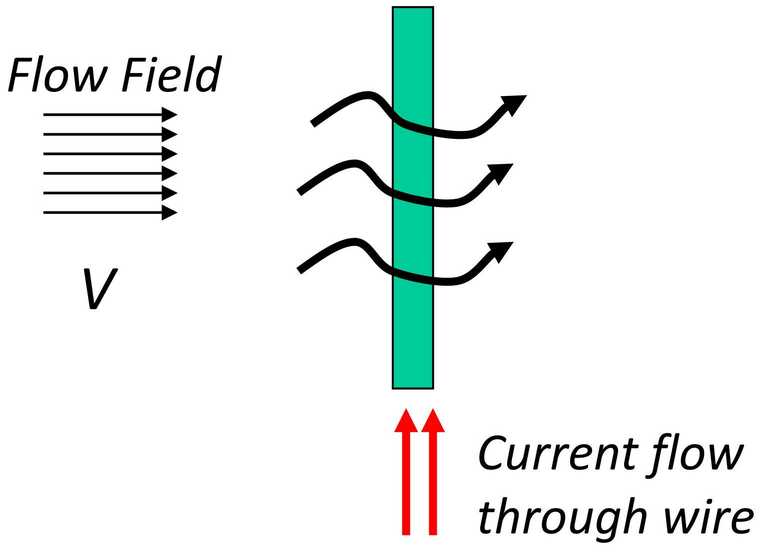
Lecture 06: Methods for local Flow Velocity Measurements: Hotwire Anemometry - Part #02

Dr. Hui Hu
Martin C. Jischke Professor in Aerospace Engineering
Dept. of Aerospace Engineering,
Iowa State University
537 Bissell Road, Ames, Iowa 50011-1096, USA.
Tel: 515-294-0094 (O) / Fax: 515-294-3262 (O)
Email: huhui@iastate.edu

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

$\dot{q}:$ convectiveheat 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-TEMPERATURE ANEMOMETRY (CTA) - 1

- ***Electric current through the sensor is adjustable continuously through an electric feedback system, and in response to the changes in convective cooling, to make the temperature of the hot wire keep in constant.***
- ***The unsteady energy equation becomes steady equation:***

$$mc\frac{dT_w}{dt} = i^2R_w - \dot{q}(V, T_w) \quad \Rightarrow \quad i^2R_w - \dot{q}(V) = 0$$

- ***Dynamic response of the anemometer is the same as its static response with a wide frequency range.***

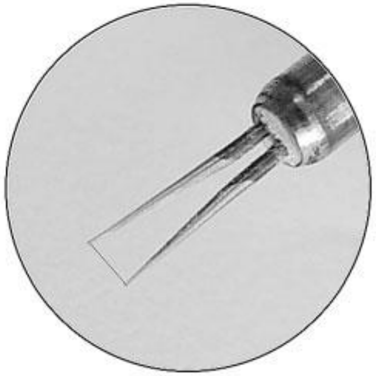
In an steady state case wire is in thermal equilibrium:

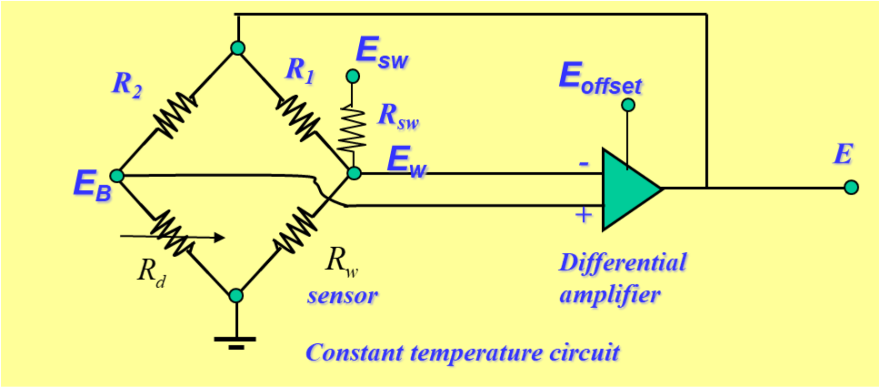
$$\frac{dQ}{dt} = 0; \qquad q_{el} = q_K$$

Assumptions:

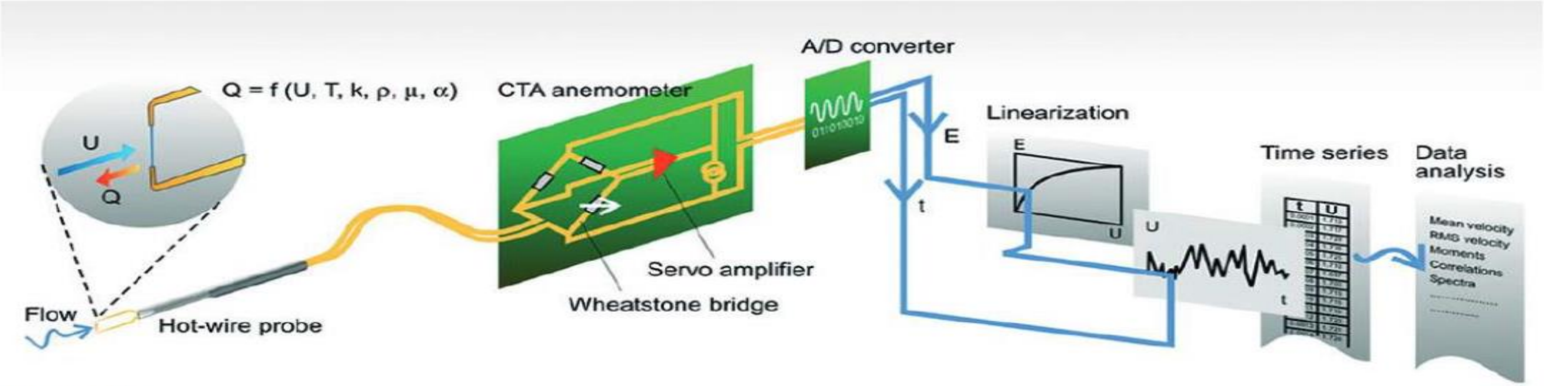
- Radiation is negligible
- Conduction to prongs is negligible ($l/d > 200$)
- Velocity is normal to wire and uniform
- Ambient temperature and viscosity is constant and uniform
- T_w is constant over wire length
- Natural convection is negligible
- Flow is subsonic

❑ Constant-temperature anemometry (CTA)-2





Thermal anemometry – system components:



DantecDynamics

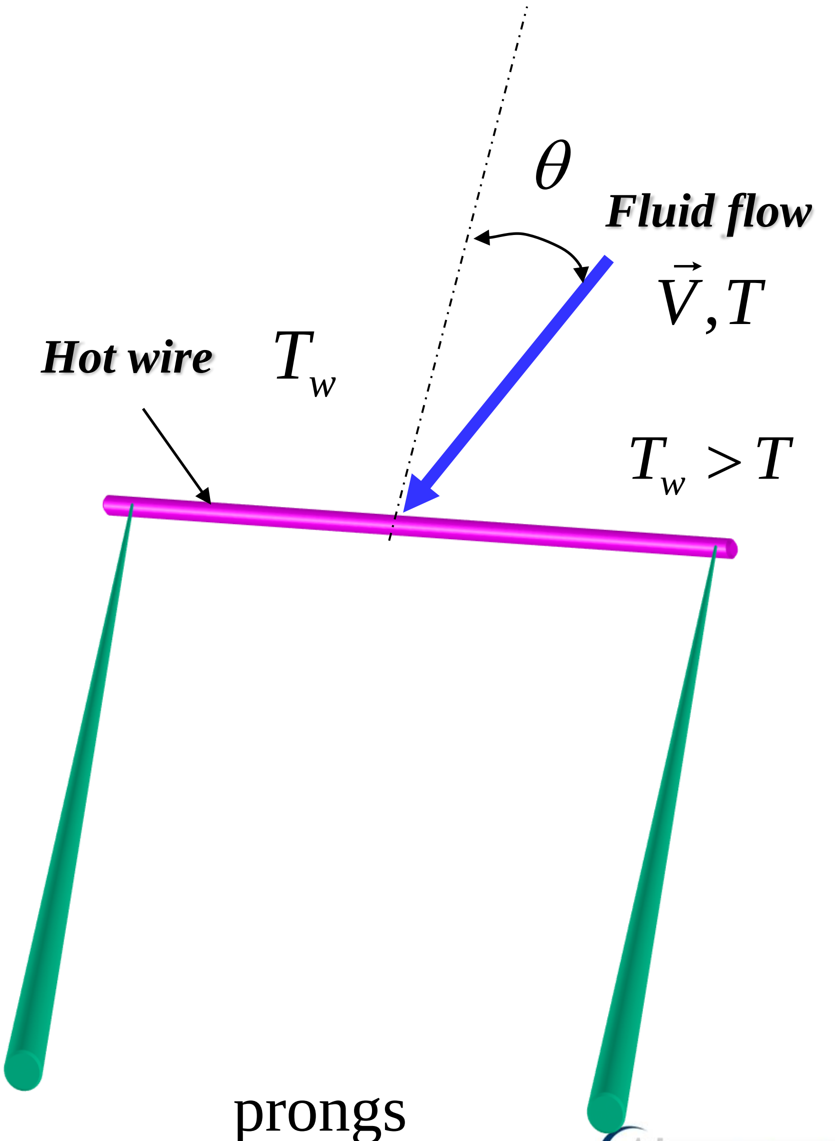
StreamLine Pro - the most reliable research-grade CTA system.

MultichannelCTA - the multiple channel version of the MiniCTA system.

MiniCTA - the most compact CTA system for educa-tional use.

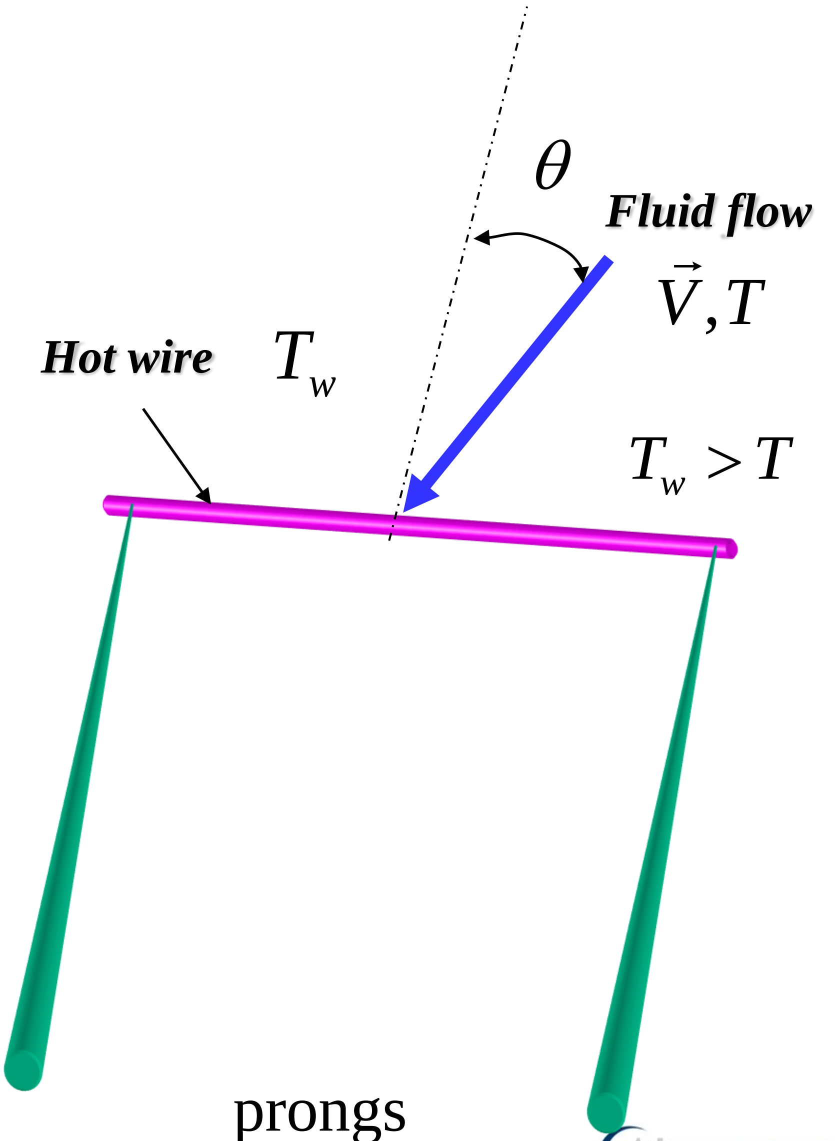
❑ VARIOUS EFFECTS AND ERROR SOURCES

- ***Velocity orientation effects:***
  - ***Effective cooling velocity $V_{eff} = V \cos\theta$.***
  - ***In reality, flow velocity tangential to the sensor would result in cooling.***
  - ***$V_{eff} = V (\cos^2\theta + k^2 \sin^2\theta)^{1/2}$***
  - ***Typical values of K^2 are 0.05 and 0.20.***



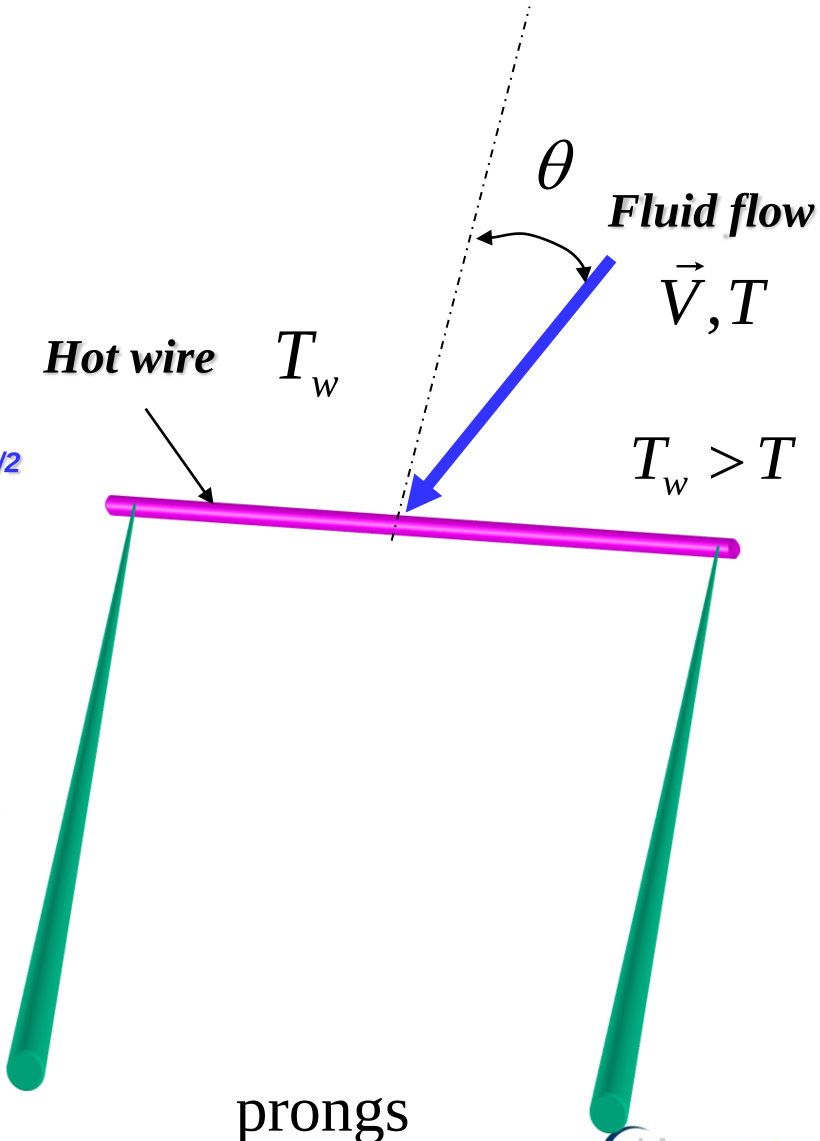
❑ Various Effects and Error Sources

- ***Prong interference effects:***
  - *Interference of the prongs and the probe body may produce additional complications of the heat transfer characteristics.*
  - *For example, a stream in binormal direction will produce higher cooling than a stream with the same velocity magnitude but in the normal direction.*
  - *In reality,* $V_{eff} = (V_N^2 + K^2 V_T^2 + h^2 V_B^2)^{1/2}$
  - V_N, V_T *and* V_B *are the normal tangitail and binormal velocity components.*
  - *Typically,* $h^2 = 1.1 \sim 1.2$
  - *To minimize the effect, it usually use long and thin prongs. Tapered prongs are also recommended.*



❑ Various effects and error sources

- *Heat conduction effects:*
  - *Previous analysis is based on 2-D assumption with $l/d = \infty$.*
  - *In reality, the effect of end conduct may effect the accuracy of the measurement results*
  - *Cold length, $l_c = 0.5{*}d\,((K_w^2/K)(1+a_R)/Nu)^{1/2}$*
  - *K_w is thermal conductivity of the sensor*
  - *K is thermal conductivity of the fluid*
  - *a_R is overheat ratio*
  - *Effect of the sensor length l/l_c*
  - *A recent study has demonstrate that end conduction effects are expected to decrease significantly as the Reynolds number increasing*



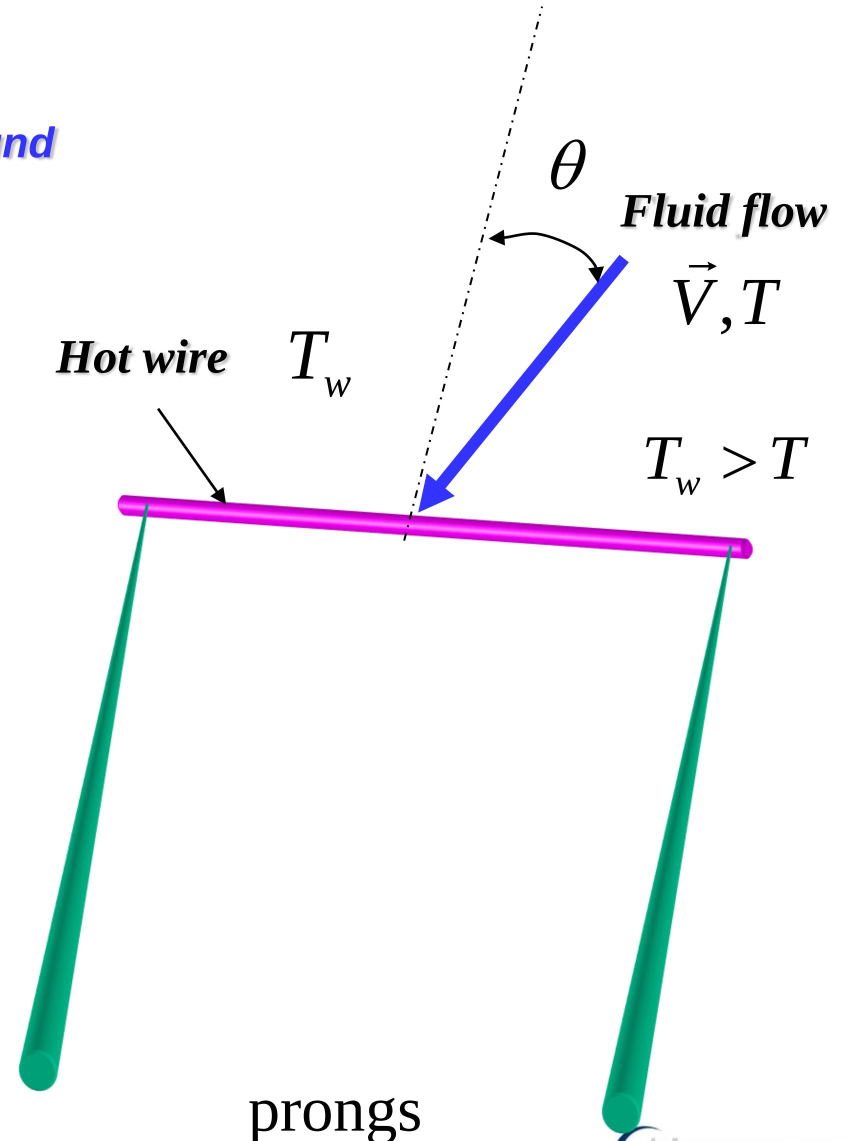
❑ Various effects and error sources

- **Compressibility effects:**
  - *The velocity and temperature fields around the sensor become quite complicated when M>0.6.*

$$V \Rightarrow S_V$$
$$\rho \Rightarrow S_\rho$$
$$T_0 \Rightarrow S_{T_0}$$
$$For\ M \geq 1.2 \qquad S_V = S_\rho$$

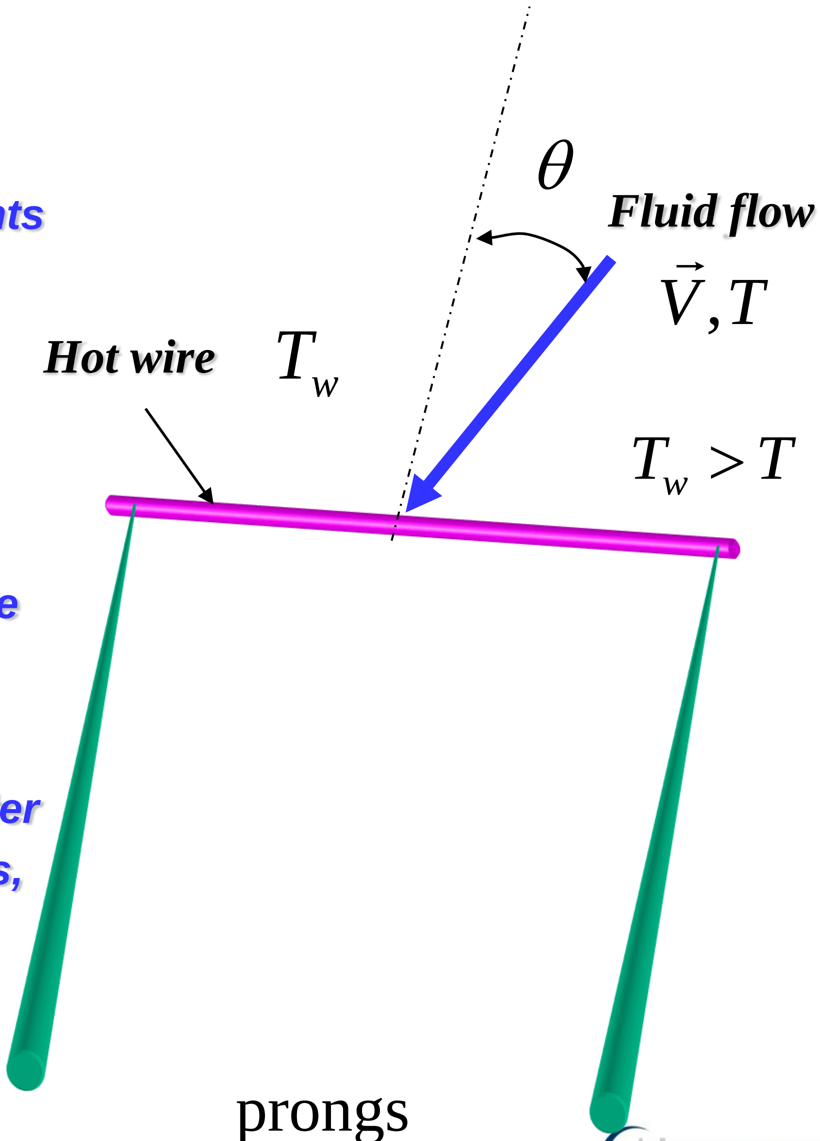
Modified King's law for compressible flow:

$$E^2 = A + B(\rho V)^n$$
$$n \cong 0.55$$



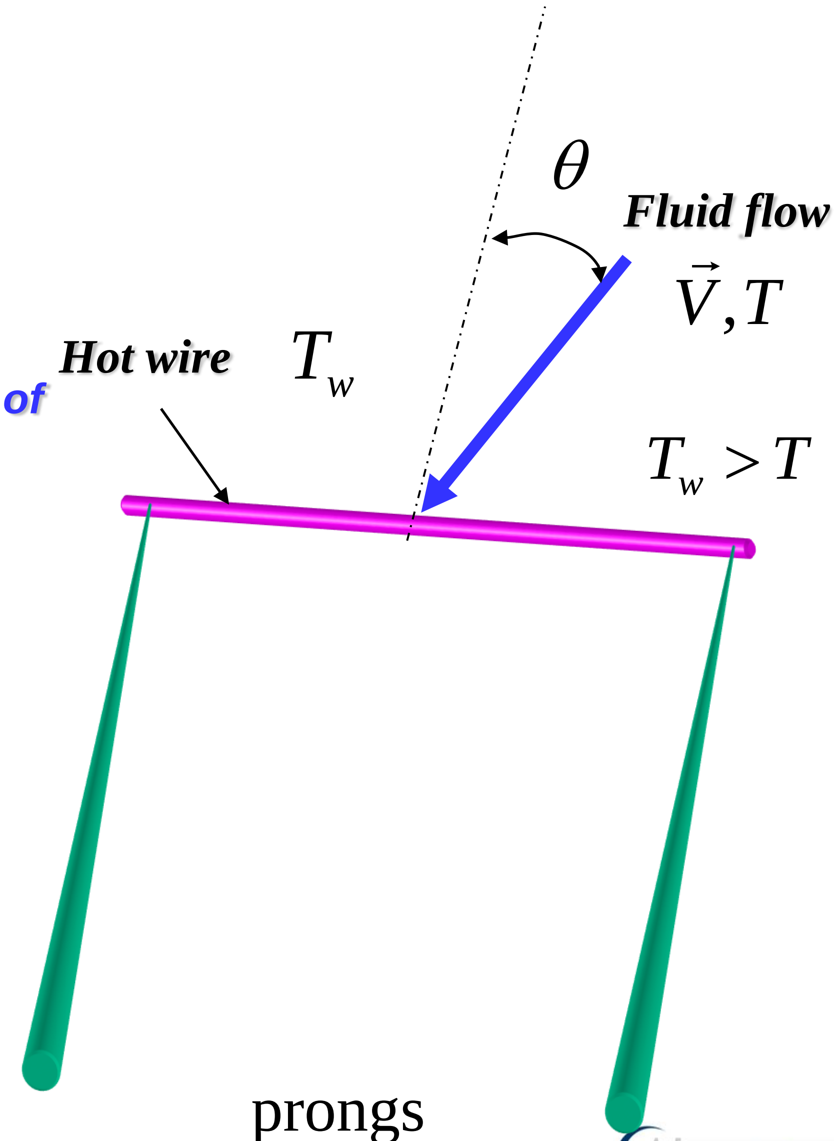
❑ Various Effects and Error Sources

- *Temperature variation effects:*
  - *Calibration at Temperature T1.*
  - *Correlation is needed if real measurements will be conducted at Temperature T2.*
  - *When the flow temperature varies from position to position or contain turbulent fluctuations, corrections is much more complicated.*
  - *It requires simultaneous flow temperature measurements.*
  - *Sv is increasing with overheat ratio a_T.*
  - *At extremely low a_T, a thermal anemometer is totally insensitive to velocity variations, and becomes a resistance thermometer. The sensor is called cold wire.*



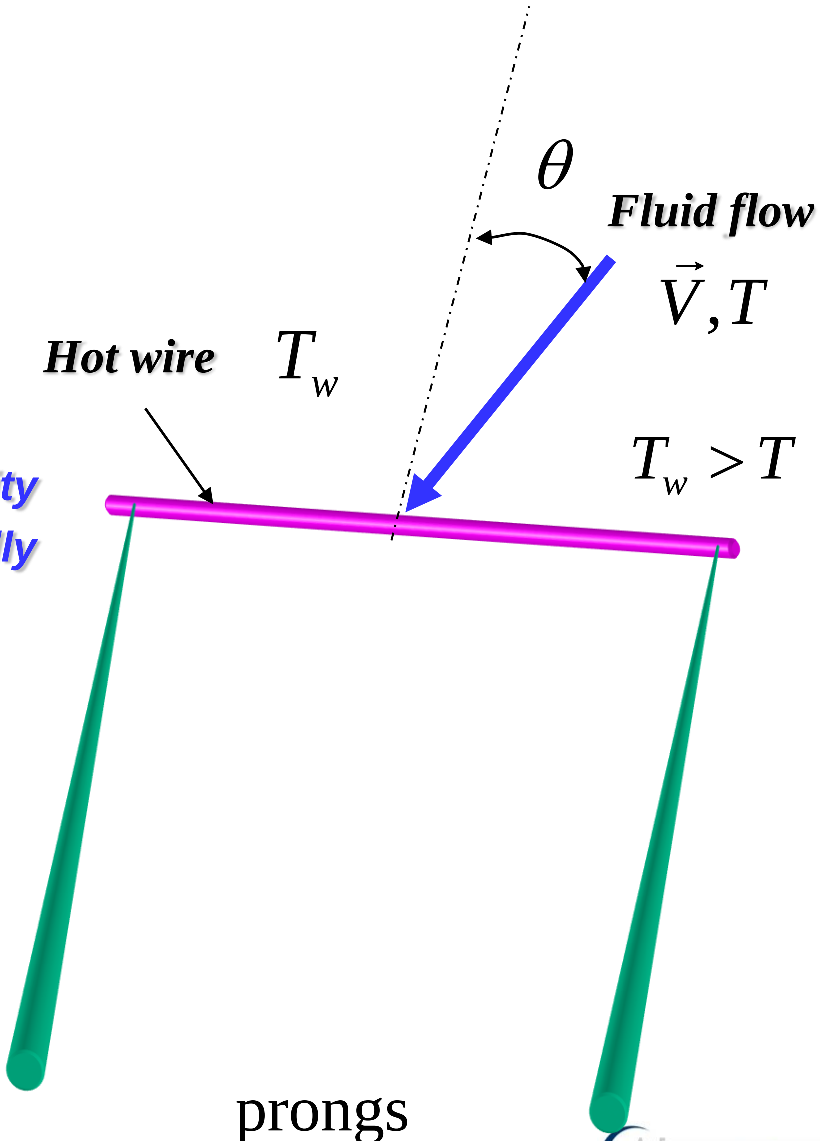
❑ Various effects and error sources

- **Composition effects:**
  - Composition of flow may affect the convective heat transfer from a thermal anemometer in as much as it affect the heat conductivity of surrounding fluid.
  - It requires simultaneous measurements of fluid species concentration.



Various effects and error source

- *Reverse flow and high-turbulence effects:*
  - *thermal anemometer could not resolve velocity orientation.*
  - *Forward flow can not be identified from reversing flow*
  - *In highly turbulent flow (turbulent intensity >25%), reverse flow will occurr statistically some time, therefore, using thermal anemometer for the flow velocity measurement may result quite large measurement uncertainty.*
  - *Pulsed Hot –wire concept*



❑ Multi-sensor probes

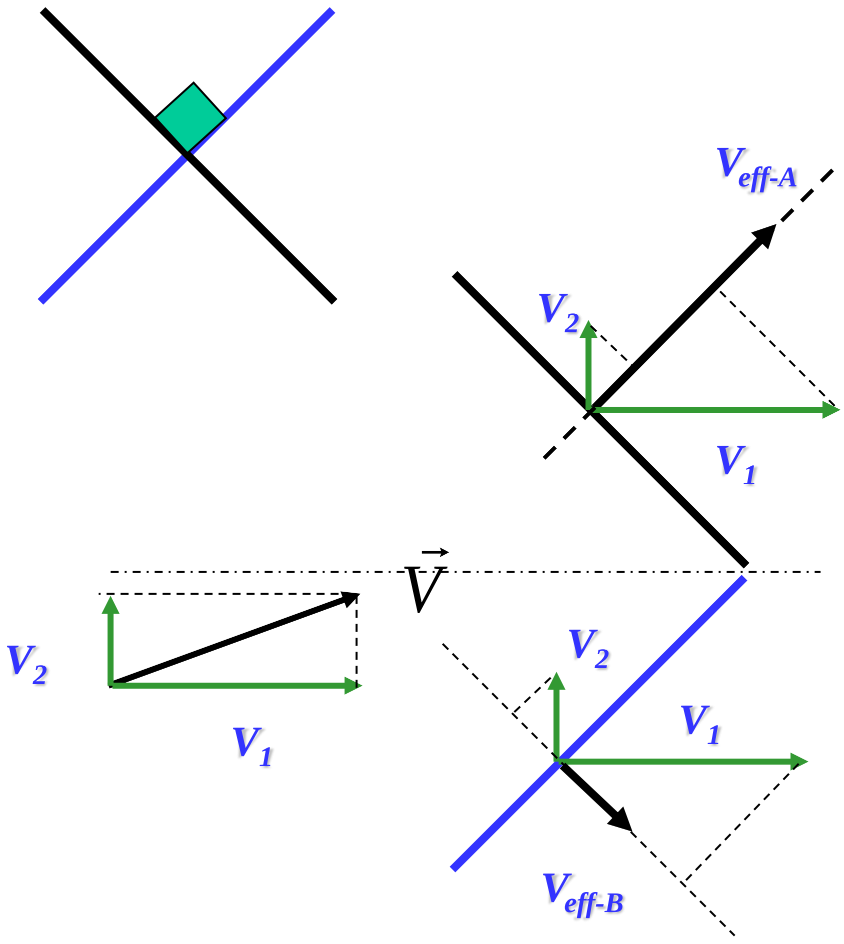
- *Cross-wire (X-wire) design:*

$$V_{eff-A} = \frac{\sqrt{2}}{2}(V_1 + V_2)$$

$$V_{eff-B} = \frac{\sqrt{2}}{2}(V_1 - V_2)$$

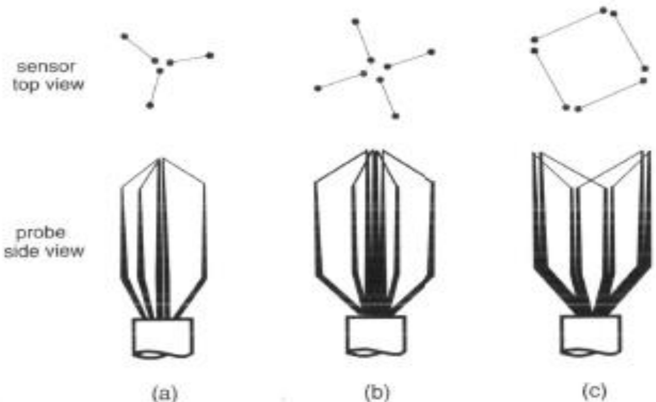
$$V_1 = \frac{\sqrt{2}}{2}(V_{eff-A} + V_{eff-B})$$

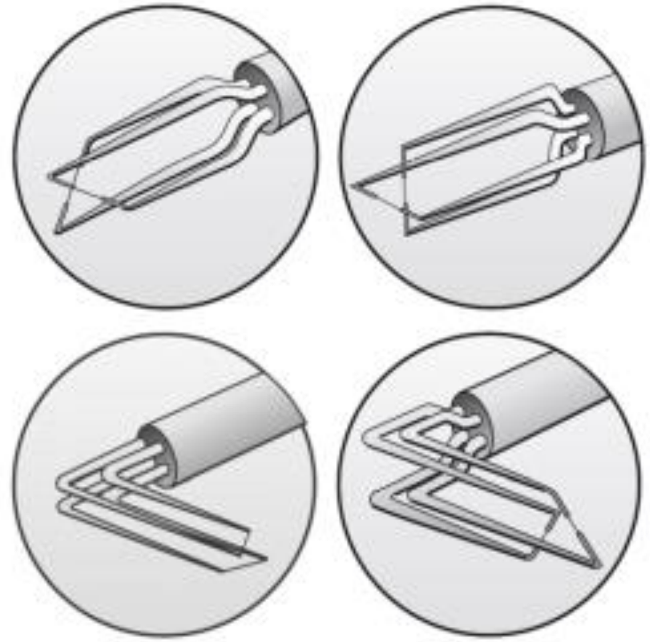
$$V_2 = \frac{\sqrt{2}}{2}(V_{eff-A} - V_{eff-B})$$

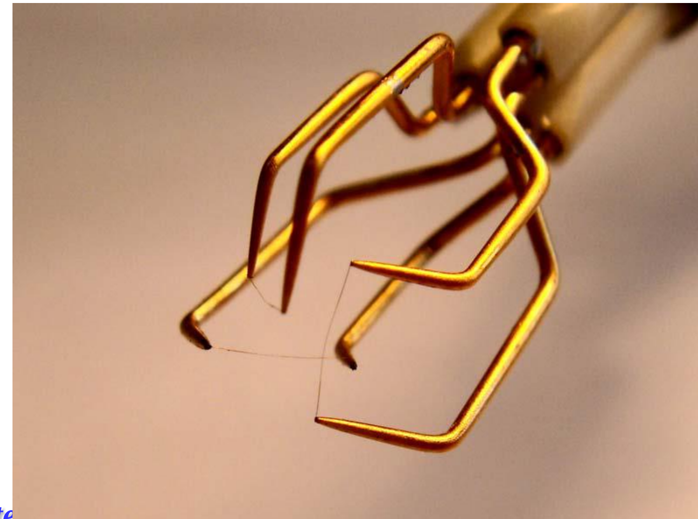


❑ Multi-sensor probes

- *Three sensor design*
- *Four sensor design:*

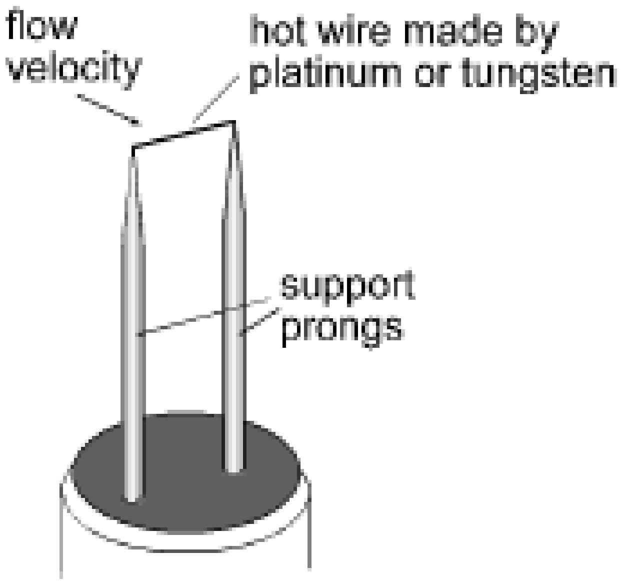


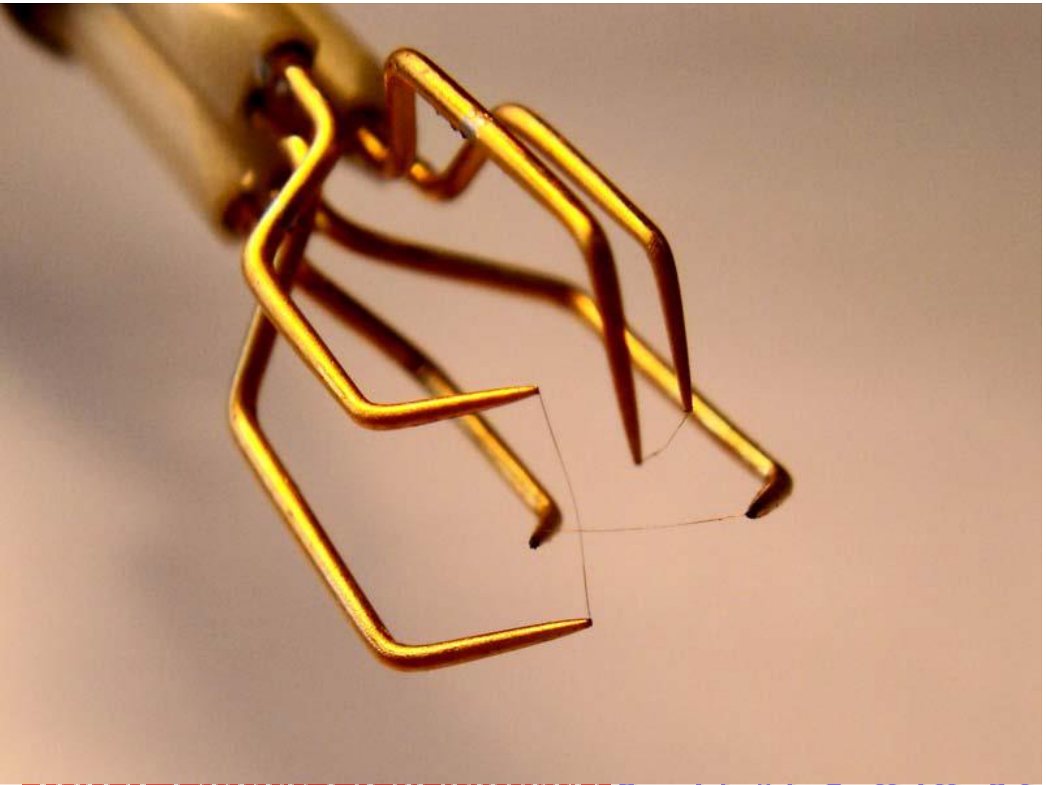




❑ Diameter of hotwires

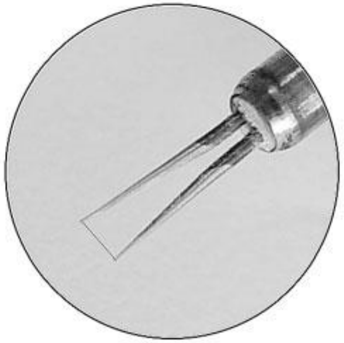
- *L = 0.8 ~ 1.5 mm*
- *D = ~ 5 μm for conventional applications*
- *D = ~ 10 μm for high-speed applications*
- *D = ~ 2 μm for low-speed applications*
- *Prongs: usually tapered to be d≤1mm*



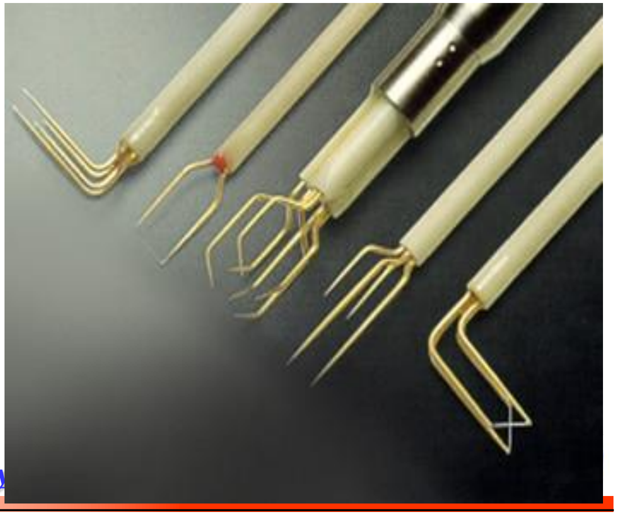


❑ Commonly-used Sensor Material

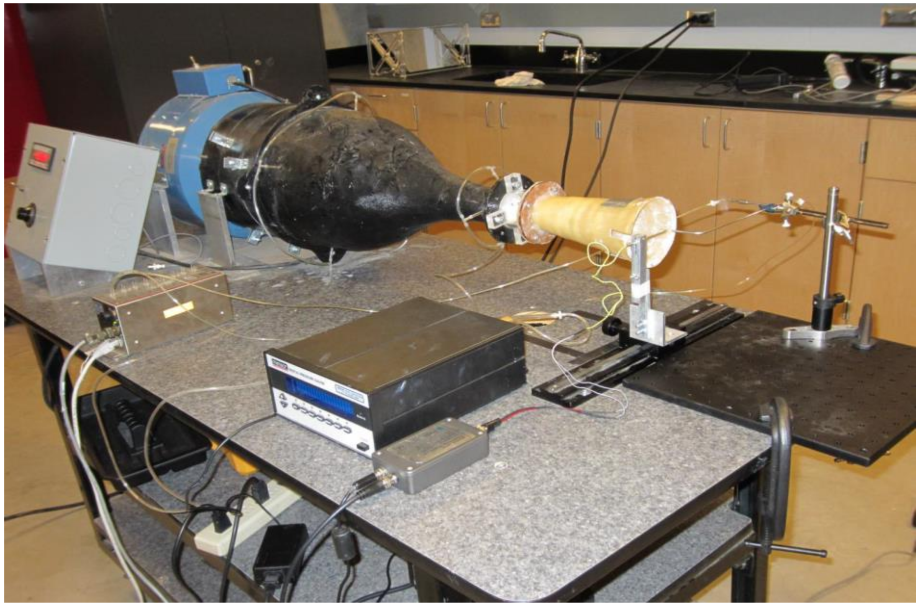
- ***Requirements for the sensor material:***
  - *Good thermal properties*
  - *Good mechanical strength*

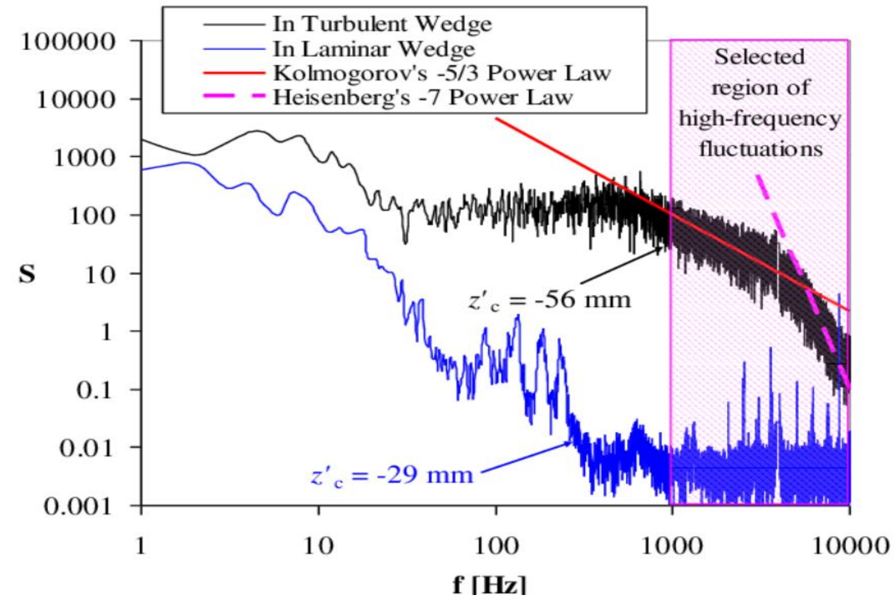


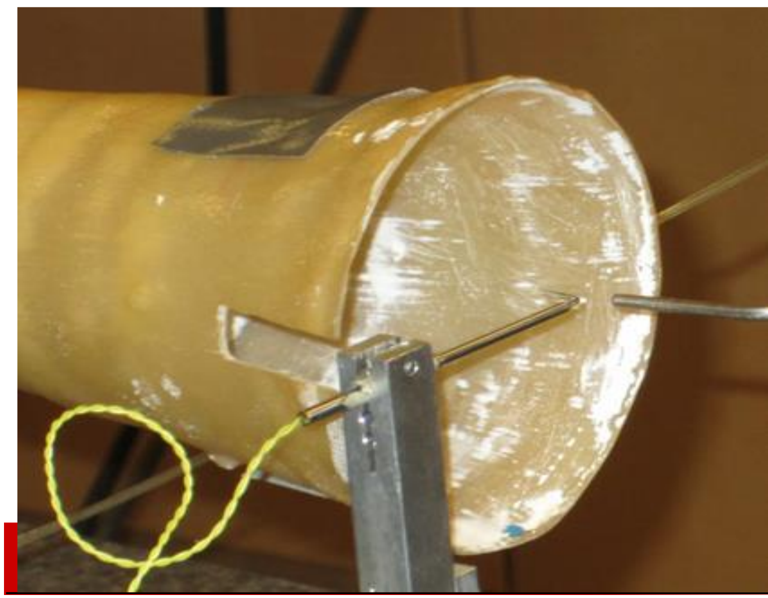
- ***Commonly-used sensor materials:***
  - *Tungsten:*
    - *High thermal resistivity, sufficient mechanical strength and high melting temperature.*
    - *However, it oxidized at about 350 ^{o}C.*
  - *Platium:*
    - *excellent thermal resistivity*
    - *low mechanical strength.*
  - *Platinum alloy:*
    - *Platinum with 20% iridium, 10% rohdium and 10% tangsten*
    - *Improved mechanical strength.*
    - *Slightly reduced thermal resistivity compared with pure platinum*



❑ Constant-temperature anemometry (CTA)







Dynamic response:

Guo & Wood (2001)