Well resolved measurements of turbulent fluxes in the atmospheric surface layer

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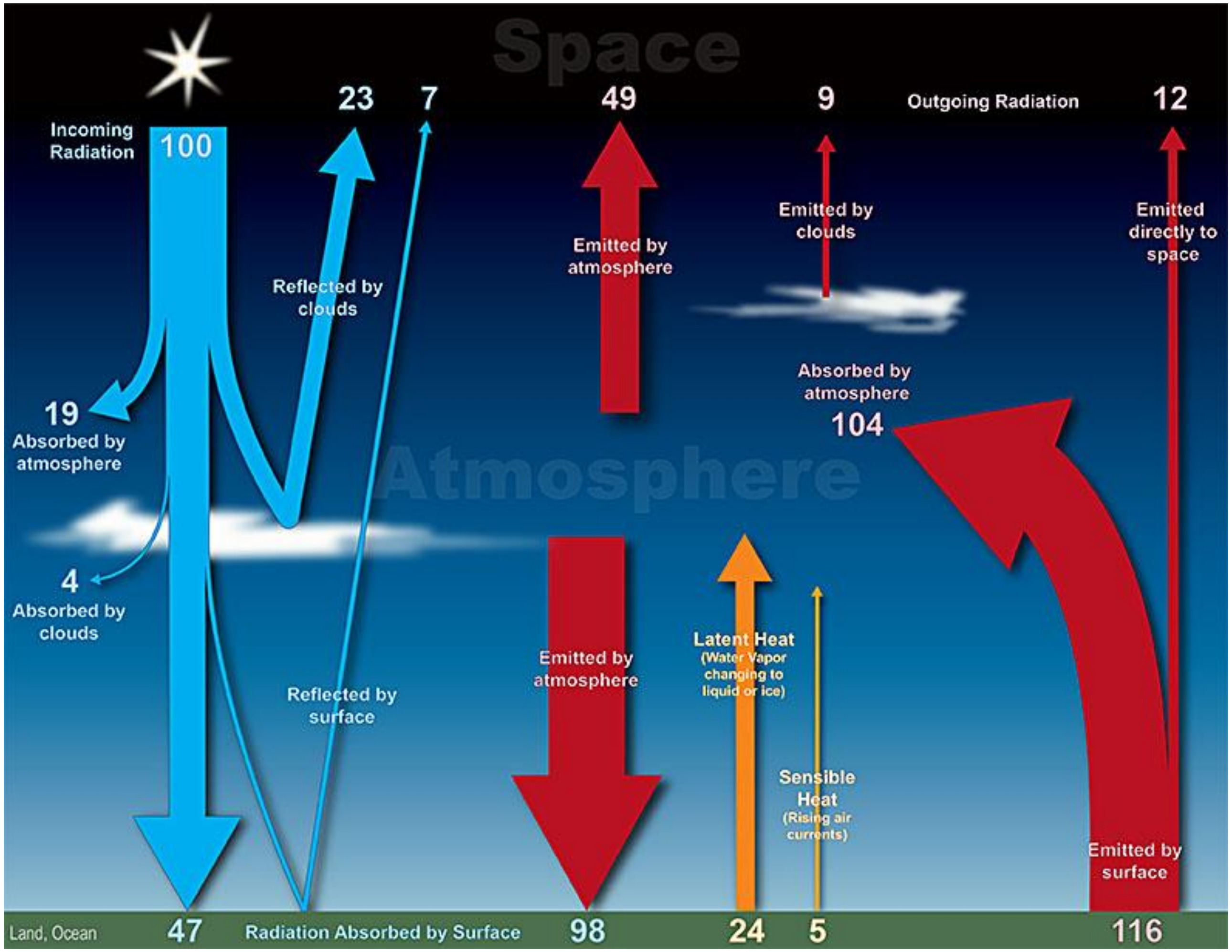
The energy balance at the surface



Typical Energy balance at the surface:

~ 80% radiation

~ 17% Latent heat flux

~ 3% Sensible heat flux

Often challenging to close the energy balance, and even in extremely carefully conducted experiments 10-20% is often missing.

From http://www.srh.noaa.gov/

A short introduction to fluxes

- The surface flux is governed by the gradient of the scalar at the surface and the diffusion coefficient.

$$q = \Gamma \frac{\partial \phi}{\partial z}\bigg|_{z=0}$$

- Turbulence will increase the flux by increasing the gradients close to the surface. **The big question is how.**
- Dynamics governed by the convection-diffusion equation (assuming no dynamical effect on fluid motion).

$$\frac{\partial \phi}{\partial t} + u_j \frac{\partial \phi}{\partial x_j} = \Gamma \nabla^2 \phi$$

- Reynolds averaging

Turbulent flux

$$\frac{\partial \Phi}{\partial t} + U \frac{\partial \Phi}{\partial x} + W \frac{\partial \Phi}{\partial z} = \Gamma \nabla^2 \Phi - \frac{\partial \overline{w'\phi'}}{\partial z}$$

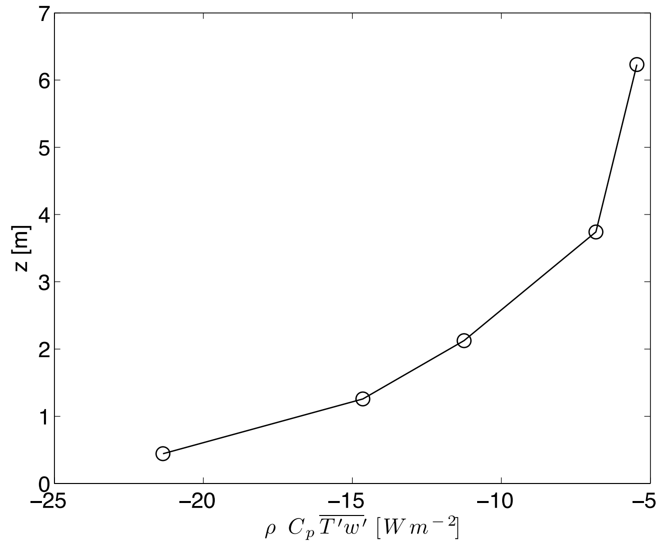
To accurately measure surface fluxes through turbulent fluxes

- Turbulent scalar flux: contribution of turbulence in the transport of the scalar.
- If convective terms are negligible (constant stress or constant flux assumption)

$$\alpha \frac{\partial^2 T}{\partial z^2} = \frac{\partial \overline{T'w'}}{\partial z} \Rightarrow \Gamma \frac{\partial \Phi}{\partial z}\bigg|_{z=0} = \overline{\phi' w'}(z)$$

- If we can measure $\overline{\phi' w'}$ away from the surface we can estimate the flux close to the surface.

Sensible Heat Flux



Oldroyd *et al.*

To accurately measure surface fluxes through turbulent fluxes

- In many cases the constant stress / constant flux assumption fails :
  - Non-negligible convection terms (e.g. heterogeneous terrain)
  - Dynamical effects not negligible (e.g. buoyancy)
- Need to measure the turbulent flux close to the surface (and really should always check constant flux assumption).
- Even when constant flux assumption is sound it can be very challenging to acquire accurate measurements.

$$\overline{\phi' w'} = \int_{-\infty}^{+\infty} F.T.\{\gamma_{\phi w}\}(f) df$$

- Sensors need to resolve all scales of turbulence (T, Q and w for latent and sensible heat flux).
- In the ABL that normally means from approx. 1 mm to 1 km.

Taylor's hypothesis and flux measurements

- In order to resolve all scales we need a sensor that is smaller than the smallest eddies and faster than the fastest frequency.

$$f = \frac{U}{\lambda} = \frac{Uk}{2\pi}$$

- Tower measurements a windy day:

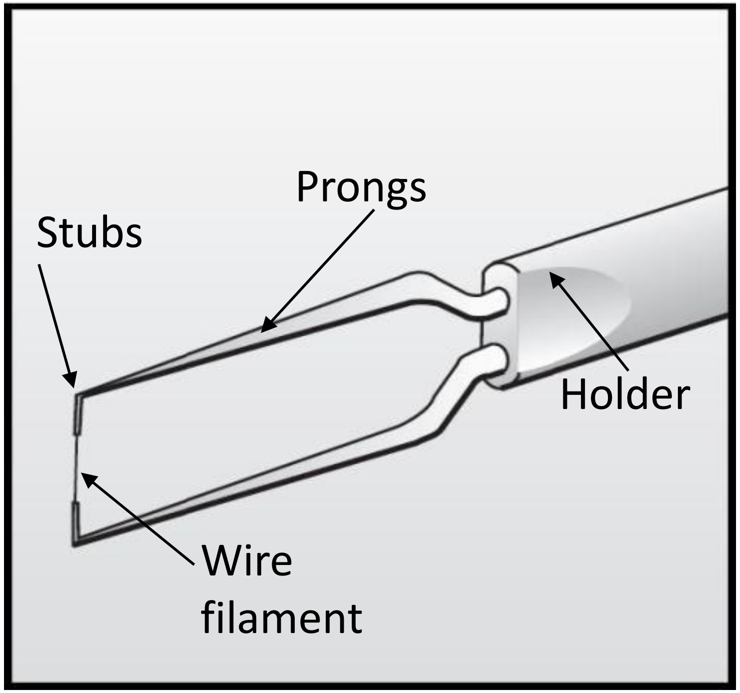
$$\frac{10m/s}{0.001m} = 10kHz$$

- Conventional sensors much slower than this!
  - Sonic anemometer (velocity): up to 20 Hz and $\sim 100\ mm$
  - Hot-wire anemometry (velocity): $\sim 20\ kHz$ and $\sim 1\ mm$
  - Fine-wire thermocouple (temperature): $\sim 100\ Hz$ and $\sim 1\ mm$
  - Cold-wire sensors (temperature): $\sim 10 - 100\ Hz$ and $\sim 1\ mm$
  - Humidity sensor: up to 20 Hz and $\sim 100\ mm$ (most sensors much slower $\sim 0.1\ Hz$)
- **Need faster and smaller temperature and humidity sensors!**

Hot and cold-wires

Principle of operation :

- Electrical current passes through a thin wire
- Wire resistance changes with temperature
- Variation in resistance is monitored
- Can measure velocity or temperature



Velocity measurement :

- The wire is heated by electrical current and cooled down by forced convection

Temperature measurement :

- The wire is kept at temperature close to the ambient temperature
- Resistance is sensitive to temperature changes

New high resolution flux sensor

Our goal:

- Three component of velocity at least 10 kHz
- Temperature sensor at least 10 kHz
- Humidity sensor at least 10 kHz
- **All in a measurement volume less than 2 mm^3**

Our solution:

- Multi-component hot-wire anemometers for velocity
- MEMS for temperature and humidity

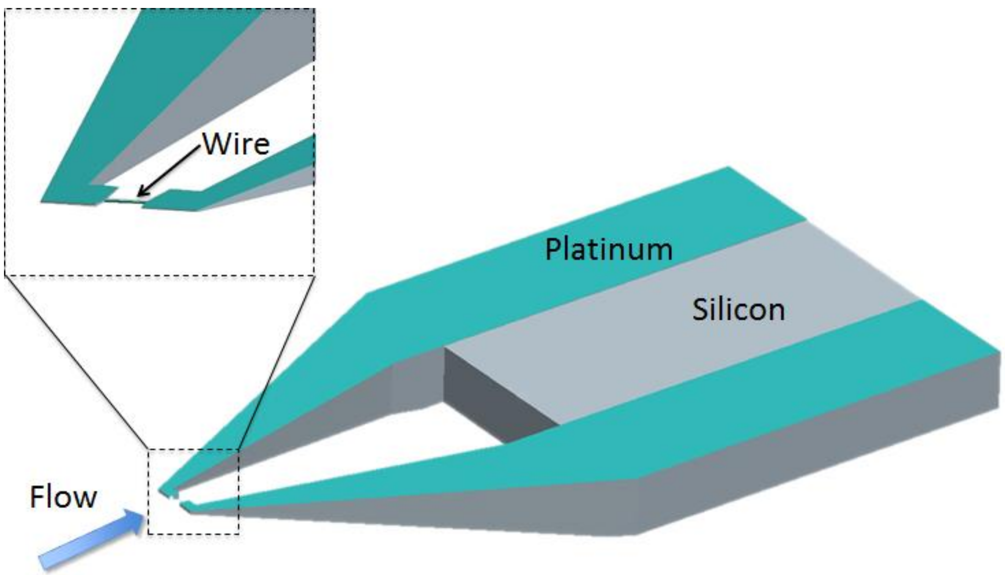
Nano-Scale Thermal Anemometry Probe (NSTAP)

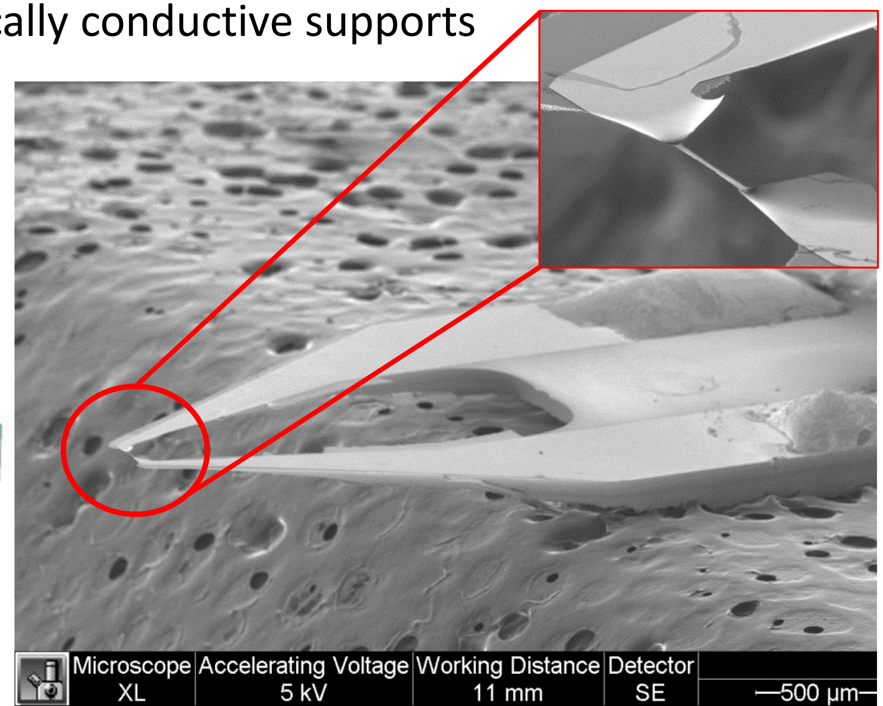
Advantages

- More than an order of magnitude smaller than conventional hot-wires
- Typical wire dimensions 30µm×1µm×100nm
- Several orders of magnitude faster

Fabrication

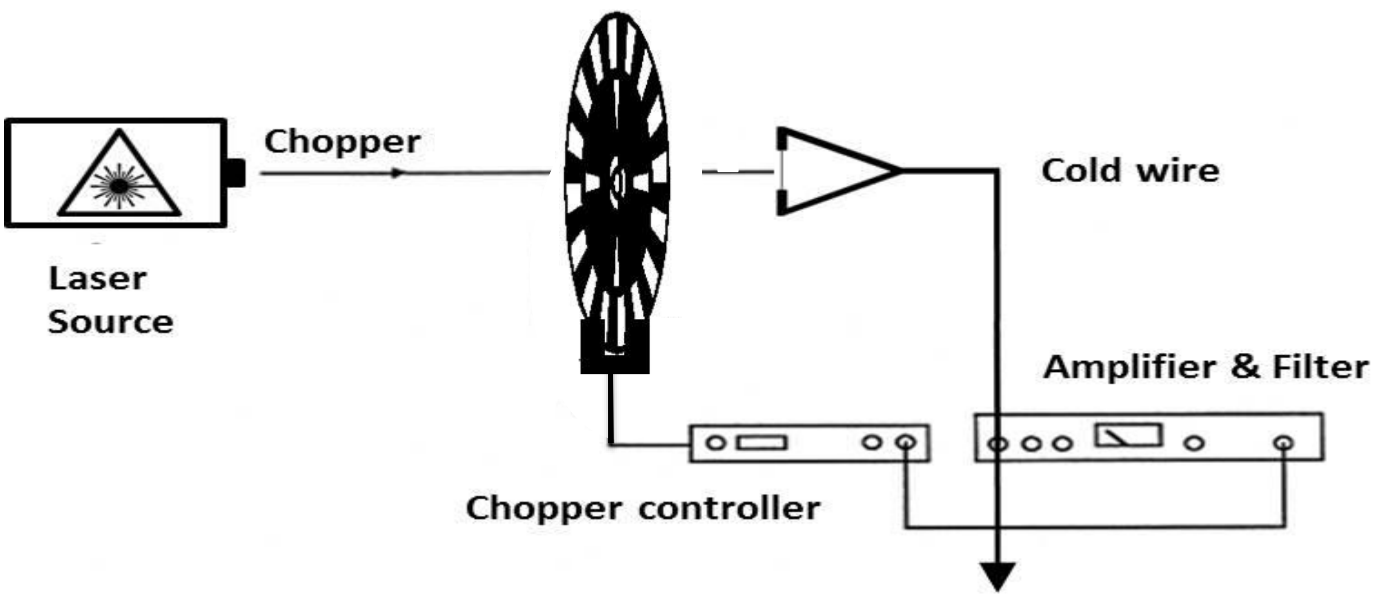
- Standard semiconductor manufacturing techniques
- Deep Reactive Ion etching in combination with conventional HF etching
- Platinum nano-wire between two electrically conductive supports





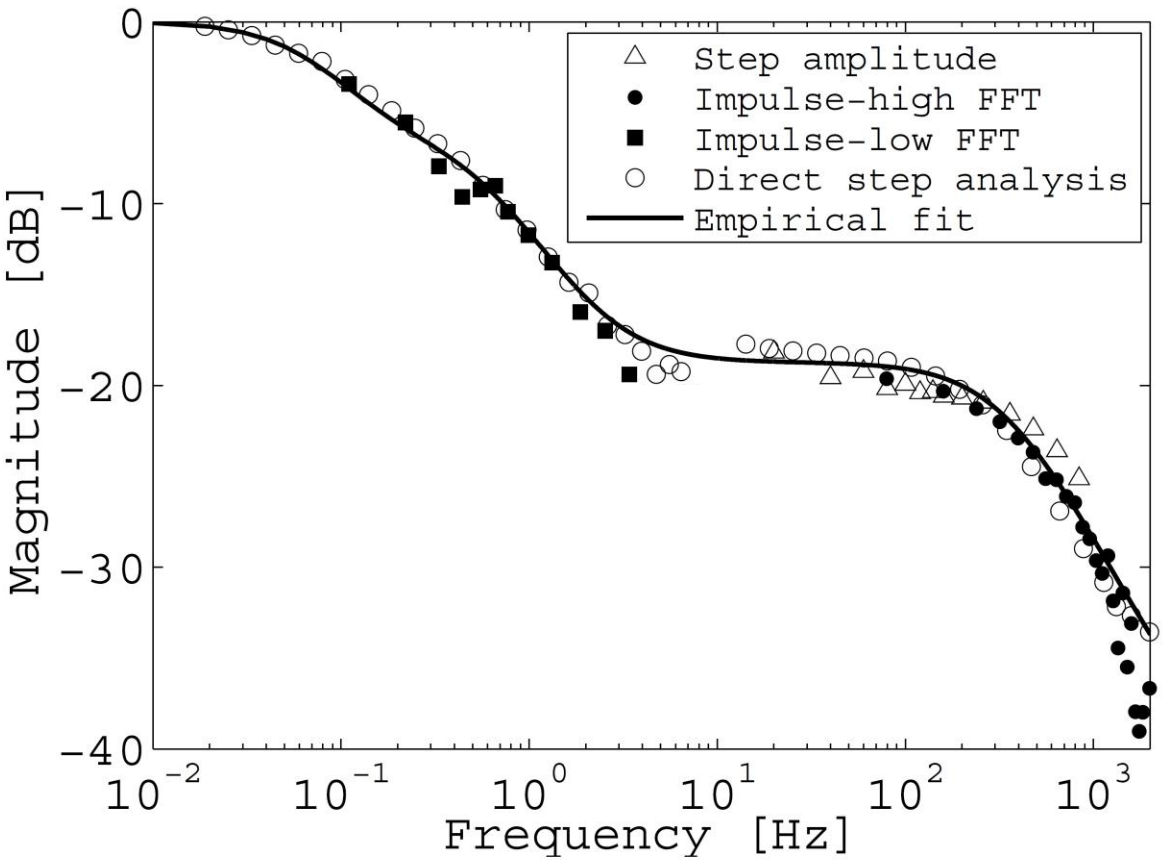
Test bench for temperature sensors

- Laser as heat source
- Optical chopper to vary the frequency
- Manual step for low frequencies



Characteristic Bode plot

- Data transferred to frequency domain
- Different methods to construct the plot



Modeling the cold wire

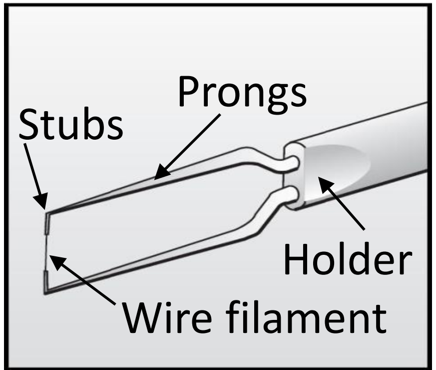
Lumped capacitance approach

$$Bi = \frac{hL}{k} < 1$$

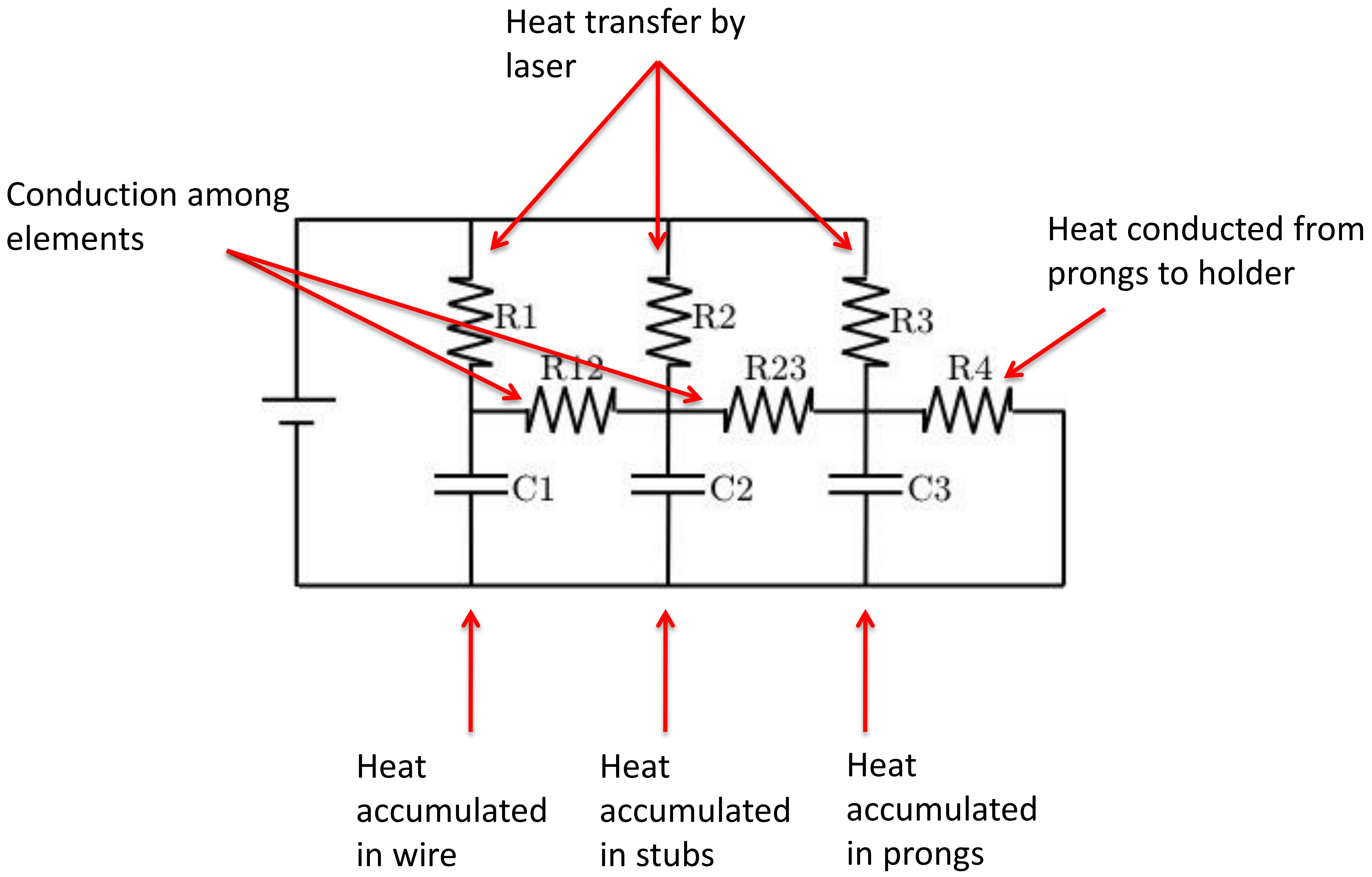
Conduction	$R = \frac{l}{kA}$	l : length k : coefficient of thermal conductivity A : area
Convection/ Radiation	$R = \frac{1}{hA}$	h : convection/radiation heat transfer coefficient A : area
Heat accumulated	$C = \rho c V$	ρ : density c : heat capacity V : volume

Considerations in constructing the model:

- Three elements: wire filament, stubs, prongs
- Heat transfer to each element through laser source
- End conduction between adjacent elements
- Holder acts as a heat sink



Cold wire model

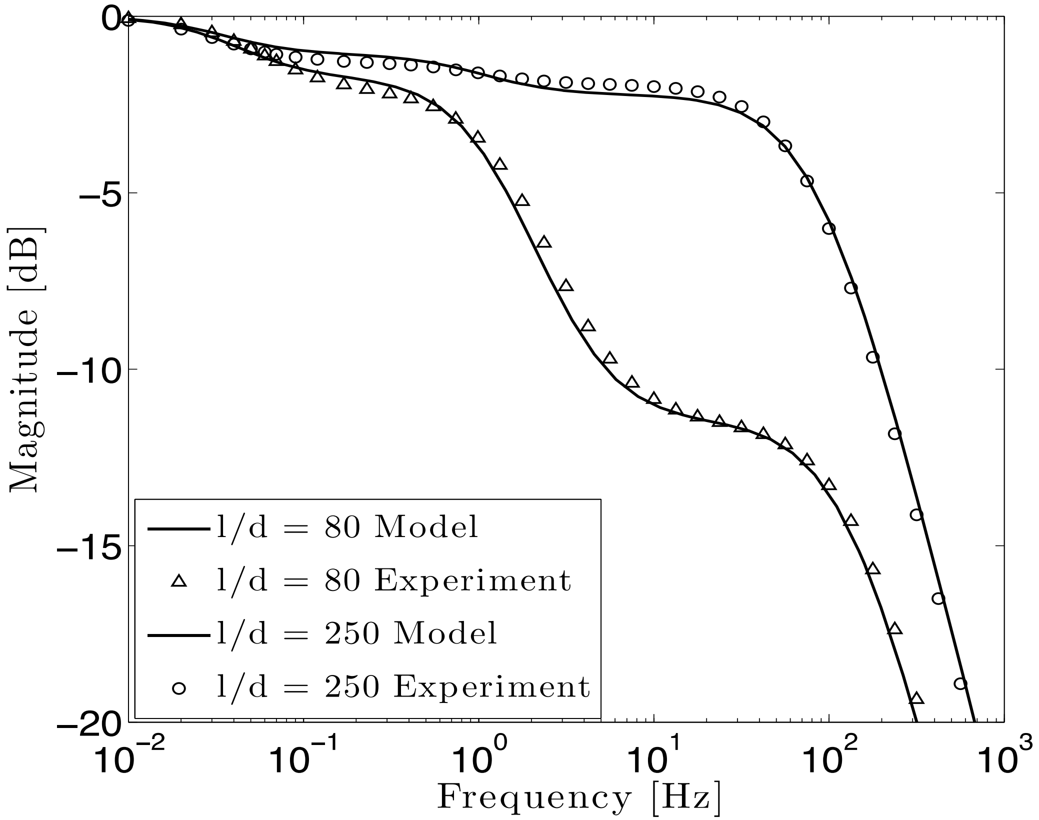


Results and model

Wire filament diameter:

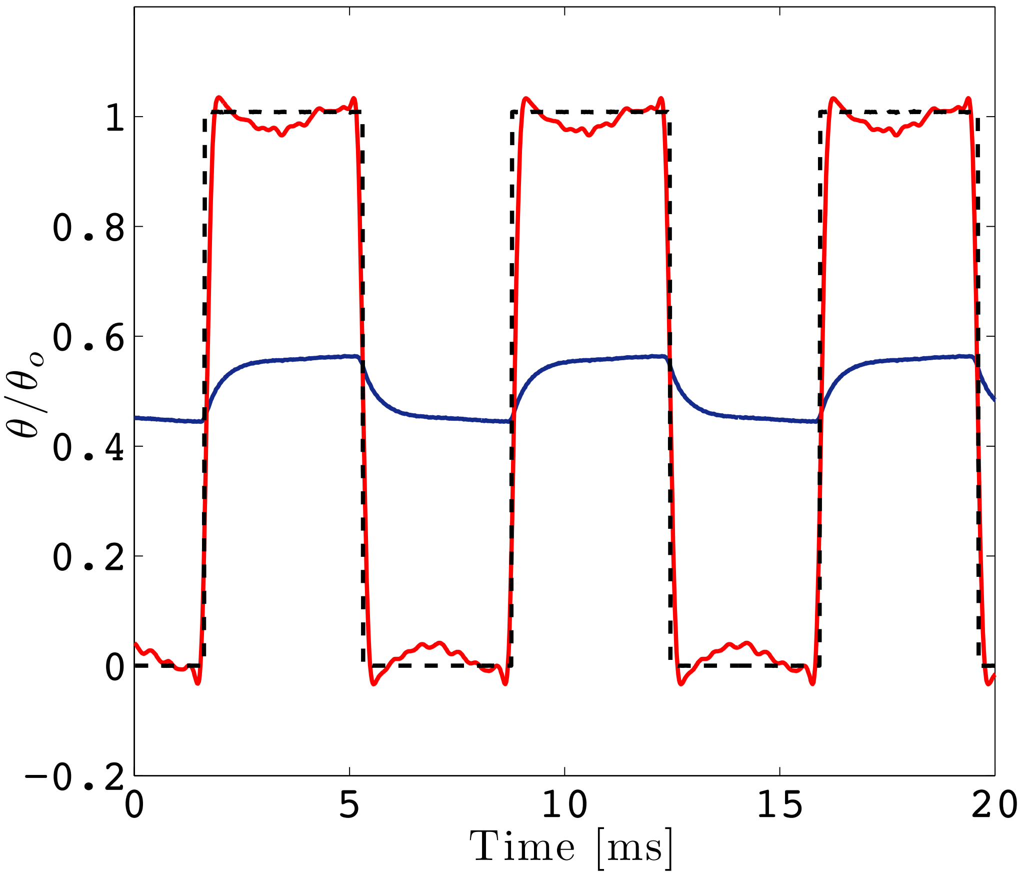
- Less attenuation for larger l/d
- Lower roll-off frequency for thicker wire

$d = 5\,\mu m$



Temperature correction

- Convolute the signal with $H_i(s)$
- Large discrepancy between measured and expected temperature
- Square wave almost perfectly restored



Design of true fast response temperature sensor

- Longer and thinner wire filament
- High conductivity prongs
- Thicker and shorter prongs

Wire filament

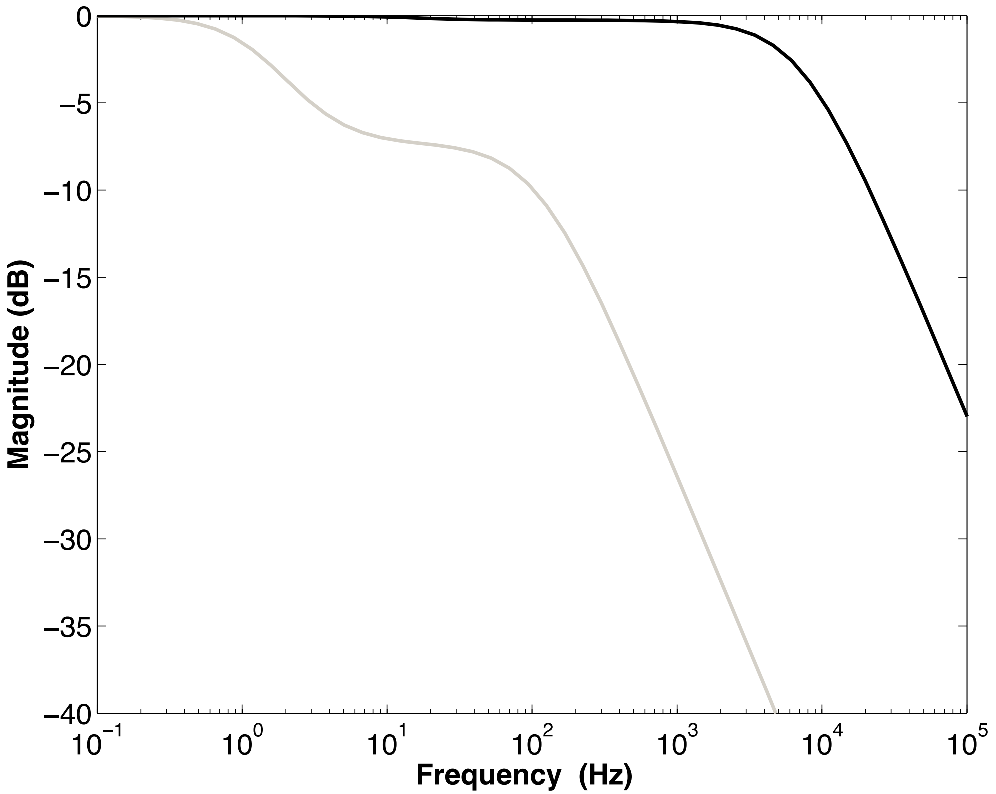
$l = 300\mu m$

$d = 200\eta m$

Gold prongs

$l_p = 1mm$

$d_p = 1mm$



Humidity sensor

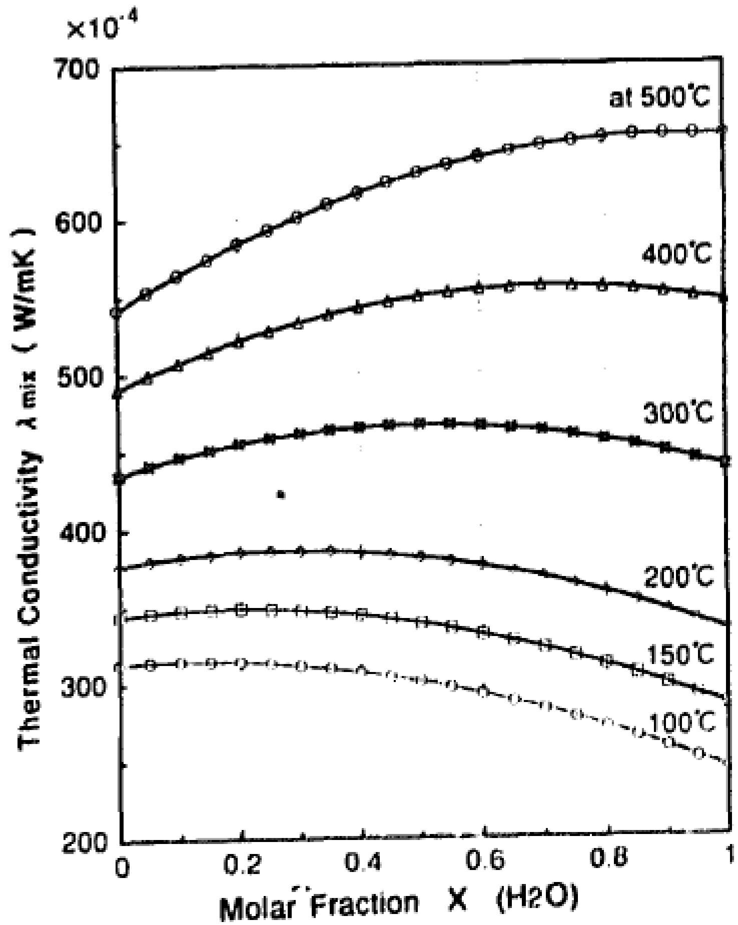
Thermal conductivity of air a strong function of humidity

- Can use a hot-wire to sense fluctuations in humidity.
- The problem is that it will also be sensitive to velocity.

$$Pe = \frac{convection\ to\ air}{conduction\ to\ air} = RePr$$

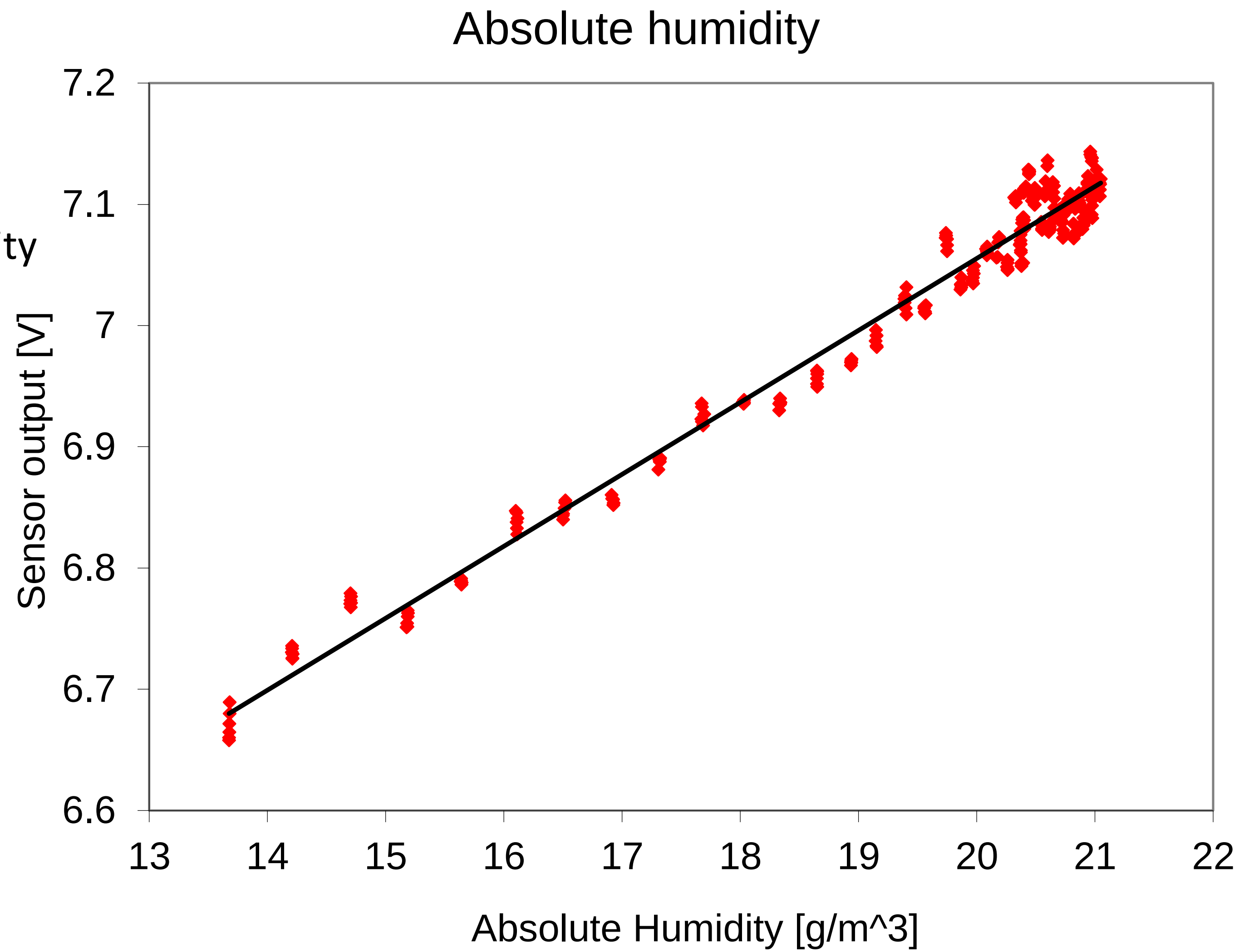
$$Re = \frac{UL}{\nu}$$

Need to make an even smaller NSTAP!

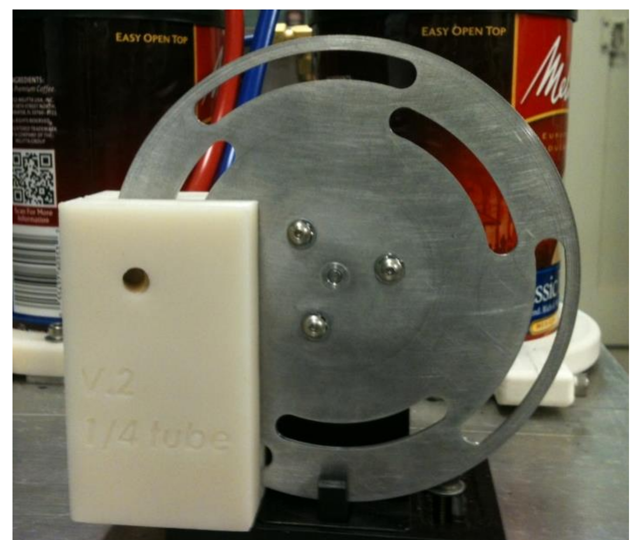


Humidity results

- Humidity steps
- Temperature correction
- Clear trend with humidity



Frequency response test bench



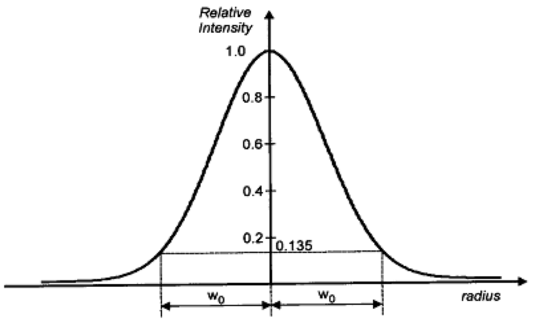
Conclusions

- Frequency response of cold-wires was tested and found to be slower than previously believed.
- A model for a cold-wire sensors was developed.
- The model can be used to correct data taken with inadequate bandwidth or as a tool to design high bandwidth temperature sensors.
- Fast response sensors have been developed using MEMS techniques, testing is in progress.
- A fast response humidity sensor is being developed, also that with MEMS techniques.
- Together these techniques will allow for the first truly unfiltered turbulent flux measurements.

Cold wire model

Radiation heat transfer coefficient h :

- Gaussian distribution
- Varies with radial position from the center of the beam
- Different for each element

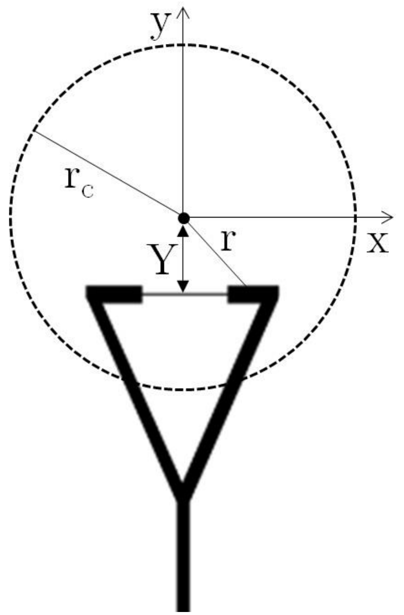


Determine the heat transfer coefficient for each element

$$h_{\max} = \frac{P}{\pi r_c^{\,2}(T_o - T_\infty)}$$

$$r_c = \frac{\int_0^\infty r e^{-r^2/w_o^2} dr}{\int_0^\infty e^{-r^2/w_o^2} dr}$$

$$h = h_{\max} e^{-r^2/w_0^2}$$



- Weighted average over the radius for each element