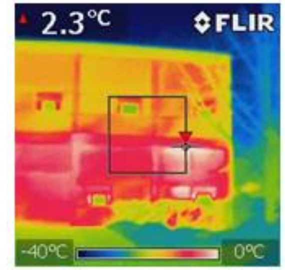
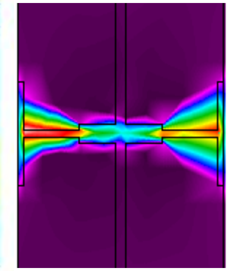
CAE 331/513
Building Science
Fall 2014





Week 6: September 30, 2014
HVAC thermodynamic and psychrometric processes

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ASHRAE Scholarships

- 8 regional/chapter and university-specific scholarships
  - $3,000 to $5,000 each
- 12 undergraduate engineering scholarships
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HW 3 – Psychrometrics chart

- Due Thursday

Revisit example from last class

Moist air exists at 22°C dry-bulb temperature with 50% RH

Find the following:

(a) the humidity ratio, W

(b) dew point temperature, T_{dew}

(c) wet-bulb temperature, T_{wb}

(d) enthalpy, h

(e) specific volume, v

(f) density, ρ

Also:

(g) degree of saturation, μ

Psychrometric equations

$$\phi = \frac{p_w}{p_{ws}} \qquad W = 0.622\frac{p_w}{p - p_w} \qquad \mu = \frac{W}{W_s}$$

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

where

C_8 = −5.800 220 6 E+03
C_9 = 1.391 499 3 E+00
C_{10} = −4.864 023 9 E−02
C_{11} = 4.176 476 8 E−05
C_{12} = −1.445 209 3 E−08
C_{13} = 6.545 967 3 E+00

p_{ws} = saturation pressure, Pa
T = absolute temperature, K = °C + 273.15

Dew point temperature:

Between dew points of 0 and 93°C,

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

Below 0°C,

$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2$$

where

t_d = dew-point temperature, °C
α = $\ln p_w$
p_w = water vapor partial pressure, kPa
C_{14} = 6.54
C_{15} = 14.526
C_{16} = 0.7389
C_{17} = 0.09486
C_{18} = 0.4569

Psychrometric equations

Wet bulb temperature (iterative solver):

$$W = \frac{(2501 - 2.326T_{wb})W_{s@T_{wb}} - 1.006(T - T_{wb})}{2501 + 1.86T - 4.186T_{wb}} \quad = \text{actual } W$$

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

$$v \approx 0.287042(T + 273.15)(1 + 1.6078W) / p$$

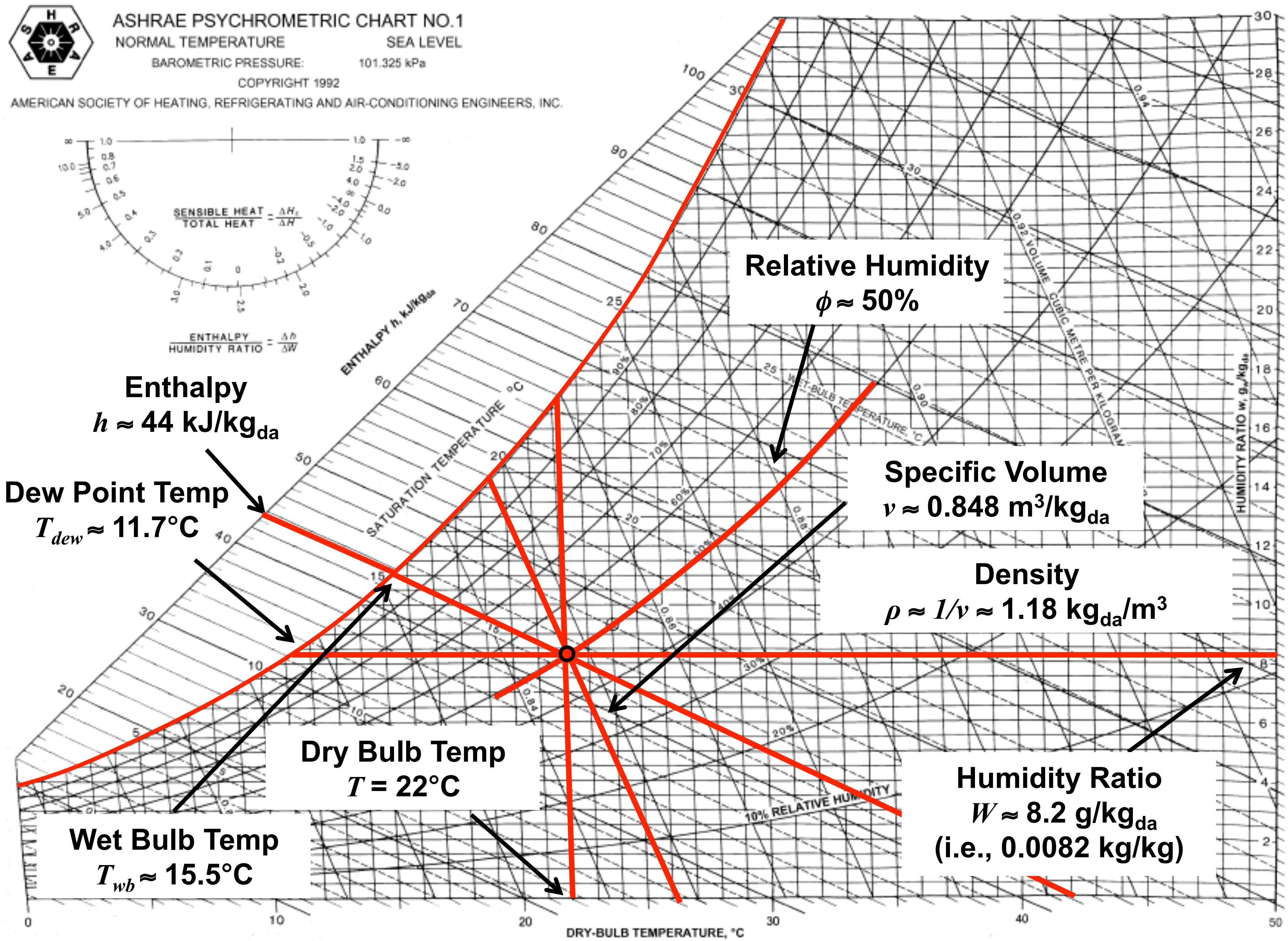
where

v = specific volume, m^3/kg_{da}
t = dry-bulb temperature, °C
W = humidity ratio, kg_w/kg_{da}
p = total pressure, kPa

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

$$h \approx 1.006T + W(2501 + 1.86T)$$

*where T is in °C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NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C
Relative Humidity
$\phi \approx 50\%$
Enthalpy
$h \approx 44$ kJ/kg$_{da}$
Dew Point Temp
$T_{dew} \approx 11.7$°C
Specific Volume
$v \approx 0.848$ m^3/kg$_{da}$
Density
$\rho \approx 1/v \approx 1.18$ kg$_{da}$/m^3
Dry Bulb Temp
$T = 22$°C
Wet Bulb Temp
$T_{wb} \approx 15.5$°C
Humidity Ratio
$W \approx 8.2$ g/kg$_{da}$
(i.e., 0.0082 kg/kg)

Revisit another example from two classes ago

Moist air exists at 30°C dry-bulb temperature with a 15°C dew point temperature

Find the following:

(a) the humidity ratio, W

(b) wet-bulb temperature, T_{wb}

(c) enthalpy, h

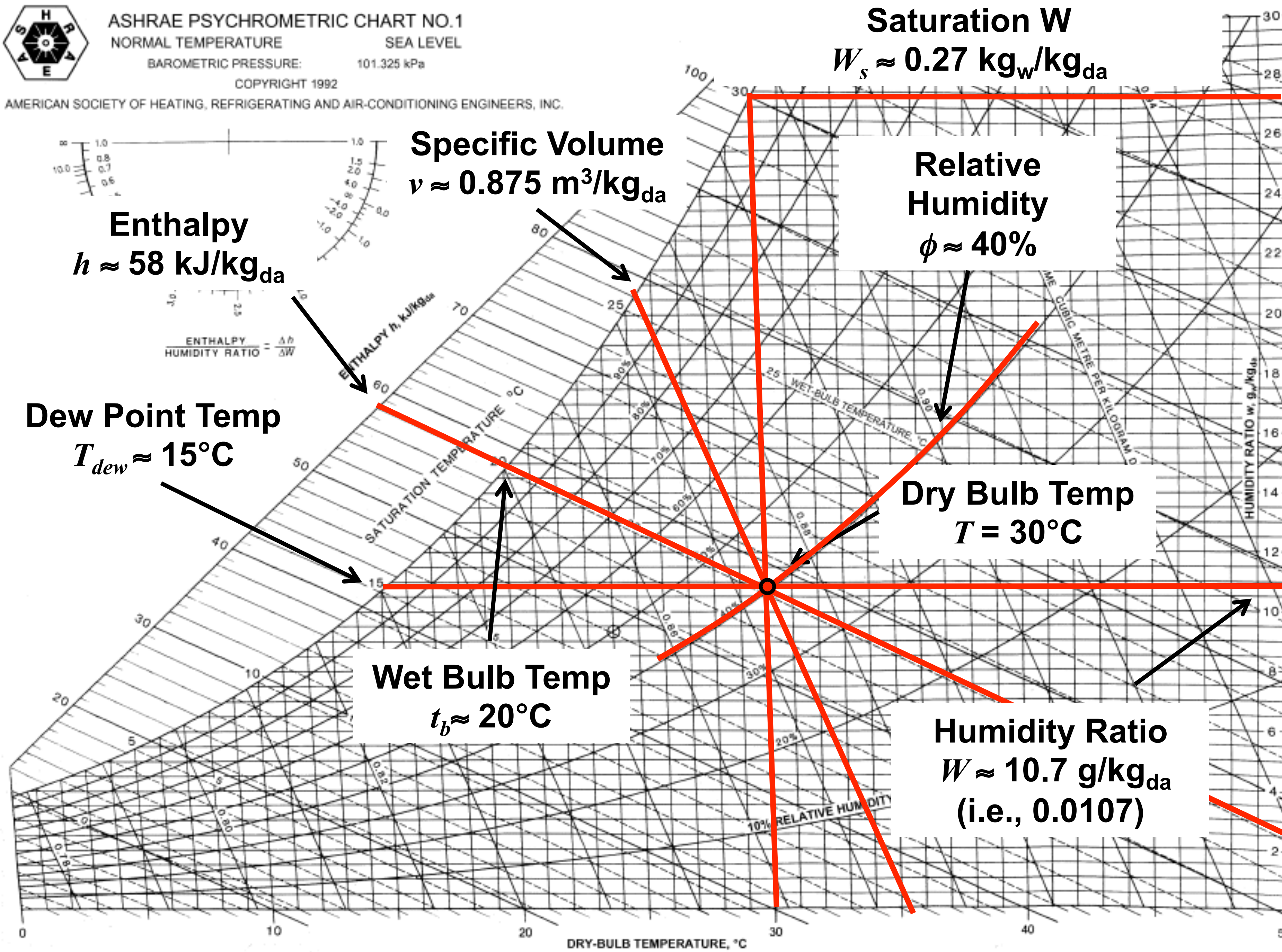
(d) specific volume, v

(e) relative humidity, ϕ

Also:

(f) degree of saturation, μ

(g) density, ρ



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Saturation W
$W_s \approx 0.27\ kg_w/kg_{da}$
Specific Volume
$v \approx 0.875\ m^3/kg_{da}$
Relative Humidity
$\phi \approx 40\%$
Enthalpy
$h \approx 58\ kJ/kg_{da}$
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)
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE °C
CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g/kg da
DRY-BULB TEMPERATURE, °C

Humidity ratio

$$W = 0.622 \left. \frac{p_w}{p - p_w} \right|_{@T=30°C}$$

Assume p = 101.325 kPa (sea level)

- For a known T_{dew} = 15°C, we know that the actual humidity ratio in the air, W, is by definition the same as the saturation humidity ratio, W_s, at an air temperature of 15°C

$$W_{@T=30°C} = W_{s@T=15°C} = 0.622 \left. \frac{p_{ws}}{p - p_{ws}} \right|_{@T=15°C}$$

Temp., °C t	Absolute Pressure p_{ws}, kPa
14	1.5989
15	1.7057

$p_{ws@15C}$ = 1.7057 kPa

$$\boxed{W_{@T=30°C} = W_{s@T=15°C} = 0.622 \frac{1.7057}{101.325 - 1.7057} = 0.01065 \frac{\text{kg}_\text{w}}{\text{kg}_\text{da}}}$$

Degree of saturation

- Need the saturation humidity ratio @ T = 30°C:

$$\mu = \left[\frac{W}{W_s}\right]_{@T=30°C}$$

$$W_{s@T=30°C} = 0.622 \left.\frac{p_{ws}}{p - p_{ws}}\right|_{@T=30°C}$$

Temp., °C t	Absolute Pressure p_{ws}, kPa
30	4.2467
31	4.4966

$p_{ws@15C}$ = 4.2467 kPa

$$W_{s@T=30°C} = 0.622 \frac{4.2467}{101.325 - 4.2467} = 0.02720 \frac{\text{kg}_\text{w}}{\text{kg}_\text{da}}$$

$$\boxed{\mu = \frac{W}{W_s} = \frac{0.01065}{0.02720} = 0.39}$$

Relative humidity

$$\phi = \frac{p_w}{p_{ws}}$$

- From previous:

$$p_{w@T=30^\circ C} = p_{ws@T=15^\circ C} = 1.7057\,kPa$$

$$p_{ws@T=30^\circ C} = 4.2467\,kPa$$

$$\boxed{\phi = \frac{1.7057}{4.2467} = 0.40 = 40\%}$$

Enthalpy

$$h \approx 1.006T + W(2501 + 1.86T)$$

*where T is in °C

$$\boxed{h \approx 1.006(30) + (0.01065)(2501 + 1.86(30)) = 57.4\,\frac{\text{kJ}}{\text{kg}}}$$

Specific volume and density

$$v \approx 0.287042(T + 273.15)(1 + 1.6078W) / p$$

$$v \approx 0.287042(30 + 273.15)(1 + 1.6078(0.01065)) / (101.325)$$

$$\boxed{v \approx 0.873 \frac{\text{m}^3}{\text{kg}_{\text{da}}}}$$

$$\boxed{\rho = \frac{1}{v}\left(1 + W\right) = \frac{1}{0.873}\left(1 + 0.01065\right) = 1.157 \frac{\text{kg}}{\text{m}^3}}$$

Wet-bulb temperature

- Wet-bulb temperature is the T_{wb} that fits this equation:

$$W = \frac{(2501 - 2.326T_{wb})W_{s@T_{wb}} - 1.006(T - T_{wb})}{2501 + 1.86T - 4.186T_{wb}} = 0.01065$$

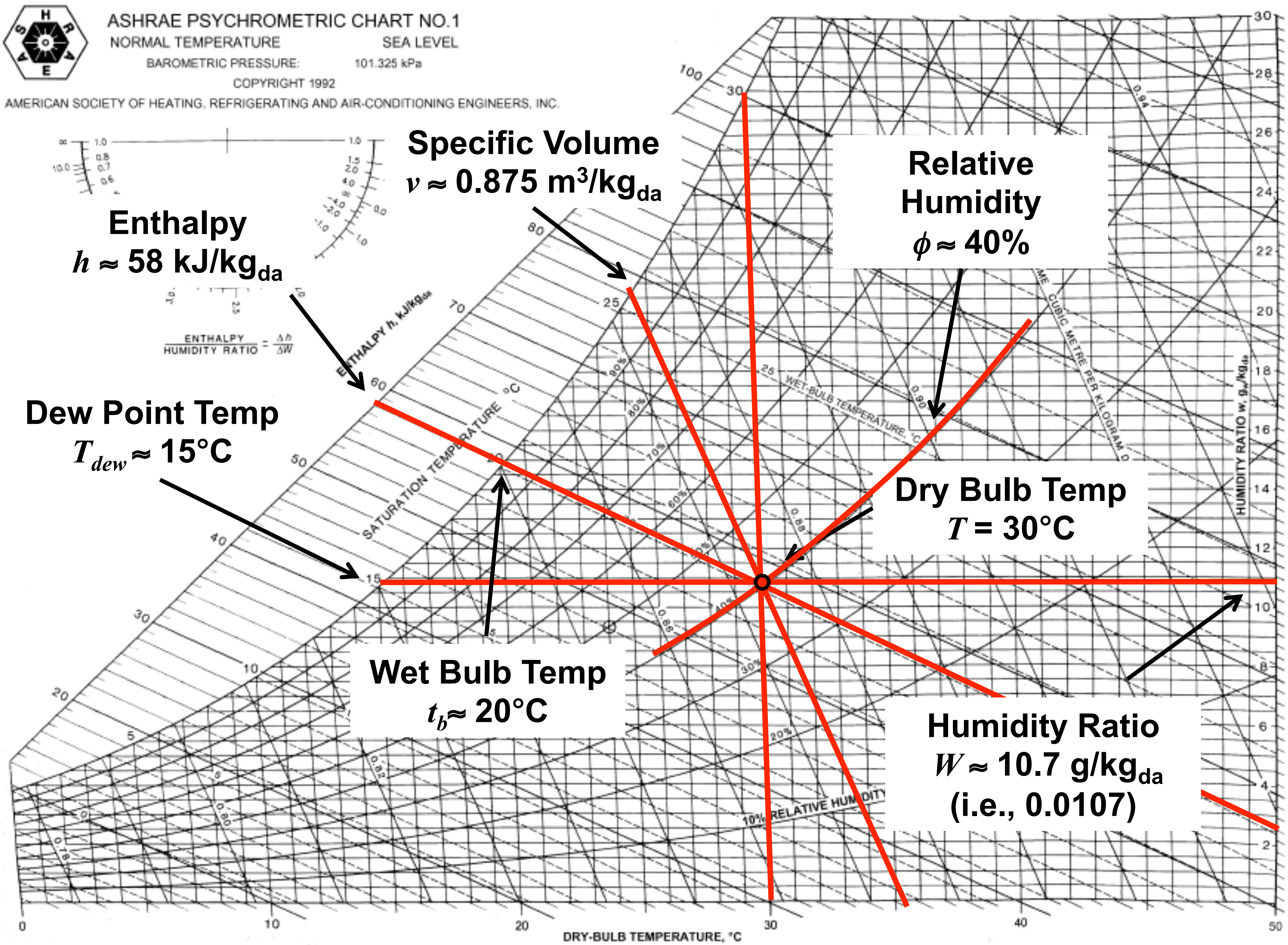
where: $T = 30°C$, $T_{wb} = ?°C$

$$W_{s@T_{wb}=?} = 0.622 \left. \frac{p_{ws}}{p - p_{ws}} \right|_{@T_{wb}=?}$$

Procedure:

- Guess T_{wb}, calculate pws for that T, calculate W_s for that T
  – Repeat until W calculated based on those values (and original T) in equation above is equal to actual W (0.01065 in our case)

$$\boxed{T_{wb} = 20.1°C}$$



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NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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Specific Volume
v ≈ 0.875 m³/kg_da
Relative Humidity
ϕ ≈ 40%
Enthalpy
h ≈ 58 kJ/kg_da
Dew Point Temp
T_dew ≈ 15°C
Dry Bulb Temp
T = 30°C
Wet Bulb Temp
t_b ≈ 20°C
Humidity Ratio
W ≈ 10.7 g/kg_da
(i.e., 0.0107)
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg_da
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE, °C
CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO W, g_w/kg_da
DRY-BULB TEMPERATURE, °C

PSYCHROMETRIC PROCESSES

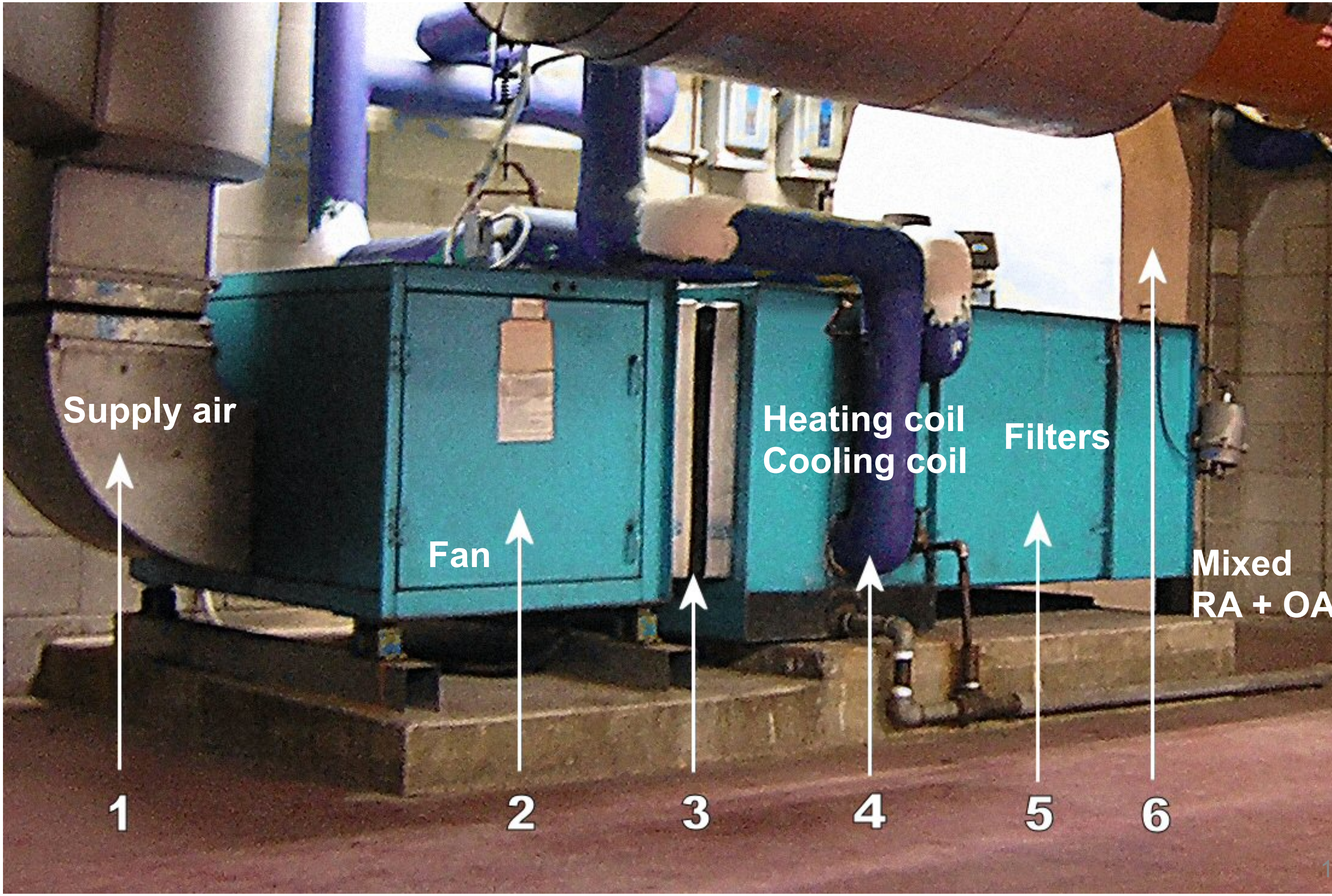
Use of the psychrometric chart for *processes*

We can use the psychrometric chart 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

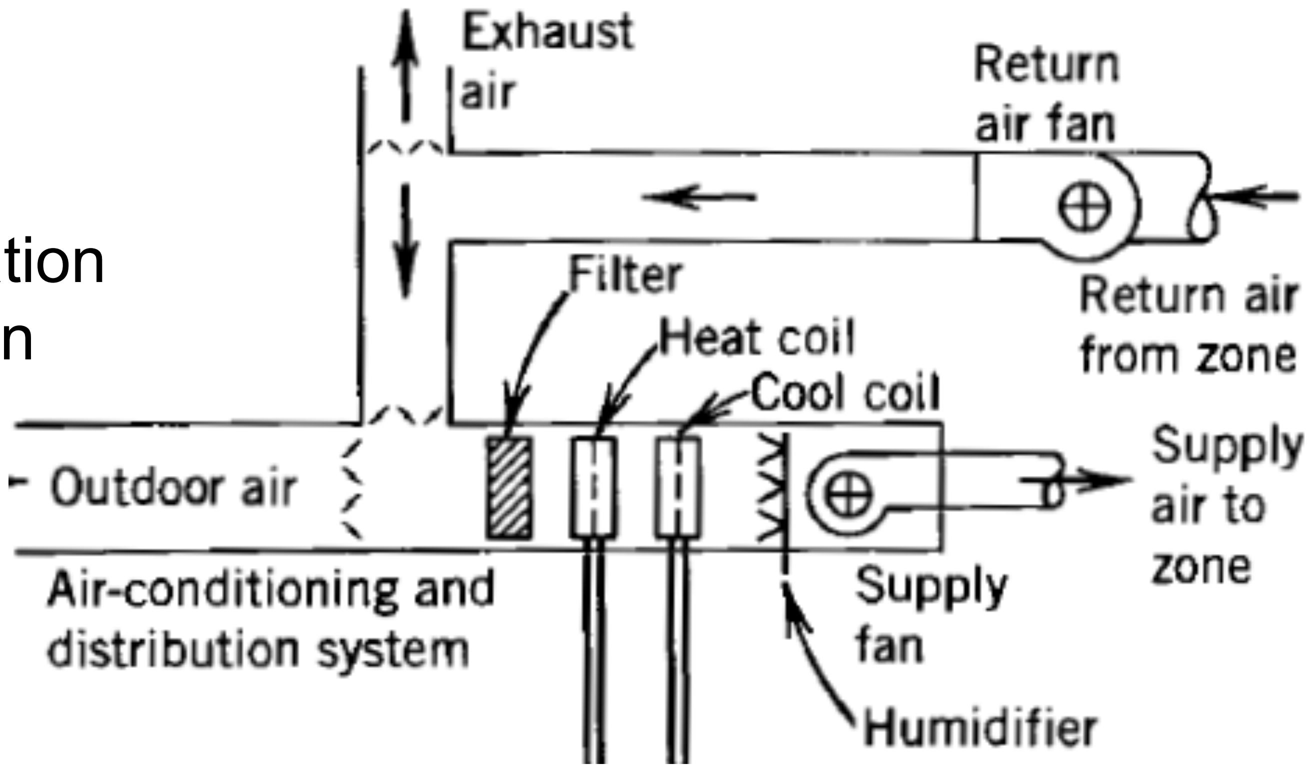
Typical commercial HVAC system air handler



Typical forced air distribution system

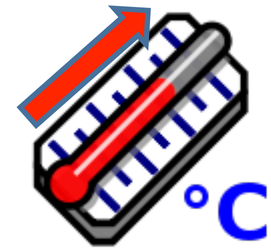
Common processes:

- Air mixing
- Heating
- Cooling
- Dehumidification
- Humidification

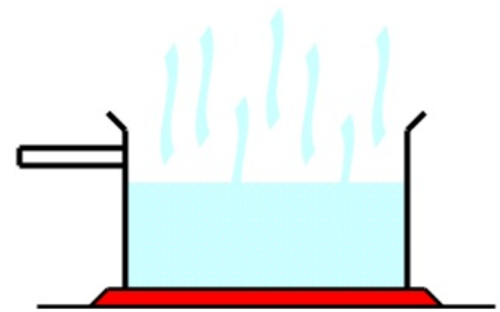


Sensible and latent heat

- **Sensible heat transfer**
  - Increases or decreases 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 req'd to change liquid to vapor)



$$Q_{total} = Q_{sensible} + Q_{latent} \qquad Q_{total} = \dot{m}_{air}(h_{exit} - h_{inlet})$$

Sensible heat transfer equation

$$Q_{sens} = \dot{m} c_p (T_{exit} - T_{inlet}) = \dot{V} \rho c_p (T_{exit} - T_{inlet})$$

Q_{sens} = Rate of sensible heat xfer [Btu/hr or ton or W]

$\dot{m}$ = mass rate of air flow [lbm/hr or kg/s]

$\dot{V}$ = volumetric flow rate of air [ft^3/hr or cfm or m^3/s]

ρ = density of air [lbm/ft^3 or kg/m^3]

c_p = specific heat of air [Btu/(lbm-F) or J/(kg-K)]

T_{exit}, T_{inlet} = exit and inlet temperature [°F or °C]

$Q_{sens} > 0$ for heating

$Q_{sens} < 0$ for cooling

Latent heat transfer equation

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

Q_{lat} = rate of latent heat transfer [Btu/hr or ton or W]

Q_{lat} is positive for humidification processes

$\dot{m}_w$ = rate of evaporation/condensation [lbm/hr or kg/s]

h_{fg} = enthalpy of vaporization [Btu/lbm or J/kg]

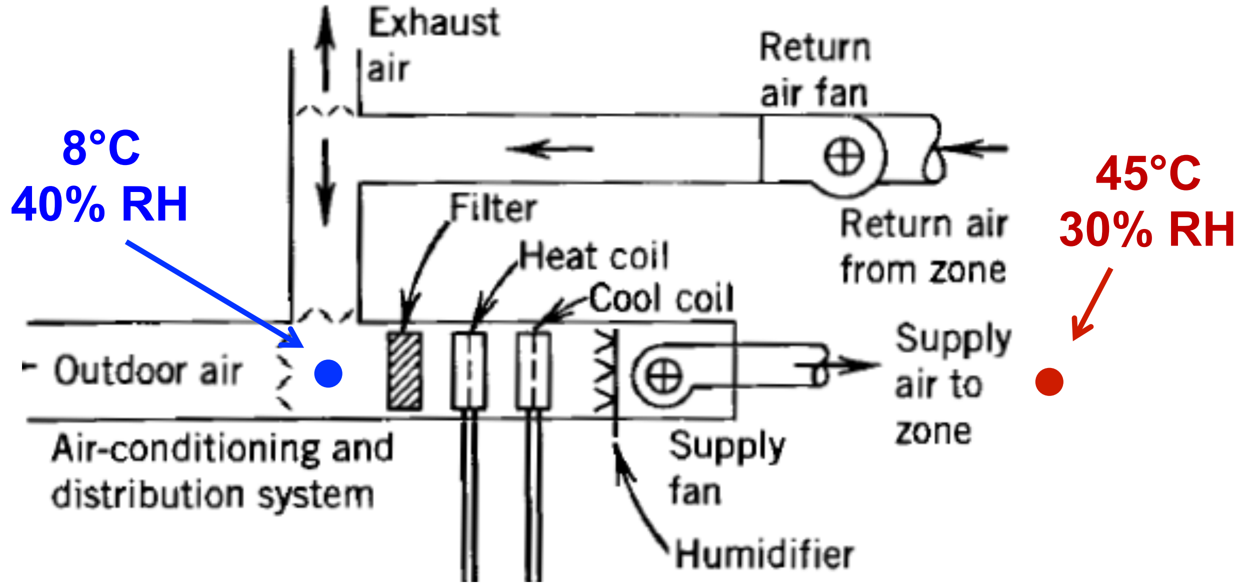
also called latent heat of vaporization

(h_{fg} = 2260 kJ/kg for water)

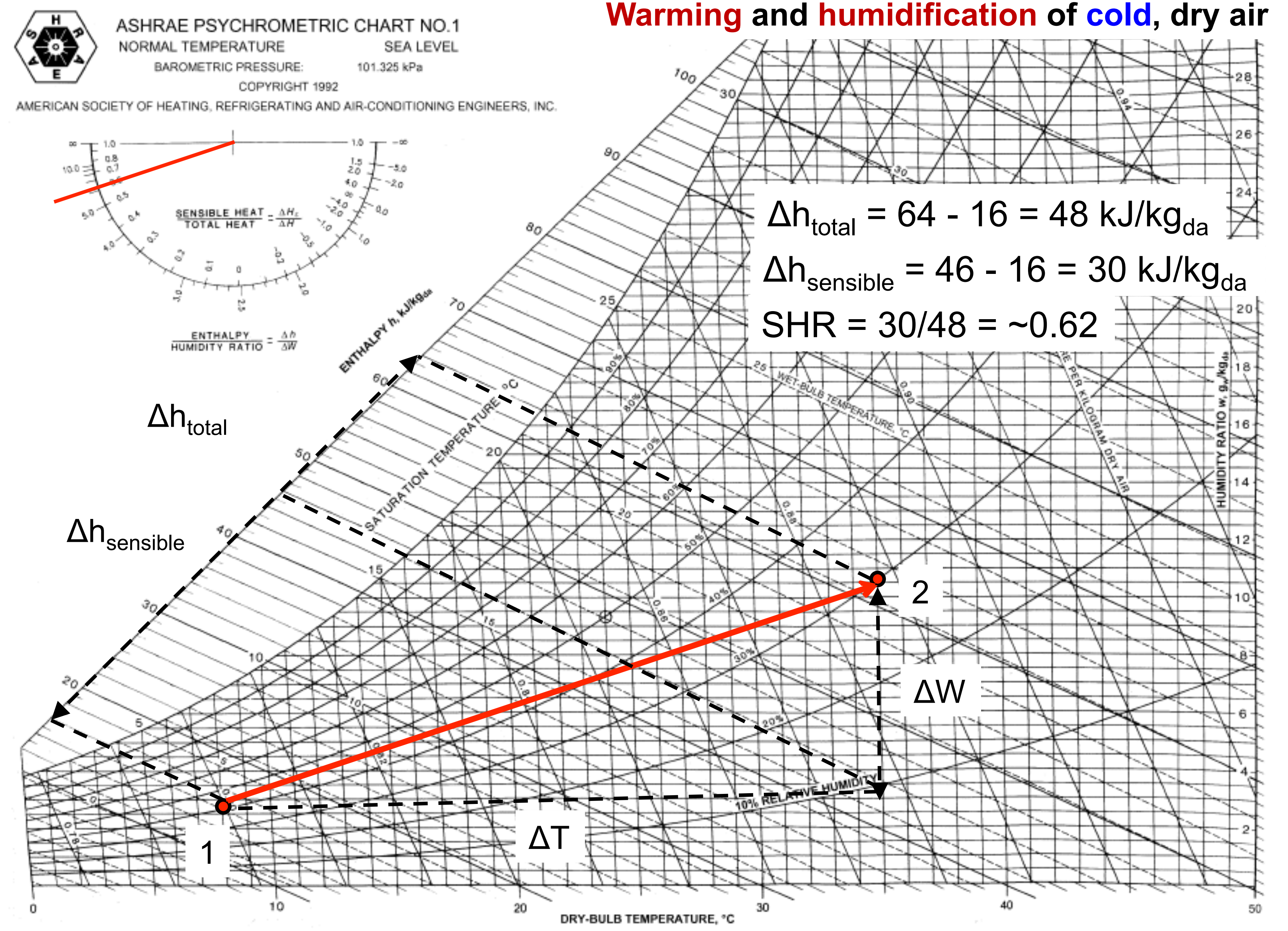
Heating and humidification of cold, dry air

- Example: Heating and humidifying coils
  - Process: Adding moisture and heat (sensible + latent heating)

Q1: What is the enthalpy change required?
Q2: What is the split between sensible and latent load?



Warming and humidification of cold, dry air



Δh_{total} = 64 - 16 = 48 kJ/kg$_{da}$

$\Delta h_{sensible}$ = 46 - 16 = 30 kJ/kg$_{da}$

SHR = 30/48 = ~0.62

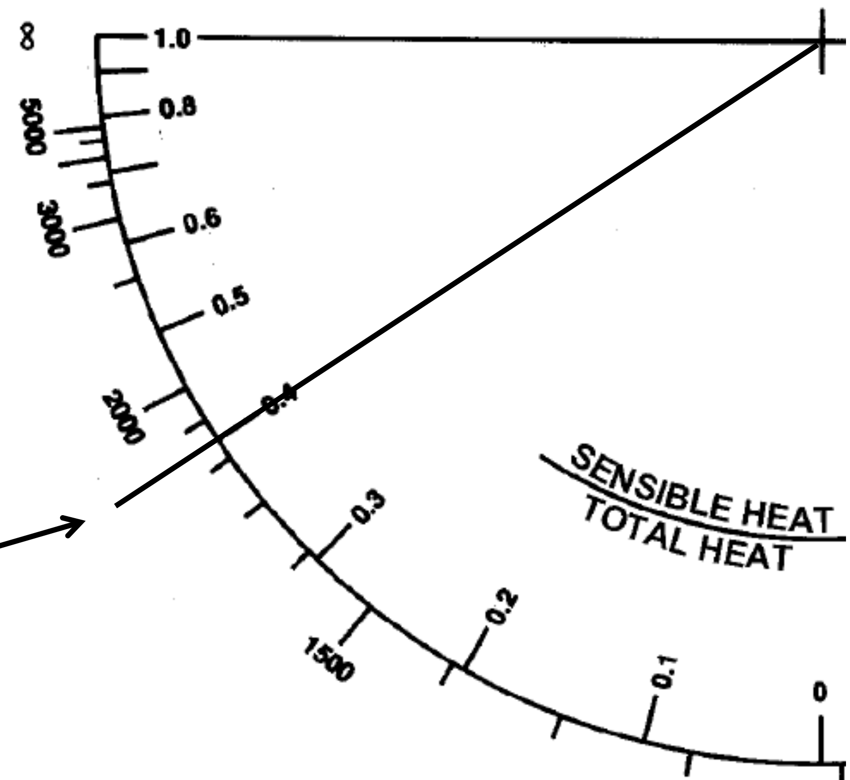
Sensible heat ratio (SHR)

- 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

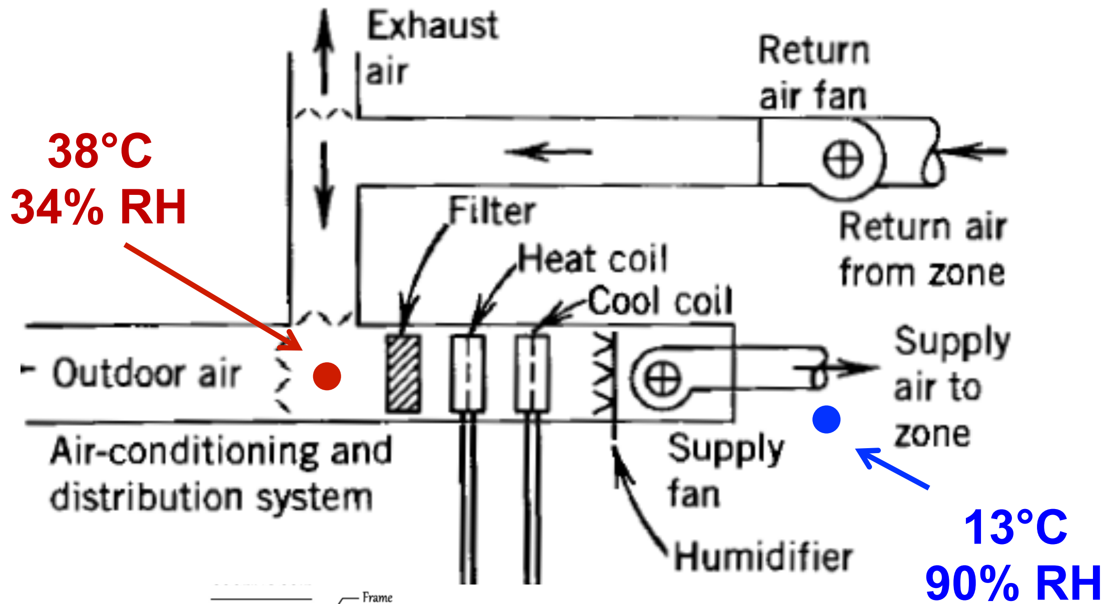
- Typical SHR: 0.6 to 0.9

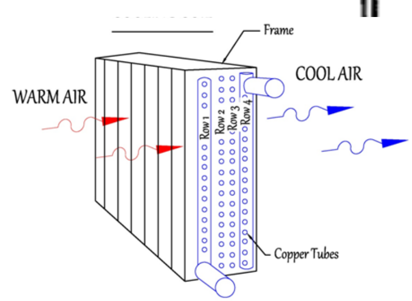


Here is a process with an SHR ≈ 0.4

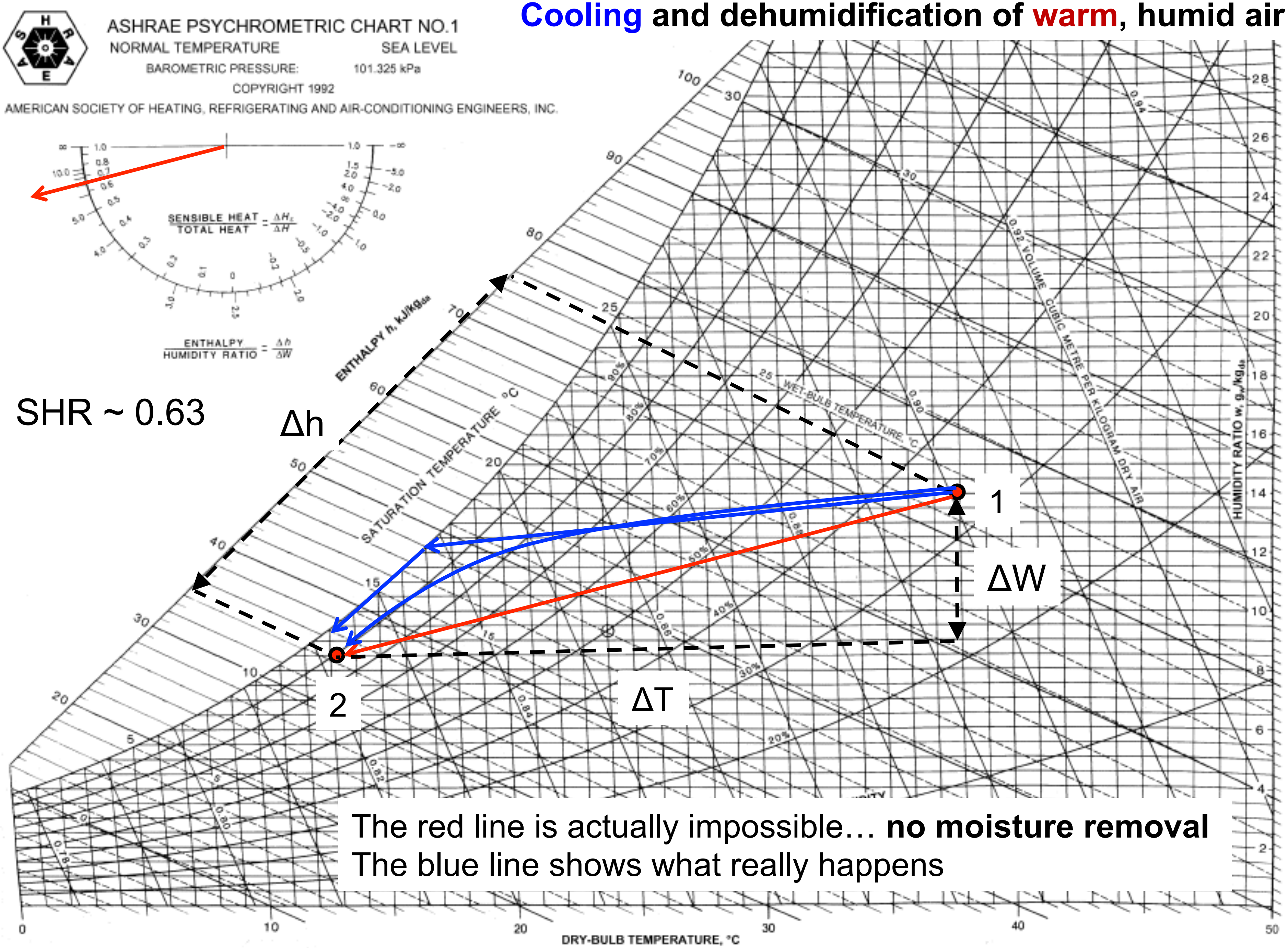
Cooling and dehumidification of warm, humid air

- Example: Cooling coil
- Removing both moisture and heat
  - Sensible + latent cooling





Cooling and dehumidification of warm, humid air

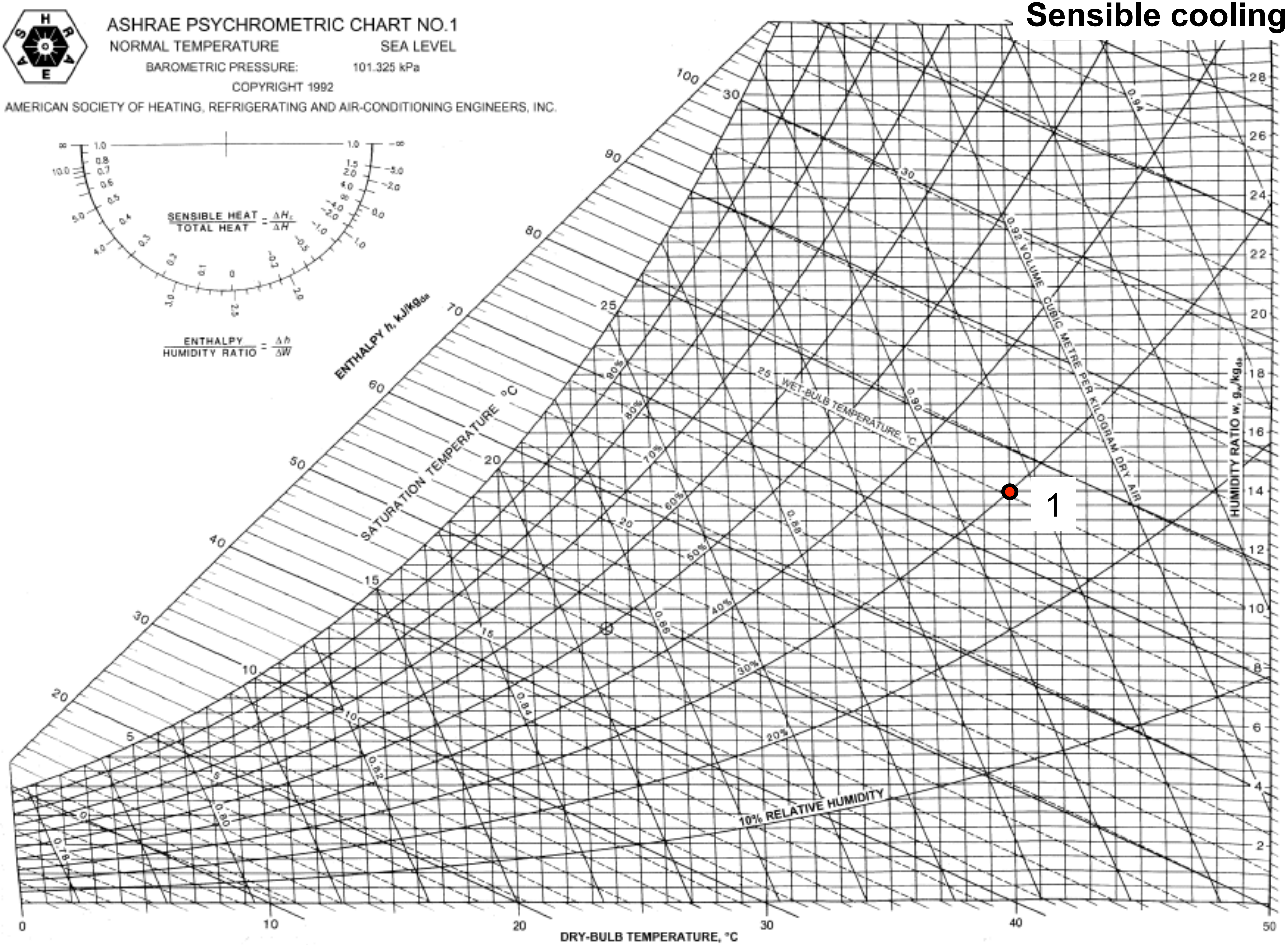


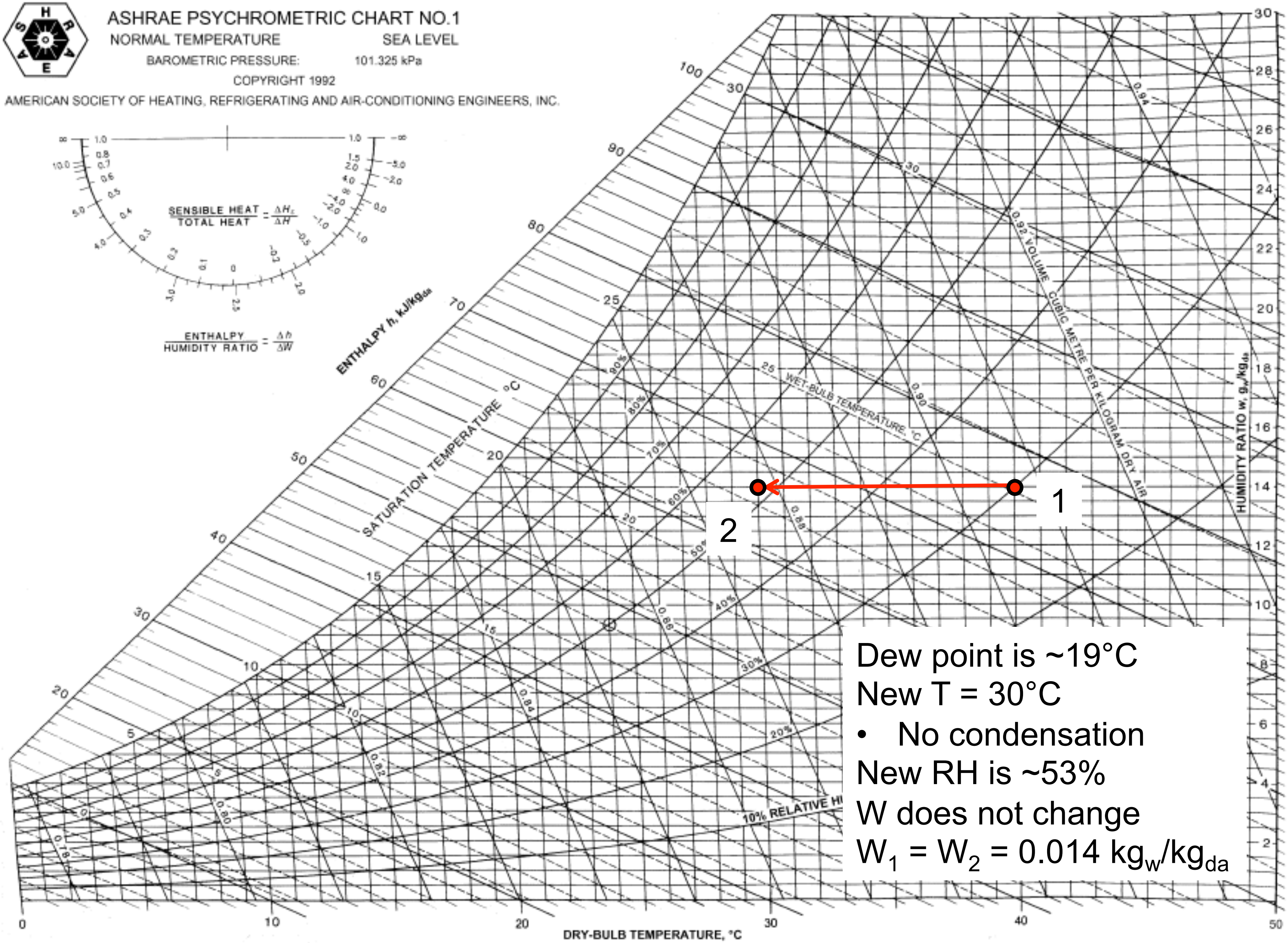
The red line is actually impossible… **no moisture removal**
The blue line shows what really happens

Example: *Sensible* cooling

- Moist air is cooled from 40°C and 30% RH to 30°C
  - Q1: Does the moisture condense?
  - Q2: What is the RH at W at the process end point?
  - Q3: What is the rate of sensible heat transfer if the airflow rate is 1000 ft^3/min?

Sensible cooling





Dew point is ~19°C

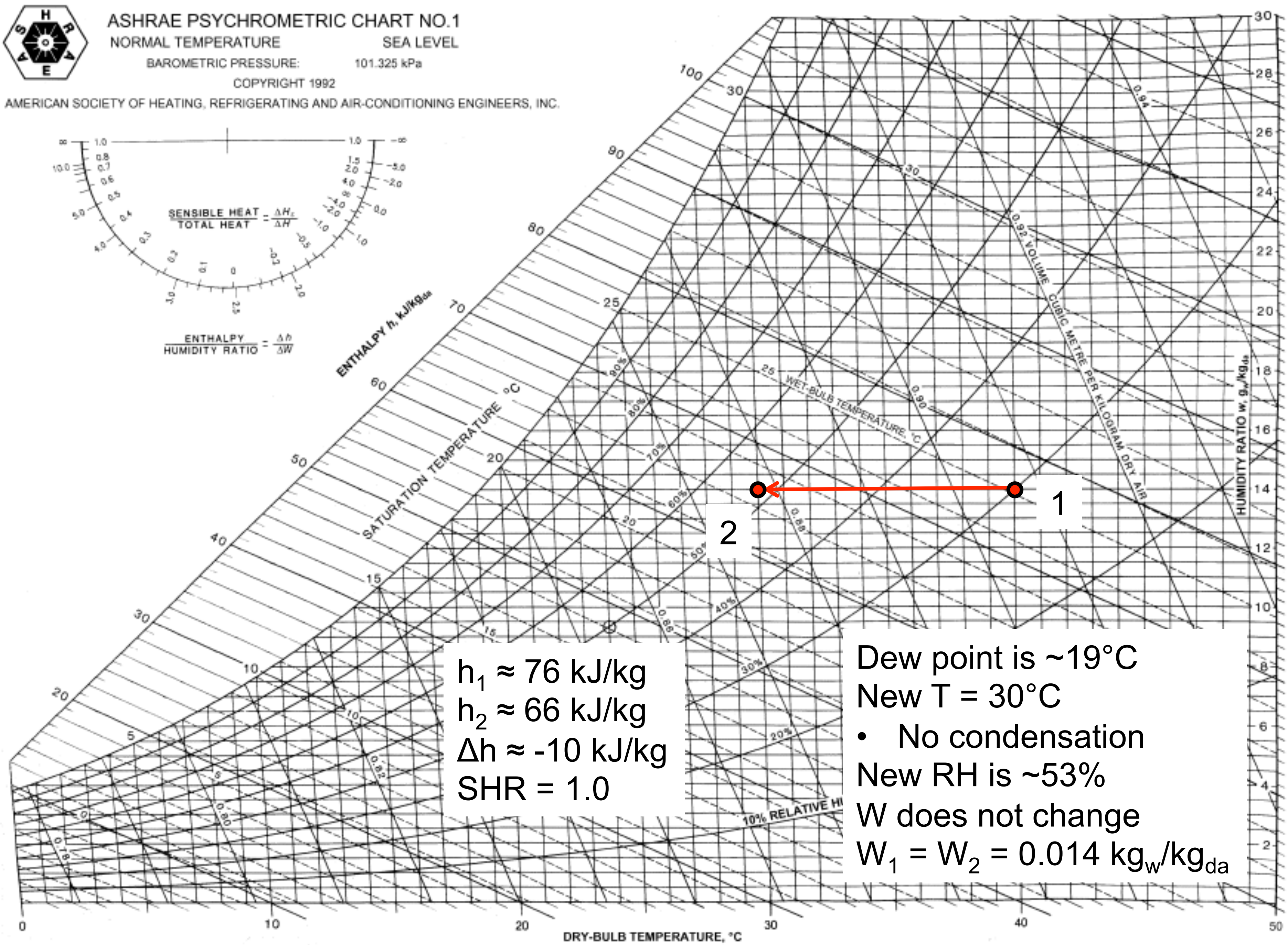
New T = 30°C

- No condensation

New RH is ~53%

W does not change

$W_1 = W_2 = 0.014\ kg_w/kg_{da}$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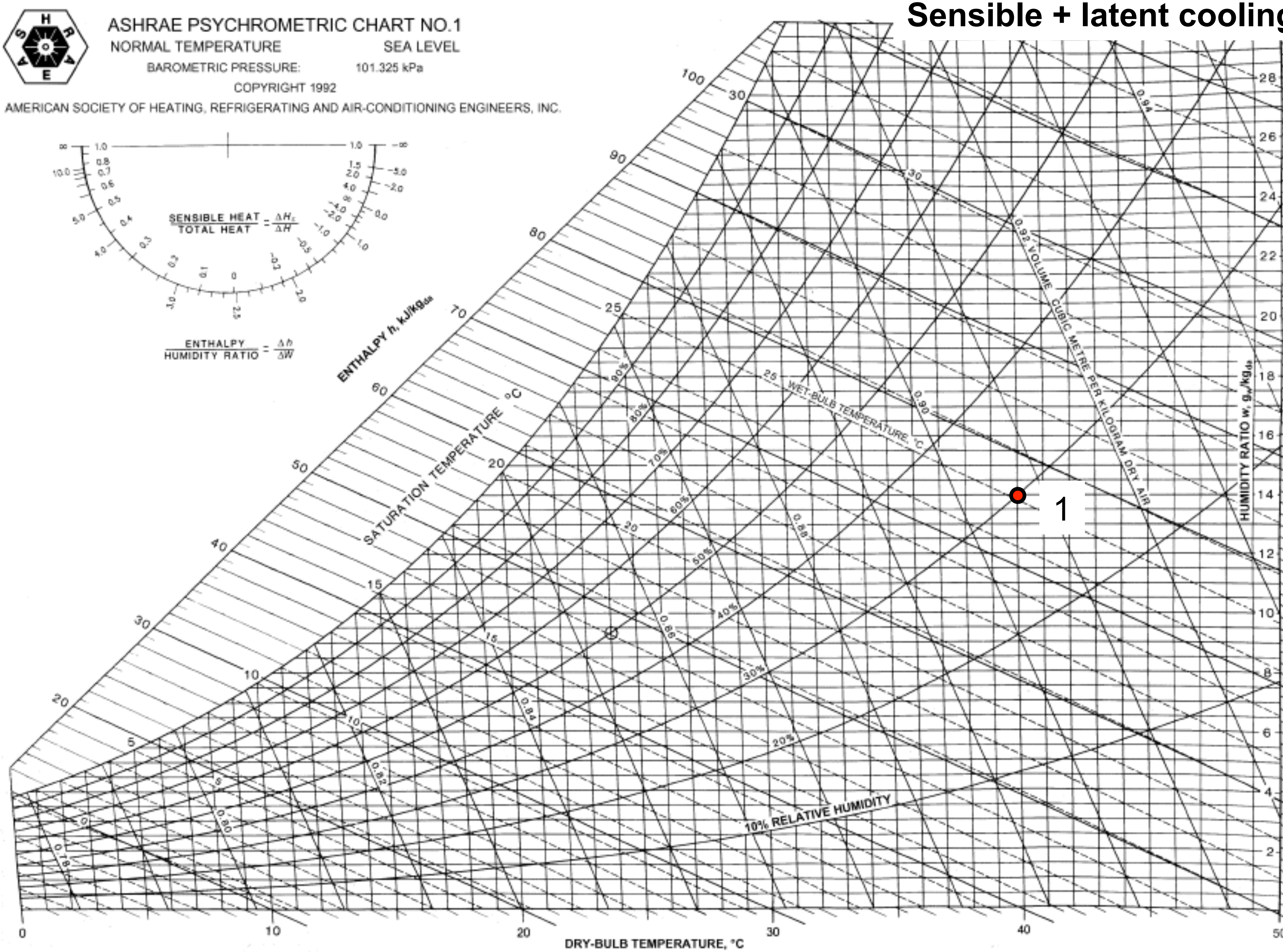
SENSIBLE HEAT / TOTAL HEAT = $\Delta H_s / \Delta H$
ENTHALPY / HUMIDITY RATIO = $\Delta h / \Delta W$
ENTHALPY h, kJ/kg_da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g_w/kg_da
DRY-BULB TEMPERATURE, °C
1
2
$h_1 \approx 76$ 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
$W_1 = W_2 = 0.014\ kg_w/kg_{da}$

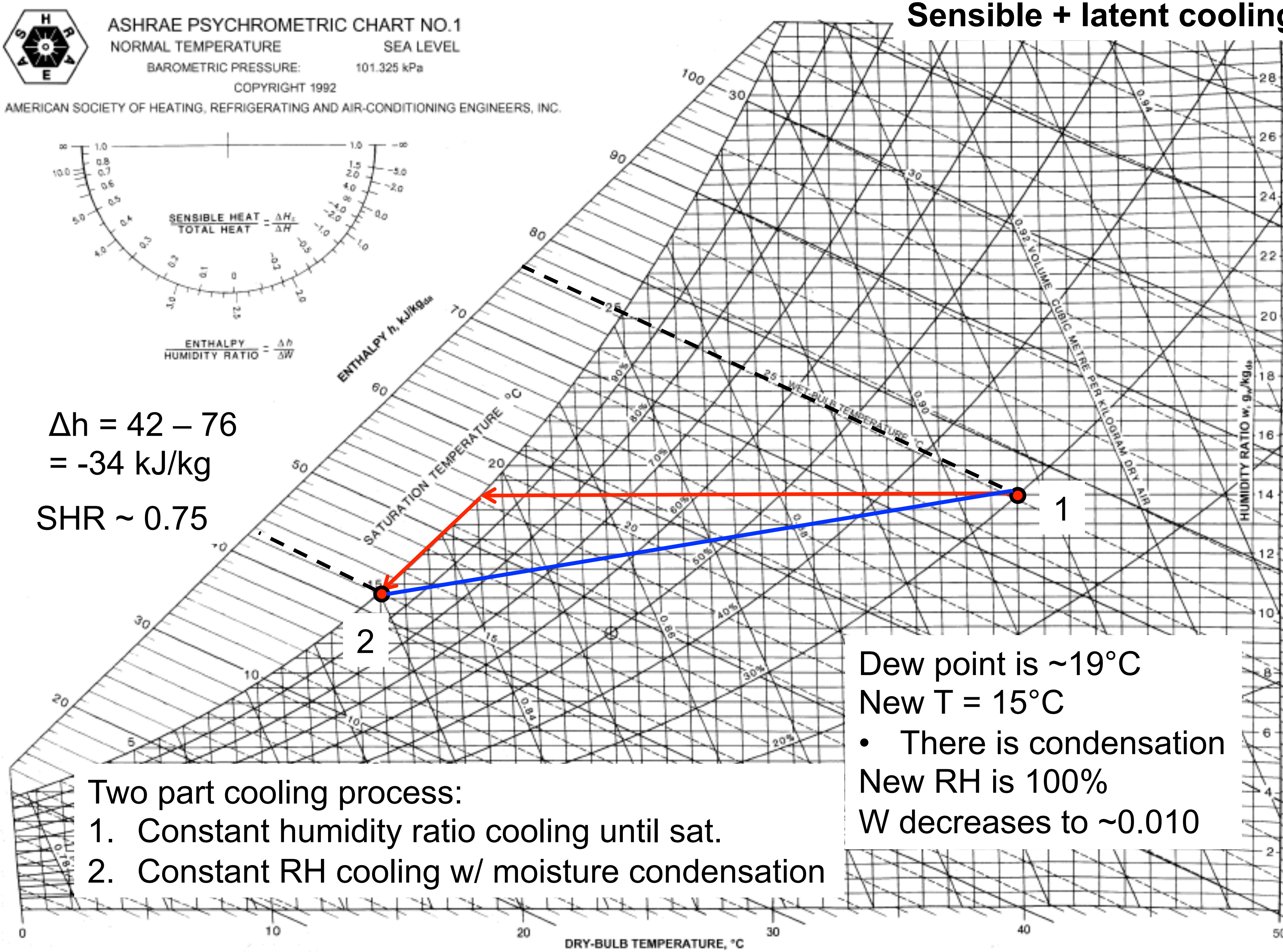
Example: *Sensible* + *latent* cooling

- Moist air is cooled from 40°C and 30% RH to 15°C
  - Q1: Does the moisture condense?
  - Q2: What is RH at W at the process end point?
  - Q3: What is the rate of heat transfer if the airflow rate is 1000 ft^3/min?

Sensible + latent cooling



Sensible + latent cooling



Δh = 42 – 76
= -34 kJ/kg

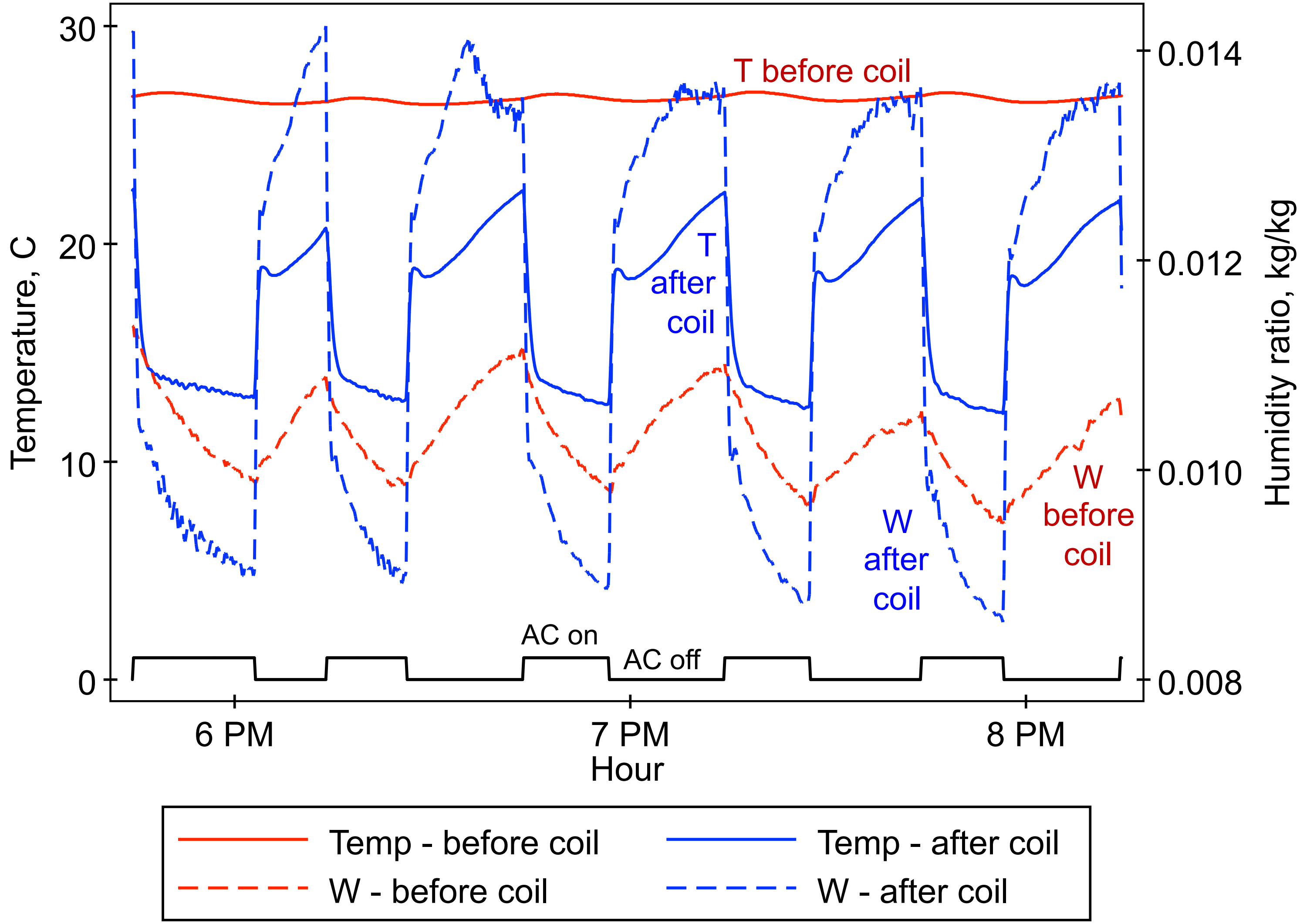
SHR ~ 0.75

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 sat.
2. Constant RH cooling w/ moisture condensation

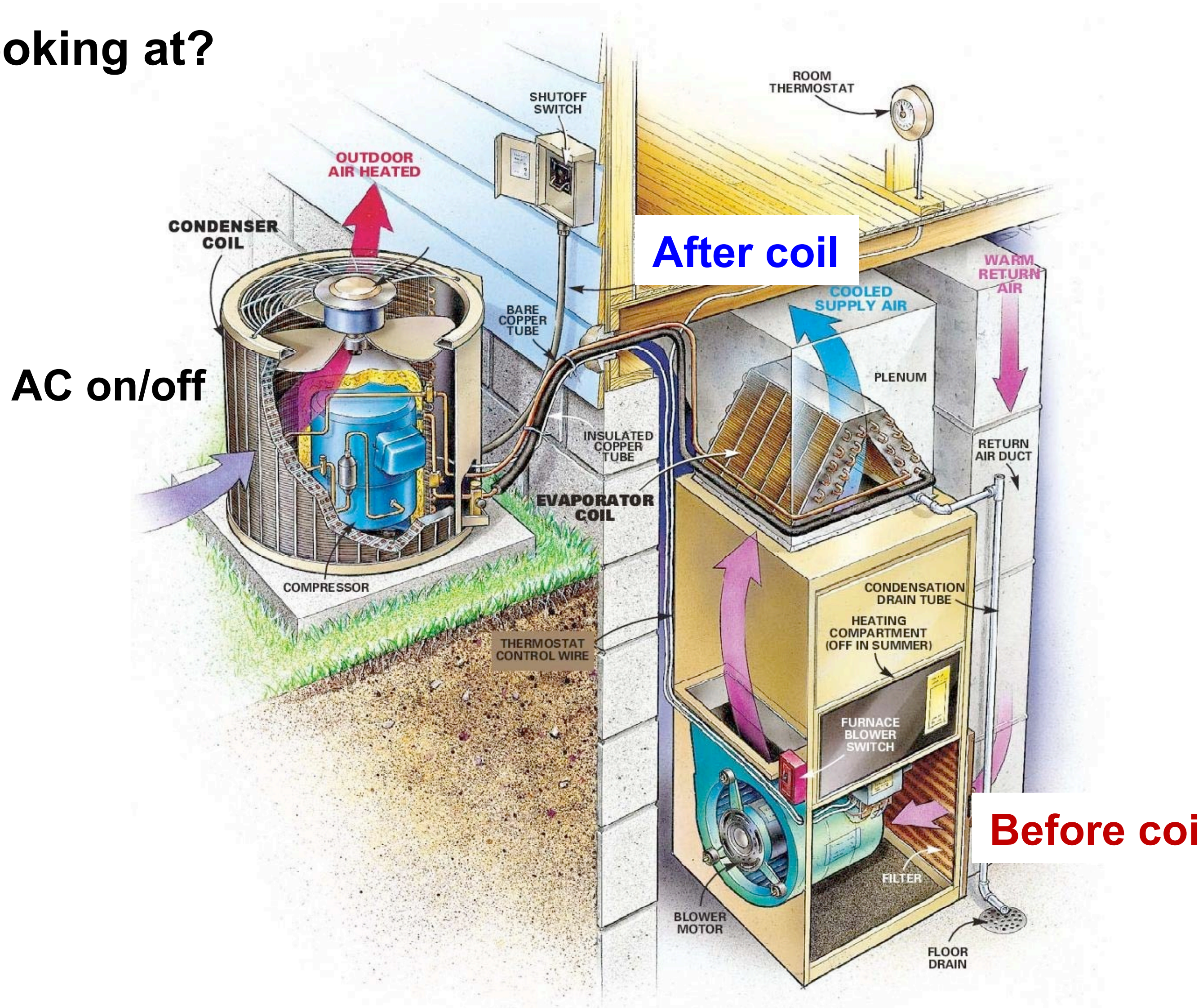
Real data: ASHRAE RP-1299
Energy implications of filters

Temperature and humidity ratio differences across AC coils in homes

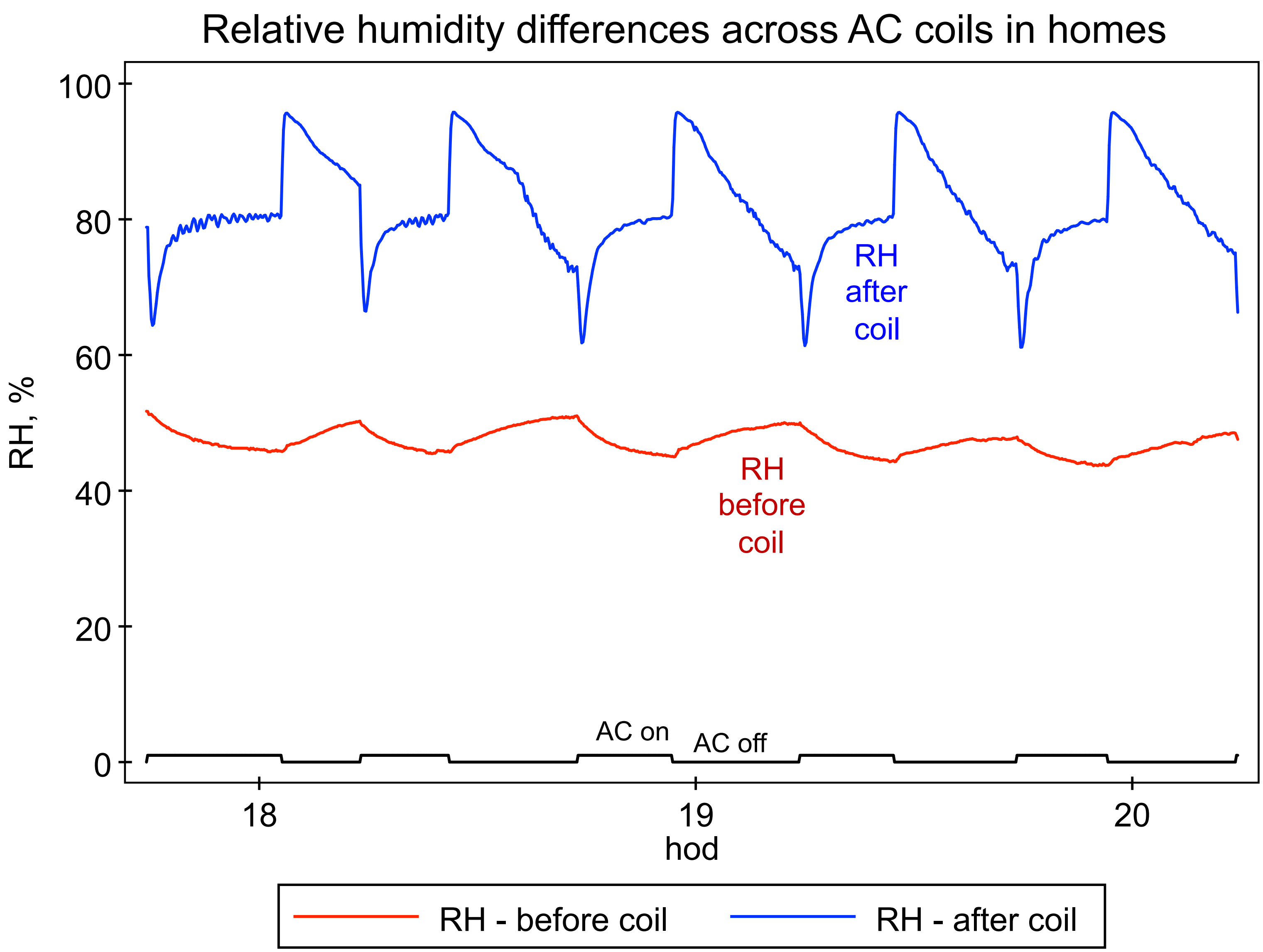


Real data: ASHRAE RP-1299
Energy implications of filters

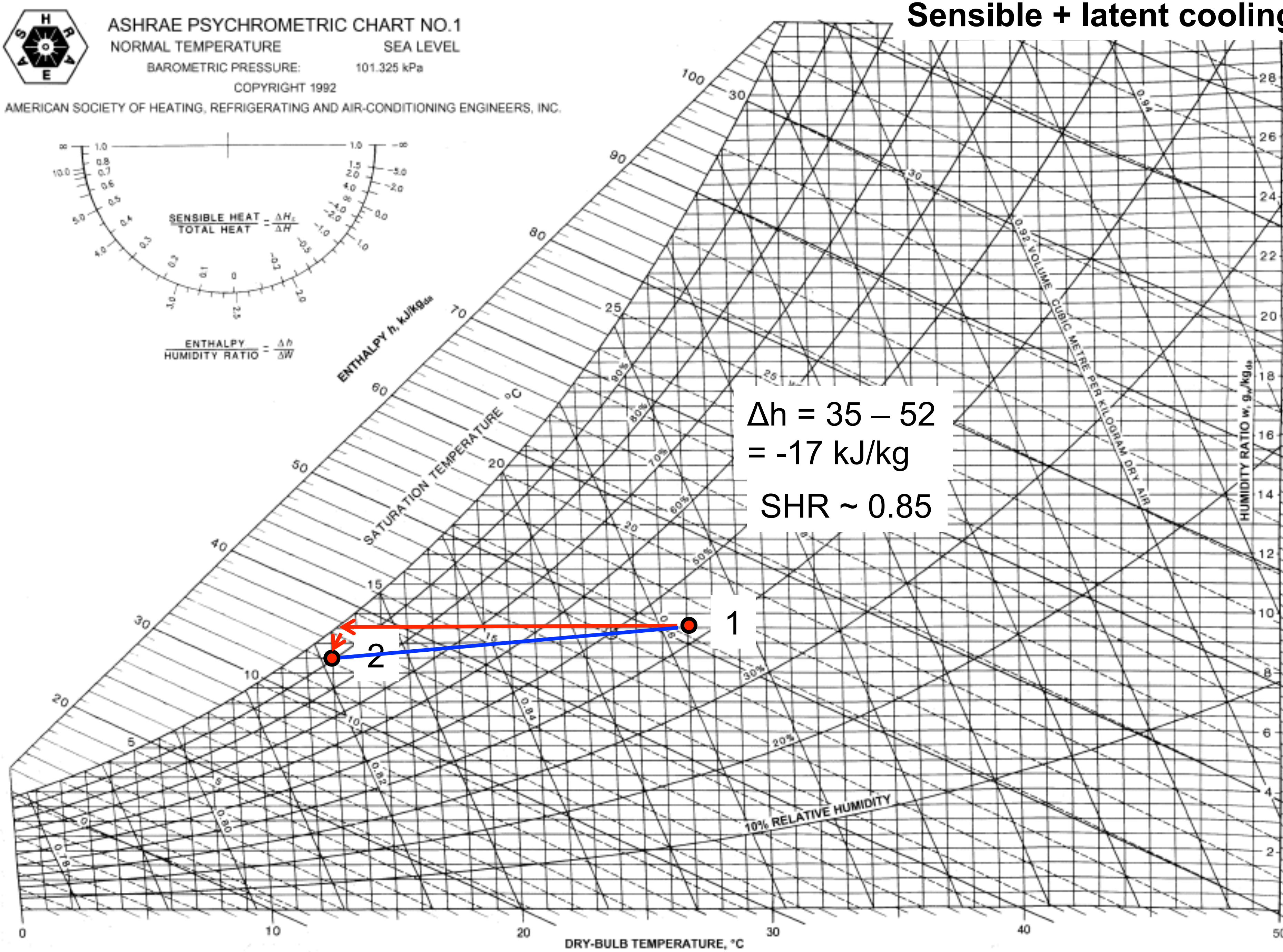
What are we looking at?



Real data: ASHRAE RP-1299
Energy implications of filters



Sensible + latent cooling



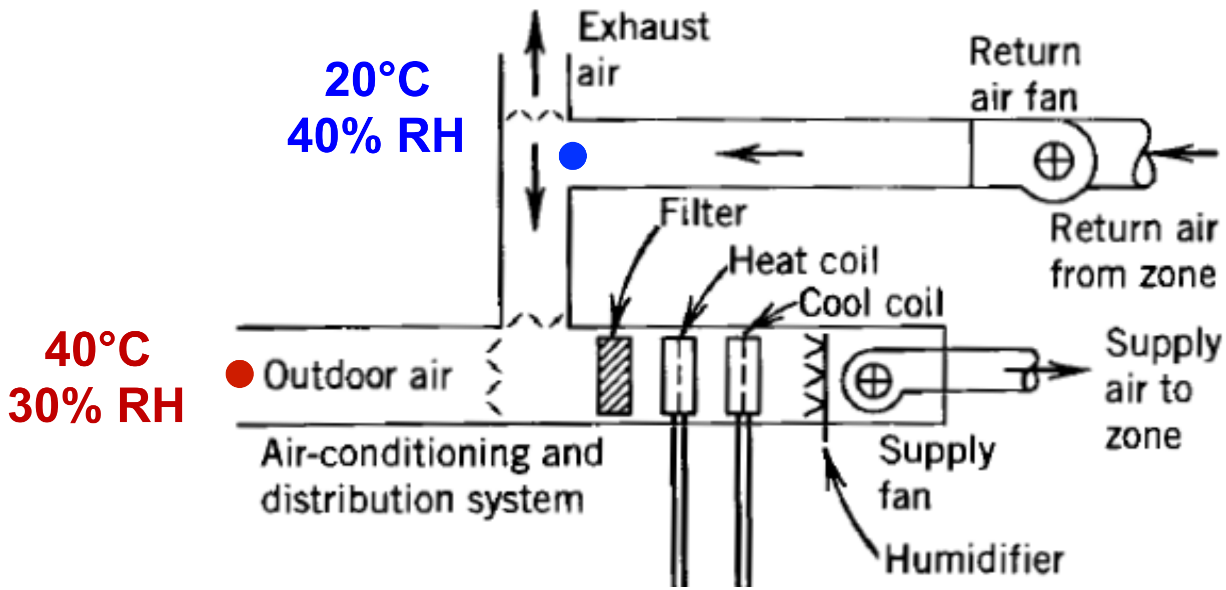
Mixing of air streams

- 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

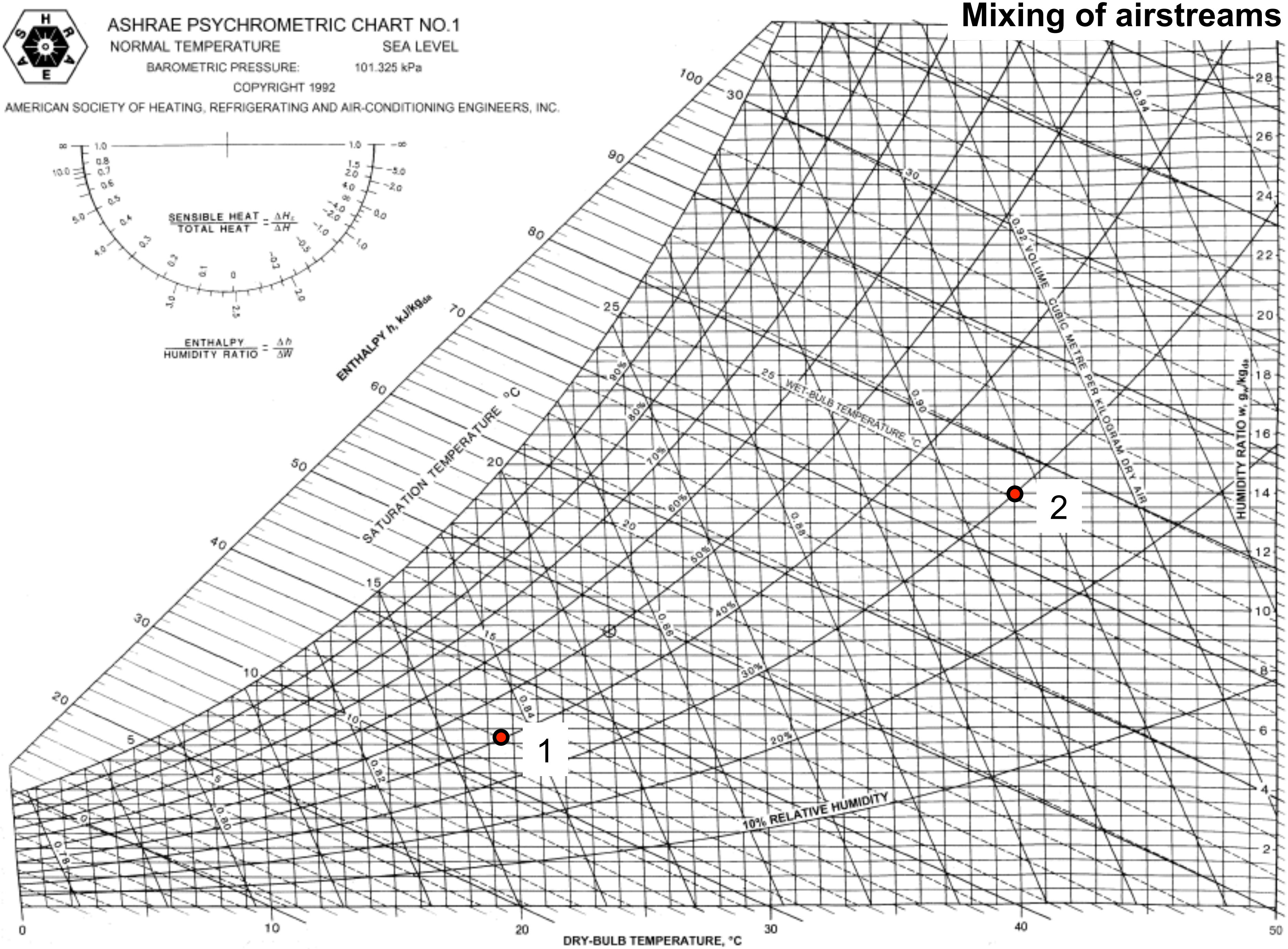
- For most parameters, the outlet conditions end up being the weighted-averages of the input conditions
  - Dry bulb temperature
  - Humidity ratio
  - Enthalpy
  - (not wet-bulb temperature or RH though)

Mixing of airstreams example

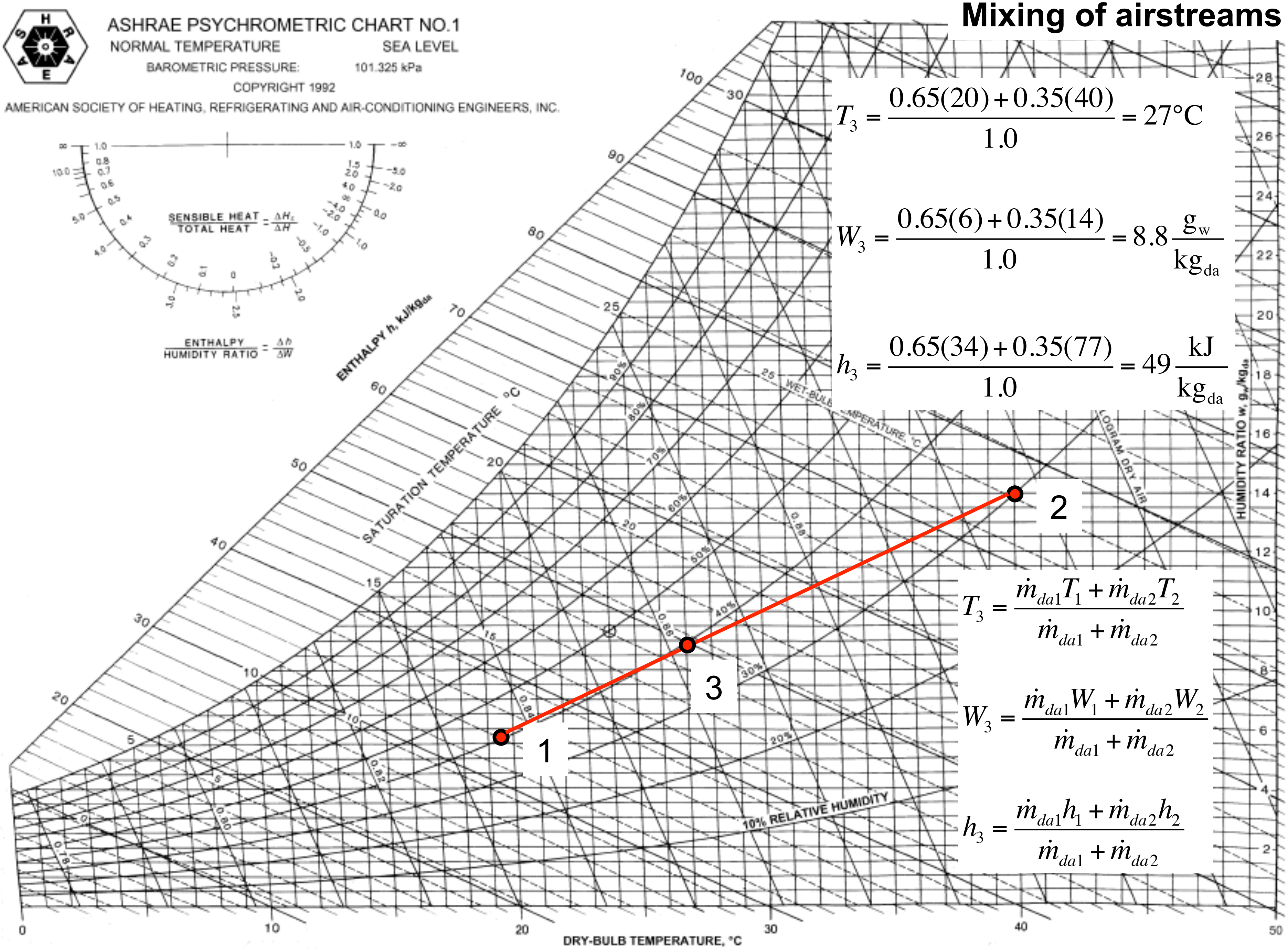
- Hot, humid outdoor air is mixed with recirculated indoor air at an outdoor air fraction of about 35%
  - Q1: What is T, W, RH, and h at the mixed condition?



Mixing of airstreams



Mixing of airstreams



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

$$W_3 = \frac{0.65(6)+0.35(14)}{1.0} = 8.8\,\frac{\text{g}_\text{w}}{\text{kg}_\text{da}}$$

$$h_3 = \frac{0.65(34)+0.35(77)}{1.0} = 49\,\frac{\text{kJ}}{\text{kg}_\text{da}}$$

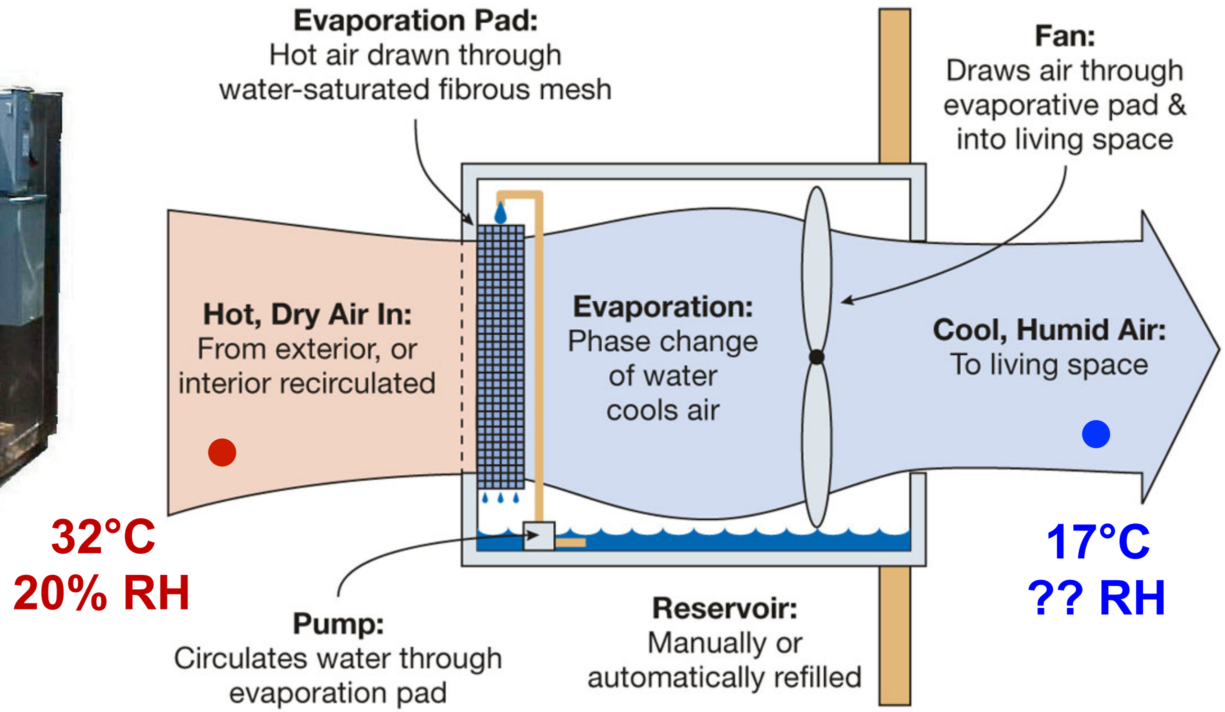
$$T_3 = \frac{\dot{m}_{da1}T_1 + \dot{m}_{da2}T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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

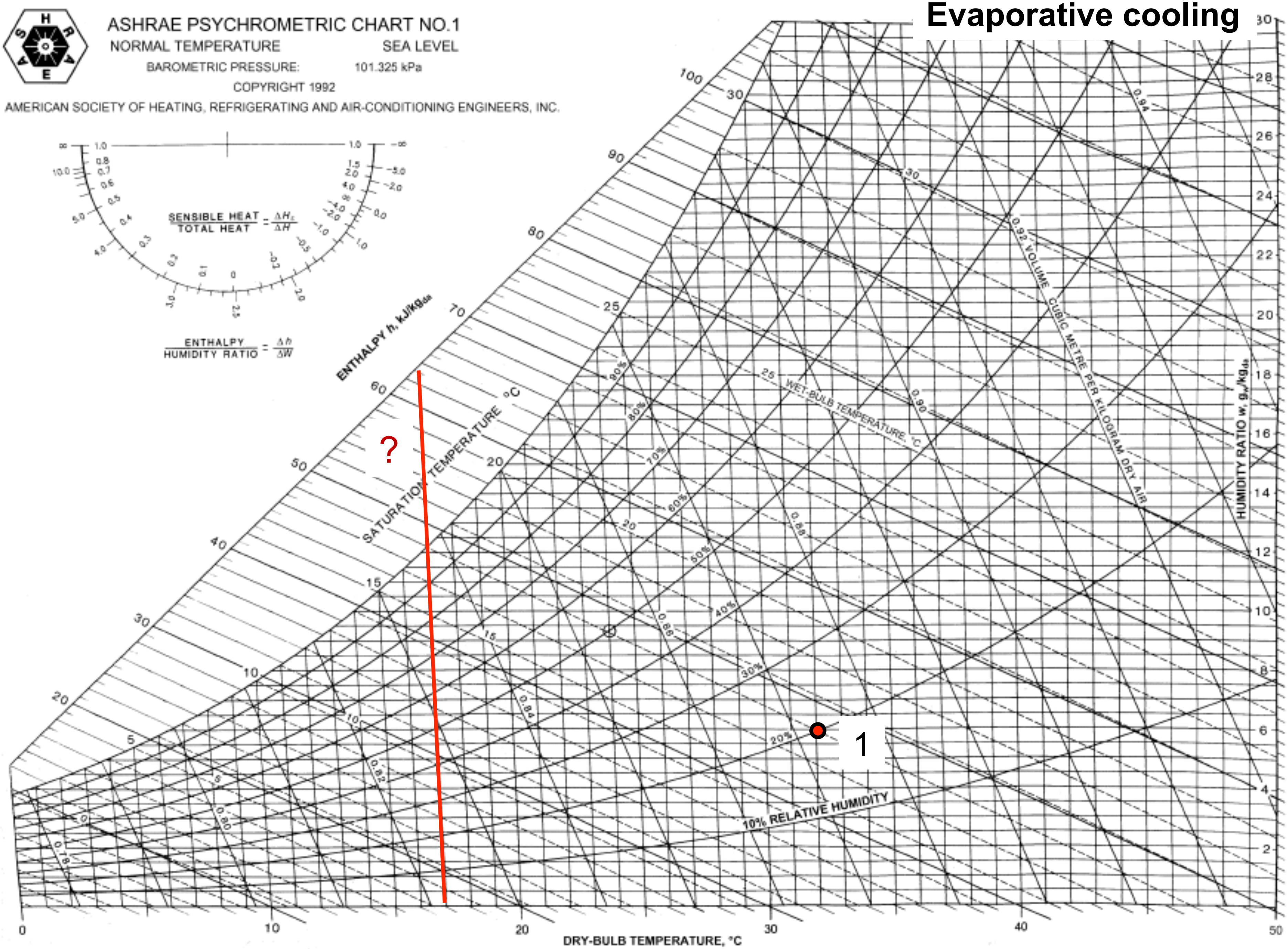
$$h_3 = \frac{\dot{m}_{da1}h_1 + \dot{m}_{da2}h_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

Evaporative cooling example

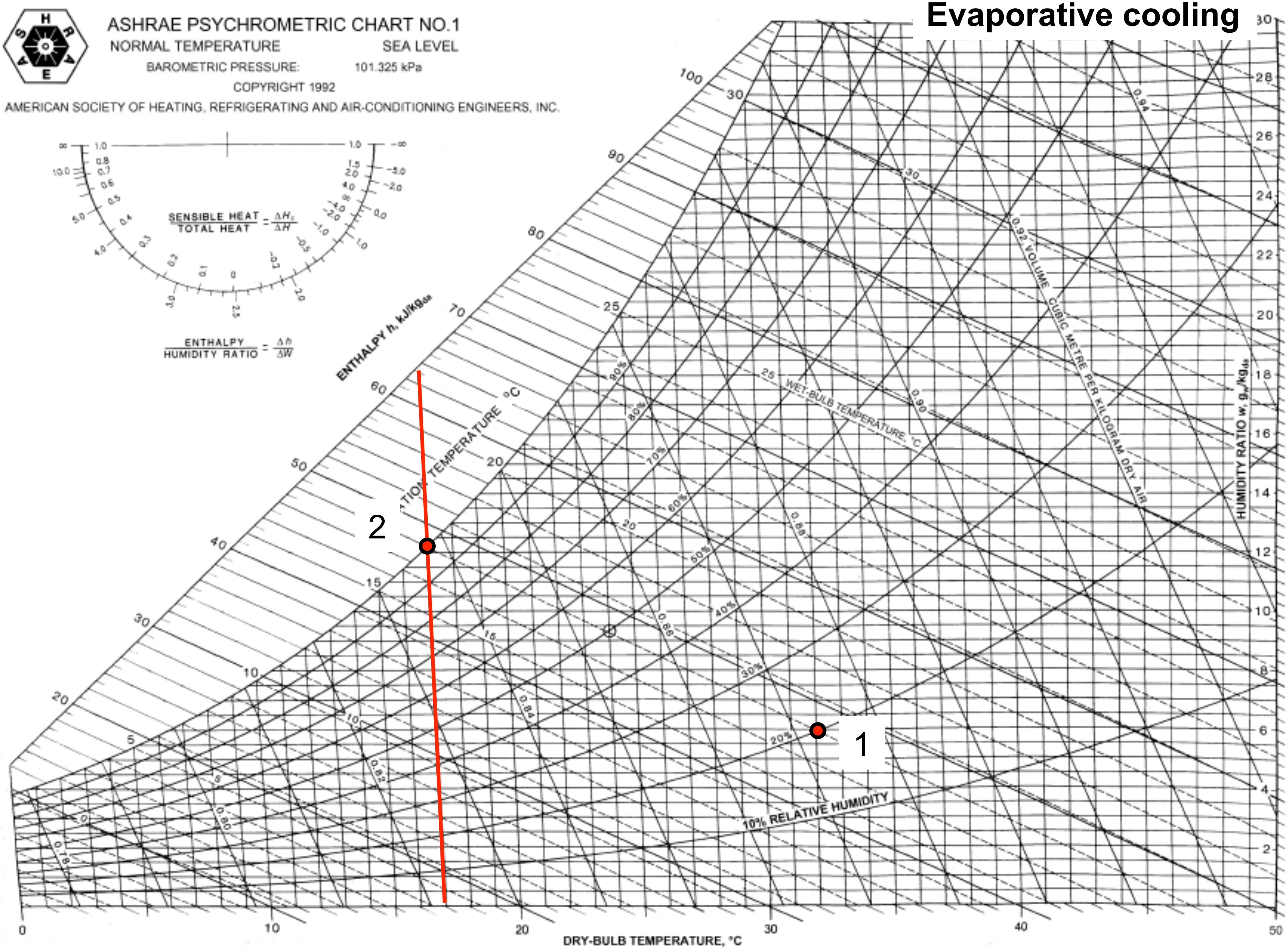
- Hot, dry outdoor air is cooled with an evaporative cooler, or “swamp cooler”
  - Q1: What is RH and W of the supply air?
  - Q2: Why would we choose this system?



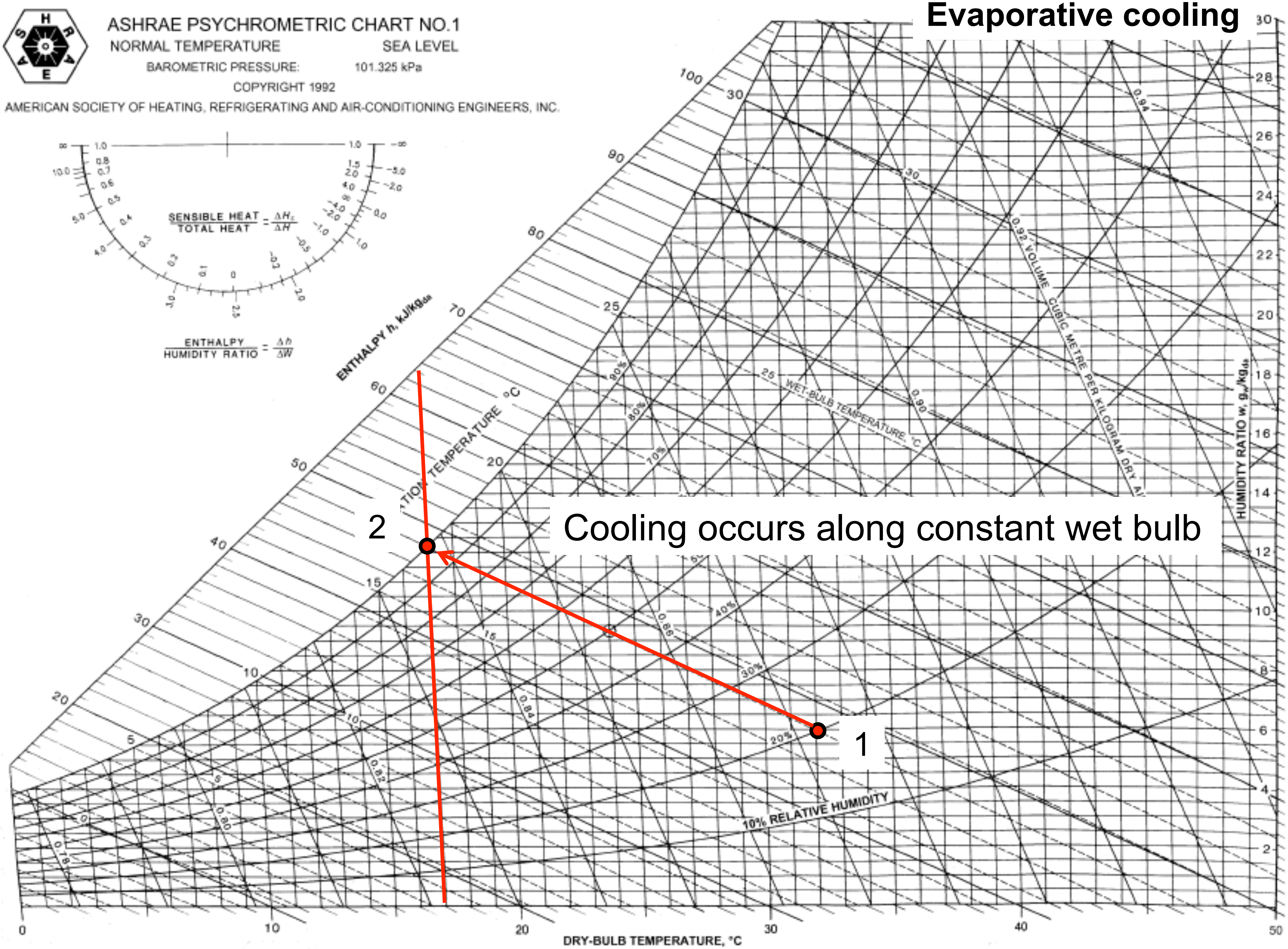
Evaporative cooling



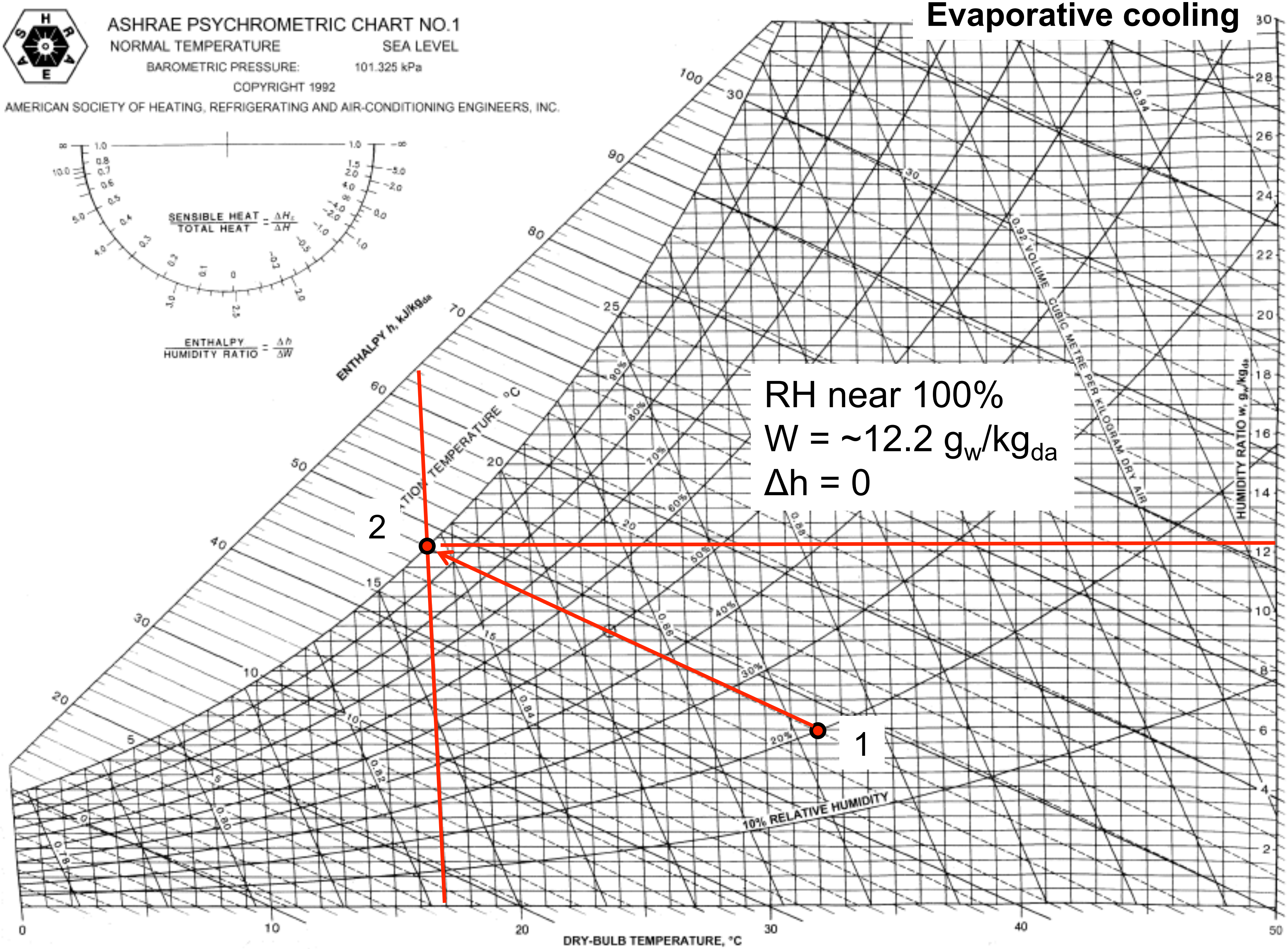
Evaporative cooling



Evaporative cooling



Evaporative cooling



Evaporative cooling