CAE 331/513
Building Science
Fall 2013

Lecture 3: September 9, 2013
Heat transfer in buildings continued
Solar radiation, windows, building energy balances

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Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu
Deliverables

• HW 1 was due last week
  – Graded and returned today
  – Any questions?

• Blog post #2 is due today
Last time

• Reviewed heat transfer fundamentals
  – Conduction
  – Convection
  – Radiation (*didn’t get to this*)

• In context: heat transfer in building science
  – Walls, roofs, windows, floors
  – HVAC systems (*didn’t get to this*)
Today’s objectives

• Finish up from last lecture on basics of heat transfer in buildings
  – Finish convection
  – Radiation
  – Some example problems

• Applications of heat transfer in building science:
  – Solar radiation
  – Windows
  – Building energy balances
# Heat transfer in building science

<table>
<thead>
<tr>
<th>Conduction through a solid or a stationary fluid</th>
<th>Convection from a surface to a moving fluid</th>
<th>Net radiation heat exchange between two surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

### Conduction

\[ q = \frac{k}{L} \left( T_{surf,1} - T_{surf,2} \right) \]

\[ k = U = \frac{1}{R} \quad R_{total} = \frac{1}{U_{total}} \]

\[ R_{total} = R_1 + R_2 + R_3 + \ldots \]

\[ U_{total} = \frac{A_1}{A_{total}} U_1 + \frac{A_2}{A_{total}} U_2 + \ldots \]

### Convection

\[ q_{conv} = h_{conv} \left( T_{fluid} - T_{surf} \right) \]

\[ R_{conv} = \frac{1}{h_{conv}} \]

### Radiation

Today…

Today…
Examples of heat transfer in a building

- Conduction of heat through a building’s skin
- Transmission of solar radiation through windows
- Cooling of occupants by HVAC systems
Typical convective surface resistances

- We estimated convection coefficients in this classroom
  - Function of flow regime, air velocity, temperature difference, surface orientation
- We often use the values for convective resistances of “air films” given below for most conditions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoors: $R_{in}$</td>
<td>0.12 m²K/W (SI)</td>
<td>0.11 m²K/W (SI)</td>
<td>0.16 m²K/W (SI)</td>
</tr>
<tr>
<td></td>
<td>0.68 h·ft²·°F/Btu (IP)</td>
<td>0.62 h·ft²·°F/Btu (IP)</td>
<td>0.91 h·ft²·°F/Btu (IP)</td>
</tr>
<tr>
<td>$R_{out}$: 6.7 m/s wind (Winter)</td>
<td>0.030 m²K/W (SI)</td>
<td>0.17 h·ft²·°F/Btu (IP)</td>
<td></td>
</tr>
<tr>
<td>$R_{out}$: 3.4 m/s wind (Summer)</td>
<td>0.044 m²K/W (SI)</td>
<td>0.25 h·ft²·°F/Btu (IP)</td>
<td></td>
</tr>
</tbody>
</table>
Convection and heat exchangers

- Heat exchangers are used widely in buildings
- Heat exchangers are devices in which two fluid streams, usually separated from each other by a solid wall, exchange thermal energy by convection
  - One fluid is typically heated, one is cooled
  - Fluids may be gases, liquids, or vapors

\[
U_o A_o = \frac{1}{R_{conv,i} + R_{pipe} + R_{conv,o} A_o}
\]

FIGURE 2.12
Schematic diagram of parallel-flow shell-and-tube heat exchanger showing fluid temperatures and equivalent thermal circuit.
Heat exchangers

- Parallel flow: fluids flowing in the same direction

\[ T_{\text{cold,in}} \rightarrow T_{\text{cold,out}} \]

\[ T_{\text{hot,in}} \rightarrow T_{\text{hot,out}} \]

\[ T_{\text{ci}} \rightarrow T_{\text{co}} \]

\[ T_{\text{hi}} \rightarrow T_{\text{ho}} \]

\[ Q \]

\[ Q \]

\[ Q \]
Heat exchangers

- Counterflow: one fluid flows in the opposite direction
  - More efficient than parallel flow
Heat exchangers

• General heat transfer in heat exchangers

\[ Q = UA\Delta T_{\text{mean}} \]

\[ \Delta T_{\text{mean}} = \frac{\Delta T_{\text{hot}} - \Delta T_{\text{cold}}}{\ln\left(\frac{\Delta T_{\text{hot}}}{\Delta T_{\text{cold}}}\right)} \]

• Method for predicting heat transfer rate in heat exchangers:
  – \( \varepsilon\)-NTU method: Effectiveness number-of-transfer-units approach
Heat exchangers: $\varepsilon$-NTU method

- Define effectiveness: ratio of actual to maximum possible heat transfer rates

\[ \varepsilon = \frac{Q}{Q_{\text{max}}} \]

- This maximum rate of heat transfer is limited to the product of the maximum temperature difference across the heat exchanger and the minimum fluid capacitance rate:

\[ Q = \varepsilon (\dot{m}C_p)_{\text{min}} (T_{\text{hot,in}} - T_{\text{cold,in}}) \]

- The idea is that heat transfer will almost never be its maximum because the hot and cold T’s are constantly changing (and changing the driving force)
Heat exchangers: $\varepsilon$-NTU method

- The effectiveness of different types of heat exchangers can be described with various equations, all using the term number of transfer units, or “NTU”

$$NTU = \frac{U_o A_o}{(\dot{m}C_p)_{\text{min}}}$$

Where the denominator is the smaller of the two fluid capacitance rates: $\dot{C}_{\text{min}} = (\dot{m}C_p)_{\text{min}}$

---

**TABLE 2.10**

<table>
<thead>
<tr>
<th>Flow Geometry</th>
<th>Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double pipe</td>
<td>$\varepsilon = 1 - \exp \left{ -N(1 + \frac{C}{C_{\text{max}}}) \right}$</td>
</tr>
<tr>
<td>Parallel flow</td>
<td>$\varepsilon = 1 - \exp \left{ -N(1 - \frac{C}{C_{\text{max}}}) \right}$</td>
</tr>
<tr>
<td>Counterflow</td>
<td>$\varepsilon = 1 - \exp \left{ -N(1 - \frac{C}{C_{\text{max}}}) \right}$</td>
</tr>
<tr>
<td>Crossflow</td>
<td>$\varepsilon = 1 - \exp \left{ \frac{1}{C_{\text{max}}} \left[ \exp (-NC) - 1 \right] \right}$ where $n = N^{-0.22}$</td>
</tr>
<tr>
<td>Both fluids unmixed</td>
<td>$\varepsilon = N \left[ \frac{N}{1 - \exp (-N)} + \frac{NC}{1 - \exp (-NC)} - 1 \right]^{-1}$</td>
</tr>
<tr>
<td>Both fluids mixed</td>
<td>$\varepsilon = C \left[ \frac{1}{N} \left[ \exp (-NC) - 1 \right] \right]$</td>
</tr>
<tr>
<td>Both fluids unmixed</td>
<td>$\varepsilon = 1 - \exp \left{ -\frac{1}{C}\left[ 1 - \exp (-NC) \right] \right}$</td>
</tr>
<tr>
<td>$\dot{C}<em>{\text{min}}$ mixed, $\dot{C}</em>{\text{min}}$ unmixed</td>
<td>$\varepsilon = 2 \left[ 1 + C + \sqrt{C^2 + 1 + \exp (-NC)} \right]^{-1}$</td>
</tr>
<tr>
<td>$\dot{C}<em>{\text{max}}$ unmixed, $\dot{C}</em>{\text{min}}$ mixed</td>
<td>$\varepsilon = 2 \left[ 1 + C + \sqrt{C^2 + 1 + \exp (-NC)} \right]^{-1}$</td>
</tr>
<tr>
<td>Shell and tube</td>
<td>$\varepsilon = 2 \left[ 1 + C + \sqrt{C^2 + 1 + \exp (-NC)} \right]^{-1}$</td>
</tr>
</tbody>
</table>
Heat exchangers: $\varepsilon$-NTU method

This subject is covered in more detail in CAE 464 HVAC Design.

FIGURE 2.14
Comparison of effectiveness of several heat exchanger designs for equal hot- and cold-side capacitance rates, $\dot{C}_{\text{min}} = \dot{C}_{\text{max}}$. 
Heat exchanger example

- Example: Potable service water is heated in a building from 20°C at a rate of 70 kg/min by using nonpotable pressurized water from a boiler at 110°C in a single-pass counterflow heat exchanger.

- Find the heat transfer rate if the hot water flow is 90 kg/min.
- Also find exit temperatures of both streams.
  - Note: The overall U value is 320 W/(m²K) and the transfer area is 20 m².
Bulk convective heat transfer: “Advection”

• Bulk convective heat transfer, or advection, is more direct than convection between surfaces and fluids

• Bulk convective heat transfer is the transport of heat by airflow
  – Air has a capacity to store heat, so air flowing into or out of a building carries heat with it

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

\[ m \text{ “dot”} = \text{mass flow rate of air (kg/s)} \]
\[ C_p = \text{specific heat capacity of air [J/(kgK)]} \]
Radiation

- **Radiation** heat transfer is the transport of energy by electromagnetic waves
  - Exchange between two surfaces at different temperatures
- Radiation must be absorbed by matter to produce internal energy
- Example: energy transported from the sun to the earth
Radiation

- Radiation should really be dealt with in terms of wavelength
  - Where 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 (diffuse, refracted, or re-emitted radiation)
Black body radiation

- Radiation from a perfect radiator follows the black body curve.
- The peak of the black body curve depends on the object’s temperature.
  - Peak radiation from the sun is in the visible region: About 0.4 to 0.7 μm.
- Radiation involved in building surfaces is in the infrared region: Greater than 0.7 μm.
Radiation: Short-wave and Long-wave

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

Terrestrial long-wave Radiation (diffuse/reflected)
Avg. $\lambda = 10 \, \mu m$
Solar radiation striking a surface (high temperature)

- Most solar radiation is at short wavelengths
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 ($\tau > 0$): $q_{solar} = \tau \alpha I_{solar}$

\[ \alpha + \tau + \rho = 1 \]
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
\( \sigma = \text{Stefan-Boltzmann constant} = 5.670 \times 10^{-8} \ \frac{W}{m^2 \cdot K^4} \)

\( T = \text{Absolute temperature in Kelvin} \)

• 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
Radiation heat transfer (surface-to-surface)

- If a material follows Kirchoff’s law, (absorptivity = emissivity for a given wavelength) we can write the net radiation heat transfer between surfaces 1 and 2 as:

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

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 and absorptivity

• 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 of common building materials

**TABLE 2.11**

Emissivities of Some Common Building Materials at Specified Temperatures

<table>
<thead>
<tr>
<th>Surface</th>
<th>Temperature, °C</th>
<th>Temperature, °F</th>
<th>ε</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>Paints 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>0.1 mm or more thick</td>
<td>40</td>
<td>100</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>

Absorptivity vs. emissivity

• For most wavelengths and most materials, $\varepsilon = \alpha$
• But we deal with surface-to-surface (long-wave) and solar (short-wave) radiation separately
  – So we treat emissivity and absorptivity separately

<table>
<thead>
<tr>
<th>Surface</th>
<th>Emittance or Absorptance</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>
<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>
<td>0.85 to 0.98</td>
</tr>
<tr>
<td>Red brick and tile, concrete and stone, rusty steel and iron, dark</td>
<td>0.85 to 0.95</td>
<td>0.65 to 0.80</td>
</tr>
<tr>
<td>Yellow and buff brick and stone, firebrick, fire clay</td>
<td>0.85 to 0.95</td>
<td>0.50 to 0.70</td>
</tr>
<tr>
<td>White or light-cream brick, tile, paint or paper, plaster, whitewash</td>
<td>0.85 to 0.95</td>
<td>0.30 to 0.50</td>
</tr>
<tr>
<td>Window glass</td>
<td>0.90 to 0.95</td>
<td>—</td>
</tr>
<tr>
<td>Bright aluminum paint; gilt or bronze paint</td>
<td>0.40 to 0.60</td>
<td>0.30 to 0.50</td>
</tr>
<tr>
<td>Dull brass, copper, or aluminum; galvanized steel; polished iron</td>
<td>0.20 to 0.30</td>
<td>0.40 to 0.65</td>
</tr>
<tr>
<td>Polished brass, copper, monel metal</td>
<td>0.02 to 0.05</td>
<td>0.30 to 0.50</td>
</tr>
<tr>
<td>Highly polished aluminum, tin plate, nickel, chromium</td>
<td>0.02 to 0.04</td>
<td>0.10 to 0.40</td>
</tr>
</tbody>
</table>
View factors

- Radiation travels only in a straight line
  - Areas and angle of incidence between two exchanging surfaces influences radiative heat transfer

Some common view factors:

\[ A_1 F_{1 \rightarrow 2} = 0.5((ac + bd) - (ad + bc)) \]

Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]
Typical view factors

- Other common view factors from ASHRAE HOF
Simplifying radiation

- We can also define a radiation heat transfer coefficient that is analogous to other heat transfer coefficients

\[ Q_{rad,1\rightarrow2} = h_{rad} A_1 (T_1 - T_2) = \frac{1}{R_{rad}} A_1 (T_1 - T_2) \]

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

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

where

\[ T_{avg} = \frac{T_1 + T_2}{2} \]
Simplifying surface radiation

- We can also often simplify radiation from:

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

- To:

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

Particularly when dealing with large differences in areas, such as sky-surface or ground-surface exchanges.
Heat transfer in building science: Summary

### Conduction

\[
q = \frac{k}{L} \left( T_{\text{surf},1} - T_{\text{surf},2} \right)
\]

\[
\frac{k}{L} = U = \frac{1}{R}
\]

\[
R_{\text{total}} = \frac{1}{U_{\text{total}}}
\]

For thermal bridges and combined elements:

\[
U_{\text{total}} = \frac{A_1}{A_{\text{total}}} U_1 + \frac{A_2}{A_{\text{total}}} U_2 + \ldots
\]

### Convection

\[
q_{\text{conv}} = h_{\text{conv}} \left( T_{\text{fluid}} - T_{\text{surf}} \right)
\]

\[
R_{\text{conv}} = \frac{1}{h_{\text{conv}}}
\]

### Radiation

#### Long-wave

\[
q_{1\rightarrow 2} = \frac{\sigma \left( T_{\text{surf},1}^4 - T_{\text{surf},2}^4 \right)}{1 - \varepsilon_1 + \frac{A_1 \left( 1 - \varepsilon_2 \right)}{\varepsilon_1 A_2} + \frac{1}{F_{12}}}
\]

\[
q_{\text{rad},1\rightarrow 2} = h_{\text{rad}} \left( T_{\text{surf},1} - T_{\text{surf},2} \right)
\]

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

\[
R_{\text{rad}} = \frac{1}{h_{\text{rad}}}
\]

\[
q_{1\rightarrow 2} = \varepsilon_{\text{surf}} \sigma F_{12} \left( T_{\text{surf},1}^4 - T_{\text{surf},2}^4 \right)
\]

### Solar radiation

- **(opaque surface)**
  \[
  q_{\text{solar}} = \alpha I_{\text{solar}}
  \]

- **(transparent surface)**
  \[
  q_{\text{solar}} = \tau \alpha I_{\text{solar}}
  \]
COMBINED-MODE HEAT TRANSFER
Combined mode heat transfer

- Nearly all heat transfer situations in buildings include more than one mode of heat transfer.
- When more than one heat transfer mode is present, we can compute heat loss using resistances (of all kinds) in series.
Combined modes of heat transfer

- Example problem: Convection and wall R-values

- Repeat example from last class for a stud wall to include the effect of inner and outer surface convection coefficients

- Assume the same interior surface resistance from our previous classroom problem
  - Assume the outer surface coefficient during winter conditions is appropriate
Combined heat transfer

- When more than one mode of heat transfer exists at a location (usually convection + radiation), we add the heat flow from each node to get the total
  - Resistances get placed in parallel
  - Example: Heat transfer to/from exterior wall or in a cavity
Combined modes of heat transfer

• Example problem: Radiant barrier in a residential wall

A building designer wishes to evaluate the R-value of a 1 inch wide air gap in a wall for its insulation effect. The resistance to heat flow offered by convection is small, so she proposes lining the cavity’s inner and outer surfaces with a highly reflecting aluminum foil film whose emissivity is 0.05.

Find the R-value of this cavity, including both radiation and convection effects, if the surface temperatures facing the gap are 7.2°C and 12.8°C.
SOLAR RADIATION
Solar radiation

• Solar radiation is an important term in the “energy balance” of a building
  – One 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

• For peak loads, we need to understand characteristics of solar radiation on a short time scale
  – Hourly or daily

• For annual energy consumption, we need to understand solar radiation on longer time scales
  – Annual
Solar radiation striking an exterior surface

- The amount of solar radiation received by a surface depends on the **incidence angle**

- This is a function of:
  - Solar geometry
    - Location
    - Time
  - Surface geometry
  - Shading/obstacles
  - Level of cloudiness

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

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

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

• Direct solar radiation \( (I_{\text{direct}}) \) is a function of the “normal incident irradiation” \( (I_{\text{ND}}) \) on the earth’s surface and the solar incidence angle of the surface of interest, \( \theta \)
  – Where \( I_{\text{ND}} \) is a function of day of the year and atmospheric properties

• Diffuse solar radiation \( (I_{\text{diffuse}}) \) is the irradiation that is scattered by the atmosphere
  – Function of \( I_{\text{ND}} \), 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 \( I_{\text{ND}} \), solar geometry, ground reflectance, and surface tilt angle
Visualizing solar relationships

• For visualizing geometry, using something like IES-VE
  – Show videos

• Videos can be downloaded here:
    • 56 mb zip file of several videos
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

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

• For hourly solar actual data (direct + diffuse in W/m\(^2\))
  – Output of interest = “direct normal radiation” \(\rightarrow\) adjust using \(\cos \theta\)
    • Note: “typical meteorological years”
What to do with solar data once you have it?

• Solar data can be used on exterior opaque surfaces to help determine external surface temperatures

• Solar data can also be used on exterior transparent surfaces (e.g. windows and skylights) to determine how much solar radiation enters an indoor environment

• Both are used for a building’s overall “energy balance”
Sol-air temperatures

• If we take an external surface with a combined convective and radiative heat transfer coefficient, \( h_{\text{conv+rad}} \)

\[
q_{\text{conv+rad}} = h_{\text{conv+rad}} \left( T_{\text{air}} - T_{\text{surf}} \right)
\]

• If that surface now absorbs solar radiation \( (\alpha I_{\text{solar}}) \), the total heat flow at the exterior surface becomes:

\[
q_{\text{conv+rad}} = h_{\text{conv+rad}} \left( T_{\text{air}} - T_{\text{surf}} \right) + \alpha I_{\text{solar}}
\]

• To simplify our calculations, we can define a “sol-air” temperature that accounts for all of these impacts:

\[
T_{\text{sol-air}} = T_{\text{air}} + \frac{\alpha I_{\text{solar}}}{h_{\text{conv+rad}}}
\]

• Now we can describe heat transfer at that surface as:

\[
q_{\text{total}} = h_{\text{conv+rad}} \left( T_{\text{sol-air}} - T_{\text{surf}} \right)
\]
Sol-air temperatures

**FIGURE 6.17**
Sol-air temperature for horizontal and vertical surfaces as a function of time of day for summer design conditions. July 21 at 40° latitude, assuming $\alpha/h_v = 0.30 \text{ (h} \cdot \text{F}^2 \cdot \text{F})/\text{Btu (m}^2 \cdot \text{K})/\text{W}$. The curves overlap when there is no direct radiation on a surface. (Courtesy of ASHRAE, *Handbook of Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1989, Table 26.1.)
Solar radiation and external surface temperatures

- We can also use air temperatures and material properties (emissivity and absorptance) to estimate exterior surface temperatures that are exposed to radiation
  - These are not perfectly accurate but provide a reasonable estimate for use in simple conduction

<table>
<thead>
<tr>
<th>Situation</th>
<th>Thermally massive</th>
<th>Thermally lightweight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roofs: direct sun</td>
<td>$t_a + 42 \alpha$</td>
<td>$t_a + 55 \alpha$</td>
</tr>
<tr>
<td>Roof: sun + reflected/emitted radiation</td>
<td>$t_a + 55 \alpha$</td>
<td>$t_a + 72 \alpha$</td>
</tr>
<tr>
<td>Roof exposed to night sky</td>
<td>$t_a - 5 \varepsilon$</td>
<td>$t_a - 10 \varepsilon$</td>
</tr>
<tr>
<td>Walls: winter sun</td>
<td>$t_a + 35 \alpha$</td>
<td>$t_a + 48 \alpha$</td>
</tr>
<tr>
<td>Walls: summer sun</td>
<td>$t_a + 28 \alpha$</td>
<td>$t_a + 40 \alpha$</td>
</tr>
<tr>
<td>Walls exposed to night sky</td>
<td>$t_a - 2 \varepsilon$</td>
<td>$t_a - 4 \varepsilon$</td>
</tr>
</tbody>
</table>

Source: Straube and Burnett
Solar radiation and windows

- Solar radiation through a single glaze

100% incident
8% reflected
80% transmitted
Thus 12% absorbed
8% rad/conv outward
4% rad/conv inward
84% total transmitted
Windows and total heat gain

• The total heat gain of a window is the sum of two terms:
  – The solar radiation heat gain from solar irradiation (transmittance)
  – Conductive/convective/radiative thermal heat gain from the temperature difference between the interior and exterior

• In the summer, both terms are positive towards the interior and add heat gains

• In the winter, solar is positive inwards but the other is negative towards the exterior
  – Net heat gain may vary in direction
Heat gain through windows

• Calculating the **thermal** heat gain through a window is easy

\[ Q = UA \Delta T \]

• Accounting for **solar** heat gain is more complicated
  – Need to include spectral and angular characteristics of radiation and glazing
  – Need to include absorption of solar energy and re-radiation of thermal energy

• We can do this with a simplified metric
  – The solar heat gain coefficient (SHGC):

\[ Q_{solar,\text{window}} = \left( I_{solar} A \right) SHGC \]
Solar heat gain coefficient, SHGC

\[ Q_{solar,\text{window}} = \left( I_{solar} A \right) SHGC \]

- For a single pane of glass:

\[
SHGC = \tau + \alpha \frac{U}{h_{ext}} \quad \frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{R_{\text{glass}}} + \frac{1}{h_{ext}}
\]

*\( R_{\text{glass}} \) is negligible

- For double glazing with a small air space:

\[
SHGC = \tau + \alpha_{\text{outer}} \frac{U}{h_{ext}} + \alpha_{\text{inner}} U \left( \frac{1}{h_{ext}} + \frac{1}{h_{\text{airspace}}} \right)
\]

\[
\frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{h_{\text{airspace}}} + \frac{1}{h_{ext}}
\]
Manufacturer supplied SHGC

• Glazing manufacturers will measure and present SHGC for normal incidence according to the methods of NFRC 200
  – National Fenestration Rating Council has developed methods for rating and labeling SHGC, U factors, air leakage, visible transmittance and condensation resistance of fenestration products
• In reality, SHGC is a function of incidence angle ($\theta$)

$$Q_{solar,\ window} = I_{\ direct} SHGC(\theta)A + (I_{\ diffuse+reflected} SHGC_{\ diffuse+reflected})A$$
Complex SHGC

- SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with incidence angles of solar radiation.
- The ASHRAE Handbook of Fundamentals 2013 Chapter 15 provides data for a large variety of glazing types.

<table>
<thead>
<tr>
<th>Table 10 Visible Transmittance ($T_v$), Solar Heat Gain Coefficient (SHGC), Solar Transmittance ($T$), Front Reflectance ($R_f$), Back Reflectance ($R_b$), and Layer Absorptance ($A_1$) for Glazing and Window Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Glazing System</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Glass Thick., mm</td>
</tr>
<tr>
<td>ID</td>
</tr>
<tr>
<td>1a</td>
</tr>
<tr>
<td>1b</td>
</tr>
</tbody>
</table>
What about window assemblies?

- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make fenestration systems

- Total heat transfer through an assembly:

\[
Q_{\text{window}} = UA_{pf} (T_{out} - T_{in}) + I_{\text{solar}} A_{pf} \cdot SHGC
\]

Where:
- \(U\) = overall coefficient of heat transfer (U-factor), \(W/m^2K\)
- \(A_{pf}\) = total projected area of fenestration, \(m^2\)
- \(T_{in}\) = indoor air temperature, \(K\)
- \(T_{out}\) = outdoor air temperature, \(K\)
- \(SHGC\) = solar heat gain coefficient, -
- \(I_{\text{solar}}\) = incident total irradiance, \(W/m^2\)
Window U-factors

• U-values (or U-factors) for windows include all of the elements of the fenestration system
  – Center of glass properties \((cg)\)
  – Edge of glass properties \((eg)\)
  – Frame properties \((f)\)

• The overall U-factor is estimated using area-weighted U-factors for each:

\[
U = \frac{U_{cg} A_{cg} + U_{eg} A_{eg} + U_{f} A_{f}}{A_{pf}}
\]
Combined U-factor data: ASHRAE 2013

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>Glass Only</th>
<th>Operable (including sliding and swinging glass doors)</th>
<th>Vertical Installation</th>
<th>Fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>Center of Glass</td>
<td>Edge of Glass</td>
<td>Aluminum Without Thermal Break</td>
<td>Aluminum With Thermal Break</td>
</tr>
<tr>
<td>1</td>
<td>5.91</td>
<td>5.91</td>
<td>7.01</td>
<td>6.08</td>
</tr>
<tr>
<td>2</td>
<td>5.00</td>
<td>5.00</td>
<td>6.23</td>
<td>5.35</td>
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<tr>
<td>3</td>
<td>5.45</td>
<td>5.45</td>
<td>6.62</td>
<td>5.72</td>
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<tr>
<td>Single Glazing</td>
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<tr>
<td>5</td>
<td>2.73</td>
<td>3.36</td>
<td>4.30</td>
<td>3.31</td>
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<td>6</td>
<td>2.90</td>
<td>3.48</td>
<td>4.43</td>
<td>3.44</td>
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<tr>
<td>7</td>
<td>2.56</td>
<td>3.24</td>
<td>4.16</td>
<td>3.18</td>
</tr>
<tr>
<td>Double Glazing, e = 0.60 on surface 2 or 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.95</td>
<td>3.52</td>
<td>4.48</td>
<td>3.48</td>
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<tr>
<td>9</td>
<td>2.50</td>
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<td>4.11</td>
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<td>10</td>
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<td>11</td>
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<td>3.08</td>
<td>3.98</td>
<td>3.01</td>
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<tr>
<td>Double Glazing, e = 0.40 on surface 2 or 3</td>
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<td></td>
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<tr>
<td>12</td>
<td>2.78</td>
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<td>3.35</td>
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<tr>
<td>13</td>
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<td>15</td>
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<td>2.79</td>
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<tr>
<td>Double Glazing, e = 0.20 on surface 2 or 3</td>
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<td></td>
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<tr>
<td>16</td>
<td>2.56</td>
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<td>4.16</td>
<td>3.18</td>
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<td>1.99</td>
<td>2.83</td>
<td>3.70</td>
<td>2.75</td>
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<tr>
<td>18</td>
<td>2.16</td>
<td>2.96</td>
<td>3.84</td>
<td>2.88</td>
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<td>19</td>
<td>1.70</td>
<td>2.62</td>
<td>3.47</td>
<td>2.53</td>
</tr>
<tr>
<td>Double Glazing, e = 0.10 on surface 2 or 3</td>
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<td></td>
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<tr>
<td>20</td>
<td>2.39</td>
<td>3.12</td>
<td>4.02</td>
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<td>2.83</td>
<td>3.70</td>
<td>2.75</td>
</tr>
<tr>
<td>23</td>
<td>1.53</td>
<td>2.49</td>
<td>3.33</td>
<td>2.40</td>
</tr>
</tbody>
</table>
What about shading?

- Shading devices, including drapes and blinds, can mitigate some solar heat gain.

- We can attempt to describe this with an **indoor solar attenuation coefficient (IAC)**.

- Heat gain through a window can be modified as follows:

\[
Q_{\text{window}} = U_A \frac{A_p f}{T_{out} - T_{in}} + I_{\text{direct}} A_p f \ SHGC(\theta) \ IAC(\theta, \Omega) + (I_{\text{diffuse+reflected}}) A_p f \ SHGC_{\text{diffuse+reflected}} \ IAC_{\text{diffuse+reflected}}
\]

*\( IAC \) is a function of incidence angle, \( \theta \), and the angle created by a shading device.*
Building energy balances

• Taken altogether, each of the heat transfer modes we’ve discussed can be combined with inputs for climate data, material properties, and geometry to make up a building’s energy balance
  – We will revisit this for heating and cooling load calculations
Next time

• The following class, on Monday September 16\textsuperscript{th}
  – HW 2 will be due
  – Will cover \textit{Psychrometrics and thermal comfort}