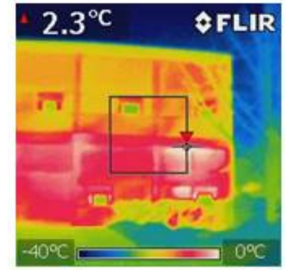
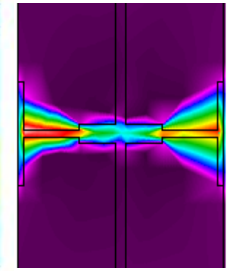
CAE 331/513
Building Science
Fall 2016





Week 8: October 11, 2016
Mechanical systems and psychrometric processes

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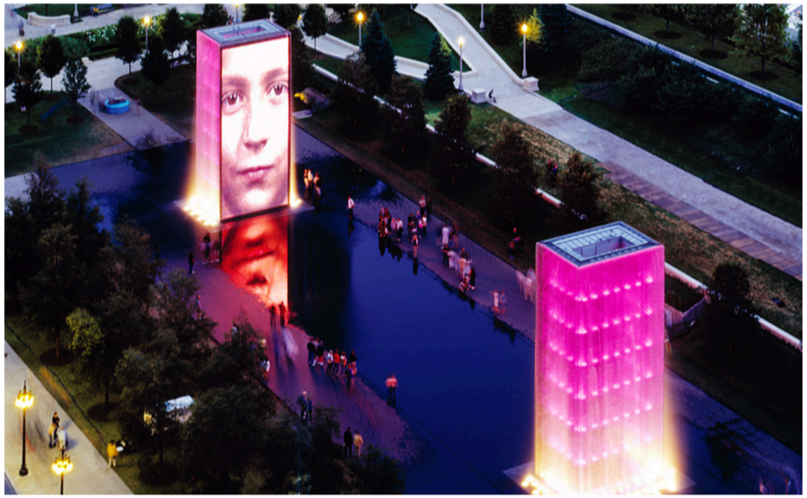
Lighting design internship opportunity



LIGHTING DESIGNERS
Schuler Shook

FALL/WINTER INTERN:

Schuler Shook's Chicago office seeks a highly motivated, detail-oriented person to be our 2016 Fall or Winter Intern. You will learn more about architectural lighting and contribute to a variety of interior and exterior lighting projects.

TO APPLY:

Email your resume and portfolio link to Jim Baney, Partner:
jbaney@schulershook.com

REQUIREMENTS:

-Be currently enrolled in a Lighting Design MFA program or an Architectural Engineering program with some lighting classes.

-Possess excellent writing and communication skills

-Proficiency with AutoCAD, Revit, Photoshop, Word, Excel, and AGI32. Experience with 3DS Max, Rhino or Daysim is a plus.

VISIT US ONLINE:

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Review from last time

- Psychrometric equations examples (SI and IP units)
- Began an overview of HVAC systems and typical components and processes involved
- **Today:** Continue HVAC systems overview and understand psychrometric processes

PSYCHROMETRIC PROCESSES

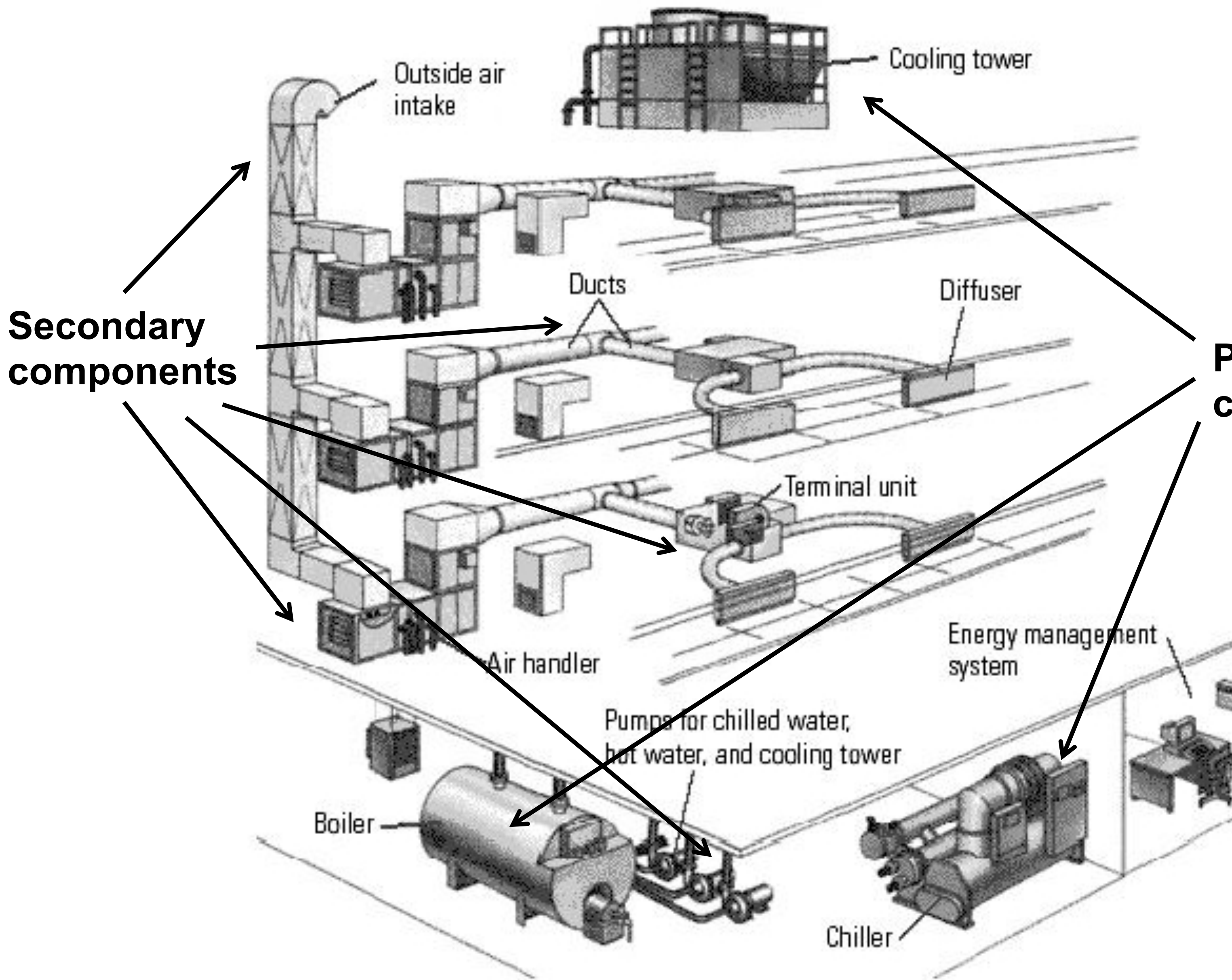
Use of the psychrometric chart for *processes*

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:

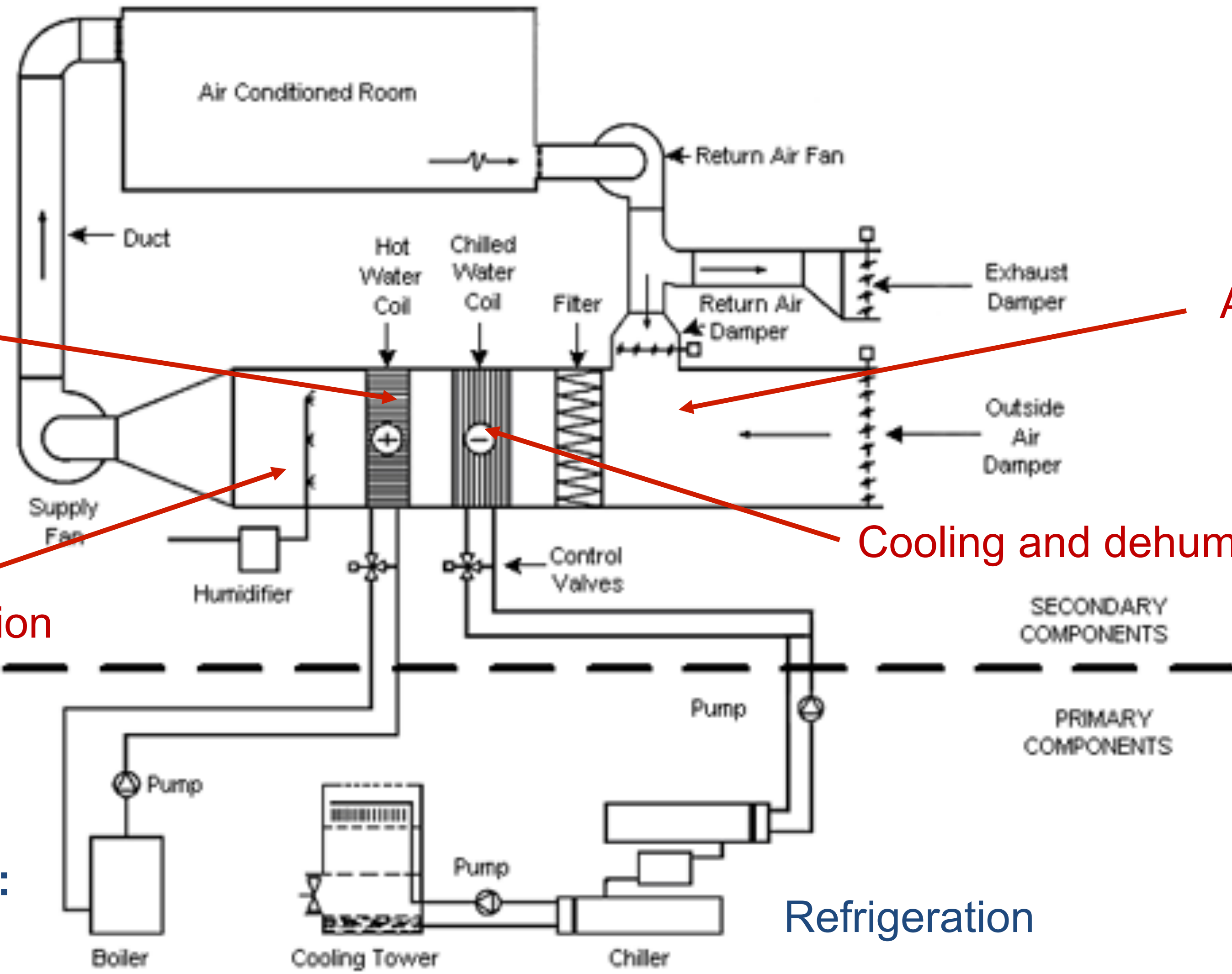
- Sensible cooling or heating
- Warming and humidification of cold, dry air
- Cooling and dehumidification of warm, humid air
  - Sensible + latent cooling
- Evaporative cooling
- Mixing of airstreams

Typical components of an HVAC system



Typical HVAC *processes*

Some common psychrometric processes:



Heating

Air mixing

Cooling and dehumidification

Humidification

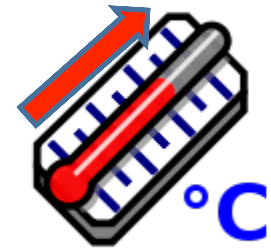
Common primary processes:

Refrigeration

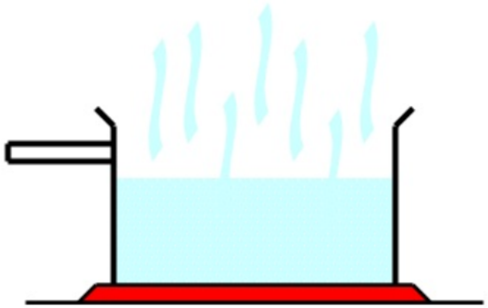
Heat generation

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

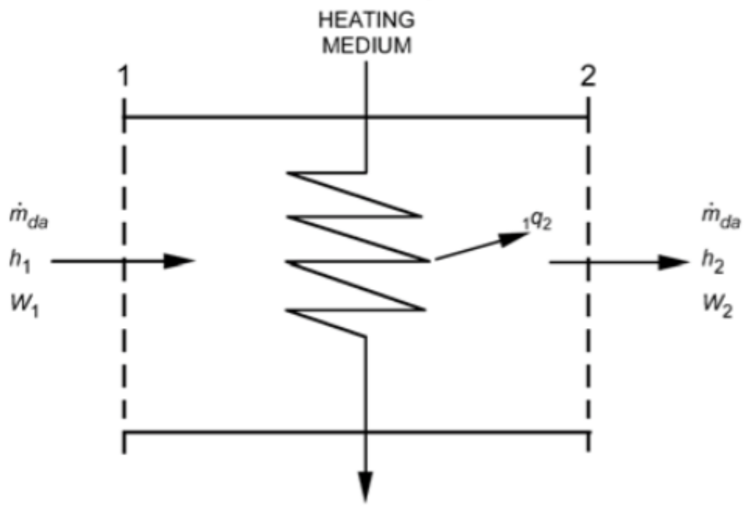


Fig. 2 Schematic of Device for Heating Moist Air

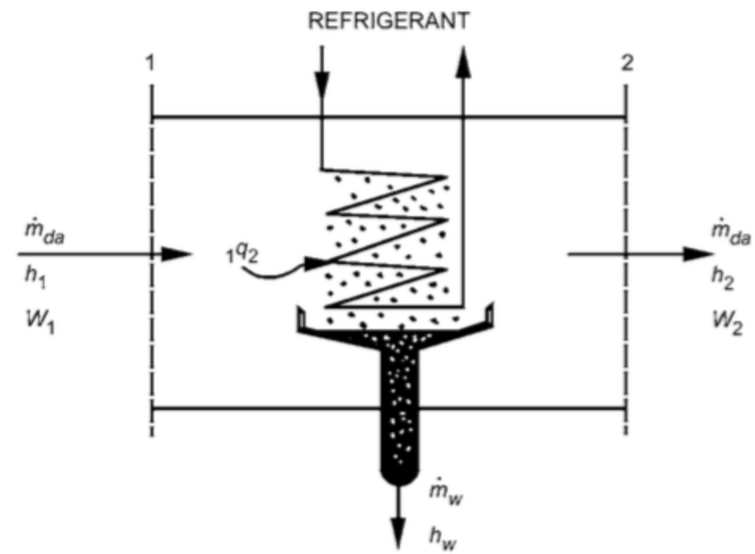


Fig. 3 Schematic of Device for Cooling Moist Air

Generic equations for both heating and cooling processes:

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

$Q_{1\rightarrow 2}$ = 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})

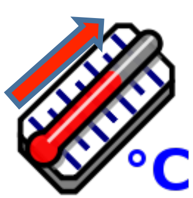
Sensible heat transfer equation

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

$Q_{sensible}$ = 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/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: $Q_{sensible} < 0$



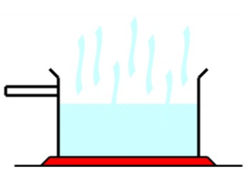
Latent heat transfer equation

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

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
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})

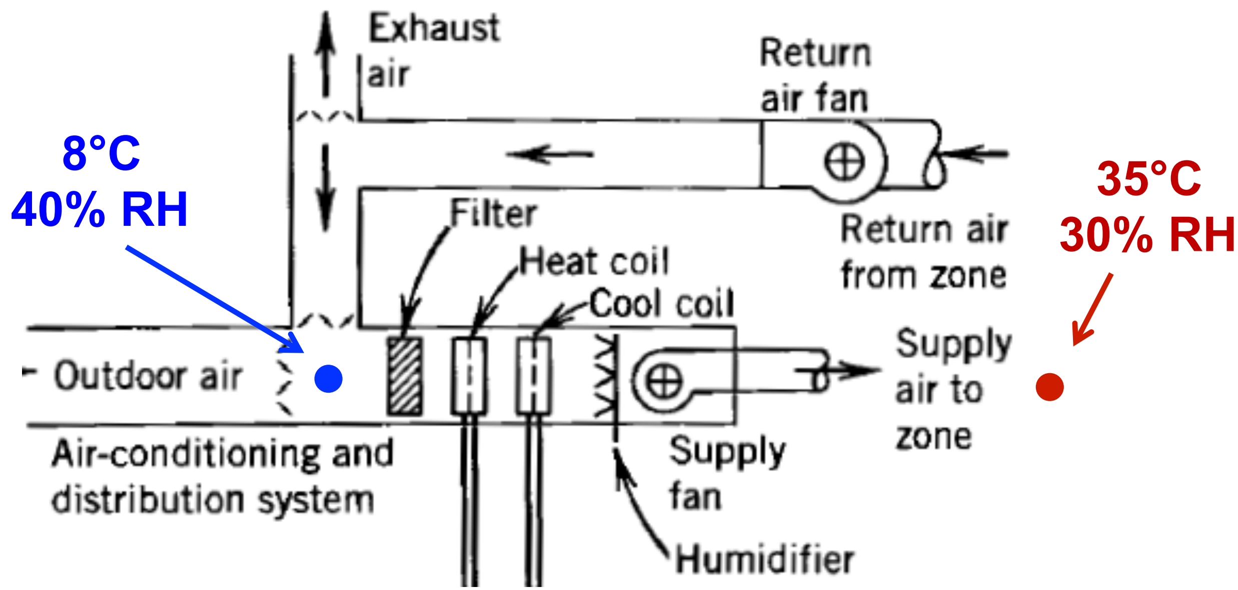
For humidification: $Q_{latent} > 0$

For dehumidification: $Q_{latent} < 0$



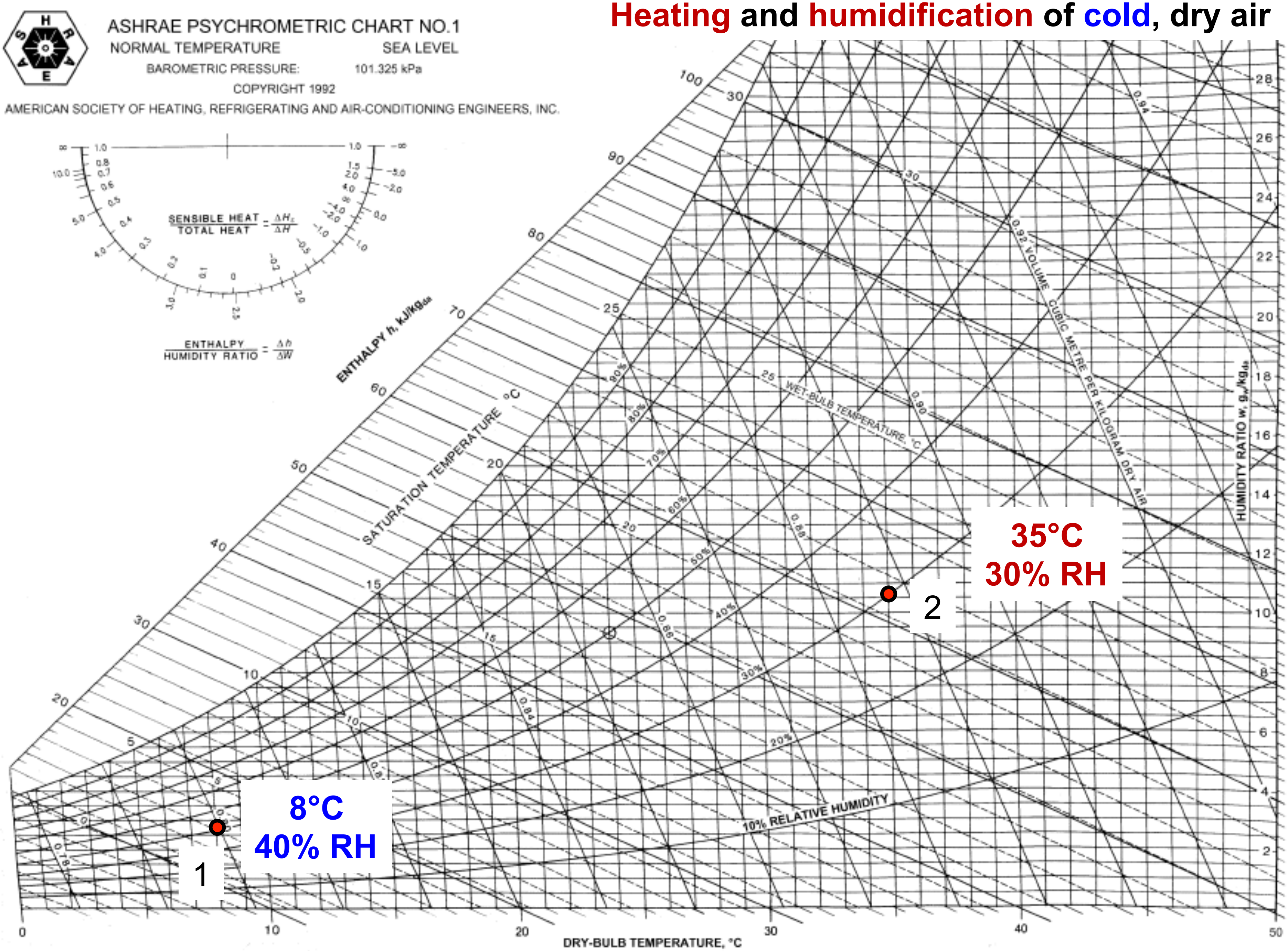
Heating and humidification of cold, dry air

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

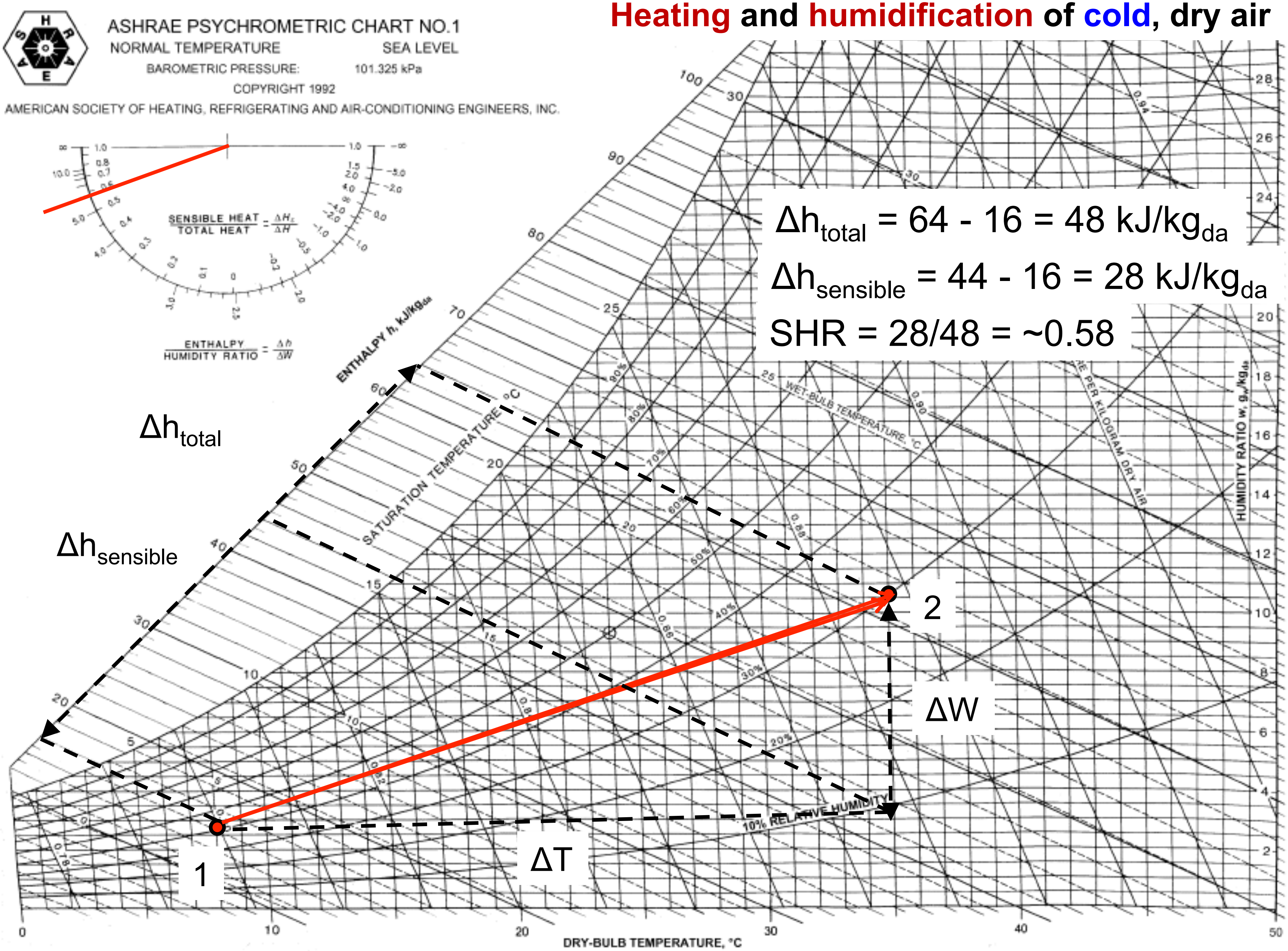


Q1: What is the enthalpy change required?
Q2: What is the total rate of heat transfer if the airflow rate is 10 m^3/s?
Q2: What is the split between sensible and latent transfer?

Heating and humidification of cold, dry air



Heating and humidification of cold, dry air

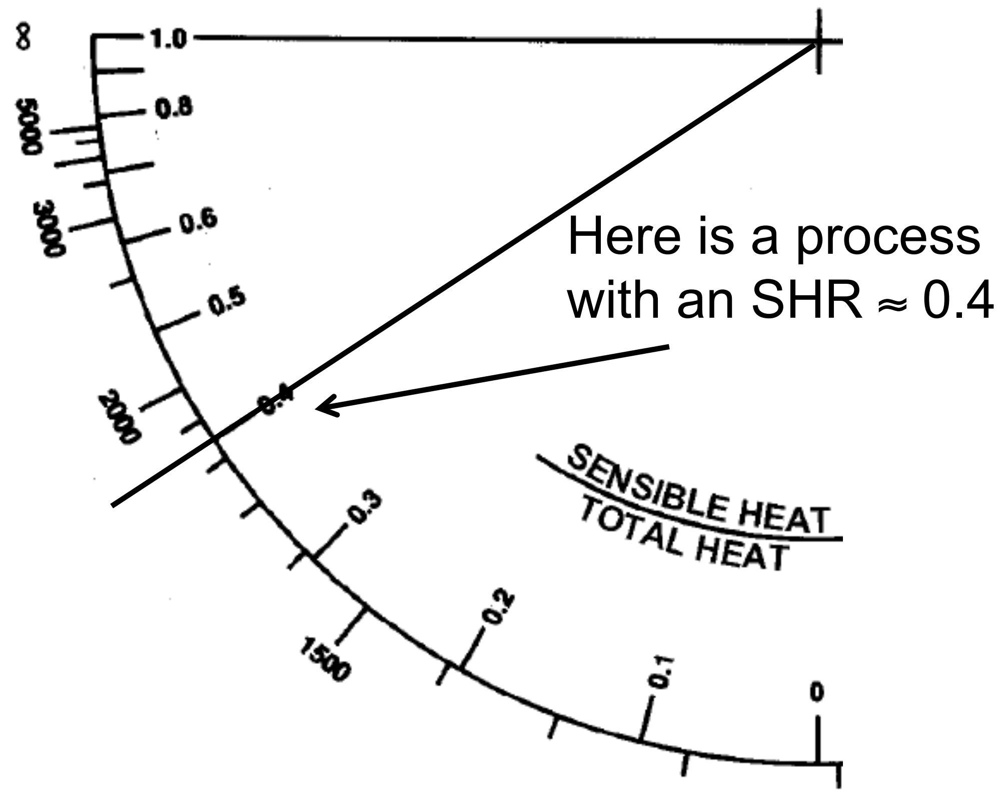


Sensible heat ratio (SHR)

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

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

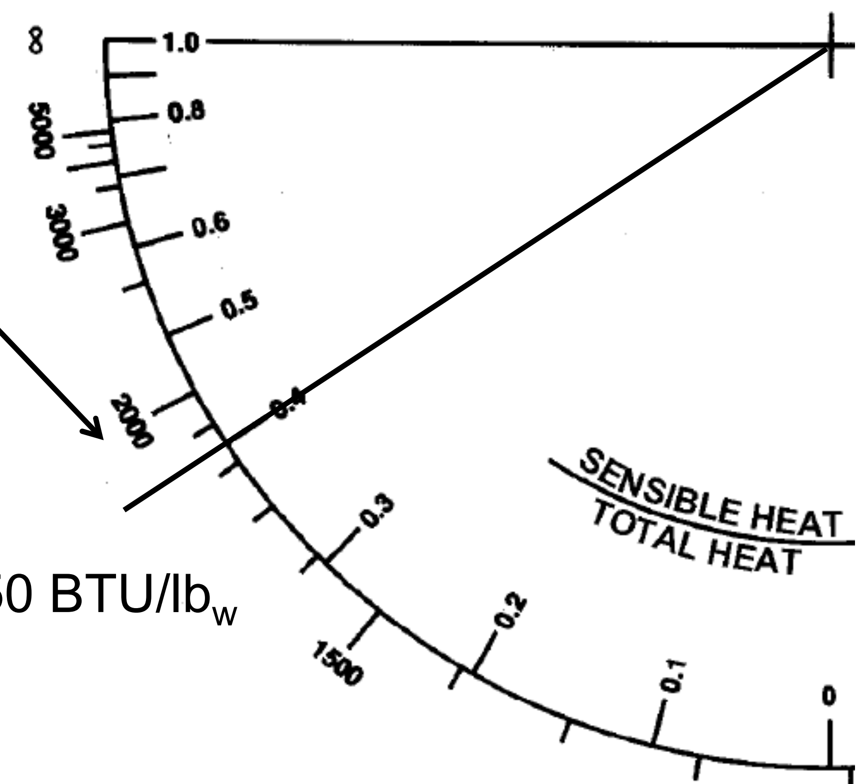
- Allows for understanding sensible load relative to latent load



Enthalpy protractor ($\Delta h/\Delta W$)

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

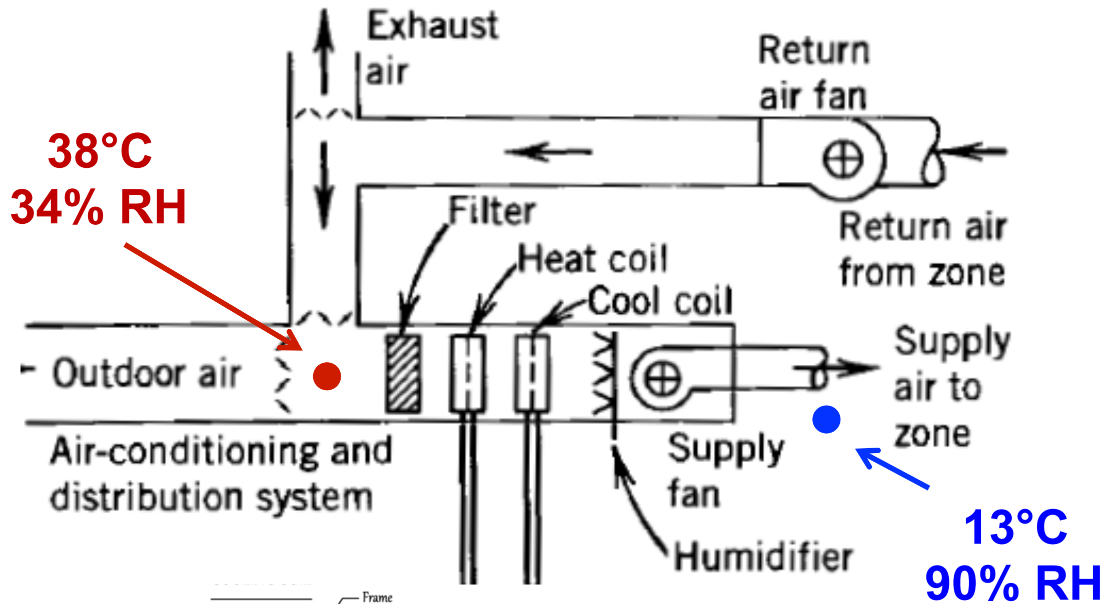
$$\frac{\Delta h_{total}}{\Delta W}$$

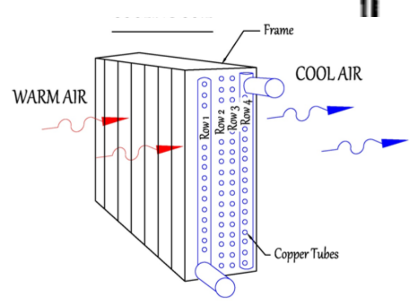


Here is a process with $\Delta h/\Delta W \approx$ 1850 BTU/lb_w
SI units: kJ/kg_w

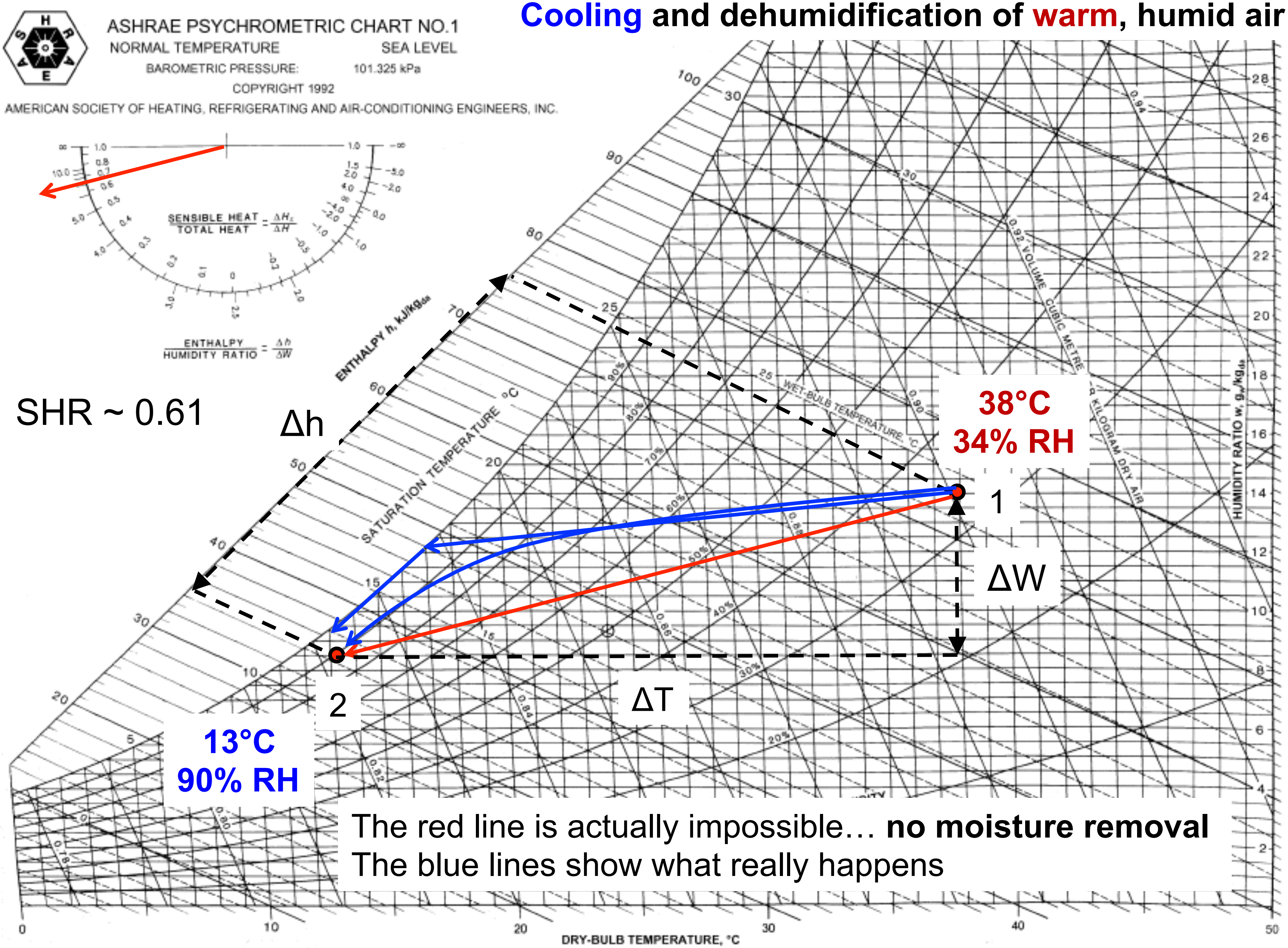
Cooling and dehumidification of warm, humid air

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





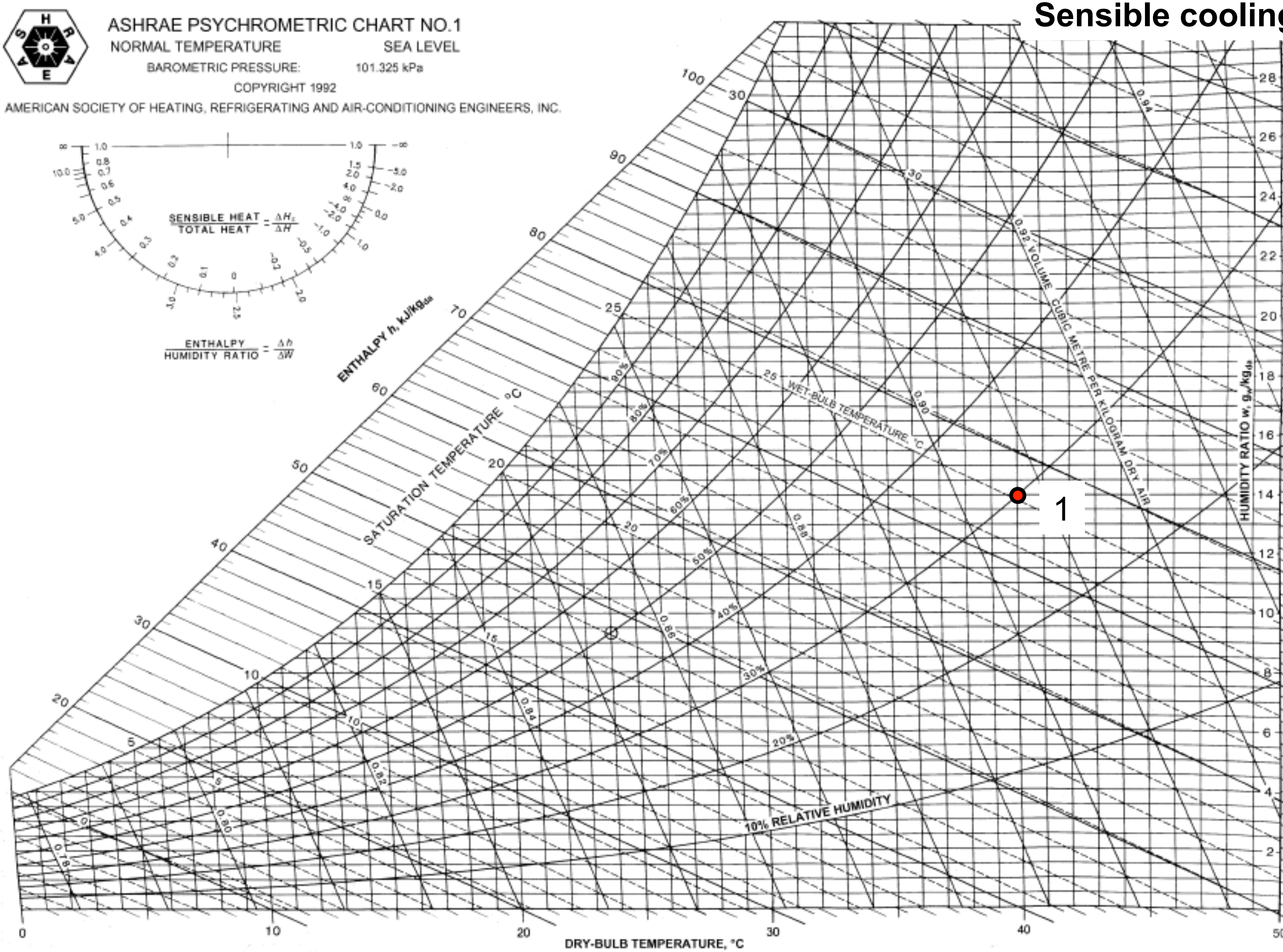
Cooling and dehumidification of warm, humid air



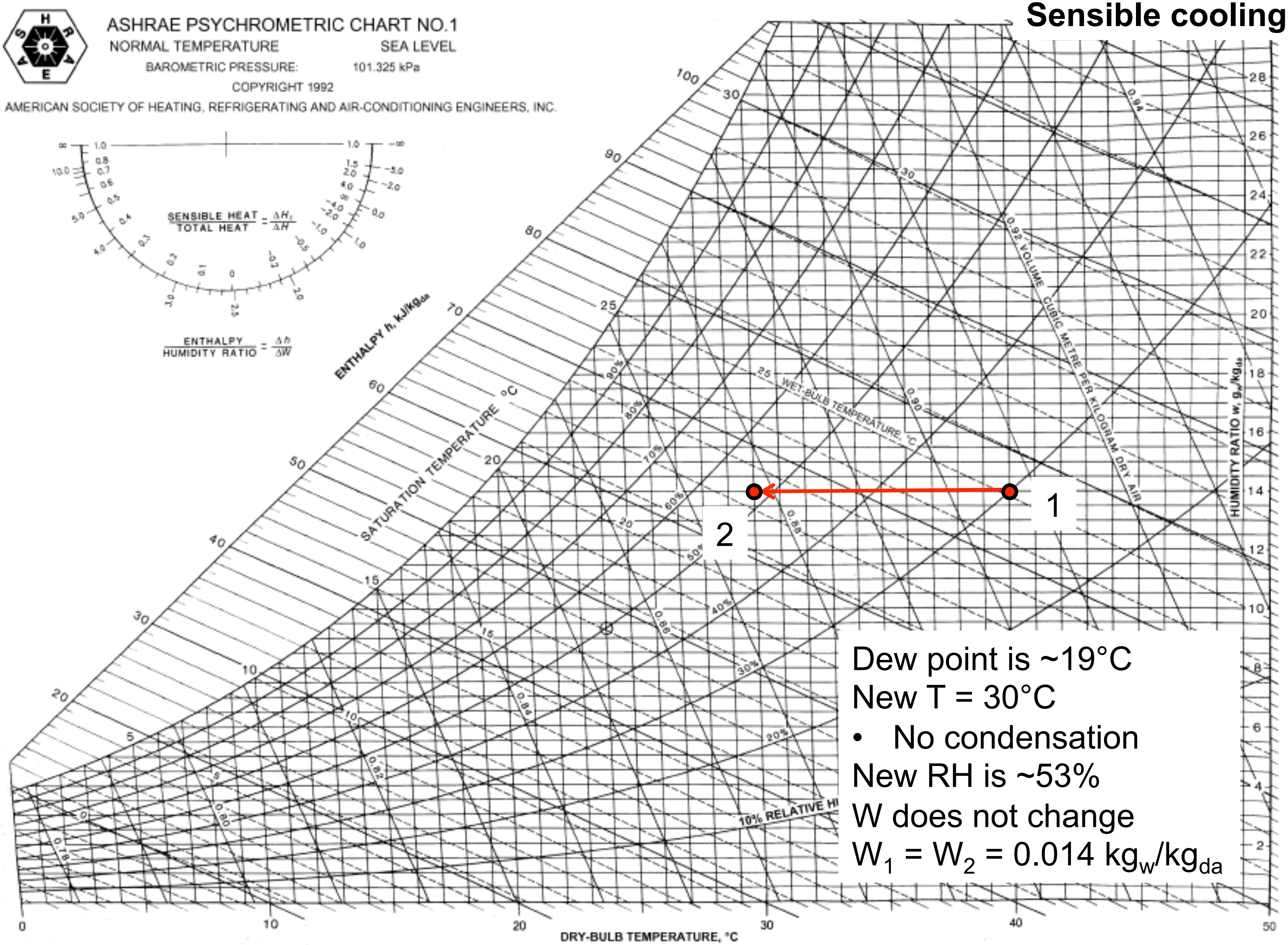
Example: ***Sensible*** **cooling**

- 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

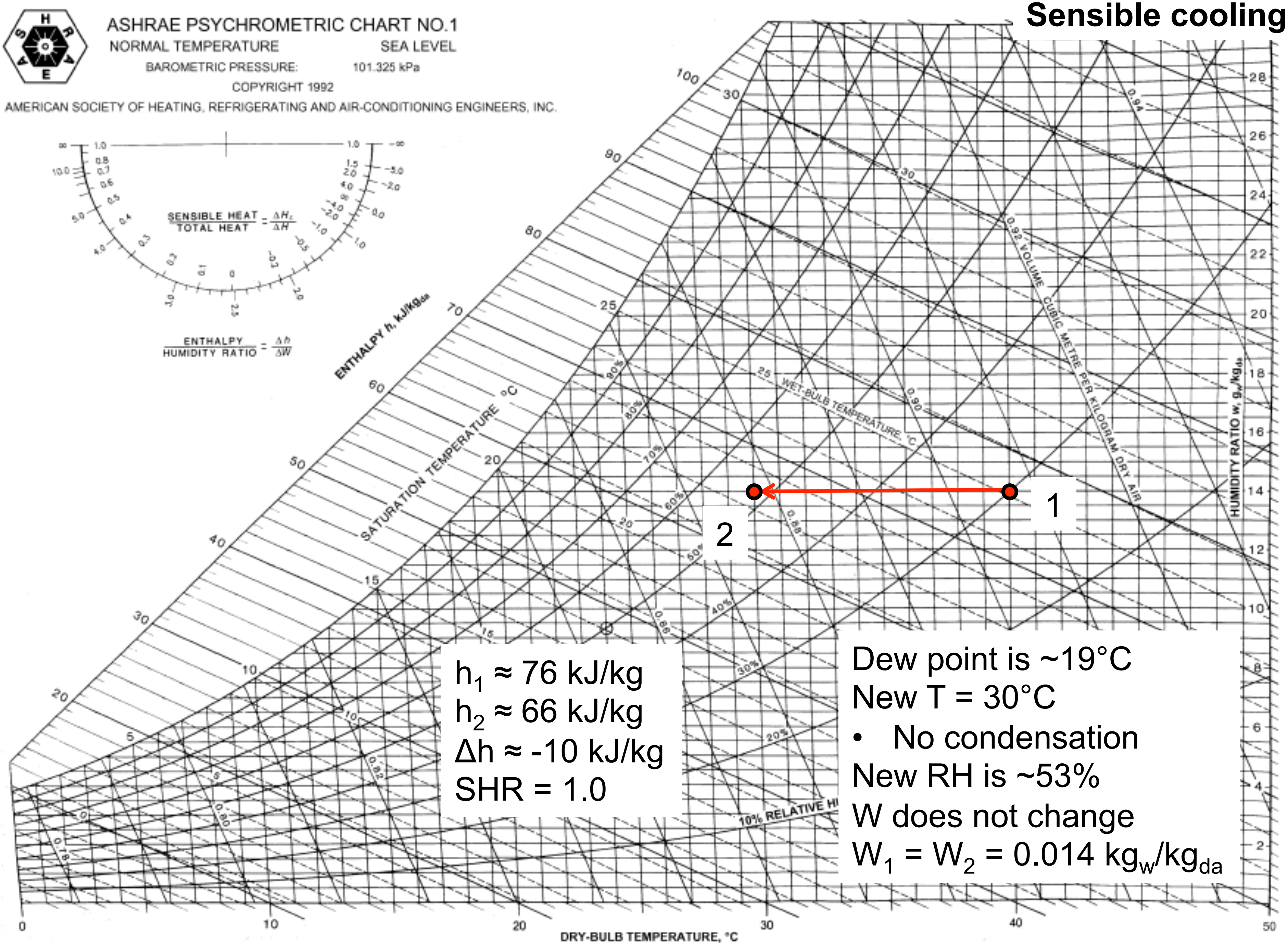
- No condensation

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

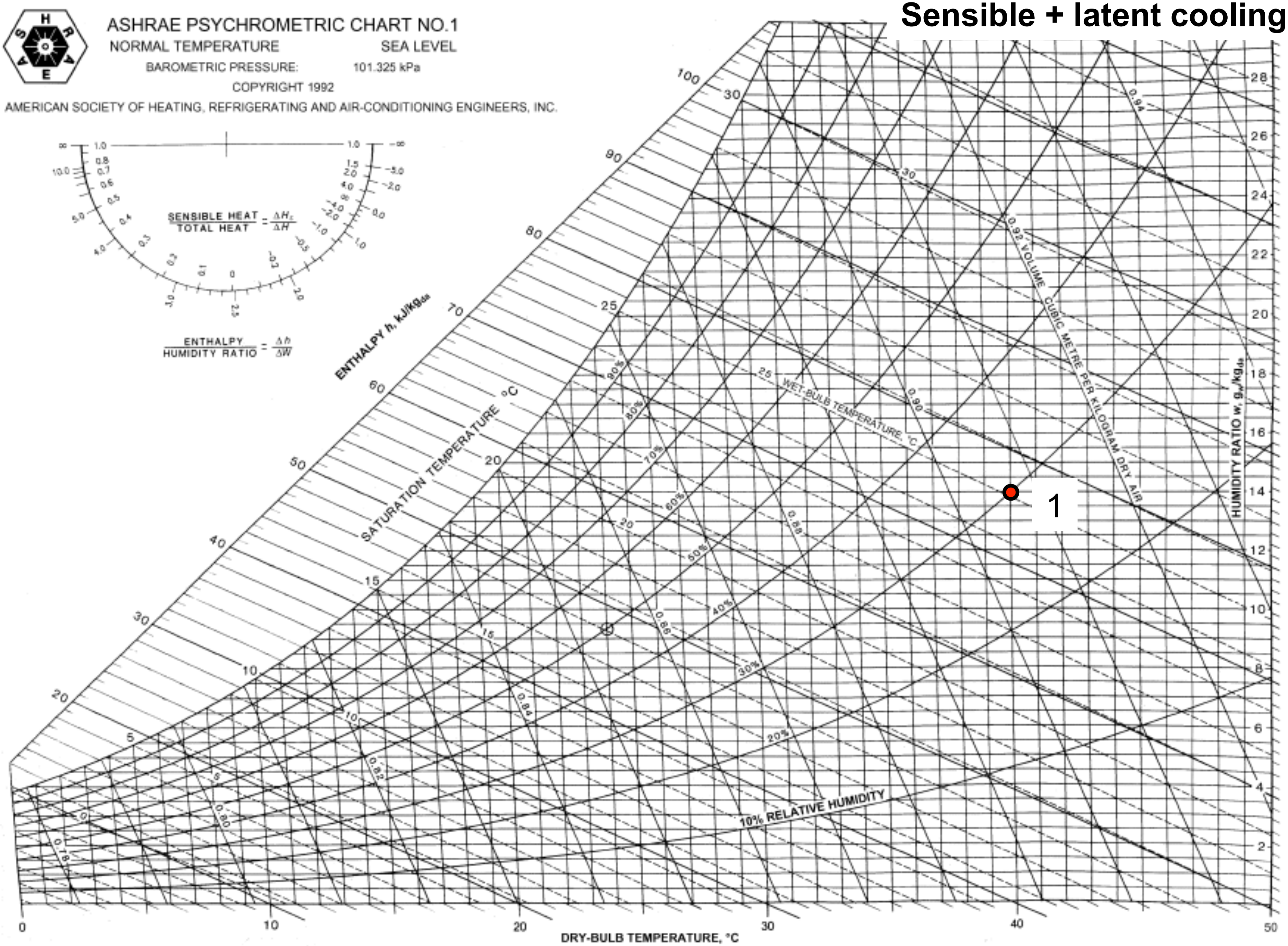
Dew point is ~19°C
New T = 30°C
- No condensation

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

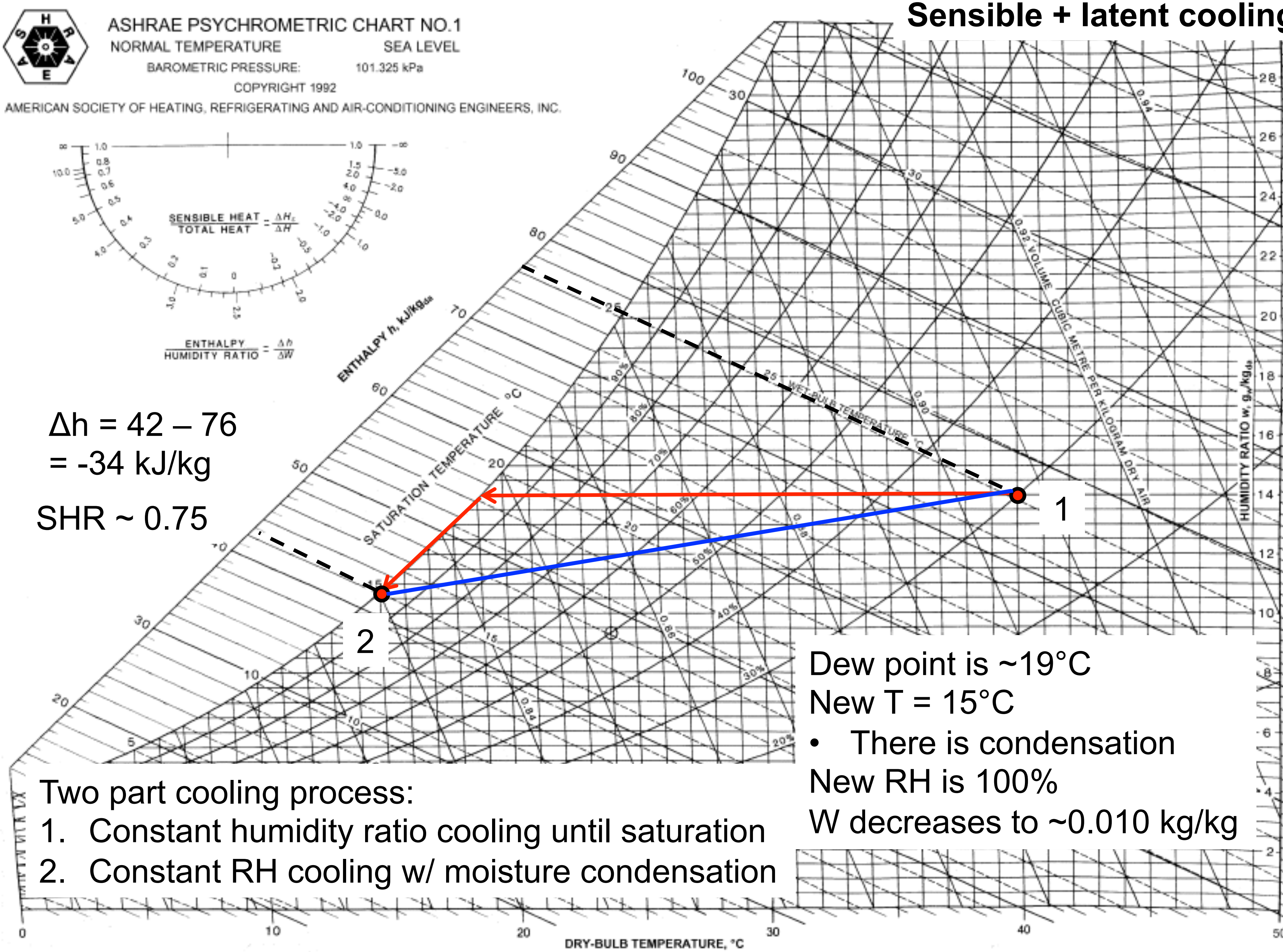
Example: ***Sensible*** **+** ***latent*** **cooling**

- 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



$\Delta h = 42 - 76$
$= -34$ kJ/kg

SHR ~ 0.75

Dew point is ~19°C
New T = 15°C

- There is condensation

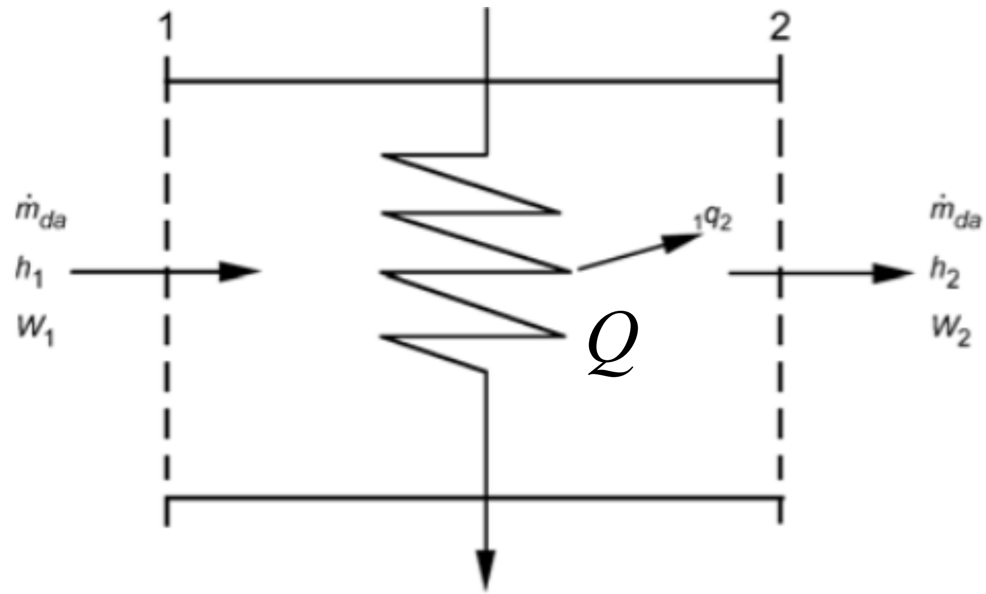
New RH is 100%
W decreases to ~0.010 kg/kg

Two part cooling process:

1. Constant humidity ratio cooling until saturation
2. Constant RH cooling w/ moisture condensation

Energy balances for psychrometric processes

Heating air



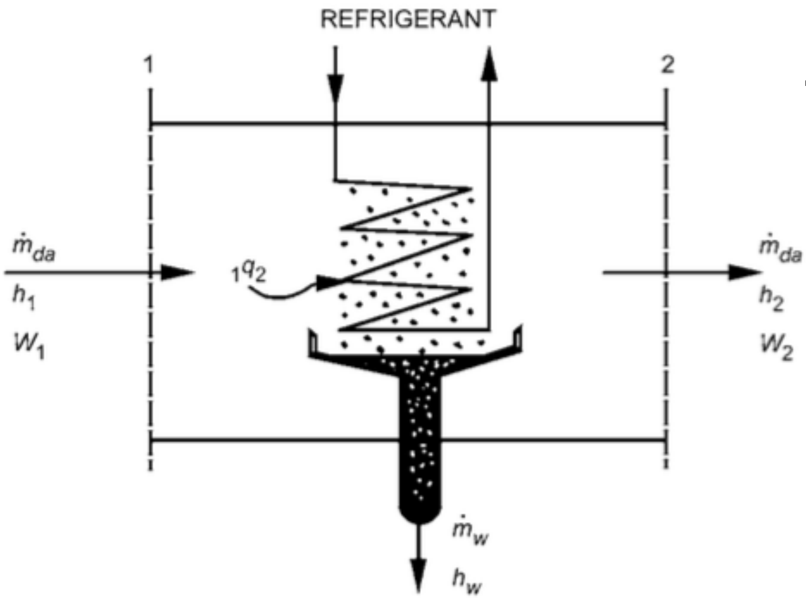
Energy balance: $\dot{m}_{da,1}h_1 + Q_{1\rightarrow 2} = \dot{m}_{da,2}h_2$

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 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: $\dot{m}_{da,1}W_1 = \dot{m}_{da,2}W_2 + \dot{m}_w$

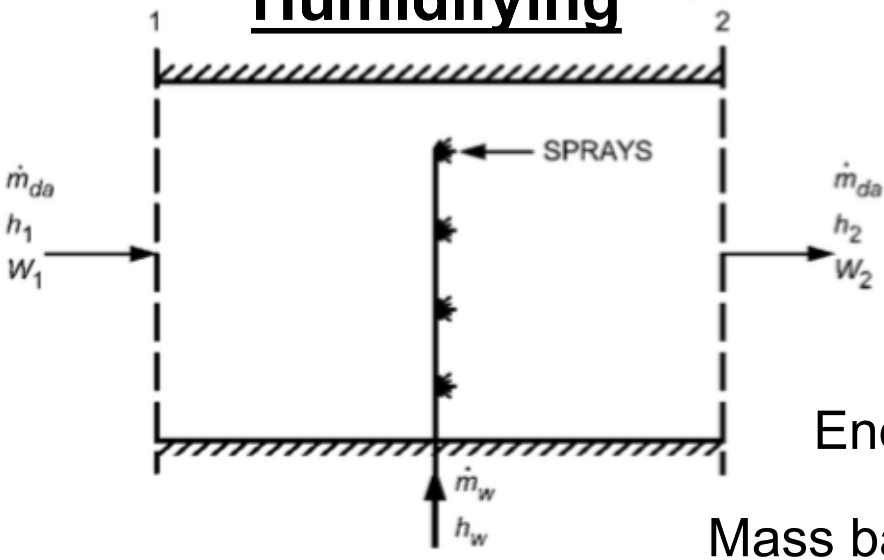
Therefore: $\dot{m}_w = \dot{m}_{da}(W_1 - W_2)$

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

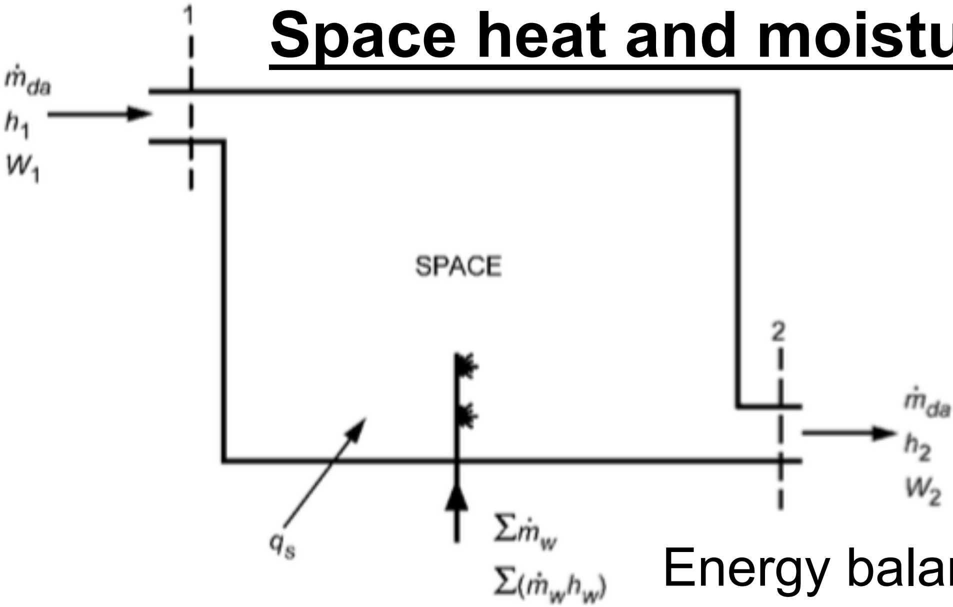
And: $\dot{m}_w h_w = \dot{m}_{da}(h_2 - h_1)$

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

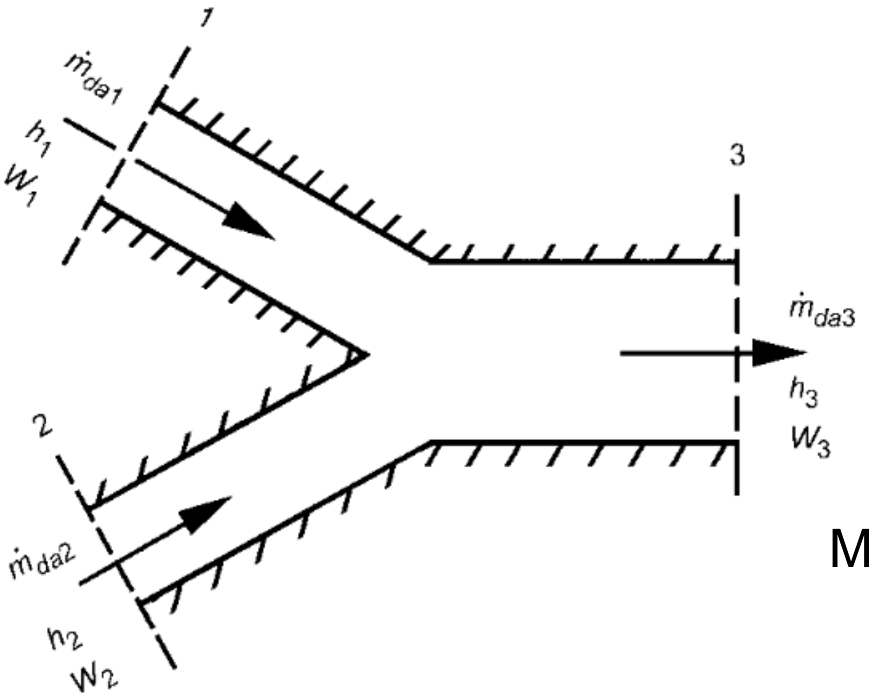
Therefore: $\sum \dot{m}_w h_w + Q_{gains} = \dot{m}_{da}(h_2 - h_1)$

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

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



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

Therefore: $\dfrac{h_2 - h_3}{h_3 - h_1} = \dfrac{W_2 - W_3}{W_3 - W_1} = \dfrac{\dot{m}_{da,1}}{\dot{m}_{da,2}}$

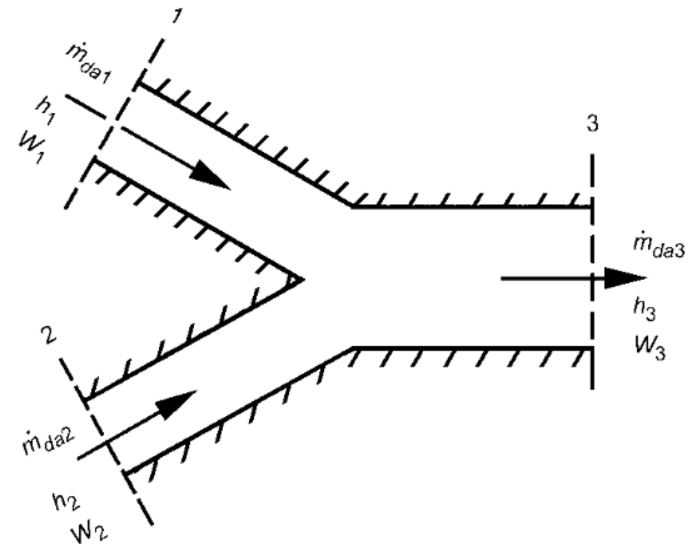
Mixing of air streams

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

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

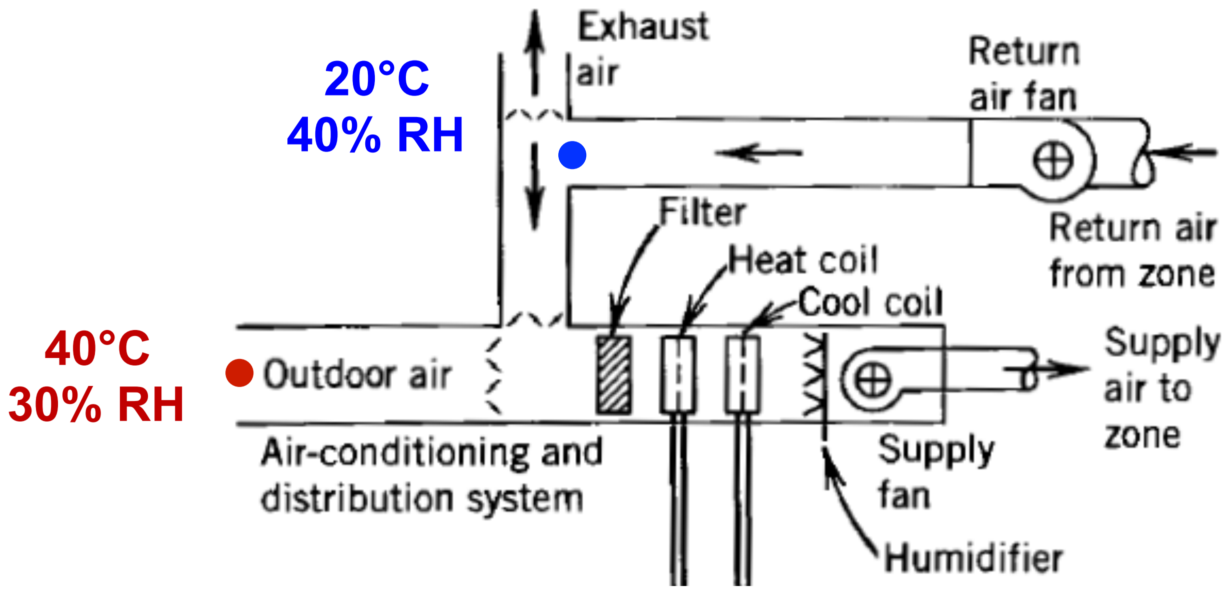
$$W_3 = \frac{\dot{m}_{da1}W_1 + \dot{m}_{da2}W_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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

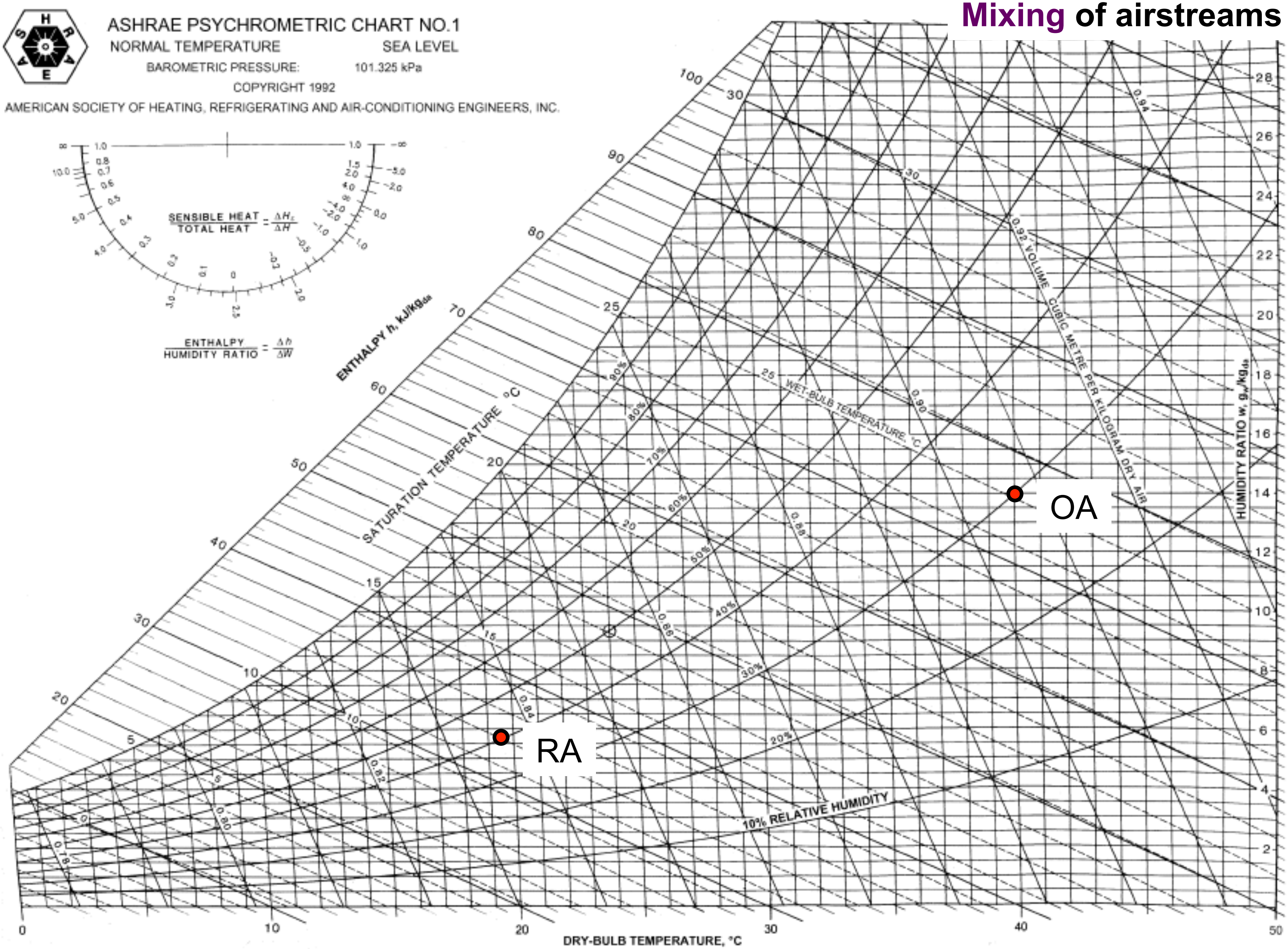


Mixing of airstreams example

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

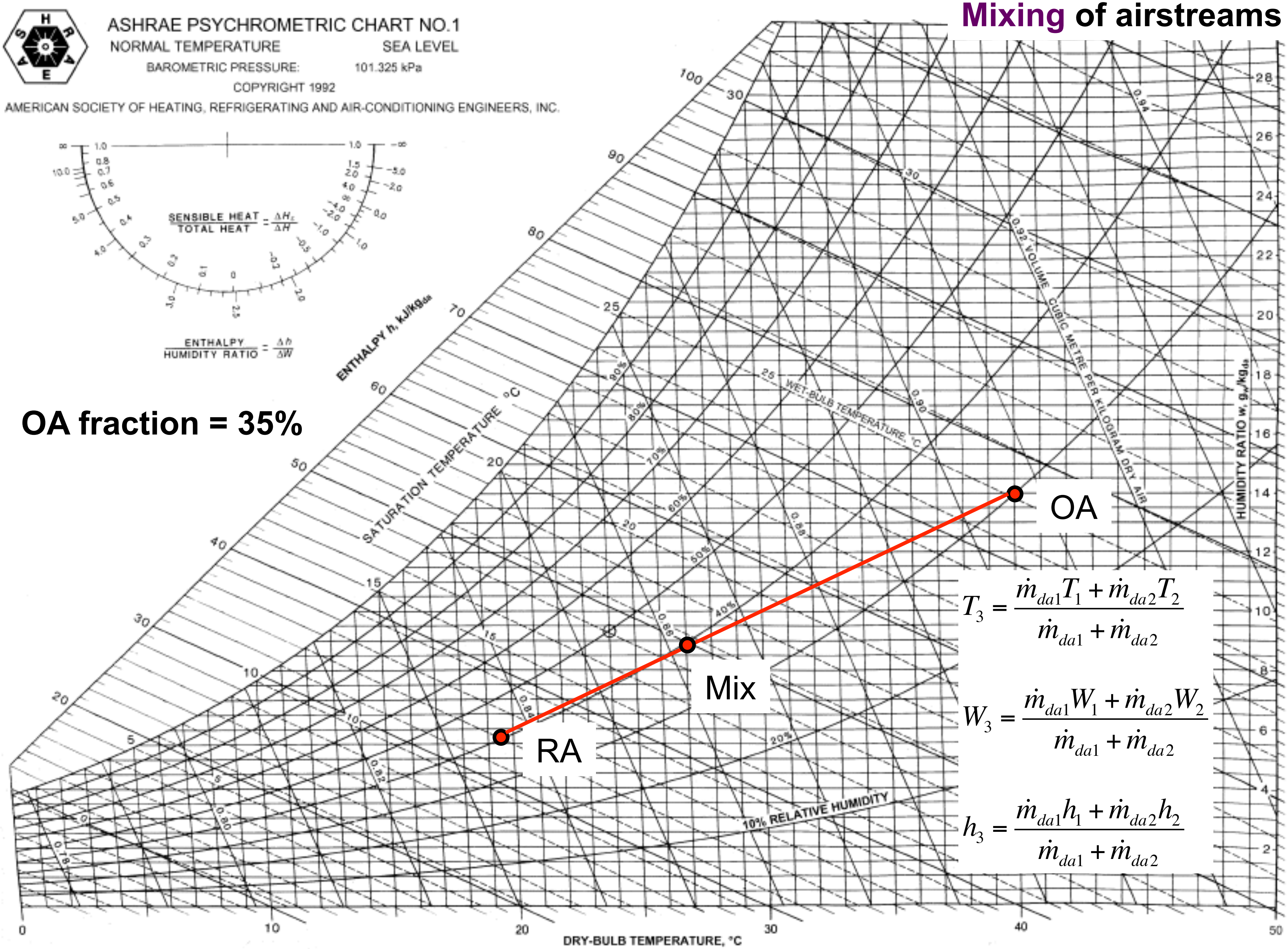


Mixing of airstreams



Mixing of airstreams

OA fraction = 35%

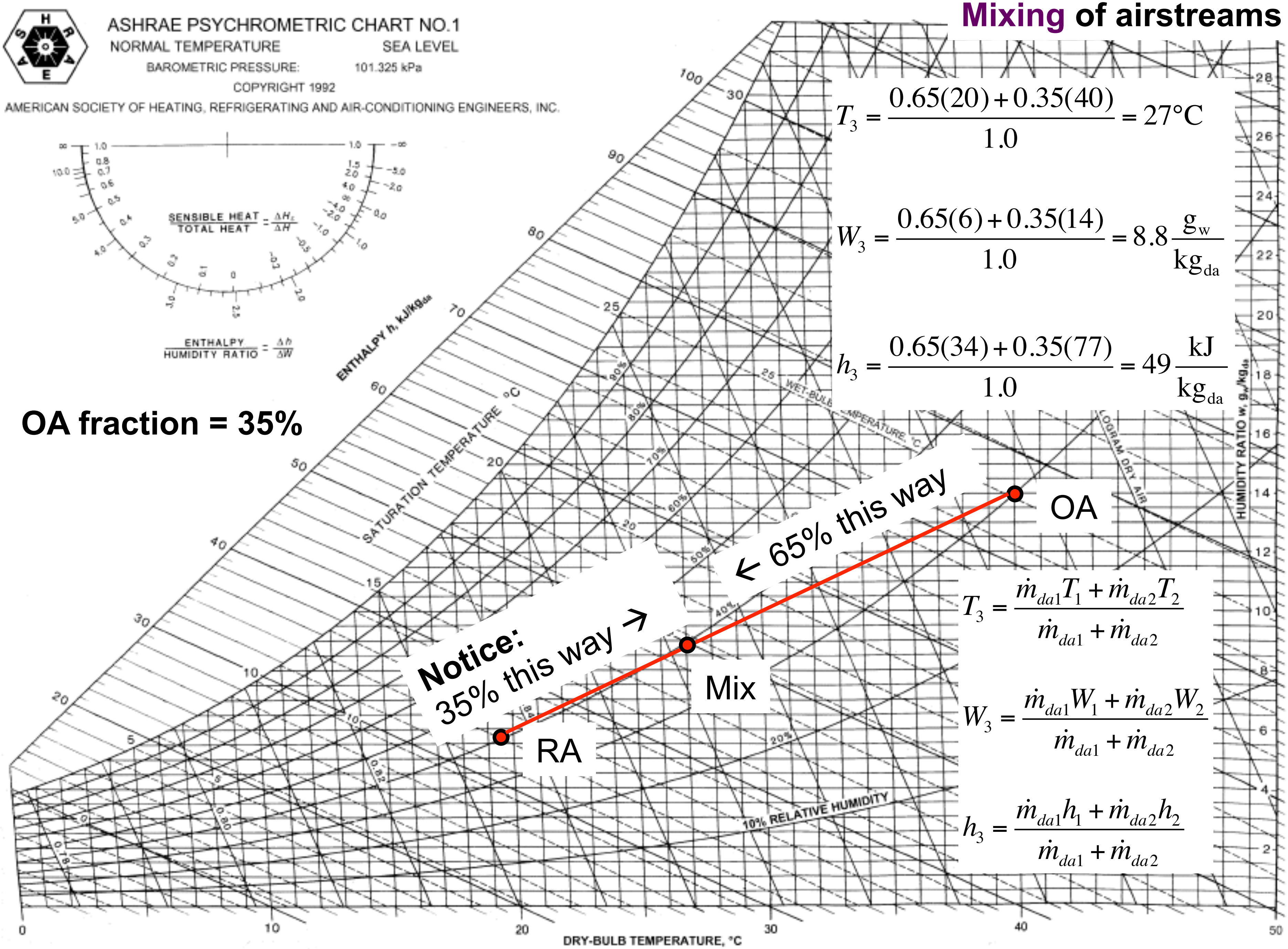


$$T_3 = \frac{\dot{m}_{da1} T_1 + \dot{m}_{da2} T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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

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

Mixing of airstreams



OA fraction = 35%

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

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

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

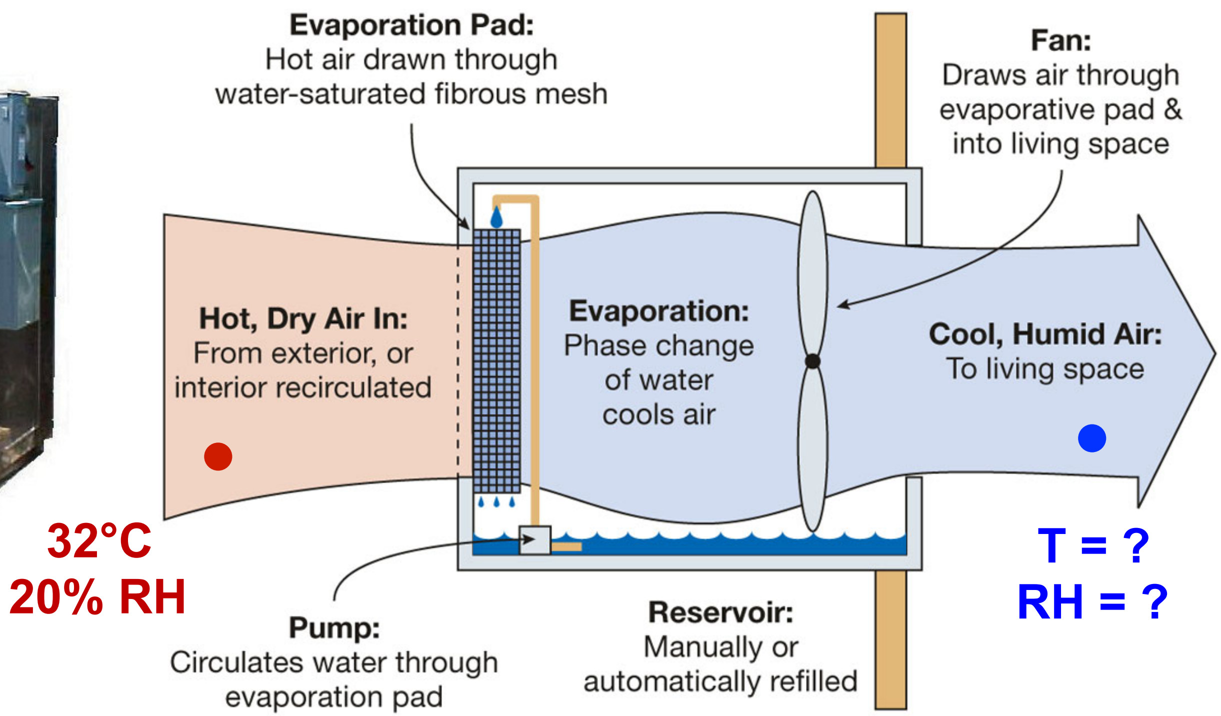
$$T_3 = \frac{\dot{m}_{da1}T_1 + \dot{m}_{da2}T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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

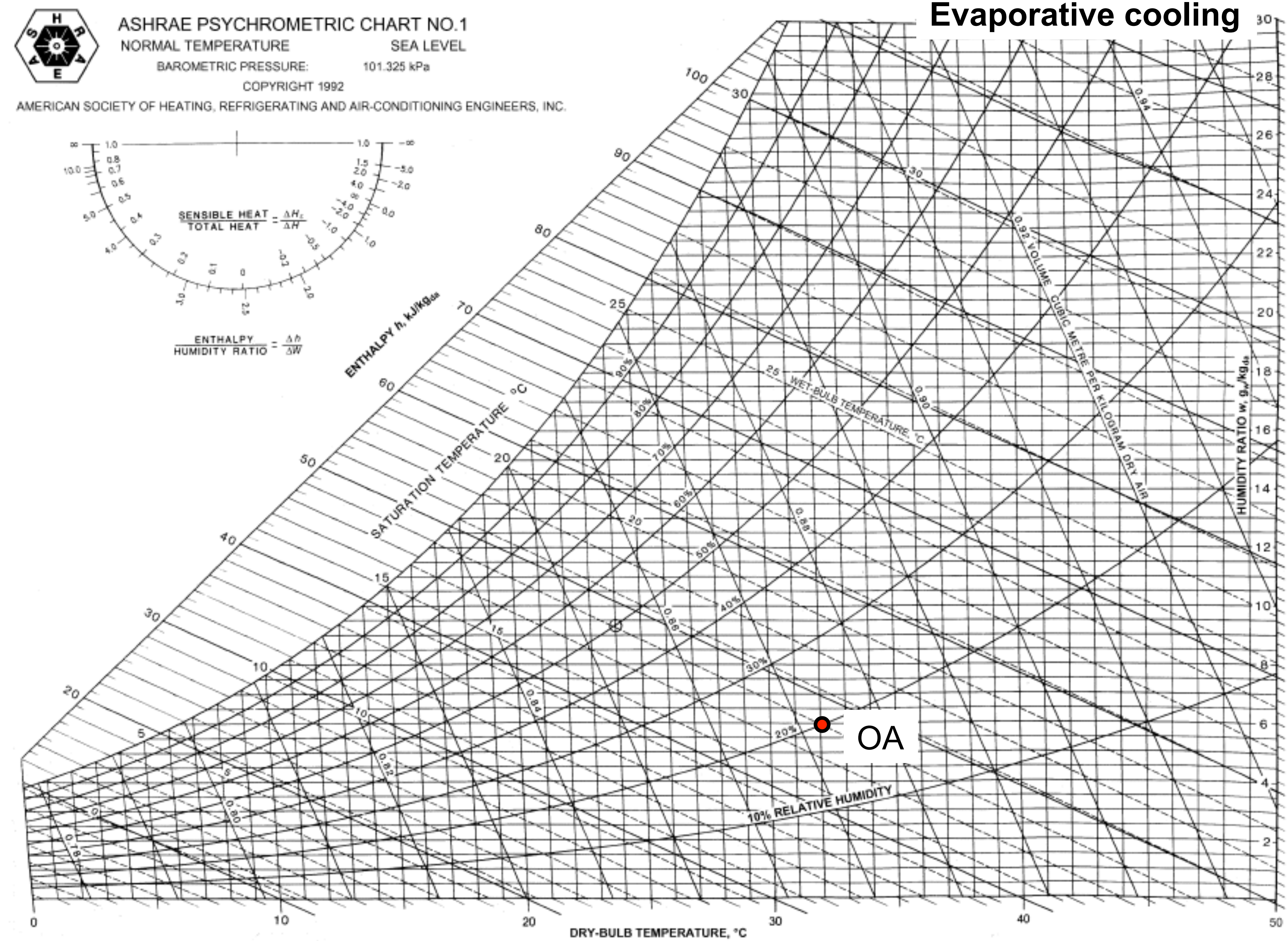
$$h_3 = \frac{\dot{m}_{da1}h_1 + \dot{m}_{da2}h_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

Evaporative cooling example

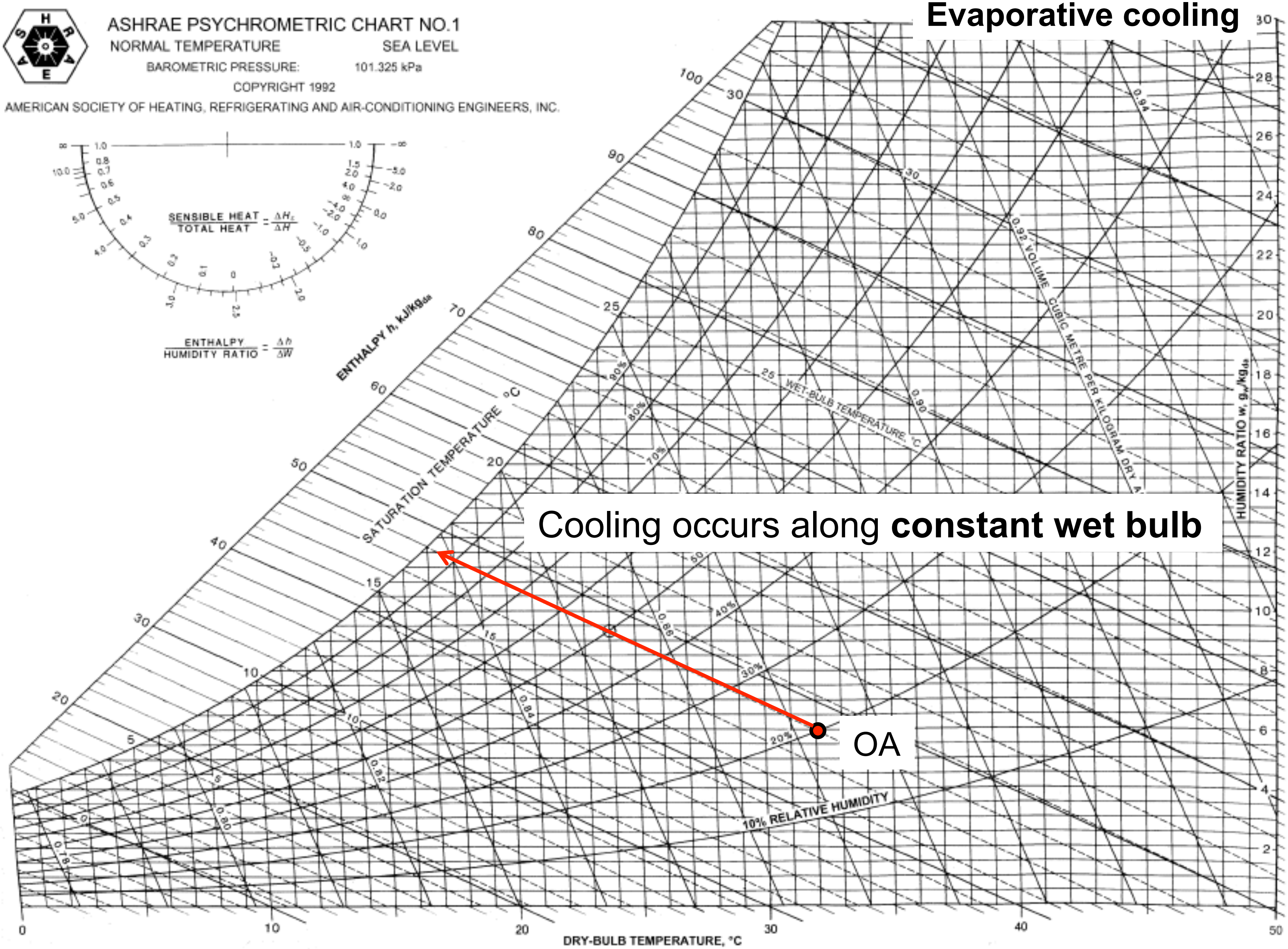
- Hot, dry outdoor air is cooled with an evaporative cooler, or "swamp cooler"
  - **Q1: What is the T, RH, and W of the supply air?**
  - **Q2: Why would we choose this system?**



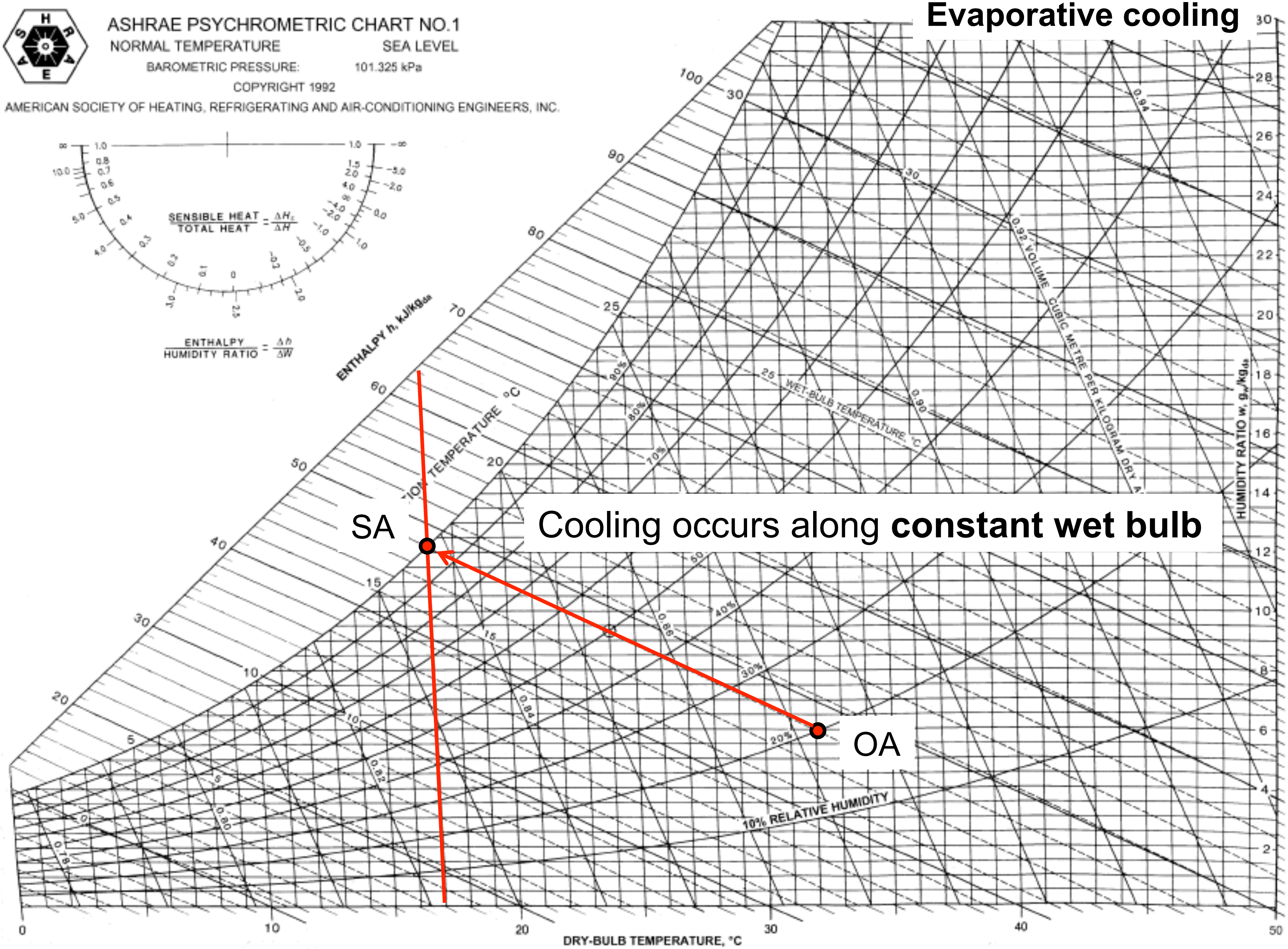
Evaporative cooling

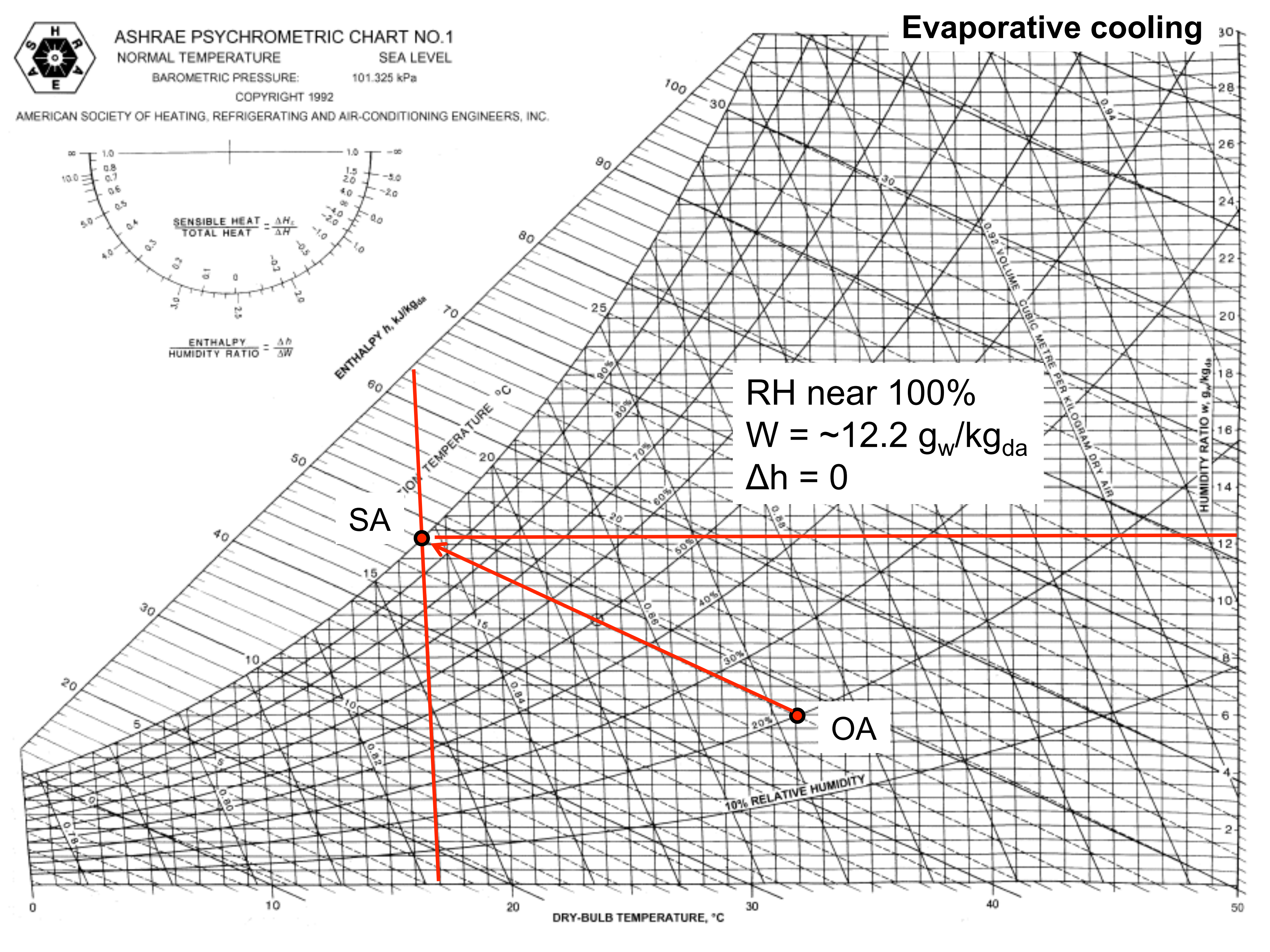


Evaporative cooling



Evaporative cooling




Evaporative cooling
ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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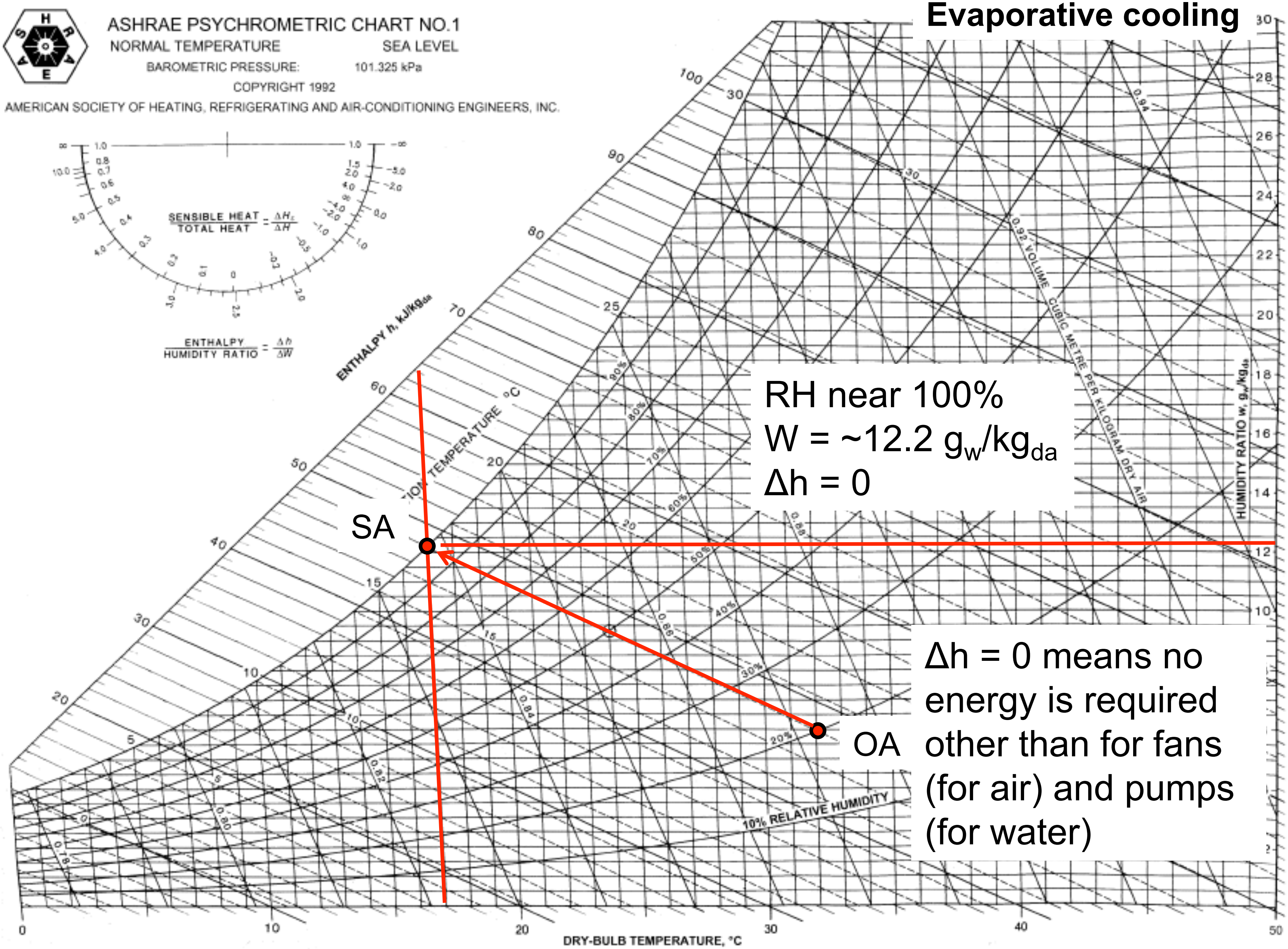
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
RH near 100%
W = ~12.2 gw/kgda
Δh = 0
SA
OA
10% RELATIVE HUMIDITY
0.92 VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C

Evaporative cooling

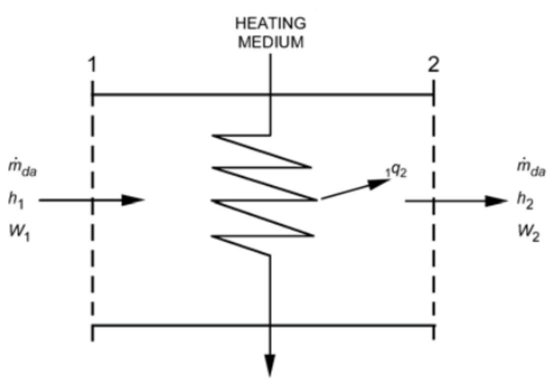


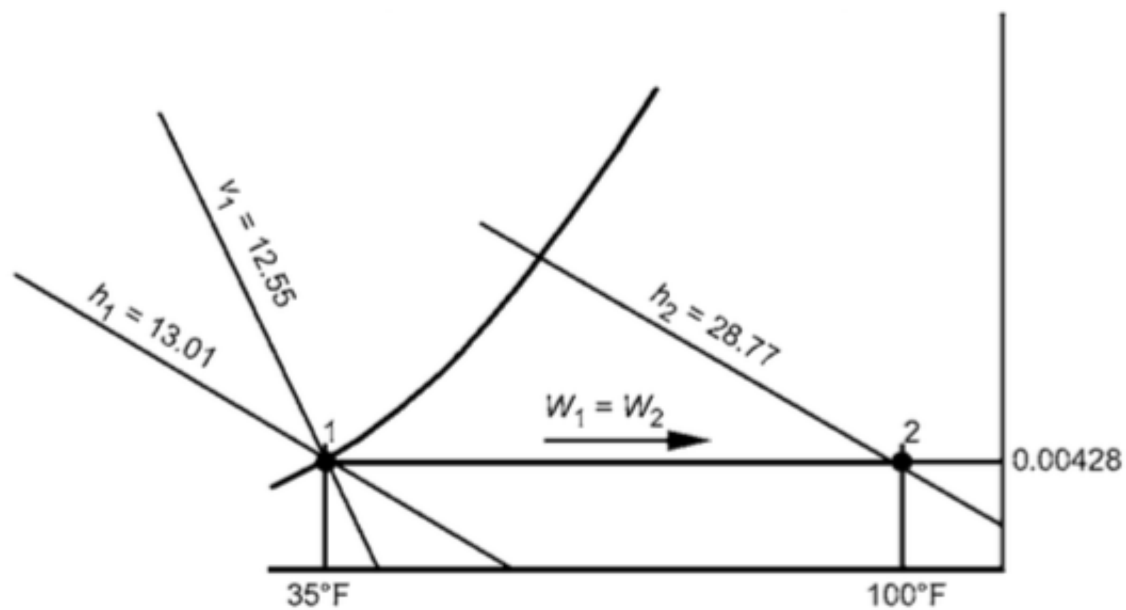
RH near 100%
$W = \sim 12.2\ g_w/kg_{da}$
$\Delta h = 0$

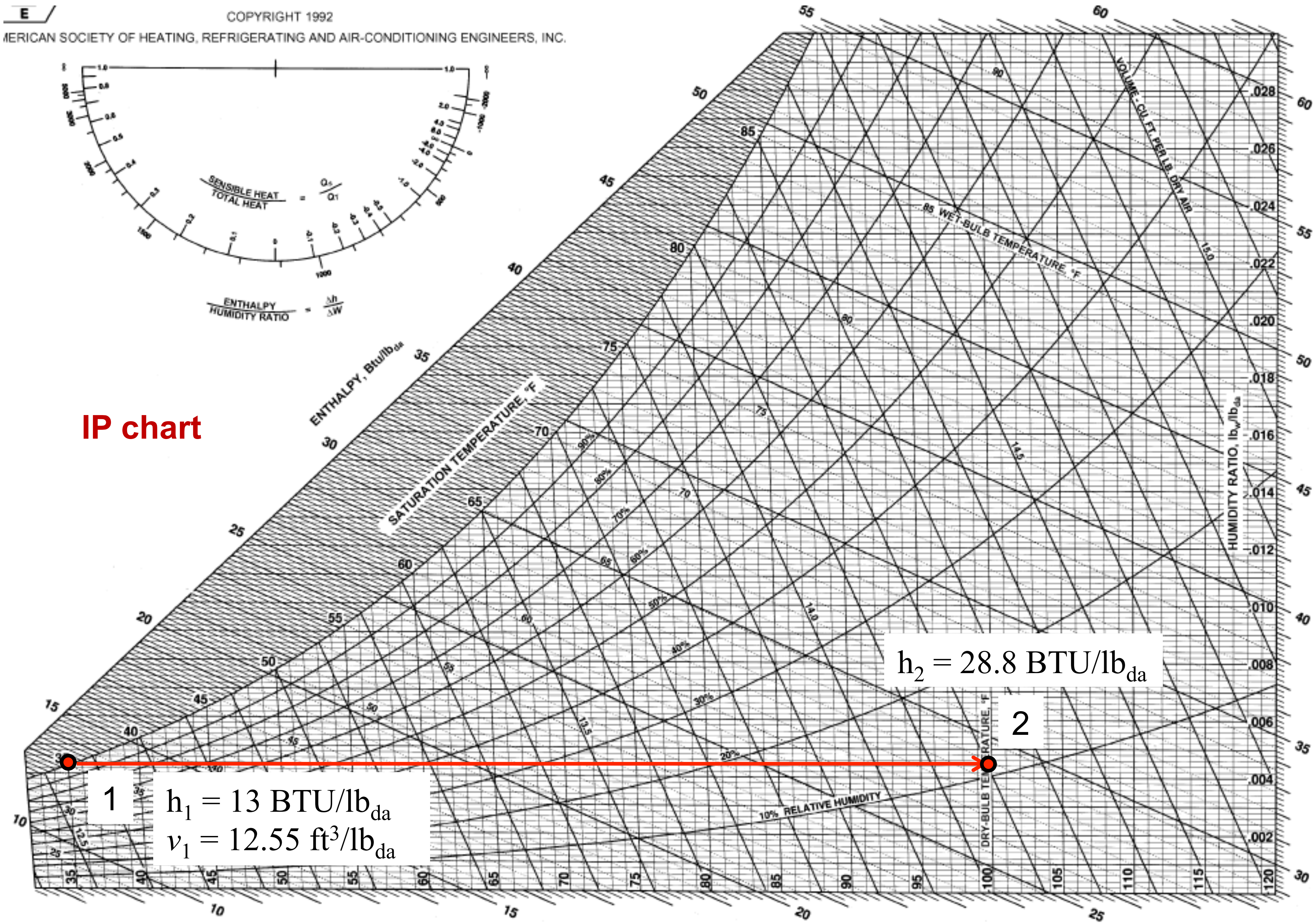
$\Delta h = 0$ means no energy is required other than for fans (for air) and pumps (for water)

IP unit examples

- Moist air, saturated at 35°F, enters a heating coil at a rate of 20,000 CFM and air leaves the coil at 100°F
  - What process is this?
  - Find the required rate of heat addition



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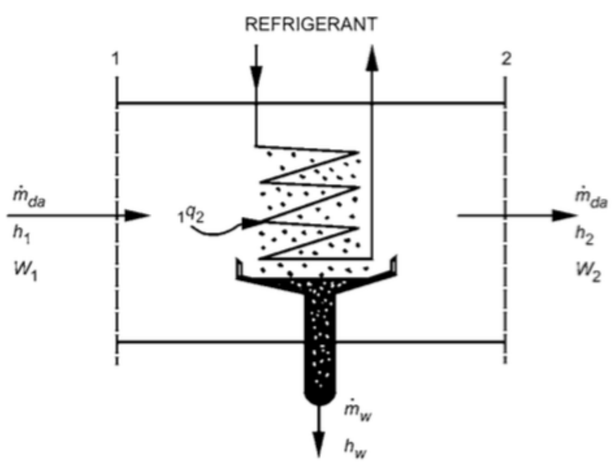
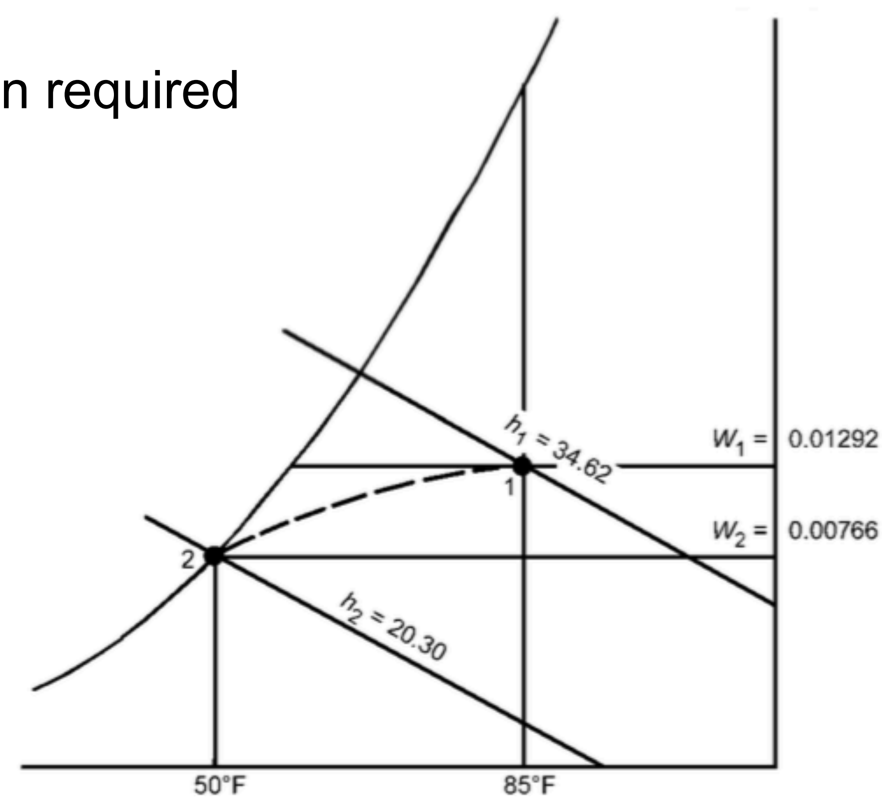
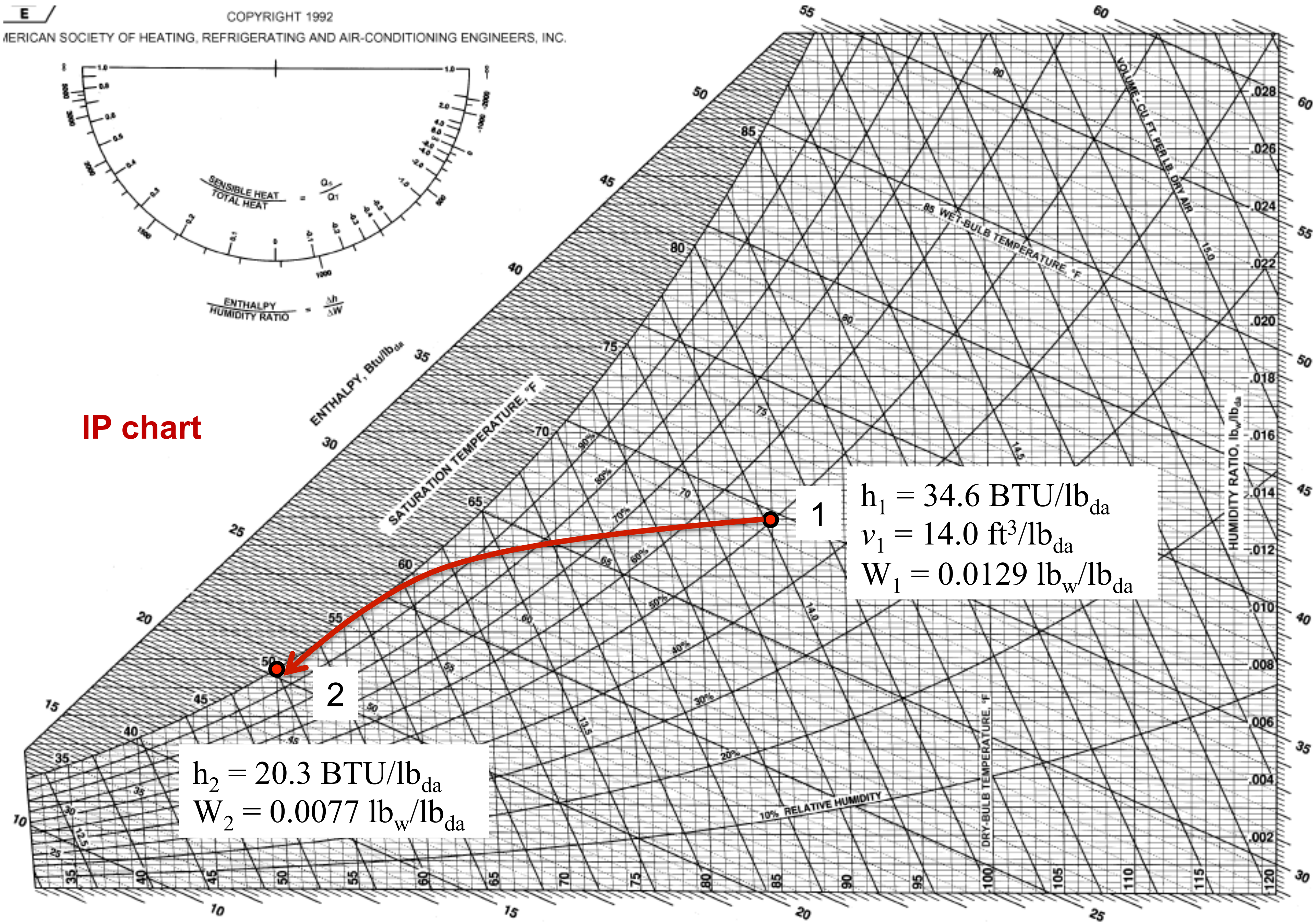
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °F
h2 = 28.8 BTU/lbda
2
1
h1 = 13 BTU/lbda
v1 = 12.55 ft3/lbda

IP unit examples

- Moist air at 85°F dry-bulb temperature and 50% RH enters a cooling coil at 10,000 CFM and is processed to final saturation conditions at 50°F
  - What processes is this?
  - Find the tons of refrigeration required





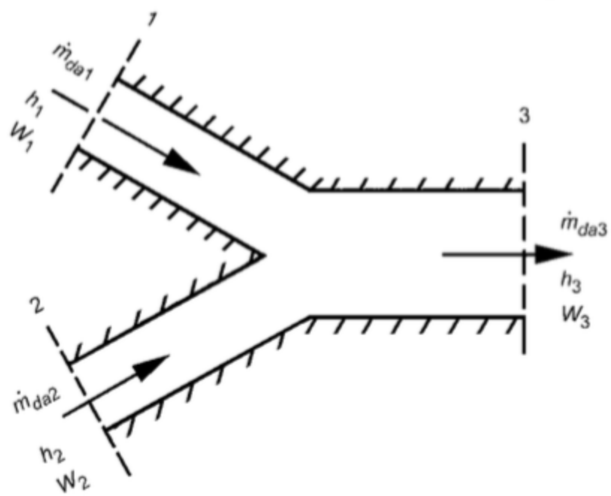


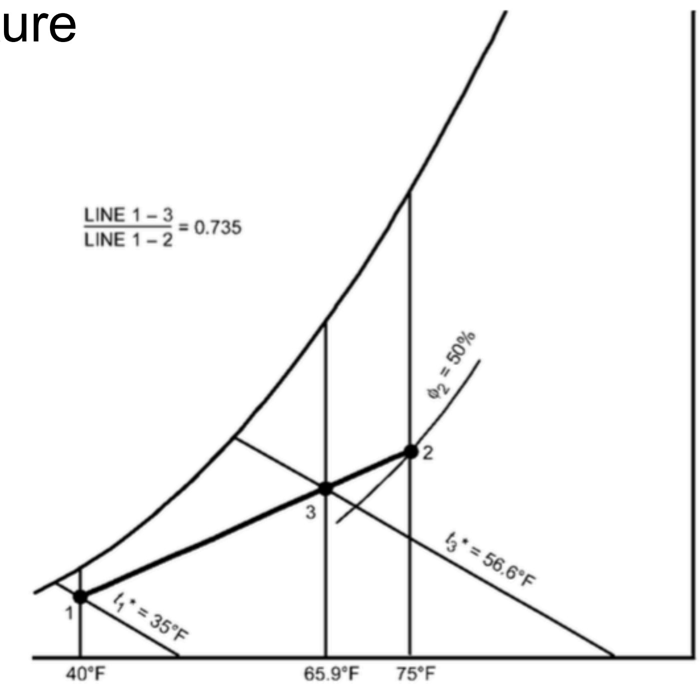
$h_1 = 34.6$ BTU/lb$_{da}$
$v_1 = 14.0$ ft^3/lb$_{da}$
$W_1 = 0.0129$ lb$_w$/lb$_{da}$

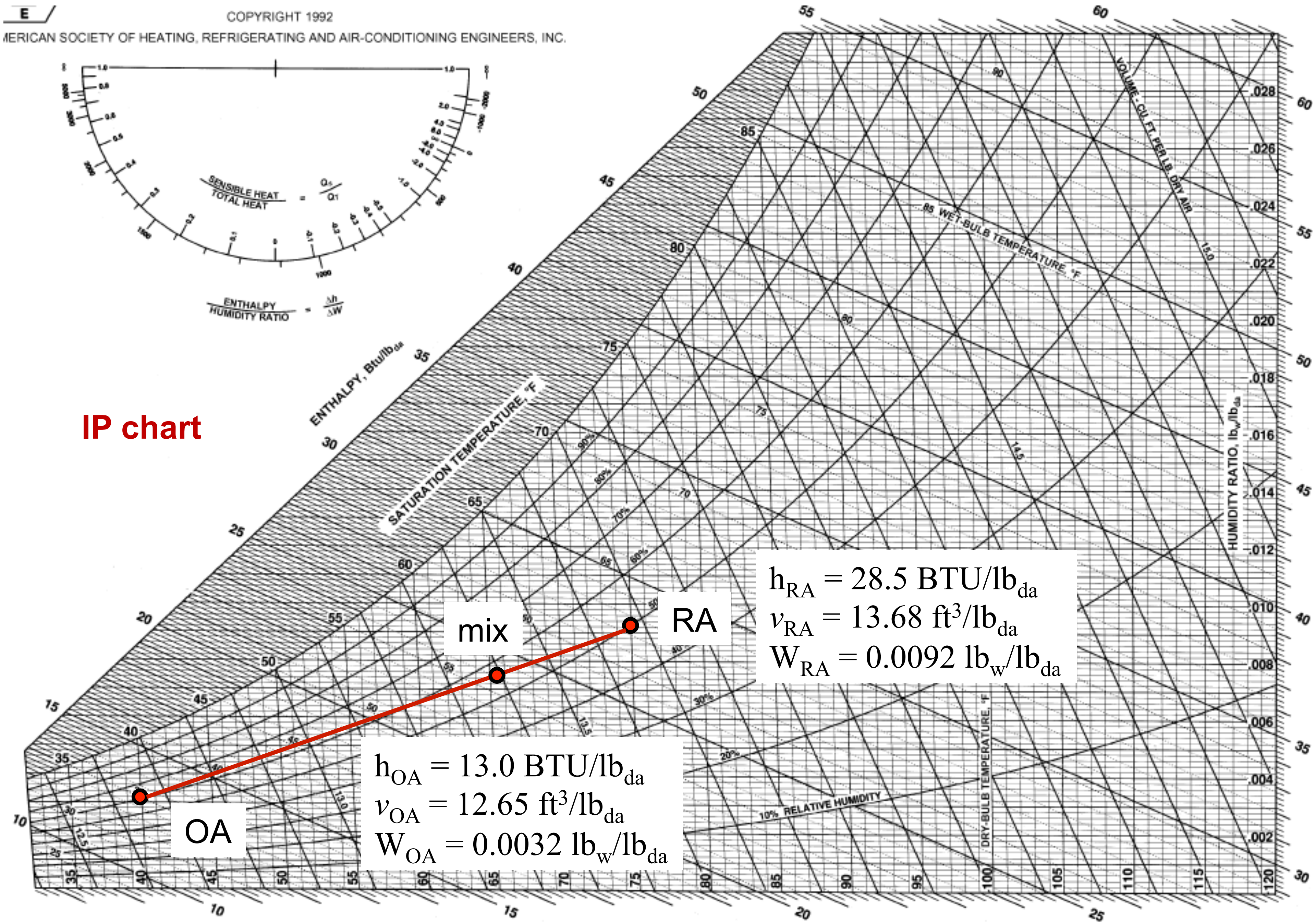
$h_2 = 20.3$ BTU/lb$_{da}$
$W_2 = 0.0077$ lb$_w$/lb$_{da}$

IP unit examples

- A stream of 5000 CFM of outdoor air at 40°F dry bulb temperature and 35°F thermodynamic wet bulb temperature is adiabatically mixed with 15,000 CFM of recirculated air at 75°F dry bulb temperature and 50% RH
  - What processes is this?
  - Find the dry bulb temperature and thermodynamic wet bulb temperature of the resulting mixture







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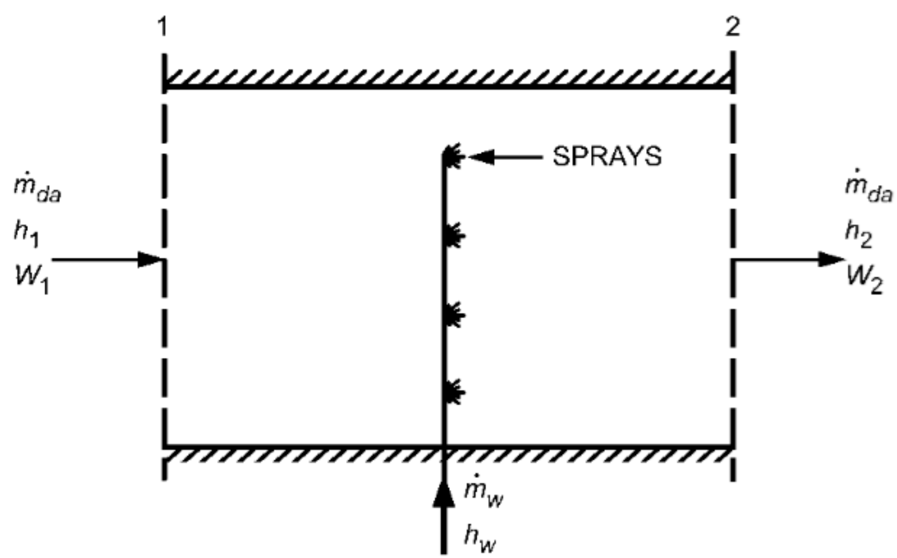
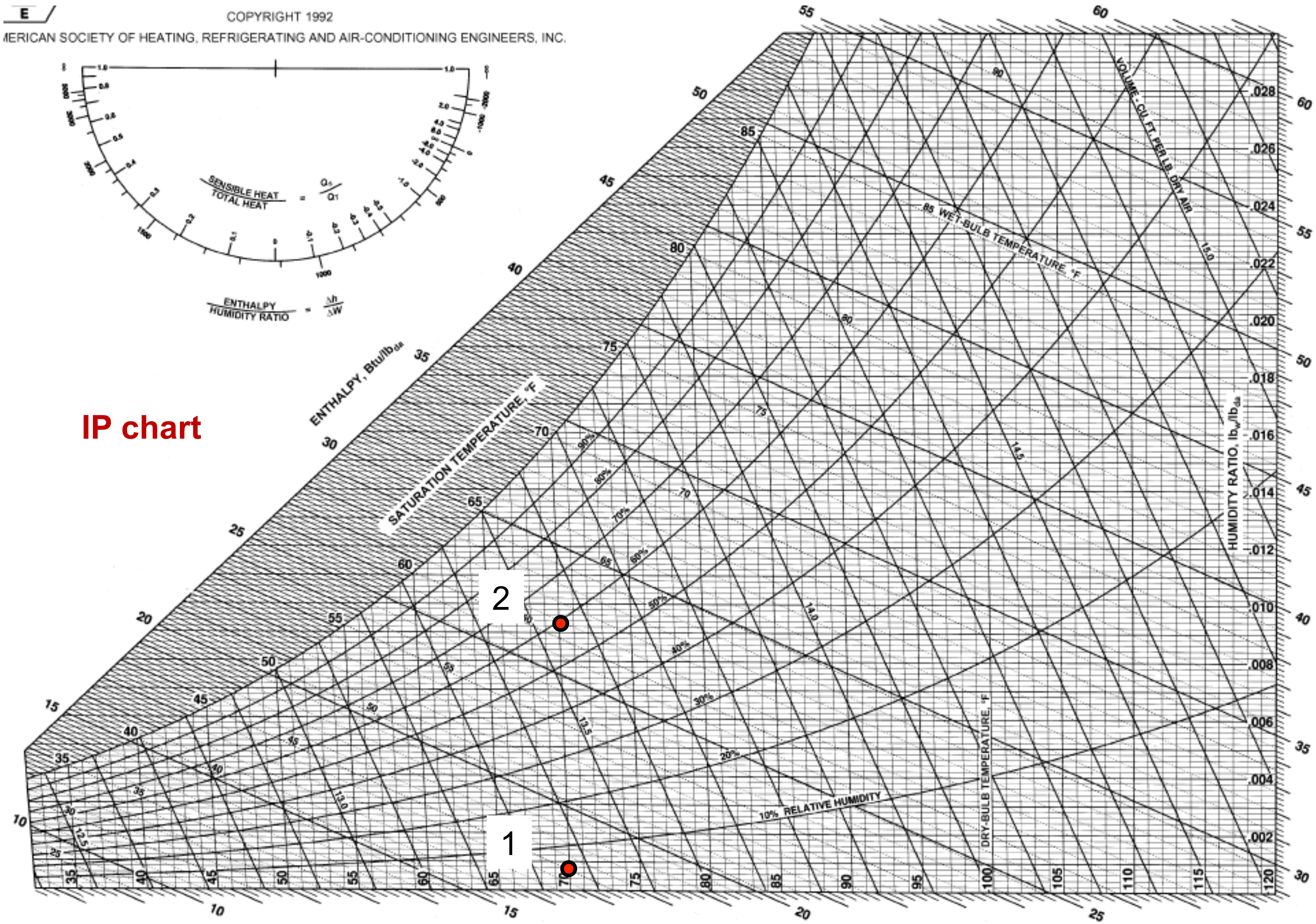
SENSIBLE HEAT / TOTAL HEAT = Q_s / Q_t
ENTHALPY / HUMIDITY RATIO = $\Delta h / \Delta W$
IP chart
ENTHALPY, Btu/lb$_{da}$
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU FT PER LB. DRY AIR
HUMIDITY RATIO, lb$_w$/lb$_{da}$
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
mix
RA
OA
h_{RA} = 28.5 BTU/lb$_{da}$
v_{RA} = 13.68 ft^3/lb$_{da}$
W_{RA} = 0.0092 lb$_w$/lb$_{da}$
h_{OA} = 13.0 BTU/lb$_{da}$
v_{OA} = 12.65 ft^3/lb$_{da}$
W_{OA} = 0.0032 lb$_w$/lb$_{da}$

IP unit examples

- Moist air at 70°F dry bulb temperature and 45°F wet bulb temperature is to be processed to a final dew point of 55°F by adiabatic injection of saturated steam at 230°F
- The air flow rate is 10,000 CFM
  - Find the rate of steam flow required





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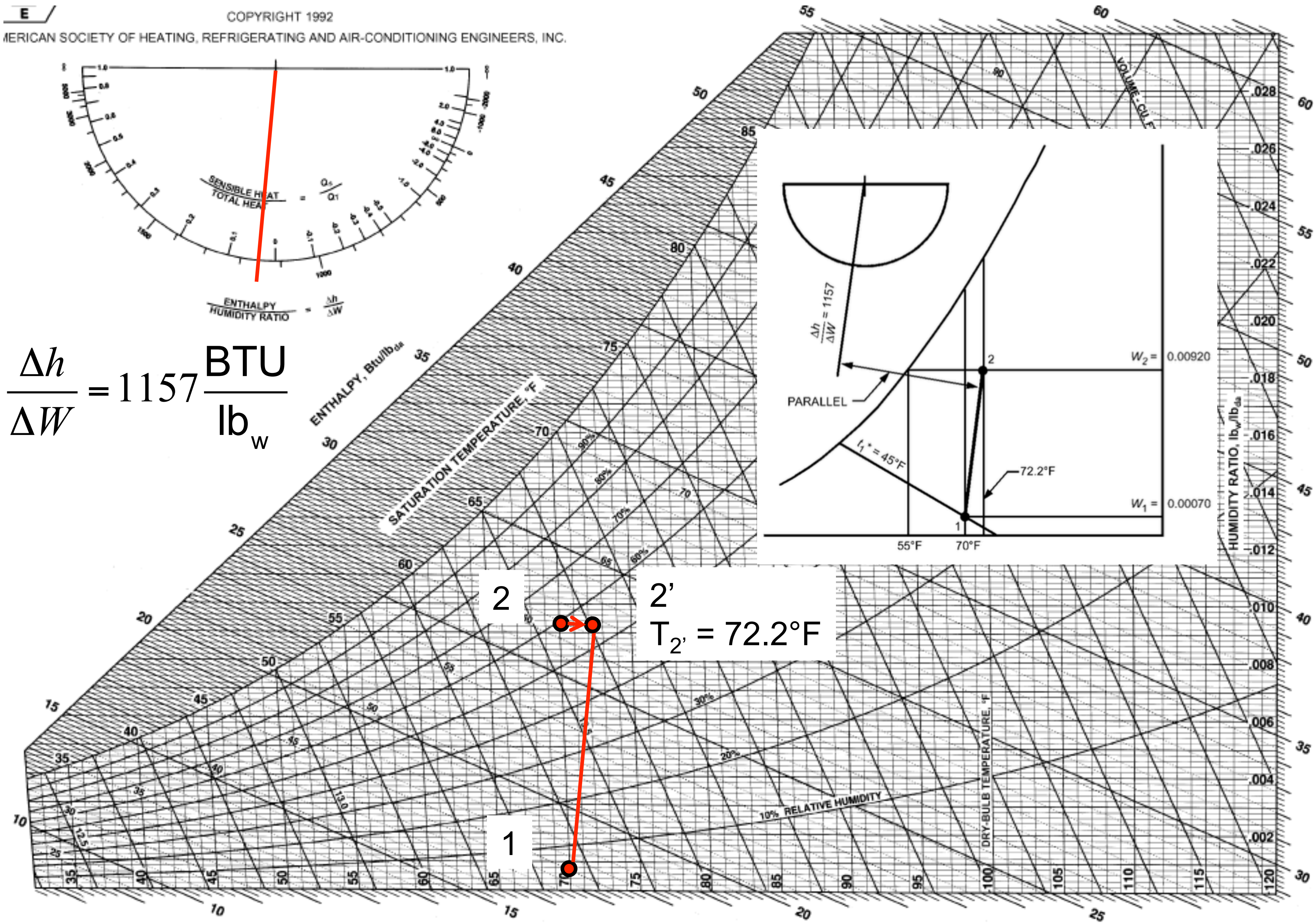
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb_w/lb_da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °F
2
1

$$\frac{\Delta h}{\Delta W} = 1157 \frac{\text{BTU}}{\text{lb}_w}$$



HW 4 assigned

- HW 4 assigned, due Tuesday, October 18