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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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*)

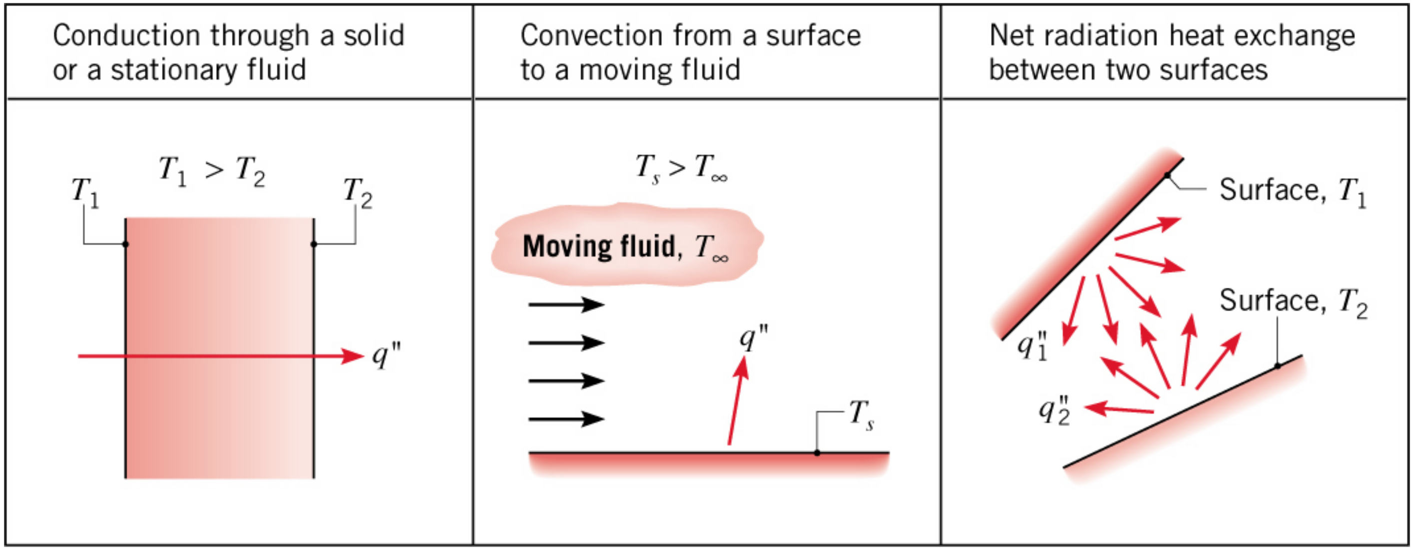
- In context: heat transfer in building science
  - Walls, roofs, windows, floors
  - HVAC systems (*didn't get to this*)

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



Conduction **Convection** **Radiation**

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

$$\frac{k}{L} = U = \frac{1}{R} \qquad R_{total} = \frac{1}{U_{total}}$$

$$R_{total} = R_1 + R_2 + R_3 + \ \ldots$$

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

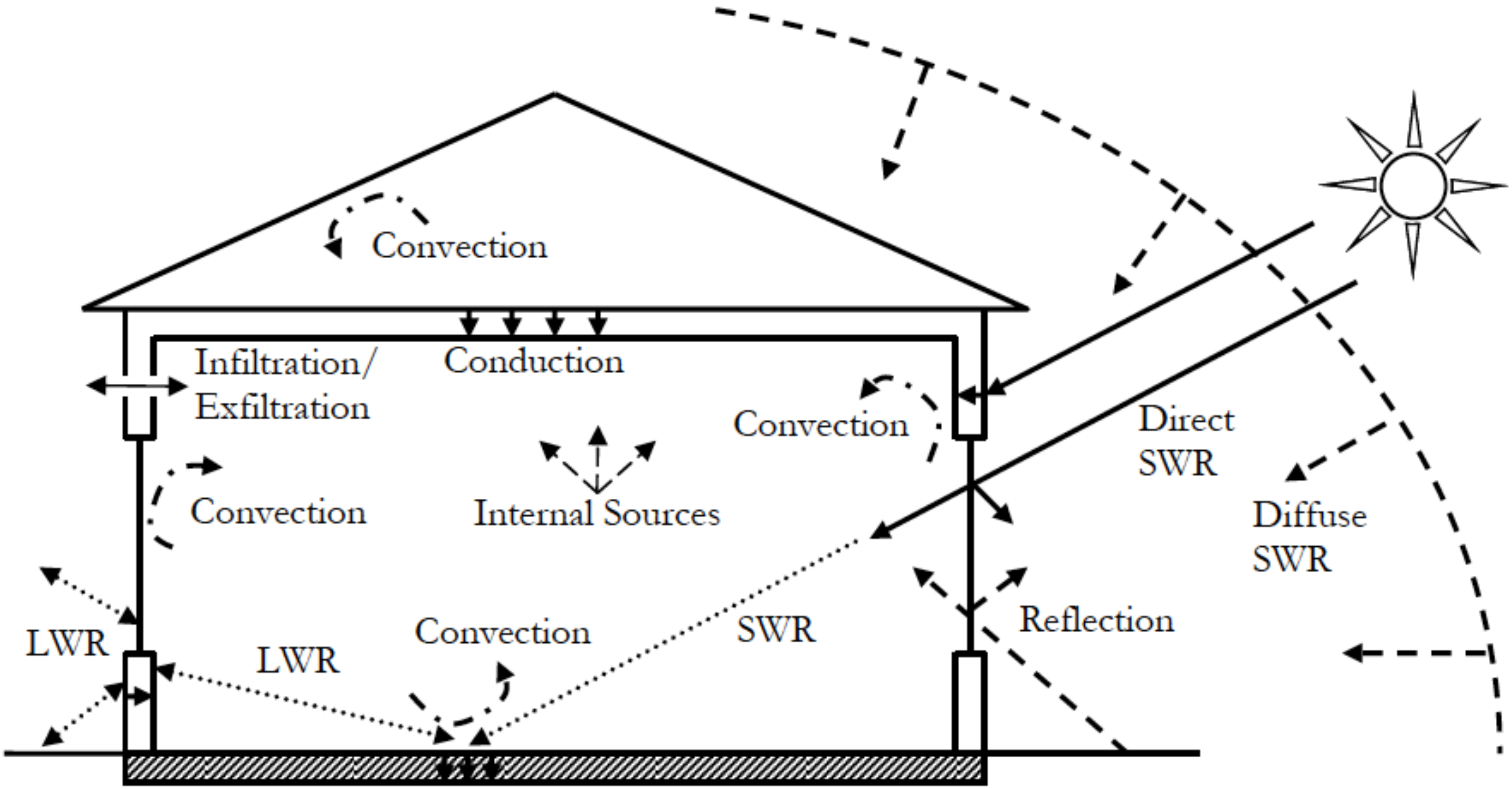
$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surf}\right)$$

$$R_{conv} = \frac{1}{h_{conv}}$$

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

Surface Conditions	Horizontal Heat Flow	Upwards Heat Flow	Downwards Heat Flow
Indoors: R_{in}	0.12 m^2K/W (SI) 0.68 $h\cdot ft^2\cdot{}^\circ F/Btu$ (IP)	0.11 m^2K/W (SI) 0.62 $h\cdot ft^2\cdot{}^\circ F/Btu$ (IP)	0.16 m^2K/W (SI) 0.91 $h\cdot ft^2\cdot{}^\circ F/Btu$ (IP)
R_{out}: 6.7 m/s wind (Winter)		0.030 m^2K/W (SI) 0.17 $h\cdot ft^2\cdot{}^\circ F/Btu$ (IP)	
R_{out}: 3.4 m/s wind (Summer)		0.044 m^2K/W (SI) 0.25 $h\cdot ft^2\cdot{}^\circ F/Btu$ (IP)	

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

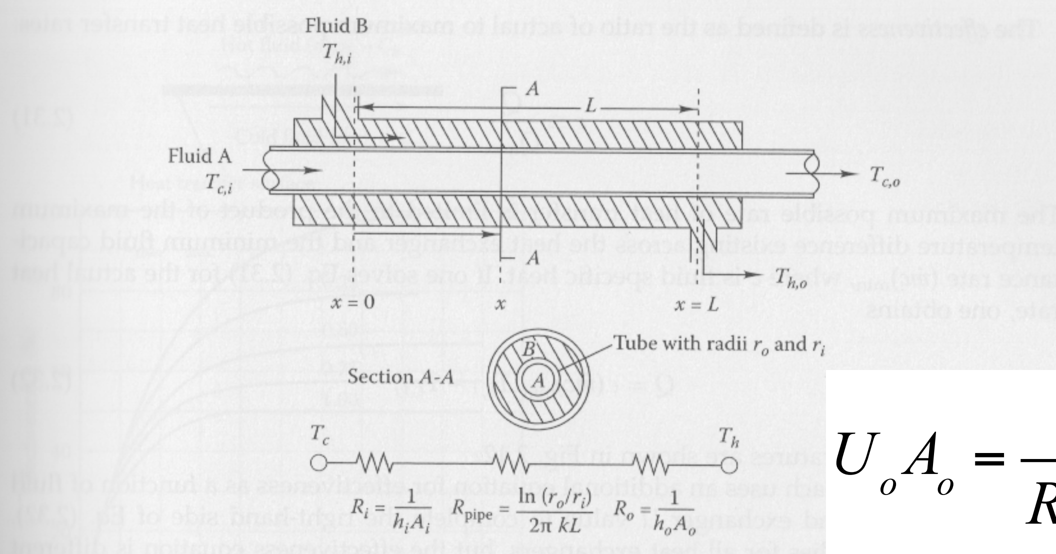
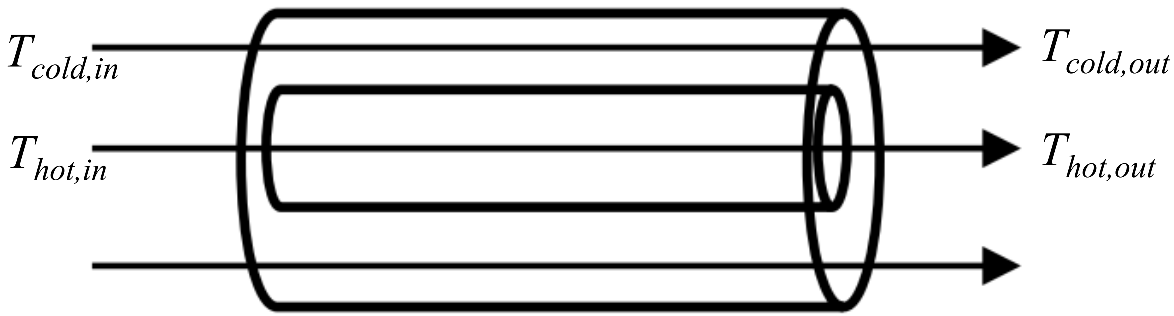


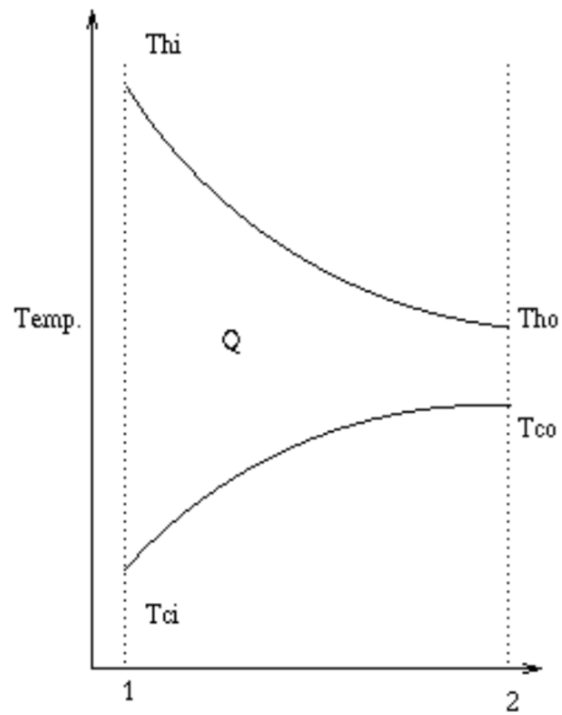
FIGURE 2.12
Schematic diagram of parallel-flow shell-and-tube heat exchanger showing fluid temperatures and equivalent thermal circuit.

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

Heat exchangers

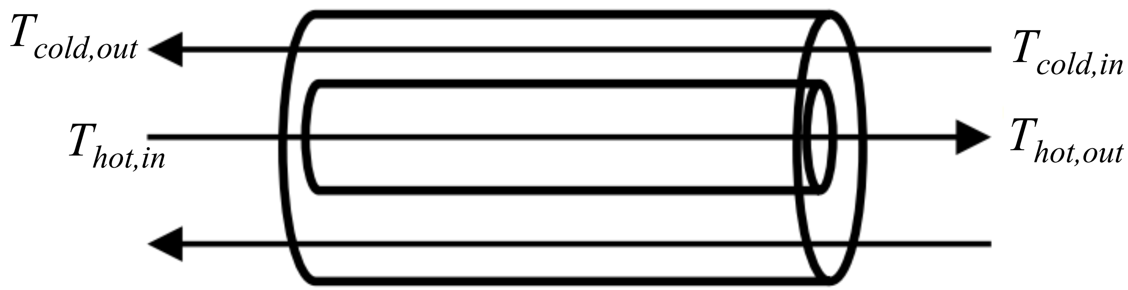
- Parallel flow: fluids flowing in the same direction

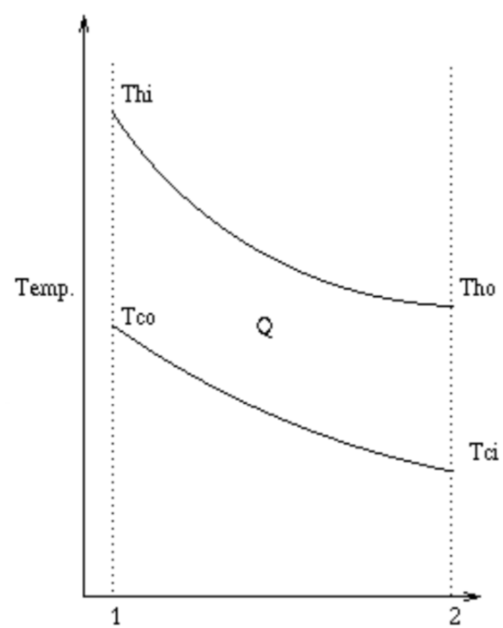




Heat exchangers

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





Heat exchangers

- General heat transfer in heat exchangers

$$Q = UA\Delta T_{mean}$$

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

- Method for predicting heat transfer rate in heat exchangers:
  - ϵ-NTU method: Effectiveness number-of-transfer-units approach

Heat exchangers: ∈-NTU method

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

$$\in = \frac{Q}{Q_{\max}}$$

- 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:

$$Q = \in (\dot{m}C_p)_{\min}\left(T_{hot,in} - T_{cold,in}\right)$$

- 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: ∊-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"

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

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

TABLE 2.10

Heat Exchanger Effectiveness Relations $N = \mathrm{NTU} = \frac{U_o A_o}{\dot{C}_{\min}}$ $C = \frac{\dot{C}_{\min}}{\dot{C}_{\max}}$

Flow Geometry	Relation
Double pipe	
Parallel flow	$\varepsilon = \frac{1 - \exp[-N(1+C)]}{1+C}$
Counterflow	$\varepsilon = \frac{1 - \exp[-N(1-C)]}{1 - C\exp[-N(1-C)]}$
Crossflow	
Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\frac{1}{Cn}[\exp(-NCn) - 1]\right\}$ where $n = N^{-0.22}$
Both fluids unmixed	$\varepsilon = N\left[\frac{N}{1-\exp(-N)} + \frac{NC}{1-\exp(-NC)} - 1\right]^{-1}$
$\dot{C}_{\max}$ mixed, $\dot{C}_{\min}$ unmixed	$\varepsilon = \frac{1}{C}\{1 - \exp[-C + C\ \exp(-N)]\}$
$\dot{C}_{\max}$ unmixed, $\dot{C}_{\min}$ mixed	$\varepsilon = 1 - \exp\left\{-\frac{1}{C}[1 - \exp(-NC)]\right\}$
Shell and tube	
One shell pass; two, four, six tube passes	$\varepsilon = 2\left[1 + C + \sqrt{1+C^2}\,\frac{1+\exp(-N\sqrt{1+C^2})}{1-\exp(-N\sqrt{1+C^2})}\right]^{-1}$

Heat exchangers: ∈-NTU method

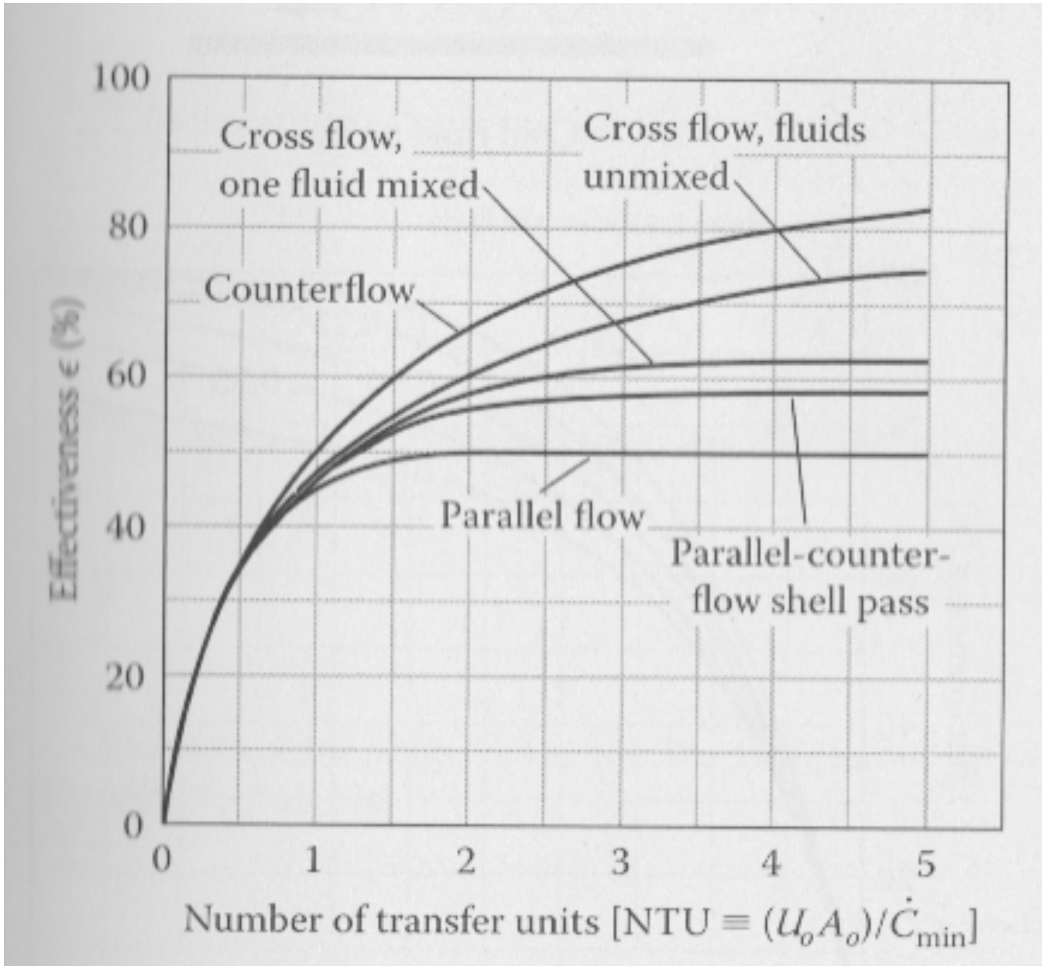
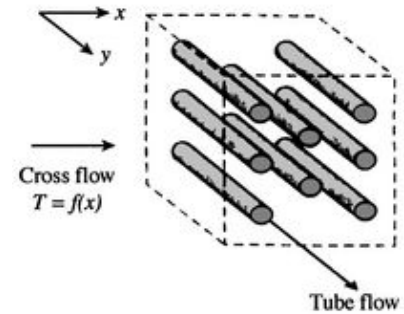


FIGURE 2.14
Comparison of effectiveness of several heat exchanger designs for equal hot- and cold-side capacitance rates, $\dot{C}_{min} = \dot{C}_{max}$.

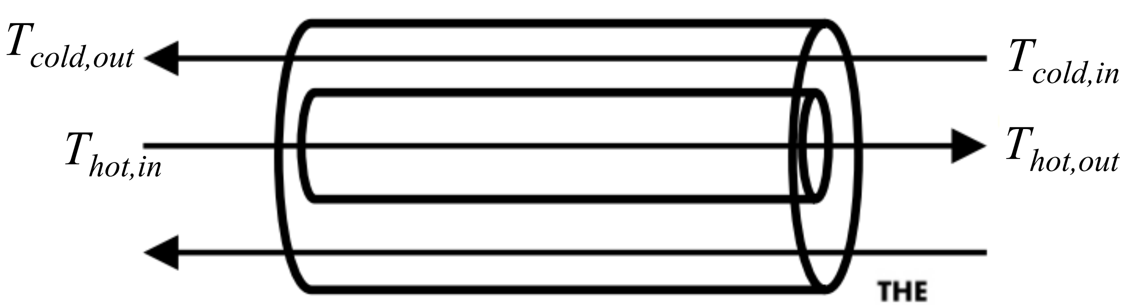


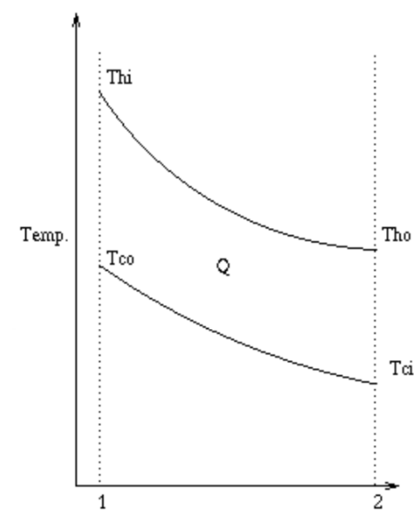
This subject is covered in more detail in CAE 464 HVAC Design

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/(m^{2}K) and the transfer area is 20 m^2





Bulk convective heat transfer: "Advection"

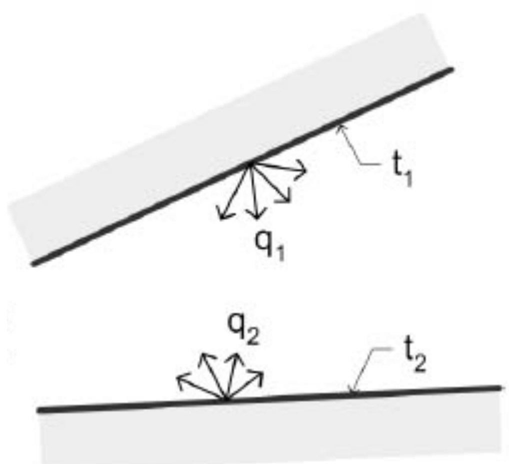
- Bulk convective heat transfer, or advection, is more direct than convection between surfaces and fluids
- Bulk convective heat transfer is the transport of heat by airflow
  - Air has a capacity to store heat, so air flowing into or out of a building carries heat with it

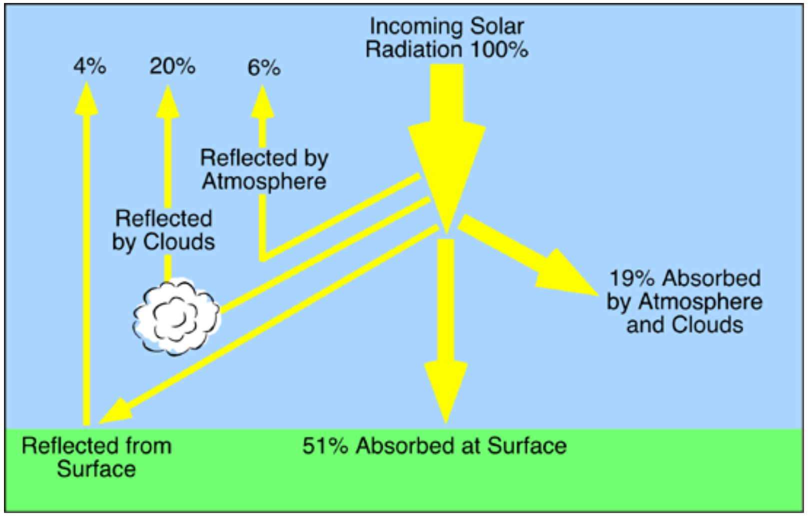
$$Q_{bulk} = \dot{m} C_p \Delta T \qquad [\mathrm{W}] = [\frac{\mathrm{kg}}{\mathrm{s}} \cdot \frac{\mathrm{J}}{\mathrm{kg} \cdot \mathrm{K}} \cdot \mathrm{K}]$$

m "dot" = mass flow rate of air (kg/s)
C_p = 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





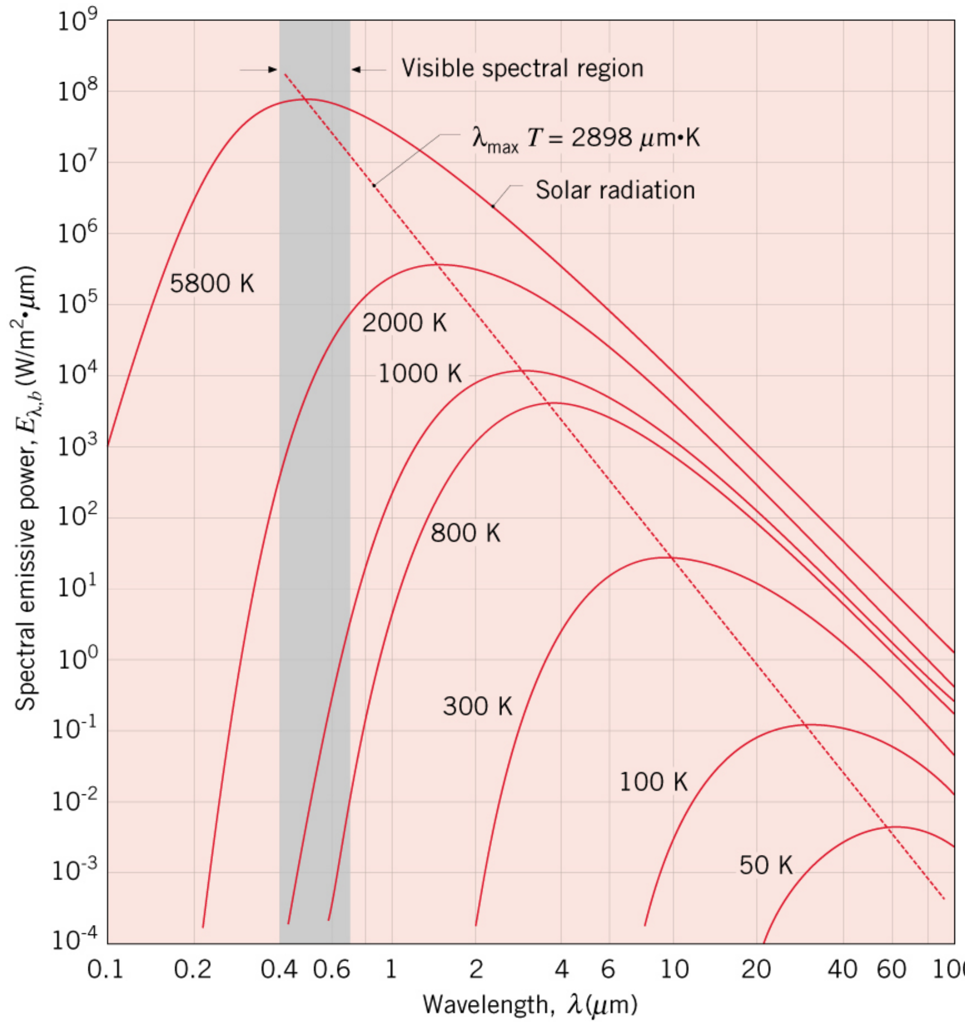
Radiation

- 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

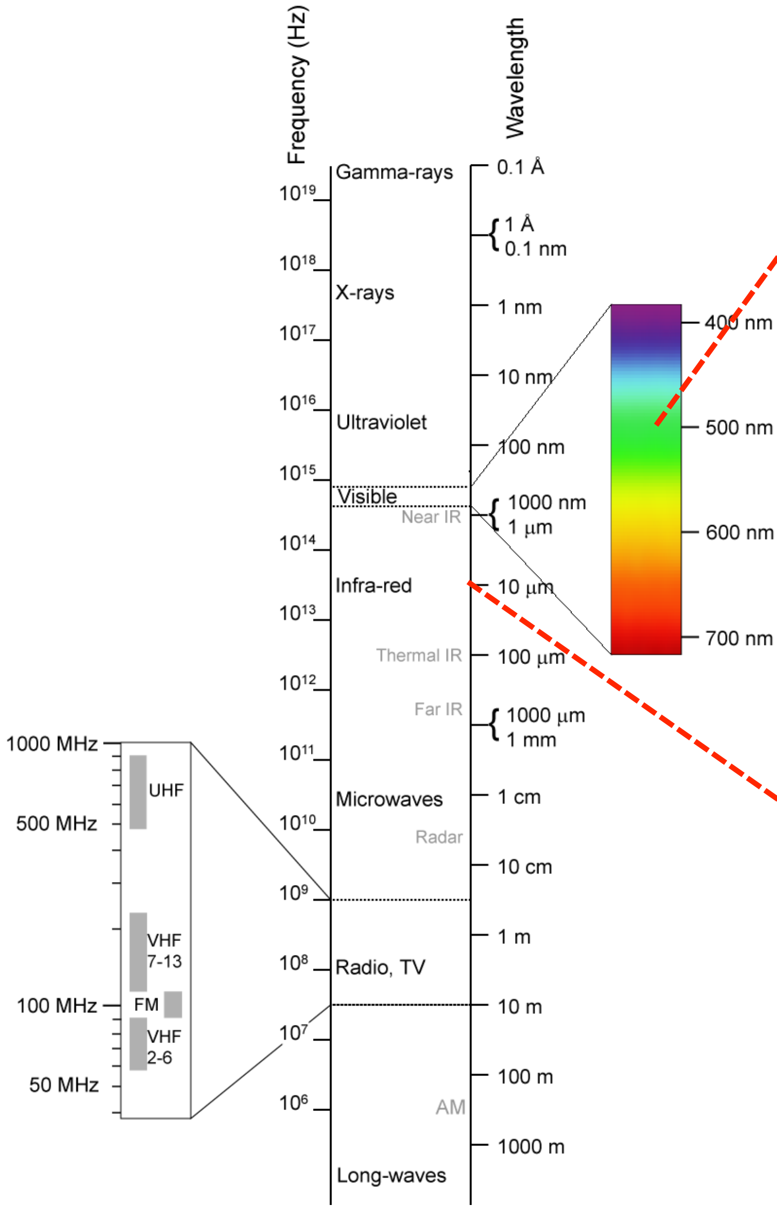
- For our purposes, it's generally appropriate to treat radiation in two groups:
  - Short-wave (solar radiation)
  - Long-wave (diffuse, refracted, or re-emitted radiation)

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

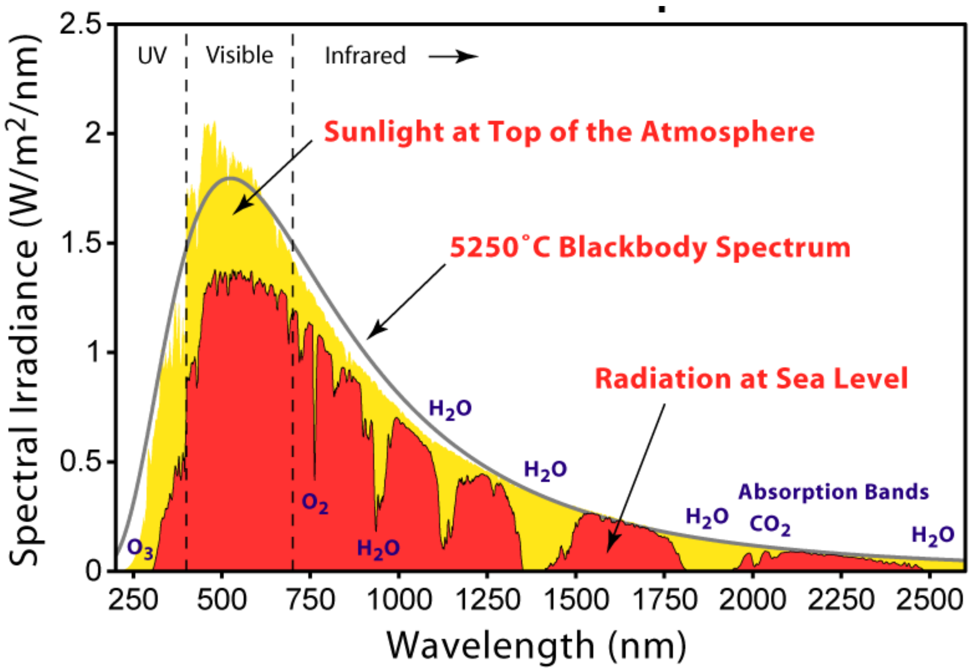


Solar short-wave Radiation (direct) Avg. λ = 0.5 μm

Terrestrial long-wave Radiation (diffuse/reflected) Avg. λ = 10 μm

Solar radiation striking a surface (high temperature)

- Most solar radiation is at short wavelengths



$$I_{solar} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

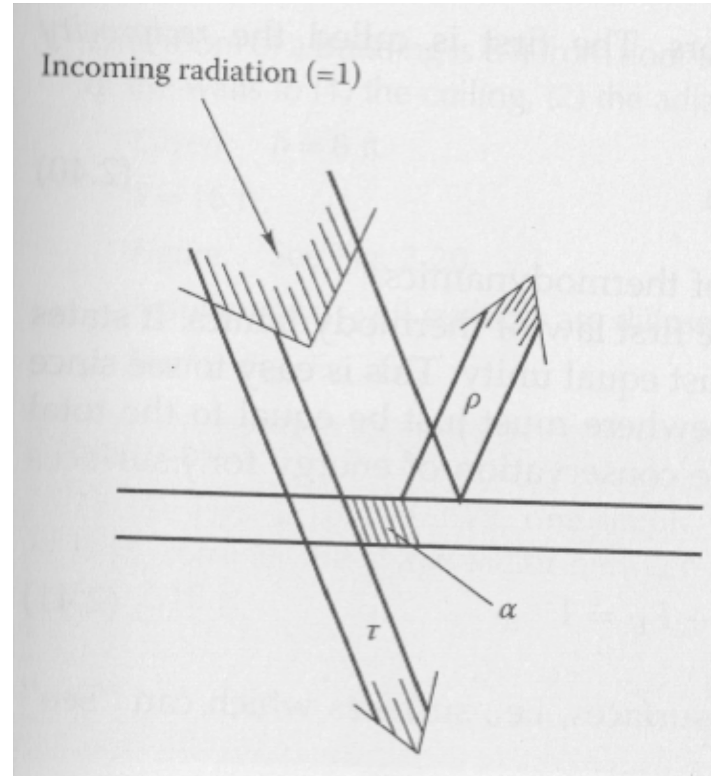
Absorptivity, transmissivity, and reflectivity

- The absorptivity, α, is the fraction of energy hitting an object that is actually absorbed

- Transmissivity, τ, is a measure of how much radiation passes through an object

- Reflectivity, ρ, is a measure of how much radiation is reflected off an object

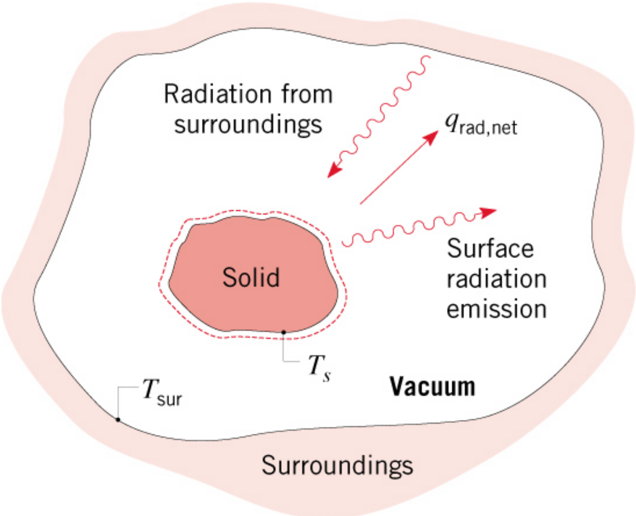
- We use these terms primarily for solar radiation
  - For an opaque surface ($\tau = 0$): $q_{solar} = \alpha I_{solar}$
  - For a transparent surface ($\tau > 0$): $q_{solar} = \tau\alpha I_{solar}$



$$\alpha + \tau + \rho = 1$$

Surface radiation (lower temperature: long-wave)

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



$$q_{rad} = \varepsilon\sigma T^4$$

Where ε=emissivity

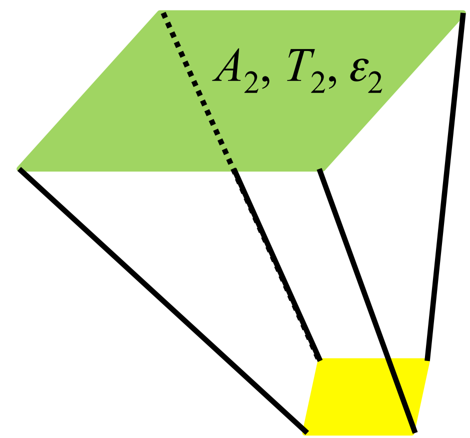
σ = Stefan-Boltzmann constant = $5.670\times10^{-8}\ \frac{\mathrm{W}}{\mathrm{m^2\cdot K^4}}$

T = 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:



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

where ε_1 and ε_2 are the surface emittances,

A_1 and A_2 are the surface areas

and $F_{1\to 2}$ is the view factor from surface 1 to 2

$F_{1\to 2}$ 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: ε

- ε is dependent on wavelength, but for most common building materials (e.g. brick, concrete, wood…), ε = 0.9 at most wavelengths

Emissivity of common building materials

TABLE 2.11

Emissivities of Some Common Building Materials at Specified Temperatures

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

Source: Courtesy of Sparrow, E.M. and Cess, R.D., *Radiation Heat Transfer*, augmented edn, Hemisphere, New York, 1978. With permission.

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 2.2 Emittance and Absorptance Values for Various Surfaces

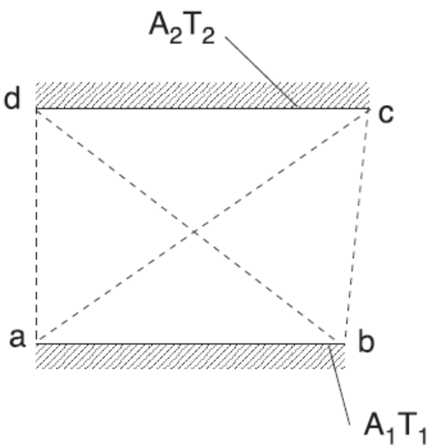
Surface	Emittance or Absorptance 50–100 °F	Emittance or Absorptance 1000 °F	Absorptance for Solar Radiation
A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99	0.97 to 0.99	0.97 to 0.99
Black nonmetallic surfaces such as asphalt, carbon, slate, paint, paper	0.90 to 0.98	0.90 to 0.98	0.85 to 0.98
Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.85 to 0.95	0.75 to 0.90	0.65 to 0.80
Yellow and buff brick and stone, firebrick, fire clay	0.85 to 0.95	0.70 to 0.85	0.50 to 0.70
White or light-cream brick, tile, paint or paper, plaster, whitewash	0.85 to 0.95	0.60 to 0.75	0.30 to 0.50
Window glass	0.90 to 0.95	—	—
Bright aluminum paint; gilt or bronze paint	0.40 to 0.60	—	0.30 to 0.50
Dull brass, copper, or aluminum; galvanized steel; polished iron	0.20 to 0.30	0.30 to 0.50	0.40 to 0.65
Polished brass, copper, monel metal	0.02 to 0.05	0.05 to 0.15	0.30 to 0.50
Highly polished aluminum, tin plate, nickel, chromium	0.02 to 0.04	0.05 to 0.10	0.10 to 0.40

SOURCE: Abstracted by permission from *ASHRAE Handbook of Fundamentals* (Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, 1993) p. 3.8.

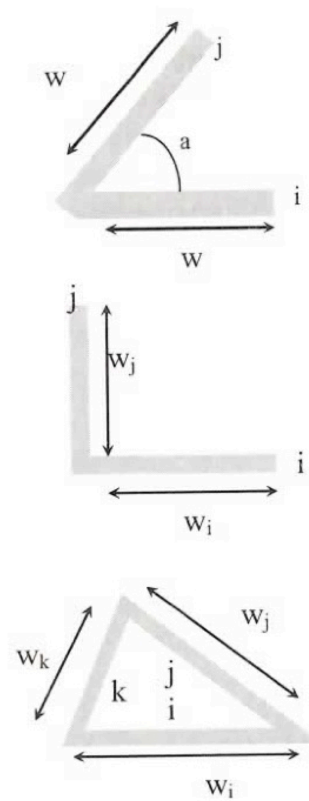
View factors

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

Some common view factors:



$$A_1F_{1\rightarrow2} = 0.5((ac+bd)-(ad+bc))$$



$$F_{ij} = 1-\sin(\frac{a}{2})$$

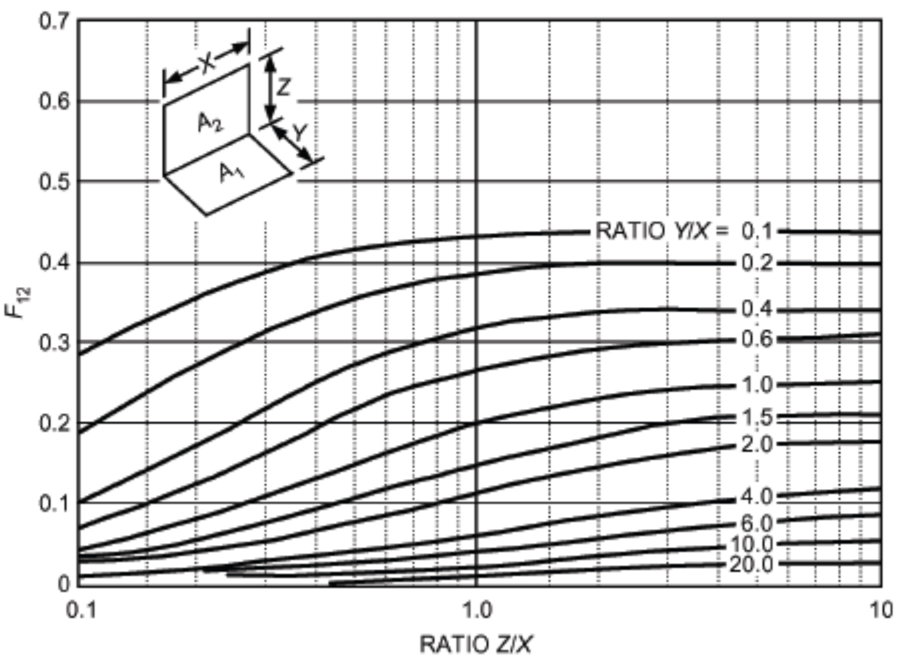
$$F_{ij} = \frac{1+(w_j/w_i)-[1+w_j/w_i)^2]^{1/2}}{2}$$

$$F_{ij} = \frac{w_j+w_i-w_k}{2w_i}$$

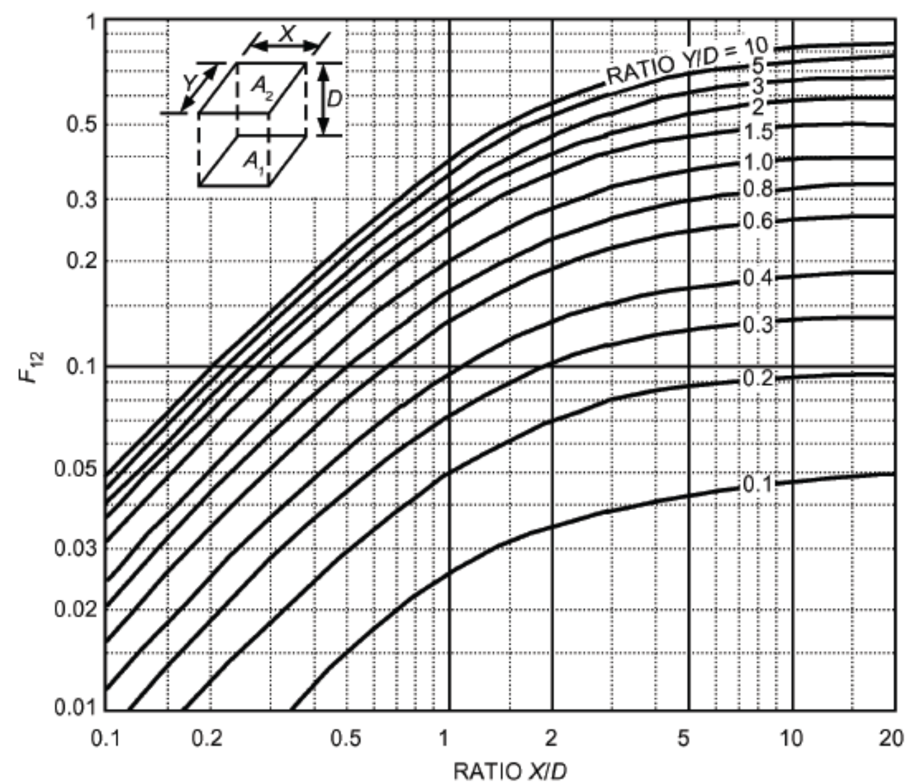
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

- Other common view factors from ASHRAE HOF



A. PERPENDICULAR RECTANGLES WITH COMMON EDGE



B. ALIGNED PARALLEL RECTANGLES

Simplifying radiation

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

$$Q_{rad,1\to 2} = h_{rad} A_1 \left(T_1 - T_2\right) = \frac{1}{R_{rad}} A_1 \left(T_1 - T_2\right)$$

- When $A_1 = A_2$, and T_1 and T_2 are within ~50°F of each other, we can approximate h_{rad} with a simpler equation:

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

where

$$T_{avg} = \frac{T_1 + T_2}{2}$$

Simplifying surface radiation

- We can also often simplify radiation from:

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

- To: $Q_{1\to 2} = \varepsilon_{surf} A_{surf} \sigma F_{12} \left(T_1^4 - T_2^4\right)$

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

Heat transfer in building science: Summary

Conduction

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

$$\frac{k}{L} = U = \frac{1}{R}$$

$$R_{total} = \frac{1}{U_{total}}$$

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

For thermal bridges and combined elements:

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

Convection

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

$$R_{conv} = \frac{1}{h_{conv}}$$

Radiation

Long-wave

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

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

$$h_{rad} = \frac{4\sigma T_{avg}^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad R_{rad} = \frac{1}{h_{rad}}$$

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

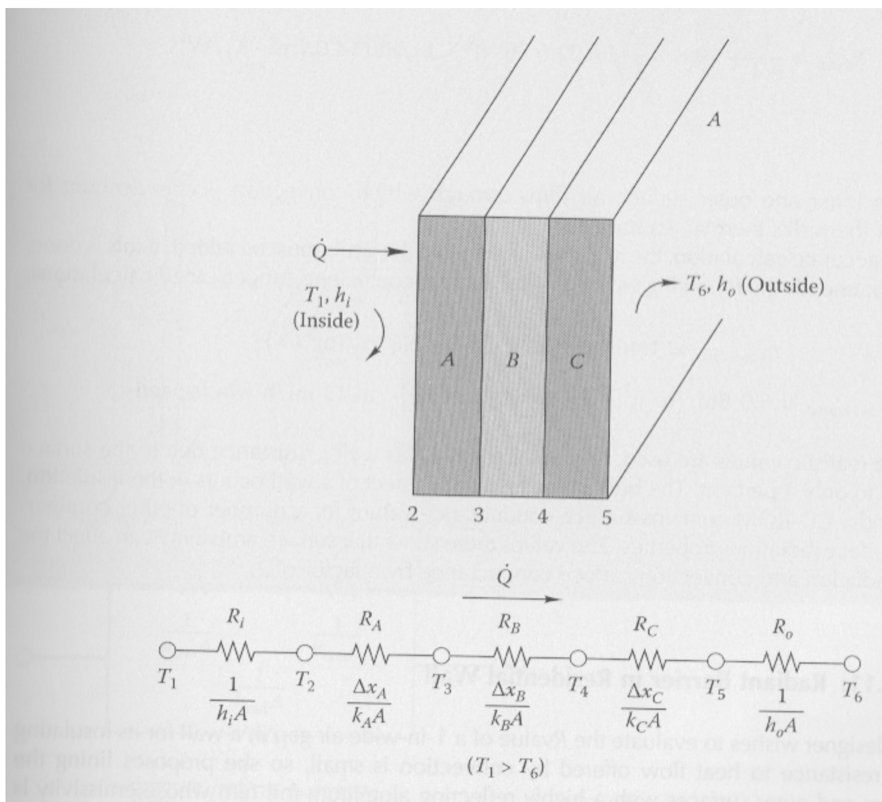
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

Transmitted solar radiation: (transparent surface) $q_{solar} = \tau\alpha I_{solar}$

COMBINED-MODE HEAT TRANSFER

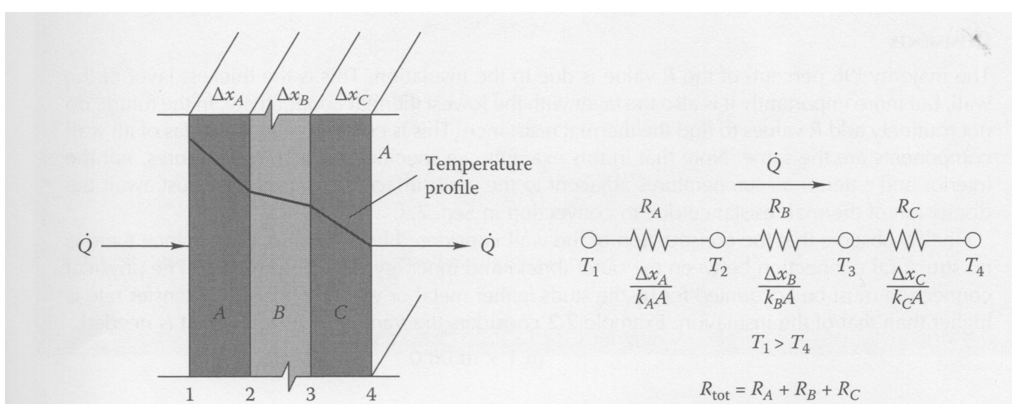
Combined mode heat transfer

- 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



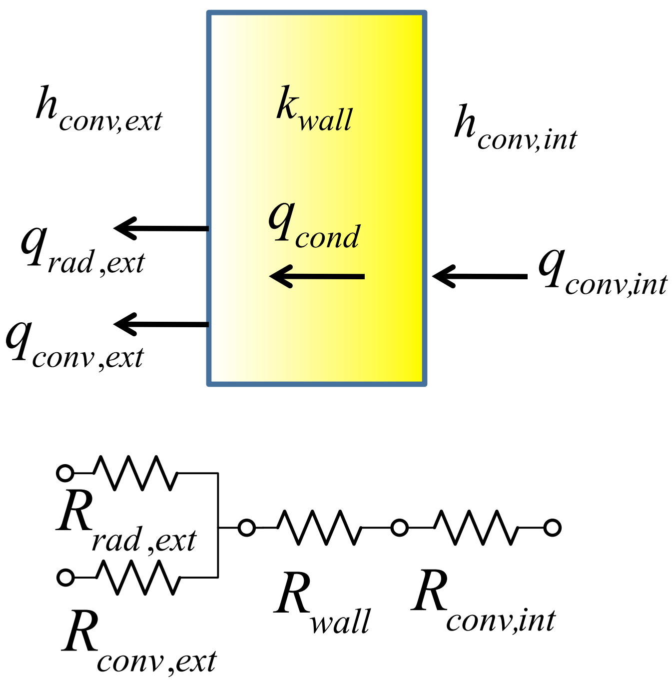
Combined modes of heat transfer

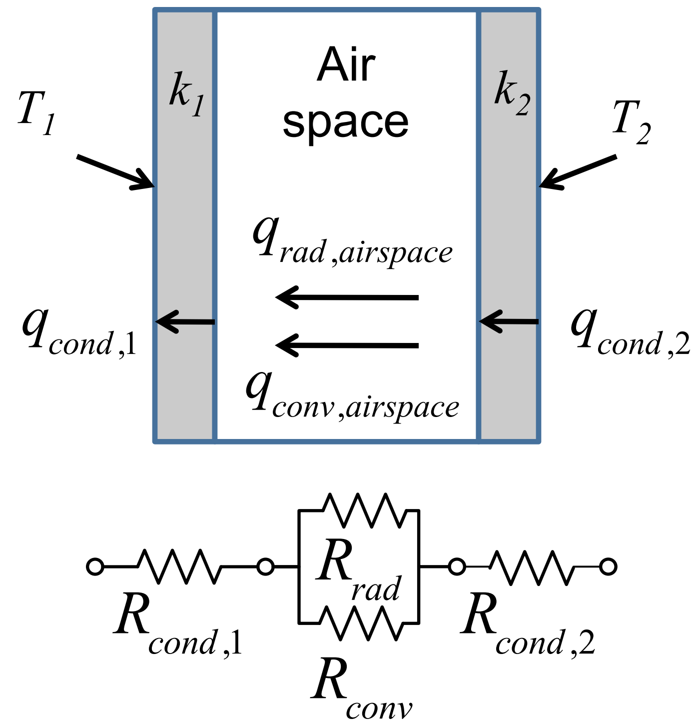
- Example problem: Convection and wall R-values
- Repeat example from last class for a stud wall to include the effect of inner and outer surface convection coefficients
- Assume the same interior surface resistance from our previous classroom problem
  - Assume the outer surface coefficient during winter 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



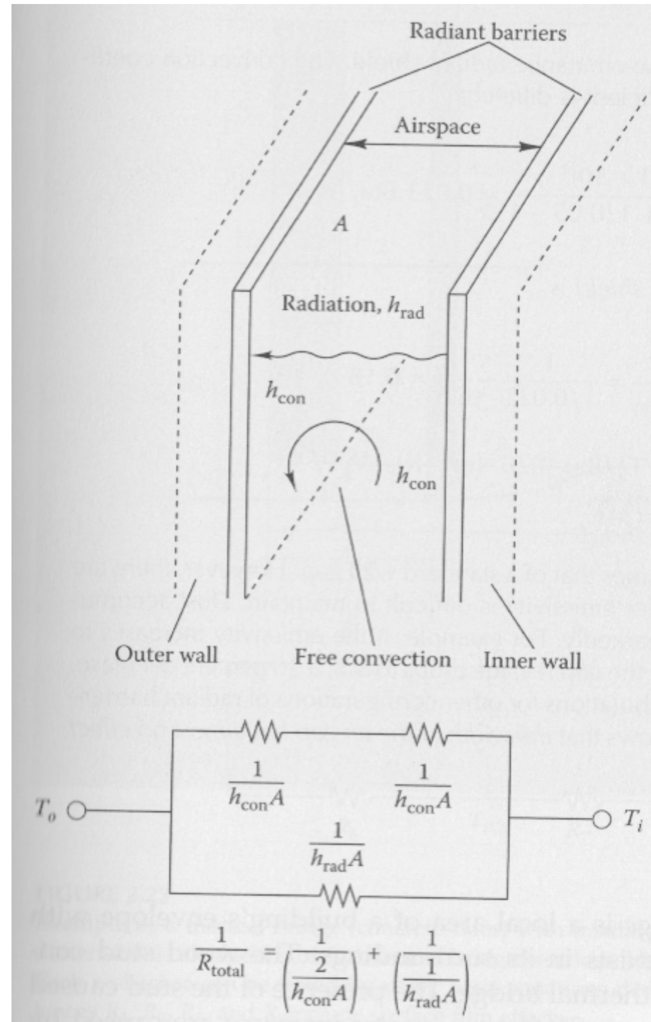


Combined modes of heat transfer

- 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

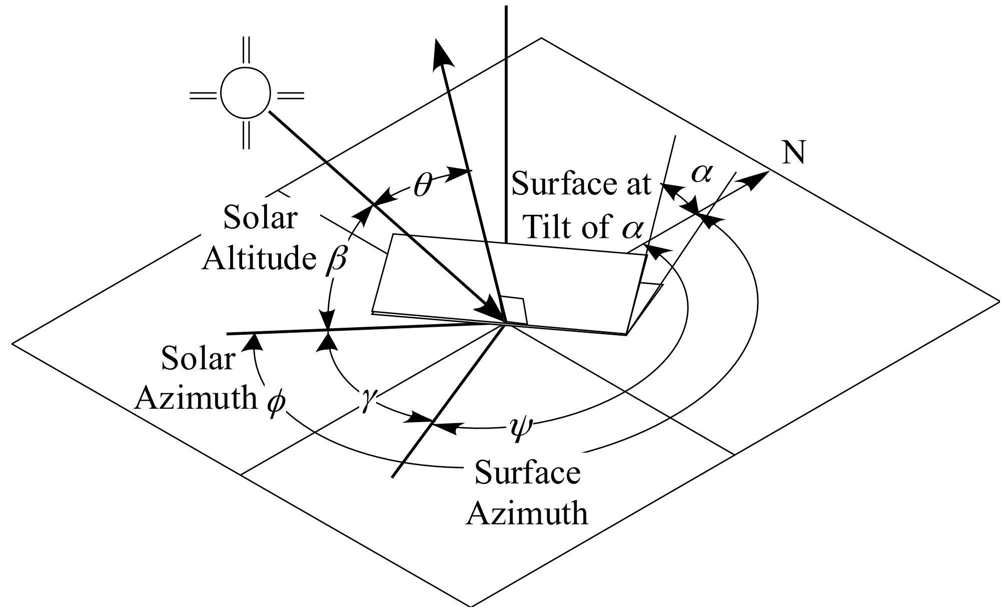
- Solar radiation is also important for daylighting design

- 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**



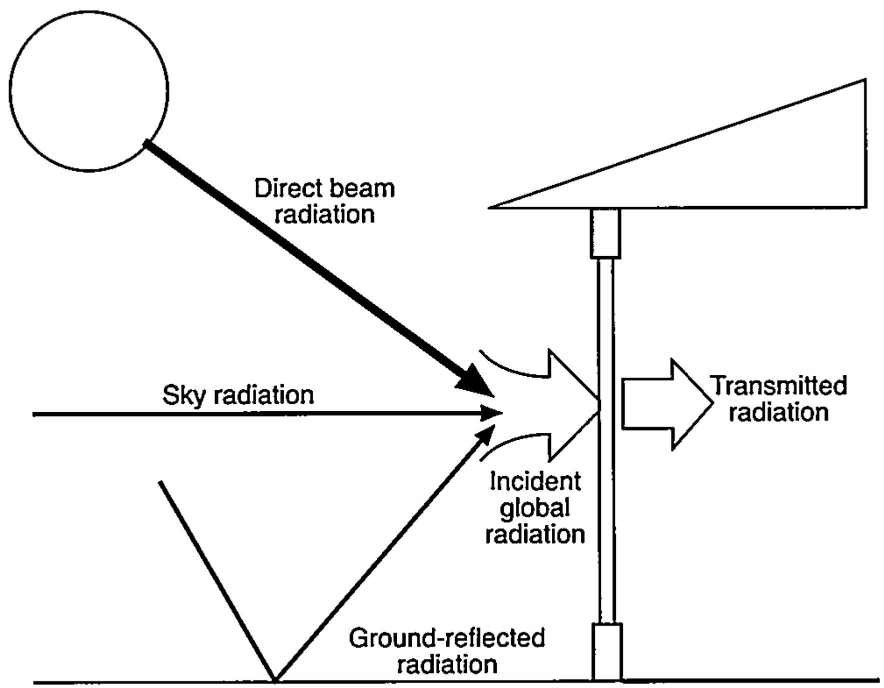
- This is a function of:
  - Solar geometry
    - Location
    - Time
  - Surface geometry
  - Shading/obstacles
  - Level of cloudiness

- 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:

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



Incident global solar radiation includes direct beam, sky, and ground-reflected radiation

Components of solar radiation

- Direct solar radiation (I_{direct}) is a function of the "normal incident irradiation" (I_{ND}) on the earth's surface and the solar incidence angle of the surface of interest, θ
  - Where I_{ND} is a function of day of the year and atmospheric properties

- Diffuse solar radiation ($I_{diffuse}$) is the irradiation that is scattered by the atmosphere
  - Function of I_{ND}, atmospheric properties, and surface's tilt angle

- Reflected solar radiation ($I_{reflected}$) is the irradiation that is reflected off the ground (it becomes diffuse)
  - Function of I_{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:
  - http://built-envi.com/wp-content/uploads/2013/07/solar_position_ies.zip
    - 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.susdesign.com/sunposition/index.php
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

- For solar position and intensity (from time and place)
  - http://www.nrel.gov/midc/solpos/solpos.html
  - Output of interest = “global irradiance on a tilted surface”

- For hourly solar *actual* data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Output of interest = “direct normal radiation” → 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, $h_{conv+rad}$

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

- If that surface now absorbs solar radiation (αI_{solar}), the total heat flow at the exterior surface becomes:

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

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

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

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

$$q_{total} = h_{conv+rad}\left(T_{sol-air} - T_{surf}\right)$$

Sol-air temperatures

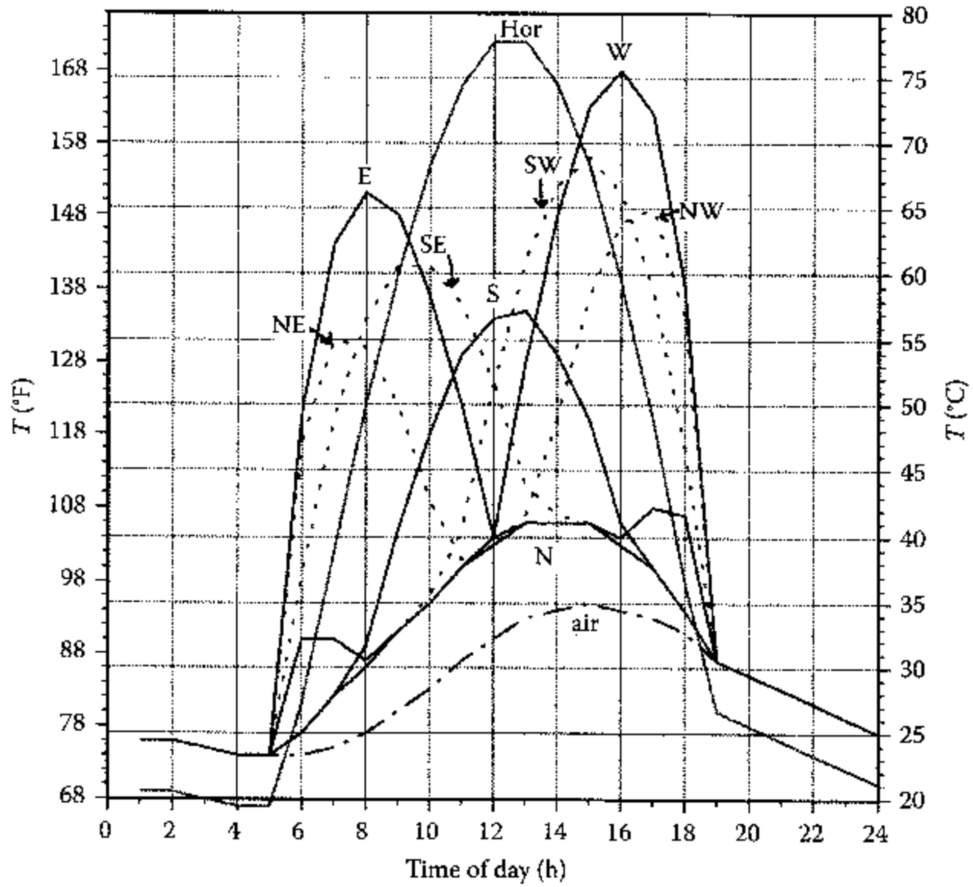


FIGURE 6.17
Sol-air temperature for horizontal and vertical surfaces as a function of time of day for summer design conditions, July 21 at 40° latitude, assuming $\alpha/h_o = 0.30$ (h · ft^2 · °F)/Btu [0.052 (m^2 · K)/W]. The curves overlap when there is no direct radiation on a surface. (Courtesy of 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

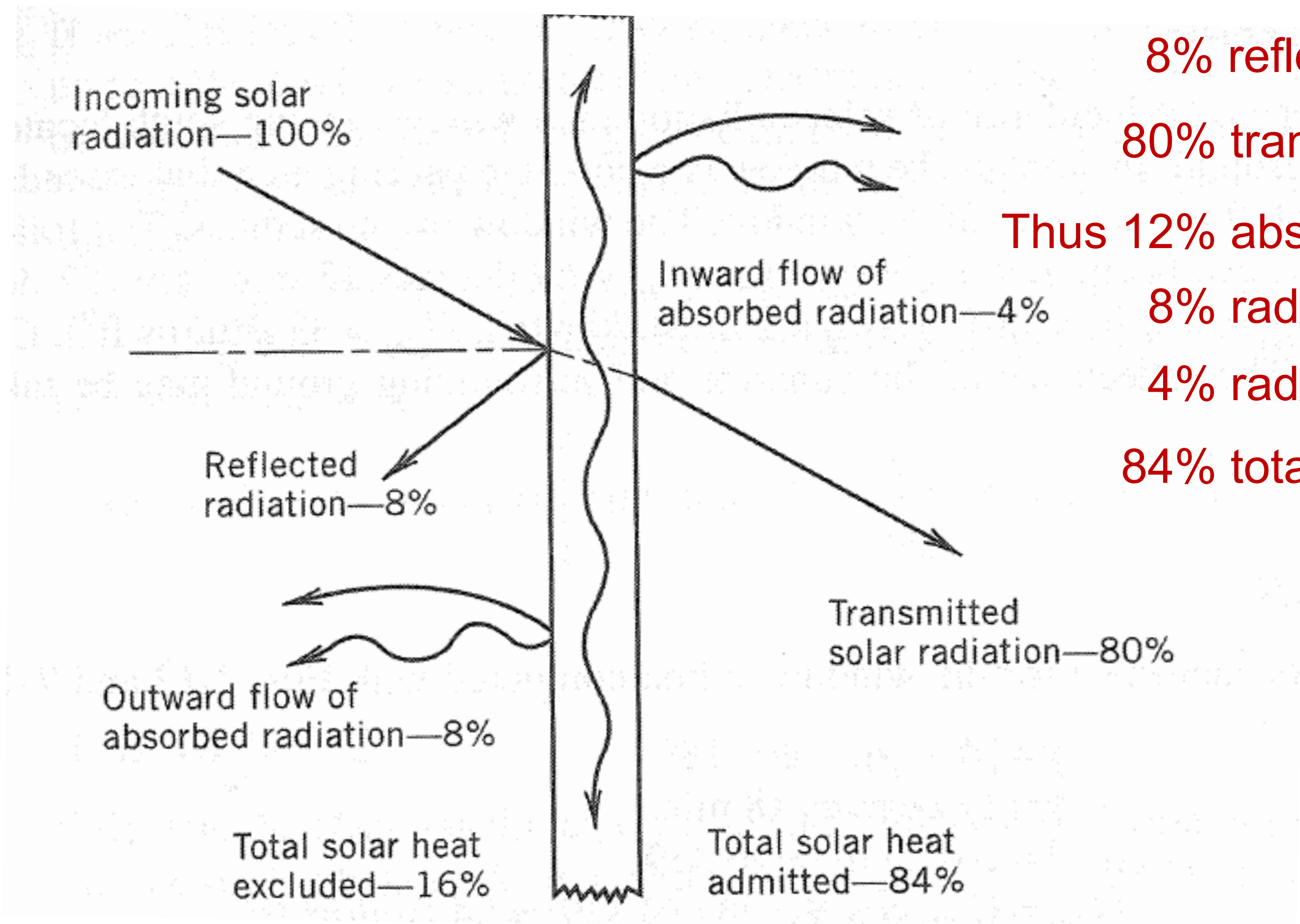
- We can also use air temperatures and material properties (emissivity and absorptance) to estimate exterior surface temperatures that are exposed to radiation
  - These are not perfectly accurate but provide a reasonable estimate for use in simple conduction

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

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):

$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

Solar heat gain coefficient, SHGC

$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

- For a single pane of glass:

$$SHGC = \tau + \alpha \frac{U}{h_{ext}} \qquad \frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{R_{glass}} + \frac{1}{h_{ext}}$$

*R_{glass} is negligible

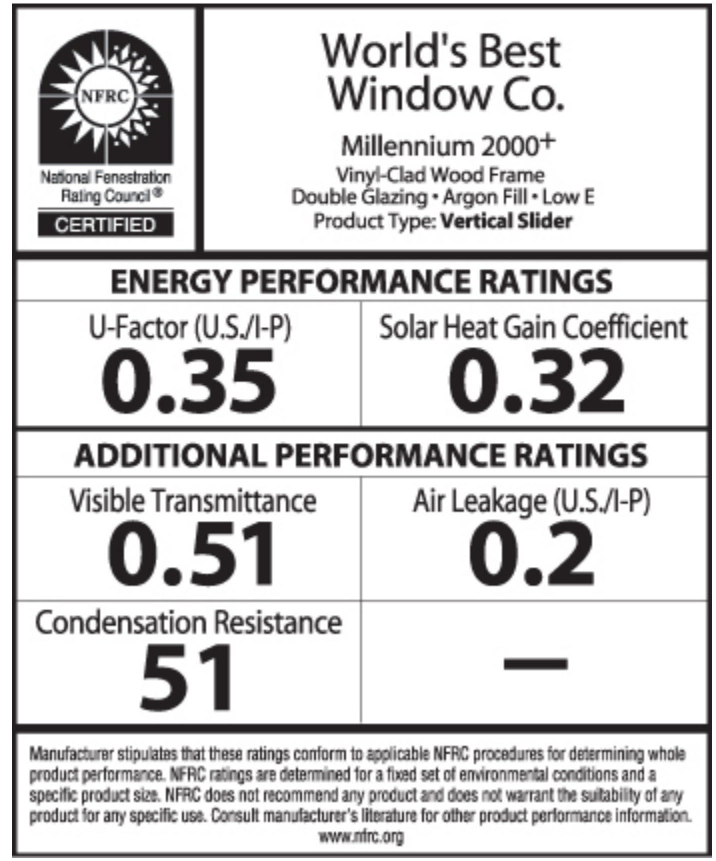
- For double glazing with a small air space:

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

$$\frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{h_{airspace}} + \frac{1}{h_{ext}}$$

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 (θ)



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

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 10 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

	Glazing System		Center-of-Glazing Properties		Incidence Angles							Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
												Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_v		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.78	0.79	0.70	0.76	0.80	0.81	0.72	0.79
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75								
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				$\mathcal{A}_1^f$	0.09	0.10	0.10	0.11	0.11	0.11	0.10								
1b	6	CLR	0.88	SHGC	0.81	0.80	0.78	0.73	0.62	0.39	0.73	0.74	0.74	0.66	0.72	0.78	0.79	0.70	0.77
				T	0.77	0.75	0.73	0.68	0.58	0.35	0.69								
				R^f	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				R^b	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				$\mathcal{A}_1^f$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

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:

$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{solar}A_{pf}SHGC$$

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_{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 4 U-Factors for Various Fenestration Products in W/(m²·K)

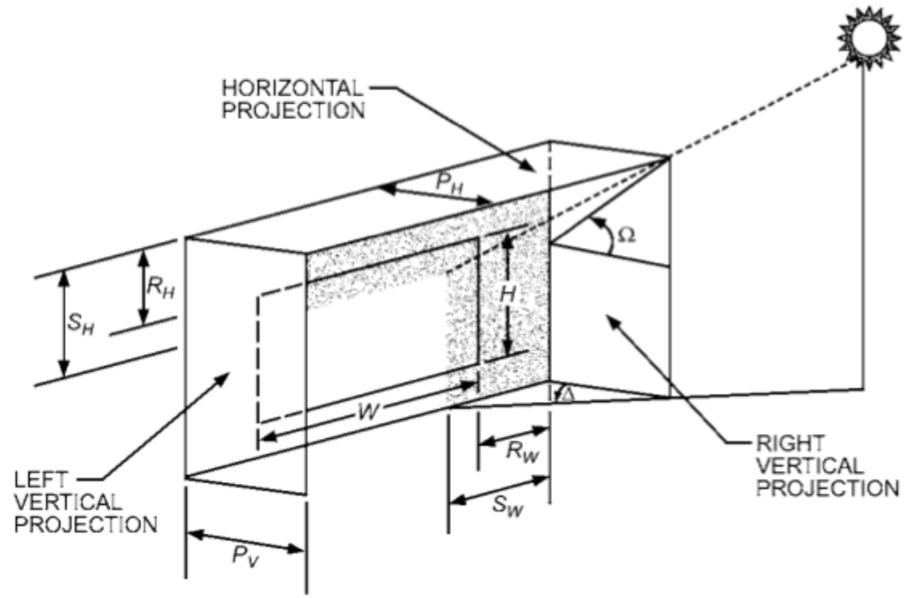
Product Type		Glass Only		Vertical Installation: Operable (including sliding and swinging glass doors)					Vertical Installation: Fixed				
Frame Type													
ID	Glazing Type	Center of Glass	Edge of Glass	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
	Single Glazing												
1	3 mm glass	*5.91*	*5.91*	7.01	6.08	5.27	5.20	4.83	6.38	6.06	5.58	5.58	5.40
2	6 mm acrylic/polycarb	*5.00*	*5.00*	6.23	5.35	4.59	4.52	4.18	5.55	5.23	4.77	4.77	4.61
3	3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.62	5.72	4.93	4.86	4.51	5.96	5.64	5.18	5.18	5.01
	Double Glazing												
4	6 mm airspace	*3.12*	*3.63*	4.62	3.61	3.24	3.14	2.84	3.88	3.52	3.18	3.16	3.04
5	13 mm airspace	*2.73*	*3.36*	4.30	3.31	2.96	2.86	2.58	3.54	3.18	2.85	2.83	2.72
6	6 mm argon space	*2.90*	*3.48*	4.43	3.44	3.08	2.98	2.69	3.68	3.33	3.00	2.98	2.86
7	13 mm argon space	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
	Double Glazing, e = 0.60 on surface 2 or 3												
8	6 mm airspace	*2.95*	*3.52*	4.48	3.48	3.12	3.02	2.73	3.73	3.38	3.04	3.02	2.90
9	13 mm airspace	*2.50*	*3.20*	4.11	3.14	2.80	2.70	2.42	3.34	2.99	2.67	2.65	2.53
10	6 mm argon space	*2.67*	*3.32*	4.25	3.27	2.92	2.82	2.54	3.49	3.13	2.81	2.79	2.67
11	13 mm argon space	*2.33*	*3.08*	3.98	3.01	2.68	2.58	2.31	3.20	2.84	2.52	2.50	2.39
	Double Glazing, e = 0.40 on surface 2 or 3												
12	6 mm airspace	*2.78*	*3.40*	4.34	3.35	3.00	2.90	2.61	3.59	3.23	2.90	2.88	2.77
13	13 mm airspace	*2.27*	*3.04*	3.93	2.96	2.64	2.54	2.27	3.15	2.79	2.48	2.46	2.35
14	6 mm argon space	*2.44*	*3.16*	4.07	3.09	2.76	2.66	2.38	3.30	2.94	2.62	2.60	2.49
15	13 mm argon space	*2.04*	*2.88*	3.75	2.79	2.48	2.38	2.11	2.95	2.60	2.29	2.27	2.16
	Double Glazing, e = 0.20 on surface 2 or 3												
16	6 mm airspace	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
17	13 mm airspace	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
18	6 mm argon space	*2.16*	*2.96*	3.84	2.88	2.56	2.46	2.19	3.05	2.70	2.38	2.36	2.26
19	13 mm argon space	*1.70*	*2.62*	3.47	2.53	2.24	2.14	1.88	2.66	2.30	2.00	1.98	1.88
	Double Glazing, e = 0.10 on surface 2 or 3												
20	6 mm airspace	*2.39*	*3.12*	4.02	3.05	2.72	2.62	2.34	3.25	2.89	2.57	2.55	2.44
21	13 mm airspace	*1.82*	*2.71*	3.56	2.62	2.32	2.22	1.96	2.76	2.40	2.10	2.08	1.98
22	6 mm argon space	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
23	13 mm argon space	*1.53*	*2.49*	3.33	2.40	2.12	2.02	1.76	2.51	2.16	1.86	1.84	1.74

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)**

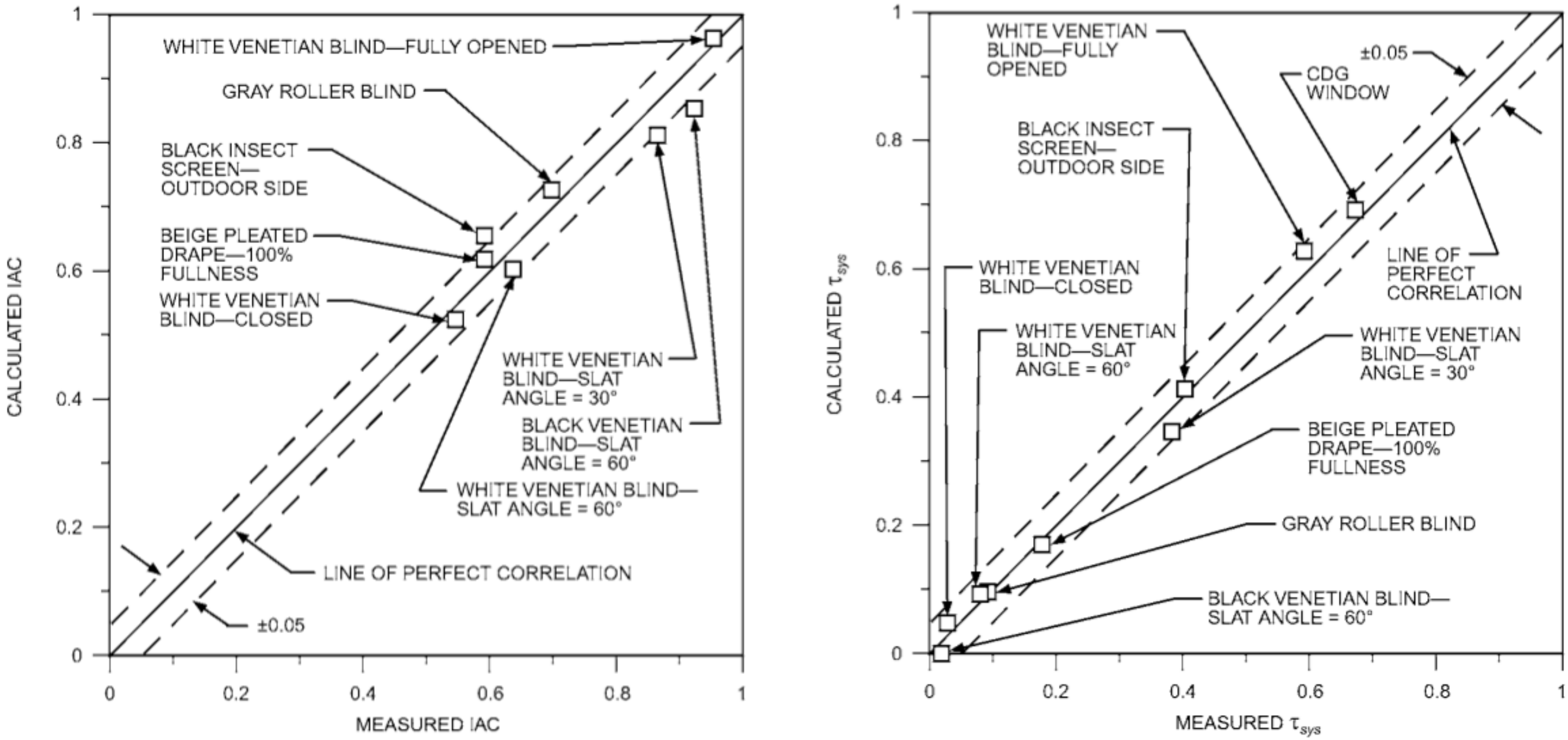
- Heat gain through a window can be modified as follows:



$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct}A_{pf}SHGC(\theta)IAC(\theta,\Omega) + (I_{diffuse+reflected})A_{pf}SHGC_{diffuse+reflected}IAC_{diffuse+reflected}$$

IAC is a function of incidence angle, θ, and the angle created by a shading device

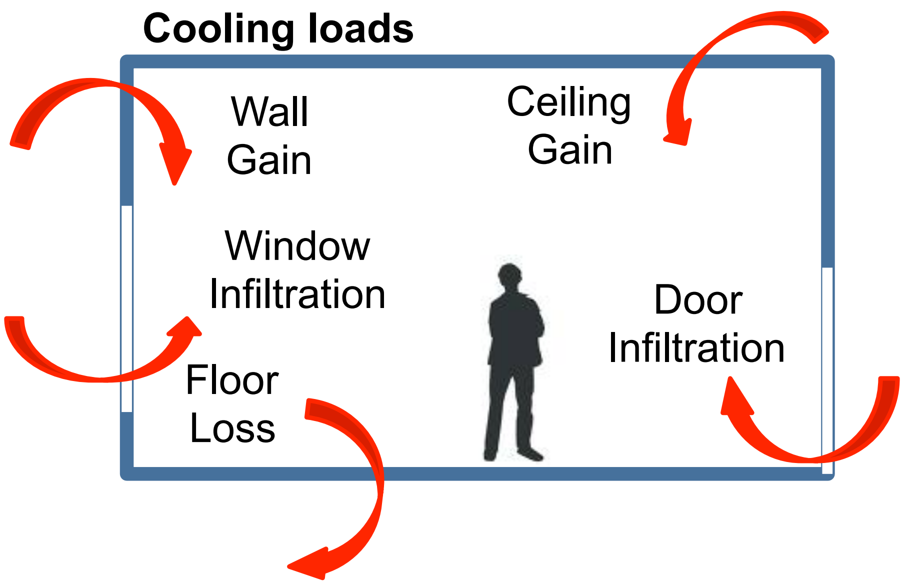
Blinds and drapes: ASHRAE Handbook



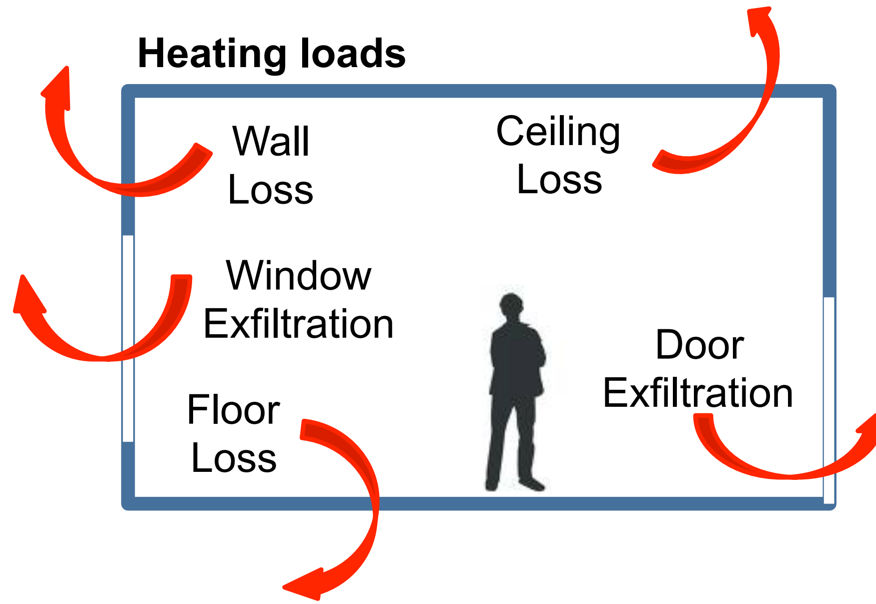
Building energy balances

- 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

Cooling loads



Heating loads



Next time

- The following class, on Monday September 16th
  - HW 2 will be due
  - Will cover ***Psychrometrics and thermal comfort***