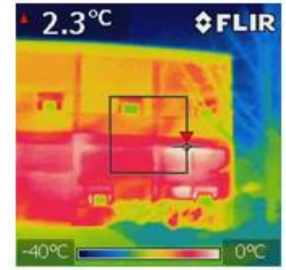
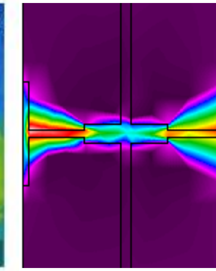
CAE 331/513
Building Science
Fall 2018





October 9, 2018
Psychrometric processes (part 1)

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Psychrometric equations summary (IP units)

$$pV = nRT$$

$$p = p_{da} + p_w$$

$$pv = \frac{p}{\rho} = RT$$

Humidity ratio:

$$W = 0.622\frac{p_w}{p - p_w}$$

RH:

$$\phi = \frac{p_w}{p_{ws}} \qquad R_i = \frac{R}{MW_i}$$

$$\rho = \frac{m_{da} + m_w}{V} = \frac{1}{v}(1 + W)$$

Air density

Saturation vapor pressure:

$$\ln p_{ws} = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T$$

where

C_8 = −1.044 039 7 E+04
C_9 = −1.129 465 0 E+01
C_{10} = −2.702 235 5 E−02
C_{11} = 1.289 036 0 E−05
C_{12} = −2.478 068 1 E−09
C_{13} = 6.545 967 3 E+00

p_{ws} = saturation pressure, psia
T = absolute temperature, °R = °F + 459.67

Dew point temperature:

Between dew points of 32 to 200°F,

$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984}$$

Below 32°F,

$$t_d = 90.12 + 26.142\alpha + 0.8927\alpha^2$$

where

t_d = dew-point temperature, °F
$\alpha = \ln p_w$
p_w = water vapor partial pressure, psia
C_{14} = 100.45
C_{15} = 33.193
C_{16} = 2.319
C_{17} = 0.17074
C_{18} = 1.2063

Psychrometric equations summary (IP units)

Wet bulb temperature (iterative solver):

$$W = \frac{(1093 - 0.556T_{wb})W_{s@T_{wb}} - 0.240(T - T_{wb})}{1093 + 0.444T - T_{wb}} \quad = \text{actual } W$$

*Where T_{wb} and T are in <u>Fahrenheit</u>

Specific volume:

$$v = \frac{R_{da}T}{p_{da}} = \frac{R_{da}T}{p_{tot} - p_w} = \frac{R_{da}T(1 + 1.6078W)}{p_{tot}}$$

$$v \approx 0.370486(T + 459.67)(1 + 1.6078W) / p_{tot}$$

where

v = specific volume, ft^3/lb_{da}
t = dry-bulb temperature, °F
W = humidity ratio, lb_w/lb_{da}
p = total pressure, psia

Specific enthalpy:

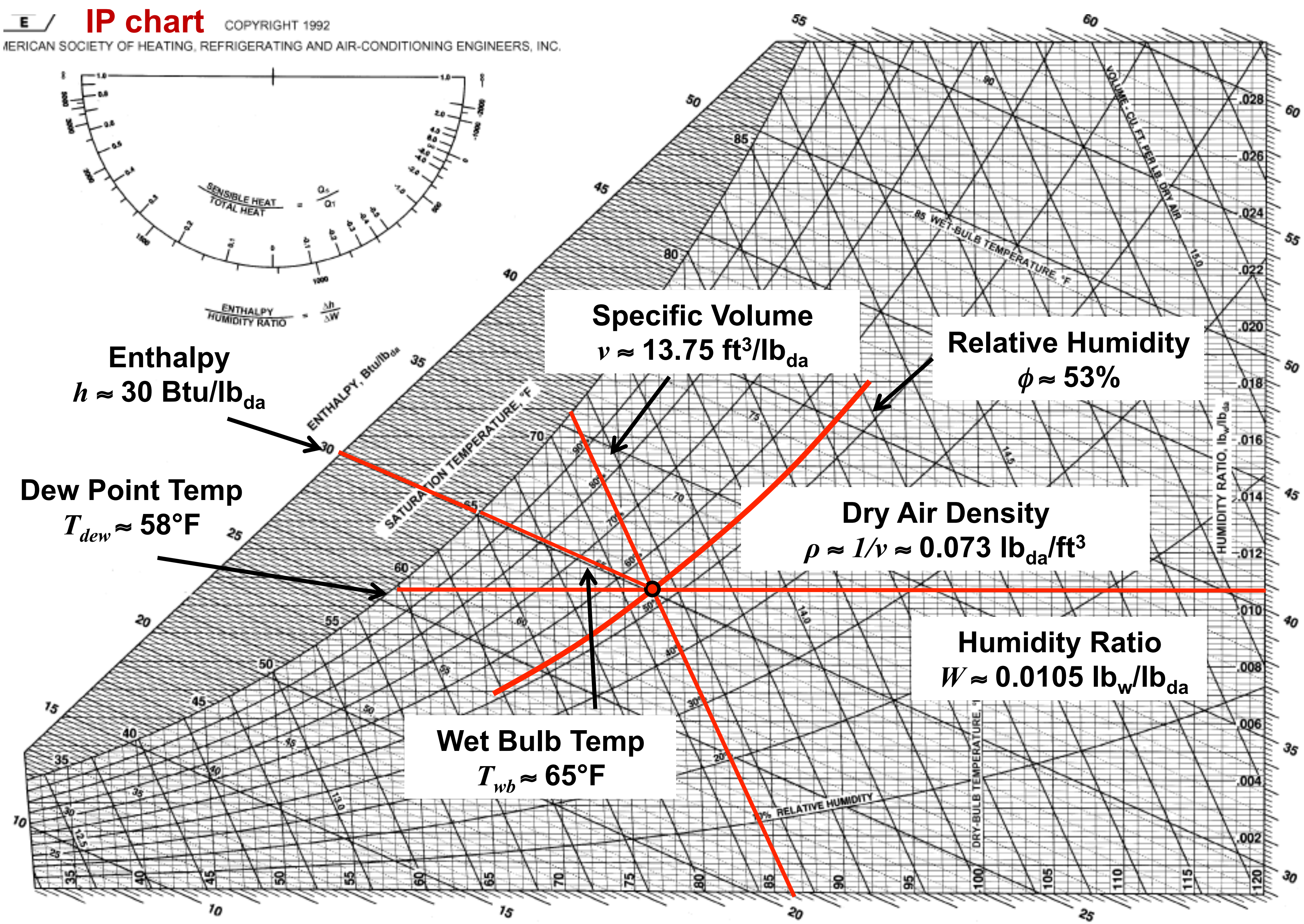
$$h \approx 0.24T + W(1061 + 0.444T)$$

*where T is in °F

Finish state points: Revisit classroom example

- Dry bulb temperature = 25°C = 77°F
- RH = 53%
- Sea level (14.696 psia)

Find all other relevant parameters using equations



IP chart
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SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb da
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °F
HUMIDITY RATIO, lbw/lbda
Enthalpy
$h \approx 30$ Btu/lb$_{da}$
Dew Point Temp
$T_{dew} \approx 58$°F
Specific Volume
$v \approx 13.75$ ft^3/lb$_{da}$
Relative Humidity
$\phi \approx 53\%$
Dry Air Density
$\rho \approx 1/v \approx 0.073$ lb$_{da}$/ft^3
Humidity Ratio
$W \approx 0.0105$ lb$_w$/lb$_{da}$
Wet Bulb Temp
$T_{wb} \approx 65$°F

Why is this stuff helpful?

PSYCHROMETRIC PROCESSES

Using the psychrometric chart

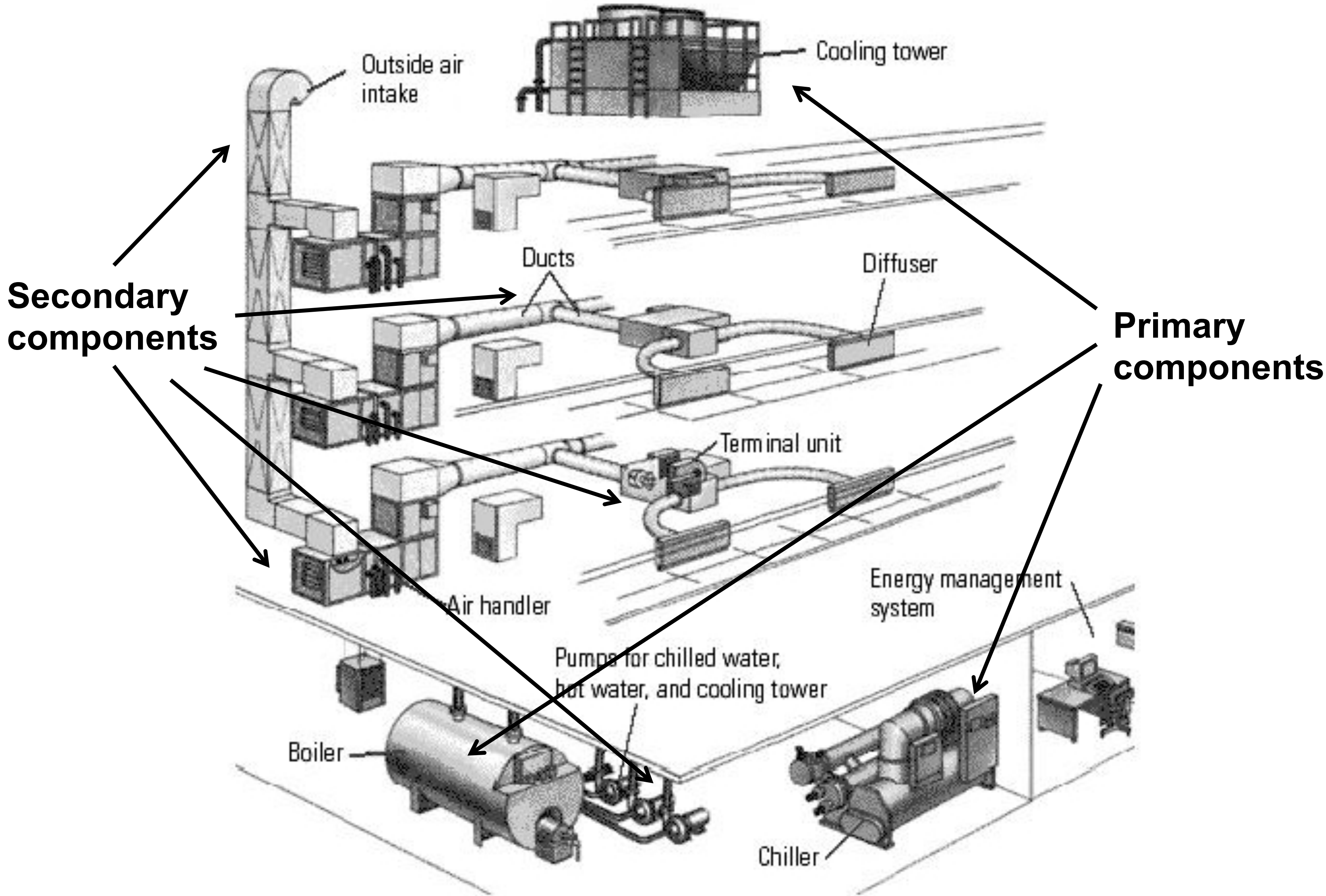
Use of the psychrometric chart for *processes*

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:

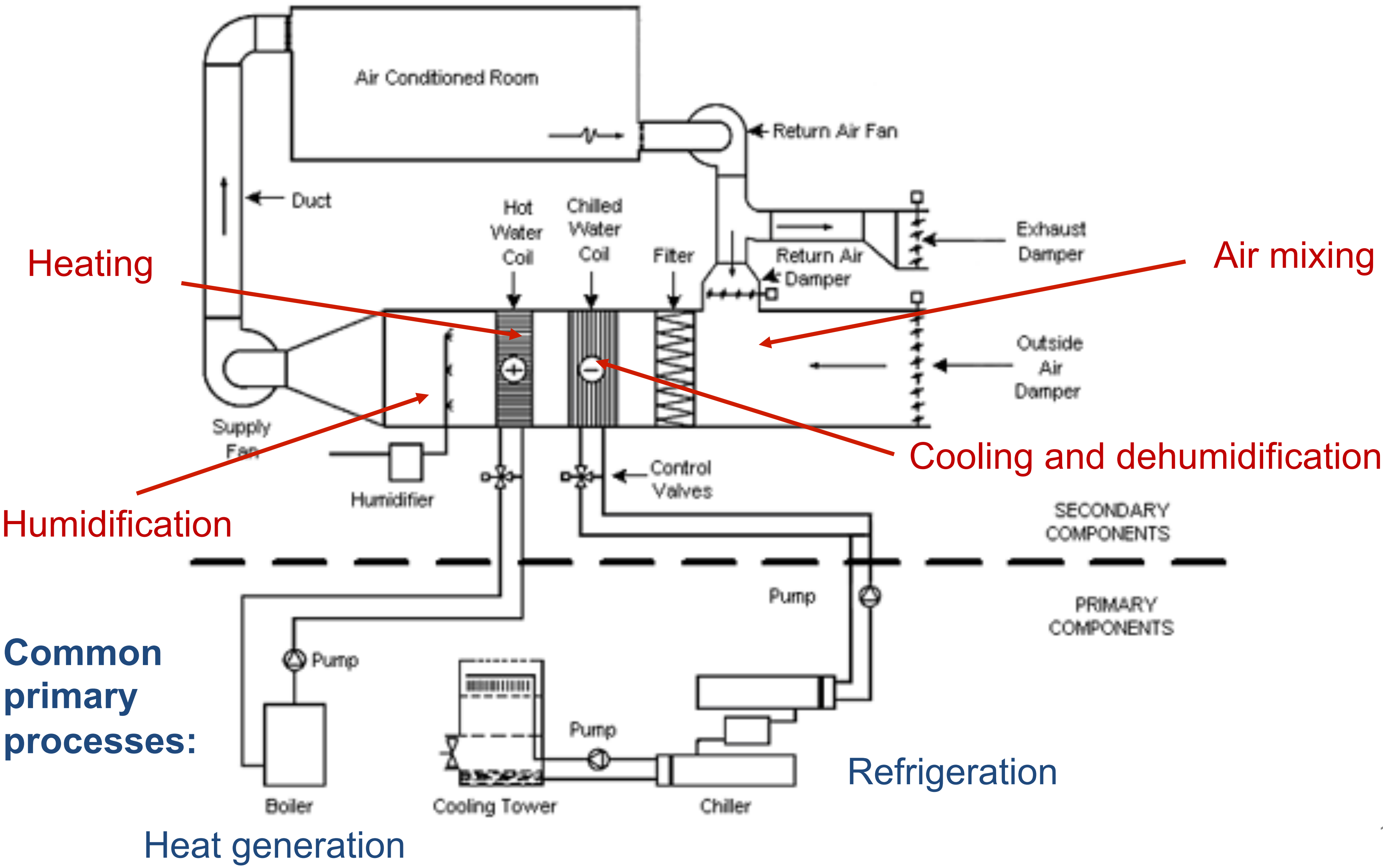
- Sensible cooling or heating
- Warming and humidification of cold, dry air
- Cooling and dehumidification of warm, humid air
  - Sensible + latent cooling
- Evaporative cooling
- Mixing of airstreams

Typical components of an HVAC system



Typical HVAC *processes*

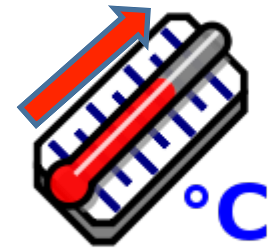
Some common psychrometric processes:



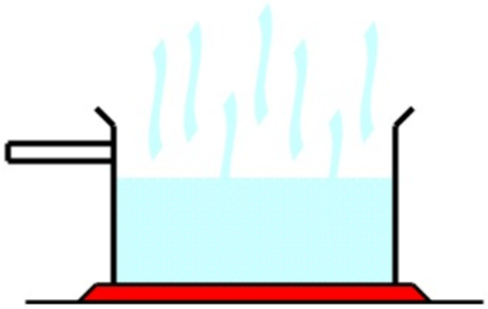
Common primary processes:

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

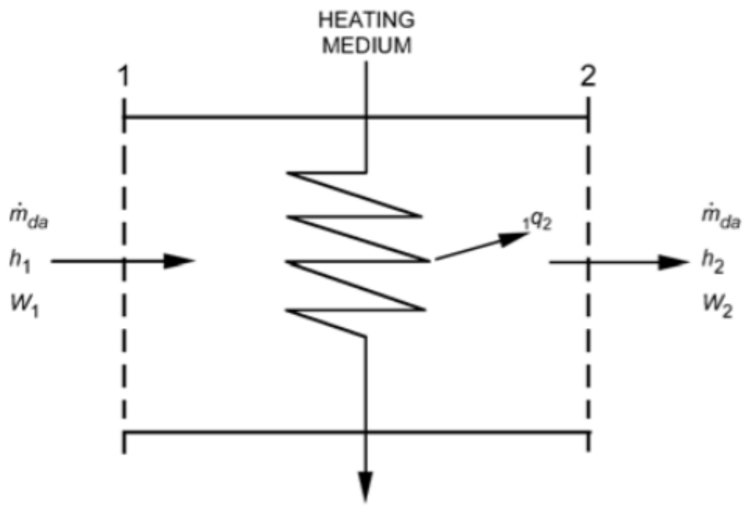


Fig. 2 Schematic of Device for Heating Moist Air

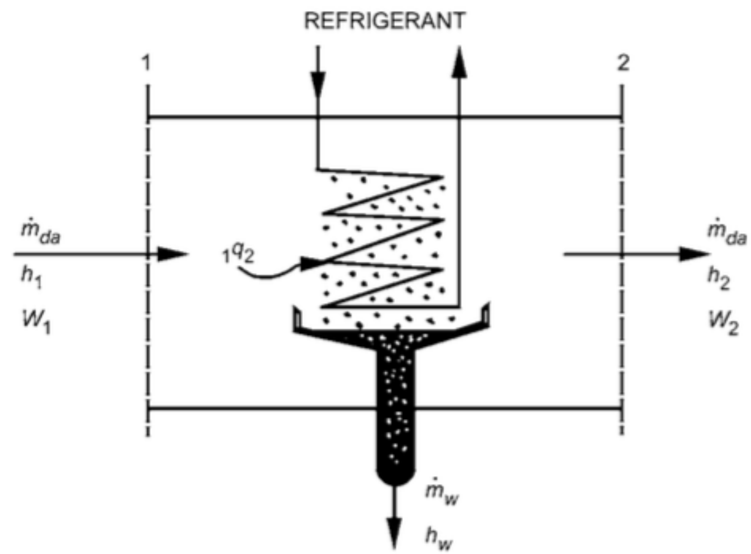


Fig. 3 Schematic of Device for Cooling Moist Air

Generic equations for both heating and cooling processes:

$$Q_{1\to2} = \dot{m}_{da}(h_2 - h_1) \qquad Q_{total} = \dot{m}_{da}(h_{exit} - h_{inlet})$$

$Q_{1\to2}$ = total rate of heat transfer from state 1 to state 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})

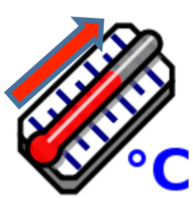
Sensible heat transfer equation

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

$Q_{sensible}$ = 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_{da}/m^3 or lb_{da}/ft^3)
T_{inlet} = inlet temperature (K or °F)
T_{exit} = exit temperature (K or °F)

For heating: $Q_{sensible} > 0$

For cooling: $Q_{sensible} < 0$



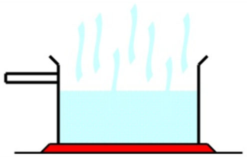
Latent heat transfer equation

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

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 at 212°F (i.e., steam)
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})

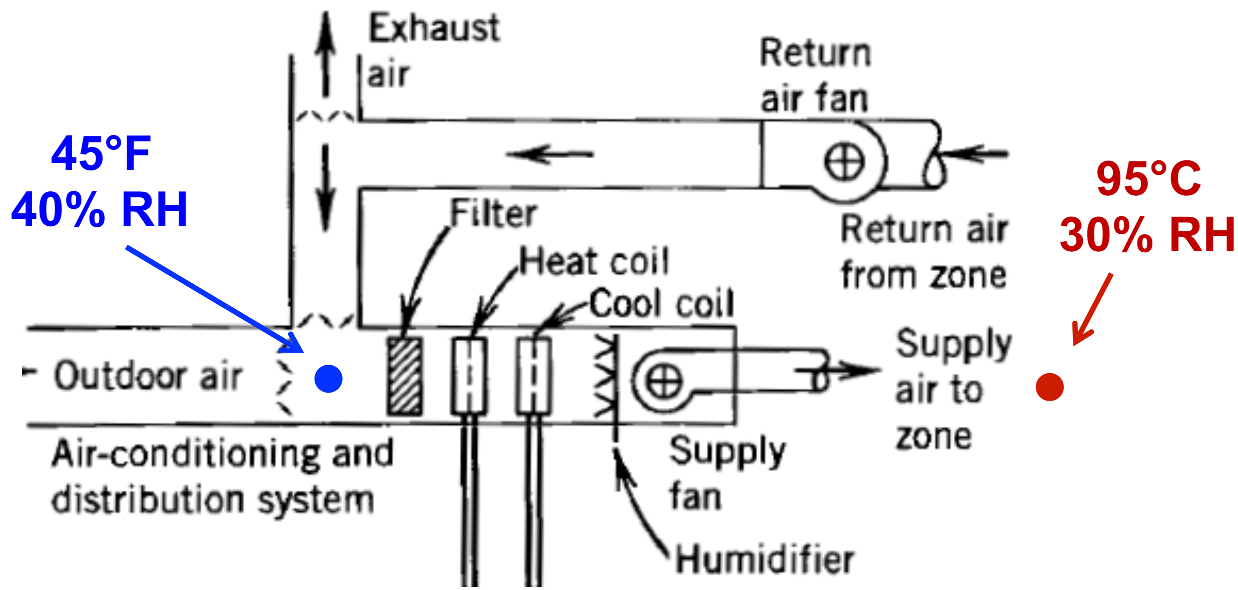
For humidification: $Q_{latent} > 0$

For dehumidification: $Q_{latent} < 0$



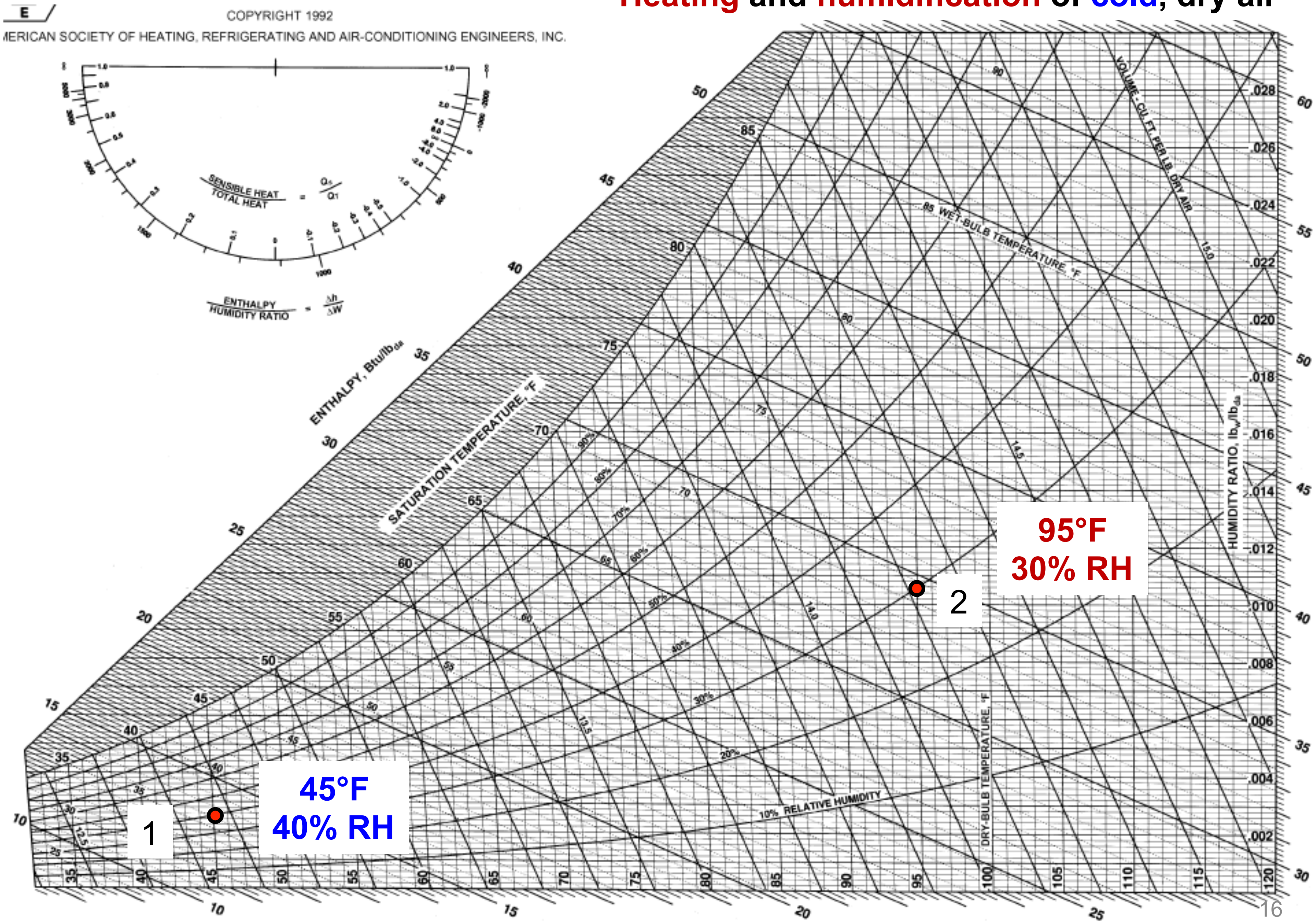
Heating and humidification of cold, dry air

- **Example:** Heating and humidification of air
  - Process: Adding moisture and heat (sensible + latent heating)

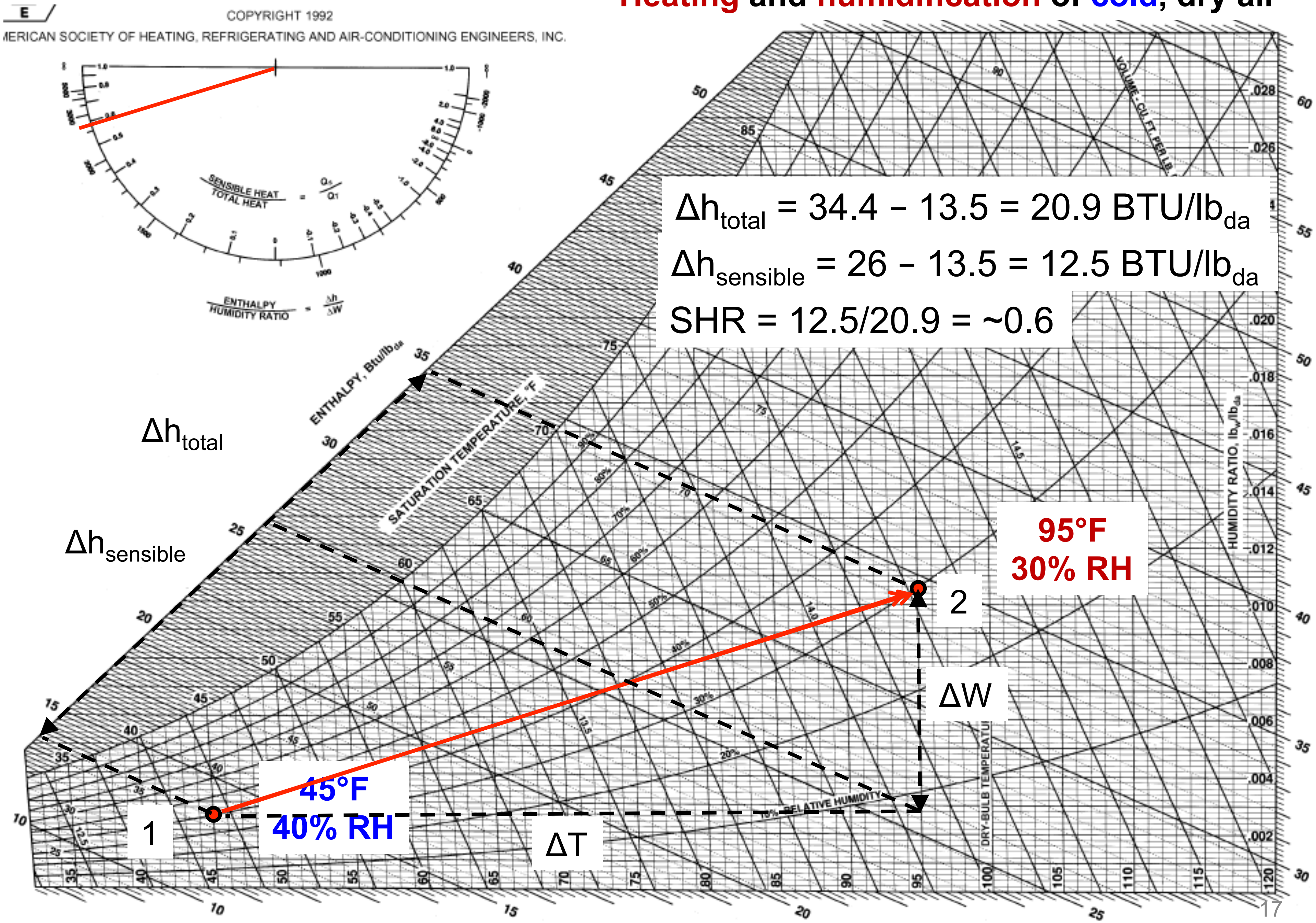


Q1: What is the enthalpy change required?
Q2: What is the total rate of heat transfer if the airflow rate is 10000 cfm?
Q3: What is the split between sensible and latent transfer?

Heating and humidification of cold, dry air



Heating and humidification of cold, dry air

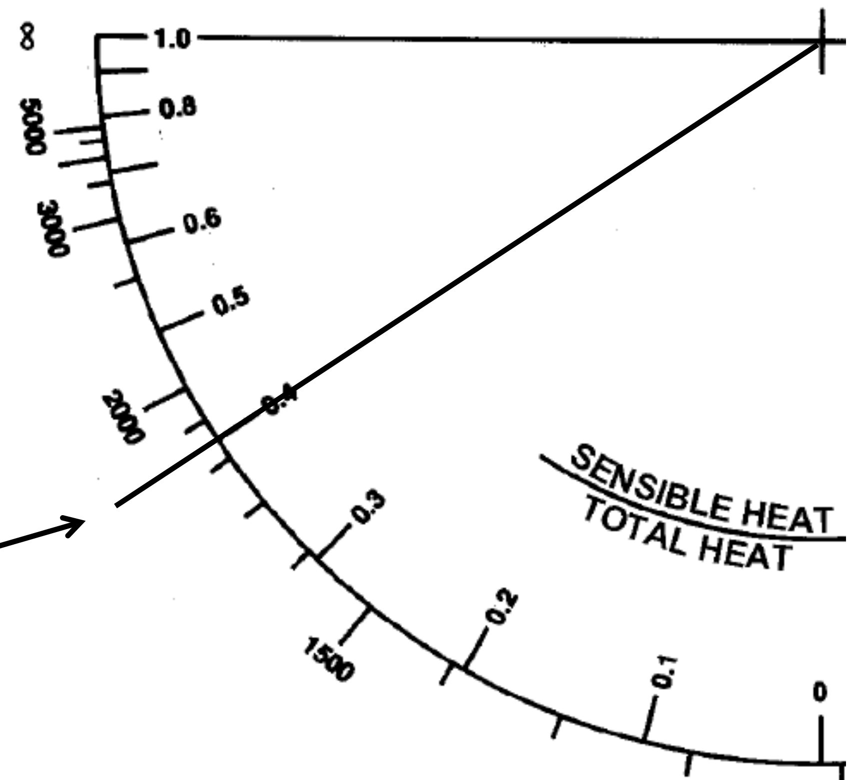


Sensible heat ratio (SHR)

- 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

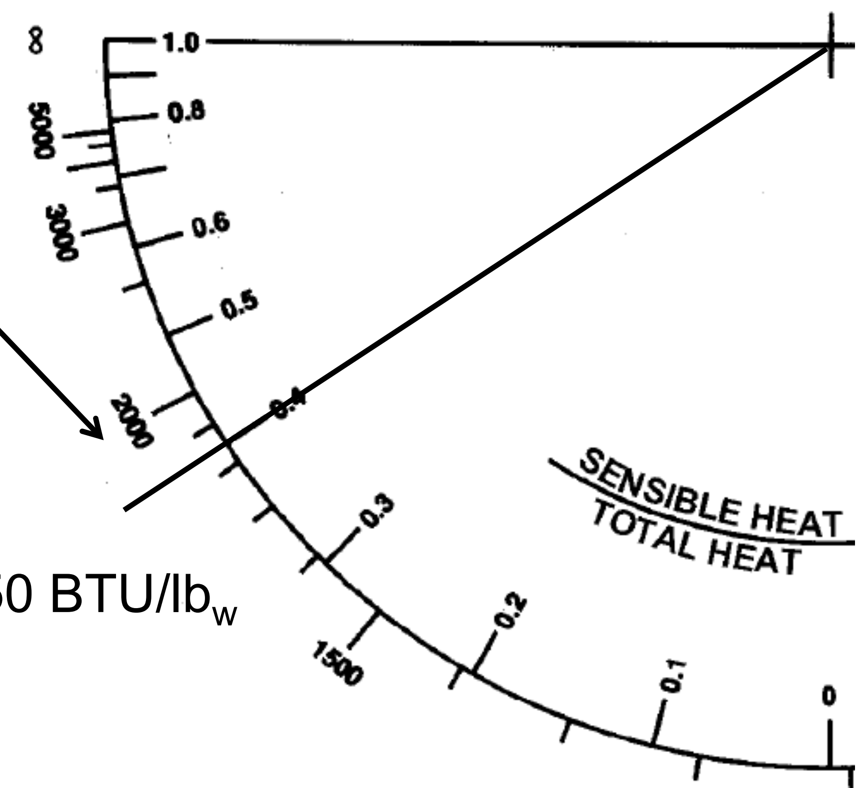


Here is a process with an SHR ≈ 0.4

Enthalpy protractor (Δ*h*/Δ*W*)

- The other side of the enthalpy protractor tells us:
  - What is the enthalpy change relative to the change in humidity ratio

$$\frac{\Delta h_{total}}{\Delta W}$$

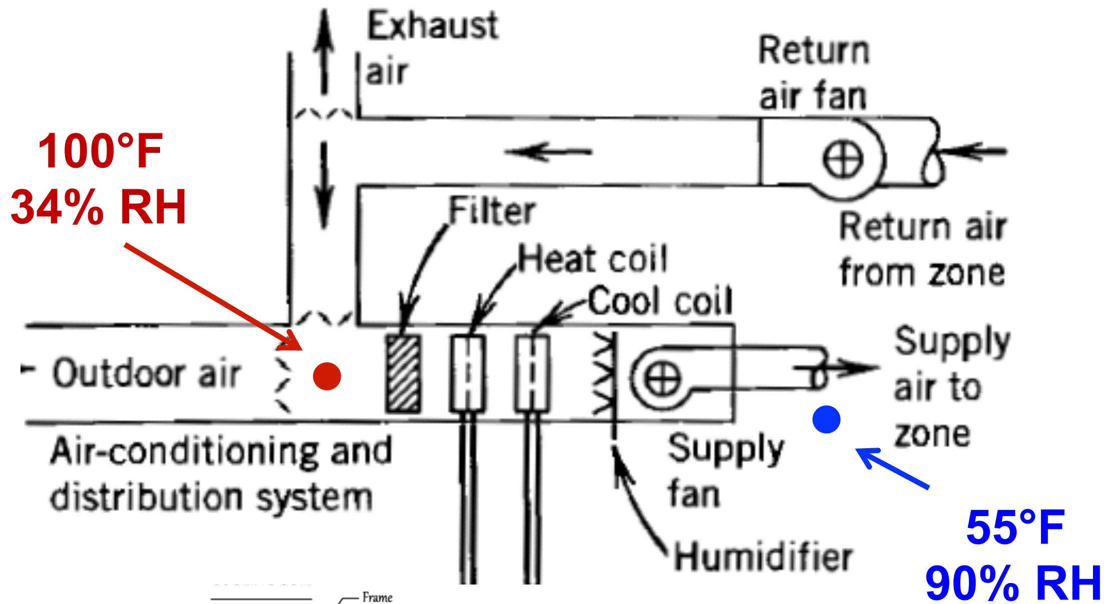


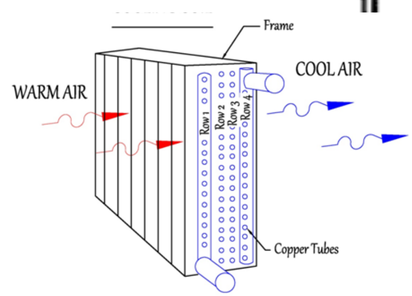
Here is a process with $\Delta h/\Delta W \approx$ 1850 BTU/lb_w

SI units: kJ/kg_w

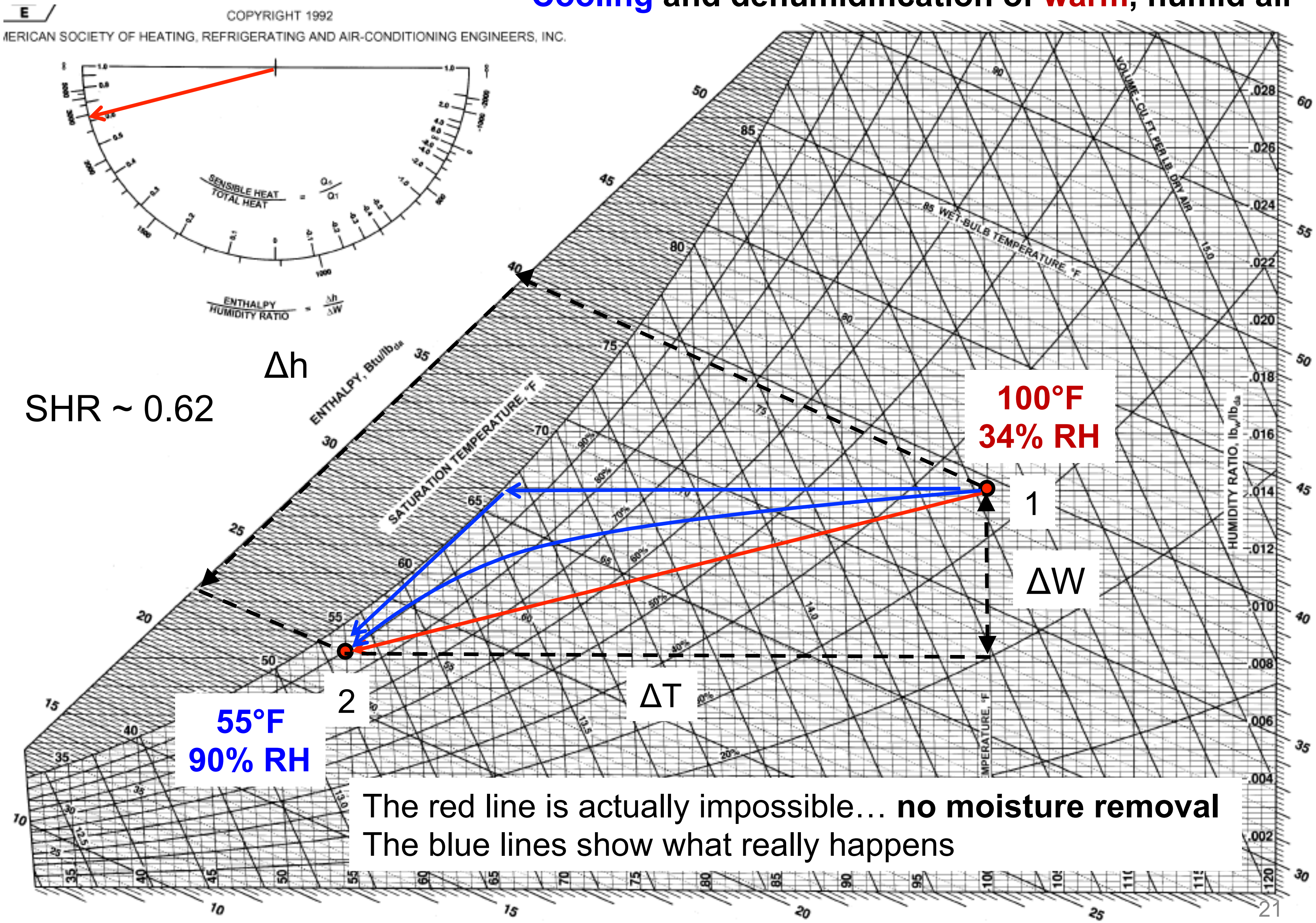
Cooling and dehumidification of warm, humid air

- **Example:** Air flowing over a cooling coil
- Removing both moisture and heat
  - Sensible + latent cooling





Cooling and dehumidification of warm, humid air

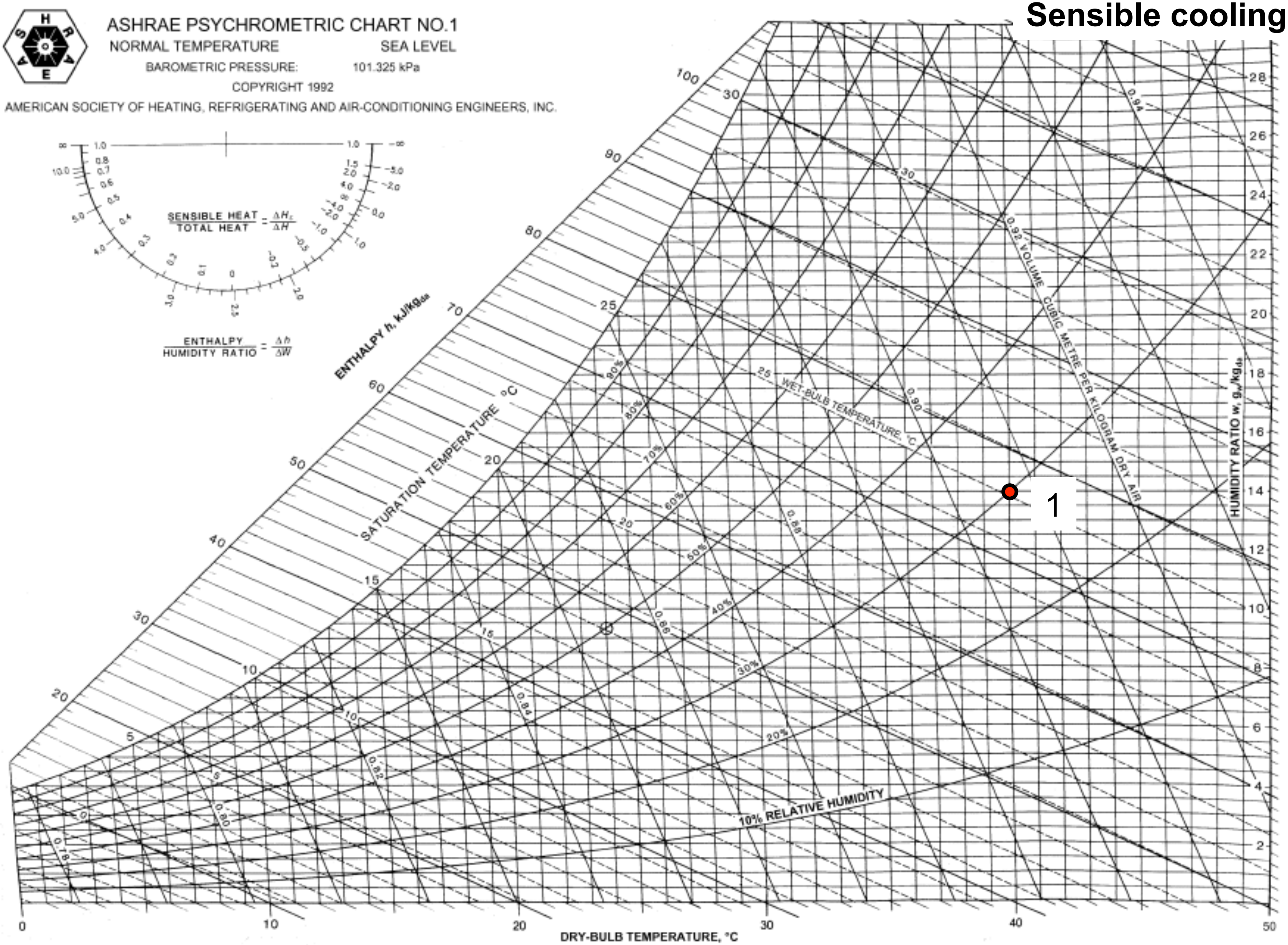


The red line is actually impossible… **no moisture removal**
The blue lines show what really happens

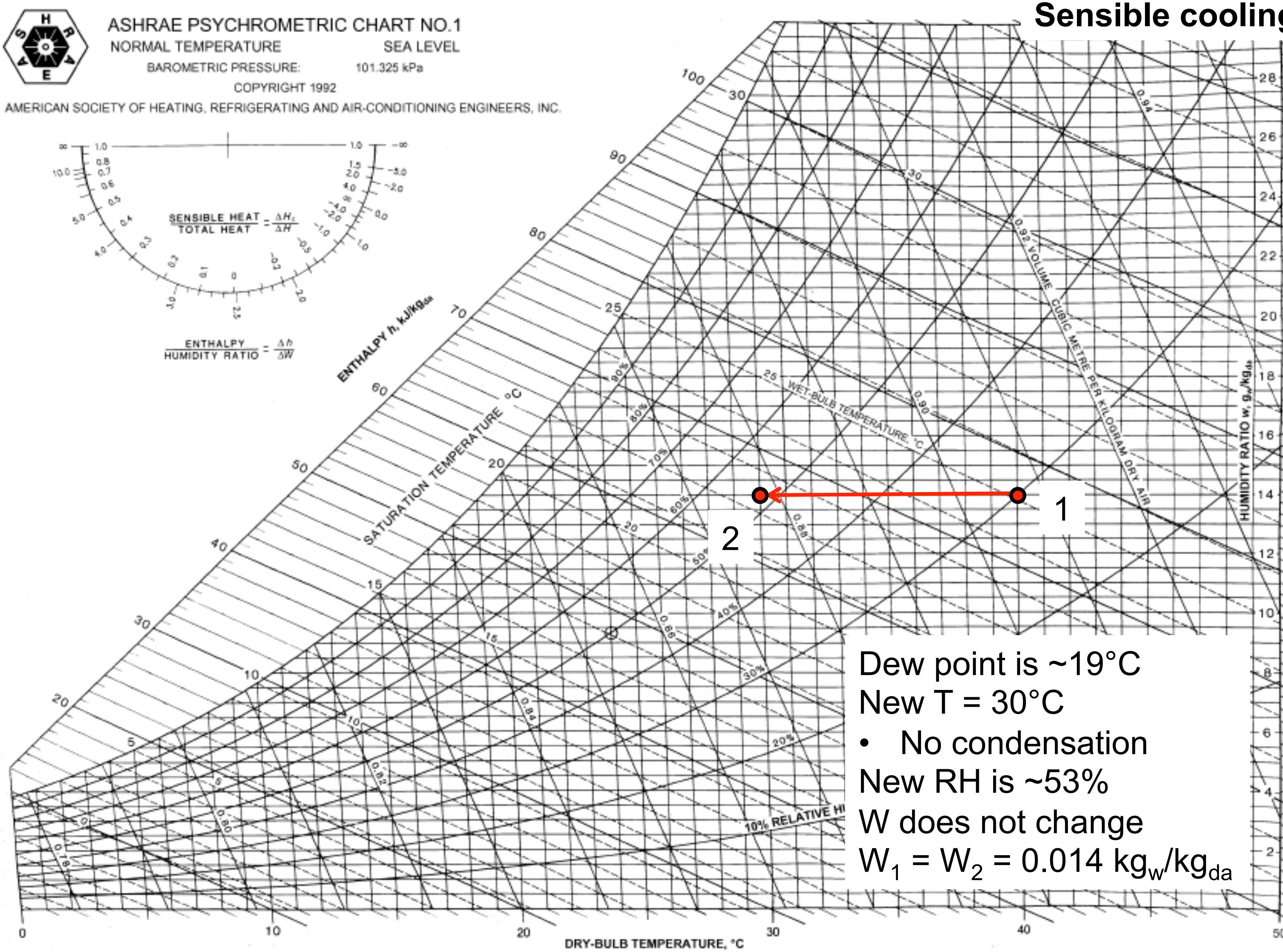
Example: *Sensible* cooling

- Moist air is cooled from 40°C and 30% RH to 30°C without condensation
  - What is the RH at W at the process end point?

Sensible cooling



Sensible cooling



Dew point is ~19°C

New T = 30°C

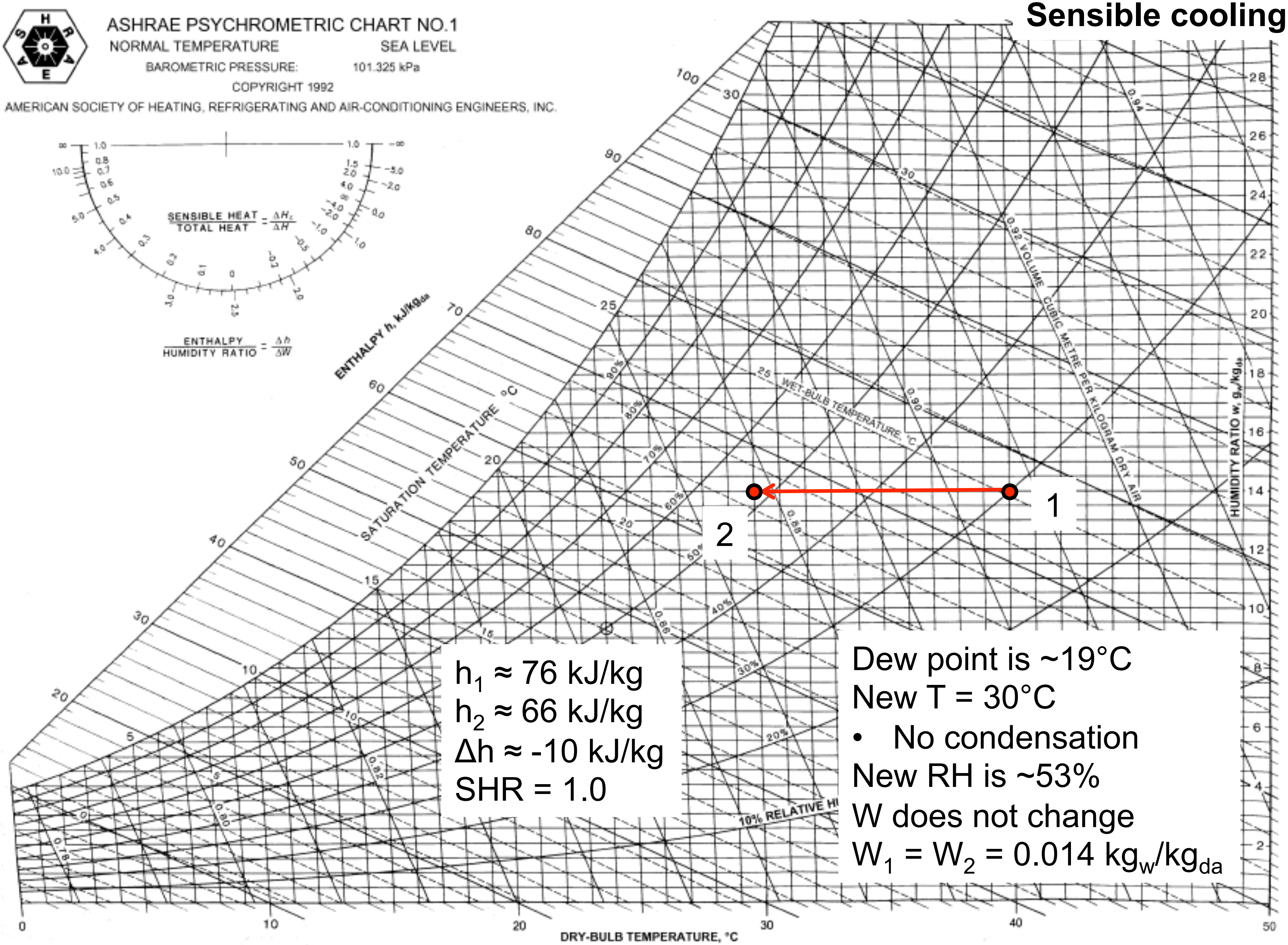
- No condensation

New RH is ~53%

W does not change

$W_1 = W_2 = 0.014\ kg_w/kg_{da}$

Sensible cooling



$h_1 \approx 76$ kJ/kg
$h_2 \approx 66$ kJ/kg
$\Delta h \approx -10$ kJ/kg
SHR = 1.0

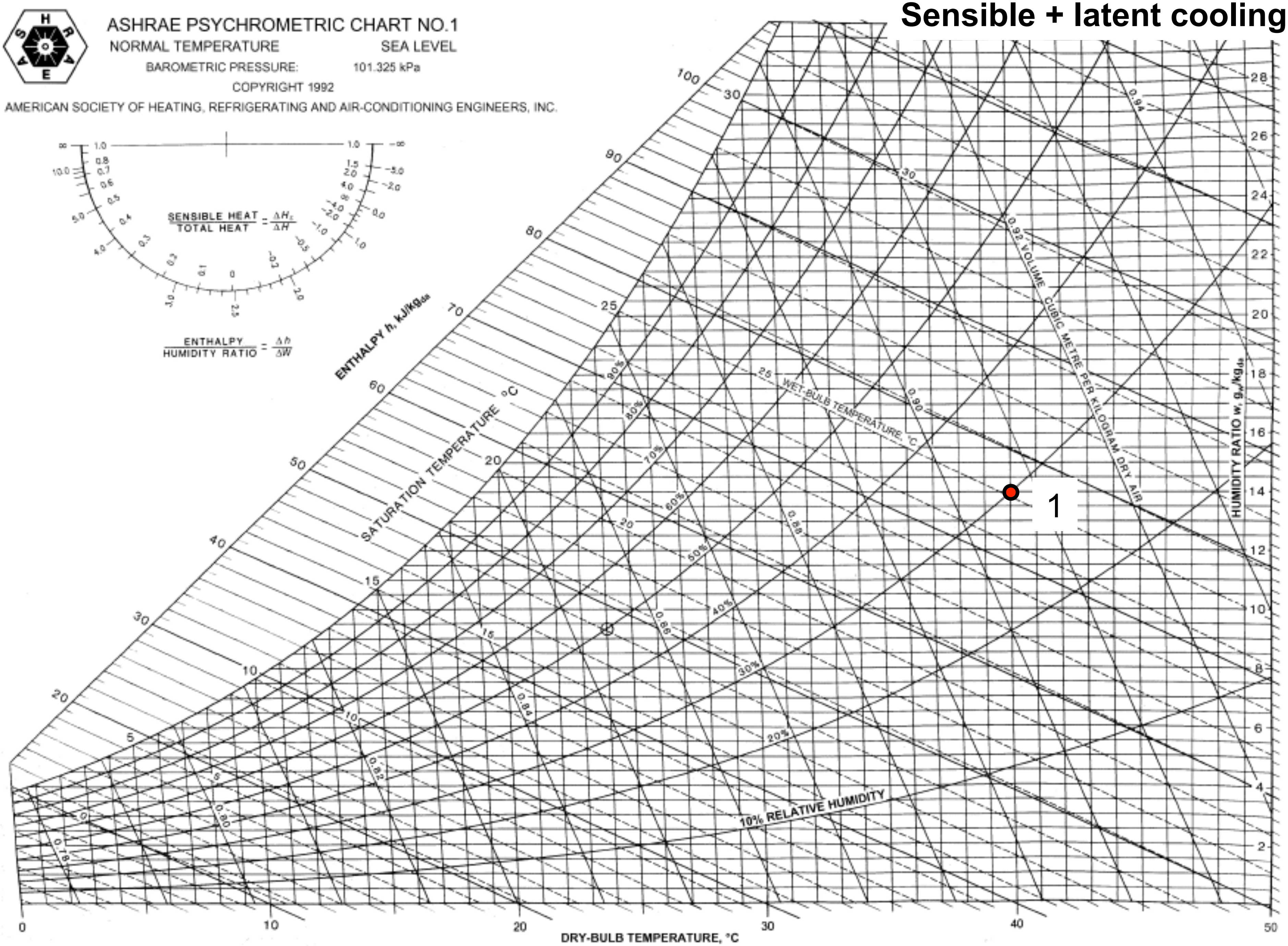
Dew point is ~19°C
New T = 30°C
- No condensation

New RH is ~53%
W does not change
$W_1 = W_2 = 0.014\ kg_w/kg_{da}$

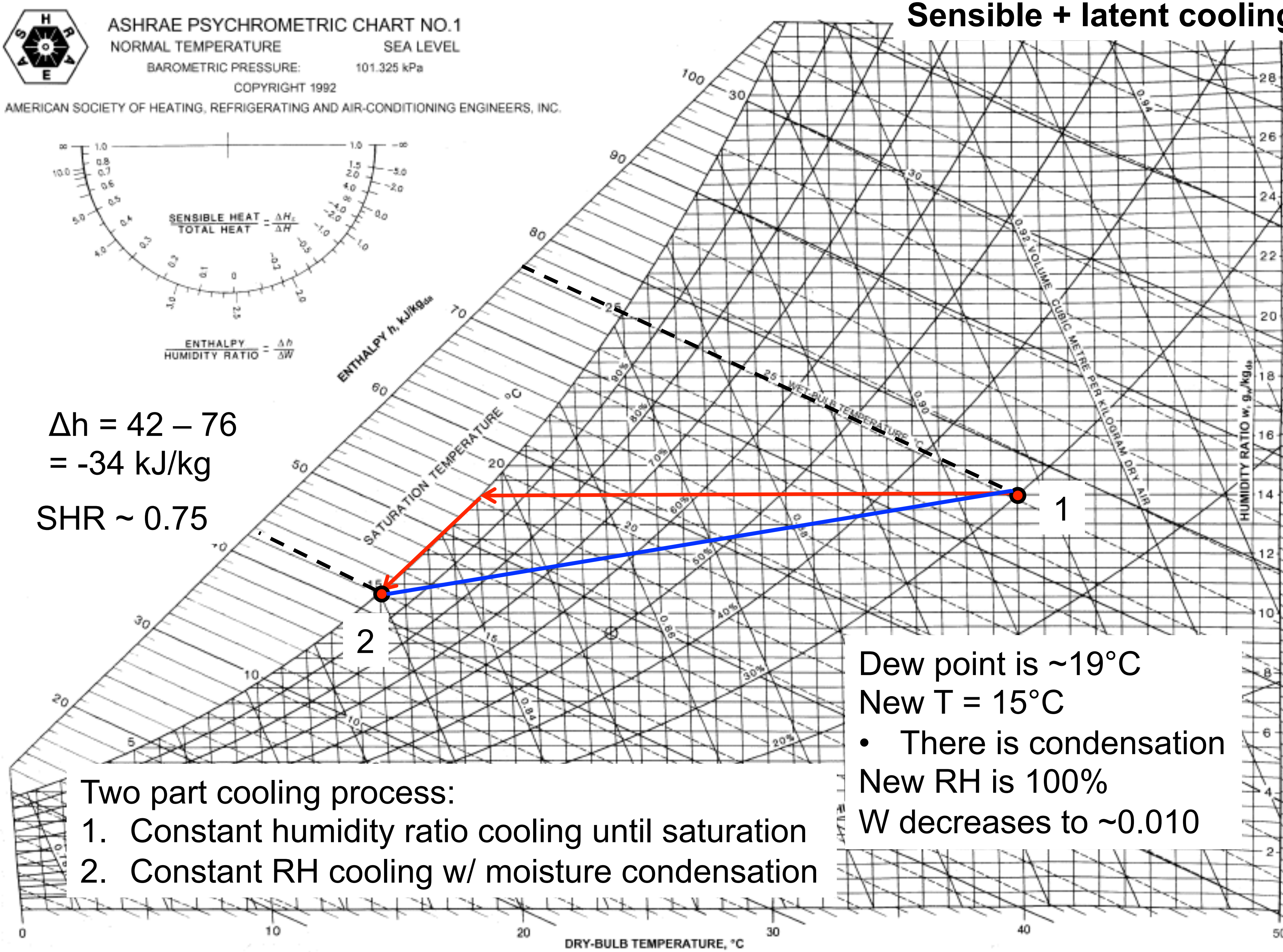
Example: ***Sensible*** **+** ***latent*** **cooling**

- Moist air is cooled from 40°C and 30% RH to 15°C
  - Q1: Does the water vapor condense?
  - Q2: What is RH at W at the process end point?

Sensible + latent cooling



Sensible + latent cooling



Δh = 42 – 76
= -34 kJ/kg

SHR ~ 0.75

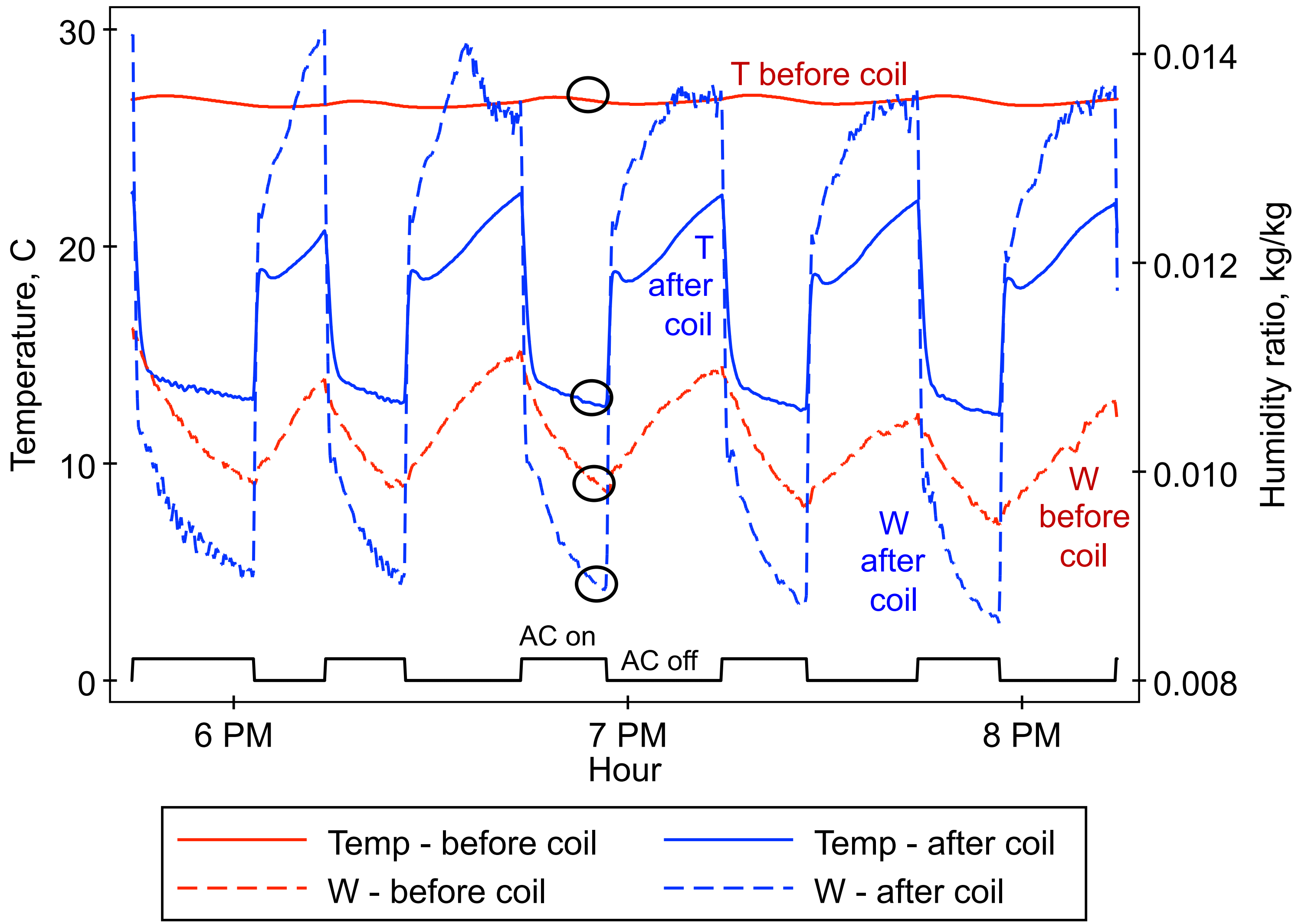
Dew point is ~19°C
New T = 15°C
- There is condensation

New RH is 100%
W decreases to ~0.010

Two part cooling process:
1. Constant humidity ratio cooling until saturation
2. Constant RH cooling w/ moisture condensation

Real data: ASHRAE RP-1299
Energy implications of filters

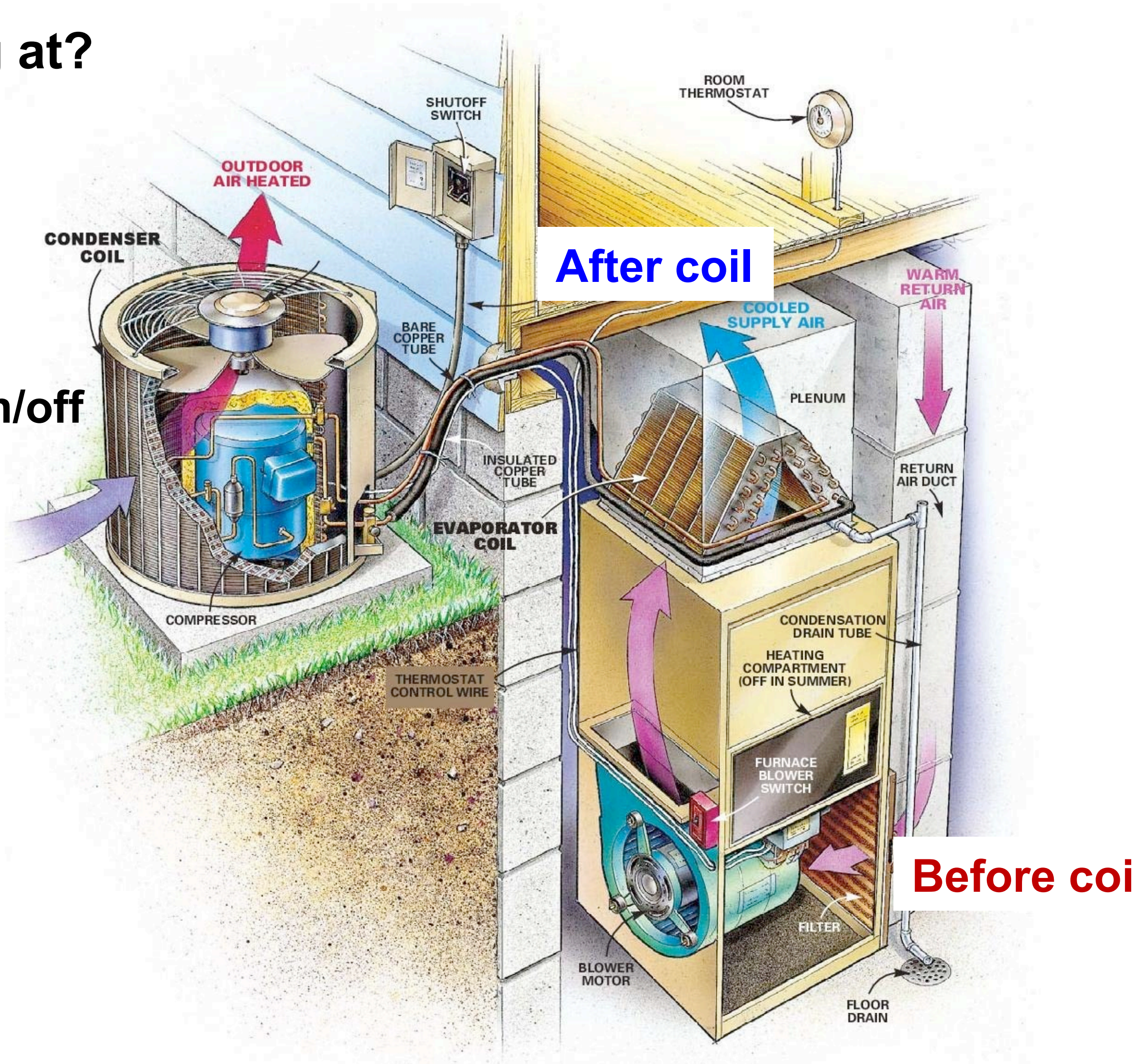
Temperature and humidity ratio differences across AC coils in homes



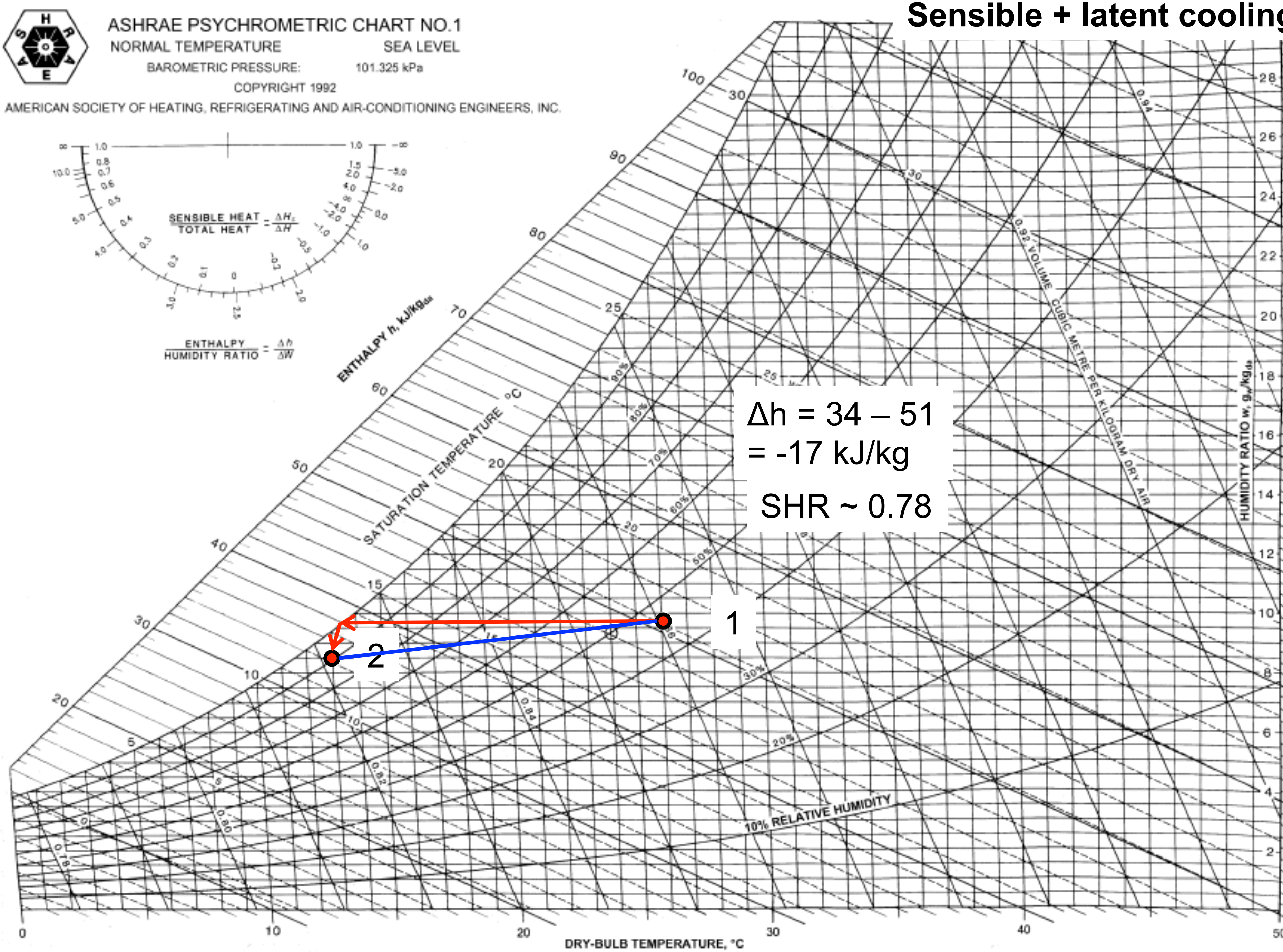
Real data: ASHRAE RP-1299
Energy implications of filters

What are we looking at?

AC on/off

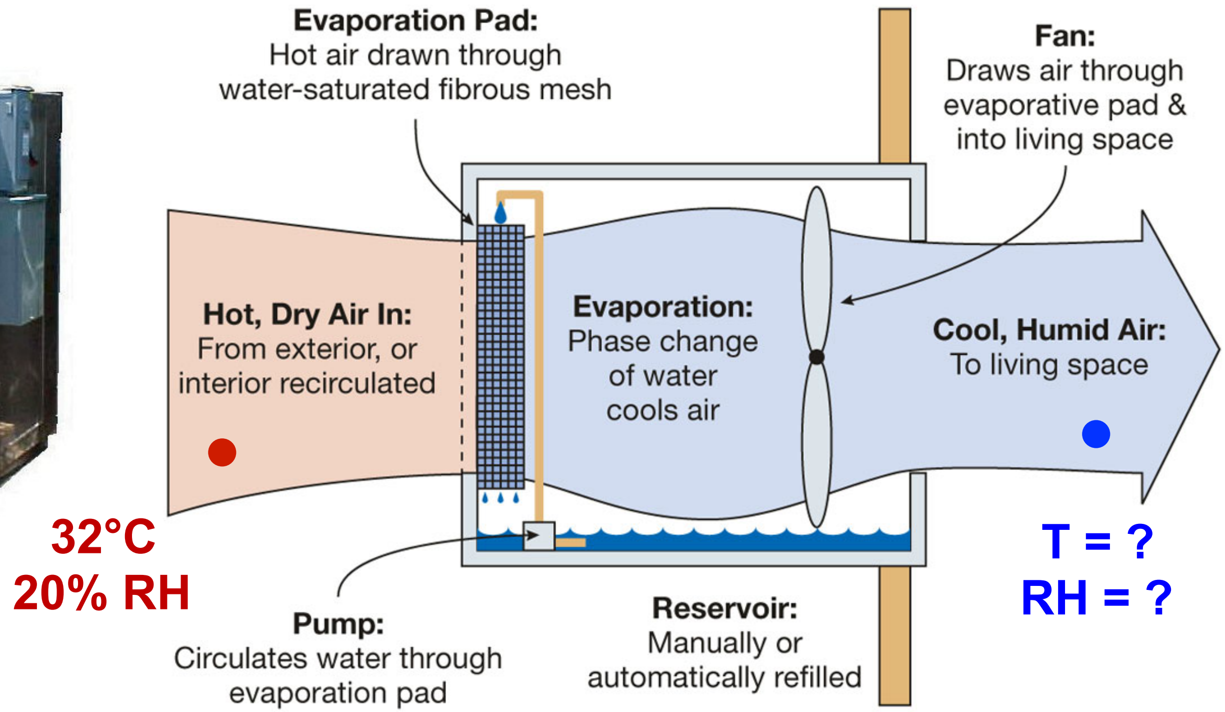


Sensible + latent cooling

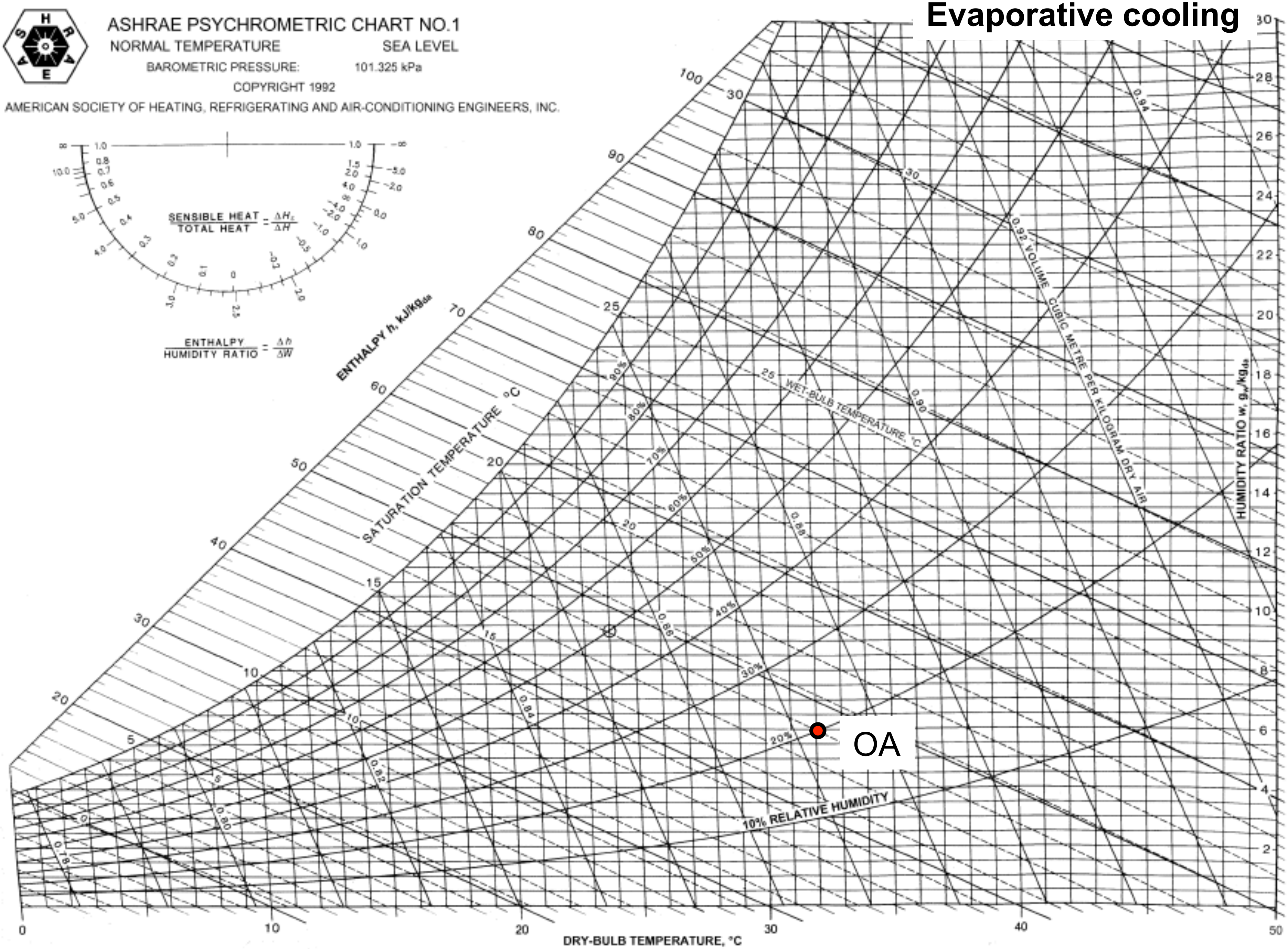


Evaporative cooling example

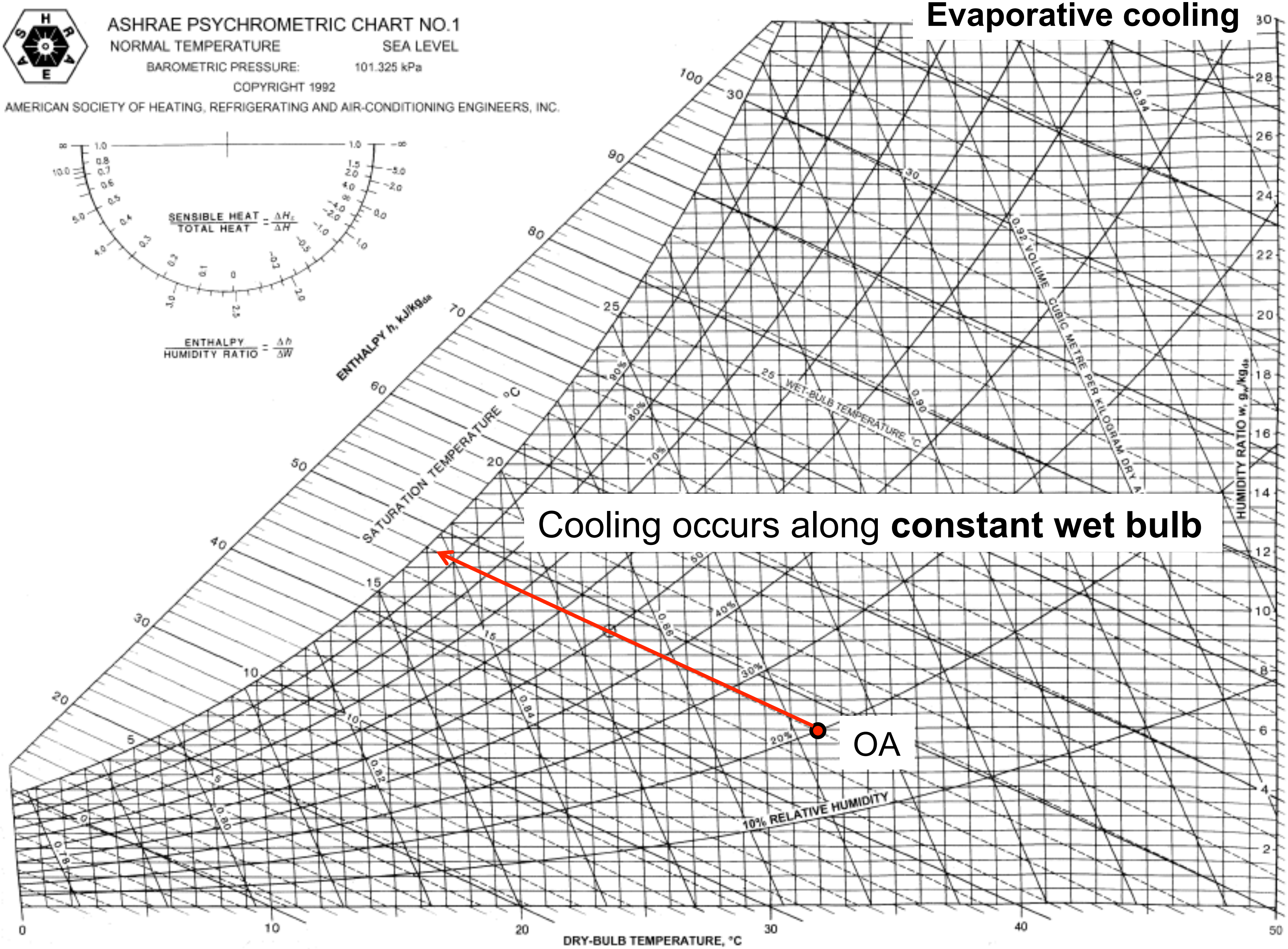
- Hot, dry outdoor air is cooled with an evaporative cooler, or “swamp cooler”
  - **Q1: What is the T, RH, and W of the supply air?**
  - **Q2: Why would we choose this system?**



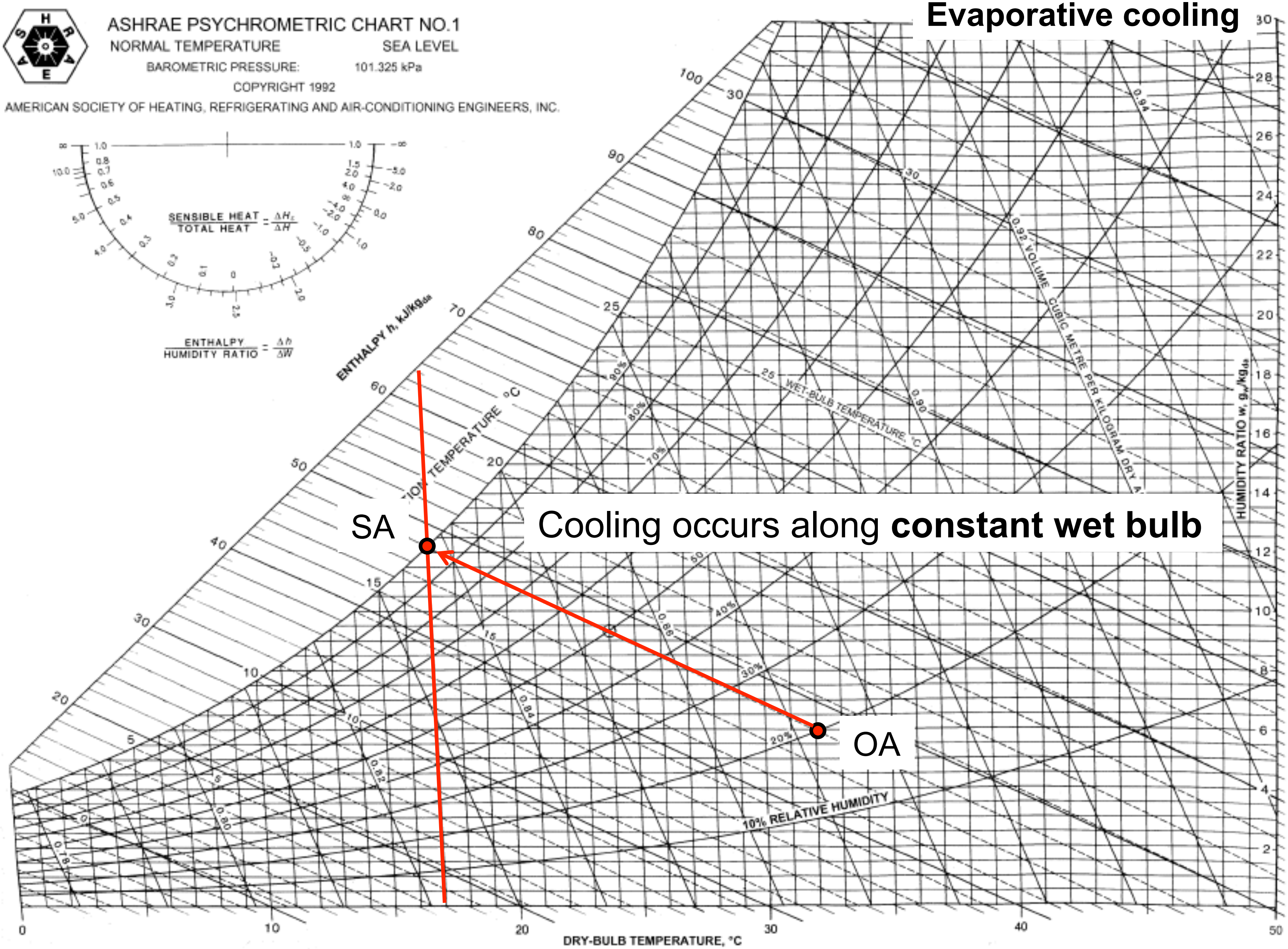
Evaporative cooling



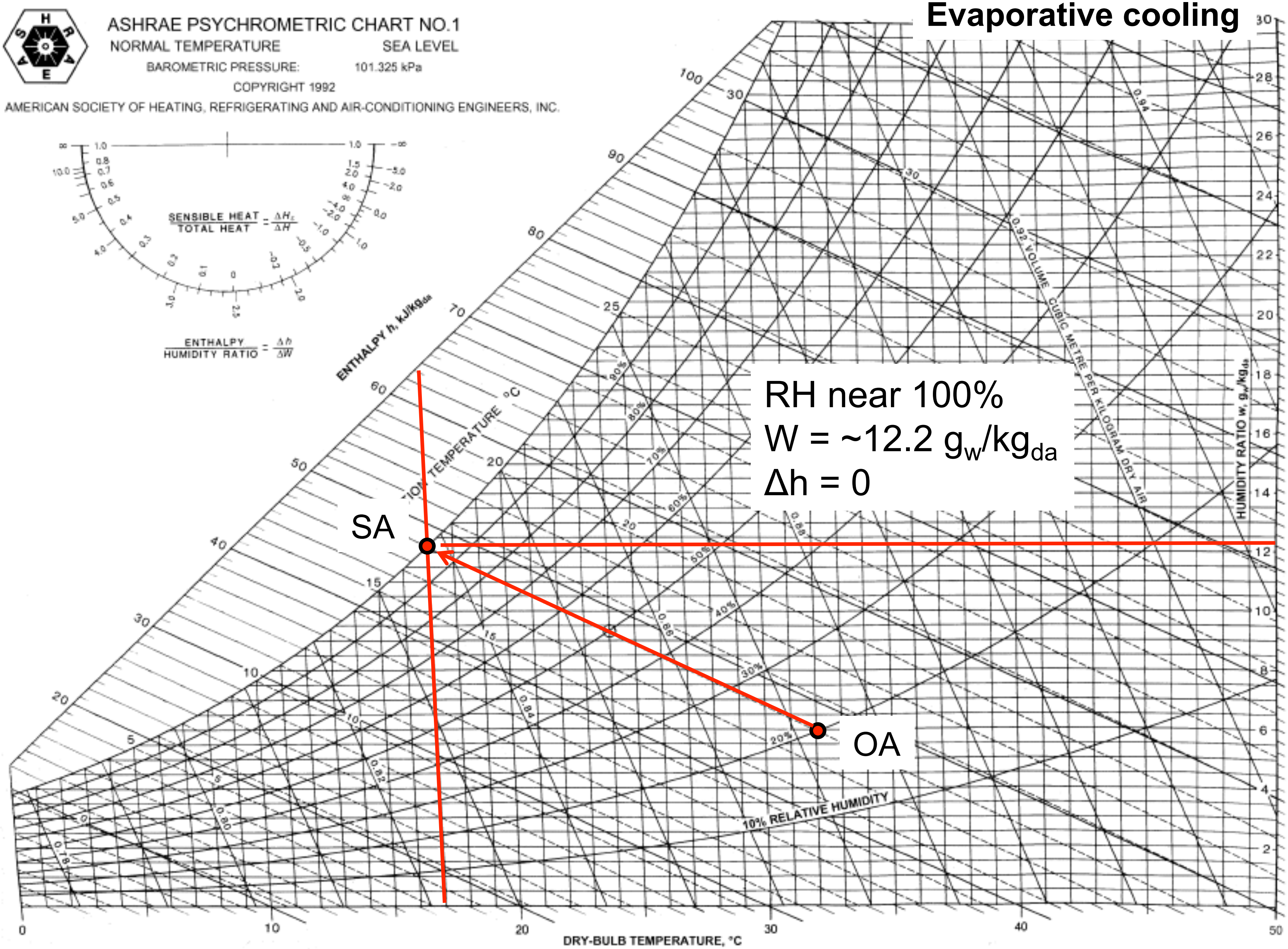
Evaporative cooling



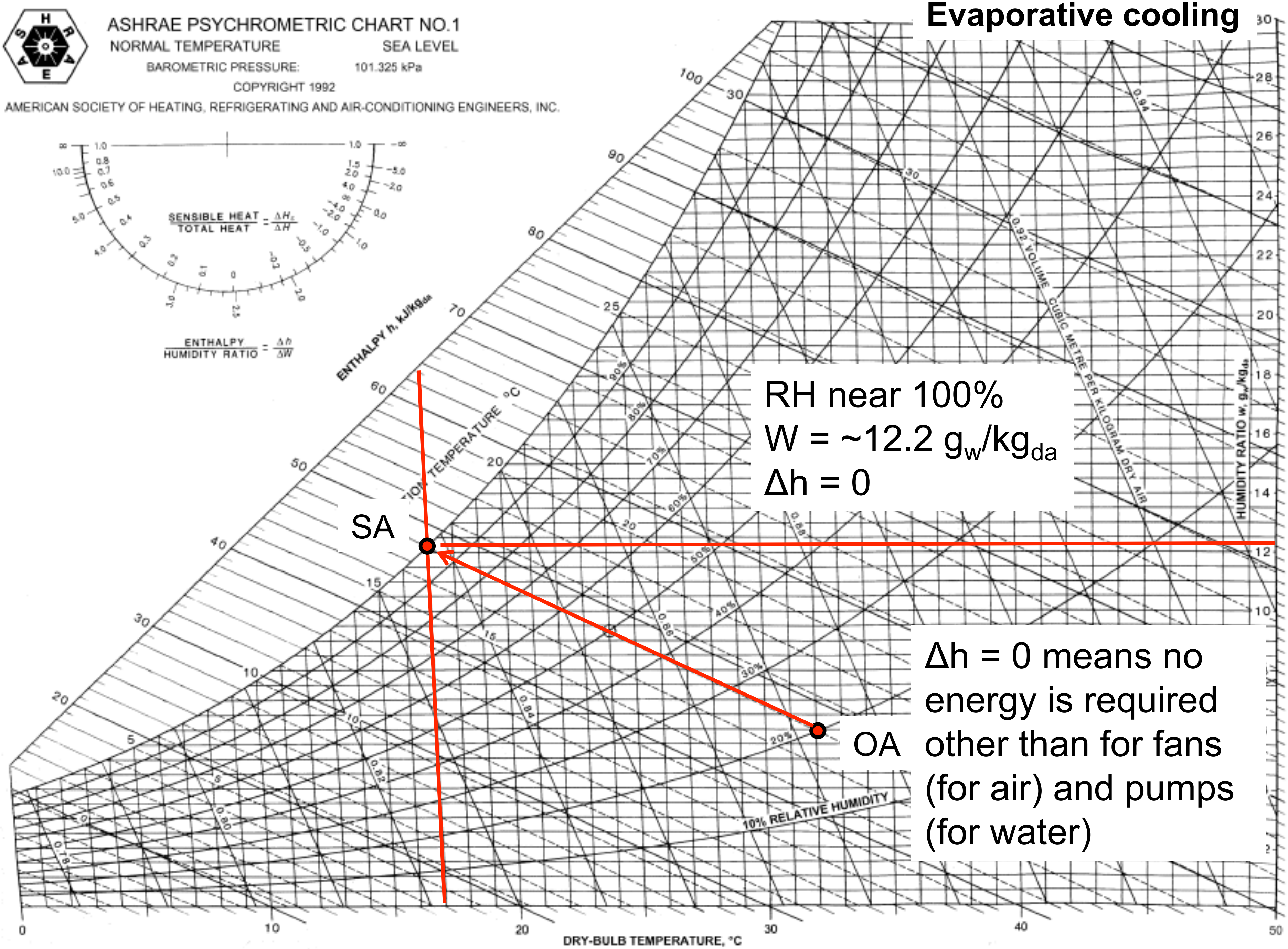
Evaporative cooling



Evaporative cooling



Evaporative cooling

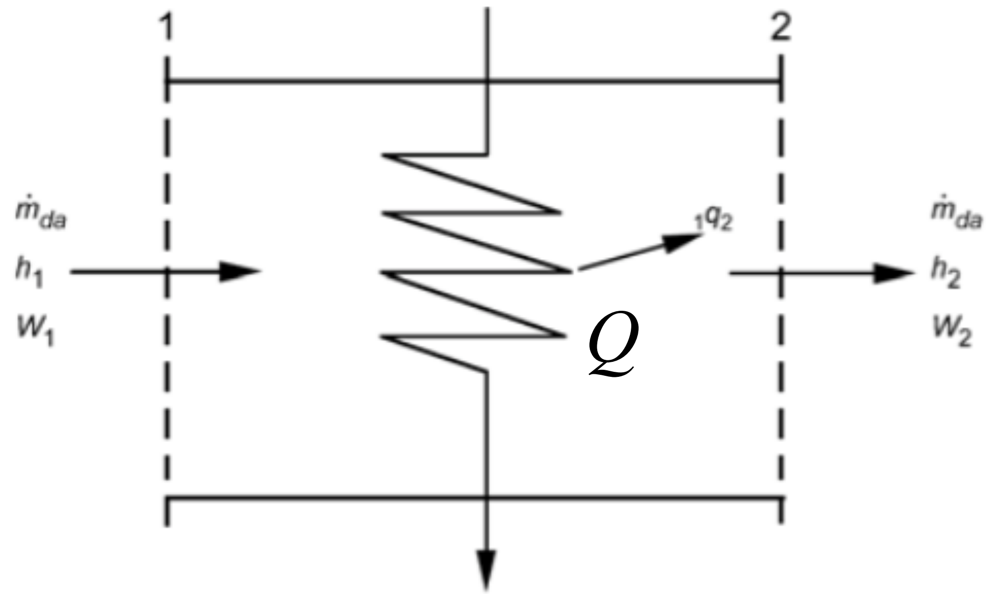


PSYCHROMETRIC **PROCESSES**

Using energy and mass balance equations

Energy/mass balances for psychrometric processes

Heating air



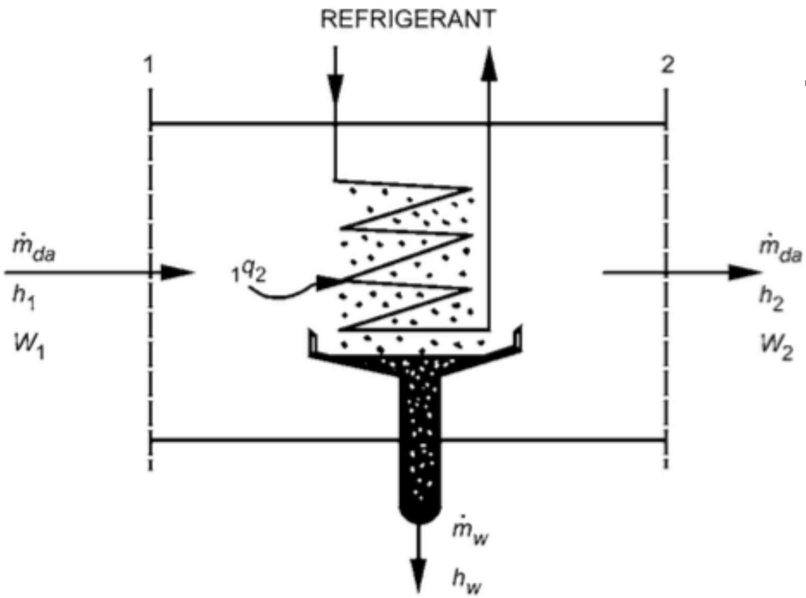
Energy balance: $\dot{m}_{da,1}h_1 + Q_{1\rightarrow 2} = \dot{m}_{da,2}h_2$

Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

Mass balance on water vapor: $\dot{m}_{da,1}W_1 = \dot{m}_{da,2}W_2$

Therefore: $Q_{1\rightarrow 2} = \dot{m}_{da}(h_2 - h_1)$

Energy/mass balances for psychrometric processes



Cooling and dehumidifying

*Note that h_w = h_g for steam/vapor and h_w = h_f for water

Energy balance: $\dot{m}_{da,1}h_1 + Q_{1\to 2} = \dot{m}_{da,2}h_2 + \dot{m}_w h_{w,2}$

Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

Mass balance on water vapor: $\dot{m}_{da,1}W_1 = \dot{m}_{da,2}W_2 + \dot{m}_w$

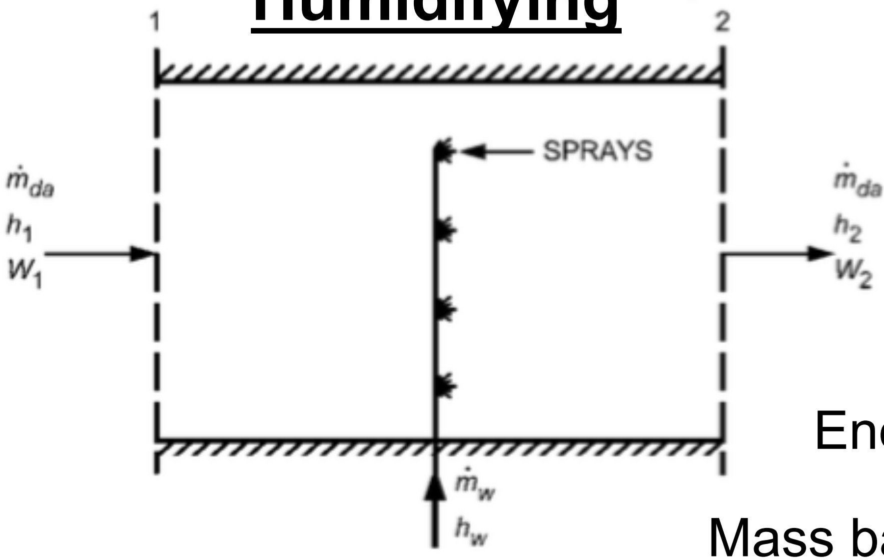
Therefore: $\dot{m}_w = \dot{m}_{da}(W_1 - W_2)$

And: $Q_{1\to 2} = \dot{m}_{da}[(h_2 - h_1) - (W_2 - W_1)h_{w,2}]$

(Q is negative for cooling)

Energy/mass balances for psychrometric processes

Humidifying



Energy balance: $\dot{m}_{da,1}h_1 + \dot{m}_w h_w = \dot{m}_{da,2}h_2$

Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

Mass balance on water vapor: $\dot{m}_{da,1}W_1 + \dot{m}_w = \dot{m}_{da,2}W_2$

Therefore: $\dot{m}_w = \dot{m}_{da}(W_2 - W_1)$

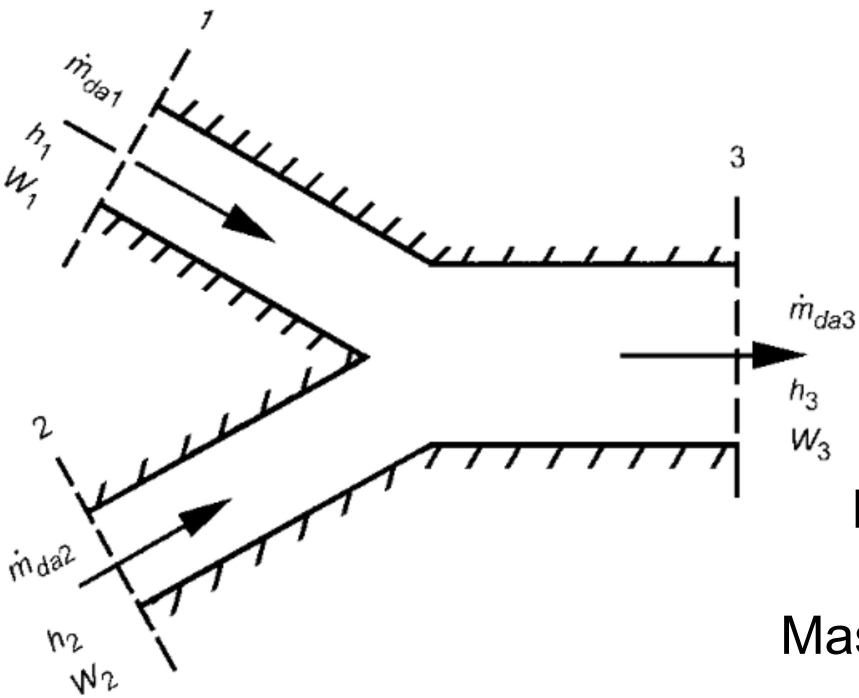
And: $\dot{m}_w h_w = \dot{m}_{da}(h_2 - h_1)$

And: $\dfrac{h_2 - h_1}{W_2 - W_1} = \dfrac{\Delta h}{\Delta W} = h_w$

*Note that h_w = h_g for steam/vapor and h_w = h_f for water

Energy/mass balances for psychrometric processes

- **<u>Mixing</u>:** Often in HVAC systems we mix airstreams adiabatically
  - **Adiabatically** = Without the addition or extraction of heat
  - e.g. outdoor air mixed with a portion of return/recirculated air



Energy: $$\dot{m}_{da,1}h_1 + \dot{m}_{da,2}h_2 = \dot{m}_{da,3}h_3$$

Mass (air): $$\dot{m}_{da,1} + \dot{m}_{da,2} = \dot{m}_{da,3}$$

Mass (water): $$\dot{m}_{da,1}W_1 + \dot{m}_{da,2}W_2 = \dot{m}_{da,3}W_3$$

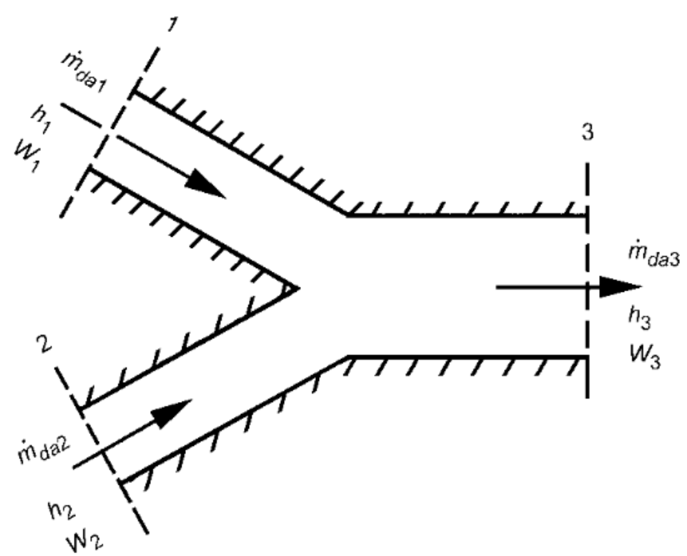
Energy/mass balances for psychrometric processes

- **<u>Mixing</u>:** For most parameters, the outlet conditions end up being the weighted averages of the input conditions based on their mass flow rates
  - Dry bulb temperature
  - Humidity ratio
  - Enthalpy
  - (not RH!)

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

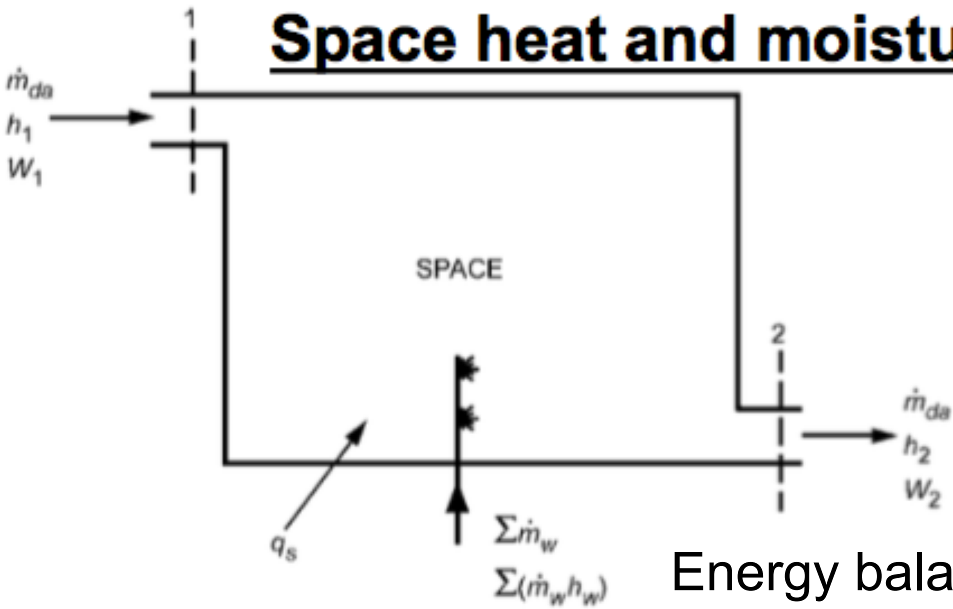
$$W_3 = \frac{\dot{m}_{da1}W_1 + \dot{m}_{da2}W_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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



Energy/mass balances for psychrometric processes

Space heat and moisture gains



Energy balance: $\dot{m}_{da}h_1 + Q_{gains} + \sum \dot{m}_w h_w = \dot{m}_{da}h_2$

Mass balance on water vapor: $\dot{m}_{da}W_1 + \sum \dot{m}_w = \dot{m}_{da}W_2$

Therefore: $\sum \dot{m}_w = \dot{m}_{da}(W_2 - W_1)$

Therefore: $\sum \dot{m}_w h_w + Q_{gains} = \dot{m}_{da}(h_2 - h_1)$

And: $$\frac{\Delta h}{\Delta W} = \frac{\sum \dot{m}_w h_w + Q_{gains}}{\sum \dot{m}_w}$$

*Note that h_w = h_g for steam/vapor and h_w = h_f for water

Next time

- Psychrometric processes: example problems