Blackbody Radiation

Thermal Fluids and Energy Systems Lab

(ME EN 4650)

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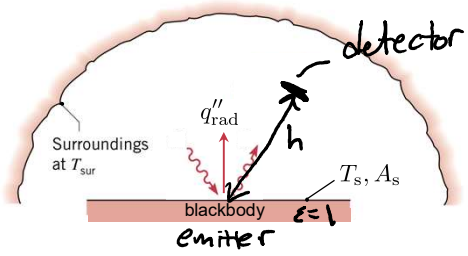
Heat Transfer by Thermal Radiation

What we want to know:

→ $\dot{q}''_{rad} = f(h, T_s, A_s)$

→ emissivity, ε

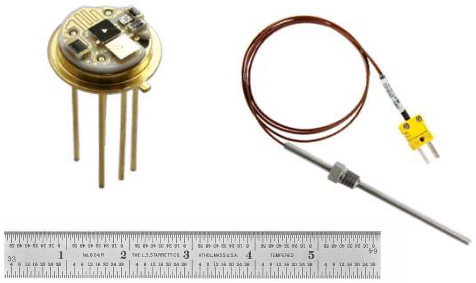


What we can measure:

→ $\dot{q}$ (pyroelectric radiometer)

→ T_s (thermocouple)

→ h, A_s (ruler)



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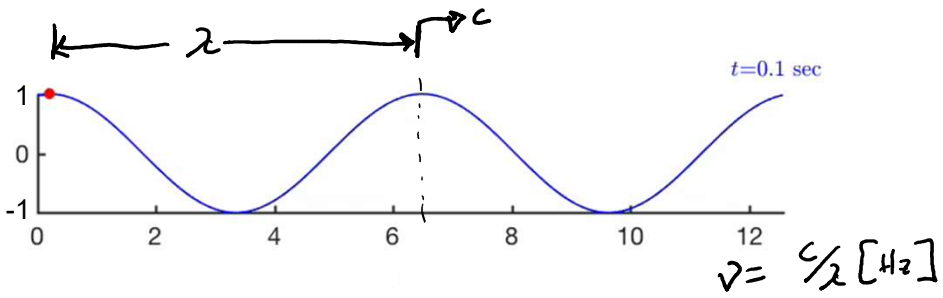
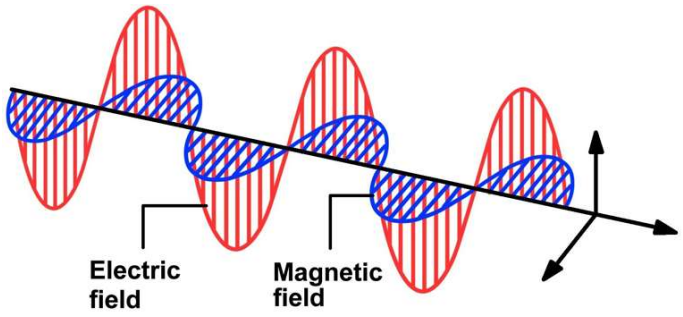
Electromagnetic Waves





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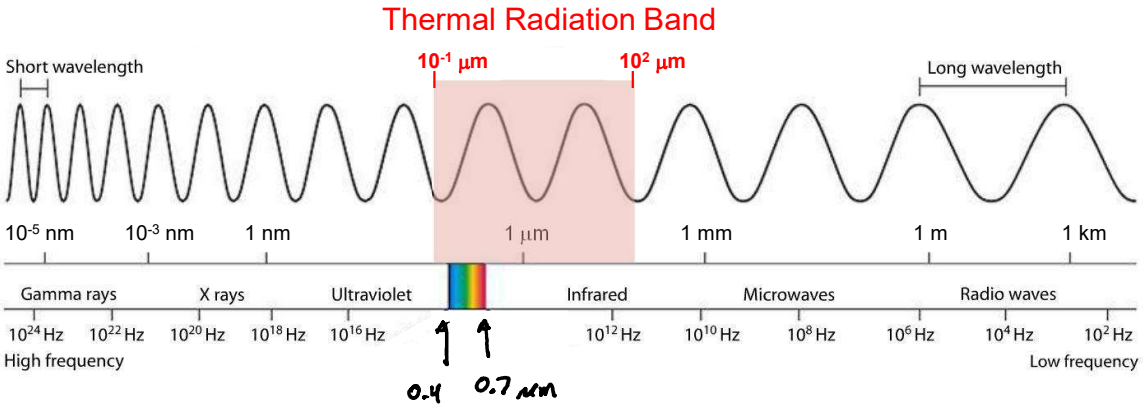
Electromagnetic Wave Spectrum



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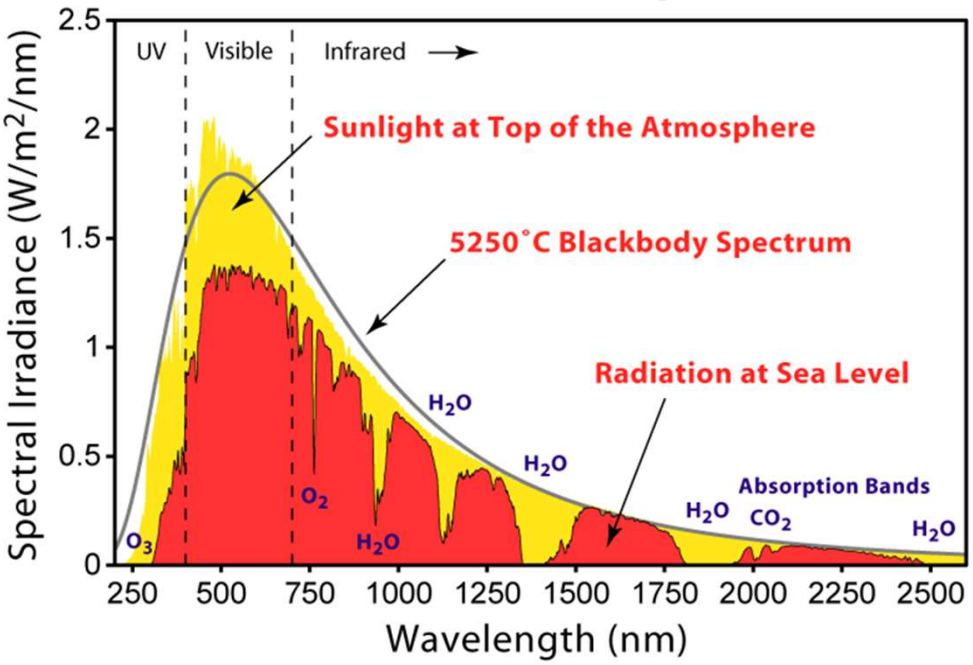
Solar Radiation Spectrum



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Solar Energy: Photovoltaic power generation

775000 PV panels, 48MW, Nevada

Rooftop PV panels

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Solar Energy: Heat for cooking

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Solar Energy: Water heaters

Evacuated Tubes

Flat plate heater

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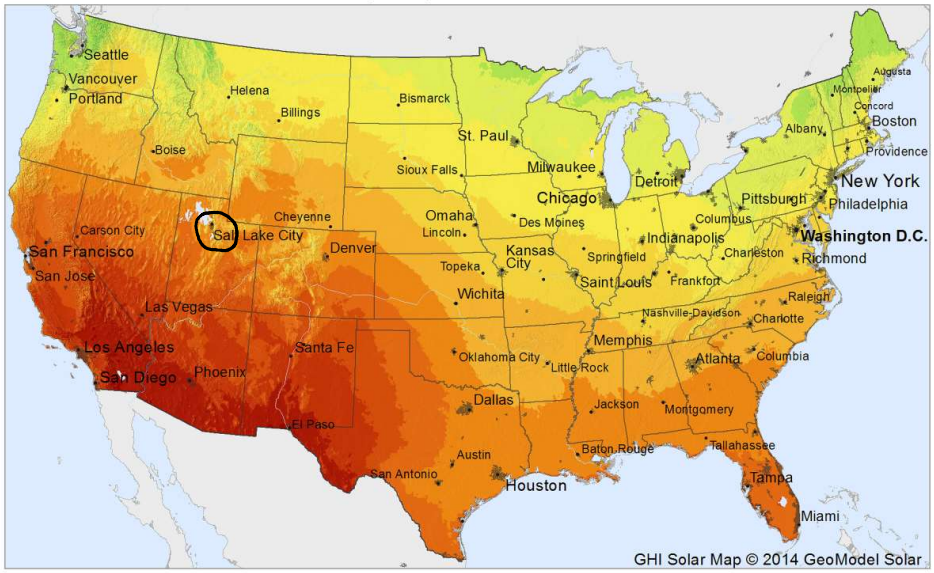
Solar Potential in the USA

Global Horizontal Irradiation (GHI) USA Mainlands



Average annual sum, period 1999-2013

<1200 1400 1600 1800 2000 2200> kWh/m²

0 200 400 km

$270\ ft^2$

$\left(500\ \frac{kWh}{mo.}\right)\left(12\ \frac{mo}{yr}\right)\left(1600\ \frac{kWh}{m^2 yr}\right) = 3.75\ m^2 \rightarrow 25\ m^2$

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Blackbody Radiation

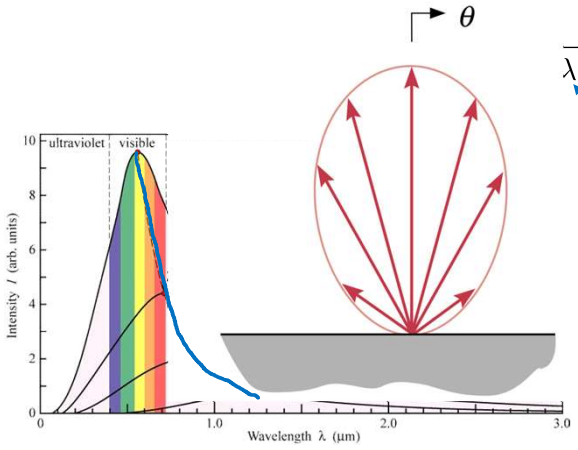
- For a prescribed temperature, no surface emits more energy
- Emitted radiation is independent of direction (diffuse emitter)
- Absorbs all incident radiation, regar[illegible] direction

$$\frac{2\,h\,c_o^2}{\lambda^5\left[\exp\left(\frac{h\,c_o}{\lambda\,k\,T}\right)-1\right]}$$

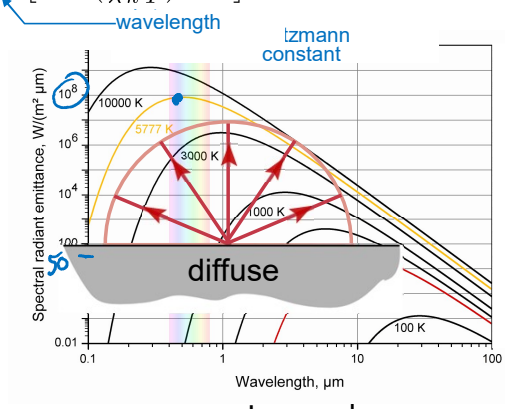
speed of sound in a vacuum

wavelength

[W/m]



Linear scale



Log scale

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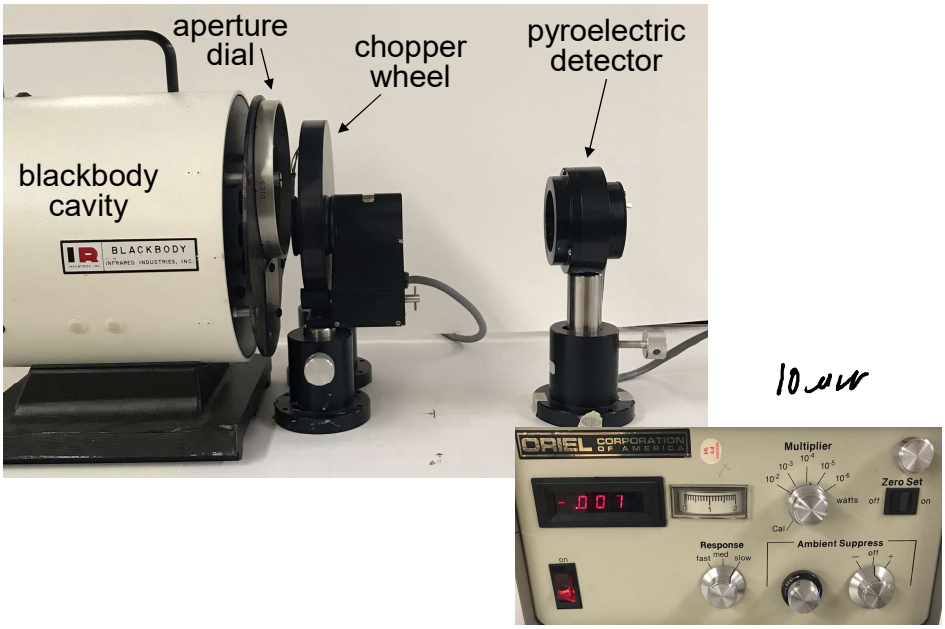
Experimental Setup



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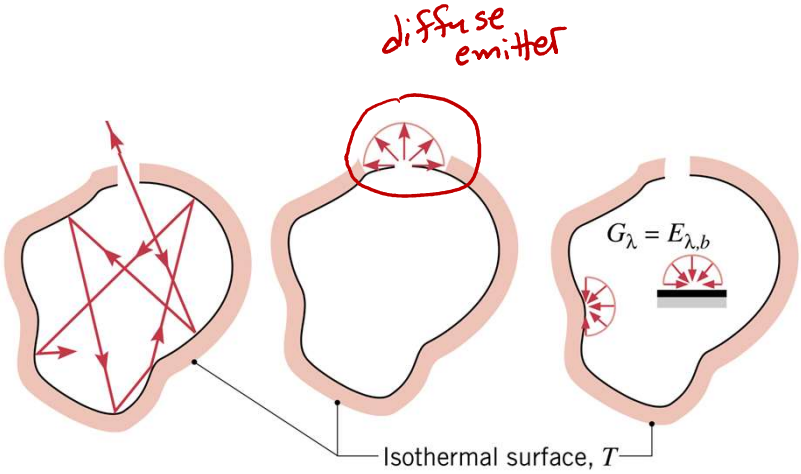
Blackbody Cavity



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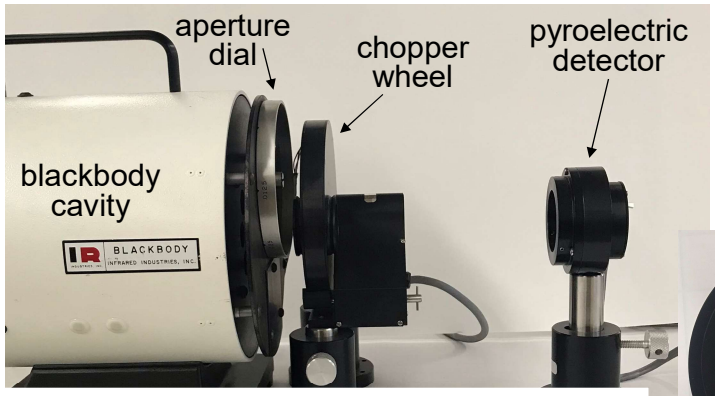
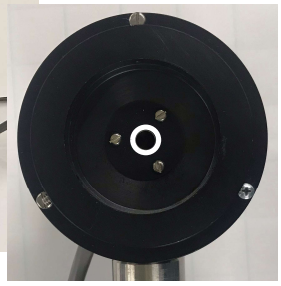
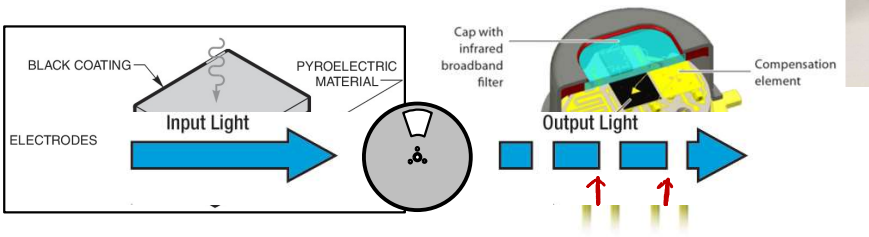
Experimental Setup







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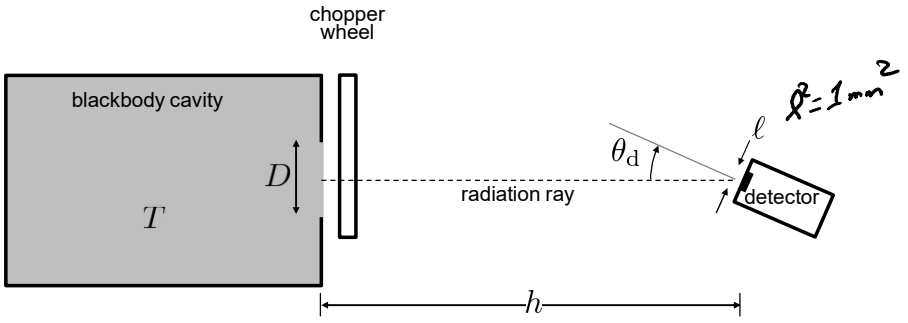
Measurements



Quantity	Symbol	Units	Instrument
Temperature of blackbody	T	°C	thermocouple
Separation distance	h	in	linear ruler
Angle of detector head	θ_d	deg	rotation table
Aperture diameter of source	D	in	markings on dial
Heat transfer rate	q	W	pyroelectric radiometer

Exp #1: h vary

Exp #2: T vary

Exp #3: D vary

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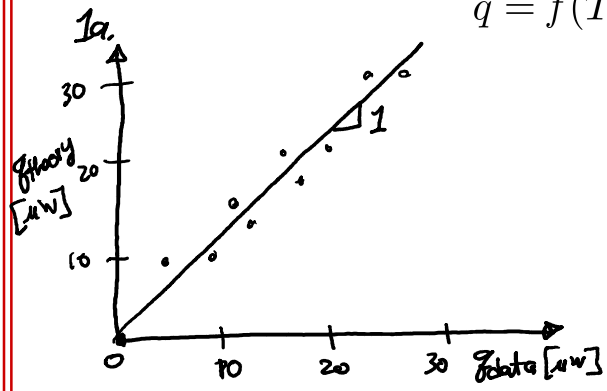
Figures and Tables

$$q = f(T, h, D)$$



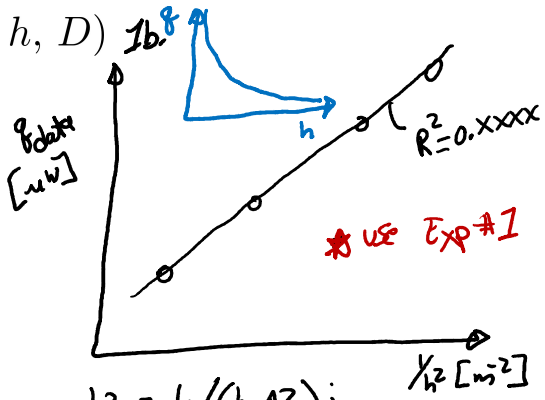
$$R^2 = 1 - S_R/S_T$$

$$S_R = \sum_{i=1}^{N} \left[y_i - (a_0 + a_1 x_i) \right]^2$$

y_i: data; $(a_0 + a_1 x_i)$: model

$$S_T = \sum_{i=1}^{N} \left[y_i - \bar{y} \right]^2$$

y_i: data; $\bar{y}$: mean




```
h2 = 1./(h.^2);
p = polyfit(h2, qdata, 1);
qfit = polyval(p, h2);
qmean = mean(qdata);
SR = sum((qdata - qfit).^2);
ST = sum((qdata - qmean).^2);
R2 = 1 - SR/ST;
```

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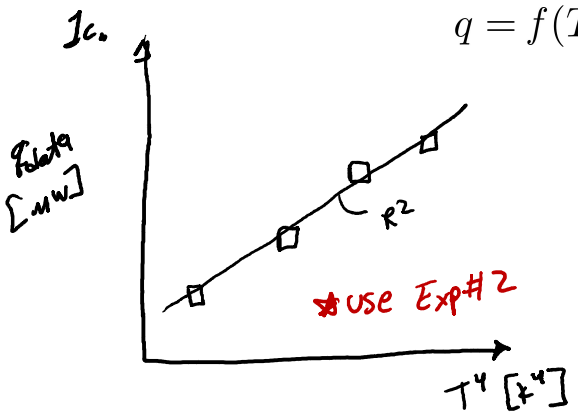
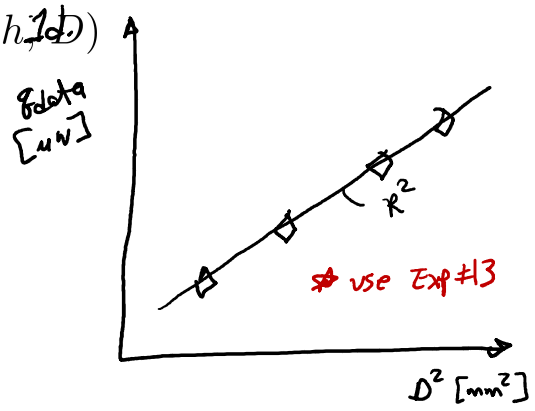
Figures and Tables

$$q = f(T, h, D)$$





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Radiation Exchange between Two Bodies

Total Emissive Power [W/m^2]:

$$E_b = \sigma T^4$$

$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$

Total Intensity [W/m^2·rad]:

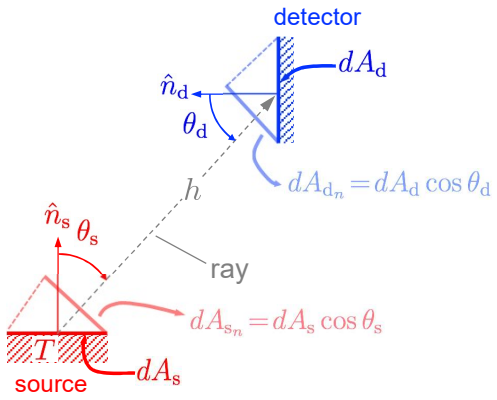
$$I_b = \frac{E_b}{\pi} = \frac{\sigma T^4}{\pi}$$

Differential Heat Transfer Rate [W]:

$$dq = I_b \, dA_{s_n} \, d\omega$$

$d\omega$ — solid angle

$$dq = \frac{\sigma T^4}{\pi} (dA_s \cos\theta_s) d\omega$$



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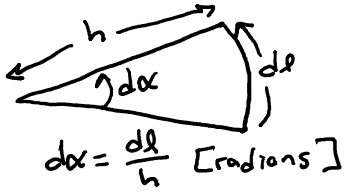
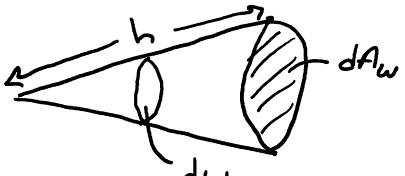
Solid Angle

Planar Angle

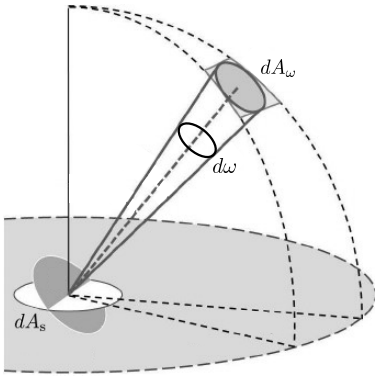


$d\alpha = \frac{dl}{h}$ [radians]

Solid Angle



$d\omega = \frac{dA_\omega}{h^2}$ [steradians]



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Radiation Exchange between Two Bodies

Differential Heat Transfer Rate [W]:

$$dq = \frac{\sigma T^4}{\pi} dA_s \cos\theta_s \, d\omega$$

Solid Angle Definition:

$$d\omega = \frac{dA_{dn}}{h^2} \simeq \frac{dA_d \cos\theta_d}{h^2}$$

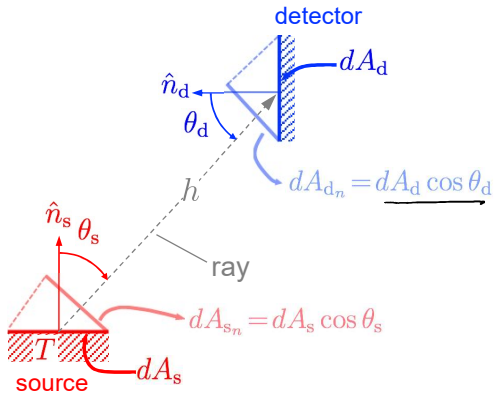
Total Heat Transfer Rate [W]:

$$dq = \frac{\sigma T^4}{\pi h^2} \cos\theta_s \cos\theta_d \, dA_s \, dA_d$$

$$q_{theory} = \sigma T^4 \int_{A_s} \int_{A_d} \frac{\cos\theta_s \cos\theta_d}{\pi h^2} dA_s \, dA_d$$

$$= A_s F_{s \to d}$$ "view factor"

$$q_{theory} = \sigma T^4 A_s F_{s \to d}$$



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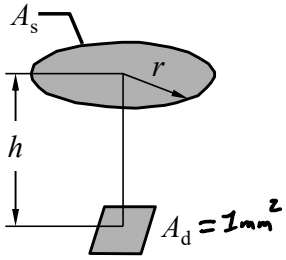
View Factor



View Factor: $F_{d\to s} = \dfrac{1}{1+\left(\frac{h}{r}\right)^2}$

Reciprocity Relation:

$$A_s F_{s\to d} = A_d F_{d\to s} \Rightarrow F_{s\to d} = \frac{A_d}{A_s} F_{d\to s}$$

Total Heat Transfer Rate [W]:

$$q_{theory} = \sigma T^4 A_s F_{s\to d}$$
$$= \sigma T^4 A_s \left(\frac{A_d}{A_s}\right) F_{d\to s}$$
$$= \sigma T^4 A_d \left[\frac{1}{1+(h/r)^2}\right]$$
$$= \sigma T^4 A_d \left[\frac{1}{(D/r)^2+(\frac{h}{r})^2}\right]$$

$r = D/2$

$$q_{theory} = \frac{\sigma T^4 A_d D^2}{D^2 + 4h^2}$$

B. Chung and P. Sumitra, J. Heat Transfer (1972)

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Questions??

Thank you for your attention!

Let me or the TAs know if you have questions

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