Sensors and Instrumentation

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- Temperature measurement – Thermocouples

- Heat Flux measurement – Heat Flux gauge
  - Gardon gauge
  - Scmidth Boelter gauge

- Wind speed measurement
  - Wind cup anemometer
  - Sonic anemometers
  - Pitot tubes
  - Hot wire anemometers

- Humidity measurement – Hygrometers

Temperature measurements : Thermocouples

- The basis of thermocouples was established by Thomas Johann Seebeck in 1821 when he discovered that a conductor generates a voltage when subjected to a temperature gradient.

- To measure this voltage, one must use a second conductor material which generates a different voltage under the same temperature gradient. The voltage difference generated by the two materials can then be measured and related to the corresponding temperature gradient.

- It is thus clear that, based on Seebeck's principle, thermocouples can only measure **temperature differences** and need a known reference temperature to yield the absolute readings

- Thermocouple is a relative not an absolute temperature sensor. In other words, a thermocouple requires a reference of known temperature
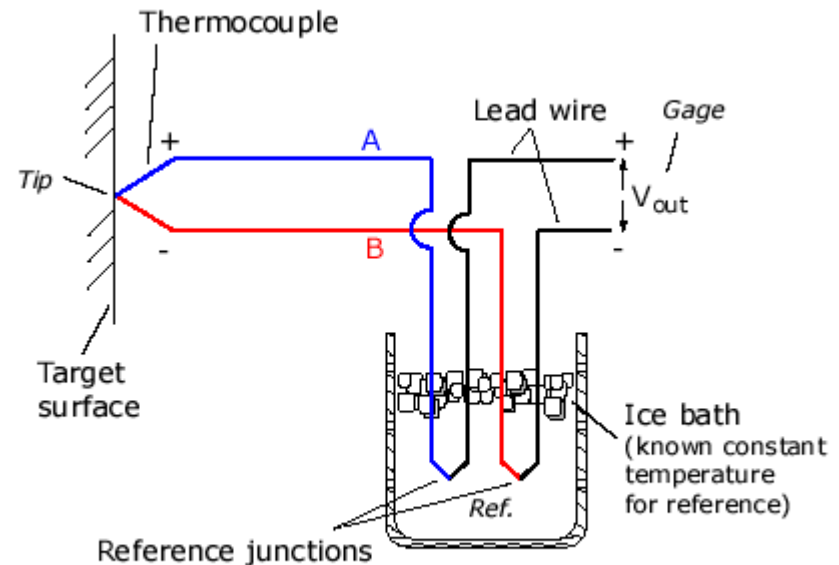
Typical Thermocouple Circuit

The temperature at the probe tip can then be related to the voltage output as,

$$T_{\text{Tip}} = a_0 + a_1 V_{\text{out}} + a_2 V_{\text{out}}^2 + \cdots + a_n V_{\text{out}}^n$$

The above formula is effective only if the reference temperature T_{Ref} in the experiment is kept the same as the reference temperature specified on the data sheet.

Types of thermocouples

Type	Materials	Typical range (deg C)	Suitable environment	Comments
T	Copper (Cu) vs Constantan	-270 to 400	Vacuum, oxidizing, reducing, and inert	High stability at sub zero and cryogenic temperatures
J	Iron (Fe) vs Constantan	-210 to 1200	Vacuum, oxidizing, reducing, and inert	Heavier gauge wire is recommended for long term life above 540 degC since Iron oxidizes at high temperatures
K	Chromel vs Alumel	-270 to 1370	Oxidizing or inert	Should not be used in alternating reducing or oxidizing atmospheres
E	Chromel vs Constantan	-270 to 1000	Oxidizing or inert	Not recommended for alternating oxidizing or inert atmospheres
S	(Pt-10% Rh) vs Pt	-50 to 1768	Oxidizing or reducing	Relatively strong. Stable calibration. Very accurate at high temperatures
B	(Pt-13% Rh) vs (Pt-6% Rh)	0 to 1820	Oxidizing or reducing	Relatively strong. Stable calibration. Very accurate at high temperatures
R	(Pt-13% Rh) vs Pt	-50 to 1768	Oxidizing or reducing	Relatively strong. Stable calibration. Very accurate at high temperatures
N	(Ni-Cr-Si) vs (Ni-Si-Mg)	-270 to 1300	Oxidizing, dry reducing or inert	Very reliable and accurate at high temperatures. Can replace type K thermocouples in many applications.

Can be quantified precisely and accurately.

An energy balance on the thermocouple takes the following form [1]:

$$\dot{Q}_{cat} + \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{cond} = m_b c_p \frac{dT_b}{dt} = \rho_b V_b c_p \frac{dT_b}{dt} \quad (1)$$

(with 0 marked over $\dot{Q}_{cat}$ and over $\dot{Q}_{cond}$)

For an unsteady system, it becomes

$$hA_b(T_g - T_b) = m_b c_p \frac{dT_b}{dt} + \varepsilon \sigma A_b (T_b^4 - T_{surr}^4) \quad (2)$$

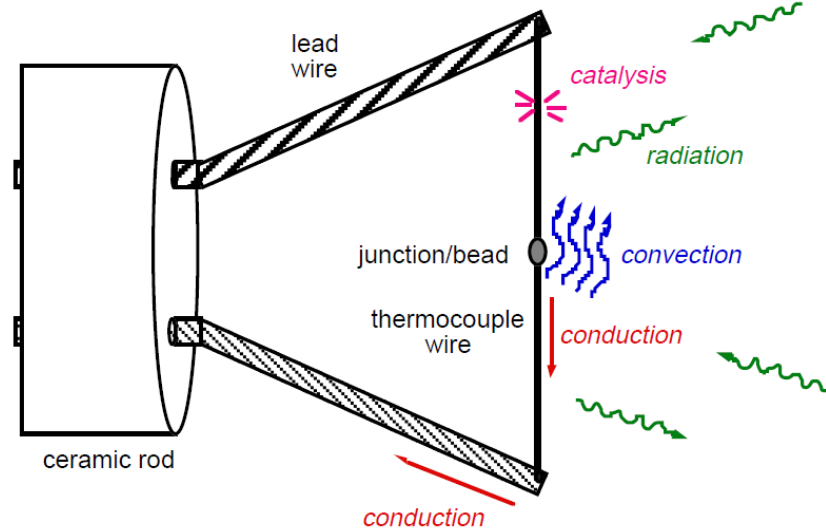$$T_g = T_b + \tau(T_g, U)\frac{dT_b}{dt} + \gamma(T_b^4 - T_{surr}^4) \quad \text{where} \quad (3)$$

$$\tau = \frac{m_b c_p}{h A_b} \qquad \gamma = \frac{\varepsilon \sigma}{h}$$

For a steady system, it becomes

$$T_g - T_b = \frac{\varepsilon \, d \, \sigma}{k Nu}(T_b^4 - T_{surr}^4) \quad (4)$$

$$Nu = \frac{hd}{k}$$

lead wire
catalysis
radiation
junction/bead
convection
thermocouple wire
conduction
ceramic rod
conduction

Emissivity of Pt can be represented as a function of absolute temperature [2]

$$\varepsilon = 1.507 \times 10^{-4} T - 1.596 \times 10^{-8} T^2$$

Here 'd' represents the diameter of fine wire or thermocouple bead depending on whether Cylindrical or Spherical Nu assumption is used

Appropriate Nusselt number correlation should be used to model the convective heat transfer about the thermocouple.

For spherical bead approximation,

(1) $$Nu_{d,sph} = 2.0 + 0.60\,\mathrm{Re}_d^{1/2}\,\mathrm{Pr}^{1/3}$$
Ranz and Marshall (1952) [3]

For Reynolds number between 0 and 200. Properties evaluated at T_∞

(2) $$Nu_{d,sph} = 2.0 + (0.4\,\mathrm{Re}_d^{1/2} + 0.06\,\mathrm{Re}_d^{2/3})\,\mathrm{Pr}^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$
Whitaker (1972) [4]

$$0.71 < \mathrm{Pr} < 380 \qquad 3.5 < \mathrm{Re} < 76000$$

Properties evaluated at T_∞ . μ_s is the gas viscosity evaluated at the surface temperature

(3) $$Nu_{d,sph} = 2 + 0.37\,\mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.33}$$
[2]

For all Re and Pr numbers of interest in low flow velocities

For cylinders, many Nusselt number correlations have been introduced,

(1) For the low Reynolds numbers applicable for fine-wire thermocouple measurements in combustion systems, the Collis and Williams (1959) [5] correlation is most commonly used,

$$Nu_{d,cyl} = (0.24 + 0.56\,\mathrm{Re}_d^{0.45})\left(\frac{T_m}{T_\infty}\right)^{0.17} \qquad 0.02 < \mathrm{Re} < 44$$

With the Reynolds number evaluated at the so-called "film temperature", $T_m = \dfrac{T_b + T_\infty}{2}$

(2) Another widely quoted correlation is that due to Kramers (1946) [6]

$$Nu_{d,cyl} = 0.42\,\mathrm{Pr}^{0.2} + 0.57\,\mathrm{Pr}^{1/3}\,\mathrm{Re}_d^{1/2} \qquad 0.01 < \mathrm{Re} < 10000$$

With the gas properties evaluated at $T_m = \dfrac{T_b + T_\infty}{2}$

(3) Andrews et. al. (1972) [7] evaluated the following expression for $0.02 < \mathrm{Re} < 20$,

$$Nu_{d,cyl} = 0.34 + 0.65\,\mathrm{Re}_d^{0.45} \qquad \text{Gas properties evaluated at} \quad T_m = \dfrac{T_b + T_\infty}{2}$$

Advantages and Limitations

Advantages :

➢ Accurate and reliable
➢ Robust
➢ Linear response over a wide temperature range
➢ Can be used in both reactive (combusting environments) and non-reactive flows

Limitations :

➢ Intrusive technique
➢ Low frequency response (typical frequency response is less than 50 Hz for fine wire thermocouples)
➢ Losses (radiation, conduction)
➢ Catalytic effects

References

[1] C.R. Shaddix, Proceedings of the 33rd National Heat Transfer Conference (1999) Aug 15-17, pp. 1-9

[2] J.A. Ang, P. J. Pagni, T.G. Mataga, J.M. Margle and V.L. Lyons, AIAA Journal 26 (1988), No. 3, pp. 323-329

[3] Ranz, W. E., and Marshall, W. R., Jr. (1952), Chem. Engr. Progress 48:141-146 and 173-180.

[4] Whitaker, S., AlChE Journal, Vol. 18, No. 2, pp. 361-371, 1972

[5] D.C. Collis, M.J. Williams, J. Fluid Mech. 6 (1959), pp. 357-384

[6] Kramers, H. (1946), Physica 12:61.

[7] Andrews, G. E., Bradley, D., and Hundy, G. F. (1972), Int. J. Heat Mass Transfer 15:1765-1786.

Heat Flux Measurements : Heat Flux gauge

- Heat flux gauges are commonly used to measure heat flux
- 2 most commonly used heat flux gauge are :
  - Gardon gauge
  - Schmidt-Boelter

- Gardon gages absorb heat in a thin metallic circular foil and transfer the heat radially (parallel to the absorbing surface) to the heat sink welded around the periphery of the foil. The emf output is generated by a single differential thermocouple between the foil center temperature and foil edge temperature.

Gardon heat flux gauge

- Schmidt-Boelter gages absorb the heat at one surface and transfer the heat in a direction normal to the absorbing surface. The emf output is generated by a multi junction thermopile responding to the difference in temperature between the surface and a plane beneath the surface.
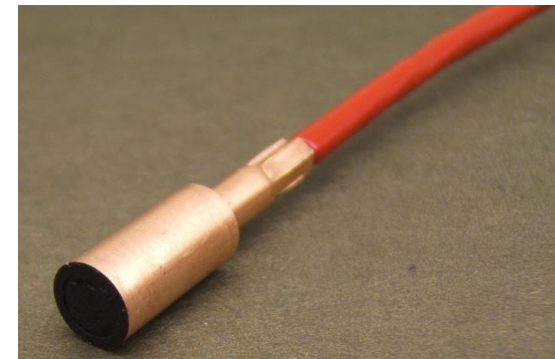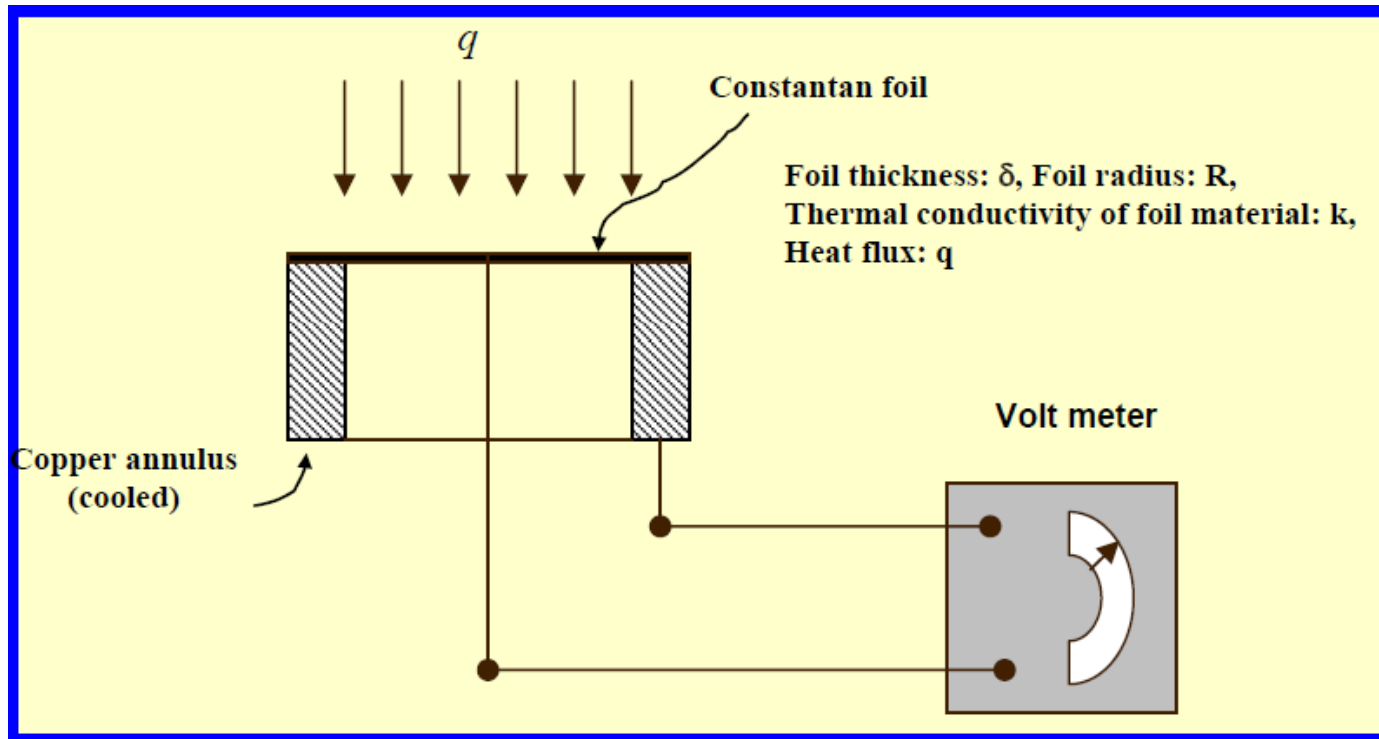

Schmidt-Boelter heat flux gauge

- The constantan foil forms two junctions with copper, the first one at its center and the second one at its periphery
- Under steady state, the thermoelectric voltage across the copper leads is a direct measure of the temperature difference set up between the center and the periphery of the constantan disk

Schematic of a foil type (Gardon gauge) Heat Flux Gauge

- Heat balance for an annular element of the foil shown in figure alongside:

Heat gained by the foil element : $q(2\pi r dr)$

Net heat conducted into the foil element : $(2\pi k\delta)\dfrac{d}{dr}\left(r\dfrac{dT}{dr}\right)dr$

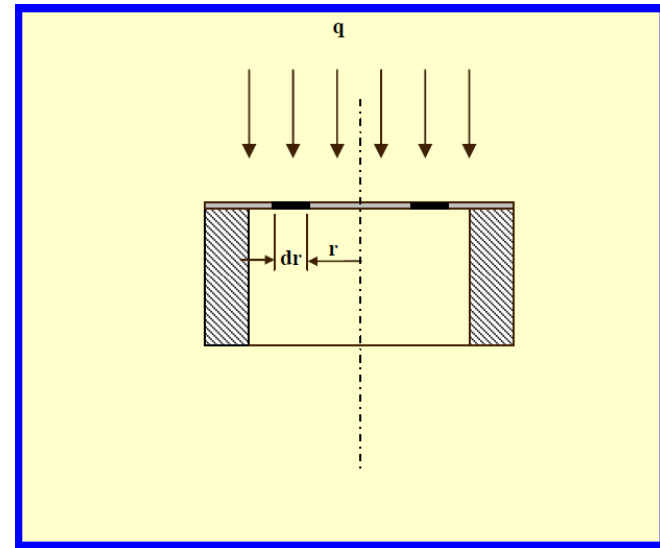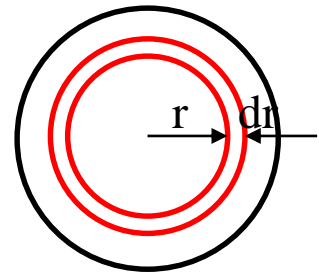Sum of these two should be zero. Cancelling the common terms we get,

$$\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{q}{k\delta}r = 0 \qquad (1)$$

The B.C.'s are :

T is finite at r = 0 ; $T = T_R$ at r = R

With this the solution for the temperature is obtained as:

$$T = T_R + \frac{q}{4k\delta}\left(R^2 - r^2\right) \qquad (2)$$

Energy balance over a foil element in the form of an annular ring

- Equation (2) may be written as:

$$q = \frac{T_0 - T_R}{\left(\dfrac{R^2}{4k\delta}\right)} = K(T_0 - T_R) = K\Delta T \qquad (3)$$

- In the above T_0 is the temperature at the center of the disk and the coefficient K is

  the gauge constant given by $K = \dfrac{4k\delta}{R^2}$ W/m^2-K

- The temperature difference between the center of the disk and the periphery is the output that appears as a proportional voltage, ΔV , across the terminals of the differential thermocouple. There is thus a linear relationship between the heat flux and the output of the heat flux gauge.

- Performing transient analysis for the foil gauge in order to determine an expression for time response of the foil gauge gives us:

Time constant

$$\tau = \frac{R^2}{4\alpha}$$

R: Foil radius
α : Thermal diffusivity of the foil material

Advantages :

➢ Robust
➢ Linear response
➢ Can be used in both reactive (combusting environments) and non-reactive flows
➢ Heat flux is inferred from the temperature difference with ease and simplicity
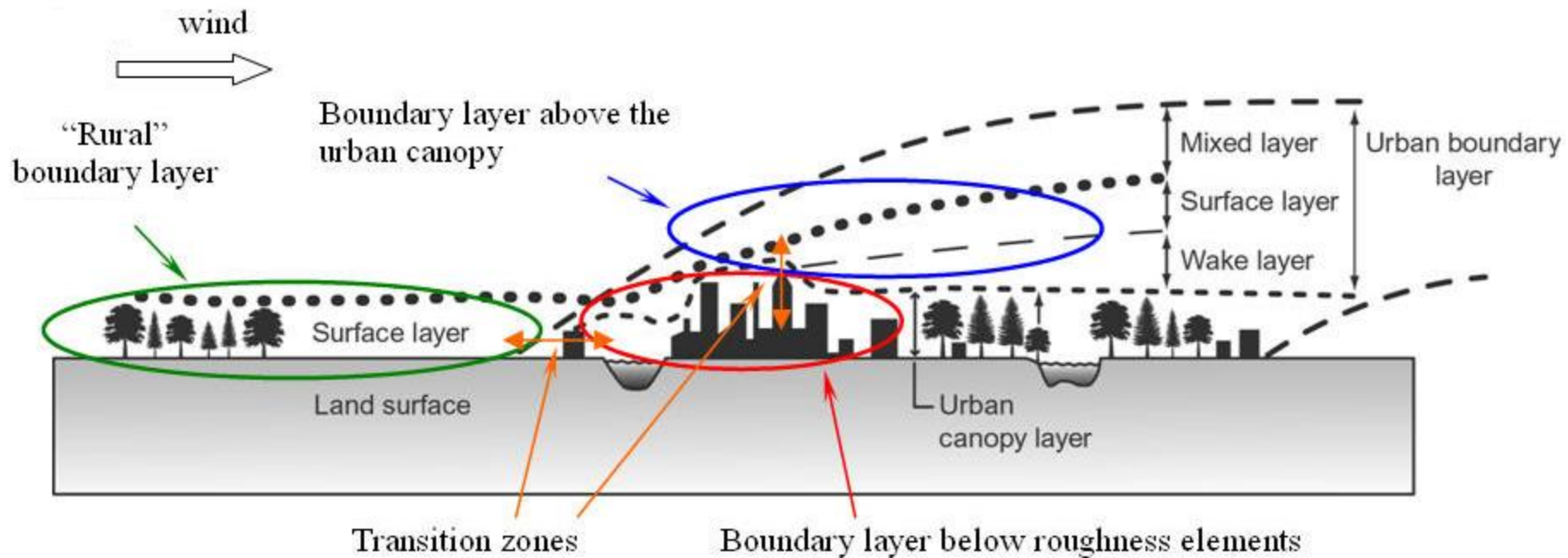
Limitations :

➢ Trade-off between frequency response (foil radius) and sensitivity
➢ High frequency heat flux gauge are quite expensive (Vatell high frequency HFG)
➢ Needs water for cooling
➢ Works best when radiation is the dominant mode of heat transfer

Wind speed measurements : Anemometers

A sensor can only provide us information on the flow in which it is imbedded if it interacts with the flow.

- **Interaction by momentum transfer (force).** Examples are cup and propeller anemometers, or the drag anemometer (one measures the drag on a cylinder or sphere, and deduces the windspeed). Classic example Pitot tubes

- **Interaction by heat transfer.** Hot wire/hot film. Hold a body much hotter than the air. It loses heat to the airstream. The rate one must supply energy to hold the body at constant temperature is an indirect measure of the windspeed.

- **Acoustic propagation.** Sonic anemometer. Acoustic pressure fluctuations travel down the x axis (eg.) at velocity c+u, where c is the speed of sound in still air (about 340 m/s) and u is the velocity component along x (u may be negative). The difference between transit times in opposing directions yields u.
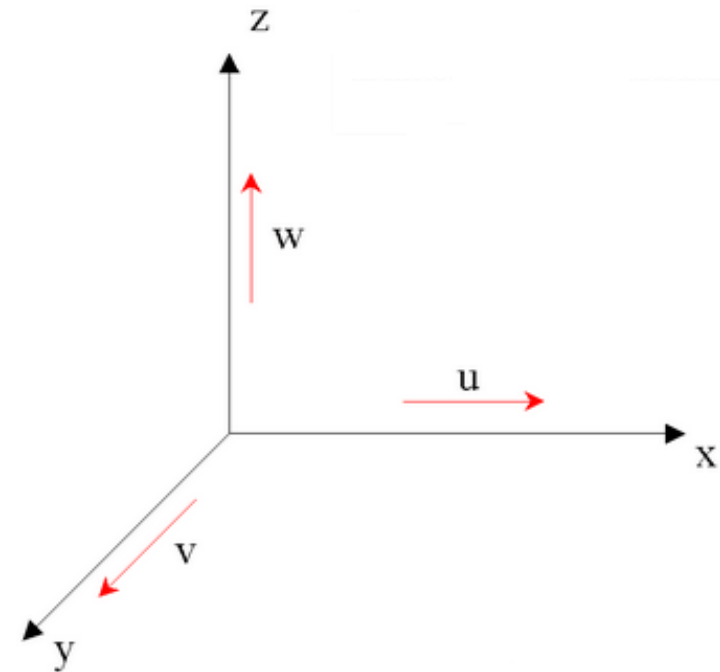
Wind cup anemometer

An anemometer measures wind velocity (a vector) or speed. The three velocity components are the projections of the velocity vector along directions (x,y,z). We will call the magnitude of the wind vector V,
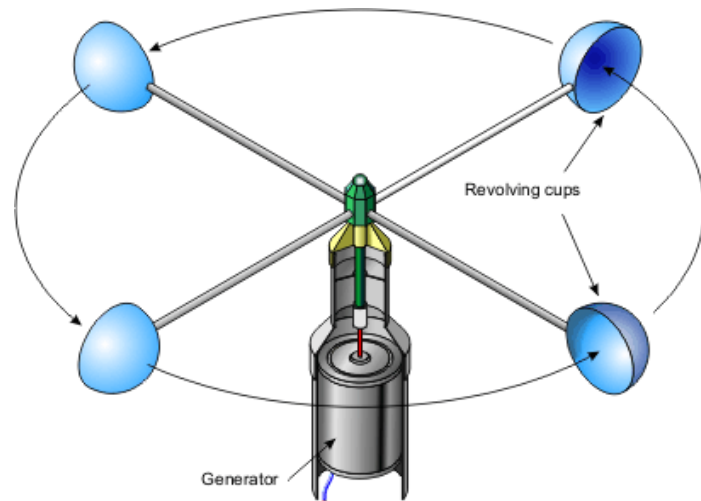
$$V = \{ u^2 + v^2 + w^2 \}^{\frac{1}{2}}$$

and we will call the speed in the horizontal plane (the "cup" windspeed, so called because in principle that is what is "seen" or measured by a cup anemometer) s,
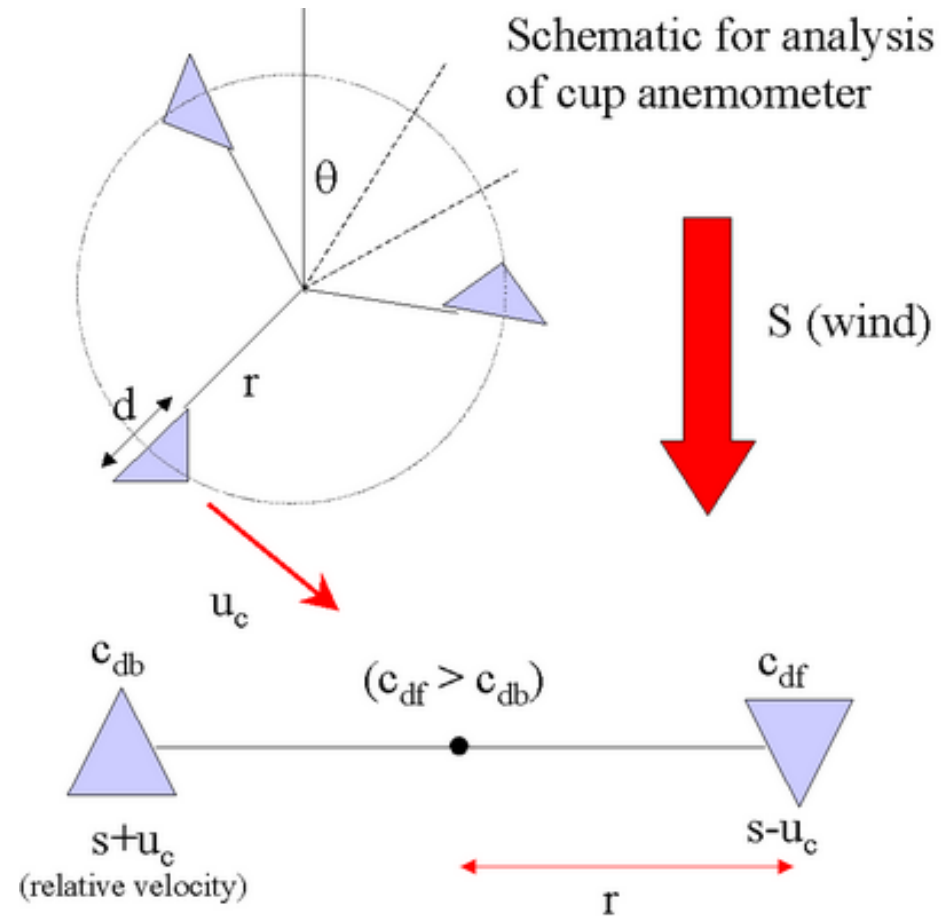
$$s = \{ u^2 + v^2 \}^{\frac{1}{2}}$$

- The most common wind speed measurement device is the cup anemometer

- Many cup anemometers have a vane attached to measure wind direction.

Wind cup anemometer

- The analysis below follows Wyngaard (1981; Ann. Rev. Fluid Mech. 13, p399). The linked figure shows an anemometer having cups of frontal diameter 'd' whose centres rotate on a circle of radius 'r'. The cups have angular velocity 'dθ/dt' and linear tangential velocity $u_c = r \, d\theta/dt$, while the true windspeed in the horizontal plane is s. Typical cup anemometers have r/d in the range (1 - 1.25) and u_c/s in the range (0.3 - 0.5).

- The governing principle of the cup anemometer is that angular momentum is conserved. In words, "moment of inertia (I) times angular acceleration ($d^2\theta/dt^2$) equals net torque acting (T).

Schematic for analysis of cup anemometer

S (wind)

u_c

c_{db}

$(c_{df} > c_{db})$

c_{df}

$s+u_c$
(relative velocity)

$s-u_c$

r

- What is moment of inertia?
- For a device like this having axial symmetry it is the sum of the masses of the cups times the square of their distance from the axis of rotation (we are neglecting the contribution of the shafts supporting the cups, but it could easily be calculated):

$$I = \Sigma\, m\, r^2 \sim 10^{-4}\ \mathrm{kg\ m^2}$$

- So the governing equation is:

$$I\, d^2\theta/dt^2 = T_d - T_f$$

where T_d is the torque due to the drag of the wind on the device and T_f is the friction torque (bearing friction, generator torque if a generator is attached to the shaft, etc).

- **Steady state analysis**: If the wind is steady (and therefore the angular acceleration of the cup is zero) and we neglect friction, the governing equation reduces to $T_d=0$ (thus the inertia is irrelevant; this is always the case in the context of steady-state response).

▪ Now we will adopt a "model" for T_d based on the two-cup simplification (2-cup model). The cups have cross-sectional area A. The front side of a cup has drag coefficient c_{df} while the back has c_{db}, with $c_{df} > c_{db}$. That cup facing into the wind and moving sympathetically downwind is pushed by a force

$$0.5 \; \rho \; A \; c_{df} \; (s-u_c)^2$$

while the other, driven back against the wind so that the relative velocity is $s+u_c$, is pushed by a force

$$0.5 \; \rho \; A \; c_{db} \; (s+u_c)^2$$

▪ Then the drag torque, force times distance from the axis of rotation, is

$$T_d = 0 = r \; \rho \; A \; [\; c_{df} \; (\; s - u_c)^2 - c_{db} \; (\; s + u_c \;)^2]$$

A couple of lines of algebra will now show that the steady state calibration factor $\gamma = u_c/s$ is governed by:

$$\gamma^2 - 2 \, G \, \gamma + 1 = 0 \qquad \text{where} \qquad G = (c_{df} + c_{db})/(c_{df} - c_{db}) = (1+\varepsilon)/(1-\varepsilon)$$

- where $\varepsilon = c_{db}/c_{df} < 1$. This is a quadratic equation for the steady state calibration factor $\gamma = u_c/s$ (remember that the anemometer output is proportional to u_c, whether it be a number of pulses per revolution, or a voltage proportional to rotation rate).

- The remarkable thing is that the calibration does not depend on the air density. Who would have guessed? The cup anemometer responds to wind forces, and those wind forces have a magnitude directly proportional to density. Yet because in a steady state those forces are balanced, density vanishes as a factor.

- If $\varepsilon = \frac{3}{4}$, $\gamma = 14 \pm 195^{1/2}$, while if $\varepsilon = \frac{1}{2}$, $\gamma = 3 \pm 8^{1/2}$. In both theses cases we have two real positive solutions for $\gamma = u_c/s$, one large and one very small. These are ostensibly eligible solutions; but for any ε, it would have been more satisfying to find only one real root. Never mind, our model is an oversimplification.

- We won't go on to look at the dynamic response (response to sudden changes). But it can be shown that a cup anemometer in turbulent flow overestimates the mean speed ("over speeds") because it accelerates more rapidly in gusts than it decelerates in lulls (example of cup over speeding error; observations from an open flat field at Ellerslie, Alberta, May 2003; Wilson, in press, J. Applied Meteorol).

- Cups also have a "w-error," a departure from true cosine response (Hyson 1972; J App. Met. 11, p843), perhaps as large as a 6% error at heights of around 4 m. Other analyses of cup anemometers and their various errors are given by:

- Kaimal (1973; Boundary-Layer Meteorology, Vol. 4)
- Kaganov and Yaglom (1975; Boundary-Layer Meteorology, Vol. 10)
- Wyngaard (1981; Ann. Rev. Fluid Mech., Vol. 13, p399)
- Coppin (1982; "An examination of cup anemometer overspeeding." Meteorol. Res.,   Vol. 35, 1-11)
- Hayashi (1987; J. Atmos. Ocean. Tech., Vol. 4, p281)

Ratio of mean wind speeds (average of 15 tests) from a cup anemometer and a 2D sonic anemometer
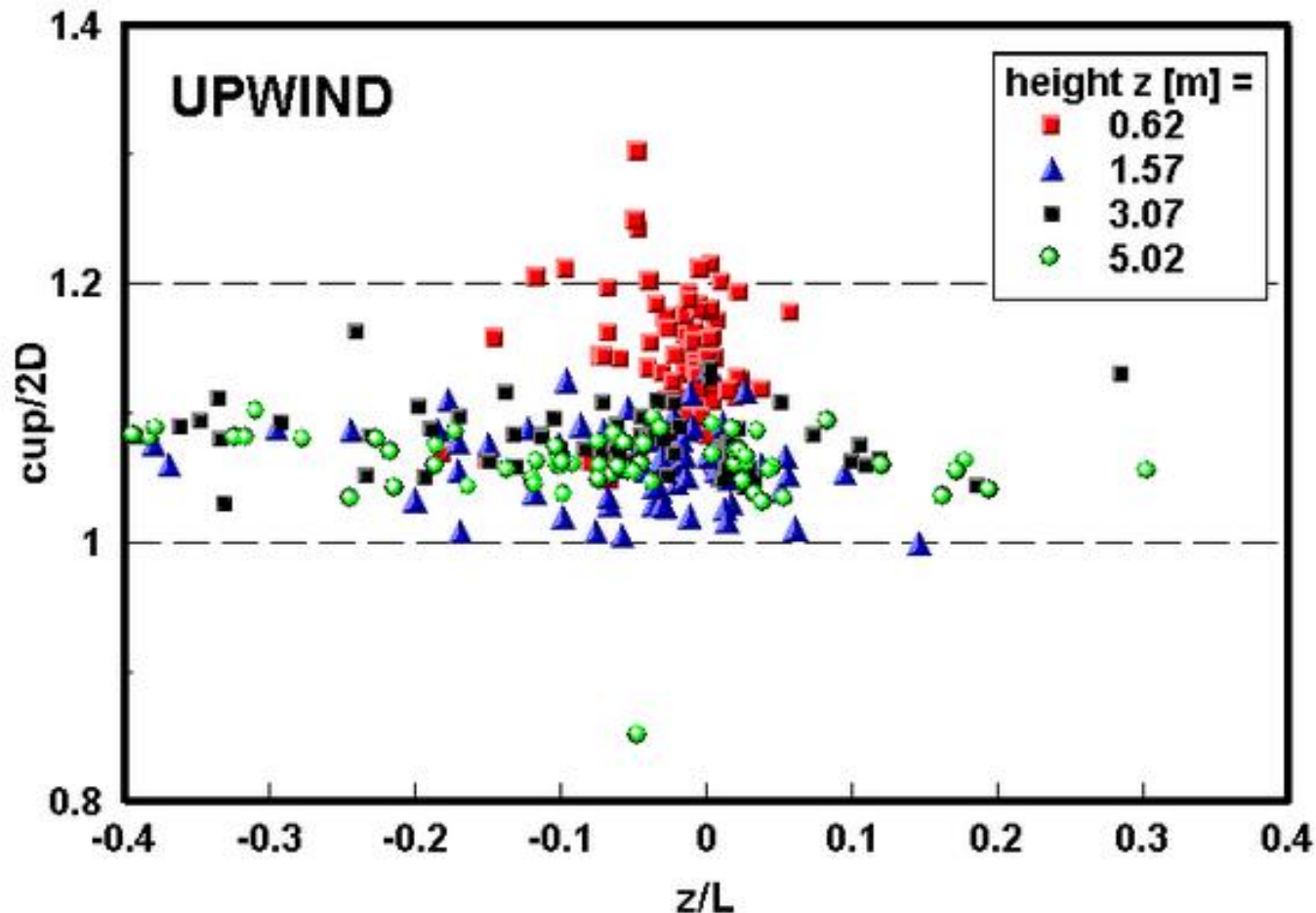
Advantages :

➤ Low price
➤ Flexible. Designs have been developed for all climates.
➤ Simple Installation.
➤ Simple operating procedure
➤ Accuracies of 1% can be achieved with higher quality devices.
➤ They remain accurate when the wind has a significant vertical component, even up to 30°

Limitations

➤ Moving parts wear out.
➤ Cheap versions are not very accurate.
➤ Without provisions for heating, they don't work well in snow or freezing rain.
➤ They don't work well in rapidly fluctuating winds.
➤ Low frequency response. Cannot be used to resolve turbulence.

Sonic anemometer

- Sonic anemometers provide fast and accurate measurements of three dimensional wind speed and are widely used to make both routine wind and detailed turbulence measurements.

- These instruments are able to make wind speed measurements over the range 0 – 60 m/s, with a resolution of 1 cm/s at rates up to 100Hz. This speed and resolution allows turbulent structure on scales of a few cm to be resolved.
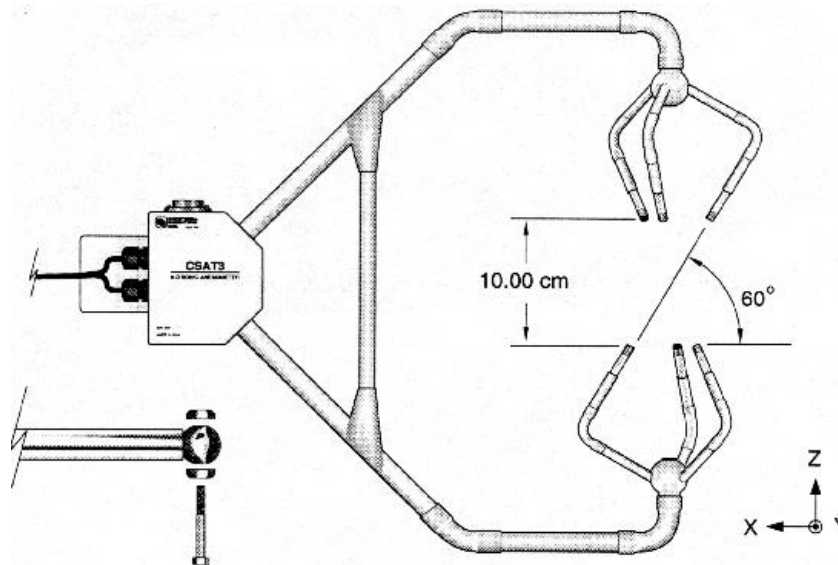

3D Sonic anemometer

Sonic anemometer

- The sonic anemometer exploits the fact that a train of sound waves (usually ultra-sound) travels in a fluid at a velocity (relative to fixed axes) that is the SUM of the intrinsic speed (c) of propagation of sound in still fluid, PLUS the bulk convective velocity of the fluid with respect to the axes.
- The speed of sound in a gas (pressure p, density ρ) is

$$c = (\gamma\, p/\rho)^{1/2}$$

where $\gamma = c_p/c_v$ (ratio of specific heats at constant pressure and constant volume).

3D sonic anemometer

- Now imagine a pulse (P1) of sound travelling vertically downward over distance d (the path length) from a speaker (these days, often a piezoelectric transducer that functions efficiently either as a highly tuned source, or as an efficient receiver of tuned ultrasound), and a reverse pulse (P2) taking the opposite path. If we define the horizontal wind velocity V_x to be positive for right motion, than the travel times will be:

The schema of sound pulse route in single measuring path of sonic anemometer

$$P1 \text{ (down): } t_1 = d \, / \, (c + V_x)$$

$$P2 \text{ (up): } t_2 = d \, / \, (c - V_x)$$
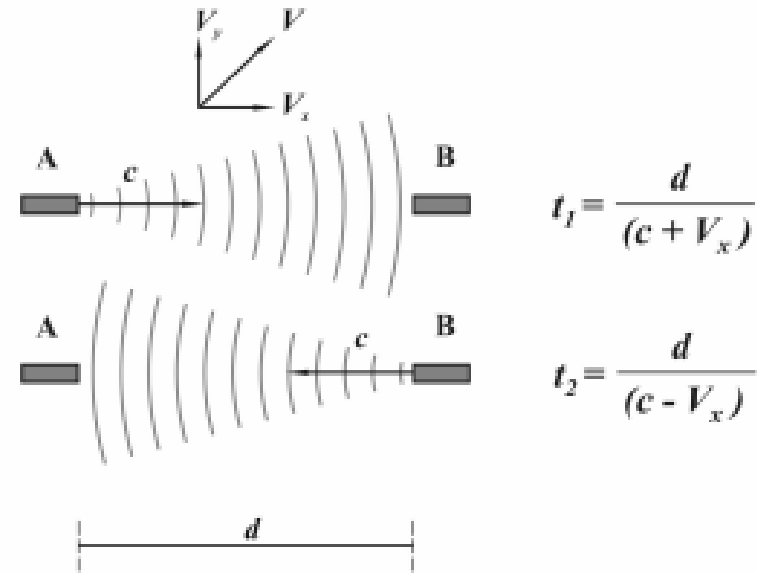
Then

$$1/t_1 + 1/t_2 = (2/d) \, c$$

while

$$1/t_1 - 1/t_2 = (2/d) \, V_x$$

$$\boxed{V_x = \frac{d}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right)}$$

Basing on it, knowing the distance **d** and having the times t_1 and t_2 registered, we can calculate the V_x component of the velocity vector **V**.

- So the sonic gives us both velocity (along the path) and temperature (ultrasonic anemometer-thermometer).

Advantages :

- No moving parts
- Higher frequency response as compared to wind cup anemometer (order of 100 Hz)
- Velocity measurements are absolute measurements
- Does not require calibration in a wind tunnel
- The device is characterized by a wide measurement range, ranging from hundredths of m/s to tens m/s
- the precision of velocity and airflow direction measurements depends only on the precision of the values t_1, t_2 and d measurements

Limitations:

- high complexity of electronic systems emitting and registering sound pulses and fragile sensors construction
- disturbances of flow caused by cantilevers and sensor heads
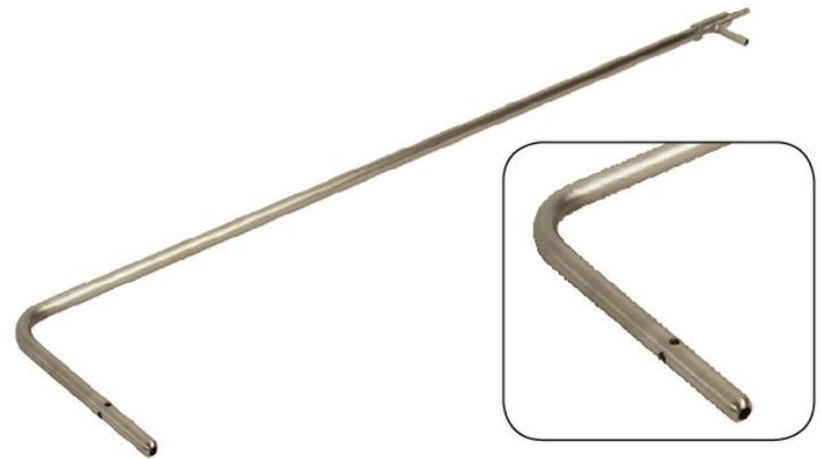
Pitot tube

- A pitot tube is an instrument to measure the fluid flow velocity

- The basic pitot tube consists of a tube pointing directly into the fluid flow. As this tube contains fluid, a pressure can be measured; the moving fluid is brought to rest (stagnates) as there is no outlet to allow flow to continue. This pressure is the stagnation pressure of the fluid, also known as the total pressure. Works on Bernoulli's principle.

Advantages :

- Cost effective measurement
- No moving parts
- Simple to use and install
- Low pressure drop

Limitations :

- Cannot accurately measure unsteady, accelerating, or fluctuating flows
- Low frequency response

Pitot Static Tube

$$(p_o - p) = \frac{1}{2}\rho V^2 \qquad (1)$$

Stagnation
pressure

Static pressure

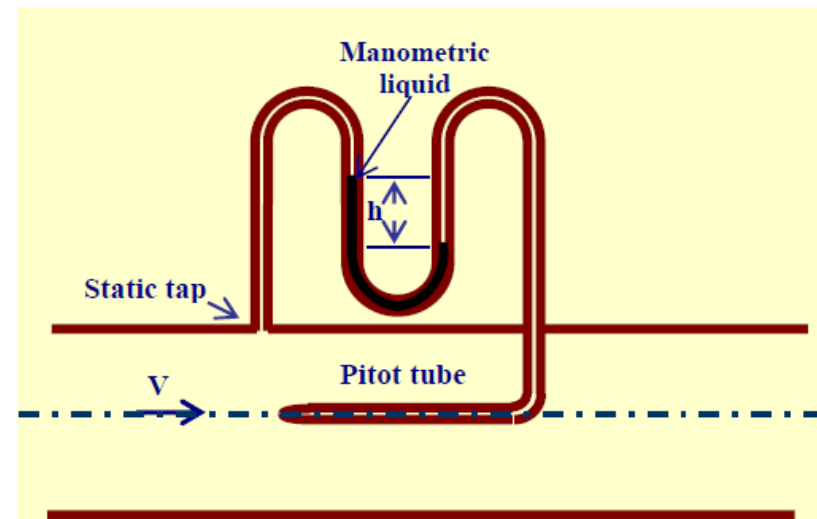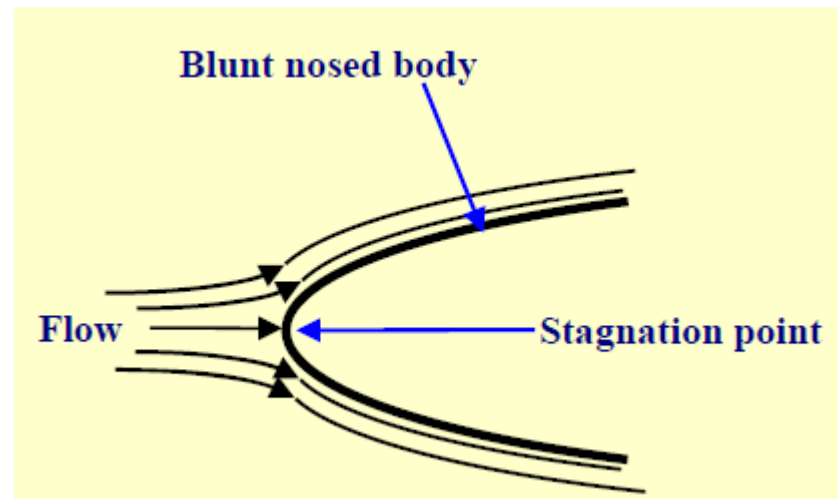With as the density of the manometer liquid the pressure difference is given as,

$$p_o - p = (\rho_m - \rho)gh \qquad (2)$$

Combining equations (1) and (2) we get,

$$V = \sqrt{2\frac{(\rho_m - \rho)}{\rho}gh} \qquad (3)$$

Blunt nosed body

Flow →

Stagnation point

Manometric liquid

h

Static tap

V

Pitot tube

(top) Flow of a fluid in the vicinity of a blunt nosed body (bottom) Schematic of Pitot tube

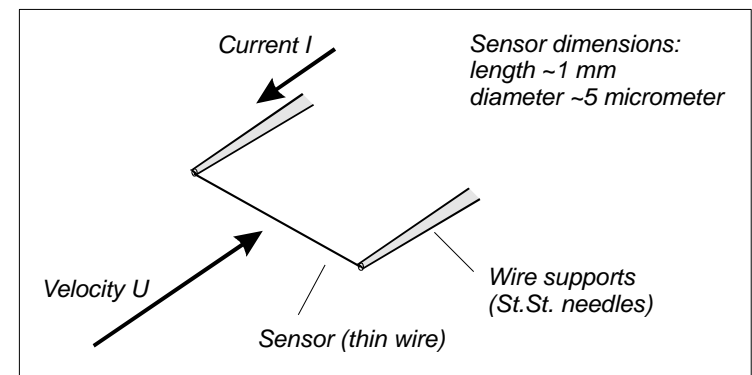# Hot wire anemometer

- **Purpose**

  To measure mean and fluctuating velocities in fluid flow

- **Principle of operation**

  Consider a thin wire mounted to supports and exposed to a velocity U. When a current is passed through wire, heat is generated ($I^2 R_w$). In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings.

  If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.

Current I

Sensor dimensions:
length ~1 mm
diameter ~5 micrometer

Velocity U

Wire supports
(St.St. needles)

Sensor (thin wire)

Steady state heat transfer:

$$I^2 R_w = hA(T_w - T_a) \qquad I^2 R_w = Nu \, k_f \, A(T_w - T_a)/d$$

h = film coefficient of heat transfer

A = heat transfer area

d = wire diameter

T_a = ambient temperature

k_f = heat conductivity of fluid

Nu = Nusselt number

$$I^2 R_w{}^2 = E^2 = (A + B \cdot U^n)$$

"King's law"

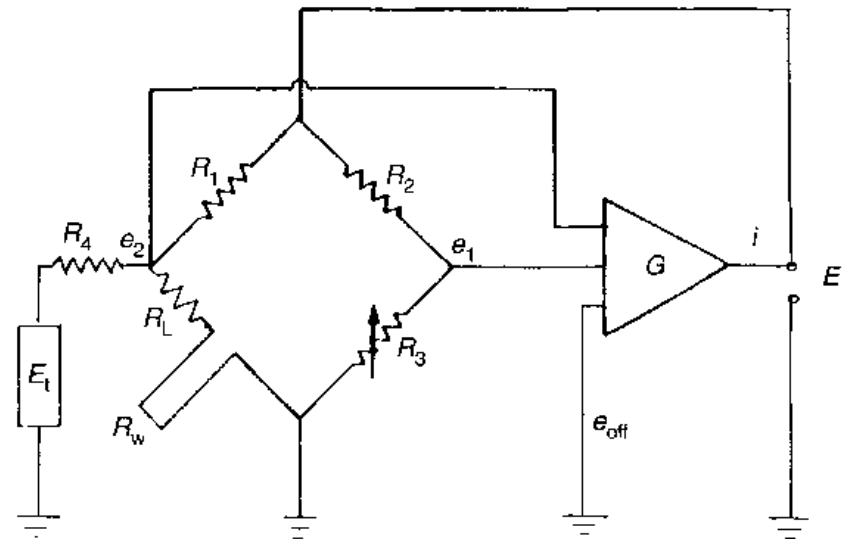- ## Constant temperature (CTA)

Principle:

Sensor resistance is kept constant by servo amplifier

Advantages:

- Easy to use
- High frequency response
- Low noise
- Accepted standard

Disadvantages:

- More complex circuit

- Constant current (CCA)
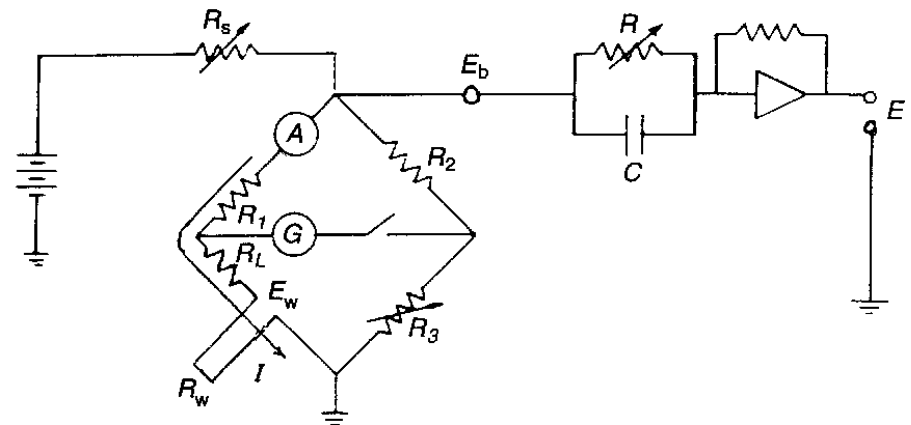
- **Principle:**

  Current through sensor is kept constant

- **Advantages:**

  - High frequency response

- **Disadvantages:**

  - Difficult to use
  - Output decreases with velocity
  - Risk of probe burnout

Advantages :

- No moving parts
- High frequency response (as high as 10 kHz)
- Fine spatial resolution
- Ideal for turbulent flows for resolving velocity fluctuations at high frequency

Limitations:

- Fragile, can be used only in clean gas flows
- Cannot be used in hot flows
- Needs to recalibrated frequently due to dust accumulations
- High cost

Humidity Measurements : Hygrometer

- A hygrometer is a device to measure the air humidity
- There are several types of hygrometers. The common ones are :
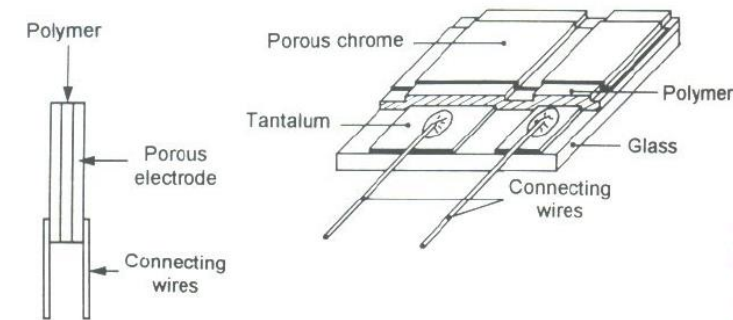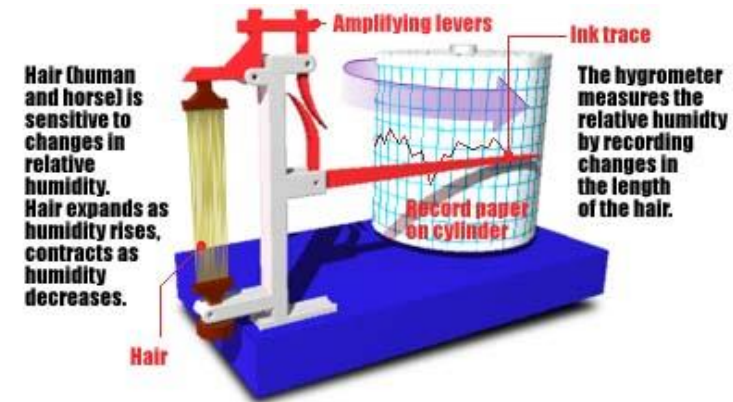
➢ **hair hygrometer**

- effect: detection of change of length of a human (or horse) hair in response to relative humidity changes
- hair length changes as in keratin hydrogen bonds are broken in the presence of water vapour
- slow response

➢ **capacitive hygrometer**

- effect: hygroscopic polymer is placed between two electrodes. In the presence of water vapour, the volume of the polymer increases, decreasing the capacitance of the device. This change in capacitance is proportional to a change in relative humidity.
- are easily contaminated

➢ **absorption hygrometer**

- a hygrometer that uses a hygroscopic chemical to absorb atmospheric moisture.
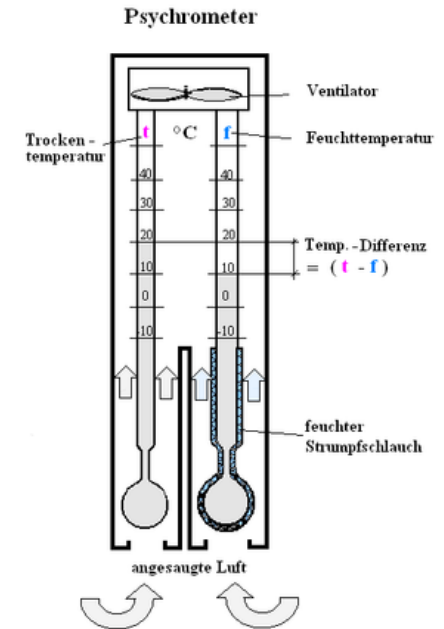
➤ **psychrometer**

- effect: T-difference between two ventilated thermometers, one of which is covered by a wet wick (wet bulb temperature). T-difference is proportional to relative humidity

- Using the formula below

$$e = e_{sat\ wet} - c\ (T_{dry} - T_{wet})$$

water vapour partial pressure

water vapour saturation pressure at T_{wet}

Psychrometer

Ventilator

Trocken - temperatur

°C

Feuchttemperatur

Temp. -Differenz = (t - f)

feuchter Strumpfschlauch

angesaugte Luft
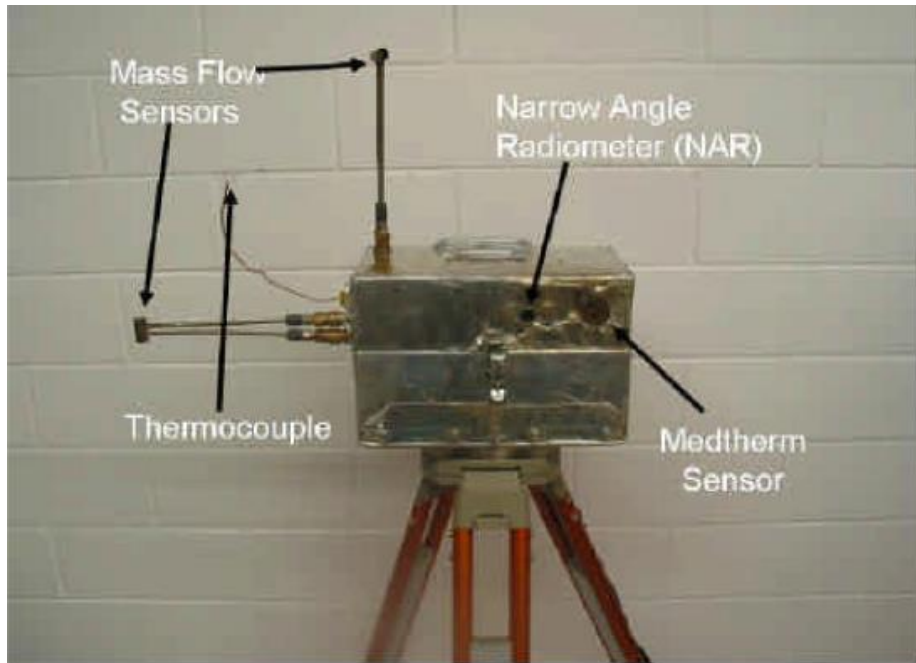
Fire Behavior Sensor Package

Figure 1—View of fire behavior package with sensors labeled.

Figure 2—View of digital camera enclosure and camera mounting plate.

[1] Dan Jimenez et. al., Fire Behavior sensor package Remote Trigger Design, USDA Forest Service Proceedings RMRS-P-46CD. 2007

Measurements in Wildland Fire

- Two Time-resolved heat flux data from two different locations and times in the same prescribed fire event were collected

- **Burn 1**: dominated by forest grasses with minimal conifer litter resulting in low fire intensity and are best described by a grassland fire behavior fuel model GR1 (Scott and Burgan 2005), **Burn 2**: modest concentration of woody fuels that are best described as a slash-blowdown fire behavior model SB1 (Scott and Burgan 2005)

- Despite the radiative and convective heat flux magnitude difference between two sets of measurements, they exhibited similar temporal characteristics

- The data was sampled at various sampling rates (100, 50, 10, 5 and 1 Hz)

- Flame arrival was preceded by several short duration but high magnitude convective pulses

- The radiative heat flux exhibits significantly lower amplitude temporal fluctuations than the convective signal which is characterized by short duration, large magnitude positive (heating) and low magnitude (cooling) pulses

- Convective heating is characterized by high-frequency and high magnitude fluctuations up to 100 Hz whereas radiative heating is limited to fluctuations less than 10 Hz. The peak magnitude of the convective heating is substantially greater than the radiative heating
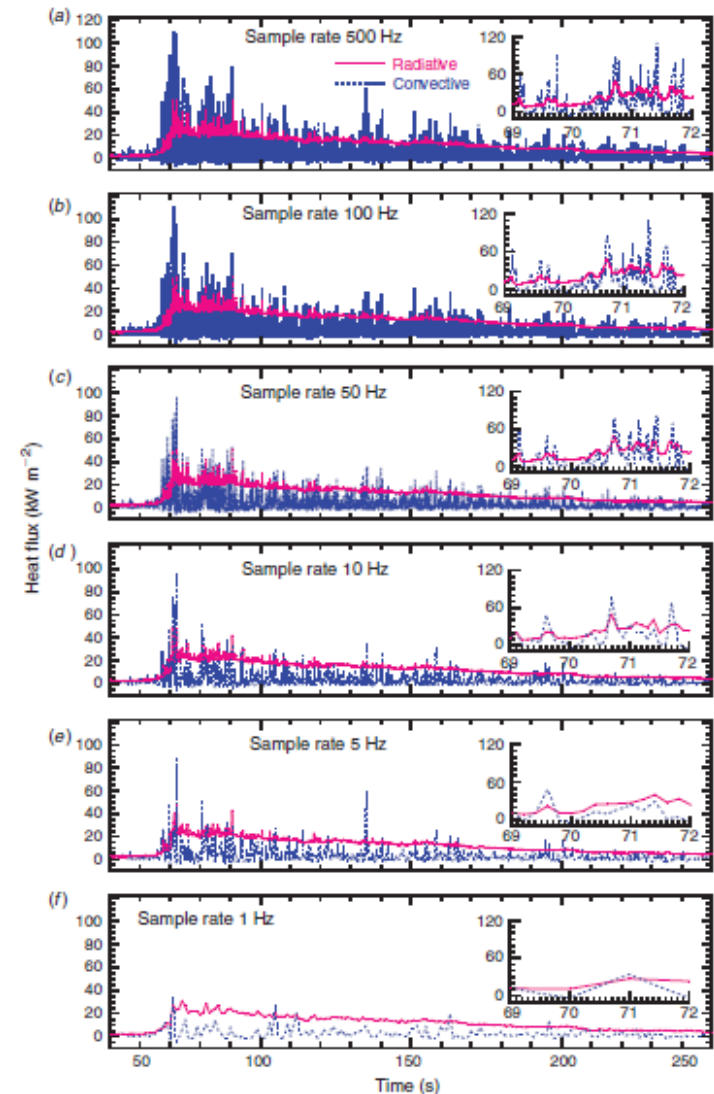
[1] D. Frankman, B.W. Webb, B.W. Butler, D. Jimenez, M. Harrington, The effect of sampling rate on interpretation of the temporal characteristics of radiative and convective heating in wildland flames, Intl. Journal of Wildland Fire, 2013, 22, 168-173

Fig. 1. The effect of sample rate on measured heat flux in Burn 2. (*a*) presents the initial signal captured at 500 Hz, (*b*) presents the 500-Hz signal down-sampled to 100 Hz and so on to 1 Hz for (*f*). The inset figures depict the signal over a 4-s time period centred at or near ignition.

- Fire Radiative Energy (FRE) has been shown to relate directly to fuel consumption

- FRE and Fire Convective Energy (FCE) was represented as the integral of the radiative and convective heat flux respectively

- From ignition onward both the cumulative radiative and convective energy rise until the combustion event is over for both datasets

- Comparison of the cumulative flux histories calculated from the six sampling rates indicates that FRE and FCE may be resolved with little loss in accuracy even at 1 Hz

- Although high frequency sampling is necessary to capture rapid temporal fluctuations and accurately resolve peak values, the cumulative heating load is dominated by longer-duration heating events in the record and can be measured at considerably lower sampling frequencies

- For sampling frequencies from 1 to 10 Hz caution should be exercised when interpreting peak radiative fluxes as it is likely that actual peaks are not resolved

- Convective heating fluctuations occur at much higher frequency than radiative heating
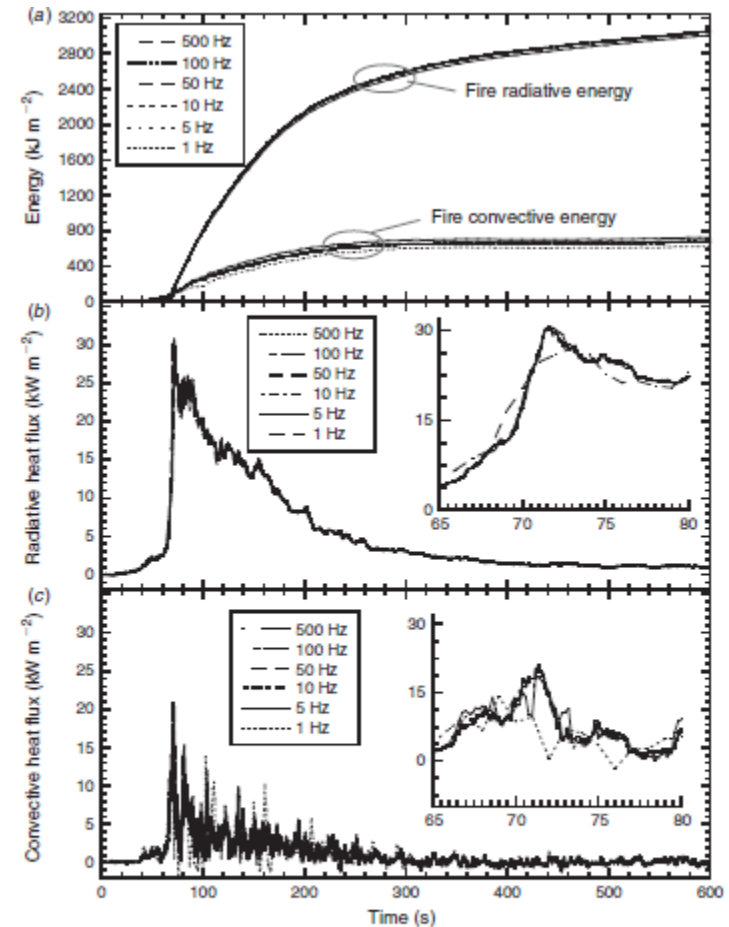

Fig. 2. Integrated energy and 2-s moving averages for Burn 2. (a) Fire radiative energy and convective energy calculated from integral of measured fluxes, (b) fluxes calculated using a 2-s moving average of the 500-, 100-, 50-, 10-, 5- and 1-Hz radiative flux signals, (c) fluxes calculated using a 2-s moving average the 500-, 100-, 50-, 10-, 5- and 1-Hz convective flux signals. Inset figures in (b) and (c) are included to further illustrate the difference in signal between the moving averages of the various sample rates over a short time frame.

[1] D. Frankman, B.W. Webb, B.W. Butler, D. Jimenez, M. Harrington, The effect of sampling rate o interpretation of the temporal characteristics of radiative and convective heating in wildland flames, Intl. Journal of Wildland Fire, 2013, 22, 168-173

Thank You