CM3110
Transport I
Part II: Heat Transfer

Radiation Heat Transfer

- ***In Unit Operations***
- ***Heat Shields***

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CM3110
Transport Processes and Unit Operations I
Part 2: Heat Transfer

Summary *(Part 2 thus far)*

Within homogeneous phases:

$$\rho \hat{C}_p \left(\frac{\partial T}{\partial t} + \underline{v} \cdot \nabla T \right) = k \nabla^2 T + S_e$$

conduction

- Microscopic Energy Balances
- 1D Steady solutions

rectangular:
$$\frac{q_x}{A} = C_1$$
$$T = ax + b$$

cylindrical:
$$\frac{q_r}{A} = \frac{C_1}{r}$$
$$T = a \ln x + b$$

- Temperature and *Newton's law of cooling* boundary conditions (if h is supplied)
- Unsteady solutions (from literature)
  - ✓ Carslaw and Jaeger
  - ✓ Heisler charts

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CM3110
Transport Processes and Unit Operations I
Part 2: Heat Transfer

Summary (Part 2 thus far)

Across phase boundaries:

- Microscopic Energy, Momentum, and Mass Balances

Micro momentum: $$\rho\left(\frac{\partial \underline{v}}{\partial t} + \underline{v}\cdot\nabla\underline{v}\right) = -\nabla p + \mu\nabla^2\underline{v} + \rho\underline{g}$$

Micro energy: $$\rho\hat{C}_p\left(\frac{\partial T}{\partial t} + \underline{v}\cdot\nabla T\right) = k\nabla^2 T + S_e$$

convection

- Simultaneous effects (complex)
- Solutions are difficult to obtain (and often not really necessary)
  ⇒ use ***dimensional analysis*** and expts to obtain ***h***
- h Data correlations for:
  - ✓ forced convection
  - ✓ natural convection
  - ✓ evaporation/condensation } phase change
  - radiation

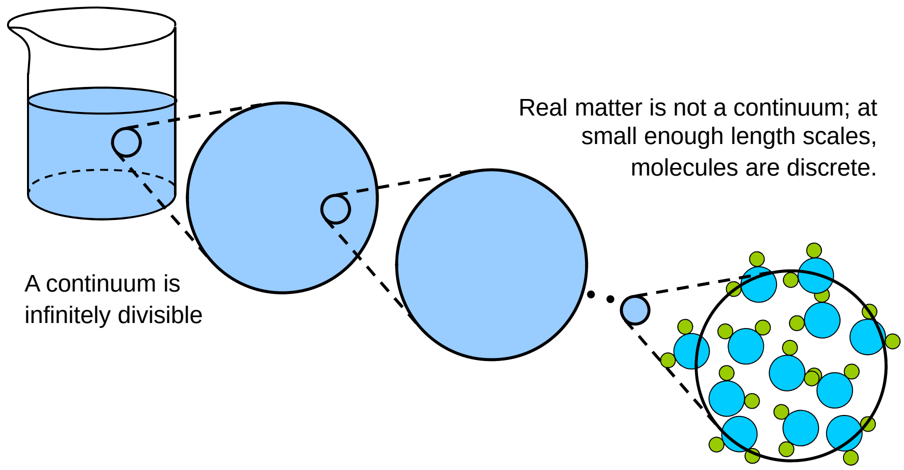
One more type of heat transfer

Radiation versus Conduction and Convection

Continuum view

- Conduction is caused by macroscopic temperature gradients
- Convection is caused by macroscopic flow
- Radiation? **NO CONTINUUM EXPLANATION**

Continuum versus Molecular description of matter



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Radiation **versus Conduction and Convection**

Continuum view

- Conduction is caused by macroscopic temperature gradients
- Convection is caused by macroscopic flow
- Radiation? **NO CONTINUUM EXPLANATION**

There is also, of course, a molecular explanation of these effects, since we know that matter is made of atoms and molecules

Molecular view

- Conduction—Brownian motion
- Convection—flow
- Radiation is caused by changes in electron energy states in molecules and atoms

Molecular view

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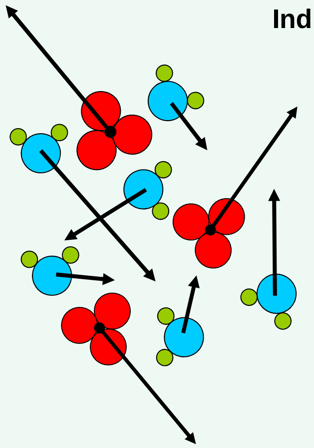
Molecular view



Individual molecules carry:

- chemical identity
- macroscopic velocity (speed and direction)
- internal energy (Brownian velocity)

When they undergo **Brownian motion** within an inhomogeneous mixture, they cause:

- ***diffusion*** (mass transport)
- ***exchange*** of momentum (viscous transport)
- ***conduction*** (energy transport)

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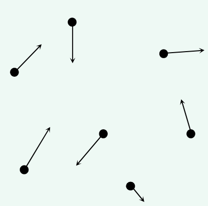
Molecular view

Kinetic Theory J. C. Maxwell, L. Boltzmann, 1860

- Molecules are in constant motion (Brownian motion)
- Temperature is related to $E_{k,av}$ of the molecules

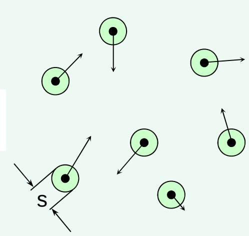
Simplest model

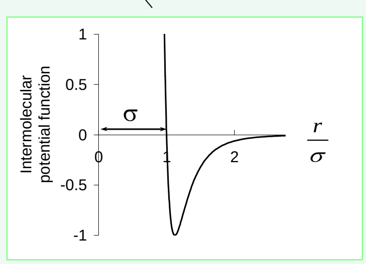
- no particle volume
- no intermolecular forces



More realistic model

- finite particle volume
- intermolecular forces





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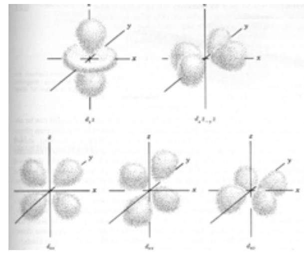
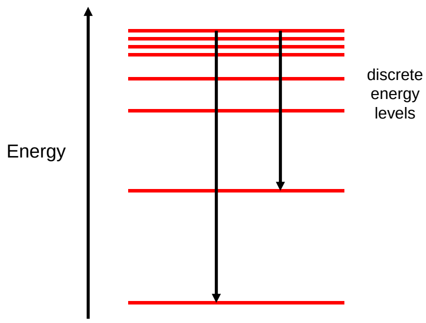
But, there is more to molecular energy than just Brownian motion…

Molecular view

- In atoms and molecules, electrons can exist in multiple, discrete energy states
- Transfers between energy states are accompanied by an emission of radiation



Sienko and Plane, Chemistry: Principles and Applications, McGraw Hill, 1979



Quantum Mechanics

Radiation Heat Transfer is related to these non-Brownian mechanisms.

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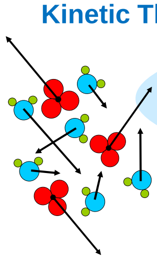
Molecular view

Kinetic Theory

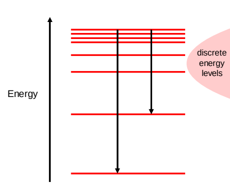


Is based on **Brownian motion** (molecules in constant motion proportional to their temperature)

Predicts that properties that are carried by individual molecules (chemical identity, momentum, average kinetic energy) will be transported **DOWN** gradients in these quantities.

⇒ Gradient transport laws are due to Brownian motion

Heat Transfer by Radiation



Is due to the release of energy stored in molecules that is **NOT** related to average kinetic energy (temperature), but rather to changing populations of excited states.

⇒ Radiation is **NOT** a Brownian effect

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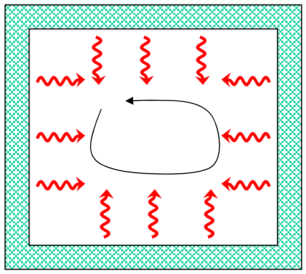
How does this relate to chemical engineering?

Consider a furnace with an internal blower:



There is heat transfer due to convection:

surface temp

$$q_{convection} = hA(T_s - T_b)$$

Bulk temp

(Use correlations)

There is also heat transfer due to radiation.

$$q_{total} = q_{conv} + q_{rad}$$

Where do we get q_{rad}?

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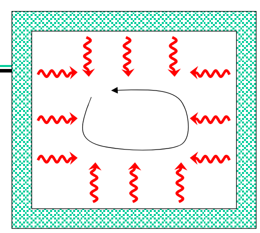
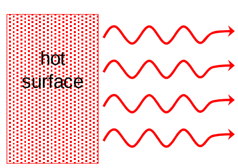
Where do we get $q_{radiation}$?

$$q_{total} = q_{conv} + q_{rad}$$



Answer:

Heat transfer due to radiation



We need to look into the *physics* of this mode of heat transfer.

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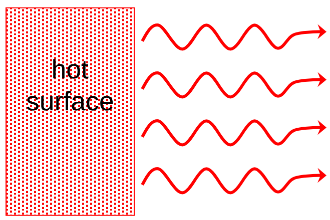
Radiation

- does not require a medium to transfer energy (works in a vacuum)
- travels at the speed of light, $c = 3 \times 101^0\ cm/s$
- travels as a *wave*; differs from x-rays, light, only by wavelength, l
- radiation is important when temperatures are high



examples:
- the sun
- home radiator
- hot walls in vacuum oven
- heat exchanger walls when ΔT is high and a vapor film has formed

$$\frac{q}{A} \propto T^4$$

Note: absolute temperature units

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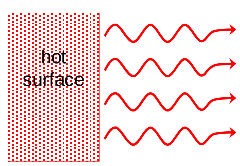

$$\frac{q}{A} \propto T^4$$

Why is radiation flux related to temperature and not to something else?

(From kinetic theory, temperature is related to average kinetic energy)

Answer:

- As a molecule gains energy, it both speeds up (increases average kinetic energy) and increases its population of excited states.
- The increase in average kinetic energy is reflected in temperature (directly proportional), and heat transfer through conduction.
- The increase in number of electrons in excited states is reflected in increased radiation heat flux. Electrons enter excited states in proportion to absolute T^4.

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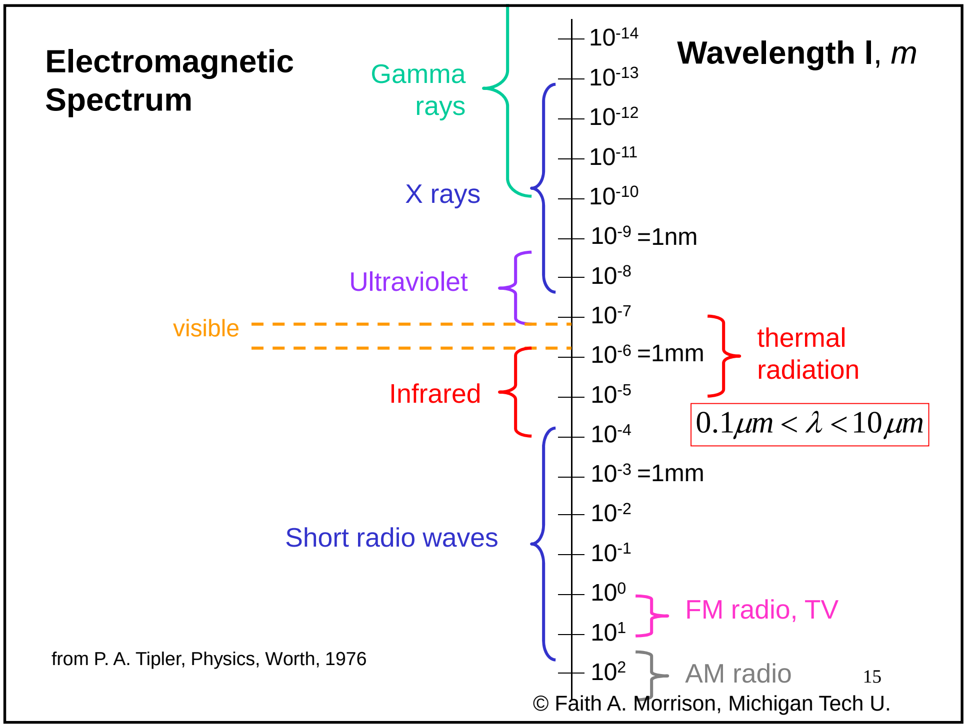
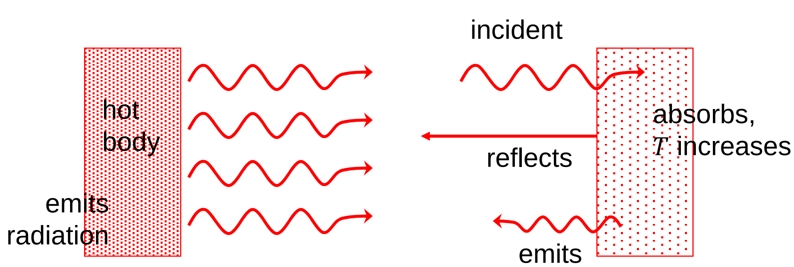


What causes energy transfer by radiation?

- energy hits surface
- pushes some molecules into an excited state
- when the molecules/atoms relax from the excited state, they emit radiation



$$\frac{q_{emit}}{A} \propto T^4$$

$\alpha = absorptivity$

$$\alpha \equiv \frac{q_{absorbed}}{q_{incident}} < 1$$

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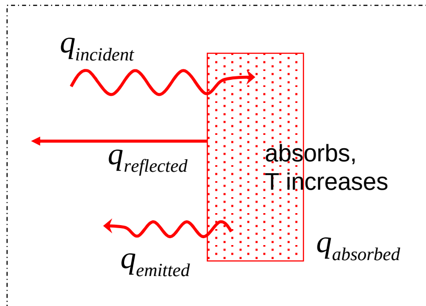
Absorption

$\alpha = absorptivity$

$$\alpha \equiv \frac{q_{absorbed}}{q_{incident}} < 1$$

In general, absorptivity α is a function of wavelength

$$\alpha = \alpha(\lambda)$$



gray body: a body for which a is constant (does not depend on λ)
black body: a body for which $\alpha = 1$, i.e. absorbs all incident radiation

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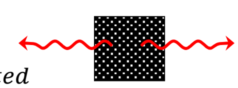
Emission

$\varepsilon = emissivity$

$$\varepsilon \equiv \frac{q_{emitted}}{q_{emitted,black\,body}} < 1$$

gray body: a body for which a is constant
black body: a body for which $\alpha = 1$

$q_{emitted}$



$\alpha = absorptivity$

$$\alpha \equiv \frac{q_{absorbed}}{q_{incident}} < 1$$

Kirchhoff's Law: emissivity equals absorptivity at the same temperature

$$\alpha = \varepsilon$$

the fraction of energy absorbed by a material = the relative amount of energy emitted from that material compared to a black body

true for black and non-black solid surfaces

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Black Bodies

$$\varepsilon = emissivity$$

$$\varepsilon \equiv \frac{q_{emitted}}{q_{emitted,black\,body}} < 1$$

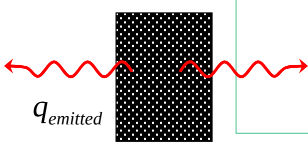
Stefan-Boltzmann Law: the amount of energy emitted by a black body is proportional to T^4

$$\frac{q_{emitted,black\,body}}{A} = \sigma T^4$$

NOTE: absolute temperature

$$\sigma = 0.1712 \times 10^{-8} \frac{BTU}{h\,ft^2 R^4}$$

$$\sigma = 5.676 \times 10^{-8} \frac{W}{m^2 K^4}$$



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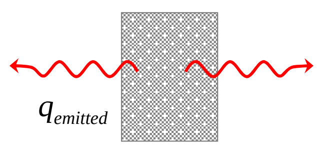
Non-Black Bodies



$$\varepsilon = emissivity$$

$$\varepsilon \equiv \frac{q_{emitted}}{q_{emitted,black\,body}}$$

$$\frac{q_{emitted,non-black\,body}}{A} = \varepsilon\, q_{emitted,black\,body}$$

$$= \varepsilon \sigma T^4$$

Stefan-Boltzmann:

$$\frac{q_{emitted,black\,body}}{A} = \sigma T^4$$

Energy emitted by a non-black body

$$\frac{q_{emitted,non-black\,body}}{A} = \varepsilon \sigma T^4$$

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Radiation

Summary:

- Absorptivity, α
  - gray body: α = constant
  - black body: $\alpha = 1$
- Emissivity, ε
  $$q_{emit} = \varepsilon q_{emit,blackbody}$$
- Kirchoff's law: $\alpha = \varepsilon$
- Stefan-Boltzman law
  $$\frac{q_{emit,blackbody}}{A} = \sigma T^4$$

$$\sigma = 0.1712 \times 10^{-8} \frac{BTU}{h\, ft^2 R^4}$$
$$\sigma = 5.676 \times 10^{-8} \frac{W}{m^2 K^4}$$

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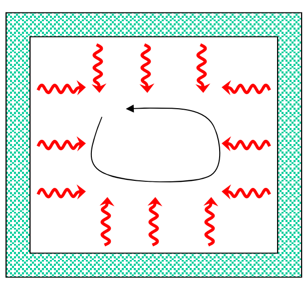
How does this relate to chemical engineering?

Consider a furnace with an internal blower:



There is heat transfer due to convection:

$$q_{convection} = hA(T_s - T_b)$$

surface temp (T_s); Bulk temp (T_b)

(Use correlations)

There is also heat transfer due to radiation:

$$q_{radiation} = h_{rad} A(T_s - T_b)$$

$$q_{total} = q_{conv} + q_{rad}$$

$$q_{total} = (h_{conv} + h_{rad}) A(T_s - T_b)$$

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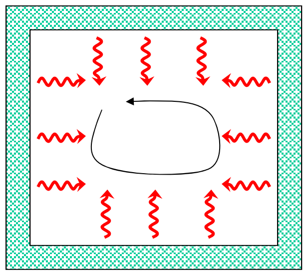

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$$q_{radiation} = h_{rad}A(T_s - T_b)$$

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$$q_{total} = (h_{conv} + h_{rad})A(T_s - T_b)$$

Where do we get h_{rad}?

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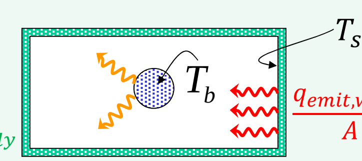
Where do we get h_{rad}?

$$\frac{q_{emit,body}}{A} = \varepsilon\sigma T_{body}^4$$



$$\frac{q_{emit,walls}}{A} = \sigma T_s^4$$

object in furnace:

$$\frac{q_{emit,body}}{A} = \varepsilon\Big|_{T_b} \sigma T_{body}^4$$

using Kirchhoff's law

$$\frac{q_{absorbed,body}}{A} = \alpha\sigma T_s^4 = \varepsilon\Big|_{T_s} \sigma T_s^4$$

energy emitted by walls, which are acting as a black body

net flux to object:

$$\frac{q_{net}}{A} = \frac{q_{abs}}{A} - \frac{q_{emit}}{A}$$

$$\frac{q_{net}}{A} = \varepsilon\Big|_{T_s} \sigma T_s^4 - \varepsilon\Big|_{T_b} \sigma T_{body}^4$$

$$\frac{q_{net}}{A} = \varepsilon\Big|_{T_s} \sigma\left(T_s^4 - T_{body}^4\right)$$

assuming: $\varepsilon|_{T_s} \approx \varepsilon|_{T_{body}}$

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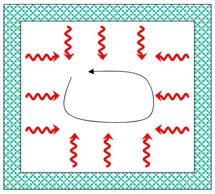

Finally, calculate h_{rad}

net energy absorbed:

$$q_{net} = A\varepsilon\Big|_{T_s}\sigma\left(T_s^4 - T_{body}^4\right)$$

assuming: $\varepsilon|_{T_s} \approx \varepsilon|_{T_b}$

equating with expression for h:

$$h_{rad}A(T_s - T_b) = A\varepsilon\Big|_{T_s}\sigma\left(T_s^4 - T_{body}^4\right)$$

$$h_{rad} = \frac{\varepsilon|_{T_s}\sigma\left(T_s^4 - T_{body}^4\right)}{\left(T_s - T_{body}\right)}$$

Geankoplis 4th ed., eqn 4.10-10 p304

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Example: Geankoplis 4.10-3

A horizontal oxidized steel pipe carrying steam and having an OD of 0.1683m has a surface temperature of 374.9 K and is exposed to air at 297.1 K in a large enclosure. Calculate the heat loss for 0.305 m of pipe.

$$\varepsilon_{steel} = 0.79$$

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Example: Geankoplis 4.10-3

A horizontal oxidized steel pipe carrying steam and having an OD of 0.1683m has a surface temperature of 374.9 K and is exposed to air at 297.1 K in a large enclosure. Calculate the heat loss for 0.305 m of pipe.

Answers:

$$h_{radiation} = 6.9 W/m^2 K$$
$$h_{convection} = 6.1 W/m^2 K$$
$$Q = 163 W$$

$$\varepsilon_{steel} = 0.79$$

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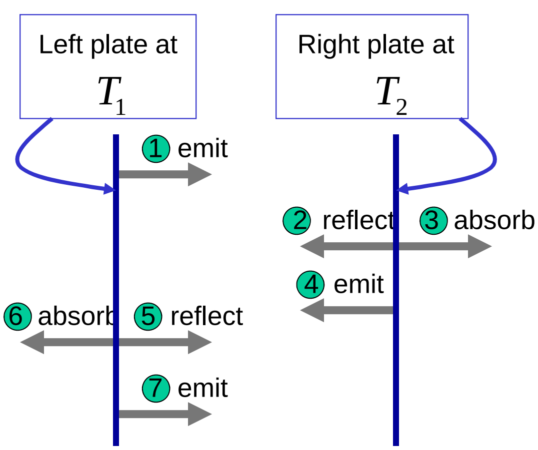
One final topic: **Radiation Heat Transfer Between Two Infinite Plates**

Consider a quantity of radiation energy that is emitted from surface 1.



See: Geankoplis, section 4.11B

Also: Bird, Stewart, and Lightfoot, "Transport Phenomena" 1960 Wiley PP446-448

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First round – surface 2

Radiation Heat Transfer Between Two Infinite Plates

Quantity of energy **incident** at surface 2:

$$\frac{q_{1-2}}{A} = \varepsilon_1 \sigma T_1^4$$

Quantity of energy **absorbed** at surface 2:

$$\alpha_2 \left(\frac{q_{1-2}}{A} \right) A = \varepsilon_2 \left(\varepsilon_1 \sigma T_1^4 \right) A$$

$$\alpha_2 = \varepsilon_2$$

Quantity of energy **reflected** from surface 2:

$$\underbrace{(1-\varepsilon_2)}_{\text{fraction reflected}} \underbrace{\left(\varepsilon_1 A \sigma T_1^4 \right)}_{\text{incident energy}}$$

This energy goes back to surface 1.

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Second round – surface 1

Radiation Heat Transfer Between Two Infinite Plates

Quantity of energy **absorbed** at surface 1 (second round):

$$\underbrace{\varepsilon_1}_{\text{fraction absorbed}} \underbrace{\left[(1-\varepsilon_2) \left(\varepsilon_1 A \sigma T_1^4 \right) \right]}_{\text{incident energy}}$$

Quantity of energy **reflected** from surface 1 (second round):

$$\underbrace{(1-\varepsilon_1)}_{\text{fraction reflected}} \underbrace{\left[(1-\varepsilon_2) \left(\varepsilon_1 A \sigma T_1^4 \right) \right]}_{\text{incident energy}}$$

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Third round – surface 2

Radiation Heat Transfer
Between Two Infinite Plates

Quantity of energy **absorbed** at surface 2 (third round):

$$\underbrace{\varepsilon_2}_{\text{fraction absorbed}} \underbrace{\left[(1-\varepsilon_1)(1-\varepsilon_2)\left(\varepsilon_1 A\sigma T_1^4\right)\right]}_{\text{incident energy}}$$

Quantity of energy **reflected** from surface 2 (third round):

$$\underbrace{(1-\varepsilon_2)}_{\text{fraction reflected}} \underbrace{\left[(1-\varepsilon_1)(1-\varepsilon_2)\left(\varepsilon_1 A\sigma T_1^4\right)\right]}_{\text{incident energy}}$$

There is a pattern.

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Radiation Heat Transfer
Between Two Infinite Plates

Now, calculate the radiation energy going from surface 1 to surface 2:

Later, calculate energy from 2 to 1; then subtract to obtain **net energy transferred**.

$$q_{1-2} = \begin{pmatrix} energy\ \ from \\ 1 \rightarrow 2 \end{pmatrix} = \sum \begin{pmatrix} energy\ absorbed \\ at\ surface\ 2 \end{pmatrix}$$

$$= \varepsilon_2\left(\varepsilon_1 A\sigma T_1^4\right)$$
$$+ \varepsilon_2(1-\varepsilon_1)(1-\varepsilon_2)\left(\varepsilon_1 A\sigma T_1^4\right)$$
$$+ \varepsilon_2(1-\varepsilon_1)^2(1-\varepsilon_2)^2\left(\varepsilon_1 A\sigma T_1^4\right)$$
$$\ldots + \varepsilon_2(1-\varepsilon_1)^n(1-\varepsilon_2)^n\left(\varepsilon_1 A\sigma T_1^4\right) + \ldots$$

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Radiation Heat Transfer
Between Two Infinite Plates

Radiation energy going from surface 1 to surface 2:

$$q_{1-2} = \varepsilon_1 \varepsilon_2 A \sigma T_1^4 \sum_{n=0}^{\infty} (1-\varepsilon_1)^n (1-\varepsilon_2)^n$$

How can we calculate $\sum_{n=0}^{\infty} x^n$?

Answer: $1/(1-x)$

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Radiation Heat Transfer
Between Two Infinite Plates

Radiation energy going from surface 1 to surface 2:

$$q_{1-2} = \frac{\varepsilon_1 \varepsilon_2 A \sigma T_1^4}{1-[(1-\varepsilon_1)(1-\varepsilon_2)]}$$

$$= \frac{\varepsilon_1 \varepsilon_2 A \sigma T_1^4}{1-[1-\varepsilon_1-\varepsilon_2+\varepsilon_1\varepsilon_2]} = \frac{\varepsilon_1 \varepsilon_2 A \sigma T_1^4}{\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2}$$

$$\frac{q_{1-2}}{A} = \frac{\sigma T_1^4}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$

Final Result

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Radiation Heat Transfer Between Two Infinite Plates

Radiation energy going from surface 1 to surface 2:

$$\frac{q_{1-2}}{A}=\frac{\sigma T_1^4}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$

Radiation energy going from surface 2 to surface 1:

$$\frac{q_{2-1}}{A}=\frac{\sigma T_2^4}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$

NET Radiation energy going from surface 1 to surface 2:

$$\frac{q_{1-2}-q_{2-1}}{A}=\frac{\sigma\left(T_1^4-T_2^4\right)}{\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)}$$

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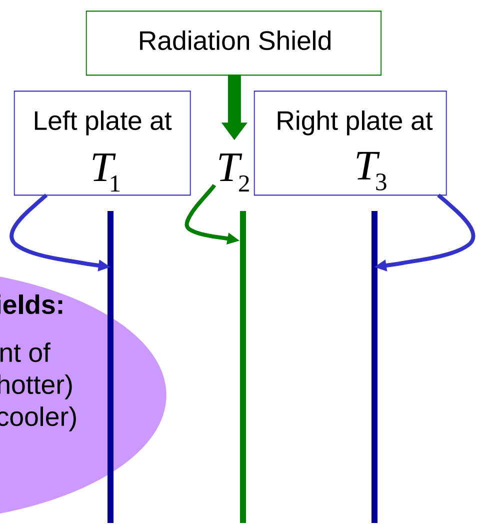
Radiation Shields



Purpose of Heat Shields:

To reduce the amount of energy transfer from (hotter) plate at T_1 to second (cooler) plate at T_3.

Note:

$$q_{net,1\rightarrow 2}=q_{net,2\rightarrow 3}=q$$

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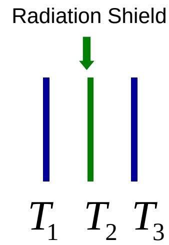
Analysis of Radiation Shields



We will assume that the emissivity is the same for all surfaces.

$$\frac{q_{net,1\rightarrow 2}}{A} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\left(\frac{1}{\varepsilon} + \frac{1}{\varepsilon} - 1\right)}$$

$$\frac{q_{net,2\rightarrow 3}}{A} = \frac{\sigma\left(T_2^4 - T_3^4\right)}{\left(\frac{1}{\varepsilon} + \frac{1}{\varepsilon} - 1\right)}$$

Now we eliminate T_2 between these equations.

Note:

$$q_{net,1\rightarrow 2} = q_{net,2\rightarrow 3} = q$$

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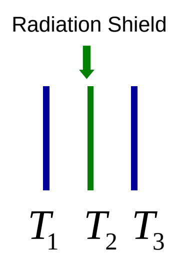
Analysis of Radiation Shields



$$\frac{q}{A} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\left(\frac{2}{\varepsilon} - 1\right)} \qquad \frac{q}{A} = \frac{\sigma\left(T_2^4 - T_3^4\right)}{\left(\frac{2}{\varepsilon} - 1\right)}$$

$$T_2^4 = \frac{q}{\sigma A}\left(\frac{2}{\varepsilon} - 1\right) + T_3^4$$

$$\frac{q}{\sigma A}\left(\frac{2}{\varepsilon} - 1\right) = T_1^4 - \frac{q}{\sigma A}\left(\frac{2}{\varepsilon} - 1\right) - T_3^4$$

$$\frac{2q}{\sigma A}\left(\frac{2}{\varepsilon} - 1\right) = T_1^4 - T_3^4$$

$$\frac{q}{A} = \left(\frac{1}{2}\right)\frac{\sigma\left(T_1^4 - T_3^4\right)}{\left(2/\varepsilon - 1\right)}$$

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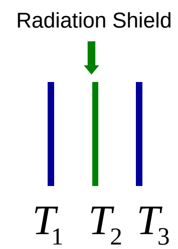
Analysis of Radiation Shields



1 Heat Shield

$$\frac{q}{A} = \left(\frac{1}{2}\right)\frac{\sigma(T_1^4 - T_3^4)}{\left(\frac{2}{\varepsilon} - 1\right)}$$

With one heat shield present, q falls by half compared to no heat shield.

by the same analysis,

N Heat Shields

$$\frac{q}{A} = \left(\frac{1}{N+1}\right)\frac{\sigma(T_1^4 - T_3^4)}{\left(\frac{2}{\varepsilon} - 1\right)}$$

With N heat shields present, q falls by a factor of *1/N* compared to no heat shield.

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Radiation Summary:

$$\sigma = 0.1712 \times 10^{-8} \frac{BTU}{h\, ft^2 R^4}$$

$$\sigma = 5.676 \times 10^{-8} \frac{W}{m^2 K^4}$$

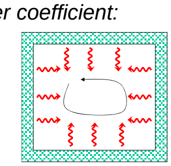
General properties:

- Absorptivity, α
  - gray body: α = constant
  - black body: $\alpha = 1$
- Emissivity, ε

  $q_{emit} = \varepsilon q_{emit,blackbody}$
- Kirchoff's law: $\alpha = \varepsilon$
- Stefan-Boltzman law

  $$\frac{q_{emit,blackbody}}{A} = \sigma T^4$$

Heat transfer coefficient:



$$h_{rad} = \frac{\varepsilon|_{T_s}\sigma\left(T_s^4 - T_{body}^4\right)}{\left(T_s - T_{body}\right)}$$

Geankoplis 4th ed., eqn 4.10-10 p304

Heat shields:

$$\frac{q}{A} = \left(\frac{1}{N+1}\right)\frac{\sigma(T_1^4 - T_3^4)}{\left(\frac{2}{\varepsilon} - 1\right)}$$

Always use absolute temperature (Kelvin) in radiation calculations.

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CM3110
Transport Processes and Unit Operations I

Part 2:

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CM3110 - Momentum and **Heat Transport**
CM3120 – Heat and Mass Transport

www.chem.mtu.edu/~fmorriso/cm310/cm310.html

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Transport Processes and Unit Operations I
Part 2: Heat Transfer

Summary

Within homogeneous phases:

$$\rho \hat{C}_p \left(\frac{\partial T}{\partial t} + \underline{v} \cdot \nabla T \right) = k \nabla^2 T + S_e$$

- Microscopic Energy Balances
- 1D Steady solutions

rectangular:
$$\frac{q_x}{A} = C_1$$
$$T = ax + b$$

cylindrical:
$$\frac{q_r}{A} = \frac{C_1}{r}$$
$$T = a \ln x + b$$

- Temperature and *Newton's law of cooling* boundary conditions (if h is supplied)
- Unsteady solutions (from literature)
  - ✓ Carslaw and Jeager
  - ✓ Heisler charts

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Summary

Across phase boundaries:

- Microscopic Energy, Momentum, and Mass Balances

Micro momentum:
$$\rho\left(\frac{\partial \underline{v}}{\partial t}+\underline{v}\cdot\nabla\underline{v}\right)=-\nabla p+\mu\nabla^2\underline{v}+\rho\underline{g}$$

Micro energy:
$$\rho\hat{C}_p\left(\frac{\partial T}{\partial t}+\underline{v}\cdot\nabla T\right)=k\nabla^2 T+S_e$$

- Simultaneous effects (complex)
- Solutions are difficult to obtain (and often not really necessary)
  → use ***dimensional analysis*** to obtain h
- h Data correlations for:
  - ✓ forced convection,
  - ✓ natural convection
  - ✓ evaporation/condensation
  - ✓ radiation

  } (use in design)

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Summary

Heat Transfer Unit Operations

- Macroscopic energy balances
- Heat Exchangers
  - ✓ double pipe (ΔT_{lm})
  - ✓ Shell-and-tube
  - ✓ Heat exchanger effectiveness
- Evaporators/ Condensers
- Ovens
- Heat Shields

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THE END

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