CAE 463/524
Building Enclosure Design
Fall 2012

Lecture 2: Solar orientation + Heat transfer

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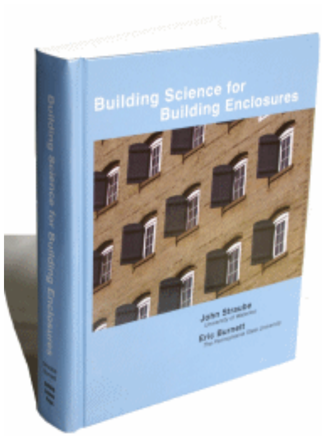
Housekeeping

- Class registrations OK?
  - Blackboard access OK?
  - Lecture capture OK?
  - Current enrollment: 18 students
  - Some schedule changes (ongoing)
- HW 1 due today
  - Will post solutions to blackboard after class today
- Will assign another HW at the end of today's lecture
  - HW 2 (due September 10… 2 weeks from today)
    - No class next Monday, September 3 (Labor Day)
- Final project topics: received from 8 students so far
  - Green roofs and walls (will be separate projects)
  - Double skin facades, all glass
  - BIPV, straw bale, conventional construction

A note on the ***recommended*** textbook

- Bookstore did not receive many copies
- Ordering it online is the easiest way
- Note: I’ve already found several mistakes in it
  - Be careful. Content is good and explained well. But example problems and equations have errors and oversimplifications



Building Science for Building Enclosures
Straube, J. and Burnett, E., 2005.
Building Science Press. Westford, MA.
ISBN: 0-9755127-4-9.
http://buildingenclosures.buildingsciencepress.com/

More information on our course projects

- Two course projects

1. Intermediate Project:

- Assessment of the enclosure of a building on IIT's main campus (15% of grade)
- Start thinking about a building to analyze now
  - Don't have to finalize until September 17, 2012
- Teams of 3
  - Email me if you have a team + a building
    - Otherwise we'll randomly assign in a few weeks
    - One student has claimed Alumni Hall thus far
- Will wait until ~October for thermal imaging
  - Need big temperature difference (i.e., 50°F outside or lower)
  - Can do walkthroughs earlier
- Report will be due in early-to-mid-November (tentatively Nov. 5)

2. Final Project:

- Research high performance enclosures (35% of grade)

Project 2: High performance enclosure research

- Objective
  - Extend what you've learned about HAM transport and failures, as well as practical considerations for building enclosures, and research a "high performance" enclosure construction
    - Literature review, product review, and examples
    - Advantages and disadvantages
    - HAM analysis
    - Cost considerations
    - Practical design considerations
    - Environmental and sustainability impacts
- Deliverables (replaces final exam)
  - Final report of findings (approx. 6-10 pages)
  - Final presentation of findings (like a conference presentation)
    - Both due/given on the last day of class (Nov. 26)
  - Will have some intermediate deliverables to keep you on track

More information on the final project

- Advanced building enclosure design/technology research project
  - Open-ended research effort
  - Must have some design and analysis component
  - Will work in groups of 2
  - Opportunity to explore an area of interest
  - Goal is to produce a professional report (undergraduates) or conference paper (graduates)

Final project ground rules

- Topic must relate to course topics
  - Topic must be approved by me
  - Via a justification
- Topic must involve some design component
- Topic must involve some analysis component
- Report must have substantial depth
  - Legitimate literature review (i.e., minimize *Wikipedia* use)

Final project deliverables

- Topic justification
  - October 1
  - ½ to 1 page justification to me of why you have chosen the high performance enclosure you have chosen
- Group consultation
  - Week of October 15 (and again later if needed)
- Final report
  - November 26 (last day of class)
- Final presentation
  - Given in class November 26 (last day of class)

Final project possible topics

Email me as soon as you have a team and/or topic

List of example technologies/designs

- Green roofs
- Green walls
- Double skin facades
- Building integrated photovoltaics
- Electro chromic windows
- Phase change materials
- Bio-based insulation materials (mushrooms, straw)
- Structural insulated panels
- Cool roofs
- SmartWrap™
- Whatever you come up with!

Review from last time

- Introduction to building enclosures
  - Keep the indoor in and the outdoor out
    - Unless we like what the outdoors has to offer
- Environmental conditions/parameters
  - Temperature, humidity, wind, precipitation, solar radiaton
- Nature of heat, air, and moisture
  - Pyschrometrics (ASHRAE Chapter 6)
  - Calculating moist air density, humidity ratio, enthalpy, etc.

Today's topics

1. Solar orientation

2. Heat transfer review

3. Heat transfer in building enclosures

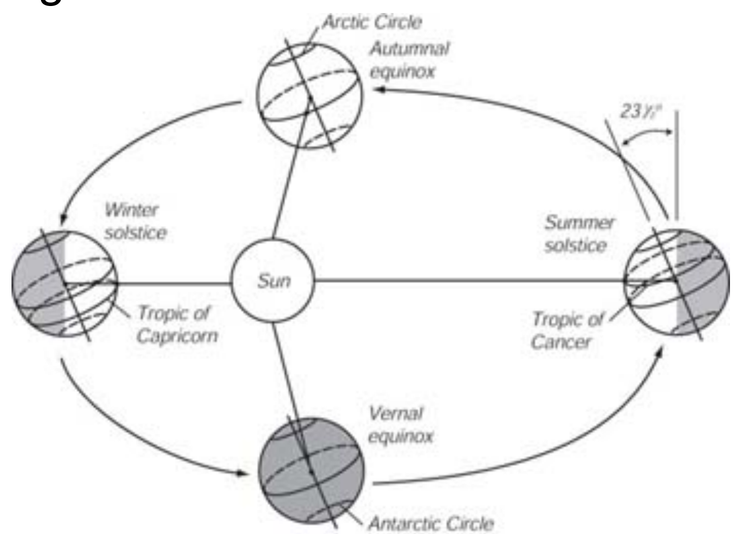
1. SOLAR ORIENTATION

Solar radiation

- The sun is the source of most energy on the earth
- Need to have a working knowledge of earth's relationship to the sun
- Should be able to estimate solar radiation intensity
  - Understand thermal effects of solar radiation and how to control or utilize them
  - Need to estimate solar gains on a building
  - Need to predict intensity of solar radiation and the direction at which it strikes building surfaces
    - Start with relationships between the sun and the earth

Solar radiation: earth-sun relationship

- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23°27’



- Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)
  - The most intense amount of solar radiation delivered to the northern hemisphere on **June 21**
  - Least amount of solar energy delivered on **December 21**
- There are methods of determining the amount of flux of solar radiation to surfaces on the earth

Earth-sun relationships

- The position of a point *P* on the earth's surface w/r/t the sun's rays can be calculated if we know:
  - Latitude of point on earth, *l* (degrees)
  - Hour angle of the point on earth, *h* (degrees)
  - Sun's declination, *d* (degrees)

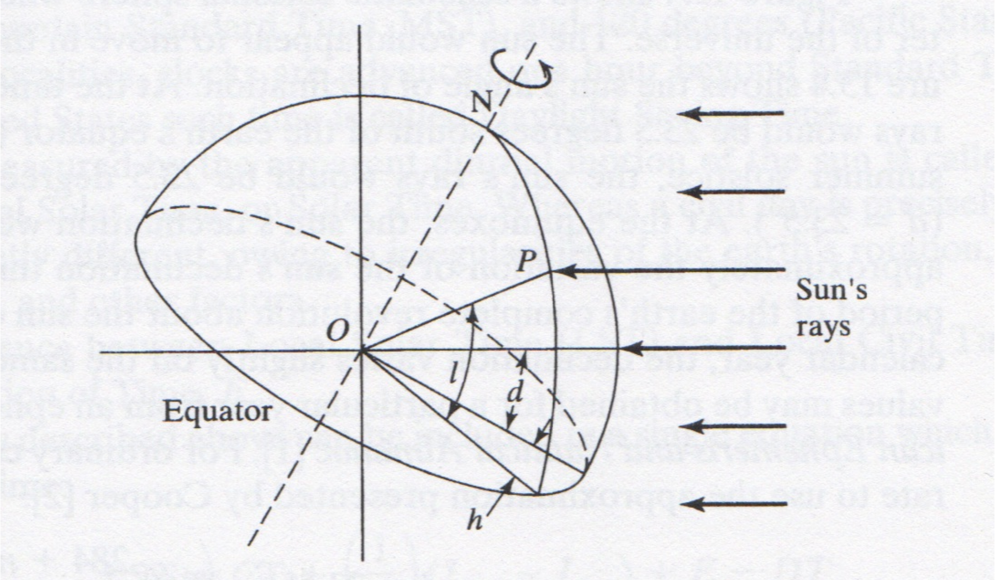


Figure 13.3 Latitude, hour angle, and sun's declination.

Earth-sun relationships

- Sun's declination, *d*, can be estimated by:

$$d = 23.45 \sin\left(360 \frac{284 + n}{365}\right)$$

Where *n* is the day of the year, which you can determine by counting on your hands, looking up online, or using this table:

TABLE 13.1 Variation in *n* throughout the Year for Eq. (13.1)

Month	*n* for the Day of the Month, *D*	Month	*n* for the Day of the Month, *D*
January	*D*	July	181 + *D*
February	31 + *D*	August	212 + *D*
March	59 + *D*	September	243 + *D*
April	90 + *D*	October	273 + *D*
May	120 + *D*	November	304 + *D*
June	151 + *D*	December	334 + *D*

Where *D* is the day of the month

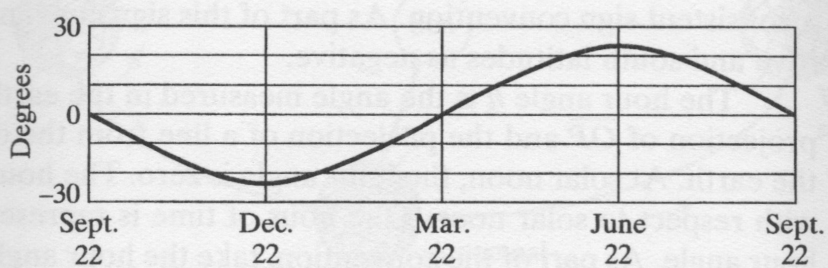


Figure 13.5 Variation of sun's declination.

d is **positive** when sun's rays are **north** of the equator

Earth-sun relationships

- Now we have latitude (*l*) and sun's declination (*d*)
  - Need hour angle (*h*)

It's all about **time:**

- Greenwich Civil Time = time at line of zero longitude
- Local Civil Time (CT) is governed by your longitude
  - 1/15th of an hour (4 mins) of time for each degree difference in long
    - Central Standard Time is 90 degrees from 0
    - 4 min per degree * 90 degrees = 360 minutes = 6 hours
- Time also measured by apparent diurnal motion of the sun
  - Apparent Solar Time (AST), Local Solar Time (LST), or Solar Time (ST)
    - Interchangeable
  - Slightly different than a civil day because of irregularities of the earth's rotation and shape of earth's orbit
  - The difference between solar time (LST) and civil time (CT) is called the Equation of Time (E)

Calculating solar time (LST)

- Local **solar** time:

$$LST = CT + \left(\frac{1}{15}\right)(L_{std} - L_{loc}) + E - DT$$

Where:
LST = local solar time (hour)
CT = clock time (hour)
L_{std} = standard meridian longitude for local time zone (degrees west)
L_{loc} = longitude of actual location (degrees west)
E = Equation of Time (hour)
DT = Daylight savings time correction (hour)
  *DT = 1 if on DST; otherwise 0

**Note that all times should be converted to decimal format from 0 to 24. For example, 3:45 PM = 15.75 hours

- Equation of Time: $E = 0.165 \sin 2B - 0.126 \cos B - 0.025 \sin B$

where $B = \frac{360(n - 81)}{364}$ and n is the day of the year. *B* is in degrees

Calculating solar time (LST)

- Finally, the solar hour angle, h, can be calculated:

$$h = 15(\text{LST} - 12) \text{ degrees}$$

h is **positive *after*** solar noon and **negative *before***

- Again, you can either calculate these values, use a website*, or look them up in a table like this:

TABLE 13.2 The Sun's Declination and Equation of Time, Calculated

	Day							
	7		*14*		*21*		*28*	
Month	*Declination, Degrees*	*Eq. of Time, Hours*	*Declination, Degrees*	*Eq. of Time, Hours*	*Declination, Degrees*	*Eq. of Time, Hours*	*Declination, Degrees*	*Eq. of Time, Hours*
January	−22.4	−0.10	−21.4	−0.15	−20.1	−0.19	−18.5	−0.22
February	−15.8	−0.24	−13.6	−0.24	−11.2	−0.24	−8.7	−0.22
March	−6.0	−0.20	−3.2	−0.17	−0.4	−0.13	2.4	−0.09
April	6.4	−0.04	9.0	−0.01	11.6	0.02	13.9	0.04
May	16.7	0.06	18.5	0.06	20.1	0.06	21.4	0.05
June	22.7	0.02	23.3	0.00	23.45	−0.03	23.3	−0.05
July	22.6	−0.08	21.7	−0.09	20.4	−0.10	18.9	−0.10
August	16.3	−0.09	14.1	−0.07	11.8	−0.04	9.2	−0.01
September	5.4	0.05	2.6	0.09	−0.2	0.13	−3.0	0.17
October	−6.6	0.22	−9.2	0.25	−11.8	0.27	−14.1	0.27
November	−17.1	0.27	−18.9	0.25	−20.4	0.22	−21.7	0.18
December	−22.8	0.12	−23.3	0.07	−23.45	0.02	−23.3	−0.04

*NOAA has website for this: http://www.esrl.noaa.gov/gmd/grad/solcalc/

Calculating solar time (*LST*) and hour angle (*h*)

- Example problem 2.1

- Determine the local solar time and sun's hour angle in Minneapolis, MN (L_{loc} = 93°W) at 2:25 PM Central Daylight Savings Time on July 21

Earth-sun relationships

- Once we have our local latitude *l*, the sun's declination angle *d*, and the hour angle *h*, we can move on to other important relationships:

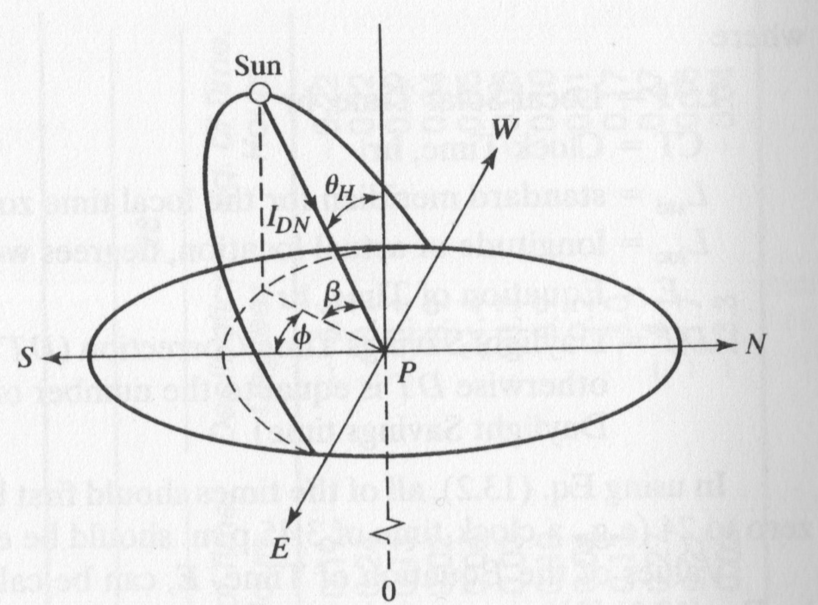


Figure 13.6 Definition of sun's zenith, altitude, and azimuth angles

<u>Three important angles (°)</u>

***θ_H* = sun's zenith angle**
angle between the sun's rays and the local vertical

***β* = altitude angle**
angle in a vertical plane between the sun's rays and the projection of the earth's horizontal plane

***ϕ* = solar azimuth angle**
angle in the horizontal plane measured from south to the horizontal projection of the sun's rays

*Note that I_{DN} represents the sun's rays

Earth-sun relationships

- Relationships between l, h, d, and θ_H, β, and ϕ can all be described in this figure:

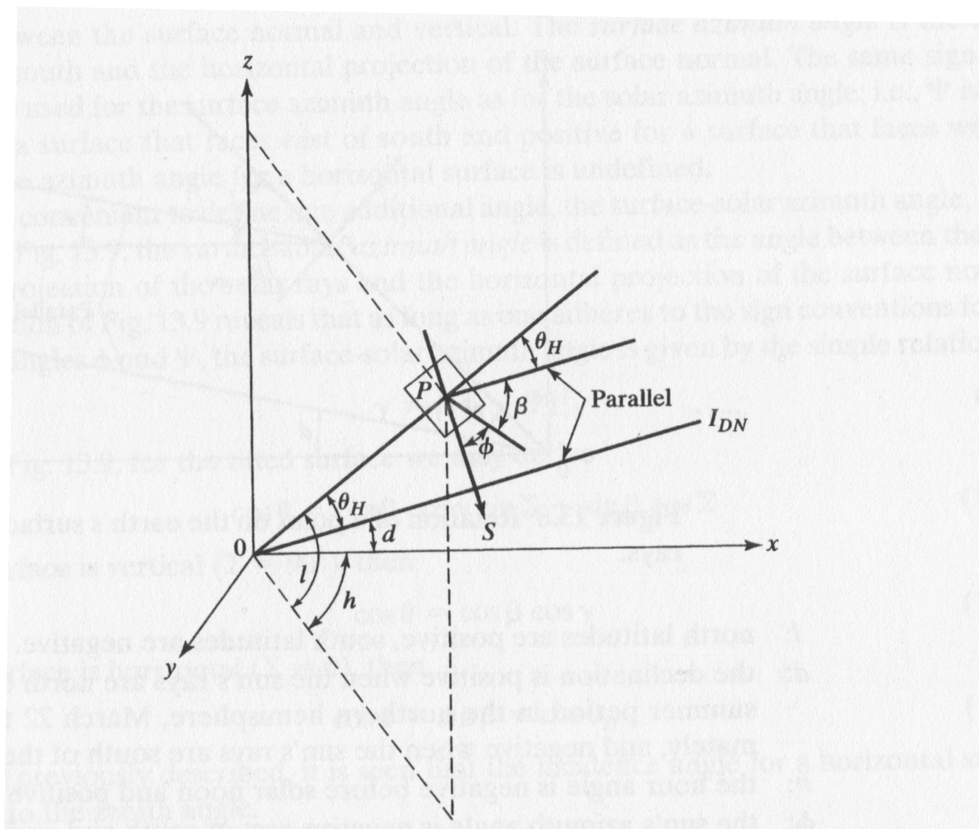


Figure 13.7 Relation of a point on the earth's surface to sun's rays.

*Don't worry if this doesn't all make sense; there are formulas!

Determining solar angles

- After a lot of complex geometry/trigonometry…

$$\cos \theta_H = \cos l \cos h \cos d + \sin l \sin d$$

$$\sin \beta = \cos l \cos h \cos d + \sin l \sin d$$

$$\cos \phi = (\cos d \sin l \cos h - \sin d \cos l) / \cos \beta$$

A note on sign conventions for all of these relationships:
North latitudes (*l*) are positive, south latitudes are negative
Declination (*d*) is positive when sun's rays are north of equator
Hour angle (*h*) is negative before solar noon, positive after
Azimuth angle (ϕ) is negative east of south and positive west of south

Note that β for solar noon = 90 degrees - | l - d |
Also note that $\beta + \theta_H$ = 90 degrees

**Keep units consistent

Earth-sun relationships

- Last but not least…
- The previous relationships identify a point on the earth's surface in relation to the sun
  – All valid for horizontal surfaces
  – Buildings are not horizontal surfaces!

- Surface-sun relationships:

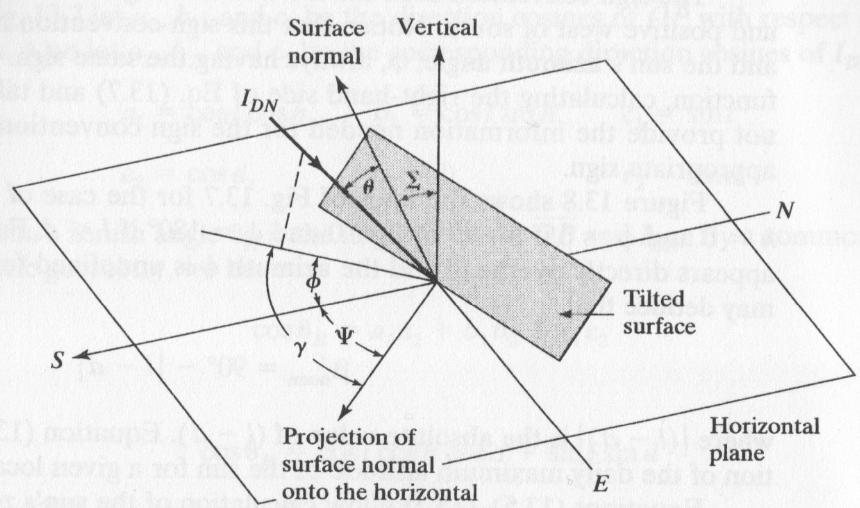


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

Surface-sun relationships

More important angles (°)

***θ* = incidence angle**

angle between the solar rays and the surface normal

***Σ* = surface tilt angle**

angle between surface normal and the vertical

Vertical surface: *Σ* = 90°

Horizontal surface: *Σ* = 0°

***Ψ* = surface azimuth angle**

angle between south and the horizontal projection of the surface normal

***γ* = surface-solar azimuth angle**

angle between horizontal projection of solar rays and the horizontal projection of the surface normal

$\gamma = | \phi - \Psi |$

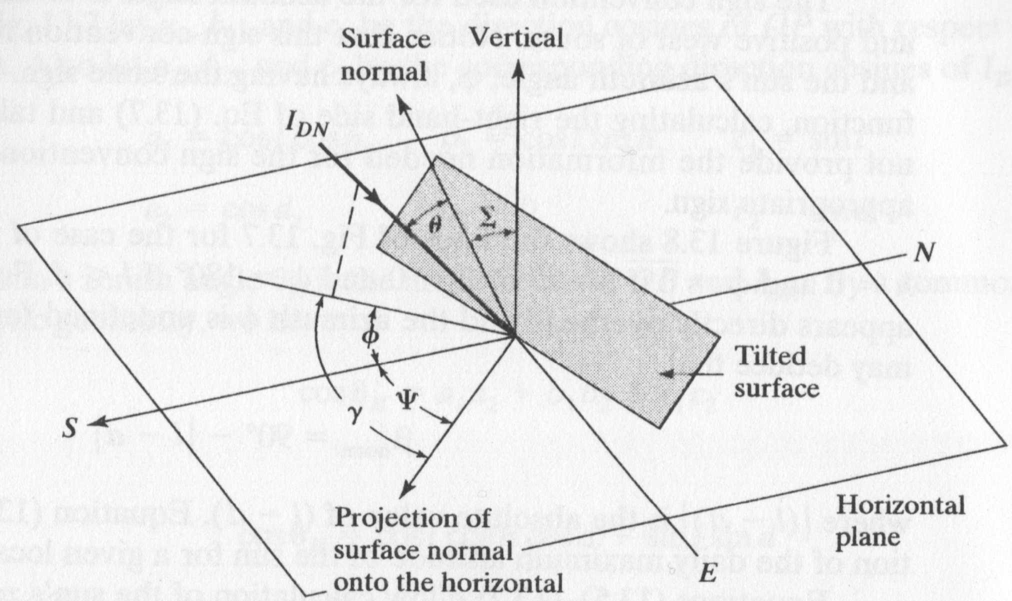


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

*Sign convention: *Ψ* is negative for a surface that faces east of south and positive for a surface that faces west of south

Tilted surface:

$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma$

Vertical surface (*Σ* = 90°):

$\cos\theta = \cos\beta \cos\gamma$

Surface-sun relationships

- Example problem 2.2
- Calculate sun’s altitude (β) and azimuth (ϕ) angles at 7:30 am solar time on August 7 for a location at 40 degrees north latitude

Surface-sun relationships

- Example problem 2.3
- Calculate sun's incidence angle for a vertical surface that faces 25 degrees east of south at the same date, time, and latitude as example 2.2

Translation:

Find θ

Given:
$\Psi, \Sigma, l, h, \beta, \phi$

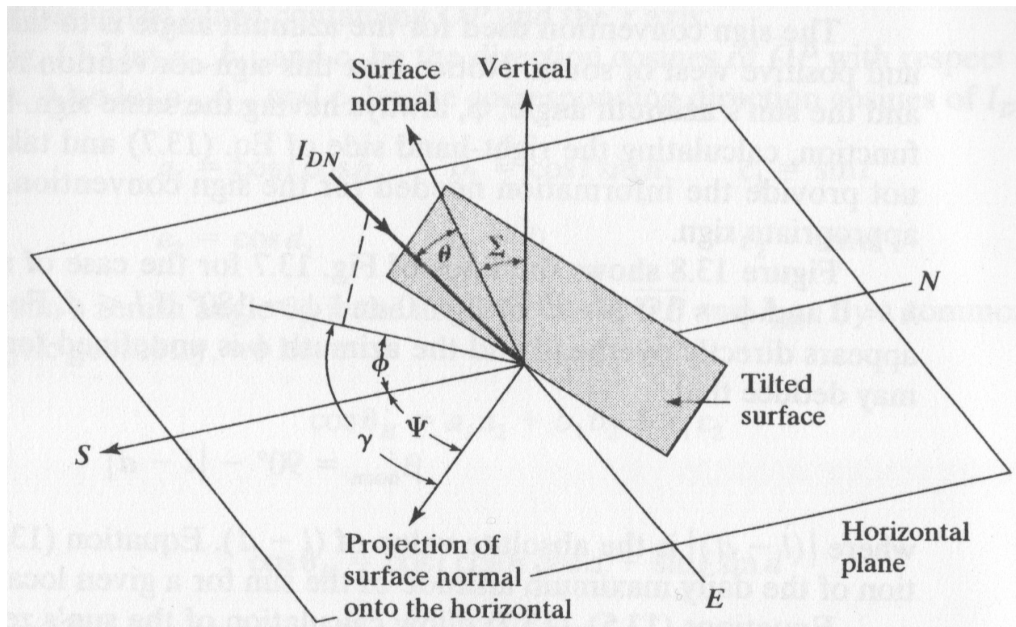


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

Solar flux

- Once we know earth-surface-sun relationships, we can eventually get to the effects of those relationships on actual solar radiation

- Solar radiation intensity is roughly constant at the outer layer of the atmosphere
  - 1367 W/m^2 – varying a few percent depending on time of year
- The earth's atmosphere depletes some direct solar radiation
  - Intercepted by other air molecules, water molecules, dust particles
  - Remaining reaches earth's surface unchanged in wavelength
    - Direct radiation
  - The deflected radiation turns aside from the direct beam
    - Diffuse radiation

Solar flux

- Estimating intensity of direct normal solar radiation
  - Many, *many* ways to estimate this
  - ASHRAE uses a relationship for "average clear days"

$$I_{DN} = Ae^{-B/\sin\beta}$$

Where:
I_{DN} = direct normal solar radiation (W/m^2)
A = apparent direct normal solar flux at outer edge of earth's atmosphere (W/m^2)
B = empirically determined atmospheric extinction coefficient (dimensionless)
β = altitude angle

- Estimating intensity of diffuse horizontal radiation

$$I_{dH} = CI_{DN}$$

Where:
I_{dH} = diffuse horizontal solar radiation (W/m^2)
C = empirically determined coefficient for typical "clear days" (dimensionless)

Typical clear day values for solar radiation

TABLE 13.3 Coefficients for Average Clear Day Solar Radiation Calculations for the Twenty-First Day of Each Month, Base Year 1964

	A		B	C		
	$\frac{Btu}{hr \cdot ft^2}$	$\frac{W}{m^2}$	*Dimensionless Ratios*		*Declination, deg*	*Equation of Time, hr*
January	390	1230	0.142	0.058	−20.0	−0.19
February	385	1215	0.144	0.060	−10.8	−0.23
March	376	1186	0.156	0.071	0.0	−0.13
April	360	1136	0.180	0.097	11.6	0.02
May	350	1104	0.196	0.121	20.0	0.06
June	345	1088	0.205	0.134	23.45	−0.02
July	344	1085	0.207	0.136	20.6	−0.10
August	351	1107	0.201	0.122	12.3	−0.04
September	365	1151	0.177	0.092	0	0.13
October	378	1192	0.160	0.073	−10.5	0.26
November	387	1221	0.149	0.063	−19.8	0.23
December	391	1233	0.142	0.057	−23.45	0.03

SOURCE: Adapted by permission from *ASHRAE Handbook, Fundamentals Edition, 1993.*

Solar flux to building surfaces (finally!)

- Solar radiation striking a surface
  - Direct + diffuse + reflected
- Direct (I_D)

$$I_D = I_{DN} \cos\theta$$

Where:
θ = incidence angle, or the angle between the solar rays and the surface normal
I_{DN} = direct normal solar radiation (W/m^2)

- Diffuse (I_d)

$$I_d = I_{dH} \frac{1 + \cos\Sigma}{2}$$

Where:
Σ = surface tilt angle, or the angle between surface normal and surface vertical
I_{dH} = diffuse horizontal solar radiation (W/m^2)

Solar flux to building surfaces (finally!)

- Reflected (I_R)
  - Radiation striking a surface after reflecting off surrounding surfaces
  - Similar to diffuse
  - Usually concerned with reflection from the ground

$$I_R = \frac{\rho_g I_H (1 - \cos\Sigma)}{2}$$

Where:
ρ_g = solar reflectance of the ground (depends on surface, usually 0.1-0.4)
I_H = total solar flux striking the horizontal ground (W/m^2)

$$\mathrm{I_H} = I_{DN} \cos\theta_H + I_{dH}$$

Solar flux to building surfaces

- Reflected (I_R)
  - Values of reflectance (ρ_g) for common ground surfaces

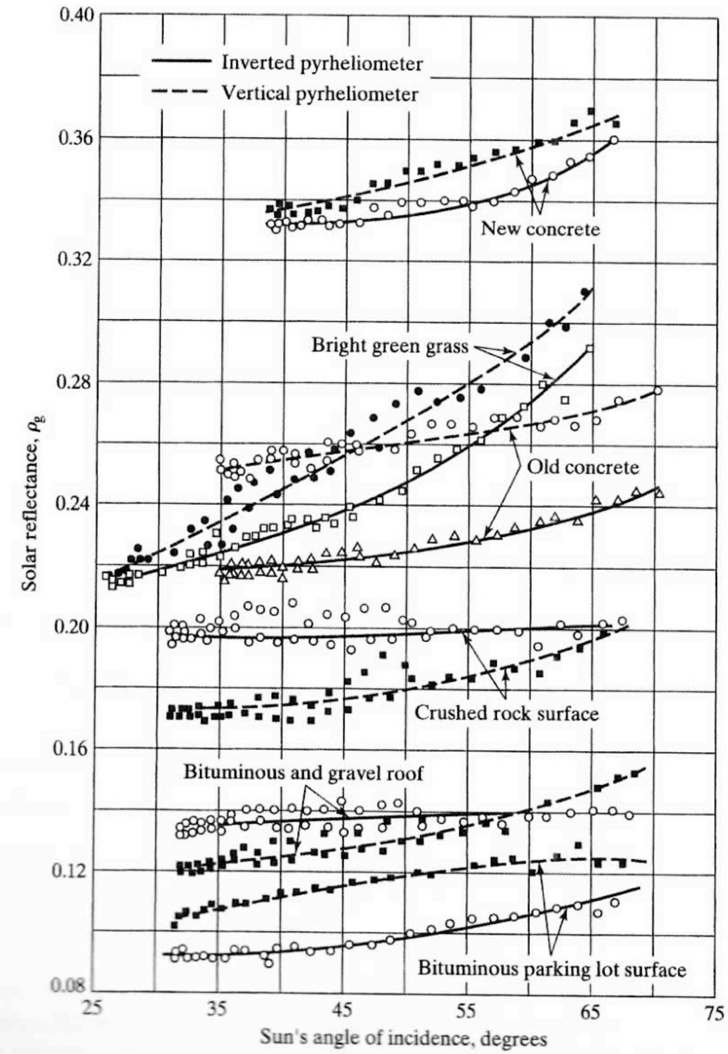


Figure 13.21 Solar reflectance for various ground surfaces. [Reprinted by permission from *ASHRAE Trans.*, 69 (1963), 31.]

Solar flux to building surfaces

- Example problem 2.4

- Find the solar flux incident on a vertical surface at the same date, time, and location used in example problems 2.2 & 2.3, with a ground reflectance of 0.15

Refined solar data

- Now, you could make all of these calculations for every hour of the day

OR

- You can build calculators or download data
- For hourly sun positions, you can build a calculator or use one from the internet
  - http://www.susdesign.com/sunposition/index.php
- For hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - You may be familiar with “typical meteorological years”
    - These data inform those databases

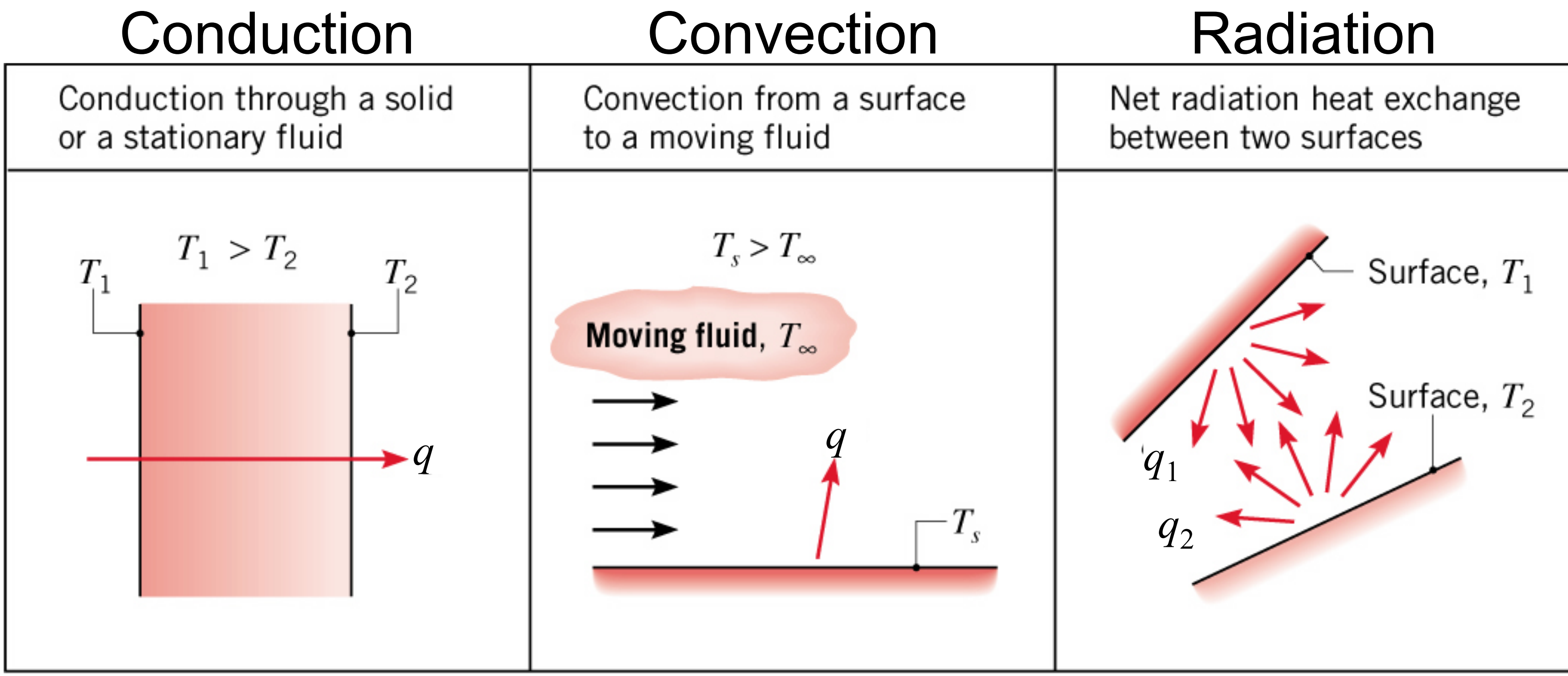
2. HEAT TRANSFER BASICS

Heat transfer

- Heat flow can be transient or steady-state
  - Transient (temperature & heat flow vary w/ time)
  - Steady-state (temperature & heat flow **don’t** vary w/ time)
    - Choice depends on what problem you’re investigating

- Heat flow occurs in 1, 2, and 3-dimensions
  - In almost all real situations, heat flow occurs in 3-D
  - 1-D is often acceptable from a practical standpoint

Three modes of heat transfer

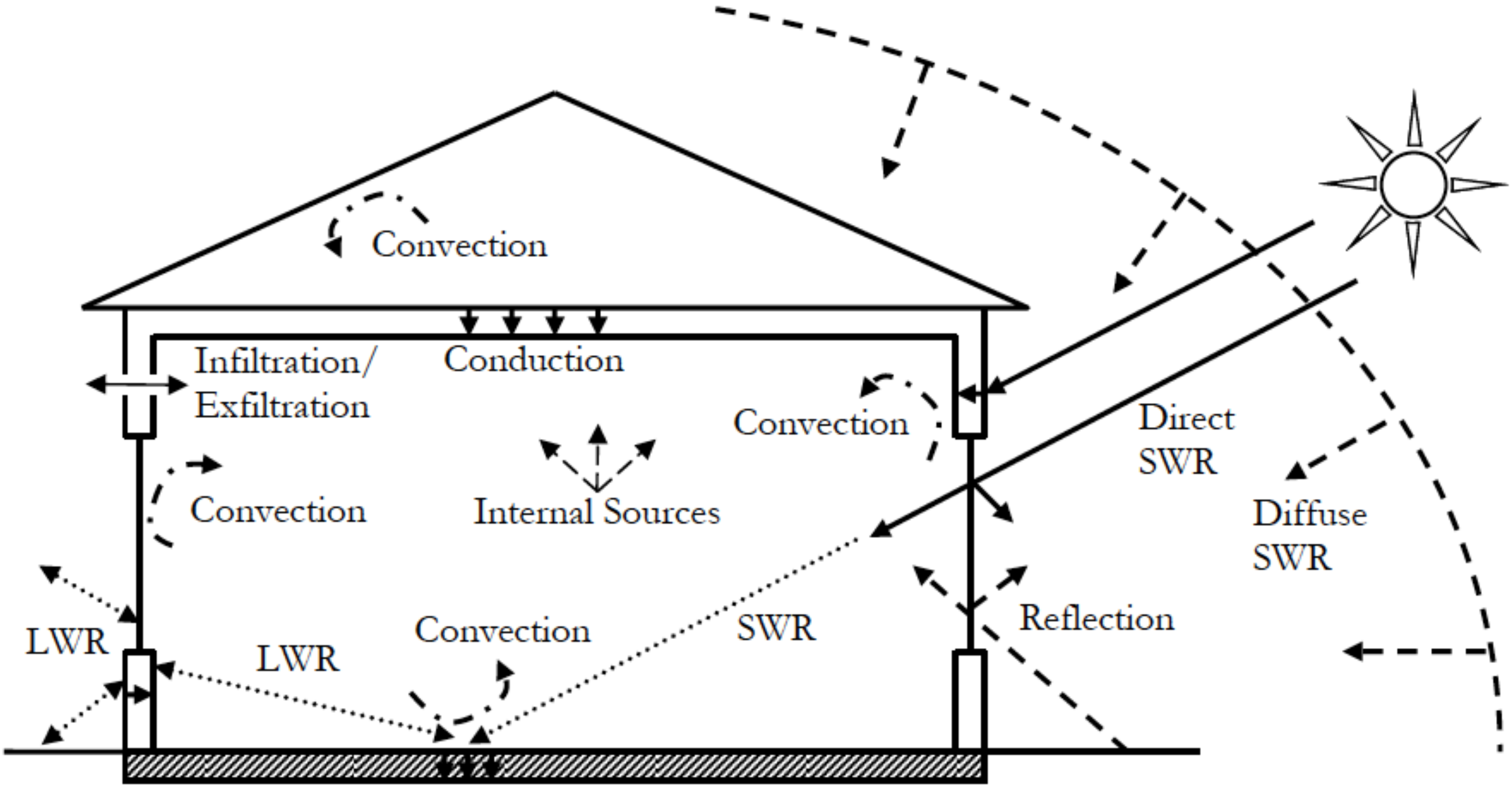


**Note: Change of physical state can also be a mechanism of heat transfer*

Example of heat transfer in a building enclosure

- The sun transmits heat by radiation to the earth where it can be absorbed by a brick wall. Heat is then transferred by conduction through the brick, then transferred by convection to indoor air and by radiation to other indoor surfaces.

Building heat transfer, visualized



Units of heat transfer

- We denote the total rate of heat energy transfer by the symbol Q
  - It is a rate of energy transfer (i.e., a *power*)
  - So the units are W (J/s) or Btu/h (1 W = 3.41 Btu/h)
- We denote the rate of heat transfer per unit area by the symbol q
  - By definition $q = Q/A$
    - Where A is the area through which the heat is moving
  - The units of q are W/m^2 or $Btu/(h \cdot ft^2)$
    - $1\ W/m^2 = 0.317\ Btu/(h \cdot ft^2)$

A tale of two Q's: Q and q

- Some books work with the total heat transfer Q as their fundamental quantity
- ASHRAE HOF heat transfer in enclosures chapters use heat transfer per unit area [$q=Q/A$] as the fundamental quantity
- Using q instead of Q makes it easier to compare the thermal properties of assemblies without regard to the actual size of them

Conduction

- Conductive heat transfer is heat transfer through direct molecular contact. It is basically the transfer of thermal momentum between atoms or molecules and follows Fourier's Law:

$$q = -k\nabla t$$

which in 1-D becomes

$$q = -k\frac{dt}{dx}$$

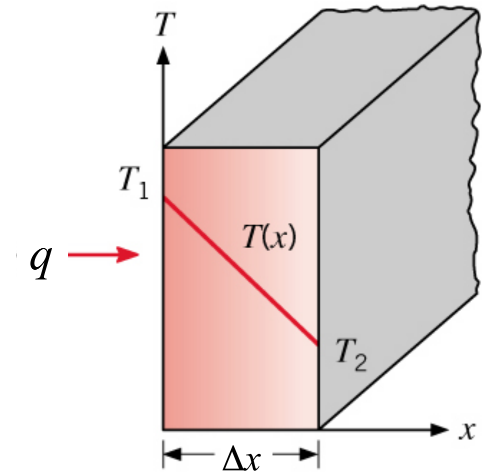
$q =$ heat flux per unit area [Btu/(h·ft^2) or W/m^2]

$k =$ thermal conducitivity [Btu/(h·ft·°F) or W/(m·K)]

$t =$ temperature [°F or K]

Simplified conductive transfer

If a material has uniform thermal conductivity throughout & consists of parallel surfaces with uniform temperatures, then:



Δx = L

$$q = k\frac{t_1 - t_2}{x_2 - x_1} = k\frac{\Delta t}{\Delta x} = \frac{k}{L}(t_1 - t_2)$$

Here t_1 and t_2 are the surface temperatures at x_1 and x_2.

Notice that this equation differs from the last by a minus sign.

I suggest you use the $\Delta t / \Delta x$ formulation and note that heat will always flow from high to low temperature

Thermal resistance of common materials

- We will often be concerned more with the ability of a material to **resist** heat flow rather than conduct it

$$q = \frac{k}{L}(t_1 - t_2) = C(t_1 - t_2) = \frac{1}{R}(t_1 - t_2)$$

Here the thermal conductivity (k) divided by thickness (L) yields "Conductance" of a material, with units of $[\mathrm{W/(m^2 \cdot K)}]$. Conductance is also called the U-value.

The inverse of conductance (C) is the resistance (R), or R-value.

Where 1/C = R, with units of $[\mathrm{(m^2 \cdot K)/W}]$.

Therefore:

$C = U = \frac{k}{L} =$ unit thermal conductance = U-value $[\mathrm{W/(m^2 \cdot K)}]$

$R = \frac{1}{U} = \frac{L}{k} =$ unit thermal resistance = R-value $[\mathrm{(m^2 \cdot K)/W}]$

Thermal conductivity of building materials

- ASHRAE HOF chapter on "thermal and water vapor transmission data"
  - Uploaded on Blackboard (see Table 4 specifically)
  - **Thermal transmission data for some typical building materials:**

	Plywood	Brick	Concrete	Fiberglass batts	Strawbales
Thermal conductivity, k W/(m·K)	0.12	1.3	2.0	0.04	0.07
Typical thickness, L	6.4 mm	10 cm	30 cm	10 cm	30 cm
Conductance, C W/(m^2·K) = *k/L*	18.2	13.0	6.7	0.4	0.2

Units of R and U-Value

- It is important to know the units of R and U to help identify which quantity we are finding when we find thermal data for a material

$$R = \text{R value} = [\ \frac{\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F}}{\text{Btu}} \text{ or } \frac{\text{m}^2\text{K}}{\text{W}}\ ]$$

$$U = \text{U value} = [\ \frac{\text{Btu}}{\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F}} \text{ or } \frac{\text{W}}{\text{m}^2\text{K}}\ ]$$

$$1.0\ \frac{\text{Btu}}{\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F}} = 0.1761\frac{\text{W}}{\text{m}^2\text{K}} \quad \text{and} \quad 5.678\frac{\text{Btu}}{\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F}} = 1.0\frac{\text{W}}{\text{m}^2\text{K}}$$

Be careful for “R” and “RSI” notations

Important note on U and R values

- If you are importing materials to/from the US, be aware of the difference in R/U units
  - R values are a factor of 5.7 lower in metric units
  - U values are a factor of 5.7 higher in metric units
- This is important because people usually say R value or U value and often DO NOT write down the units!!!!
  - Suppose someone in the US imports a window from Europe with U=1.5.
  - If the units are in Btu/(h ft^2 F) the window is bad for heat transfer but if the units are W/m^2K, the window is pretty good.

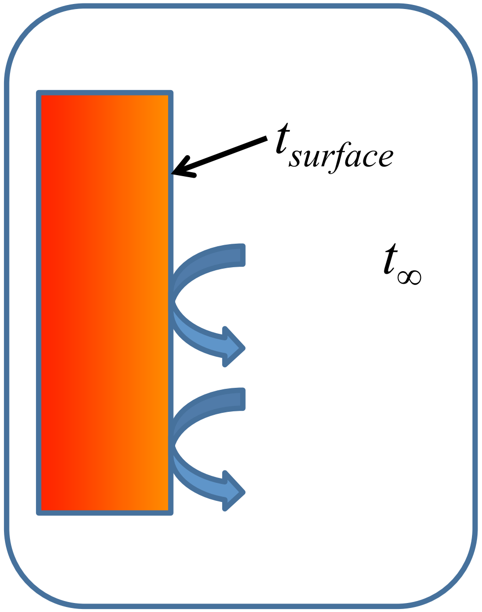
Second important note on conduction

- The R value of most materials is temperature **independent** (in *most* conditions), so …

- The rate of conductive heat transfer depends ONLY on the temp difference Δt between the two sides of the material.
  - Just as must heat is transferred if the interior is 90 and exterior is 70 as when the interior is 70 and the exterior is 50.

Convection

- Convective heat transfer occurs between a solid and a moving fluid.
  - Since heat transfer to a still fluid causes buoyancy which moves the fluid, **all** solid-fluid heat transfer is convective
- The heat transfer coefficient, h_c relates the heat transfer to the difference between the solid wall temp, $t_{surface}$, and the effective temperature of the fluid far from the surface, t_∞



$$q_{\text{conv}} = h_c\left(t_\infty - t_{surface}\right) = \frac{t_\infty - t_{surface}}{R_c} = \frac{\Delta t}{R_c}$$

where $t_\infty =$ environmental temp far enough not to be affected by t_{surface}

$h_c =$ conductive heat transfer coefficient $[\text{W}/(\text{m}^2 \cdot \text{K})]$

and $R_c = \dfrac{1}{h_c} =$ convective thermal resistance $[(\text{m}^2 \cdot \text{K})/\text{W}]$

Important notes on convection

- Convective heat transfer coefficients can depend upon details of the surface-fluid interface
  - Rough surfaces have higher rates of convection
  - Orientation matters for natural convection
  - Natural heat transfer coefficients can depend upon the actual fluid temperature and not just the temperature difference

Heat Transfer Coefficient, h_c

- The convective heat transfer coefficient, h_c, will take on many forms depending upon whether the convection is forced or natural
  - Natural convection occurs when buoyancy effects induce air motion
    - *Temperature-dependent density differences*

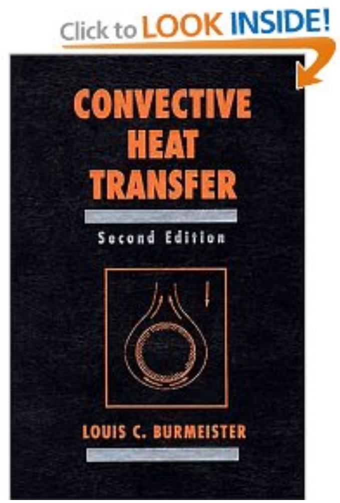
$$\rho = \frac{n}{V} = \frac{P}{RT}$$

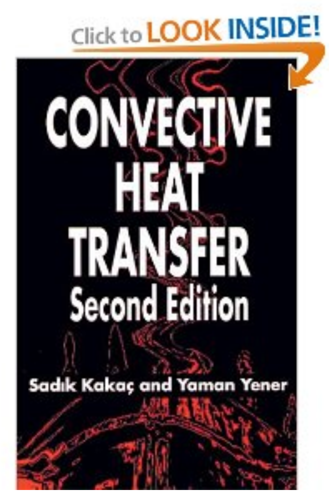
Hold P and R constant…

$$T \downarrow \rho \uparrow \qquad T \uparrow \rho \downarrow$$

  - Forced convection occurs when an external force (e.g. fan or wind) imposes air motion (more random and chaotic)
  - h_c is also known as the film coefficient or the surface conductance
- On the next few slides are some of the important convective equations that arise in computing heat transfer to/from walls, floors,
  - Taken from “Heating and cooling for Buildings, 2nd ed” by Jan Kreider et al.

Convection is really a field of its own





Laminar vs. Turbulent

- When the temperature differences are high enough the natural motion is turbulent, the result is more mixing and higher heat transfer
  – So, for high temp differences the heat transfer coefficient is larger and has a different equation than for lower Δt

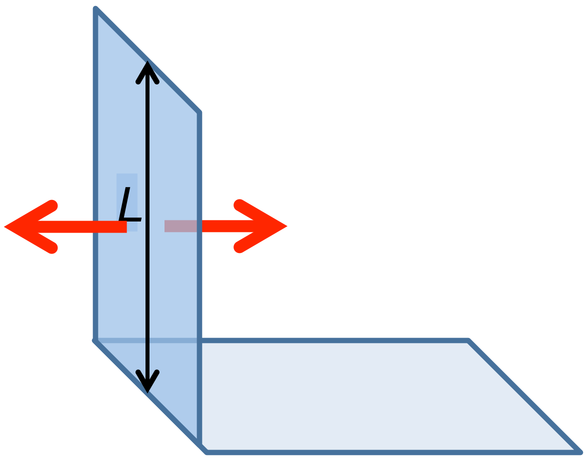
- For the equations that follow, turbulent heat transfer occurs when:

$$L^3 \Delta t > 1.0 \qquad [\mathrm{m^3 \cdot K}]$$

where L is the average length of the side of the surface

- L typically equals (4*area)/perimeter

h_c for natural convection and vertical walls



h_c in [W/(m^2 K)]

For natural convection to or from either side of a vertical surface

For laminar: $h_c \approx 1.42\left(\frac{\Delta t}{L}\right)^{\frac{1}{4}}$ [Straube 5.9]

For turbulent: $h_c \approx 1.31\left(\Delta t\right)^{\frac{1}{3}}$ [Straube 5.14]

h_c for natural upward convection

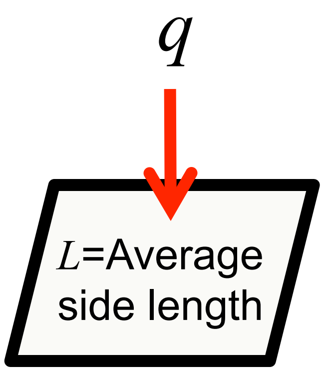
- Up from a warm floor or up to a cold ceiling

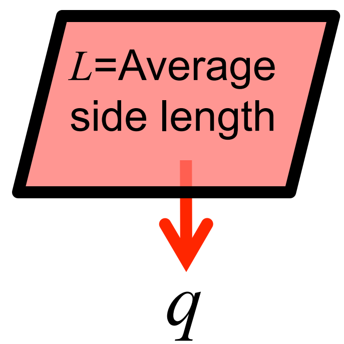
laminar: $h_c \approx 1.32\left(\dfrac{\Delta t}{L}\right)^{1/4}$ [Straube 5.12]

turbulent: $h_c \approx 1.52\left(\Delta t\right)^{1/3}$ [Straube 5.13]

h_c for natural downward convection

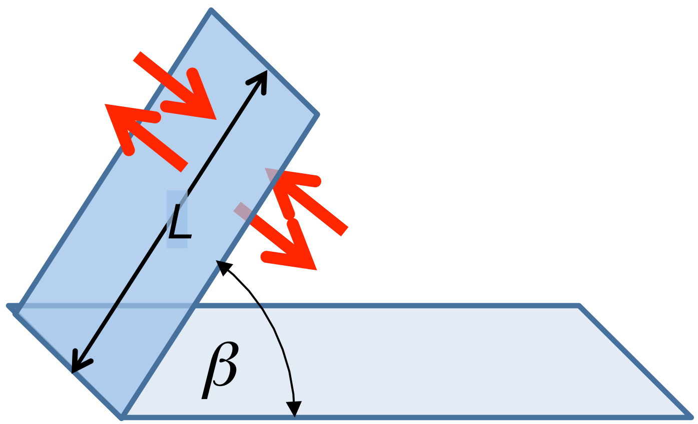
- Heat transfer down to a cold floor or down from a warm ceiling (working *against* buoyancy)





$h_c \approx 0.59\left(\frac{\Delta t}{L}\right)^{1/4}$ [Straube 5.11] both laminar and turbulent

h_c to/from Sloped Surfaces



h_c in [W/(m2 K)]

For natural convection to or from either side of a vertical surface or a sloped surface with $\beta > 30°$

For laminar: $h_c = 1.42\left(\frac{\Delta t}{L}\sin\beta\right)^{\frac{1}{4}}$ [Kreider 2.18SI]

For turbulent: $h_c = 1.31\left(\Delta t \sin\beta\right)^{\frac{1}{3}}$ [Kreider 2.19SI]

Summary of h_c equations for natural convection (SI)

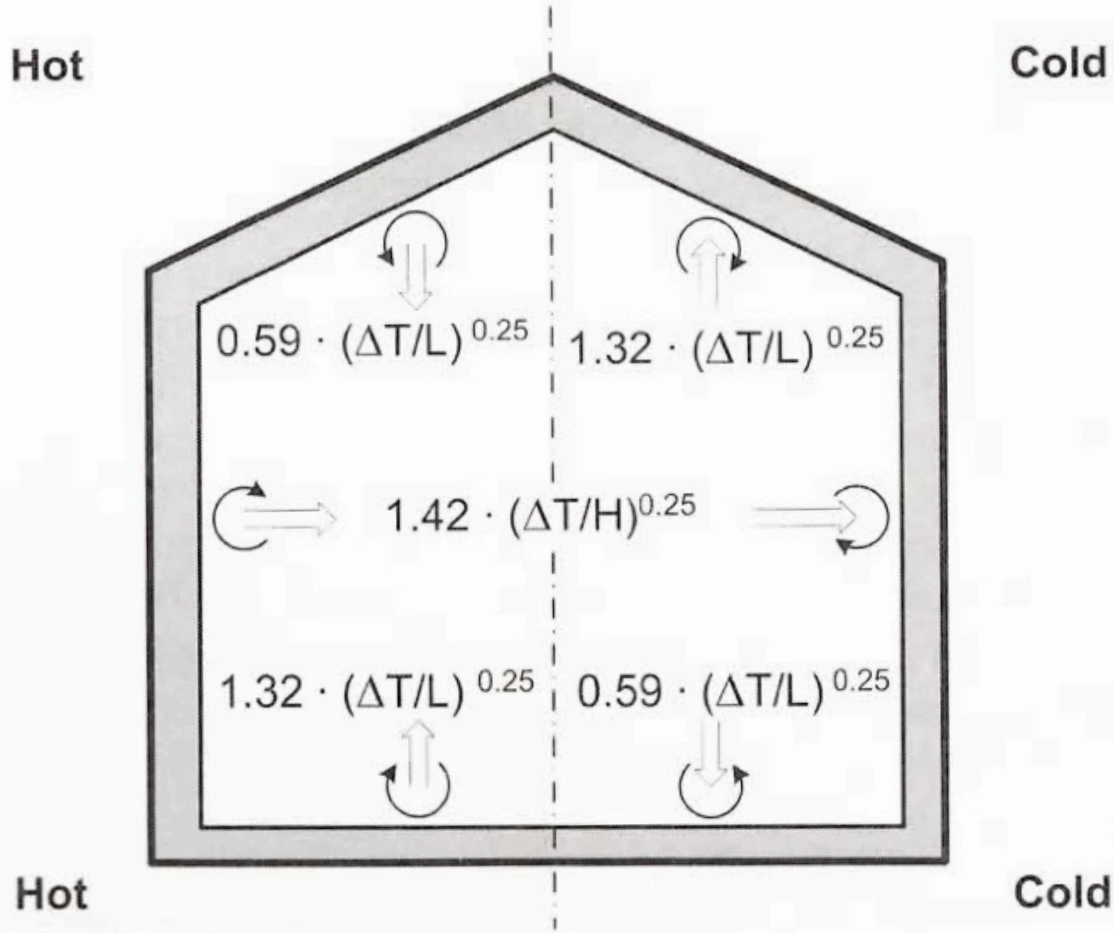
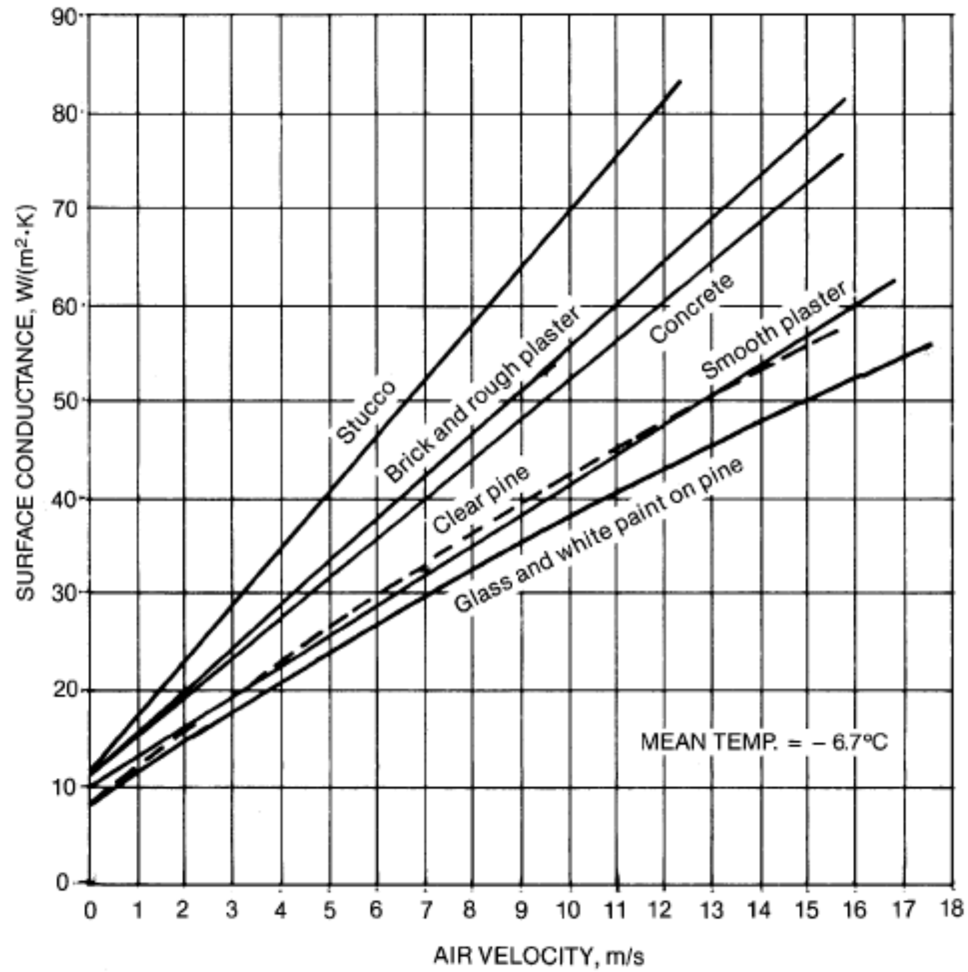


Figure 5.4: Natural convection coefficients for laminar flow

h_c for forced convection

- For forced convection h_c depends upon surface roughness and air velocity but not orientation

- The figure at right is taken from ASHRAE HOF



Most popular general h_c for forced convection

There are two relationships for h_c (forced convection) which are commonly used, depending on wind speed:

- For $1 < v_{wind} < 5$ m/s

  $h_c = 5.6 + 3.9v_{wind}$ [W/(m²·K)] [Straube 5.15]

- For $5 < v_{wind} < 30$ m/s

  $h_c = 7.2v_{wind}^{0.78}$ [W/(m²·K)] [Straube 5.16]

*Good for use with external surfaces

Convective R-Value

- Convective heat transfer can be considered an conductive layer in contact with air and so we can assign an R value to it

- Looking at our definitions we can see that the equivalent R value is simply the reciprocal of the heat transfer coefficient so

$$R_c = \frac{1}{h_c}$$

Typical convective surface resistances

- We often use the values given below for most conditions, just to simplify our lives

Surface Conditions	Horizontal Heat Flow m^2K/W	Upwards Heat Flow m^2K/W	Downwards Heat Flow m^2K/W
Indoors: R_i	0.12	0.11	0.16
6.7 m/s wind (Winter)		0.030	
3.4 m/s wind (Summer)		0.044	

Values from ASHRAE Fundamentals 2005 Table 25.1 with emissivity = 0.9. Values change significantly with emissivity and condensation.

Bulk convective heat transfer

- Bulk convective heat transfer is more direct than convection as we previously discussed
- 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

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

$$q_{bulk} = \frac{\dot{m} C_p \Delta t}{A} \qquad [\mathrm{W/m^2}]$$

m "dot" = mass flow rate of air (kg/s)
C_p = specific heat capacity of air [J/(kgK)]

Bulk convective heat transfer

- Bulk convective heat transfer can also be described in terms of the “air exchange rate”
  - Rate at which indoor air is replaced by outdoor air
  - Volume normalized

$$Q_{bulk} = \dot{m} C_p \Delta t = \dot{V} \rho_{air} C_p \Delta t$$

$$\dot{V} = AER \cdot V$$

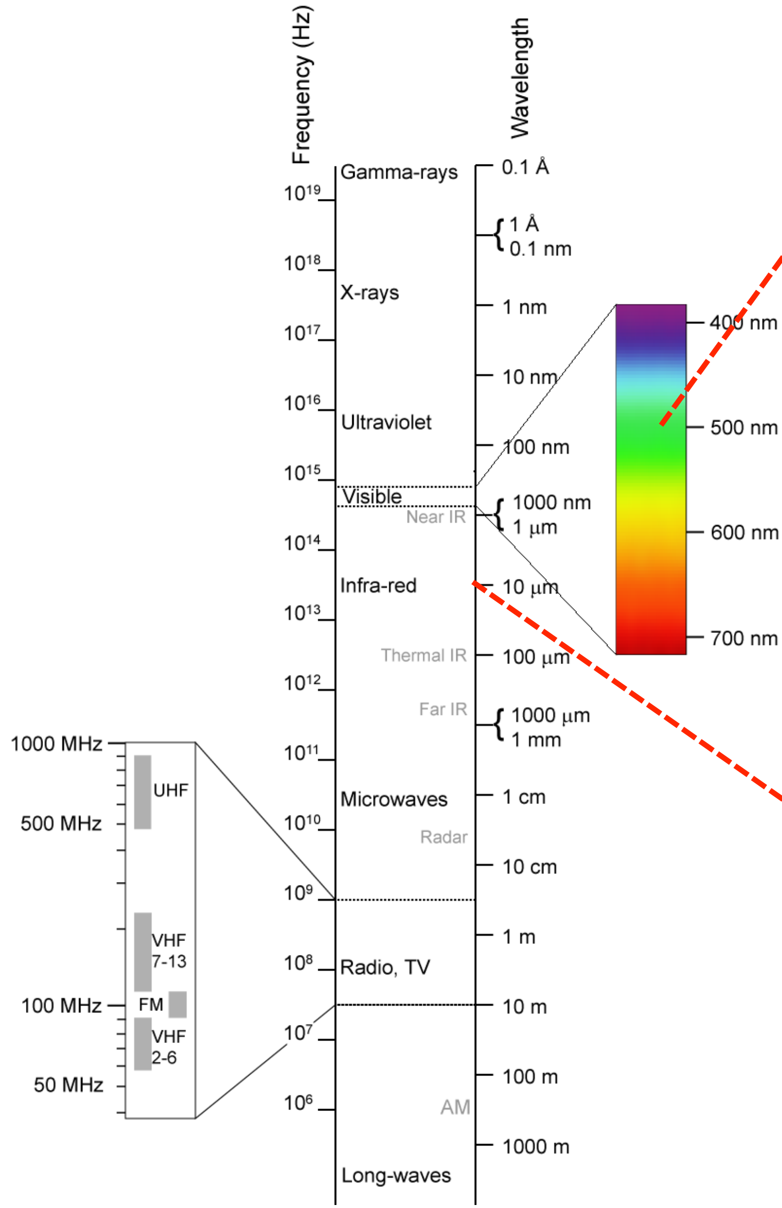
$$Q_{bulk} = AER \cdot \rho_{air} \cdot C_p \cdot \Delta t \cdot V$$

V “dot” = volumetric flow rate of air (m^3/s)
ρ = air density (kg/m^3)
V = volume of indoor air (m^3)
AER = air exchange rate (1/hr)

Radiation

- We’ve already discussed solar orientation and solar radiation striking a surface
- We’ve already made some simplifications to make our lives easier
  - For one, solar 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
  - However, it’s generally appropriate for our purposes lump all wavelengths into “solar radiation”
    - Sometimes into shortwave and longwave

Radiation: shortwave and longwave



Solar shortwave Radiation (direct)
Avg. λ = 0.5 µm

Terrestrial longwave Radiation (diffuse/reflected)
Avg. λ = 10 µm

Radiation

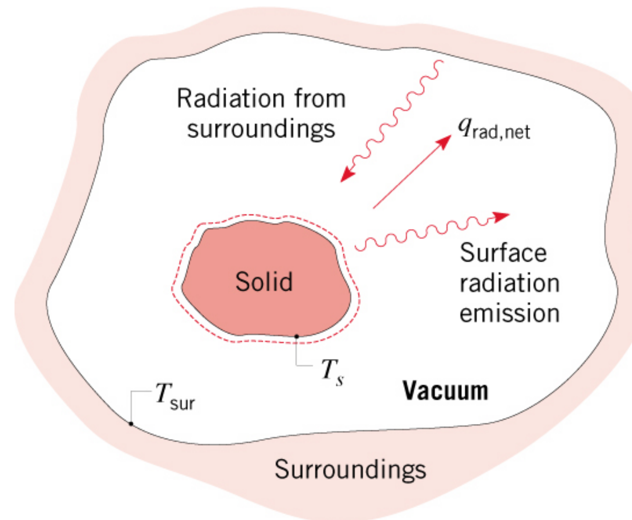
- All objects above absolute zero radiate electromagnetic energy according to:

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

Where ε=emissivity

σ = Stefan-Boltzmann constant = $5.670 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$

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.

Surface-to-air radiation

- General surface-to-air radiation

$$q_{rad} = \frac{Q_{rad}}{A} = \varepsilon\sigma(T_{surface}^4 - T_{air}^4)$$

- A note on emissivity
  - Fraction of energy re-radiated – depends on material

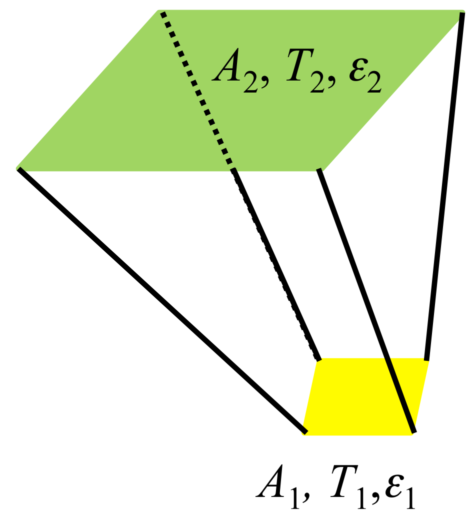
See ASHRAE HOF for many more

Table 5 Emissivities and Absorptivities of Some Surfaces

Surface	Total Hemispherical Emissivity	Solar Absorptivity*
Aluminum		
Foil, bright dipped	0.03	0.10
Alloy: 6061	0.04	0.37
Roofing	0.24	
Asphalt	0.88	
Brass		
Oxidized	0.60	
Polished	0.04	
Brick	0.90	
Concrete, rough	0.91	0.60

Radiation heat transfer (surface-to-surface)

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



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

where ε_1 and ε_2 are the surface emittances,

A_1 and A_2 are the surface areas

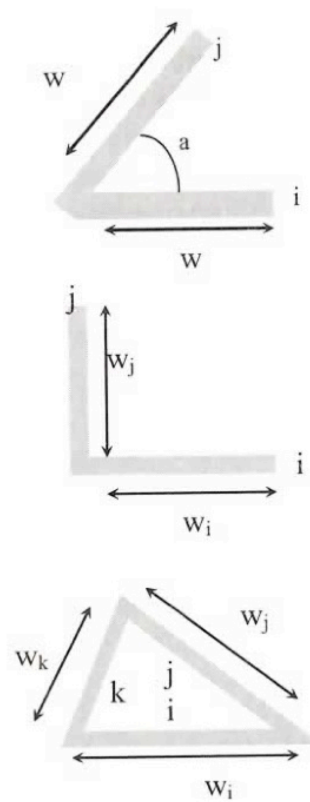
and $F_{1\rightarrow 2}$ is the view factor from surface 1 to 2

$F_{1\rightarrow 2}$ is a function of geometry only

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



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

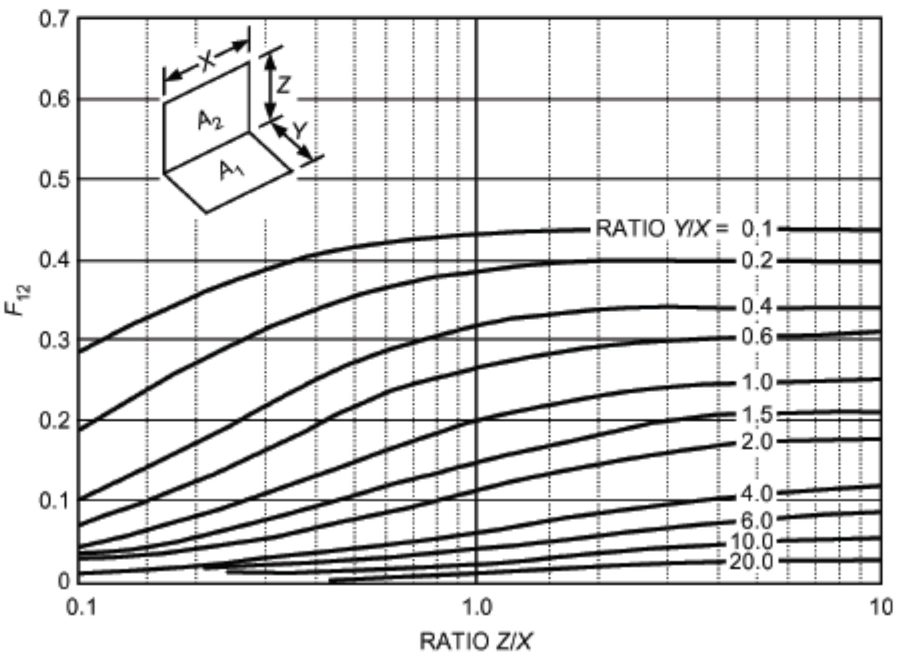
$$F_{ij} = \frac{1 + (w_j / w_i) - [1 + w_j / w_i)^2]^{1/2}}{2}$$

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

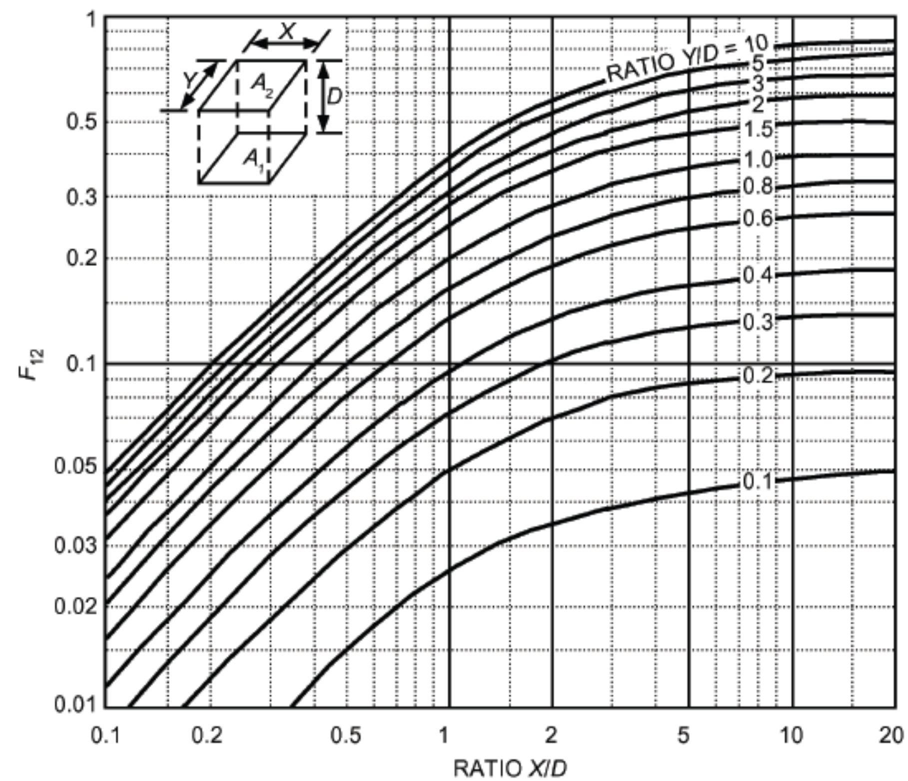
Figure 5.6: View factors for common situations in building enclosures [Hagentoft 2000]

Typical view factors

- Other common view factors from ASHRAE HOF



A. PERPENDICULAR RECTANGLES WITH COMMON EDGE



B. ALIGNED PARALLEL RECTANGLES

Simplifying radiation

- We will sometimes simplify the equation for radiation heat transfer
  - Particularly when emissivities & areas are equal
- From:

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

- To:

$$q_{r,1\rightarrow 2} = \frac{Q_{1\rightarrow 2}}{A_1} = \varepsilon_1 \varepsilon_2 \sigma F_{12}\left(T_1^4 - T_2^4\right)$$

Radiation heat transfer coefficient

We can also rewrite the radiation equation so it looks like convection or conduction if we properly define a heat transfer coefficient or thermal resistance

$$q_{r,1\to 2} = h_r\left(T_1 - T_2\right) = \left(T_1 - T_2\right) / R_r$$

$$\text{where } h_r = \frac{1}{R_r} = \frac{\left(T_1^4 - T_2^4\right) \big/ \left(T_1 - T_2\right)}{\dfrac{1-\varepsilon_1}{\varepsilon_1} + \dfrac{A_1}{A_2}\dfrac{1-\varepsilon_2}{\varepsilon_2} + \dfrac{1}{F_{1\to 2}}}$$

- For the special case when $A_1 \approx A_2$ and $F_{1\to 2} \approx 1$ (such as wall cavities) we can rewrite h_r more simply as

$$h_r = \frac{\varepsilon_{eff}\left(T_1^4 - T_2^4\right)}{T_1 - T_2} \approx 4\varepsilon_{eff}\left(T_{avg}^3\right) \text{ where } \frac{1}{\varepsilon_{eff}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$$

Notes on radiation heat transfer

- Radiation heat transfer depends upon the view factor, which is a function of geometry
  - Also depends on both absolute T and differential T

- The view factor from one side of a wall cavity to the other does not change much at all as the cavity gets wider. This means that radiation heat transfer does not change much as cavity spacing is increased!

- Radiation heat transfer depends on T^4, which complicates things mathematically

- Obvious importance of low-emissivity materials
  - Generally only important that **one** material is **low-ε**

Multi-surface radiative transfer

- If we have more than two dominant surfaces we have a fairly complicated system
  - Best solved using computers rather than by hand

- To do these by hand we would need to develop full thermal networks for multi-surface radiation
  - We are not going to do that today

Stage change

- When materials change state, they release or absorb a material-specific amount of latent energy
  - Usually concerned with water evaporation/condensation

- All materials above absolute zero contain some heat energy
  - This amount of energy (E, in J or kJ) is equal to:

$$E = C_p m T$$

where C_p is the specific heat capacity [kJ/(kgK)]

m is the mass (kg), T is absolute temperature (K)

Stage change

- The amount of heat energy required to change a material from one temperature to another is:

$$E = C_p m \Delta T$$

where C_p is the specific heat capacity [kJ/(kgK)]

m is the mass (kg), ΔT is the temperature difference (K)

Single-mode heat transfer examples

- Let's perform some example calculations, first treating conduction, convection, and radiation individually

3. HEAT TRANSFER THROUGH BUILDING ENCLOSURES

Example 2.5: Single-layer conduction

- A 2 m wide, 3 m high, and 50 mm thick piece of extruded polystyrene material has a surface temperature of 20°C on one side and 40°C on the other
  - a) Calculate heat flow rate and heat flux
  - b) Calculate conductance (U-value)
  - c) Calculate resistance (and R-value)

ASHRAE HOF (2005 Ch. 25):

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] (*Continued*)

Description	Density, kg/m^3	Conductivity[b] (k), $W/(m \cdot K)$	Conductance (C), $W/(m^2 \cdot K)$	Resistance[c] (R) $1/k$, $(m \cdot K)/W$	Resistance[c] (R) For Thickness Listed ($1/C$), $(m^2 \cdot K)/W$	Specific Heat, $kJ/(kg \cdot K)$
Expanded polystyrene, extruded (smooth skin surface) (HCFC-142b exp.)[h]	29-56	0.029	—	34.7	—	1.21

Example 2.6: Convection

- The interior face of an insulated exterior enclosure wall 2.4 m wide and 2.4 m high is 3°C cooler than the interior air (t_{indoor} = 21°C)
  a) Calculate convective heat transfer coefficient at the face
  b) Calculate rate of convective heat transfer

Example 2.7: Bulk convection

- A building has an outdoor air delivery rate of 400 m^3 per hour. The outdoor temperature is 35°C. The indoor air temperature is 20°C.
  a) Calculate the rate at which heat is added to the indoor air from outdoors

Example 2.8: Radiation

- Interior surfaces of two perpendicular walls (both are 2.4 m by 2.4 m) are 3°C different from each other. One is at 294 K, the other at 291 K. They both have an emissivity of 0.90.
  a) Calculate the rate of radiative heat transfer between the two surfaces

  b) What if the emissivity of one surface decreases to 0.1?

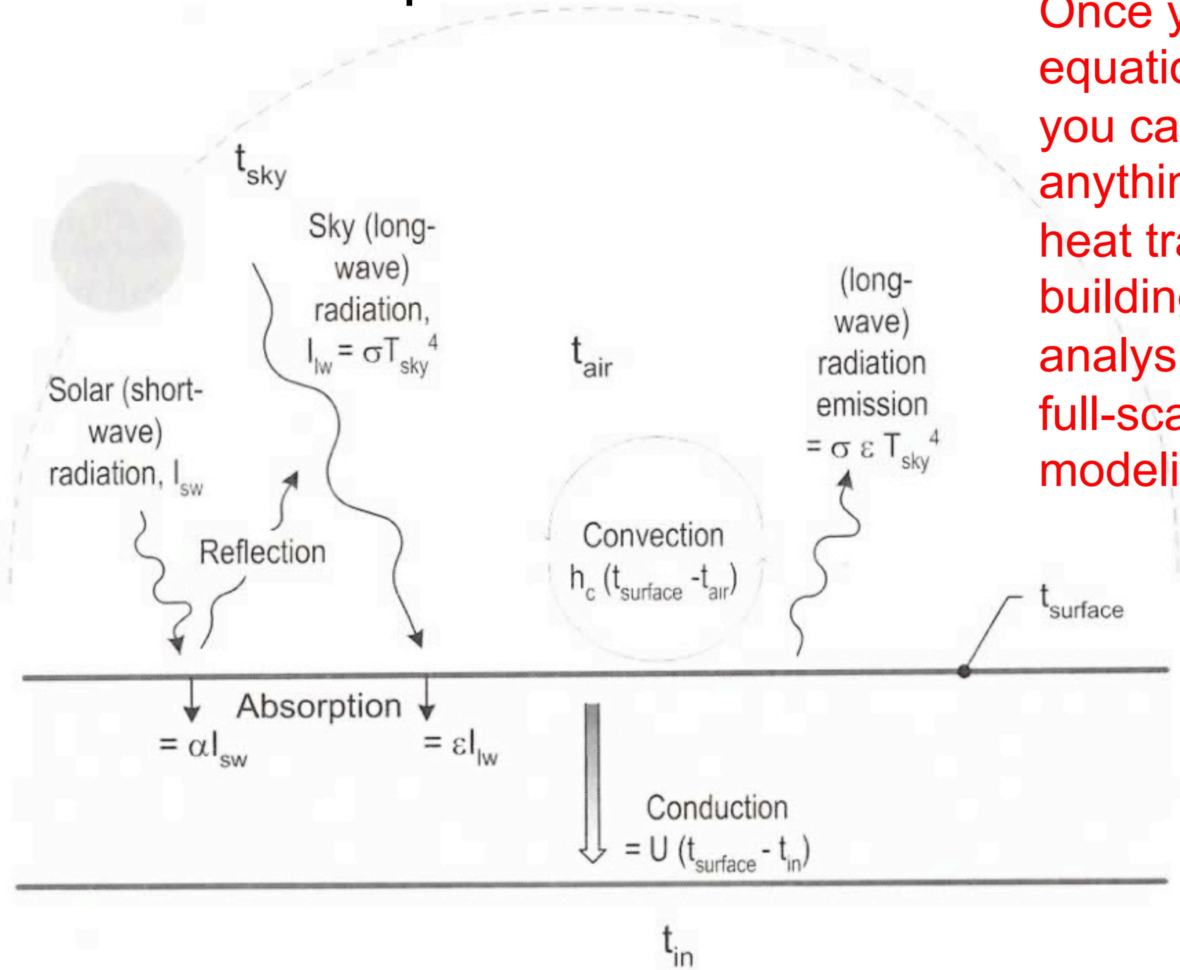
Combined heat transfer

- In some cases, heat transfer from a surface is dominated by either convection or radiation
  - In many cases both are about the same magnitude

- In cavities (window spaces, wall cavities, crawl spaces) this is usually the case
  - So, heat transfer is fairly complicated

Bringing all the modes together

- Exterior surface example



Once you have this equation described, you can do just about anything regarding heat transfer in building enclosure analysis, leading into full-scale energy modeling

$$q = \alpha I_{SW} + F_A \varepsilon_{surface} \sigma (T_{sky}^4 - T_{air}^4) - F_A \varepsilon_{surface} \sigma (T_{surface}^4 - T_{sky}^4) - h_c (T_{air} - T_{surface}) - U (T_{surface} - T_{in})$$

(A note on sky temperature)

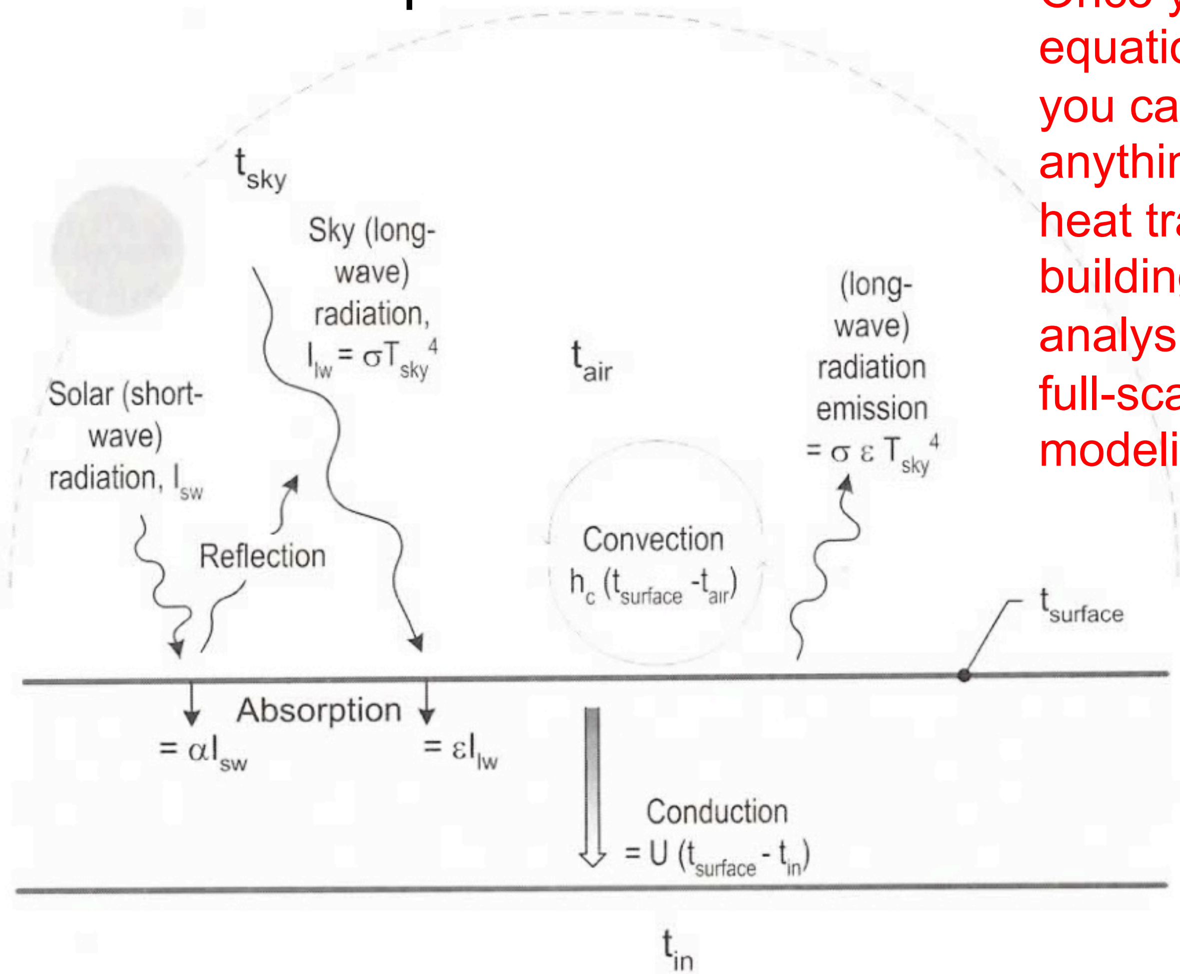
- Many ways to get sky temperature
  - Varying levels of detail and accuracy

- For a partly cloudy night sky

$$t_{sky} = t_{air}\left[0.8 + \frac{(t_{dewpoint} - 273)}{250}\right]^{1/4}$$

Bringing all the modes together

- Exterior surface example



Once you have this equation described, you can do just about anything regarding heat transfer in building enclosure analysis, leading into full-scale energy modeling

We will spend much of the next class working on this term

$$q = \alpha I_{SW} + F_A \varepsilon_{surface} \sigma (T_{sky}^4 - T_{air}^4) - F_A \varepsilon_{surface} \sigma (T_{surface}^4 - T_{sky}^4) - h_c (T_{air} - T_{surface}) - U (T_{surface} - T_{in})$$

Conduction through multiple layers

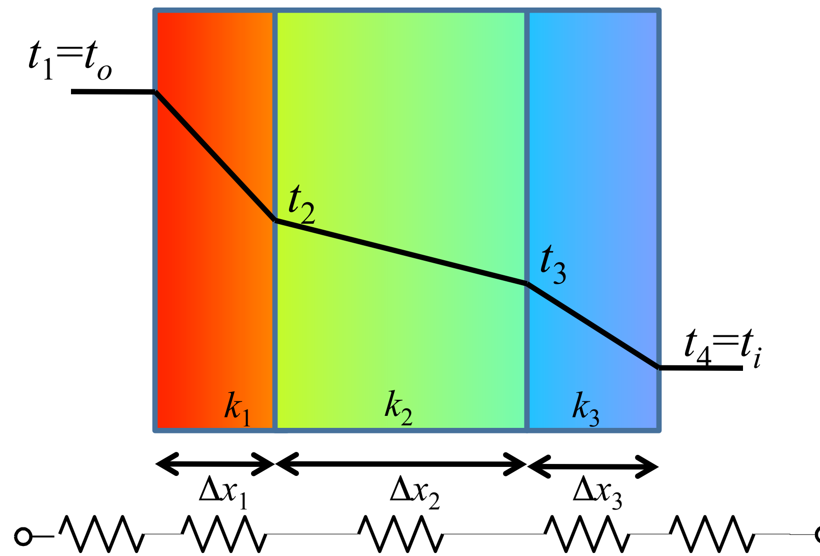
- Just as in electrical circuits, the overall thermal resistance of a series of elements (layers) can be expressed as the sum of the resistances of each layer
  - Do not forget the interior and exterior convective resistances!

- By continuity of energy we can write

$$q = \frac{t_1 - t_2}{R_1} = \frac{t_2 - t_3}{R_2} = \frac{t_3 - t_4}{R_3}$$

so

$$q = \frac{t_1 - t_4}{R_{total}} \quad \text{where} \quad R_{total} = R_o + R_1 + R_2 + R_3 + R_i$$



$R_o = 0.044 \quad R_1 = \frac{\Delta x_1}{k_1} \quad R_2 = \frac{\Delta x_2}{k_2} \quad R_3 = \frac{\Delta x_3}{k_3} \quad R_i = 0.11$

Typical “film” values

Can only add resistances (R), not conductances (C or U)

Limitations to Summation Rule

The summation rule for finding R_{total} has several limitations:

- Only works for **layers**
- Layers must be **same area**
- Layers must be **uniform thickness**
- Layers must have **constant material properties**
  - This is the **biggest** limitation

What do we do with more realistic constructions?

Parallel path or ISO thermal equivalents

Will cover next lecture

Simple conduction through multiple layers

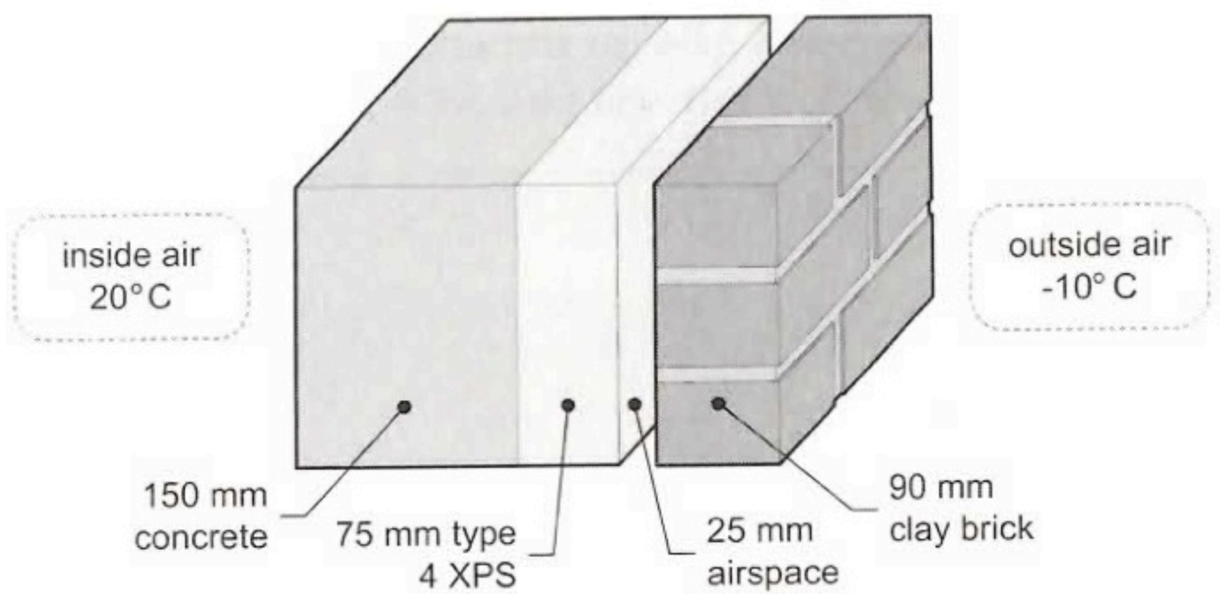
- Calculate the R-value of an enclosure assembly

Steps:

1. List each material in the assembly
   – And its conductivity and thickness
2. Calculate conductance of each layer
   – $C = k/L$
3. Calculate thermal resistance of each layer
   – $R = 1/C$
4. Sum the individual thermal resistances to get R_{total}

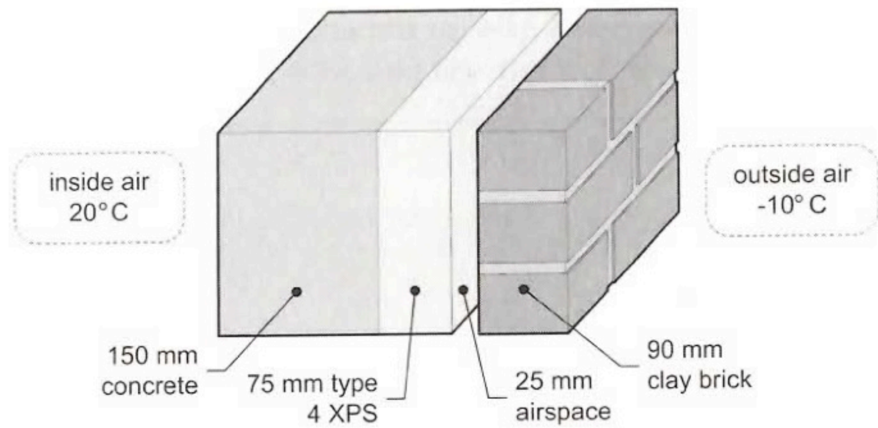
Conduction through multiple layers

- Example problem 2.9
- Calculate the total thermal resistance, R_{total}, and overall heat transfer coefficient, U_{total}, of the wall shown below



Conduction through multiple layers

- Refer to ASHRAE 2005 HOF Ch. 25 for data



Layer material	Conductivity, k W/mK	Thickness m	Conductance W/m^{2}K	Resistance m^{2}K/W
Interior film	n/a	n/a	8.3	0.121
Concrete	1.8	0.15	12	0.083
Type 4 XPS	0.029	0.075	0.4	2.564
Air space	n/a	0.025	n/a	0.17
Brick	1.3	0.09	14.4	0.069
Exterior film	n/a	n/a	34	0.029
			R_{total} (m^{2}K/W)	3.04
			U_{total} (W/m^{2}K)	0.33

A note on R-values of air cavities

- ASHRAE has measured the combined convective + radiative R-values for thin planar cavities of various orientations and depths with various ε_{eff}.
- These are the best data to use for air spaces in assemblies
  – If you do not know that the material in the cavity is reflective or "low e", just assume that both walls of the cavity have ε=0.9 for each surface, so that when combined, ε_{eff}=0.82

ASHRAE HOF 2005, Chapter 25 (small cavities)

R-values for different air gap characteristics

Table 3 Thermal Resistances of Plane Air Spaces[a,b,c], $(m^2 \cdot K)/W$

Position of Air Space	Direction of Heat Flow	Air Space		13 mm Air Space[c]					20 mm Air Space[c]				
				Effective Emittance ε_{eff}[d,e]					Effective Emittance ε_{eff}[d,e]				
		Mean Temp.[d], °C	Temp. Diff.[d], °C	0.03	0.05	0.2	0.5	0.82	0.03	0.05	0.2	0.5	0.82
Horiz.	Up	32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
		10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
		10.0	5.6	0.37	0.36	0.28	0.20	0.15	0.40	0.39	0.30	0.20	0.15
		−17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
		−17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
		−45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
		−45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
45° Slope	Up	32.2	5.6	0.43	0.41	0.29	0.19	0.13	0.52	0.49	0.33	0.20	0.14
		10.0	16.7	0.36	0.35	0.27	0.19	0.15	0.35	0.34	0.27	0.19	0.14
		10.0	5.6	0.45	0.43	0.32	0.21	0.16	0.51	0.48	0.35	0.23	0.17
		−17.8	11.1	0.39	0.38	0.31	0.23	0.18	0.37	0.36	0.30	0.23	0.18
		−17.8	5.6	0.46	0.45	0.36	0.25	0.19	0.48	0.46	0.37	0.26	0.20
		−45.6	11.1	0.37	0.36	0.31	0.25	0.21	0.36	0.35	0.31	0.25	0.20
		−45.6	5.6	0.46	0.45	0.38	0.29	0.23	0.45	0.43	0.37	0.29	0.23
Vertical	Horiz.	32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
		−17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
		−17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
		−45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
		−45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27
		32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15

Usually we use values from the $\varepsilon_{eff} = 0.82$ column

ASHRAE HOF 2005, Chapter 25 (larger cavities)

R-values for different air gap characteristics

Position of Air Space	Direction of Heat Flow	Mean Temp.[d], °C	Temp. Diff.[d], °C	40 mm Air Space[c] Effective Emittance ε_{eff}[d,e] 0.03	0.05	0.2	0.5	0.82	90 mm Air Space[c] Effective Emittance ε_{eff}[d,e] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up	32.2	5.6	0.45	0.42	0.30	0.19	0.14	0.50	0.47	0.32	0.20	0.14
		10.0	16.7	0.33	0.32	0.26	0.18	0.14	0.27	0.35	0.28	0.19	0.15
		10.0	5.6	0.44	0.42	0.32	0.21	0.16	0.49	0.47	0.34	0.23	0.16
		–17.8	11.1	0.35	0.34	0.29	0.22	0.17	0.40	0.38	0.32	0.23	0.18
		–17.8	5.6	0.43	0.41	0.33	0.24	0.19	0.48	0.46	0.36	0.26	0.20
		–45.6	11.1	0.34	0.34	0.30	0.24	0.20	0.39	0.38	0.33	0.26	0.21
		–45.6	5.6	0.42	0.41	0.35	0.27	0.22	0.47	0.45	0.38	0.29	0.23
45° Slope	Up	32.2	5.6	0.51	0.48	0.33	0.20	0.14	0.56	0.52	0.35	0.21	0.14
		10.0	16.7	0.38	0.36	0.28	0.20	0.15	0.40	0.38	0.29	0.20	0.15
		10.0	5.6	0.51	0.48	0.35	0.23	0.17	0.55	0.52	0.37	0.24	0.17
		–17.8	11.1	0.40	0.39	0.32	0.24	0.18	0.43	0.41	0.33	0.24	0.19
		–17.8	5.6	0.49	0.47	0.37	0.26	0.20	0.52	0.51	0.39	0.27	0.20
		–45.6	11.1	0.39	0.38	0.33	0.26	0.21	0.41	0.40	0.35	0.27	0.22
		–45.6	5.6	0.48	0.46	0.39	0.30	0.24	0.51	0.49	0.41	0.31	0.24
Vertical	Horiz.	32.2	5.6	0.70	0.64	0.40	0.22	0.15	0.65	0.60	0.38	0.22	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.47	0.45	0.33	0.22	0.16
		10.0	5.6	0.67	0.62	0.42	0.26	0.18	0.64	0.60	0.41	0.25	0.18
		–17.8	11.1	0.49	0.47	0.37	0.26	0.20	0.51	0.49	0.38	0.27	0.20
		–17.8	5.6	0.62	0.59	0.44	0.29	0.22	0.61	0.59	0.44	0.29	0.22
		–45.6	11.1	0.46	0.45	0.38	0.29	0.23	0.50	0.48	0.40	0.30	0.24
		–45.6	5.6	0.58	0.56	0.46	0.34	0.26	0.60	0.58	0.47	0.34	0.26
		32.2	5.6	0.89	0.80	0.45	0.24	0.16	0.85	0.76	0.44	0.24	0.16

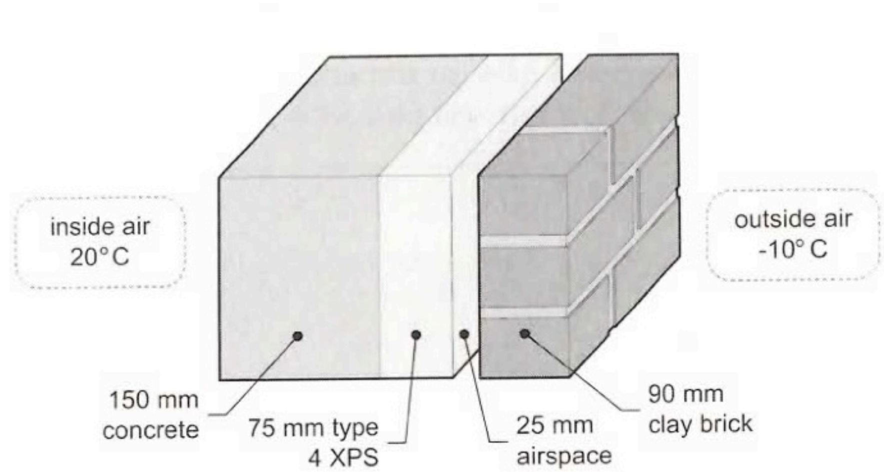
Usually we use values from the $\varepsilon_{eff} = 0.82$ column

R Value of deeper cavities

- The R-value of cavities stops increasing much at 3 inches (75 mm) depth
  - Beyond 3 inches (75 mm), they are dominated by radiation heat transfer
  - For a deep cavity, either compute R with more advanced methods or use the 3 inch (75 mm) value
- Do **NOT** take the R value of a 1 inch (25 mm) cavity and multiply by the thickness of the cavity for thick cavities
  - If you did that you would guess that an 8 ft attic would have an R value of about 100 BTU/(hr ft^2 F), which too high by a factor of 20!

Conduction through multiple layers

- $U_{total} = 0.33\ W/m^2K$



- Calculate steady-state heat flow through the enclosure

- $q = U\Delta t$
- $q = (0.33\ W/m^2K)*(t_{inside} - t_{outside})$
- $q = (0.33\ W/m^2K)*(30\ K) = 10\ W/m^2$
  – From inside to outside

Conduction through multiple layers

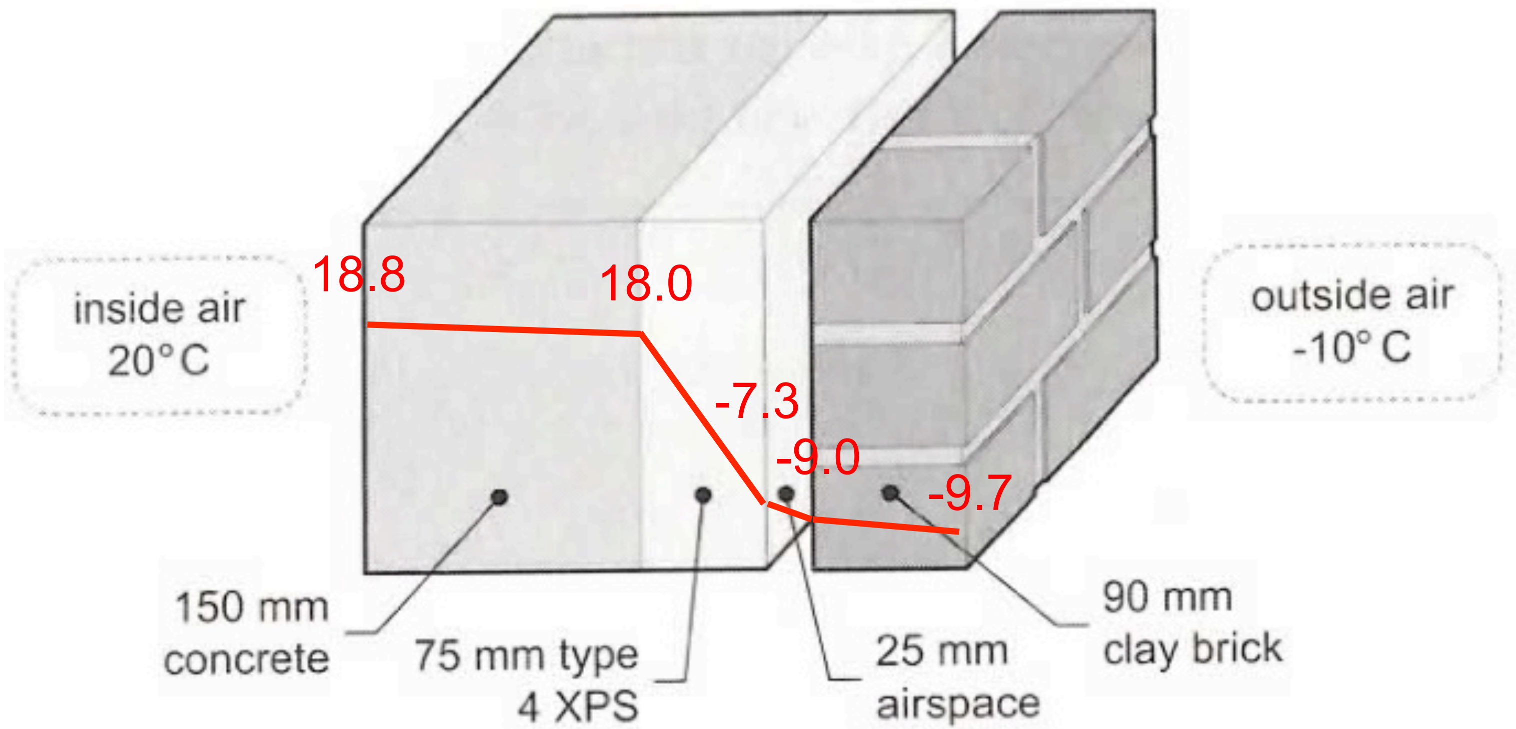
- Calculating the temperature gradient through an enclosure

$$\Delta T_i = \frac{t_{internal} - t_{external}}{\sum_{i=0}^{n} R_i} R_i$$

Layer	Conductivity, k W/mK	Thickness m	Conductance W/m²K	Resistance m²K/W	ΔT_i °C	t_i °C
Interior film	n/a	n/a	8.3	0.121		20
					1.2	
Concrete	1.8	0.15	12	0.083		18.8
					0.8	
Type 4 XPS	0.029	0.075	0.4	2.564		18.0
					25.3	
Air space	n/a	0.025	n/a	0.17		-7.3
					1.7	
Brick	1.3	0.09	14.4	0.069		-9.0
					0.7	
Exterior film	n/a	n/a	34	0.029		-9.7
					0.3	
			R_{total} (m²K/W)	3.04	Exterior t:	-10
			U_{total} (W/m²K)	0.33		

Conduction through multiple layers

- Calculating the temperature gradient through an enclosure



Total heat transfer through multiple layers

- Continue to use the electrical resistance analogy

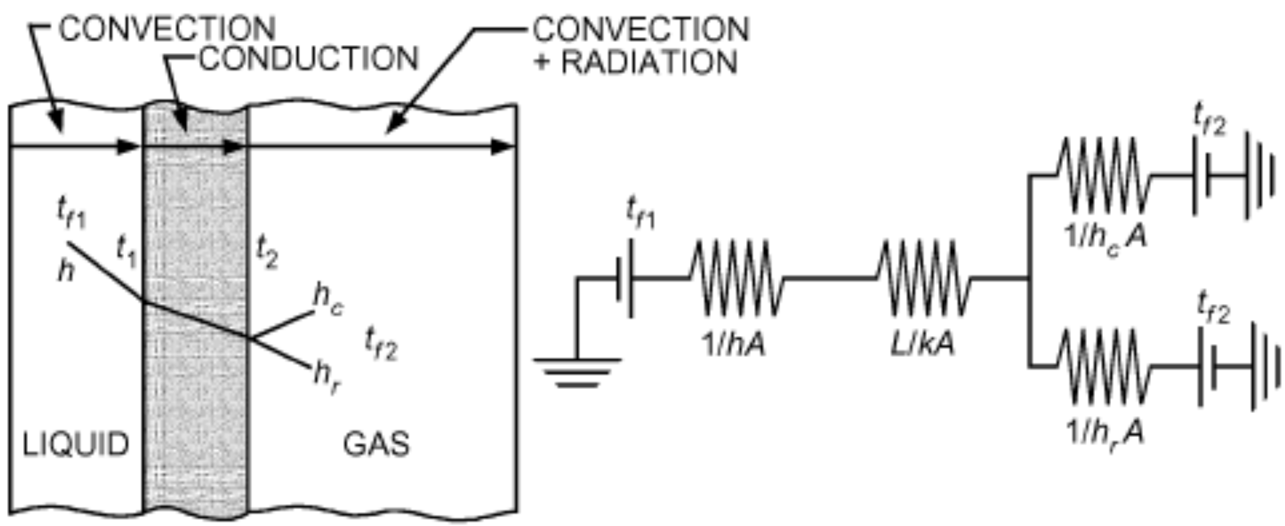


Fig. 1 Thermal Circuit

Next lecture

- Heat transfer through layers of enclosure elements
  - Thermal networks
- Heat transfer through more complex enclosure assemblies
  - Various methods
- HW 2 will be due September 10 in class
  - Will post within 24-48 hours