Sensors and Instrumentation

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Outline

- Temperature measurement – Thermocouples

- Heat Flux measurement – Heat Flux gauge
  - Gardon gauge
  - Schmidth 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.

\[ T_{Tip} = a_0 + a_1 V_{out} + a_2 V_{out}^2 + \ldots + a_n V_{out}^n \]

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

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

Can be quantified precisely and accurately.

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

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

For an unsteady system, it becomes

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

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

\[ \tau = \frac{m_b c_p}{hA_b} \quad \gamma = \frac{\varepsilon \sigma}{h} \]

For a steady system, it becomes

\[ T_g - T_b = \frac{\varepsilon d \sigma}{kNu} (T_b^4 - T_{\text{surr}}^4) \] (4)

\[ Nu = \frac{hd}{k} \]

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,

\[ \text{Nu}_{d,sph} = 2.0 + 0.60 \text{Re}_{d}^{1/2} \text{Pr}^{1/3} \]

Ranz and Marshall (1952) [3]

For Reynolds number between 0 and 200. Properties evaluated at \( T_{\infty} \)

\[ \text{Nu}_{d,sph} = 2.0 + (0.4 \text{Re}_{d}^{1/2} + 0.06 \text{Re}_{d}^{2/3}) \text{Pr}^{0.4} \left( \frac{\mu_{\infty}}{\mu_s} \right)^{1/4} \]

Whitaker (1972) [4]

\[ 0.71 < \text{Pr} < 380 \quad 3.5 < \text{Re} < 76000 \]

Properties evaluated at \( T_{\infty} \). \( \mu_s \) is the gas viscosity evaluated at the surface temperature

\[ \text{Nu}_{d,sph} = 2 + 0.37 \text{Re}^{0.6} \text{Pr}^{0.33} \]

[2]

For all Re and Pr numbers of interest in low flow velocities
Cylindrical Nusselt number Correlations

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,

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

With the Reynolds number evaluated at the so-called “film temperature”,

$$ T_m = \frac{T_b + T_\infty}{2} $$

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

$$ Nu_{d,cyl} = 0.42 \text{Pr}^{0.2} + 0.57 \text{Pr}^{\frac{1}{3}} \text{Re}_d^{\frac{1}{2}} \quad 0.01 < \text{Re} < 10000 $$

With the gas properties evaluated at

$$ T_m = \frac{T_b + T_\infty}{2} $$

(3) Andrews et. al. (1972) [7] evaluated the following expression for

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

$$ 0.02 < \text{Re} < 20 $$
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

Heat Flux Measurements: Heat Flux gauge
Heat Flux Gauge: Governing principle

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

- Gardon gauges 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.

- Schmidt-Boelter gauges 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.
Heat Flux Gauge: Governing principle

- 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

- Foil thickness: \( \delta \), Foil radius: \( R \), Thermal conductivity of foil material: \( k \), Heat flux: \( q \)
Heat Flux Gauge: Governing principle

- 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: \( (2\pi k \delta) \frac{d}{dr} \left( r \frac{dT}{dr} \right) dr \)

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

\[
\frac{d}{dr} \left( r \frac{dT}{dr} \right) + \frac{q}{k \delta} r = 0 \quad (1)
\]

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:

\[
T = T_R + \frac{q}{4k \delta} (R^2 - r^2) \quad (2)
\]
Heat Flux Gauge: Governing principle

- Equation (2) may be written as:
  \[ q = \frac{T_0 - T_R}{R^2} = K(T_0 - T_R) = K\Delta T \]  \hspace{0.5cm} (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 \( K = \frac{4k\delta}{R^2} \) 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, \( \Delta V \), 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:

  \[
  \tau = \frac{R^2}{4\alpha} 
  \]

  - R: Foil radius
  - \( \alpha \): Thermal diffusivity of the foil material
Advantages and Limitations

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
Introduction: Atmospheric boundary layer

- Wind
- "Rural" boundary layer
- Boundary layer above the urban canopy
- Surface layer
- Land surface
- Urban canopy layer
- Transition zones
- Boundary layer below roughness elements
- Mixed layer
- Surface layer
- Wake layer
- Urban boundary layer
Wind speed measurement principles

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,

\[ V = \sqrt{u^2 + v^2 + w^2} \]

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,

\[ s = \sqrt{u^2 + v^2} \]
The most common wind speed measurement device is the cup anemometer.

Many cup anemometers have a vane attached to measure wind direction.
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 \( u_c = r \frac{d\theta}{dt} \), 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 \( (T) \).
Wind cup anemometer: Governing Principle

- 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):

  \[ I = \sum m r^2 \sim 10^{-4} \text{ kg m}^2 \]

- So the governing equation is:

  \[ I \frac{d^2 \theta}{dt^2} = T_d - T_f \]

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:

$$\gamma^2 - 2G \gamma + 1 = 0 \quad \text{where} \quad G = (c_{df} + c_{db})/(c_{df} - c_{db}) = (1+\varepsilon)/(1-\varepsilon)$$
Wind cup anemometer: Governing Principle

- where \( \varepsilon = \frac{c_{db}}{c_{df}} < 1 \). This is a quadratic equation for the steady state calibration factor \( \gamma = \frac{u_c}{s} \) (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 \( \gamma = \frac{u_c}{s} \), one large and one very small. These are ostensibly eligible solutions; but for any \( \varepsilon \), it would have been more satisfying to find only one real root. Never mind, our model is an oversimplification.
Wind cup anemometer: Potential errors

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

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.
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 \( \rho \)) is

\[
c = (\gamma \frac{p}{\rho})^{1/2}
\]

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

- **P1 (down):** $t_1 = d / (c + V_x)$
- **P2 (up):** $t_2 = d / (c - V_x)$

Then

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

while

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

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

**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
Pitot tube: Introduction

- 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
Pitot tube: Governing principle

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

Stagnation pressure \hspace{1cm} Static pressure

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

$$ p_o - p = (\rho_m - \rho) gh $$ \hspace{1cm} (2)

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

$$ V = \sqrt{2 \frac{(\rho_m - \rho)}{\rho} gh } $$ \hspace{1cm} (3)
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 ($I^2R_w$). 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.
Steady state heat transfer:

\[ I^2 R_w = hA(T_w - T_a) \quad I^2 R_w = Nu k_f A(T_w - T_a)/d \]

- \( h \) = 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”
Modes of Anemometer operation

- 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
Modes of Anemometer operation

- **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 and Limitations

**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
  \[ e = e_{\text{sat wet}} - c (T_{\text{dry}} - T_{\text{wet}}) \]

- water vapour partial pressure
- water vapour saturation pressure at \( T_{\text{wet}} \)
Fire Behavior Sensor Package
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.

Measurements in Wildland Fire
Wildland fire measurements

- 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.

Wildland fire measurements

- 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

Thank You