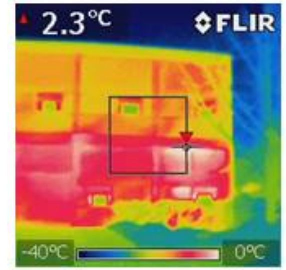
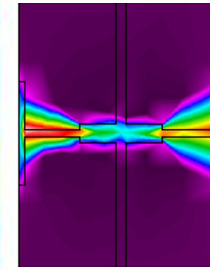
CAE 331/513 Building Science

Fall 2015





Week 7: October 8, 2015

Review for exam 1

Built
Environment
Research
@ IIT

Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

Twitter: @built_envi

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

Objectives for today

- Review key concepts from class thus far
- Answer any questions you have about HW problems/solutions or the exam
- Investigate why this room is always so hot

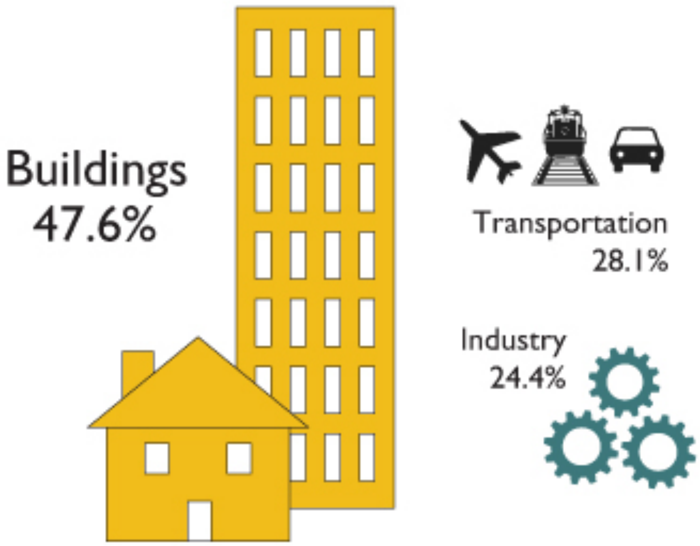
Schedule reminder

- **Tuesday, October 13:** No class
- **Thursday, October 15:** Exam 1 in class
  - If you are taking the class online can CANNOT show up to take the test in person, please contact me immediately

Topics covered thus far (and potential for coverage on exam 1)

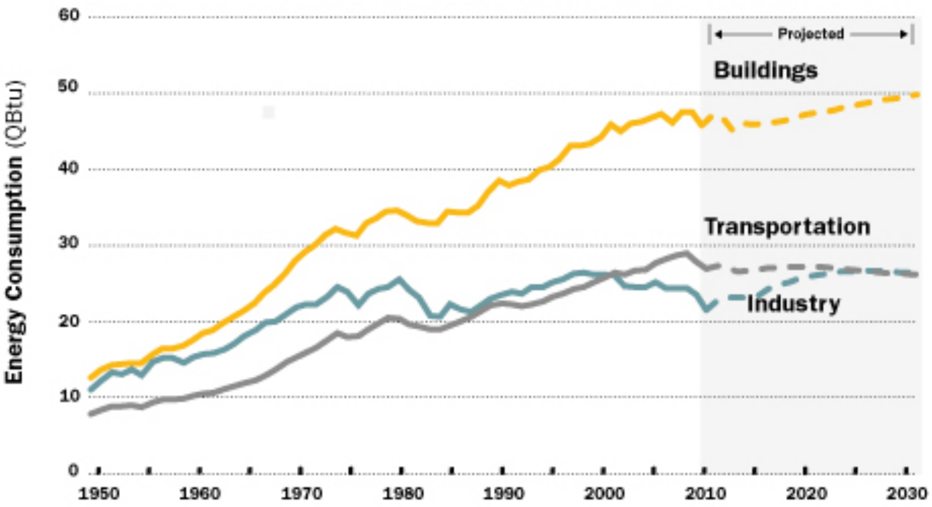
- Energy concepts and unit conversions
- Heat transfer in buildings
  - Conduction
  - Convection
  - Radiation
    - Solar radiation and long-wave radiation
  - Combined heat transfer
- Human thermal comfort
- Psychrometrics
  - Concepts
  - Chart
  - Equations
  - Processes in mechanical systems

Buildings use *a lot* of energy



U.S. Energy Consumption by Sector

Data Source: U.S. Energy Information Administration (2012).



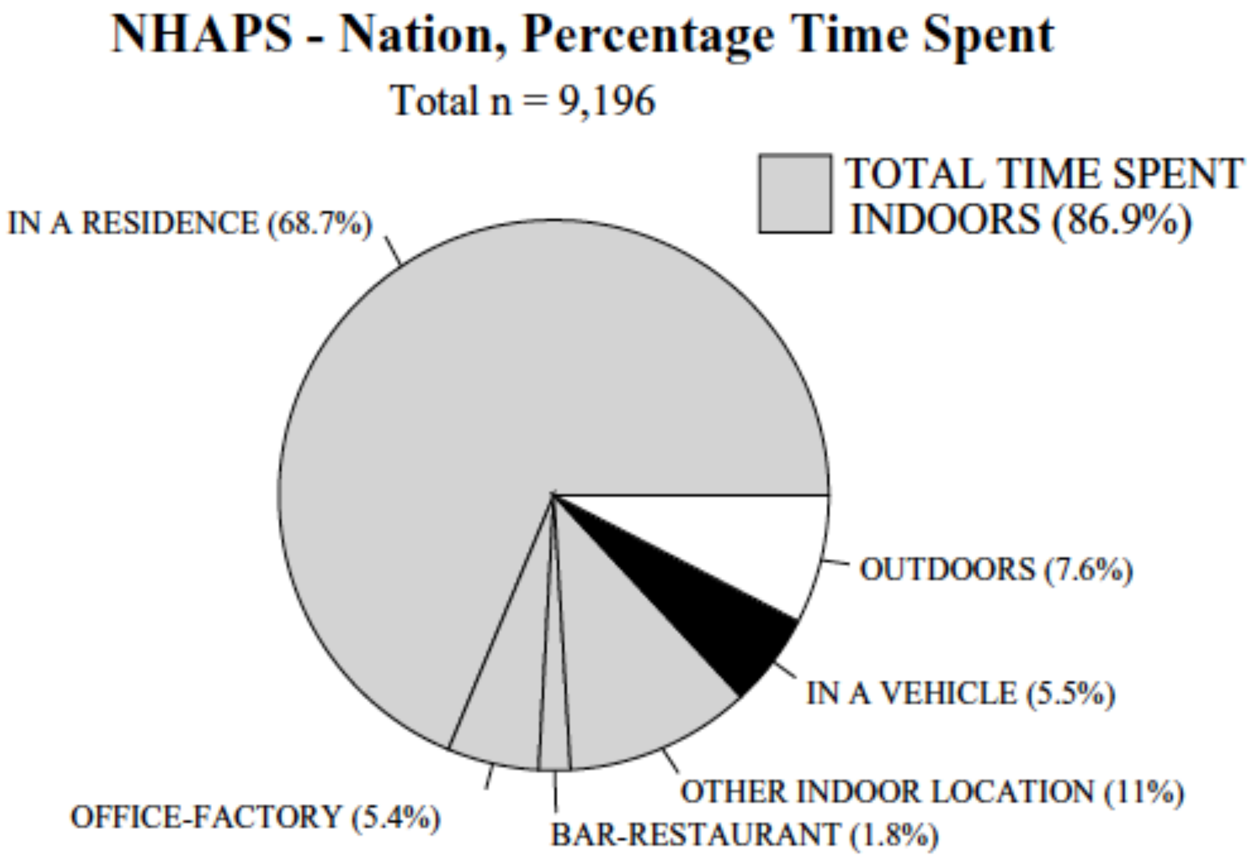
U.S. Energy Consumption by Sector (Historic / Projected)

Data Source: U.S. Energy Information Administration (2012).

Buildings account for ~47% of energy in the U.S.
(Operations: ~41% | Construction and materials: ~6%)

Buildings in the U.S. account for ~7% of the total amount of energy used in the world

We spend *a lot* of time in buildings



- Americans spend almost 90% of their time indoors
  - 75% at home or in an office

Klepeis et al., *J Exp. Anal. Environ. Epidem.* **2001**, 11, 231-252

Some very important definitions: Energy

Energy

- Energy is the capacity of a system to do work
  - We use this term a lot
  - Primary units: Joules, kWh or Btu (or MMBTU = 10^6 BTU)
- Different forms of energy:
  - Thermal, radiative, solar, nuclear, geothermal, hydrocarbon
  - Energy efficiency
    - Energy that is utilized versus energy that is not utilized
  - Embodied or embedded energy
    - The energy required to extract resources, manufacture, and transport a product
- Energy use depends on the rate of energy use and the time/duration of operation
  - Rate of energy use = Power

Some very important definitions: Power

Power

- Power is the rate at which energy is produced or consumed
  - Units are energy per time
  - IP: Btu per hour (Btu/hr) or kBTU per hour (1000 BTU/hr)
  - SI: Watt (W = J/s) or kilowatt (kW = kJ/s) or megawatt (MW = MJ/s)

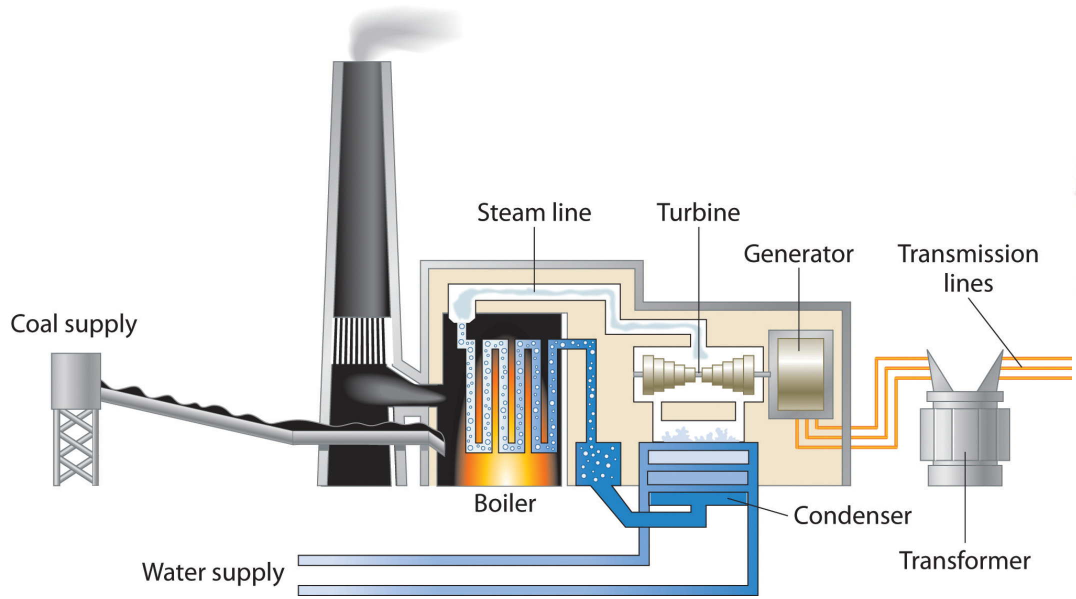
- Be careful when using units associated with energy and power
  - People often confuse these

- Example: Batteries don't store power; they store energy
  - They release that energy (Watt-hours) at a rate determined by the equipment's power draw (Watts, or amperage)

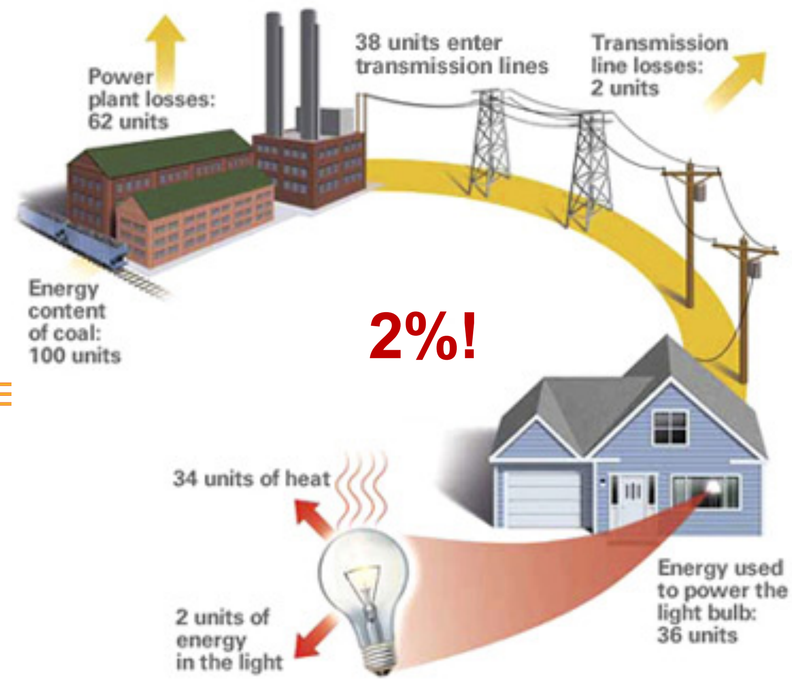
Conversion efficiency for electric generators

1st law of thermodynamics: Energy can be transformed from one form to another, but cannot be created or destroyed

- **Q:** What is a typical electric power plant efficiency? **30-45%**
- **Q:** What is the "round trip" efficiency for an incandescent light bulb?



Typical power plant schematic

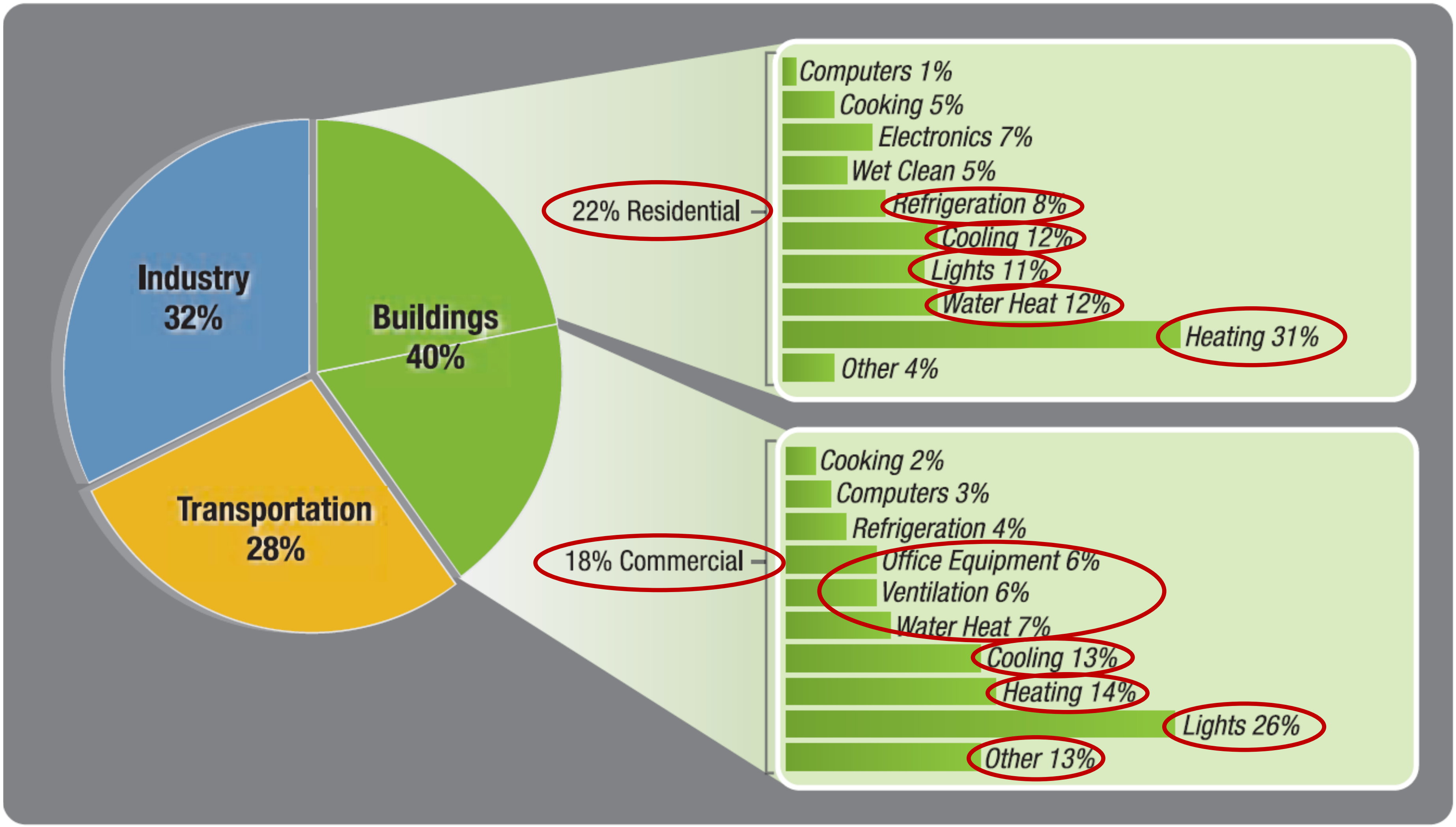


Natural gas used directly in buildings is typically **80-90%** efficient or more

http://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3

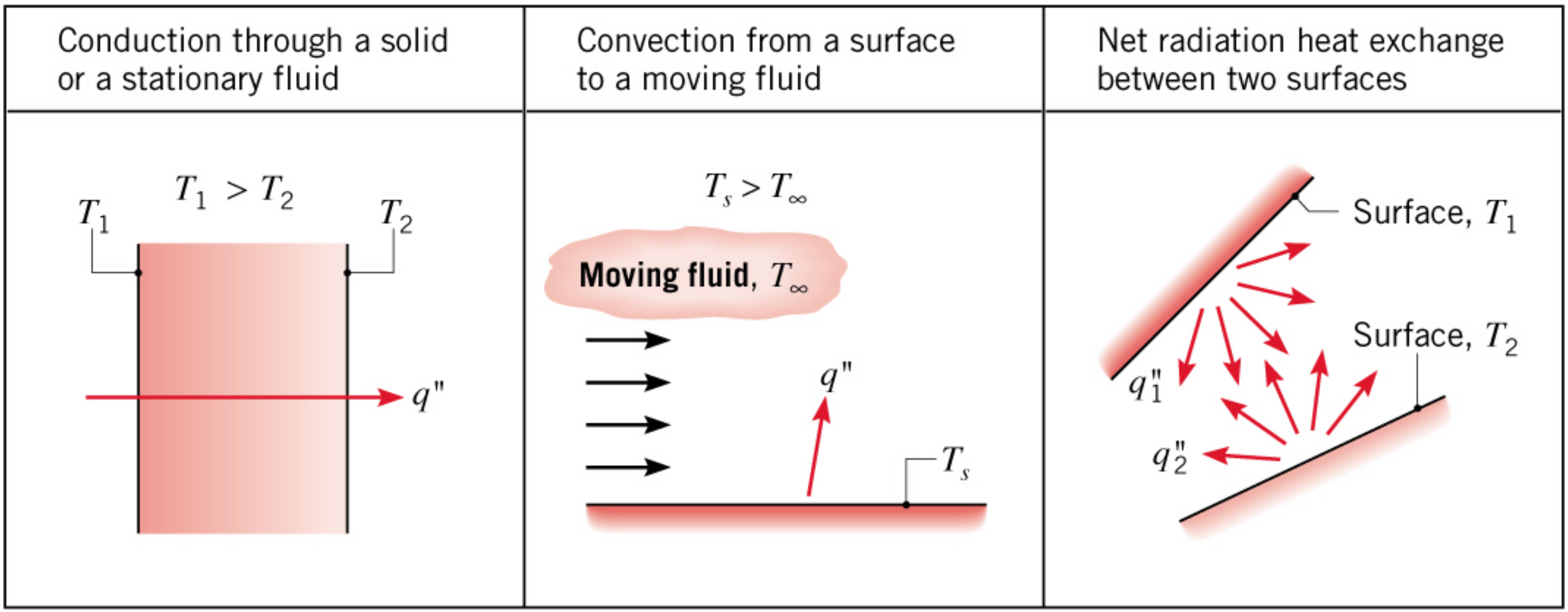
How do buildings use energy?

Figure 1-1 U.S. Primary Energy Consumption, 2005[2]



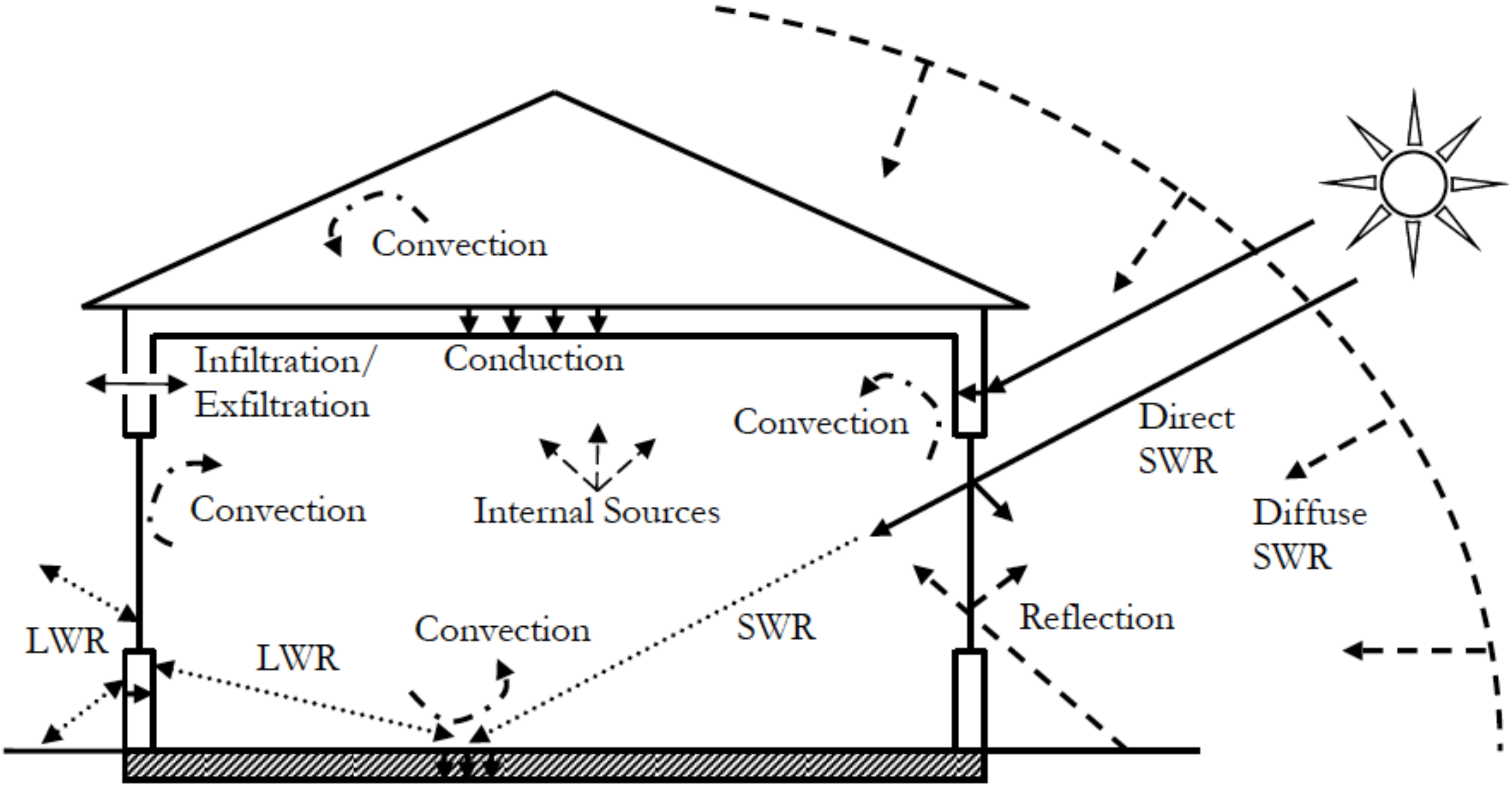
Heat transfer

- Three primary modes of heat transfer



Conduction **Convection** **Radiation**

Primary modes of heat transfer in a building



Thermal conductance and resistance

- Conductivity and length can also be described in other terms

$$Q = A\boxed{\frac{k}{L}}\left(T_1 - T_2\right)$$

$$\frac{k}{L} = U \qquad \text{and} \qquad R = \frac{1}{U}$$

where:

U = unit thermal conductance [$\frac{\text{Btu}}{\text{h·ft}^2\text{·°F}}$] or [$\frac{\text{W}}{\text{m}^2\text{K}}$]

R = unit thermal resistance [$\frac{\text{h·ft}^2\text{·°F}}{\text{Btu}}$] or [$\frac{\text{m}^2\text{K}}{\text{W}}$]

Conductive heat flux: $q = \frac{k}{L}\left(T_1 - T_2\right) = U\left(T_1 - T_2\right) = \frac{1}{R}\left(T_1 - T_2\right)$

Units of R and U-Value

- R values are typically used for insulating materials
  - For example: wall insulation materials
- U values are typically used for conductive materials
  - For example: windows
- SI units are easier for most to work with, but most products in the US are sold in IP units
  - Remember this conversion! R(IP) = R(SI) × 5.678

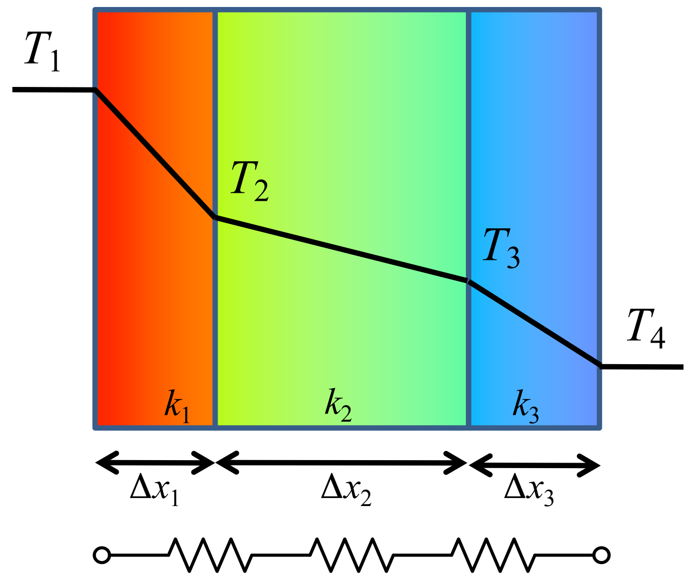
R-SI

$$1\,\frac{m^2K}{W} = 5.678\,\frac{h\cdot ft^2\cdot {}^\circ F}{Btu}$$

R-IP

Thermal resistances of series/layers of materials

- Just as in electrical circuits, the overall thermal resistance of a series of elements can be expressed as the sum of the resistances of each layer:



$$R_1 = \frac{\Delta x_1}{k_1} \qquad R_2 = \frac{\Delta x_2}{k_2} \qquad R_3 = \frac{\Delta x_3}{k_3}$$

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

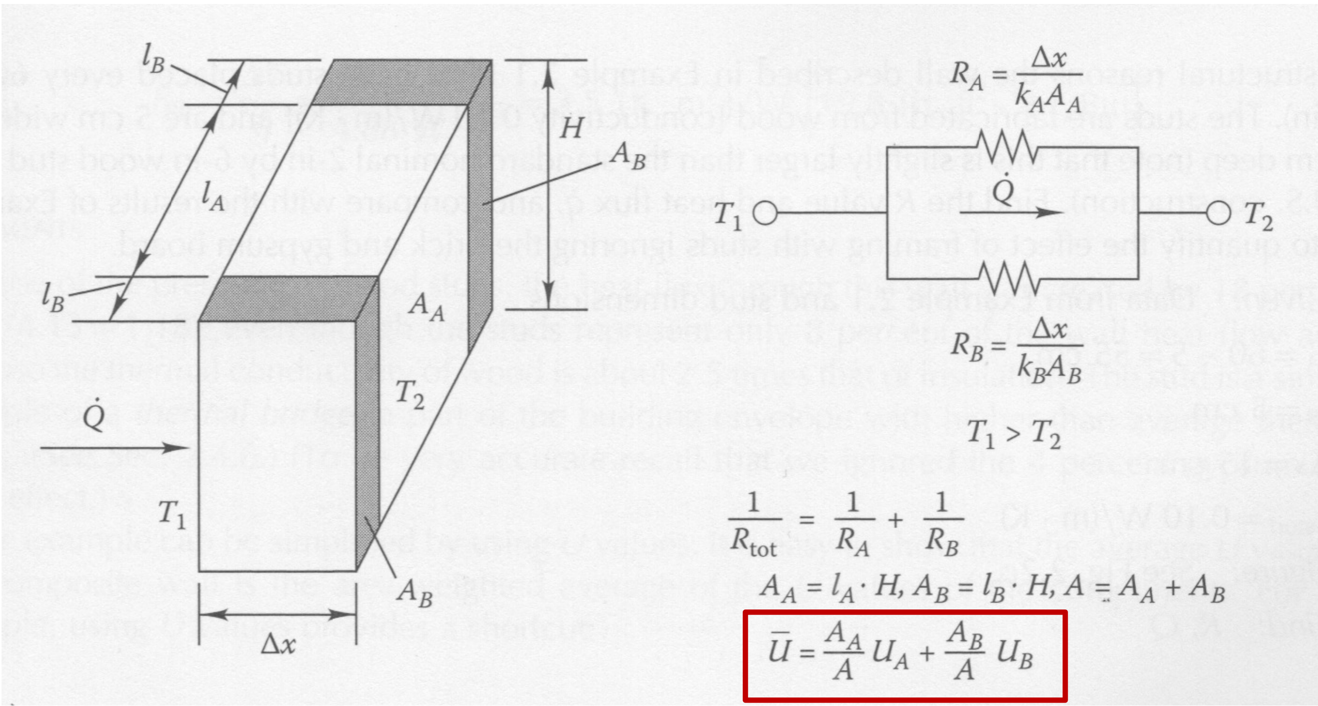
$$q = \frac{1}{R_{total}}\left(T_1 - T_4\right)$$

$$q = U_{total}\left(T_1 - T_4\right)$$

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

Accounting for structural elements (studs)

- Parallel-resistance heat flow



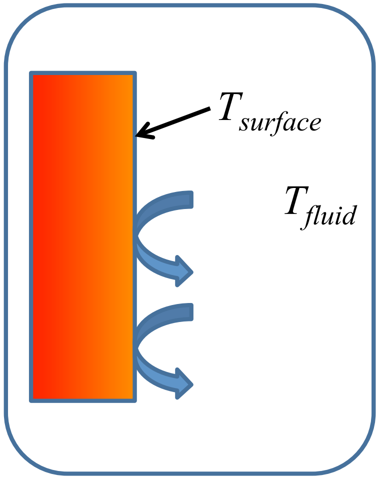
Treat resistances like resistors in series

- Simply use **weighted average U values**:

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

Convection

- Convective heat transfer occurs between a <u>solid</u> and a <u>moving fluid</u>
- When a fluid comes in contact with a surface at a different temperature (e.g., heat transfer between the air in a duct and the duct wall)
- We use a <u>heat transfer coefficient</u>, h_{conv}, to relate the rate of heat transfer to the difference between the solid surface temperature, $T_{surface}$, and the temperature of the fluid far from the surface, T_{fluid}



$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surface}\right) = \frac{1}{R_{conv}}\left(T_{fluid} - T_{surface}\right)$$

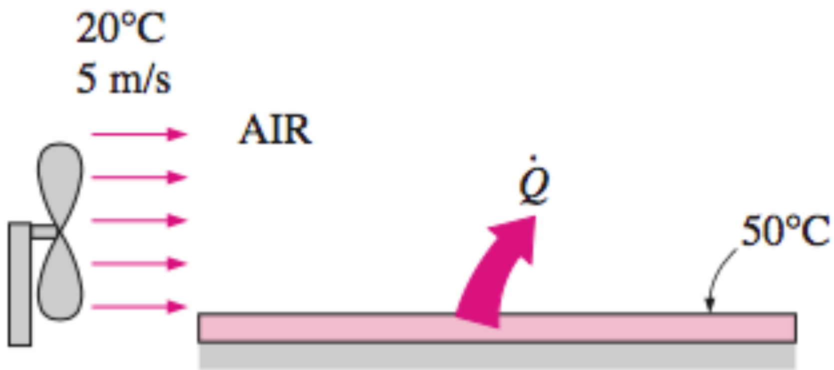
An application of Newton's law of cooling

where T_{fluid} = fluid temperature far enough not to be affected by $T_{surface}$

h_{conv} = convective heat transfer coefficient [W/(m^2·K)] or [BTU/(hr·ft^2·°F)]

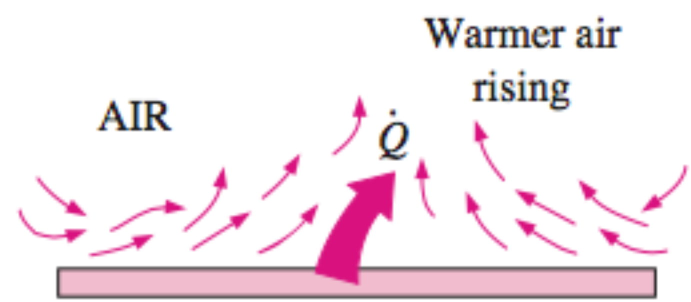
and $R_{conv} = \dfrac{1}{h_{conv}}$ = convective thermal resistance [(m^2·K)/W] or [(hr·ft^2·°F)/BTU]

Two types of convective heat transfer



(*a*) Forced convection

$$\rho = \frac{n}{V} MW = \frac{P}{RT} MW \qquad T \downarrow \rho \uparrow \qquad T \uparrow \rho \downarrow$$



(*b*) Free convection

Typical convective surface resistances

- We often use the values 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 $h·ft^2·°F/Btu$ (IP)	0.11 m^2K/W (SI) 0.62 $h·ft^2·°F/Btu$ (IP)	0.16 m^2K/W (SI) 0.91 $h·ft^2·°F/Btu$ (IP)
R_{out}: 6.7 m/s wind (Winter)		0.030 m^2K/W (SI) 0.17 $h·ft^2·°F/Btu$ (IP)	
R_{out}: 3.4 m/s wind (Summer)		0.044 m^2K/W (SI) 0.25 $h·ft^2·°F/Btu$ (IP)	

We can still sum resistances in series,
even if it involves different modes of heat transfer

Bulk convective heat transfer: Advection

- Finally, there is one last type of convection
- 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 fluid flow (e.g., air or water)
- Fluids, such as air, have the capacity to store heat, so fluids flowing into or out of a control volume also carry heat with it

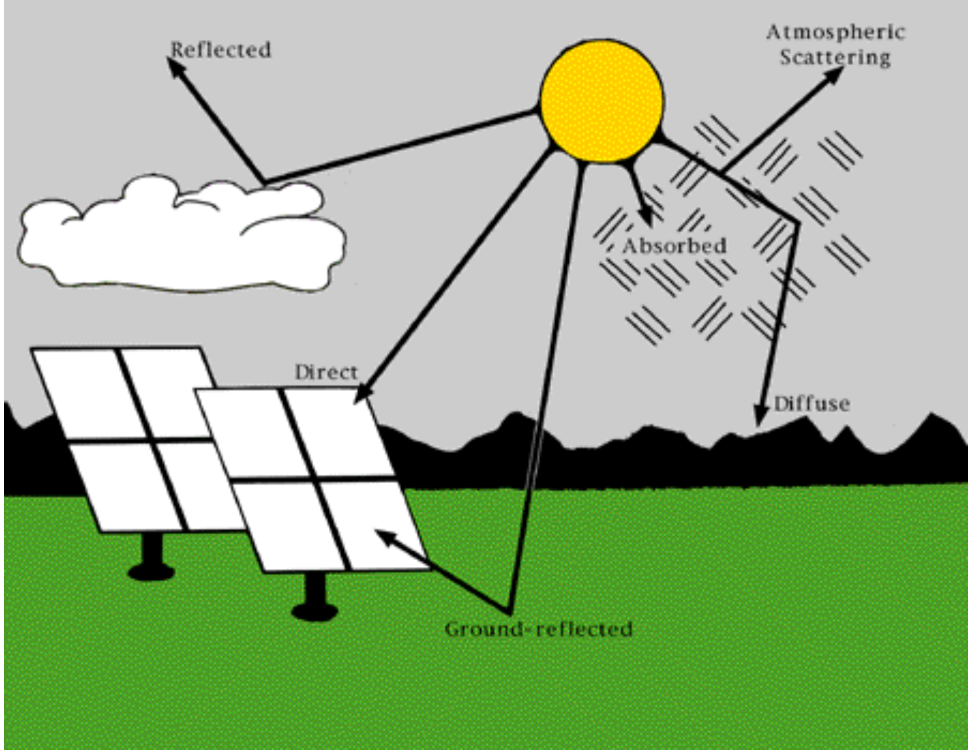
$$Q_{bulk} = \dot{m} C_p \Delta T \qquad [W] = [\frac{kg}{s} \cdot \frac{J}{kg \cdot K} \cdot K]$$

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

Components of solar radiation

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

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



Solar radiation:
(opaque surface)

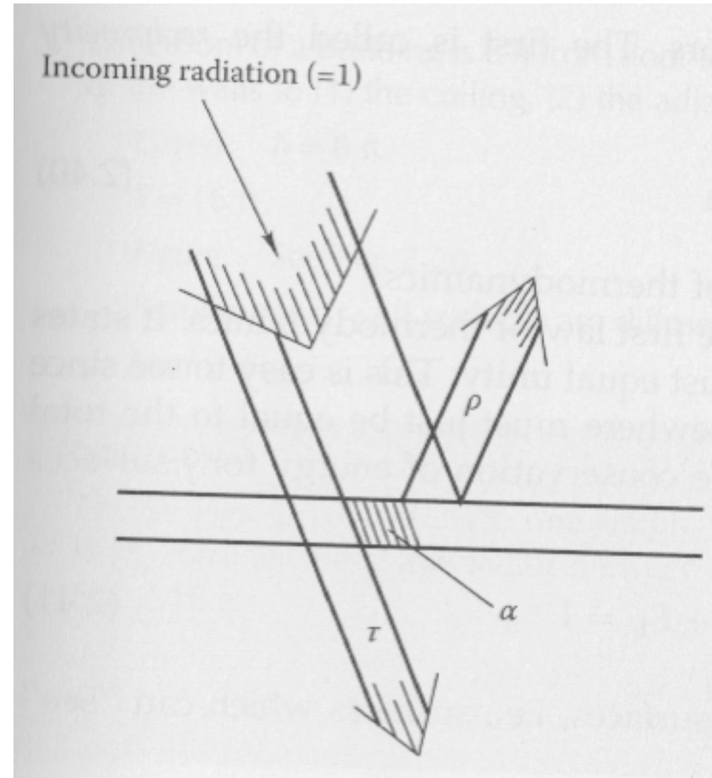
$$q_{solar} = \alpha I_{solar}$$

Transmitted solar radiation:
(transparent surface)

$$q_{solar} = \tau I_{solar}$$

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 ($\tau > 0$): $q_{solar} = \tau I_{solar}$

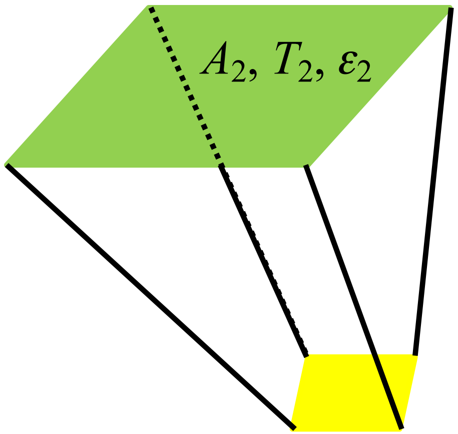


$$\alpha + \tau + \rho = 1$$

Long-wave radiation heat transfer (surface-to-surface)

- We can write the net thermal 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

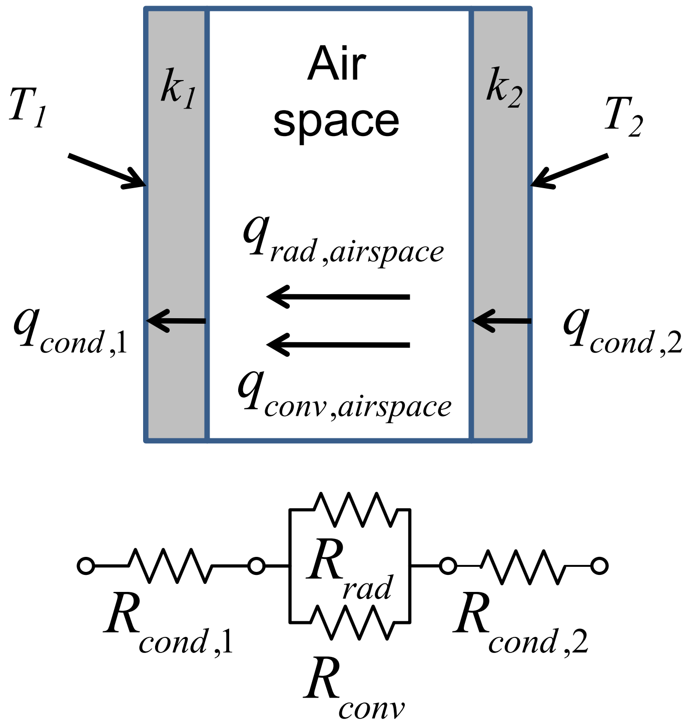
and $F_{1\to 2}$ is the view factor from surface 1 to 2

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

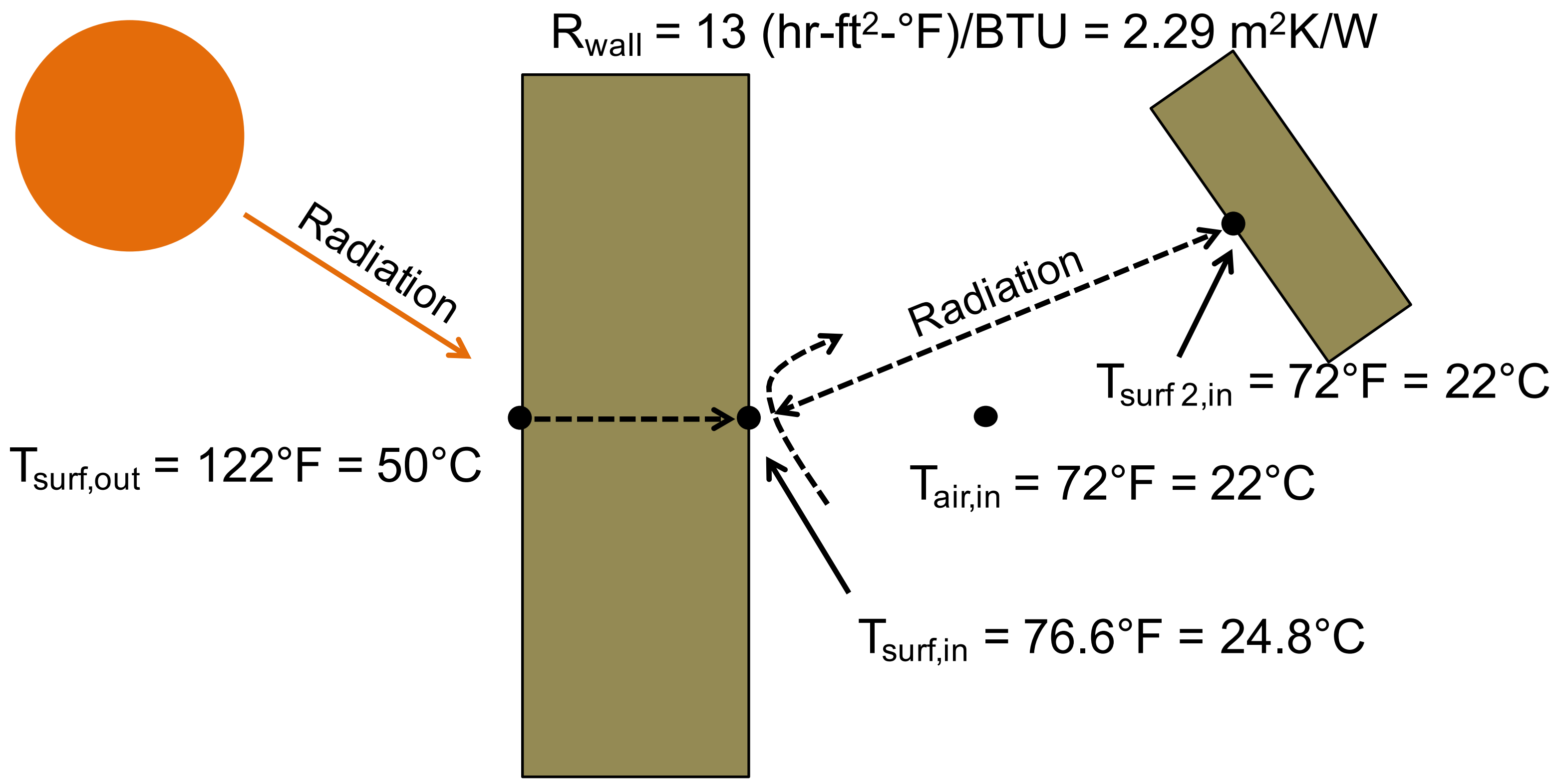
Or: $$Q_{1\to 2} = \varepsilon_{surf} A_{surf} \sigma F_{12}\left(T_1^4 - T_2^4\right)$$

Combined heat transfer

- When more than one mode of heat transfer exists at a location (usually convection + radiation), resistances get placed in parallel
  - Example: Heat transfer in a building cavity



Surface energy balances and combined heat transfer



Sol-air temperatures

- If we take an external surface with a combined convective and radiative heat transfer coefficient, $h_{conv+rad}$

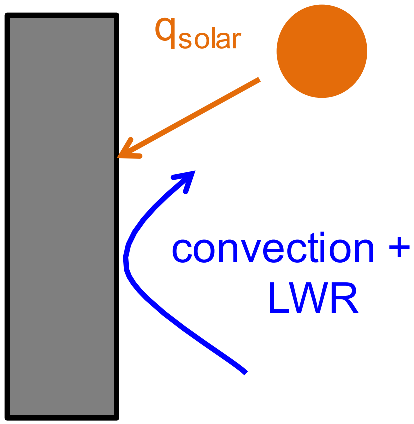
$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right)$$

- 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:

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

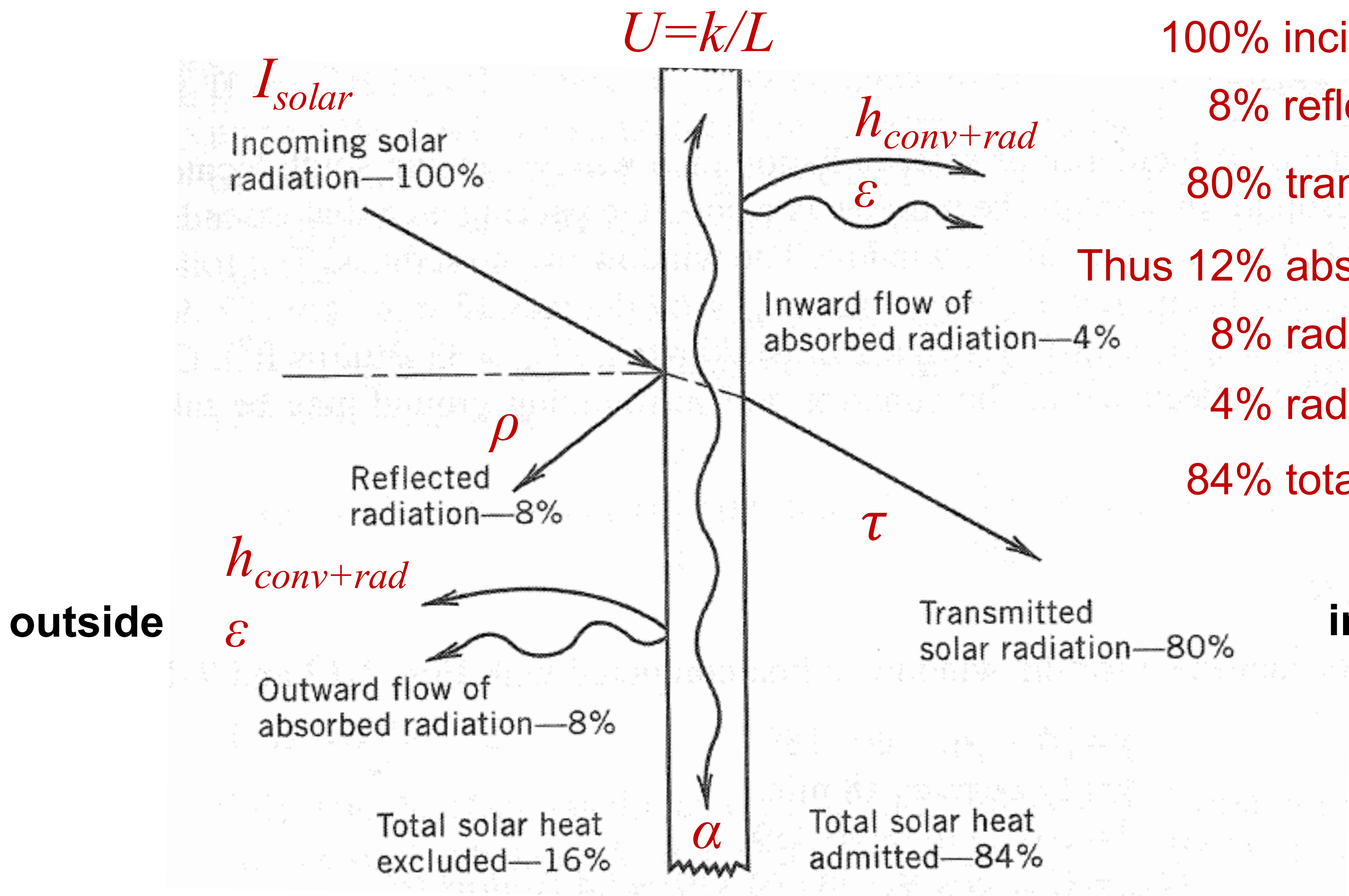


- Now we can describe heat transfer at that surface as:

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

Solar radiation and windows (i.e., fenestration)

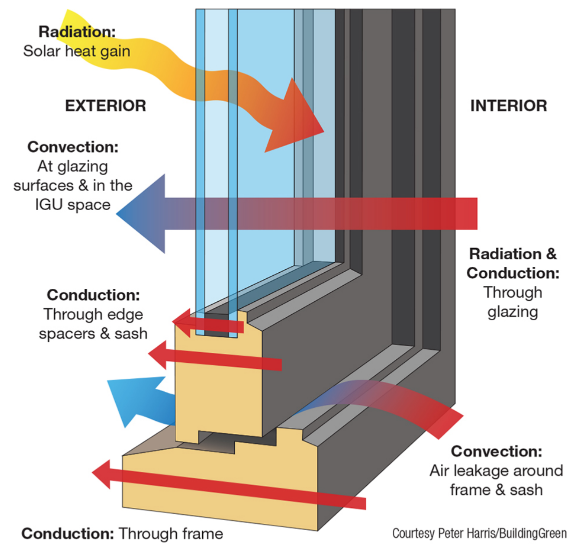
- Solar radiation through a single glaze



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

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^{2}K

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

Summary: Modes of heat transfer in a building

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

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

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

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

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

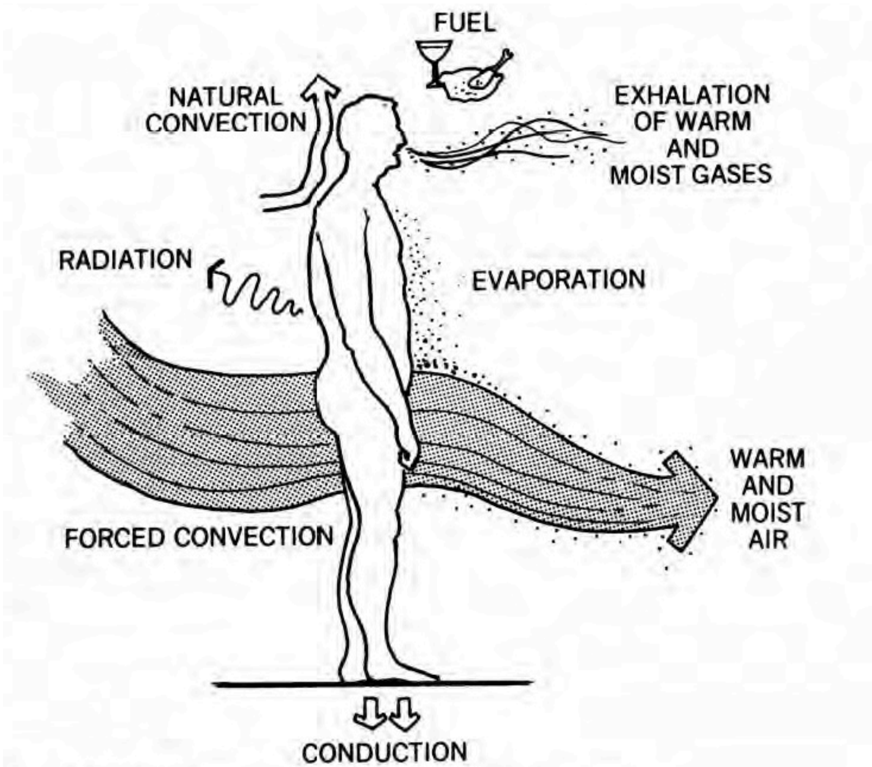
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

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

Window (combined modes)

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

Human thermal comfort



$$\dot{Q} = MA_{skin}$$

$$1\text{ met} = 18.4\frac{\text{Btu}}{\text{h}\cdot\text{ft}^2} = 58\frac{\text{W}}{\text{m}^2}$$

$$\dot{Q} + \dot{W} = MA_{skin} \approx (1\text{ met})(1.8\text{ m}^2)$$

$$\approx (58.2\ \frac{\text{W}}{\text{m}^2})(1.8\text{ m}^2) \approx 100\text{ W } (\pm 20\text{ W})$$

-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

Key terms/resources:

- MRT
- PMV and PPD
- Operative temperatures
- ASHRAE Std 55 comfort zone

https://ssb2012emilyashby.files.wordpress.com/2012/10/metabolism.jpg
http://www.theseus-fe.com/images/thermal-manikin/manikinBoundaryConditions_big.JPG

Key terms for describing moist air: Psychrometrics

1. Ideal gas law
2. Dry bulb temperature
3. Vapor pressure
4. Saturation (and saturation vapor pressure)
5. Relative humidity
6. Absolute humidity (or humidity ratio)
7. Dew point temperature
8. Wet bulb temperature
9. Enthalpy
10. Density
11. Specific volume

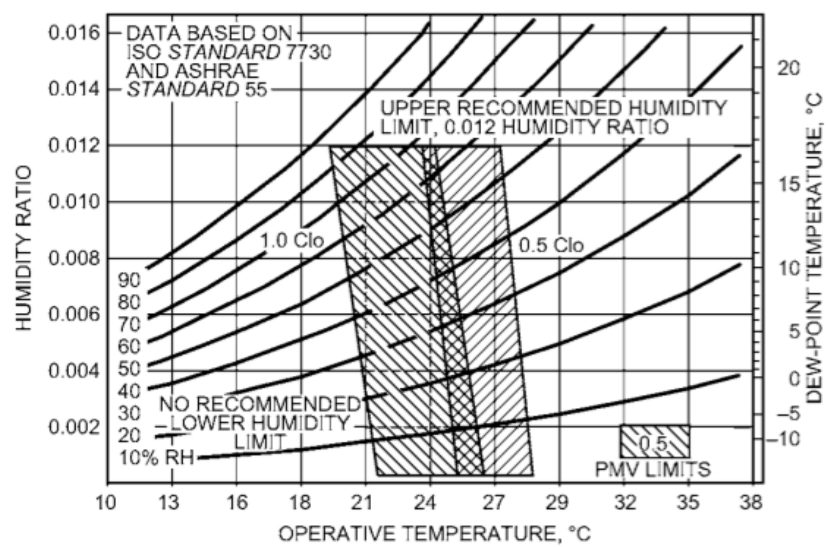
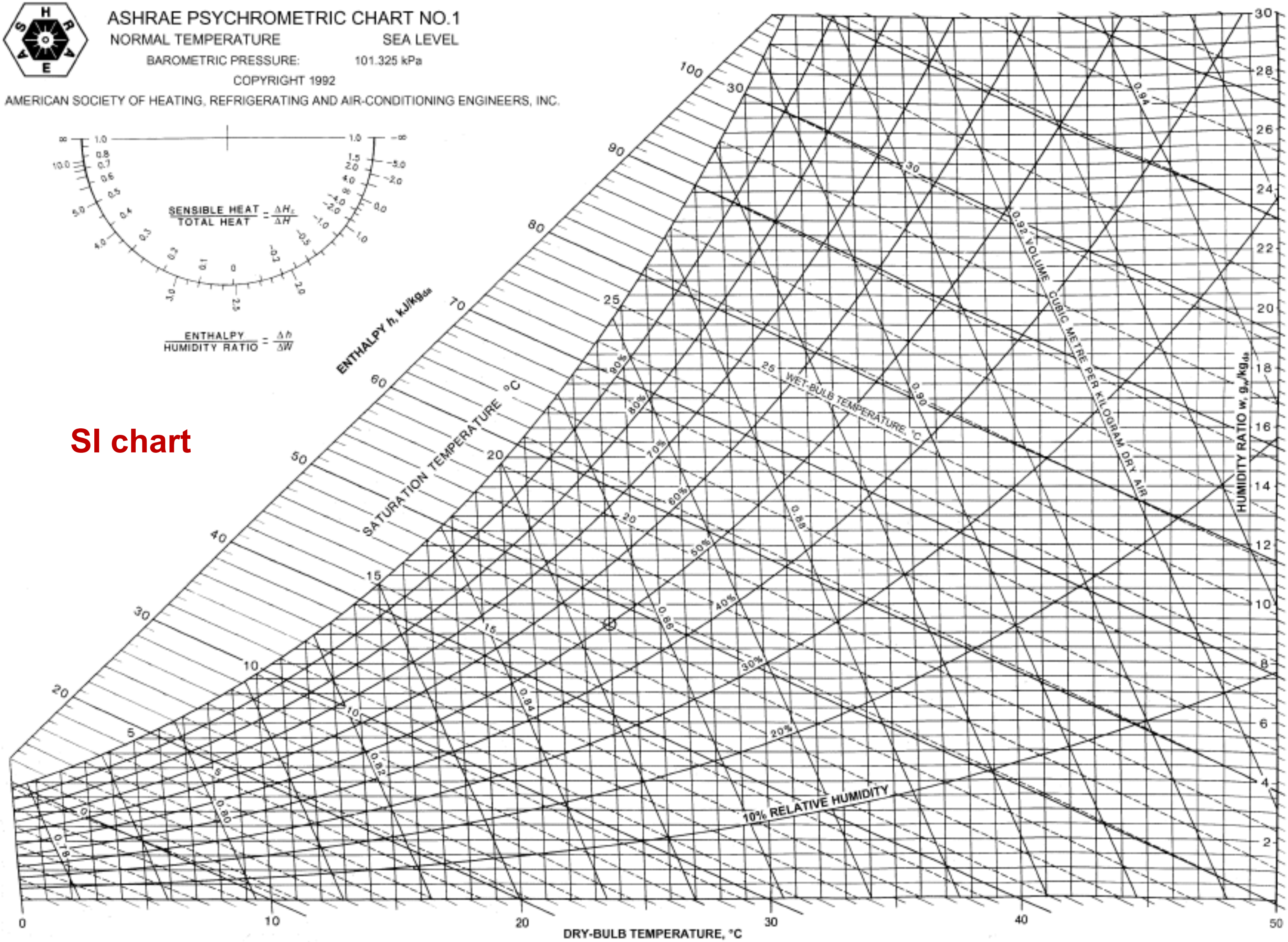
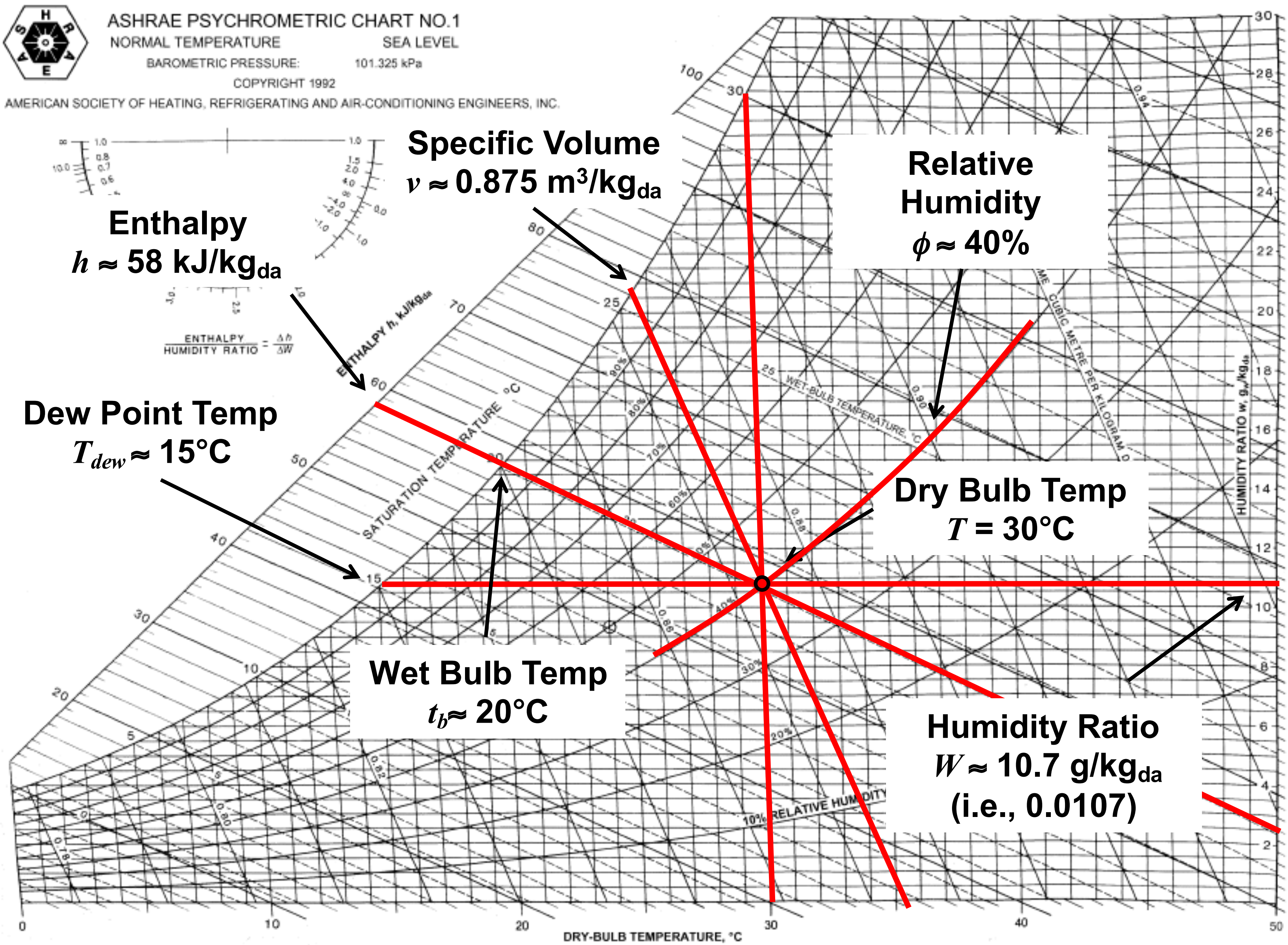
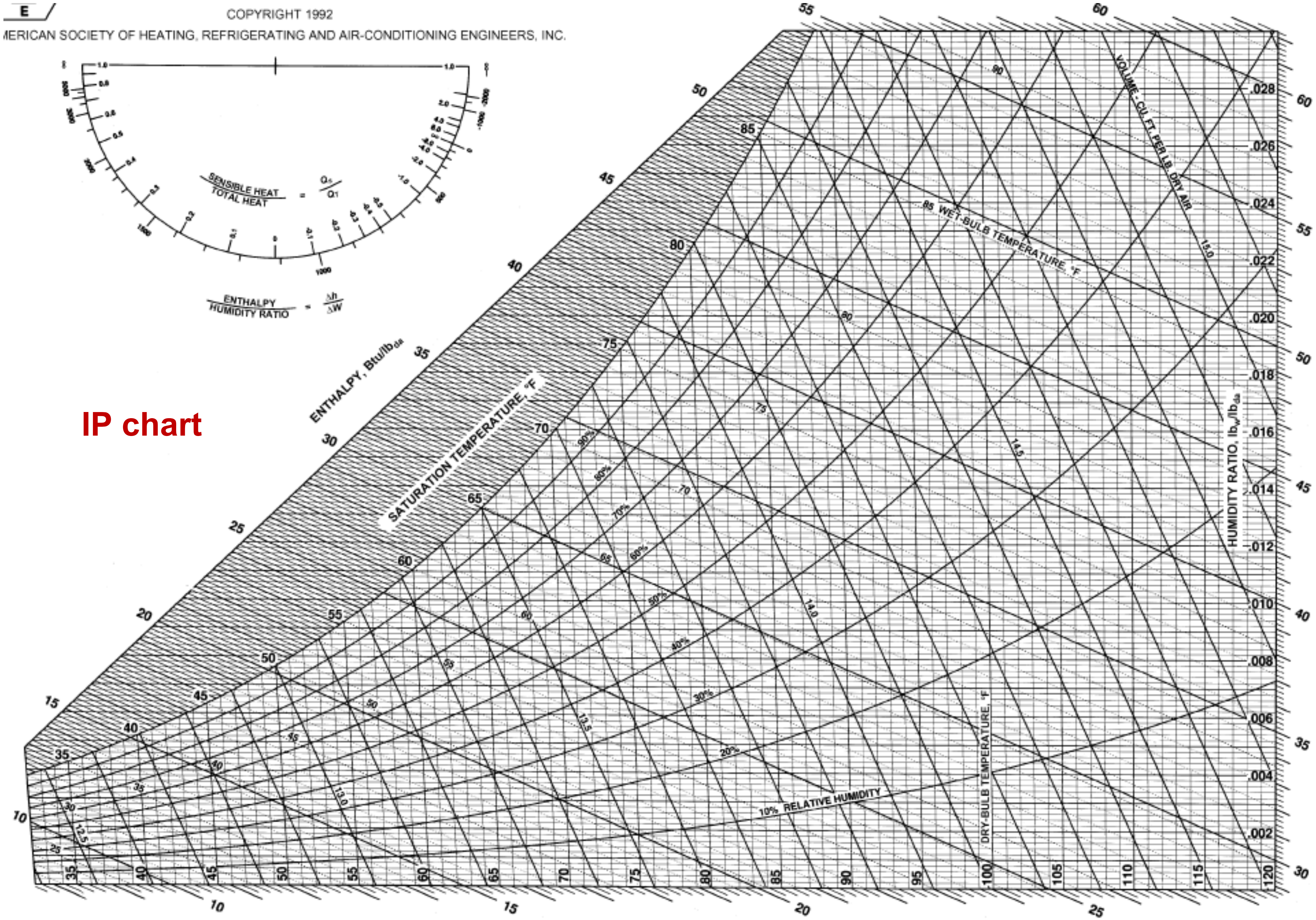


Fig. 5 ASHRAE Summer and Winter Comfort Zones
[Acceptable ranges of operative temperature and humidity with air speed ≤ 0.2 m/s for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤1.1 met)].



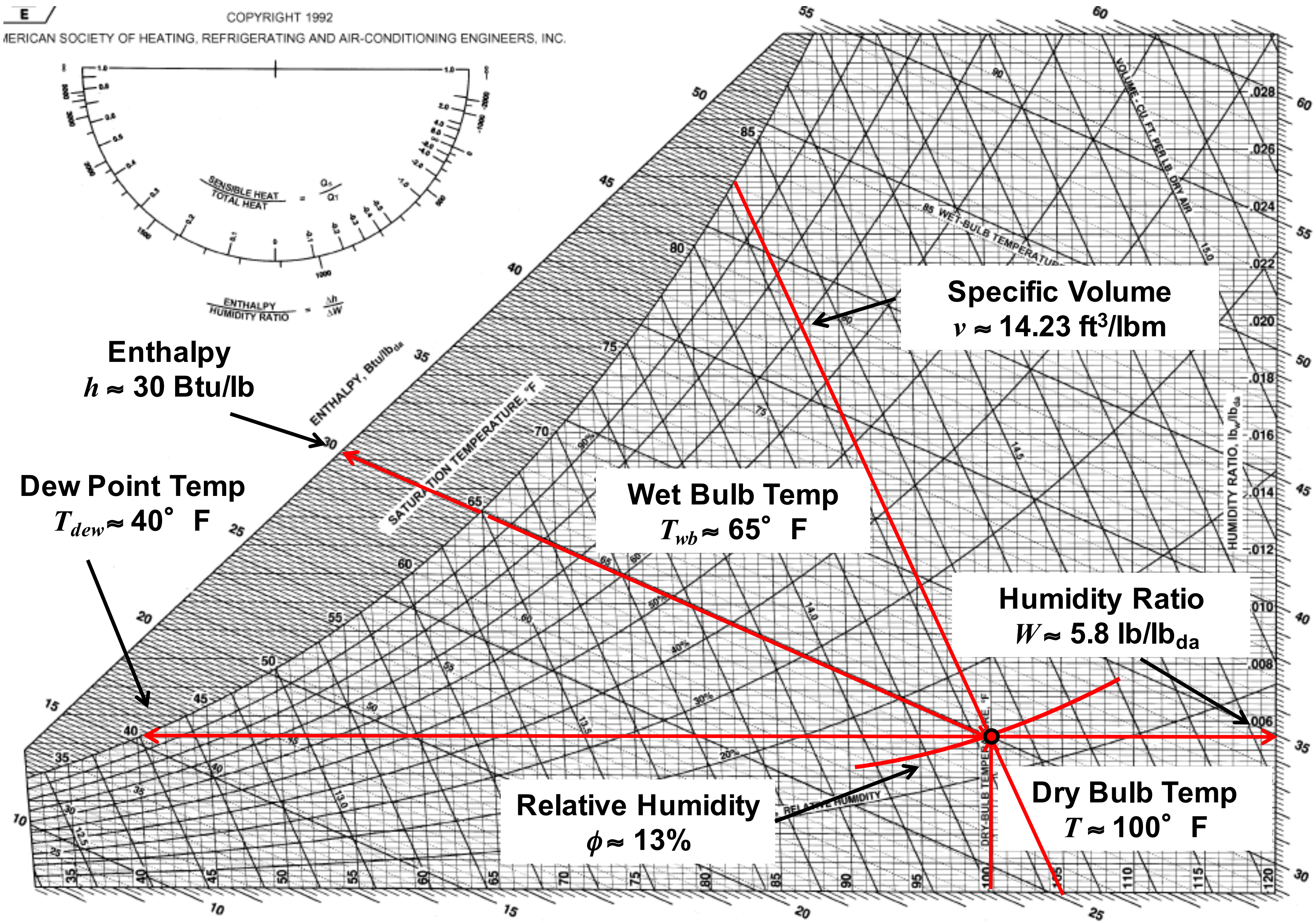
ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
COPYRIGHT 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
SI chart
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
COPYRIGHT 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
Specific Volume
$v \approx$ 0.875 m^3/kg$_{da}$
Relative Humidity
$\phi \approx$ 40%
Enthalpy
$h \approx$ 58 kJ/kg$_{da}$
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg$_{da}$
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
CUBIC METRE PER KILOGRAM DRY AIR
Dew Point Temp
$T_{dew} \approx$ 15°C
Dry Bulb Temp
T = 30°C
Wet Bulb Temp
$t_b \approx$ 20°C
Humidity Ratio
$W \approx$ 10.7 g/kg$_{da}$
(i.e., 0.0107)
10% RELATIVE HUMIDITY
HUMIDITY RATIO W, g$_w$/kg$_{da}$
DRY-BULB TEMPERATURE, °C



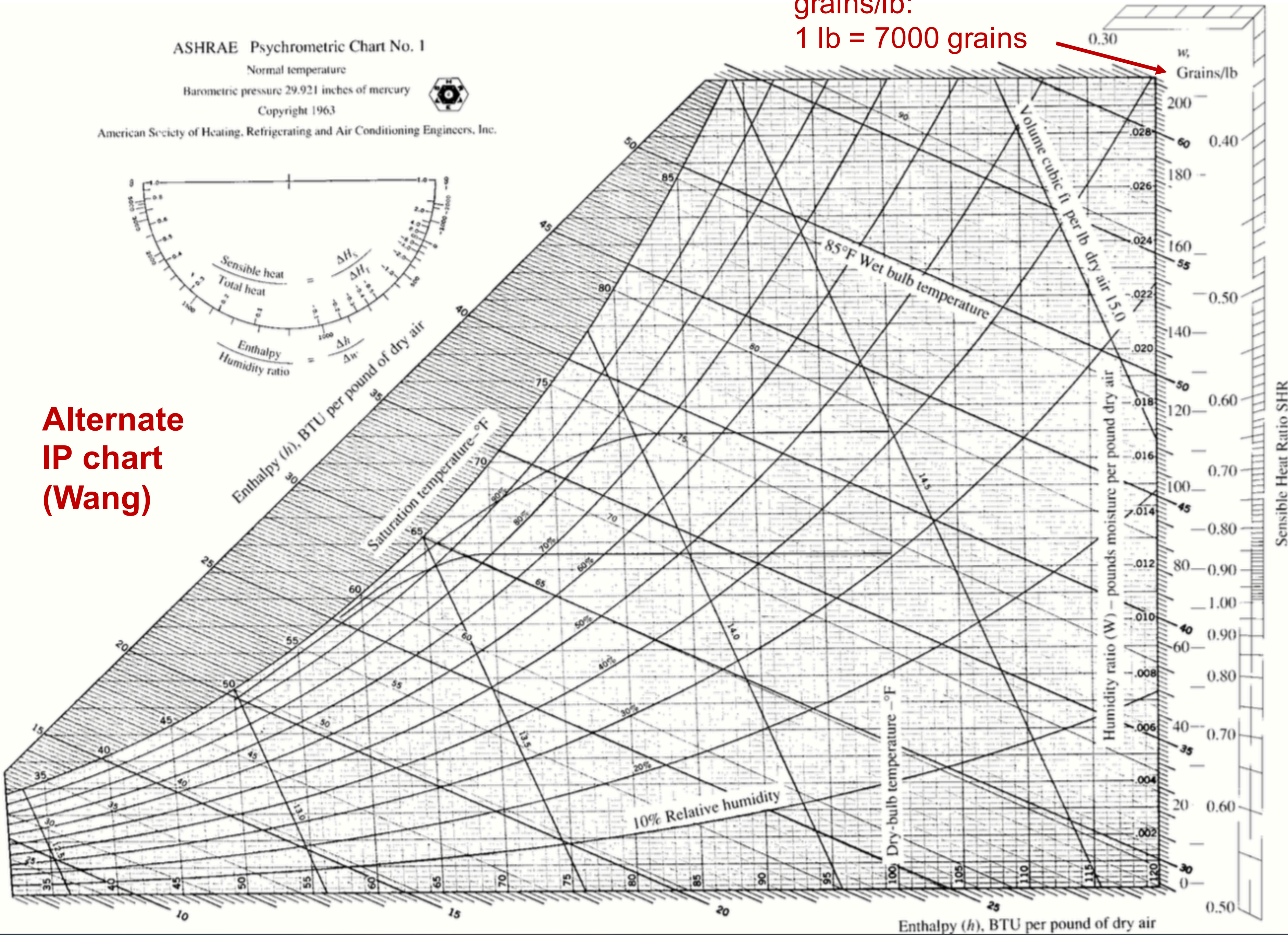
COPYRIGHT 1992
MERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb_w/lb_da
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY

IP chart


COPYRIGHT 1992
MERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Enthalpy
h ≈ 30 Btu/lb
ENTHALPY, Btu/lb da
SATURATION TEMPERATURE, °F
Dew Point Temp
T_dew ≈ 40° F
Specific Volume
v ≈ 14.23 ft³/lbm
85 WET-BULB TEMPERATURE
VOLUME - CU.FT. PER LB. DRY AIR
Wet Bulb Temp
T_wb ≈ 65° F
HUMIDITY RATIO, lb_w/lb_da
Humidity Ratio
W ≈ 5.8 lb/lb_da
Relative Humidity
φ ≈ 13%
RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Dry Bulb Temp
T ≈ 100° F

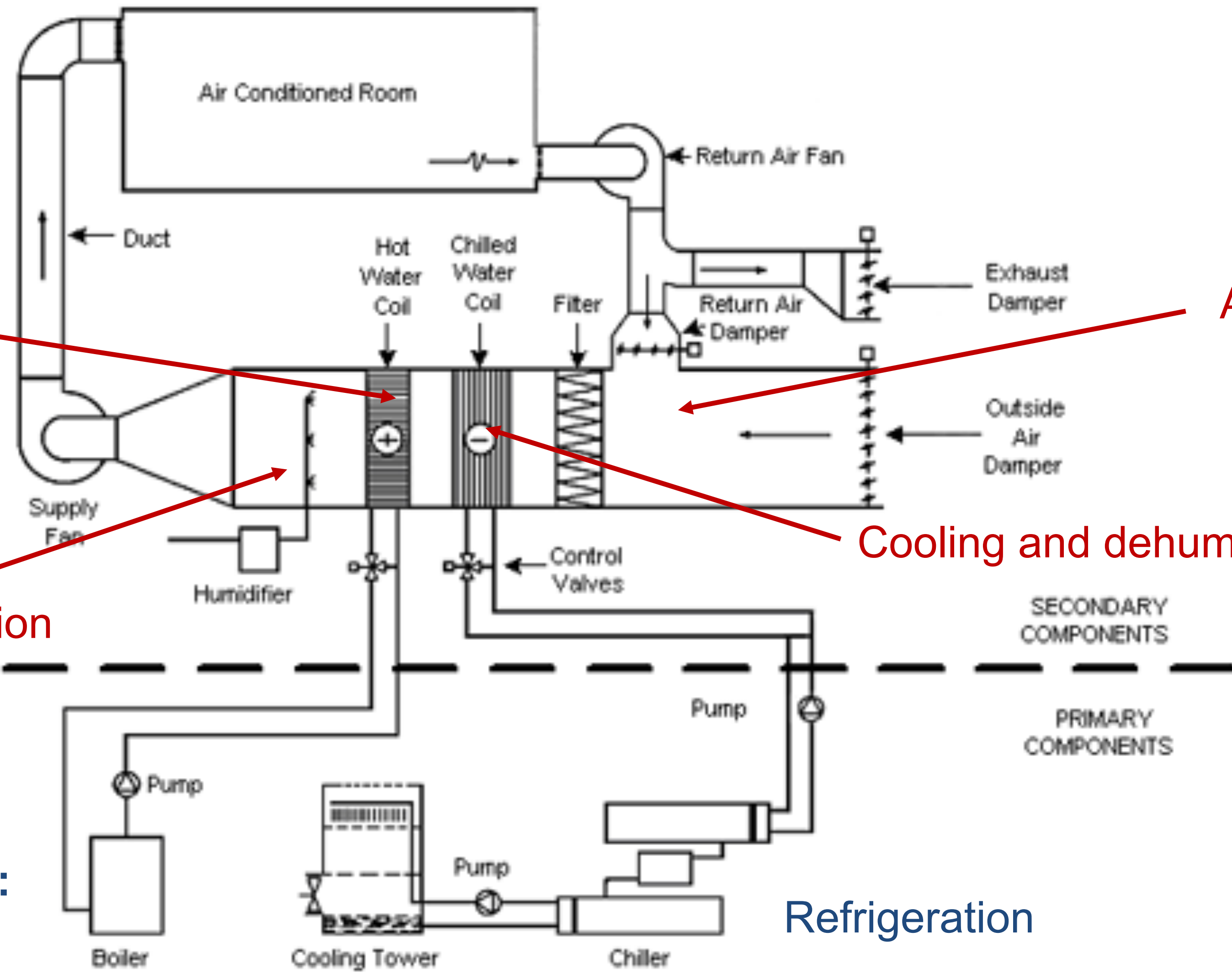
grains/lb:
1 lb = 7000 grains

Alternate IP chart (Wang)



Primary and secondary components of HVAC

Some common psychrometric processes:



Heating

Air mixing

Cooling and dehumidification

Humidification

Common primary processes:

Heat generation

Refrigeration

Use of the psychrometric chart for *processes*

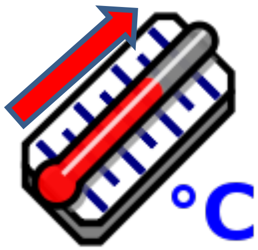
We can use the psychrometric chart (and equations) not only to describe states of moist air, but for a number of **processes** that are important for building science and HVAC applications

Examples:

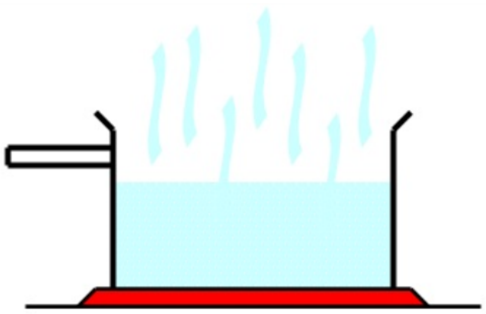
- Sensible cooling or heating
- Warming and humidification of cold, dry air
- Cooling and dehumidification of warm, humid air
  - Sensible + latent cooling
- Evaporative cooling
- Mixing of airstreams

Definitions: Sensible and latent heat

- **Sensible heat transfer**
  - Increase or decrease in temperature of a substance *without* undergoing a phase change



- **Latent heat transfer**
  - Heat transfer required to change the phase of a substance (e.g., heat required to change liquid to vapor)



$$Q_{total} = Q_{sensible} + Q_{latent}$$

Units of [W], [BTU/hr], or [ton]

Sensible and latent heat transfer equation

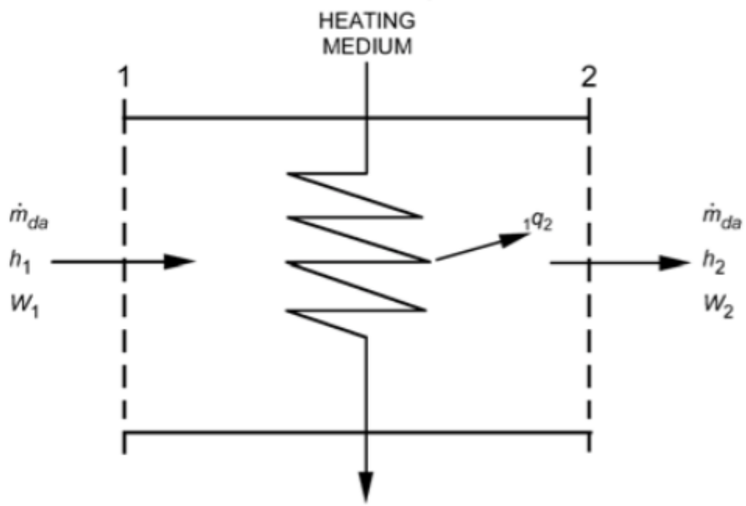


Fig. 2 Schematic of Device for Heating Moist Air

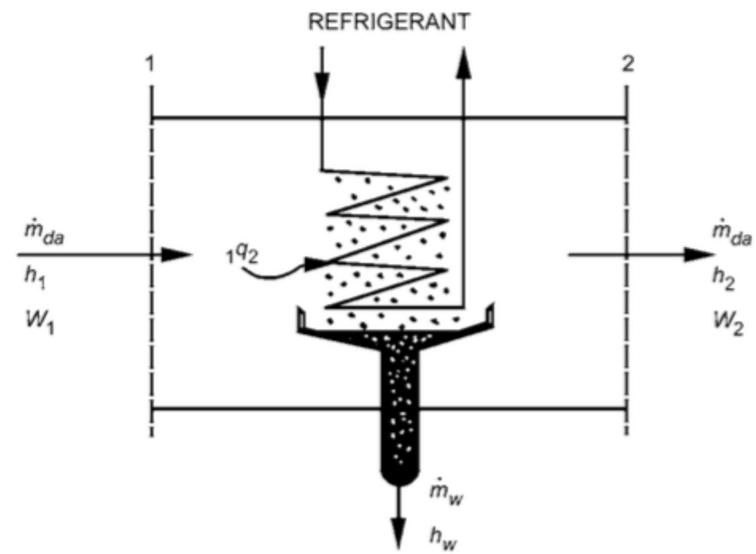


Fig. 3 Schematic of Device for Cooling Moist Air

Generic equations for both heating and cooling processes:

$$Q_{1\rightarrow 2} = \dot{m}_{da}(h_2 - h_1) \qquad Q_{total} = \dot{m}\,(h_{exit} - h_{inlet})$$

$Q_{1\rightarrow 2}$ = total rate of heat transfer from 1 to 2 (W or BTU/hr or ton)
$\dot{m}_{da}$ = mass flow rate of dry air (kg_{da}/s or lb_{da}/hr)
$h_{exit,2}$ = enthalpy at the exit (J/kg_{da} or BTU/lb_{da})
$h_{inlet,1}$ = enthalpy at the inlet (J/kg_{da} or BTU/lb_{da})

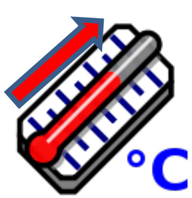
Sensible heat transfer equation

$$Q_{sensible} = \dot{m}_{da} C_p (T_{exit} - T_{inlet}) = \dot{V}_{da} \rho_{da} C_p (T_{exit} - T_{inlet})$$

$Q_{sensible}$ = rate of sensible heat transfer (W or BTU/hr or ton)
C_p = specific heat of air (J/kgK or BTU/lb°F)
ρ_{da} = dry air density (kg/m^3 or lb/ft^3)
T_{inlet} = inlet temperature (K or °F)
T_{exit} = exit temperature (K or °F)

For heating: $Q_{sensible} > 0$

For cooling: $Q_{sensible} < 0$



Latent heat transfer equation

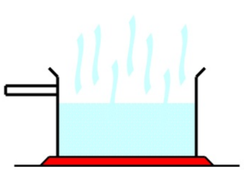
$$Q_{latent} = \dot{m}_w h_{fg}$$

$$Q_{latent} = \dot{m}_{da}(W_{exit} - W_{inlet})h_{fg} = \dot{V}_{da}\rho_{da}\,(W_{exit} - W_{inlet})\,h_{fg}$$

Q_{latent} = rate of latent heat transfer (W or BTU/hr or ton)
m_w = mass flow rate of water vapor (kg_w/s or lb_w/hr)
h_{fg} = enthalpy, or latent heat, of vaporization (J/kg or BTU/lb)
* h_{fg} = 2260 kJ/kg or 970 BTU/lb for water
W_{inlet} = inlet humidity ratio (kg_w/kg_{da} or lb_w/lb_{da})
W_{exit} = exit humidity ratio (kg_w/kg_{da} or lb_w/lb_{da})

For humidification: $Q_{latent} > 0$

For dehumidification: $Q_{latent} < 0$

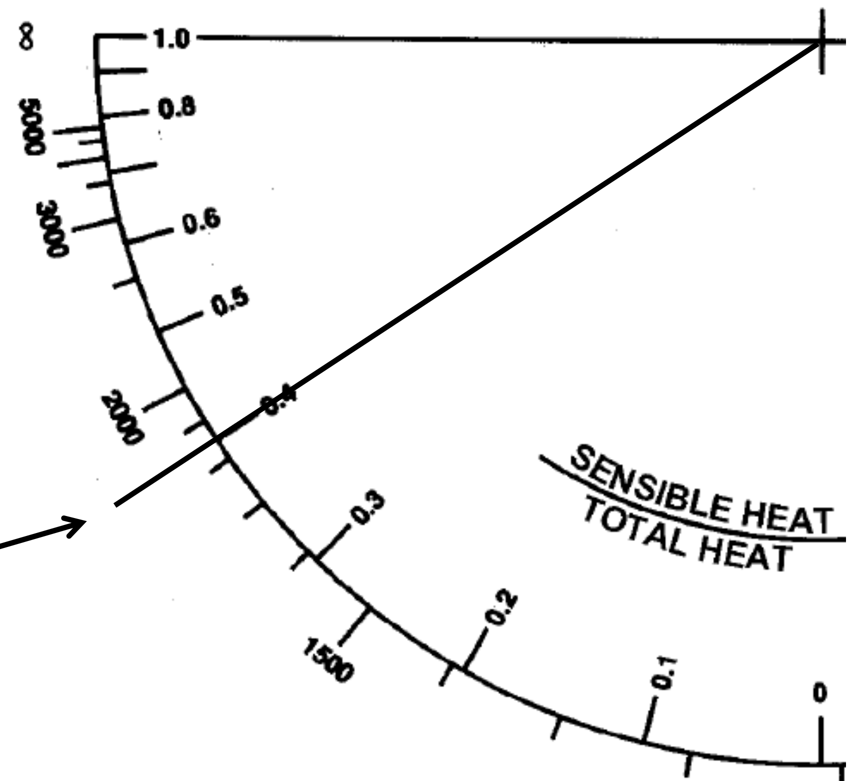


Sensible heat ratio (SHR)

- The **sensible heat ratio** is defined as:

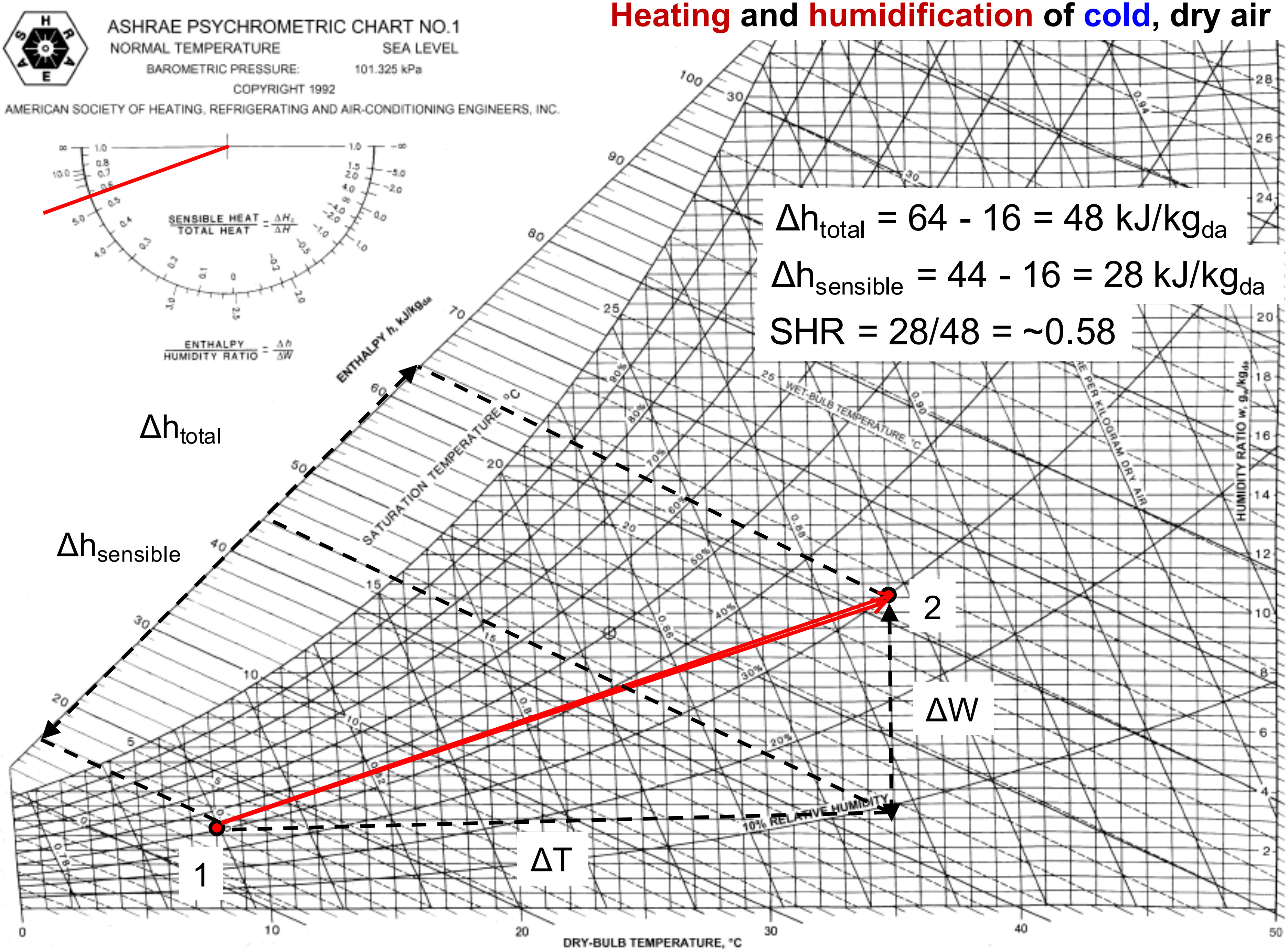
$$SHR = \frac{\dot{q}_{sens}}{\dot{q}_{total}} = \frac{\dot{q}_{sens}}{\dot{q}_{sens} + \dot{q}_{latent}} = \frac{\Delta h_{sens}}{\Delta h_{total}}$$

- Allows for understanding sensible load relative to latent load



Here is a process with an SHR ≈ 0.4

Heating and humidification of cold, dry air

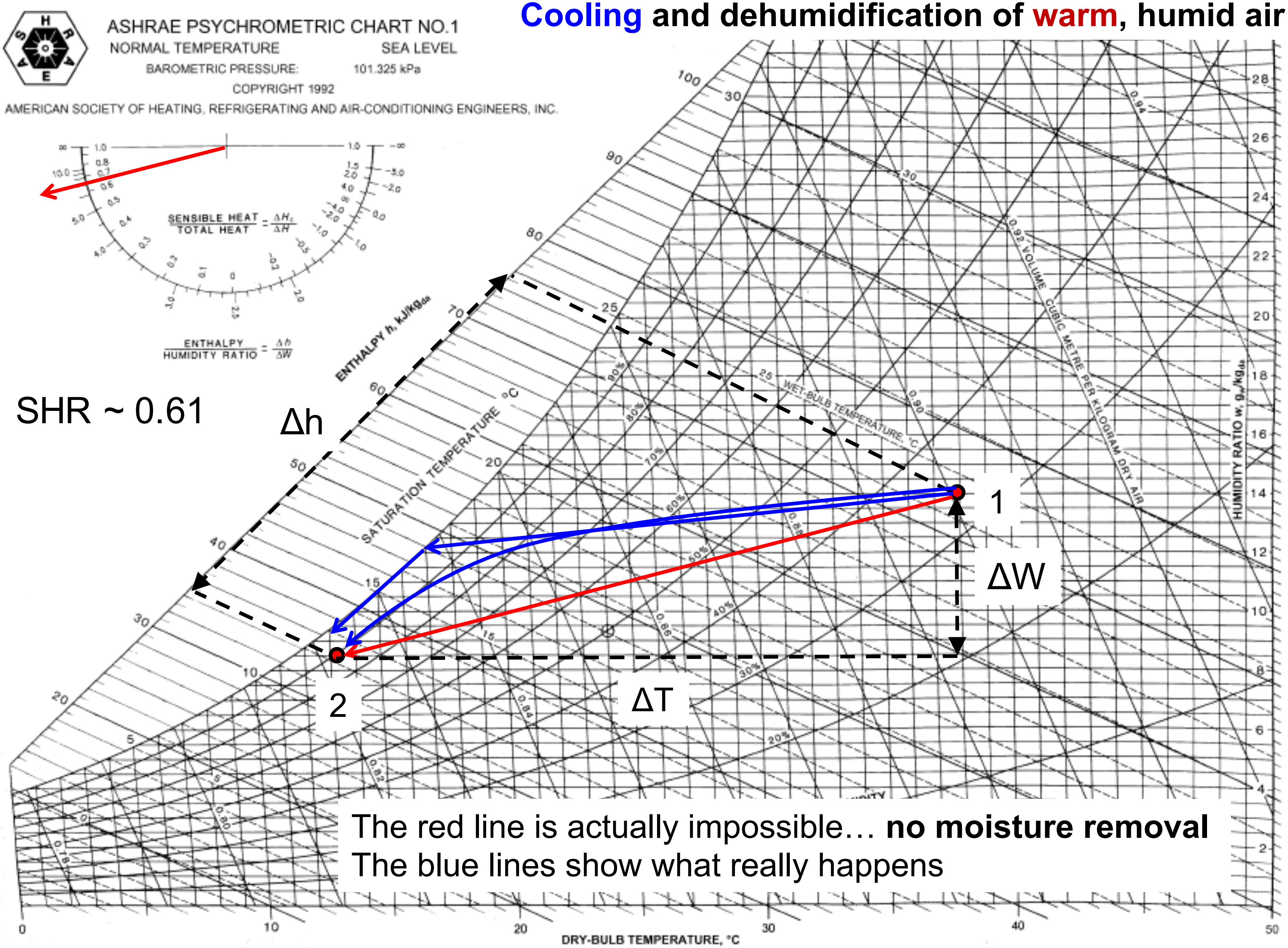


$\Delta h_{total} = 64 - 16 = 48\ kJ/kg_{da}$

$\Delta h_{sensible} = 44 - 16 = 28\ kJ/kg_{da}$

$SHR = 28/48 = \sim 0.58$

Cooling and dehumidification of warm, humid air

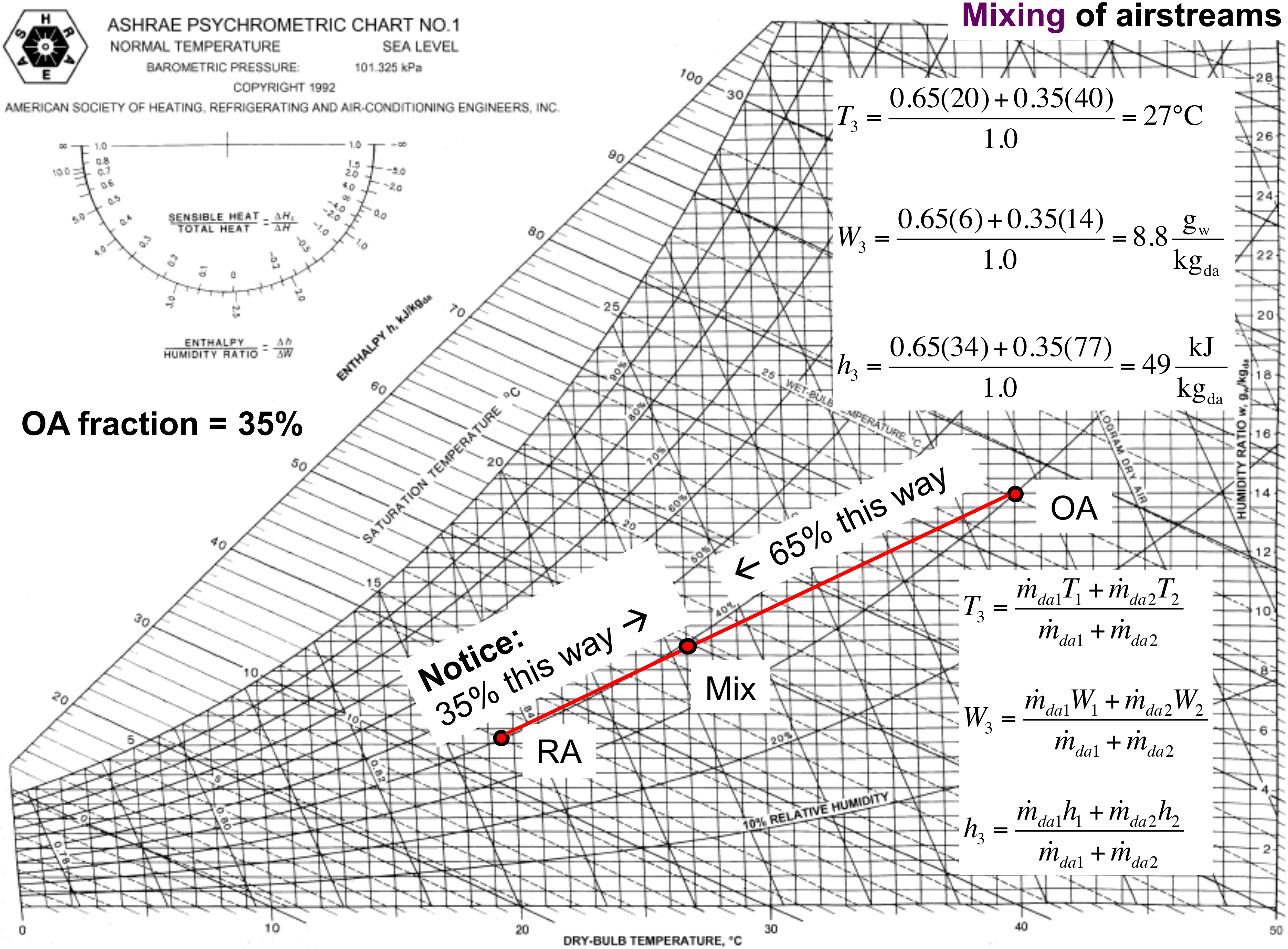


The red line is actually impossible… **no moisture removal**

The blue lines show what really happens

Mixing of airstreams

OA fraction = 35%



$$T_3 = \frac{0.65(20) + 0.35(40)}{1.0} = 27°C$$

$$W_3 = \frac{0.65(6) + 0.35(14)}{1.0} = 8.8 \frac{g_w}{kg_{da}}$$

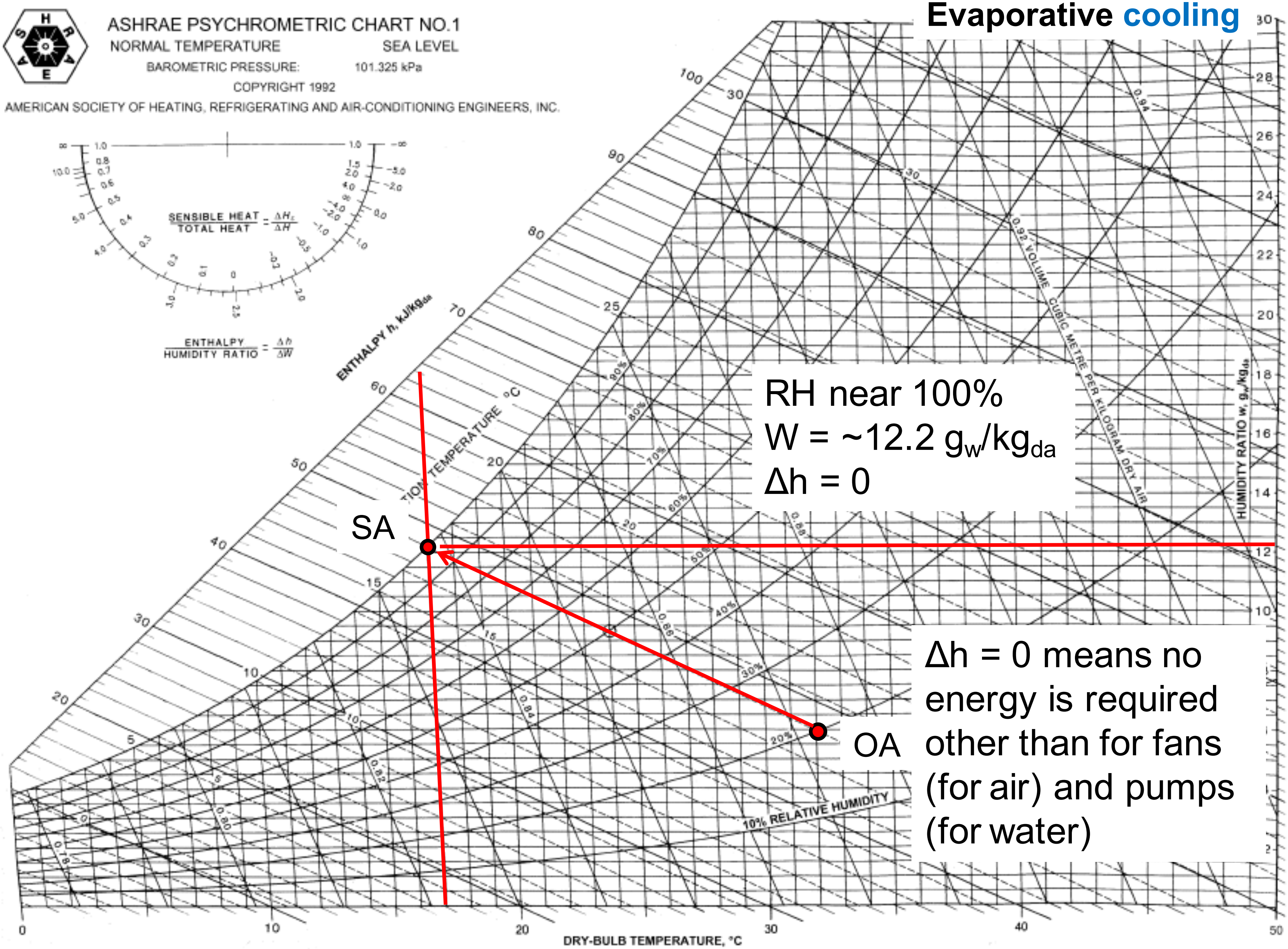
$$h_3 = \frac{0.65(34) + 0.35(77)}{1.0} = 49 \frac{kJ}{kg_{da}}$$

$$T_3 = \frac{\dot{m}_{da1} T_1 + \dot{m}_{da2} T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

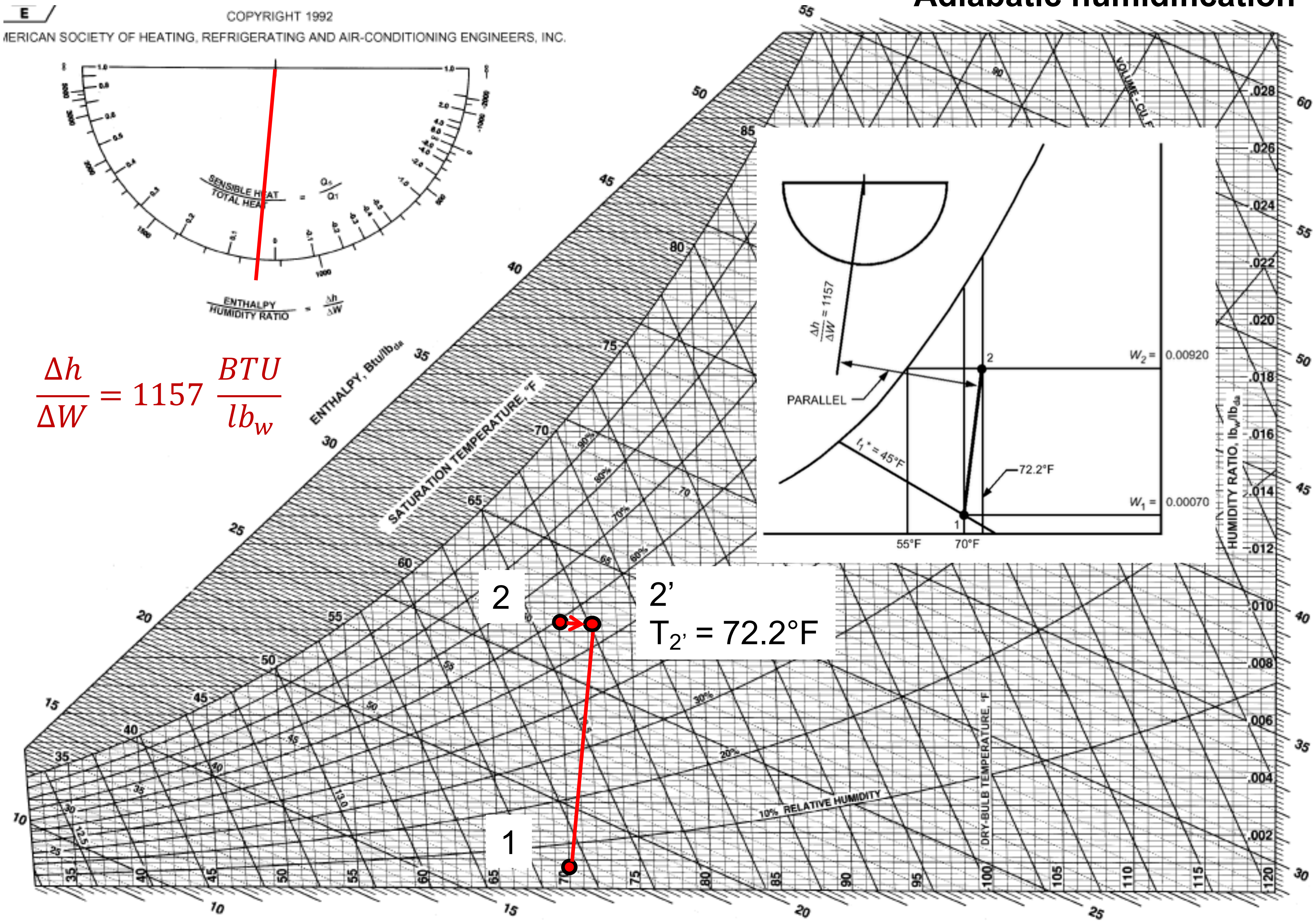
$$W_3 = \frac{\dot{m}_{da1} W_1 + \dot{m}_{da2} W_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

$$h_3 = \frac{\dot{m}_{da1} h_1 + \dot{m}_{da2} h_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

Evaporative cooling



Adiabatic humidification



$$\frac{\Delta h}{\Delta W} = 1157\ \frac{BTU}{lb_w}$$