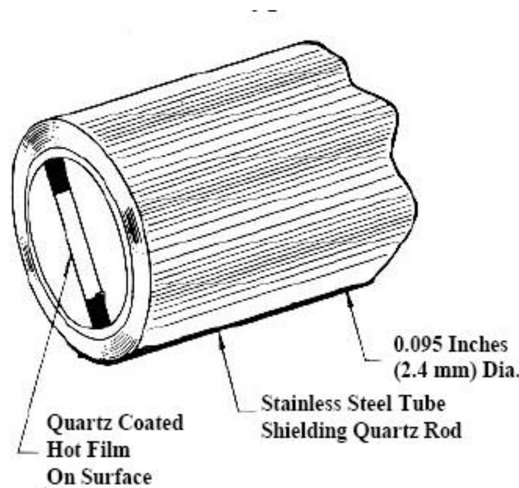


Figure 6: Hot Film Flush Mounted Probe

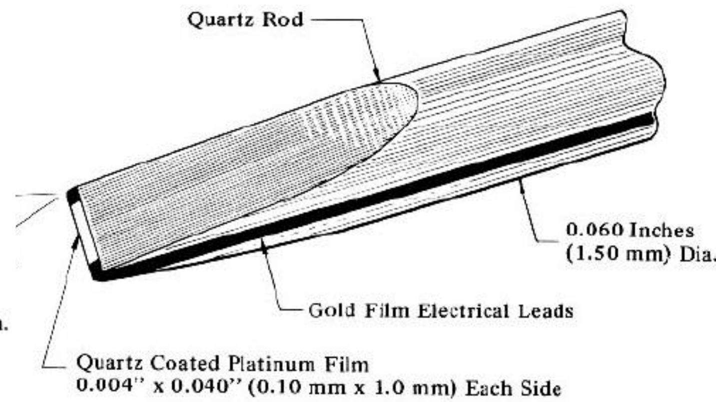
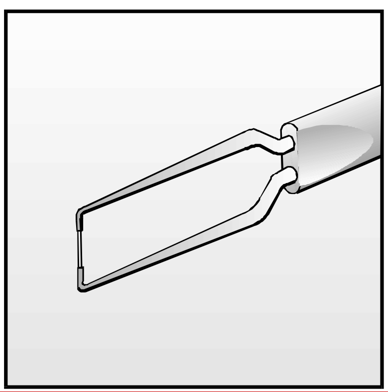
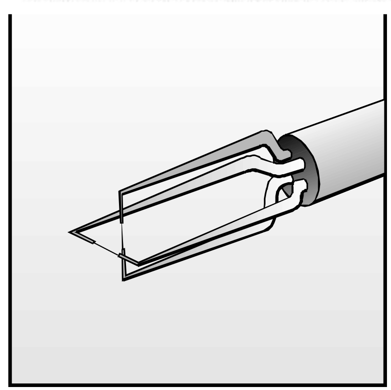
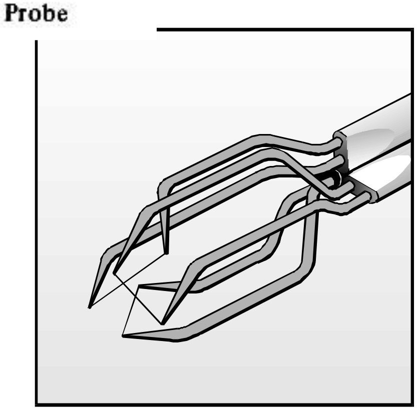


Figure 7: Hot Film Wedge Probe



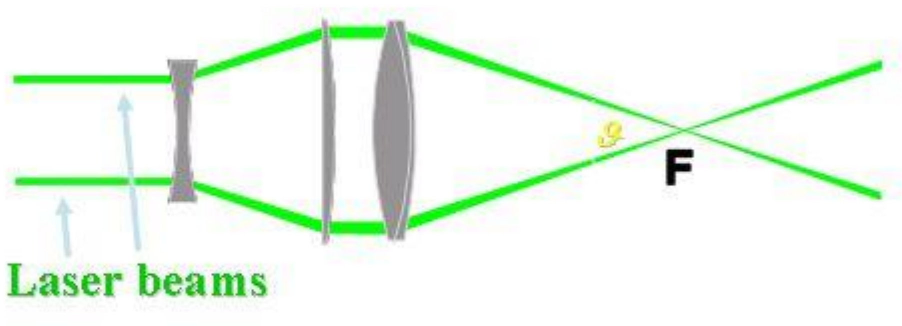


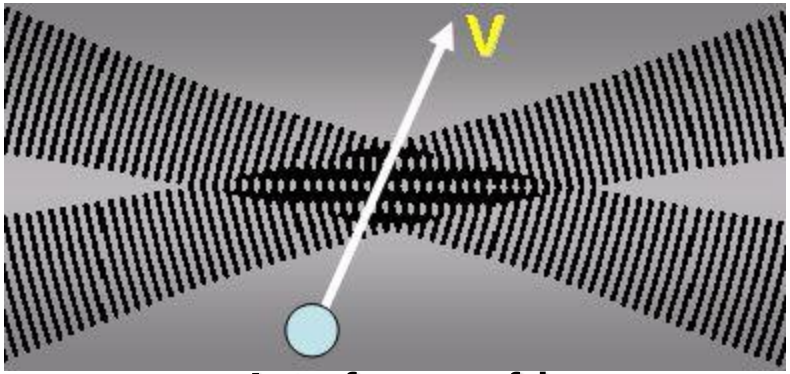


❑ Methods to Measure Local Flow Velocity - 4

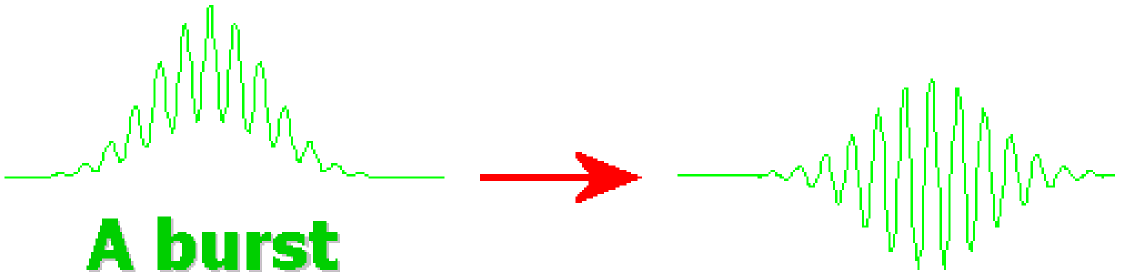
• *Frequency-shift methods:*

- *Based on the Doppler phenomenon, namely the shift of the frequency of waves scattered by moving particles.*
- *Laser Doppler Velocimetry(LDV) or Laser Doppler Anemometry (LDV)*
- *Planar Doppler Velocimetry (PDV) or Planar Doppler Anemometry (PDA)*





Interference fringes

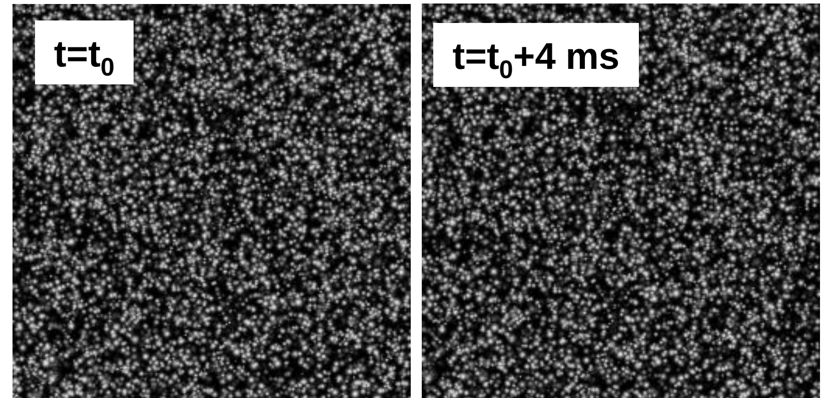


$$v_{\perp} = \frac{\lambda}{2\sin\frac{\vartheta}{2}} f$$

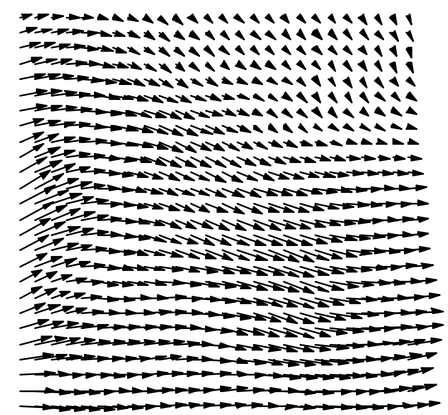
❑ Methods to Measure Local Flow Velocity - 5

• ***Marker tracing methods:***

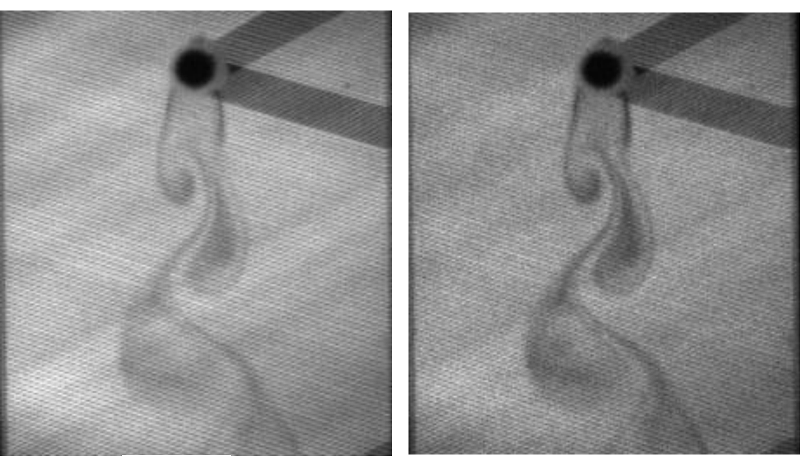
- Trace the motion of suitable flow makers, optically or by other means to derive local flow velocity.
- Particle Imaging Velocimetry (PIV)
- Particle Tracking Velocimetry (PTV)
- Molecular Tagging Velocimetry (MTV)



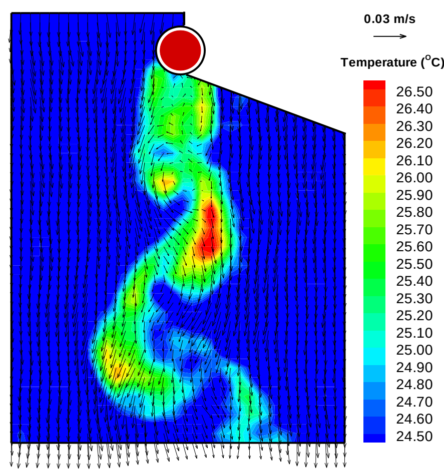
PIV image pair



Corresponding flow velocity field



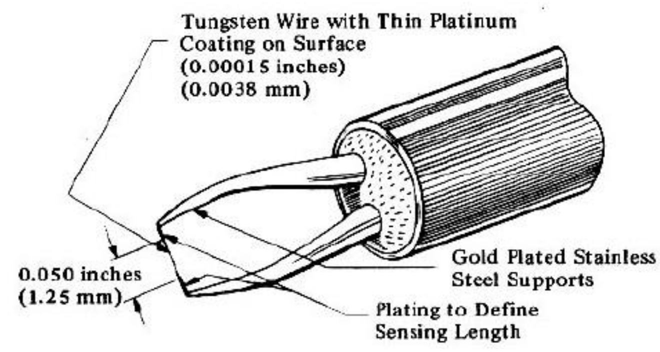
$t=t_0$ $t=t_0$+5ms



MTV&T image pair

❑ How Does a Hot wire Sensor Work

- ***Thermal anemometers:*** *Measure the local flow velocity through its relationship to the convective cooling of electrically heated metallic sensors.*
  - ***Hot wire anemometers:***
    - ***for clean air or other gas flows***
  - ***Hot film anemometers:***
    - ***for liquid or some gas flows***



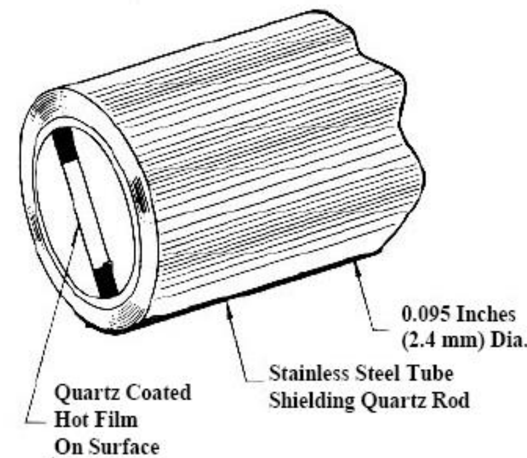
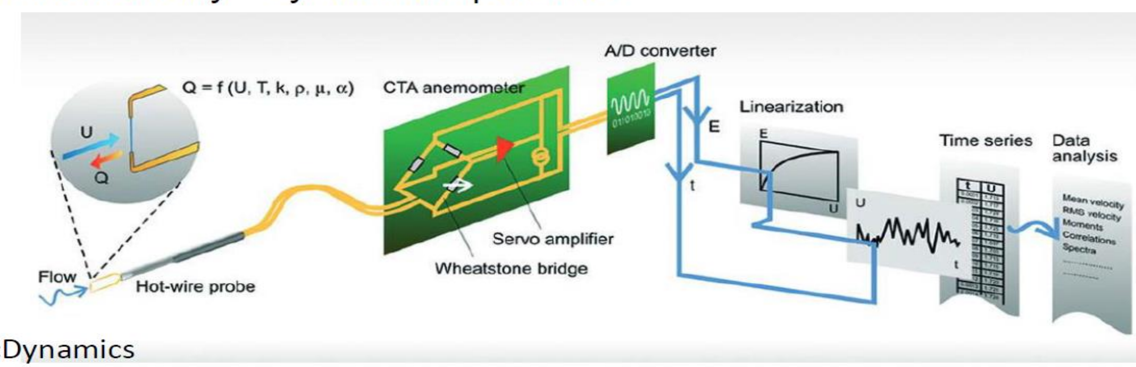


Figure 6: Hot Film Flush Mounted Probe

Thermal anemometry – system components:



DantecDynamics

StreamLine Pro - the most reliable research-grade CTA system.

MultichannelCTA - the multiple channel version of the MiniCTA system.

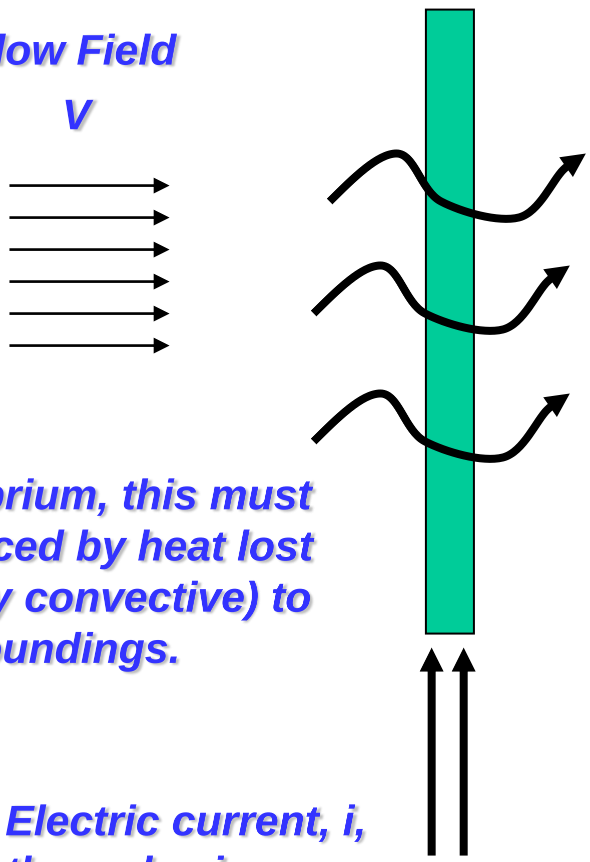
MiniCTA - the most compact CTA system for educational use.

❑ How Does a Hot wire Sensor Work

The electric current (i) flowing through the wire generates heat (i^2R_w)

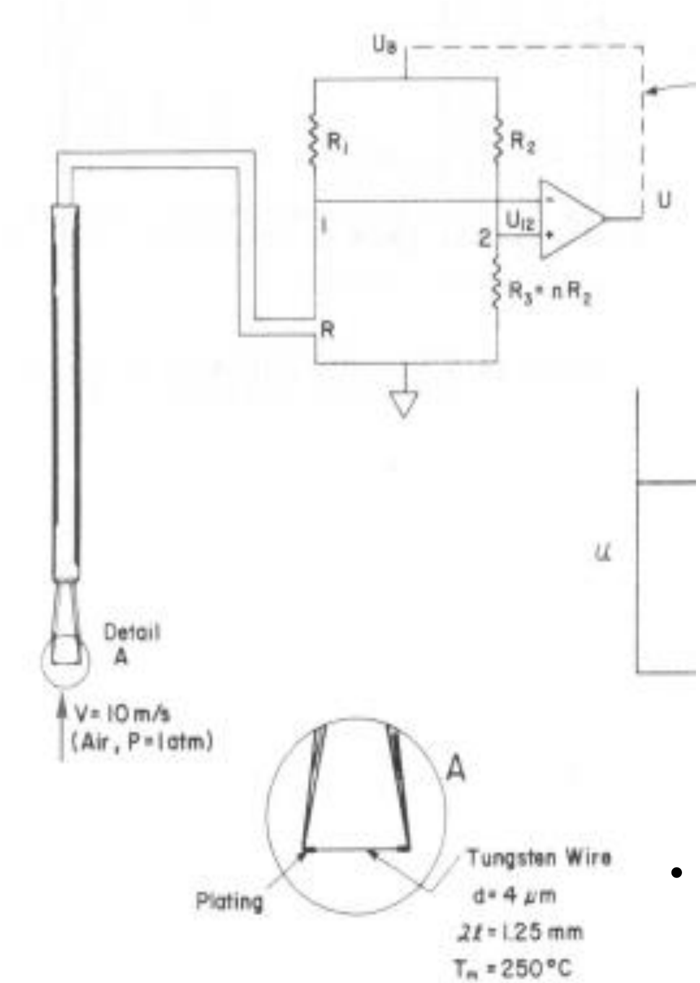
Flow Field

V



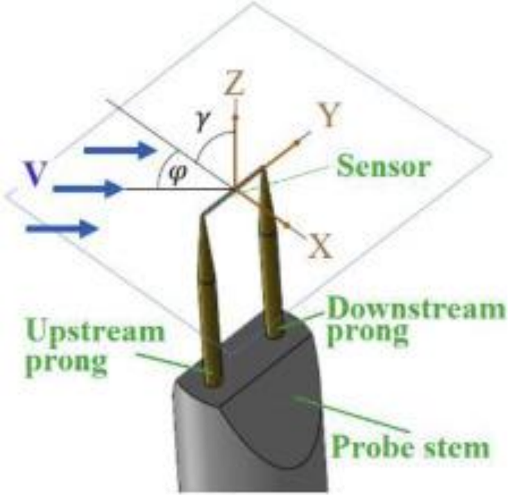
In equilibrium, this must be balanced by heat lost (primarily convective) to the surroundings.

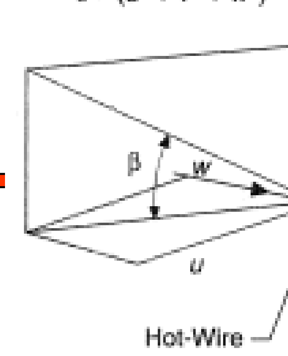
Electric current, i, through wire



- ***Price: ~$2750***

❑ How Does a Hot wire Sensor Work





Basic principle:

Heat transfer

Resistive heating: $q_{el} = \frac{E^2}{R_w} = I^2 R_w$ E : voltage I: current

Heat loss to the environment through:

Radiation (often negligible)

$$q_s = f(T_w^4 - T_a^4)$$ a – ambient; w – wire

Conduction through prongs:

$$q_H = f(T_w, I_w, k_w, T_{prongs})$$ If $l >> d$ → negligible ($l/d > 200$)

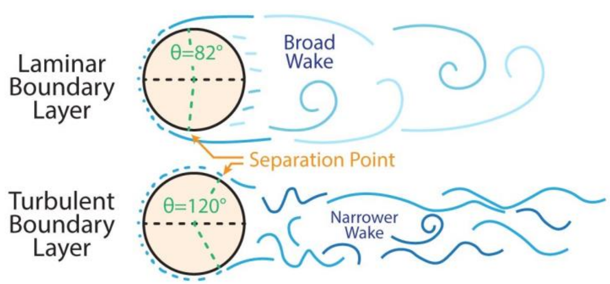
Convection:

$$q_K = h A_w (T_w - T_a)$$

Nusselt number: $\mathrm{Nu} = hd/k = f(\mathrm{Re}, \mathrm{Pr}, \mathrm{M}, \mathrm{Gr}, \text{direction})$

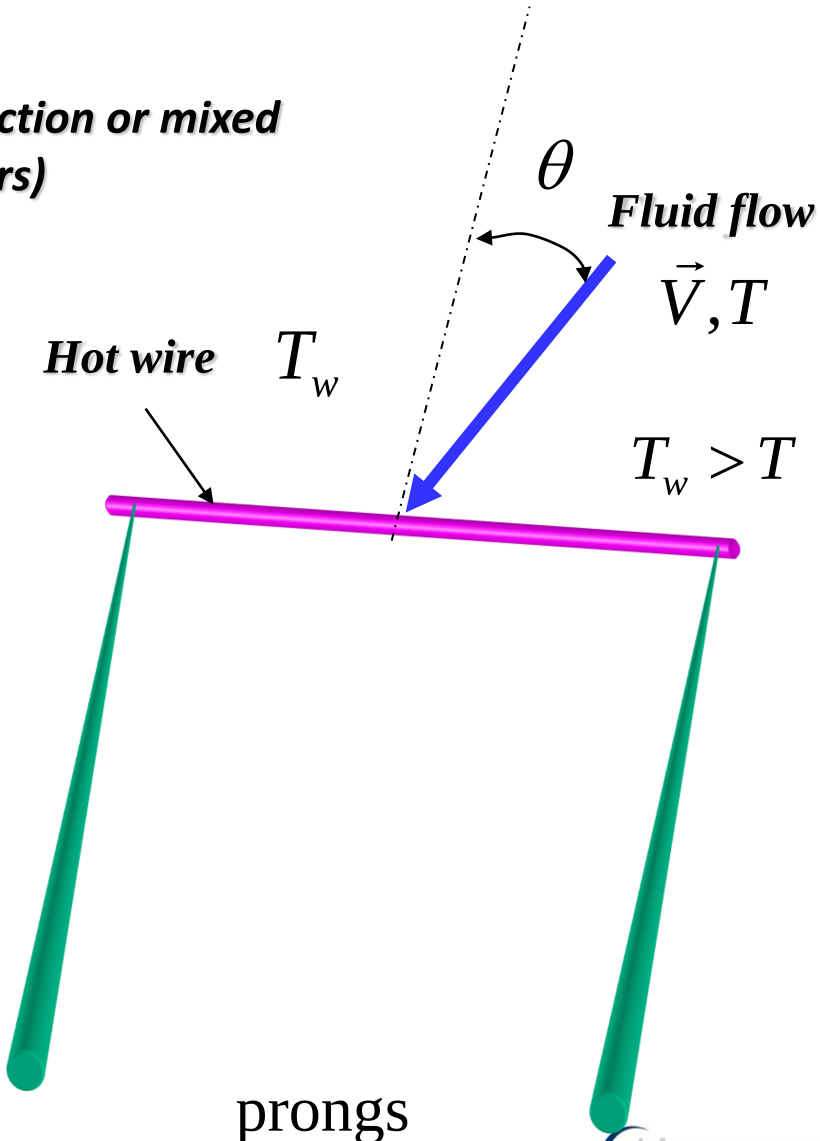
Reynolds number: $\mathrm{Re} = \rho U d / \mu$

CONVECTIVE HEAT TRANSFER: CYLINDER



How Does a Hot wire Sensor Work

- ***Heat transfer characteristics:***
  - ***Convection (nature convection, forced convection or mixed convection depending on Richardson numbers)***
  - ***Conduction to the supporting prong***
  - ***Radiation: <0.1%, is negligible.***



$$Nu = \frac{\dot{q}}{\pi l k (T_w - T)} = Nu(\mathrm{Re}, \mathrm{Pr}, Gr, M, Kn, a_T, l/d, \theta)$$

$$\mathrm{Re} = \frac{\rho U d}{\mu}; \qquad \mathrm{Pr} = \frac{\nu}{\gamma}$$

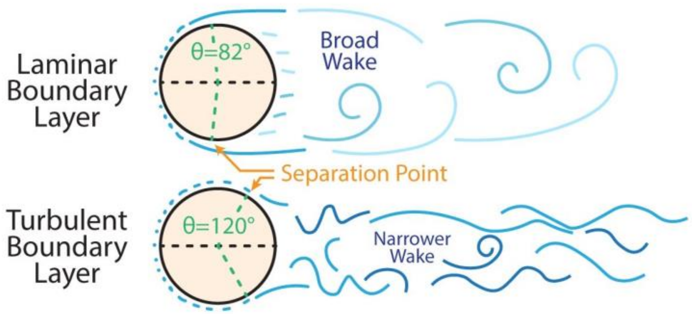
$$Gr = \frac{g\alpha (T_w - T) d^3}{\nu^2}; \qquad M = \frac{V}{c}$$

$$Kn = \frac{\lambda}{d} = \sqrt{\frac{1}{2}\pi c_p / c_v}\,\frac{M}{\mathrm{Re}}$$

$$a_T = \frac{T_w - T}{T}$$

❑ How a Hot wire Sensor Works

CONVECTIVE HEAT TRANSFER: CYLINDER



- ***Following King's Law (1915),***

$$Nu = (A + B\,\mathrm{Re}^n)(1 + \frac{1}{2}a_T)^m$$

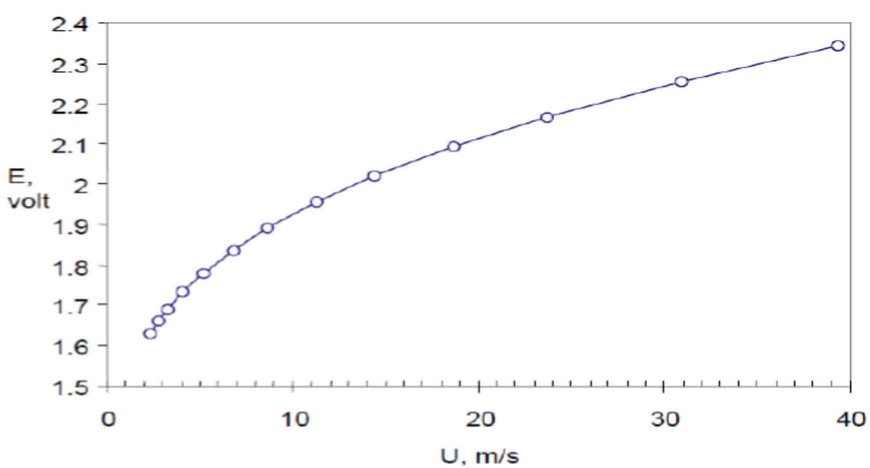
- ***According to Collis and Willams (1959):***

$$Nu = (0.24 + 0.56\,\mathrm{Re}^{0.45})(1 + \frac{1}{2}a_T)^{0.17}, \qquad for \quad 44 < \mathrm{Re} < 140$$

$$Nu = 0.48\,\mathrm{Re}^{0.51})(1 + \frac{1}{2}a_T)^{0.17}, \qquad for \quad 0.02 < \mathrm{Re} < 44$$

For a wire with constant temperature and a constant ambient temperature, one can develop a general relationship between voltage and velocity:

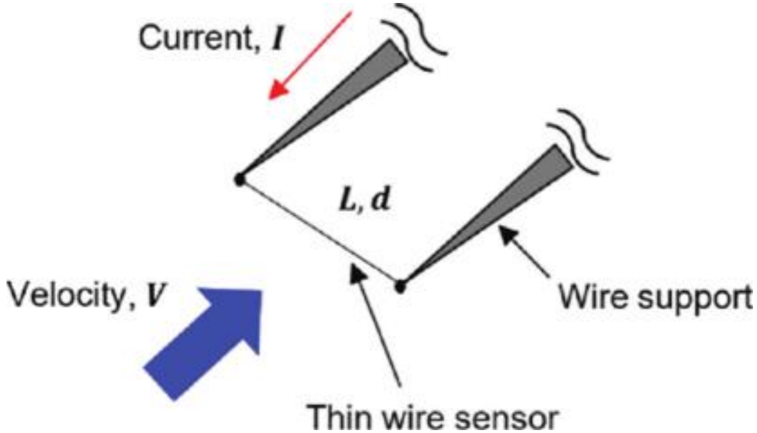
$$E^2 = A + BU^n$$ King's law

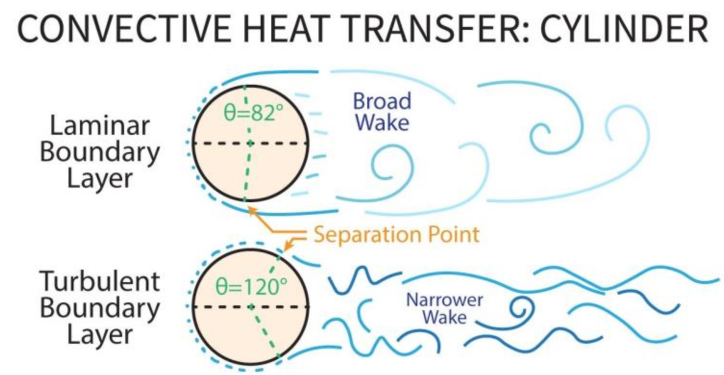


Coefficients are then obtained through calibration. Example of typical values:

	A	*B*	*C*	*n*	ε_U (%)
$E^2 = A + BU^n$					
A,B,n gleichzeitig gelöst	5,980	4,608	-	0,4137	0,11
schrittweise in ***n***	6,018	4,587	-	0,4145	0,15
schrittweise in ***A***	6,005	4,592	-	0,4143	0,15
$E^2 = A + BU^{0,5} + CU$	7,544	3,449	-0,005	0,5000	0,46

❑ How a Hot wire Sensor Works





- *For a given sensor and fixed overheat ratio, The above equation can transfer as the relationship between the voltage output, E, of the hot-wire operation circuit and the flow velocity*

$$\frac{E}{T_w - T} = A + BV^n$$

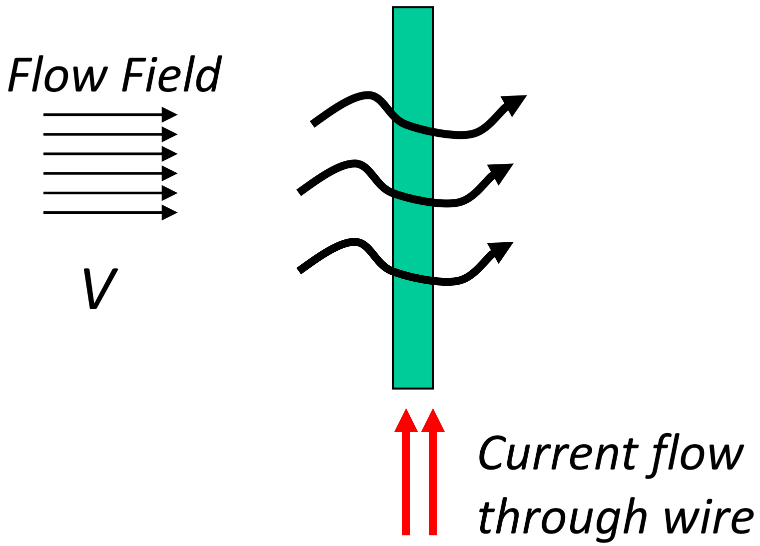
- *Wire temperature cannot be measured directly, but can be estimated from its relationship to the wire resistance, R_w, directly measured by the operating bridge.*
- *For metallic wires:*

$$R_w = R_r[1 + a_r(T_w - T)]$$

a_r : thermal resistivity coefficient

T_r : reference temepature

How a Hot wire Sensor Works



- For a sensor placed in a unsteady flow, the unsteady energy equation will become:

$$mc\frac{dT_w}{dt} = i^2 R_w - \dot{q}(V, T_w)$$

$m:$ the mass of the sensor

$c:$ specifich heat of the sensor

$\dot{q}:$ convective heat flux $\quad \dot{q} = \dot{q}(V, T_w)$

The above equation has three unknowns: i, T_w (or R_w) and V

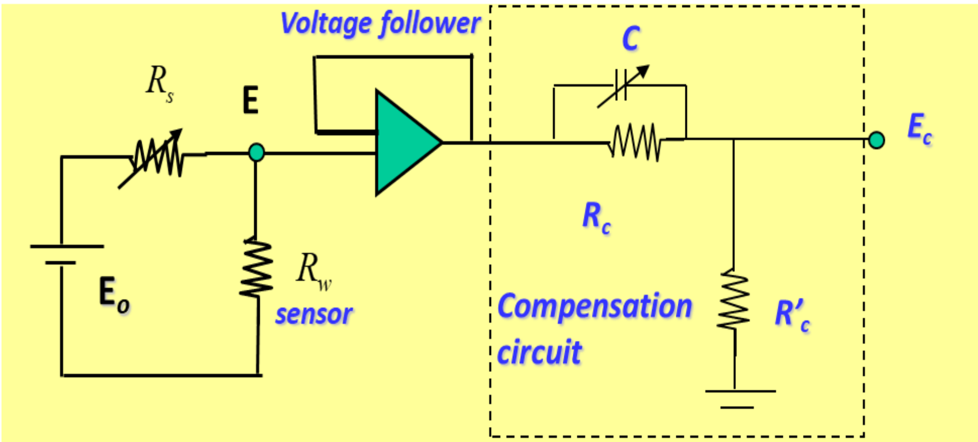
To render this equation solvable, one must keep with the electric current, i, or the sensor temperature (T_w) constant, which can be achieved with the use of suitable electric circuits.

The corresponding methods are known as:

(1). Constant Current Anemometry

(2). Constant Temperature Anemometry

❑ CONSTANT-CURRENT ANEMOMETRY (CCA)



$$mc\frac{dT_w}{dt} = i^2 R_w - \dot{q}(V, T_w) \quad \Rightarrow \quad \tau_w \frac{dT_w}{dt} + (T_w - T_{wop}) = K_T(V - V_{op})$$

τ_w : *a time constant, which is proportional to the overheat ratio, and a static sensitivity,* K_T

Since voltage, E, is proportional to, Rw , which, in turn, is linearly related to Tw, the linearized E-V relationship will be:

$$\tau_w \frac{dE}{dt} + (E - E_{op}) = K(V - V_{op})$$

τ_w : *is usually ~ 1ms for thin hot-wire and ~ 10 ms for slim cylindrical hot-film.*

- *For flow with variable velocity or temperature, overheat ratio will vary as well.*
- *Flow low speed flow, it may result in "burnout", for high-speed flow, sensitivity is low*