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Building Science
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Radiation heat exchange

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Last time

- Convection
  - Natural vs. forced
  - Internal vs. external
  - Laminar vs. turbulent

\[ q_{\text{conv}} = h_{\text{conv}} (T_{\text{fluid}} - T_{\text{surface}}) \left[ \frac{W}{m^2} \right] \]

\[ Q_{\text{conv}} = h_{\text{conv}} A (T_{\text{fluid}} - T_{\text{surface}}) \left[ W \right] \]

Forced:
\[ \text{Nu} = \frac{h L_c}{k} \quad \text{Nu} = f(\text{Re}, \text{Pr}) \]
\[ \text{Re}_x = \frac{\rho \nu x}{\mu} = \frac{\nu x}{\nu} \quad \text{Pr} = \frac{\mu C_p}{k} \]

Natural:
\[ \text{Nu} = \frac{h L_c}{k} = f(\text{Ra}_{Lc}, \text{Pr}) \]
\[ \text{Gr}_L = \frac{g \beta (T_s - T_\infty) L^3}{\nu^2} \text{ for vertical flat plates} \]

- Advection

\[ Q_{\text{bulk}} = m C_p \Delta T \left[ W \right] = \left[ \frac{\text{kg}}{s} \cdot \frac{\text{J}}{\text{kg} \cdot \text{K}} \cdot \text{K} \right] \]

\( m \text{ "dot"} = \) mass flow rate of fluid (kg/s)
\( C_p = \) specific heat capacity of fluid [J/(kgK)]
1. Long-wavelength infrared light
2. Short-wavelength infrared light
3. Visible light

RADIATION
Radiation

- **Radiation** heat transfer is the transport of energy by electromagnetic waves
  - Oscillations of electrons that comprise matter
  - Exchange between matter at different temperatures
- Radiation must be **absorbed** by matter to produce internal energy; **emission** of radiation corresponds to reduction in stored thermal energy
Radiation

- Radiation needs to be dealt with in terms of wavelength (\(\lambda\))
  - Different wavelengths of solar radiation pass through the earth’s atmosphere more or less efficiently than other wavelengths
  - Materials also absorb and re-emit solar radiation of different wavelengths with different efficiencies

- For our purposes, it’s generally appropriate to treat radiation in two groups:
  - **Short-wave** (solar radiation)
  - **Long-wave** (emitted and re-emitted radiation)
• **Thermal radiation** is confined to the infrared, visible, and ultraviolet regions ($0.1 < \lambda < 100 \, \mu m$)
Black body radiation: Spectral (Planck) distribution

- Radiation from a perfect radiator follows the “black body” curve (ideal, black body emitter)
- The peak of the black body curve depends on the object’s temperature
  - Lower T, larger $\lambda$ peak
- Peak radiation from the sun is in the visible region
  - About 0.4 to 0.7 $\mu$m
- Radiation involved in building surfaces is in the infrared region
  - Greater than 0.7 $\mu$m

$$q = \sigma T^4$$
$$\sigma = \text{Stefan-Boltzmann constant} = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$$

$T = \text{Absolute temperature [K]}$
Radiation: Short-wave and Long-wave

Solar short-wave Radiation (direct)  
Avg. \( \lambda = 0.5 \) \( \mu m \)

Terrestrial long-wave Radiation (diffuse/reflected)  
Avg. \( \lambda = 10 \) \( \mu m \)

\( \lambda (\mu m) \):

- X Rays
- Ultraviolet
- Visible
- Infrared
- Microwave

\( 10^{-5} \)  \( 10^{-4} \)  \( 10^{-3} \)  \( 10^{-2} \)  \( 10^{-1} \)  \( 1 \)  \( 10 \)  \( 10^{2} \)  \( 10^{3} \)  \( 10^{4} \)
SOLAR (SHORT-WAVE) RADIATION
Solar radiation

- Solar radiation is a very important term in the energy balance of a building
  - We must account for it while calculating loads
  - This is particularly true for perimeter zones and for peak cooling loads

- Solar radiation is also important for daylighting design

- We won’t cover the full equations for predicting solar geometry and radiation striking a surface in this class
  - CAE 463/524 Building Enclosure Design goes into more detail
  - But will discuss basic relationships and where to get solar data
Solar radiation striking a surface (high temperature)

- Most solar radiation is at short wavelengths

\[ I_{\text{solar}} \left[ \frac{W}{m^2} \right] \]
Solar radiation striking a surface (high temperature)

- Solar radiation data \((I_{\text{solar}})\) can be used on opaque surfaces to help determine surface temperatures

\[
q_{\text{solar}} = \alpha I_{\text{solar}}
\]

- Solar radiation data \((I_{\text{solar}})\) can also be used on exterior fenestration (e.g. windows and skylights) to determine how much solar radiation enters an indoor environment

\[
q_{\text{solar}} = \tau I_{\text{solar}}
\]
Absorptivity, transmissivity, and reflectivity

- The absorptivity, $\alpha$, is the fraction of energy hitting an object that is actually absorbed.

- Transmissivity, $\tau$, is a measure of how much radiation passes through an object.

- Reflectivity, $\rho$, is a measure of how much radiation is reflected off an object.

- We use these terms primarily for solar radiation.
  - For an opaque surface ($\tau = 0$): $q_{solar} = \alpha I_{solar}$
  - For a transparent surface ($\tau > 0$): $q_{solar} = \tau I_{solar}$

\[ \alpha + \tau + \rho = 1 \]
Absorptivity ($\alpha$) for solar (short-wave) radiation

<table>
<thead>
<tr>
<th>Surface</th>
<th>Absorptance for Solar Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A small hole in a large box, sphere, furnace, or enclosure</td>
<td>0.97 to 0.99</td>
</tr>
<tr>
<td>Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper</td>
<td>0.85 to 0.98</td>
</tr>
<tr>
<td>Red brick and tile, concrete and stone, rusty steel and iron, dark</td>
<td>0.65 to 0.80</td>
</tr>
<tr>
<td>paints (red, brown, green, etc.)</td>
<td></td>
</tr>
<tr>
<td>Yellow and buff brick and stone, firebrick, fire clay</td>
<td>0.50 to 0.70</td>
</tr>
<tr>
<td>White or light-cream brick, tile, paint or paper, plaster, whitewash</td>
<td>0.30 to 0.50</td>
</tr>
<tr>
<td>Window glass</td>
<td>---</td>
</tr>
<tr>
<td>Bright aluminum paint; gilt or bronze paint</td>
<td>0.30 to 0.50</td>
</tr>
<tr>
<td>Dull brass, copper, or aluminum; galvanized steel; polished iron</td>
<td>0.40 to 0.65</td>
</tr>
<tr>
<td>Polished brass, copper, monel metal</td>
<td>0.30 to 0.50</td>
</tr>
<tr>
<td>Highly polished aluminum, tin plate, nickel, chromium</td>
<td>0.10 to 0.40</td>
</tr>
</tbody>
</table>
Components of solar radiation \((I_{solar})\)

- Solar radiation striking a surface consists of three main components:

\[
I_{solar} = I_{direct} + I_{diffuse} + I_{reflected} \quad \left[ \frac{W}{m^2} \right]
\]

- Direct
- Diffuse
- Reflected
Components of solar radiation

• **Direct solar radiation** \( (I_{\text{direct}}) \) is a function of the normal incident irradiation \( (I_{DN}) \) on the earth’s surface and the solar incidence angle of the surface of interest, \( \theta \)
  - Where \( I_{DN} \) is the amount of solar radiation received per unit area by a surface that is always perpendicular to the sun’s direct rays
  - Function of day of the year and atmospheric properties

\[
I_D = I_{DN} \cos \theta
\]

• **Diffuse solar radiation** \( (I_{\text{diffuse}}) \) is the irradiation that is scattered by the atmosphere
  - Function of \( I_{DN} \), atmospheric properties, and surface’s tilt angle

• **Reflected solar radiation** \( (I_{\text{reflected}}) \) is the irradiation that is reflected off the ground (it becomes diffuse)
  - Function of \( I_{DN} \), solar geometry, ground reflectance, and surface tilt angle
Solar radiation: earth-sun relationships

- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23.45°
  - Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)
Solar radiation striking an exterior surface

• The amount of solar radiation received by a surface depends on the **incidence angle**, $\theta$

• This is a function of:
  – Solar geometry ($I_{DN}$)
    • Location
    • Time
  – Surface geometry
  – Shading/obstacles

\[
I_D = I_{DN} \cos \theta
\]
Visualizing solar relationships

http://energy.concord.org/energy3d/
Downloading solar data

• For hourly sun positions, you can build a calculator or use one from the internet
  – [http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html](http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html)

• For solar position and intensity (from time and place)
  – Output of interest = “global irradiance on a tilted surface”

• For *actual* hourly solar data (direct + diffuse in W/m²)
  – Output of interest = “direct normal radiation” → adjust using \( \cos \theta \)
    • Note: “typical meteorological years”
Typical meteorological year (TMY)

• For heating and cooling load calculations and for hourly building energy simulations, we often rely on a collection of weather data for a specific location

• We generate this data to be representative of more than just the previous year
  – Represents a wide range of weather phenomena for our location
  – TMY3: Data for 1020 locations from 1960 to 2005
    • Composed of 12 typical meteorological months
    • Each month is pulled from a random year in the range
    • Actual time-series climate data
    • Mixture of measured and modeled solar values
  – Variables include: outdoor temperature, direct normal radiation, wind speed, wind direction, outdoor RH, cloud cover, and more
Typical meteorological year (TMY): Solar data

Data for typical September 10th at Midway, Chicago, IL

- **Direct Normal Irradiance**
- **Cloud Cover**
- **Air temperature**
- **Wind speed**
SURFACE (LONG-WAVE) RADIATION
Surface radiation (lower temperature: long-wave)

• All objects above absolute zero radiate electromagnetic energy according to:

\[ q_{rad} = \varepsilon \sigma T^4 \]

Where \( \varepsilon \) = emissivity

\( \sigma \) = Stefan-Boltzmann constant = \( 5.67 \times 10^{-8} \) \( \frac{W}{m^2 \cdot K^4} \)

\( T \) = Absolute temperature [K]

• Net radiation heat transfer occurs when an object radiates a different amount of energy than it absorbs

• If all the surrounding objects are at the same temperature, the net will be zero

“Gray bodies”
Radiation heat transfer (surface-to-surface)

- We can write the net thermal radiation heat transfer between surfaces 1 and 2 as:

\[
Q_{1\rightarrow 2} = \frac{A_1 \sigma \left( T_1^4 - T_2^4 \right)}{1 - \varepsilon_1 + \frac{A_1}{A_2} \frac{1 - \varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}
\]

\[
q_{1\rightarrow 2} = \frac{Q_{1\rightarrow 2}}{A_1}
\]

where \(\varepsilon_1\) and \(\varepsilon_2\) are the surface emittances, \(A_1\) and \(A_2\) are the surface areas and \(F_{1\rightarrow 2}\) is the view factor from surface 1 to 2. 

\(F_{1\rightarrow 2}\) is a function of geometry only.
Emissivity (“gray bodies”)

- Real surfaces emit less radiation than ideal “black” ones
  - The ratio of energy radiated by a given body to a perfect black body at the same temperature is called the emissivity: $\varepsilon$
- $\varepsilon$ is dependent on wavelength, but for most common building materials (e.g. brick, concrete, wood...), $\varepsilon = 0.9$ at most wavelengths
**Emissivity ($\varepsilon$) of common materials**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Emittance (50–100 °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A small hole in a large box, sphere, furnace, or enclosure</td>
<td>0.97 to 0.99</td>
</tr>
<tr>
<td>Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper</td>
<td>0.90 to 0.98</td>
</tr>
<tr>
<td>Red brick and tile, concrete and stone, rusty steel and iron, dark</td>
<td>0.85 to 0.95</td>
</tr>
<tr>
<td>paints (red, brown, green, etc.)</td>
<td></td>
</tr>
<tr>
<td>Yellow and buff brick and stone, firebrick, fire clay</td>
<td>0.85 to 0.95</td>
</tr>
<tr>
<td>White or light-cream brick, tile, paint or paper, plaster, whitewash</td>
<td>0.85 to 0.95</td>
</tr>
<tr>
<td>Window glass</td>
<td>0.90 to 0.95</td>
</tr>
<tr>
<td>Bright aluminum paint; gilt or bronze paint</td>
<td>0.40 to 0.60</td>
</tr>
<tr>
<td>Dull brass, copper, or aluminum; galvanized steel; polished iron</td>
<td>0.20 to 0.30</td>
</tr>
<tr>
<td>Polished brass, copper, monel metal</td>
<td>0.02 to 0.05</td>
</tr>
<tr>
<td>Highly polished aluminum, tin plate, nickel, chromium</td>
<td>0.02 to 0.04</td>
</tr>
</tbody>
</table>
## Emissivity ($\varepsilon$) of common building materials

<table>
<thead>
<tr>
<th>Surface</th>
<th>Temperature, °C</th>
<th>Temperature, °F</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red, rough</td>
<td>40</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough</td>
<td>40</td>
<td>100</td>
<td>0.94</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>40</td>
<td>100</td>
<td>0.94</td>
</tr>
<tr>
<td>Ice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>0</td>
<td>32</td>
<td>0.97</td>
</tr>
<tr>
<td>Marble</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>40</td>
<td>100</td>
<td>0.95</td>
</tr>
<tr>
<td>Paints</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black gloss</td>
<td>40</td>
<td>100</td>
<td>0.90</td>
</tr>
<tr>
<td>White</td>
<td>40</td>
<td>100</td>
<td>0.89-0.97</td>
</tr>
<tr>
<td>Various oil paints</td>
<td>40</td>
<td>100</td>
<td>0.92-0.96</td>
</tr>
<tr>
<td>Paper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>40</td>
<td>100</td>
<td>0.95</td>
</tr>
<tr>
<td>Sandstone</td>
<td>40–250</td>
<td>100–500</td>
<td>0.83–0.90</td>
</tr>
<tr>
<td>Snow</td>
<td>−12–−6</td>
<td>10–20</td>
<td>0.82</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 mm or more thick</td>
<td>40</td>
<td>100</td>
<td>0.96</td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oak, planed</td>
<td>40</td>
<td>100</td>
<td>0.90</td>
</tr>
<tr>
<td>Walnut, sanded</td>
<td>40</td>
<td>100</td>
<td>0.83</td>
</tr>
<tr>
<td>Spruce, sanded</td>
<td>40</td>
<td>100</td>
<td>0.82</td>
</tr>
<tr>
<td>Beech</td>
<td>40</td>
<td>100</td>
<td>0.94</td>
</tr>
</tbody>
</table>

• Radiation travels in directional beams
  – Thus, areas and angle of incidence between two exchanging surfaces influences radiative heat transfer

Some common view factors:

\[ A_{1}F_{1\rightarrow 2} = 0.5((ac + bd) - (ad + bc)) \]
Typical view factors

Other common view factors from the ASHRAE Handbook of Fundamentals:

A. PERPENDICULAR RECTANGLES WITH COMMON EDGE

B. ALIGNED PARALLEL RECTANGLES
Long-wave radiation example

• What is the net radiative exchange between the two interior wall surfaces below if the room is 5 m x 5 m x 3 m?

Q: What if $T_{\text{surf1,in}}$ dropped to 50°F (10°C)?
Simplifying surface radiation

• We can also often simplify radiation from:

\[ Q_{1\rightarrow 2} = \frac{A_1 \sigma \left( T_1^4 - T_2^4 \right)}{1 - \varepsilon_1} + \frac{A_1}{\varepsilon_1} \frac{1 - \varepsilon_2}{A_2} + \frac{1}{F_{12}} \]

• To:

\[ Q_{1\rightarrow 2} = \varepsilon_{surf} A_{surf} \sigma F_{12} \left( T_1^4 - T_2^4 \right) \]

Particularly when dealing with large differences in areas, such as sky-surface or ground-surface exchanges.
Simplifying radiation

• We can also define a **radiation heat transfer coefficient** that is analogous to other heat transfer coefficients:

\[ Q_{\text{rad},1\rightarrow 2} = h_{\text{rad}} A_1 (T_1 - T_2) = \frac{1}{R_{\text{rad}}} A_1 (T_1 - T_2) \]

• When \( A_1 = A_2 \), and \( T_1 \) and \( T_2 \) are within \( \sim 50^\circ\text{F} \) of each other, we can approximate \( h_{\text{rad}} \) with a simpler equation:

\[
h_{\text{rad}} = \frac{4\sigma T_{\text{avg}}^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}
\]

where

\[
T_{\text{avg}} = \frac{T_1 + T_2}{2}
\]
Radiation visualizations