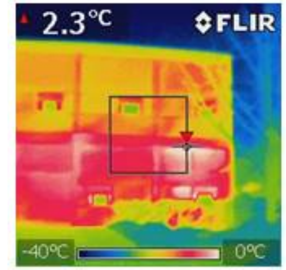
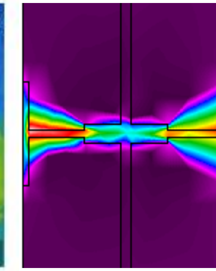
# CAE 331/513
# Building Science
Fall 2019



## October 10, 2019
Psychrometric processes (part 2)

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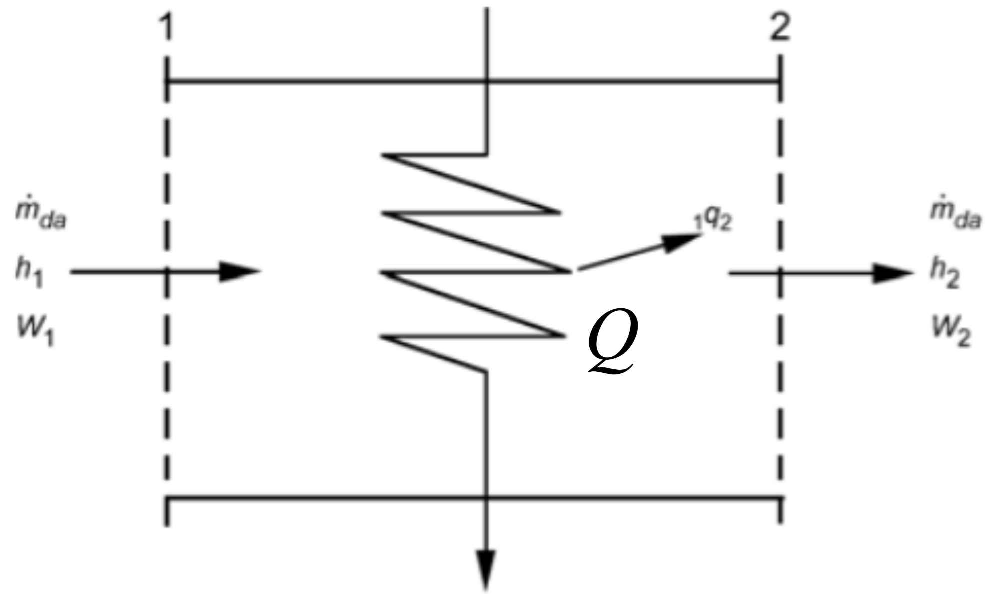
# PSYCHROMETRIC PROCESSES

Using energy and mass balance equations

# Energy/mass balances for psychrometric processes

## Heating air




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

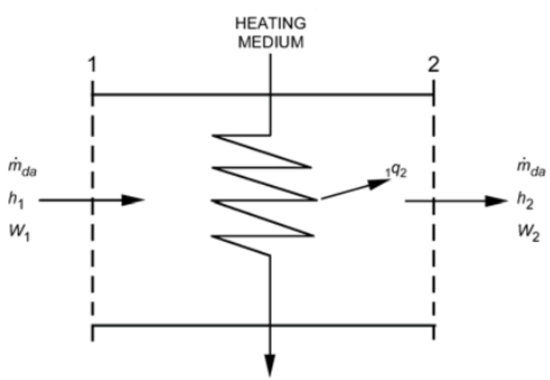
Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

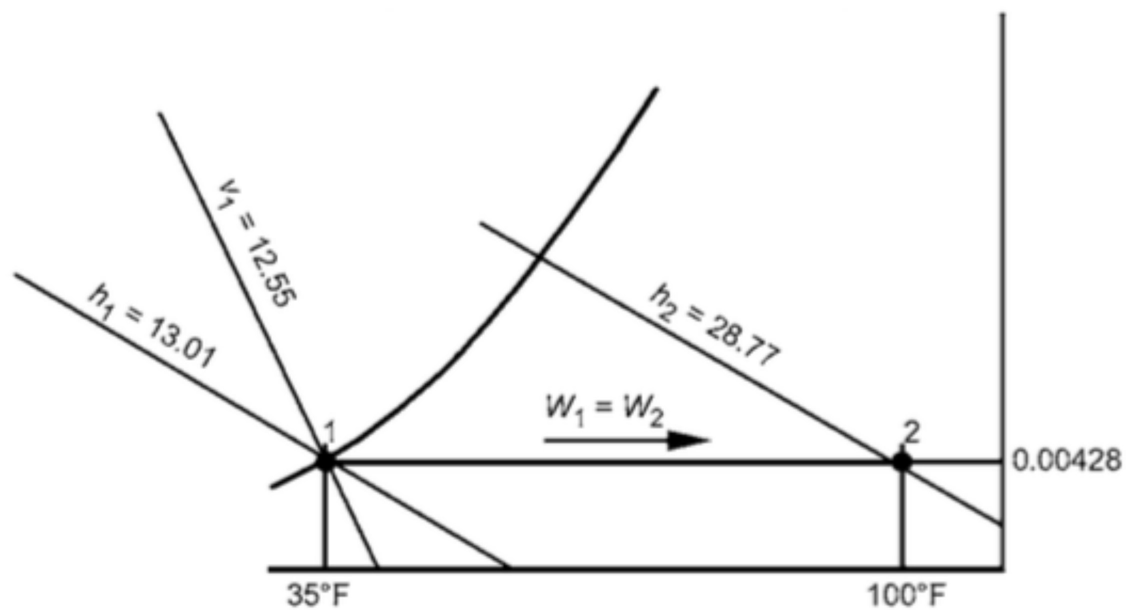
Mass balance on water vapor: $\dot{m}_{da,1}W_1 = \dot{m}_{da,2}W_2$

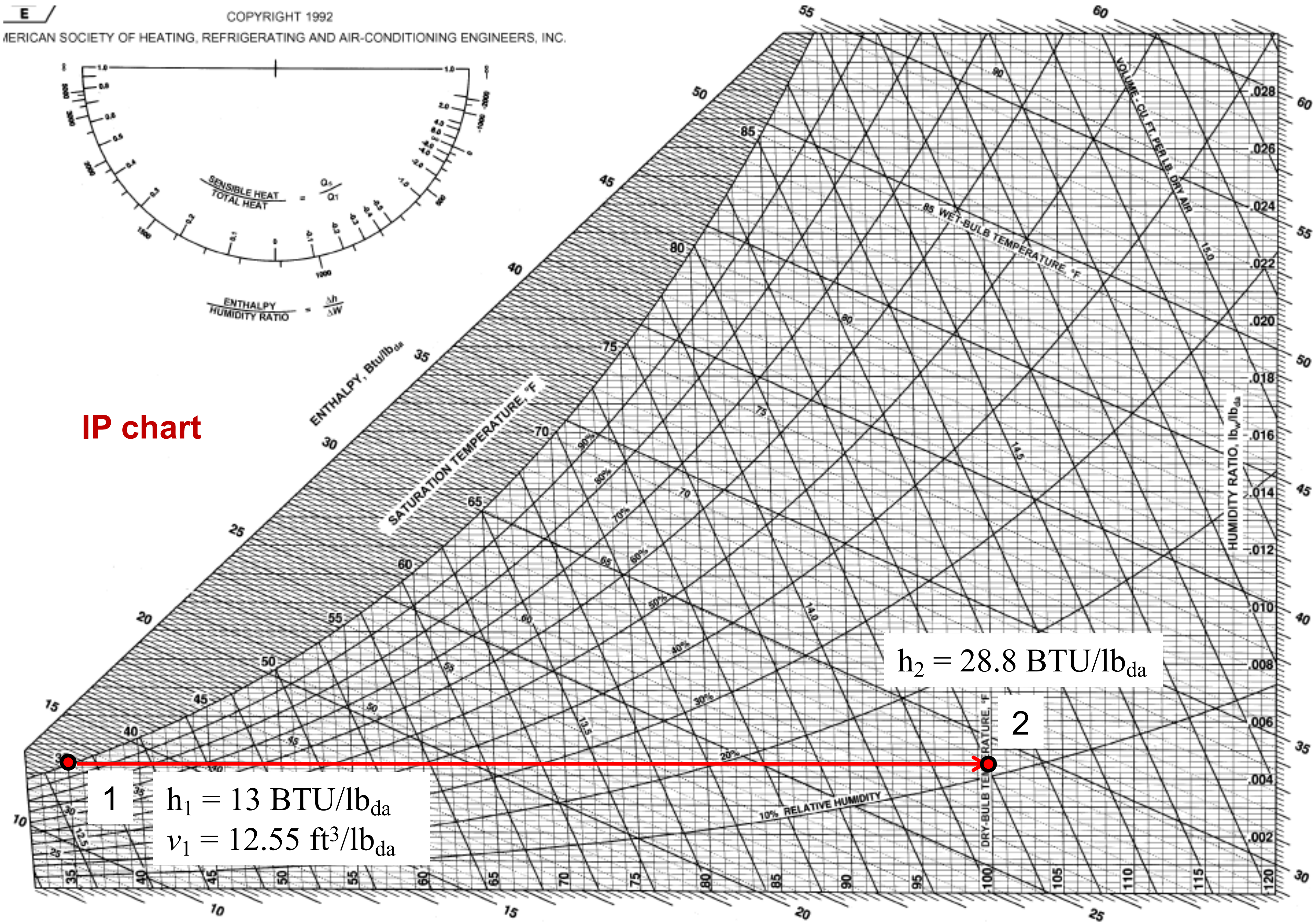
Therefore: $Q_{1\rightarrow 2} = \dot{m}_{da}(h_2 - h_1)$

# Example 1: Heating (IP)

- 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
  - Find the required rate of heat addition





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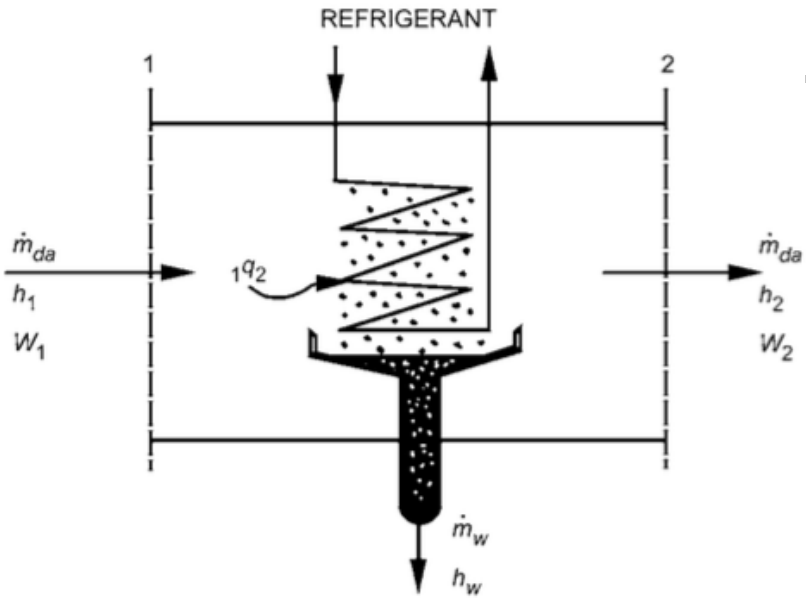
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °F
h2 = 28.8 BTU/lbda
2
1
h1 = 13 BTU/lbda
v1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

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

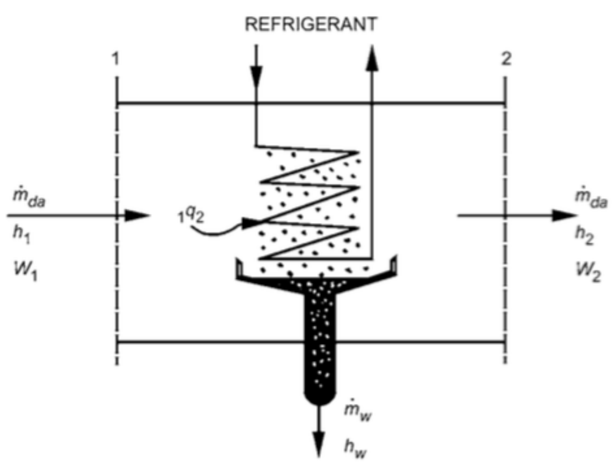
Therefore: $\dot{m}_w = \dot{m}_{da}(W_1 - W_2)$

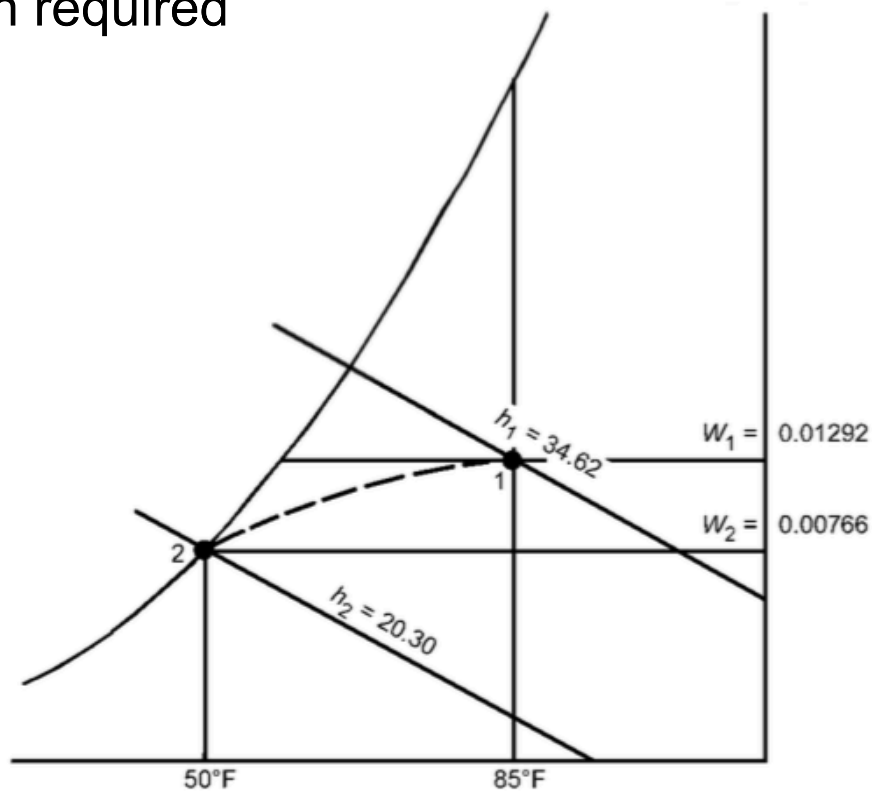
And: $Q_{1\to 2} = \dot{m}_{da}[(h_2 - h_1) - (W_2 - W_1)h_{w,2}]$

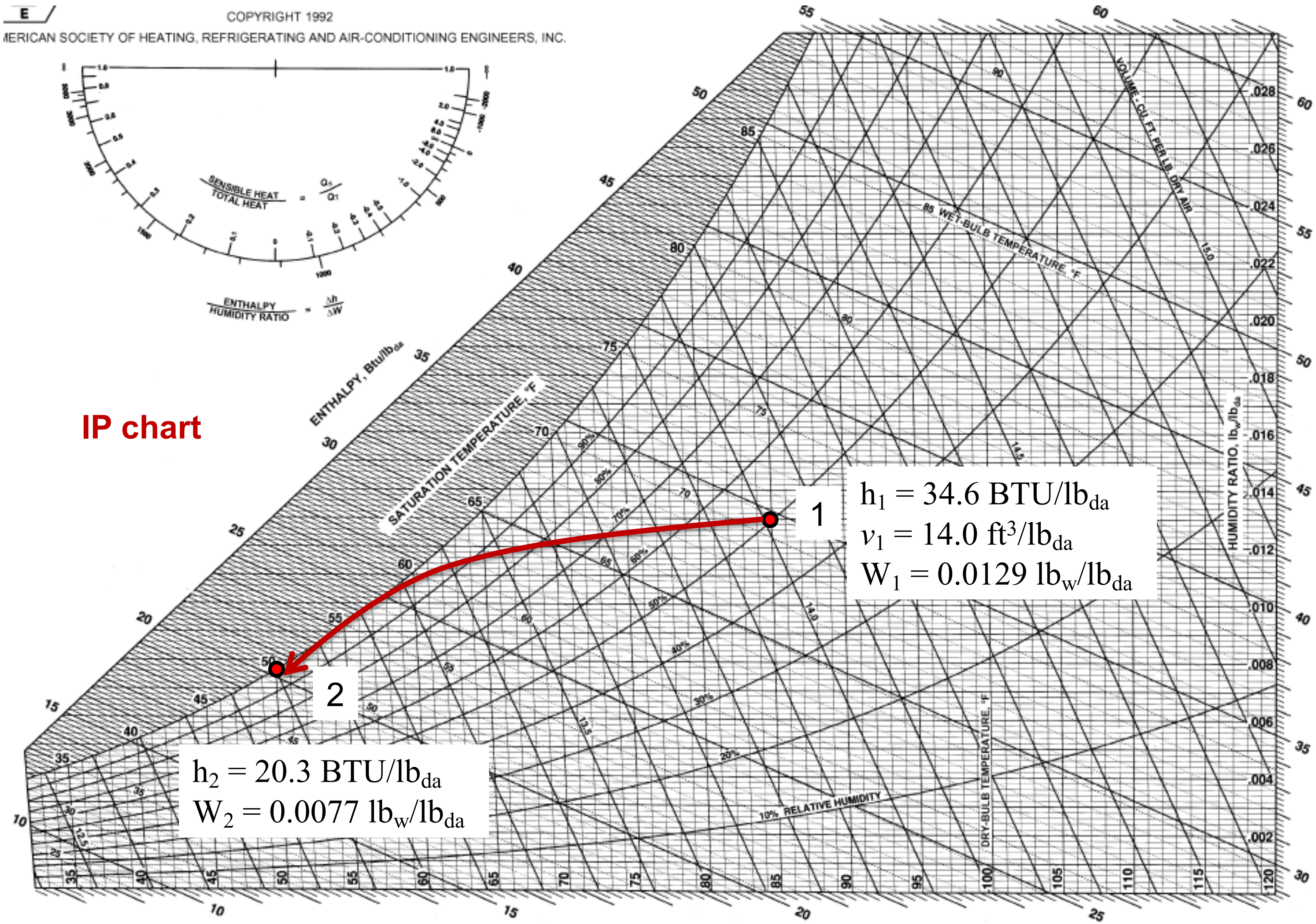
*(Q is negative for cooling)*

# Example 2: Cooling and dehumidification (IP)

- 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
  - Find the tons of refrigeration required





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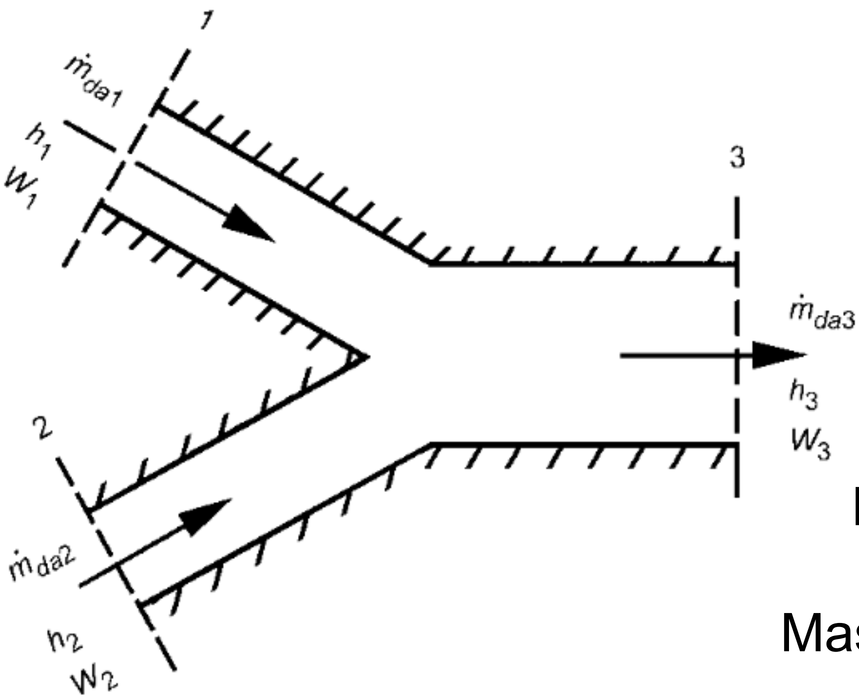
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
1
h1 = 34.6 BTU/lbda
v1 = 14.0 ft3/lbda
W1 = 0.0129 lbw/lbda
2
h2 = 20.3 BTU/lbda
W2 = 0.0077 lbw/lbda

# Energy/mass balances for psychrometric processes

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

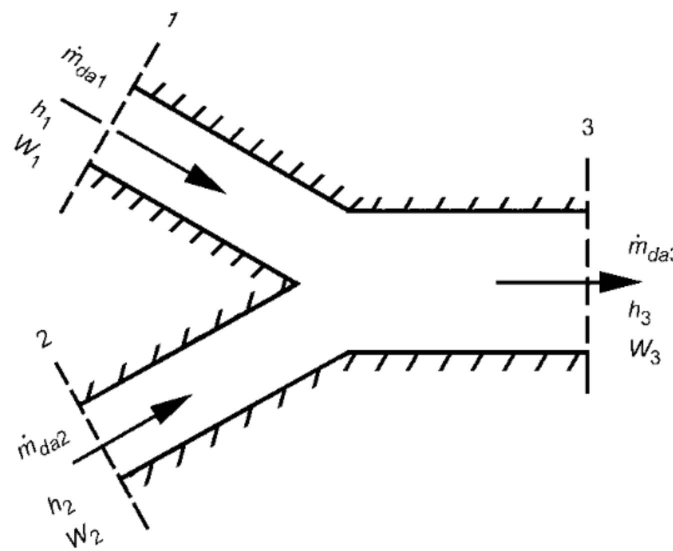
# Energy/mass balances for psychrometric processes

- **Mixing**: 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!)

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

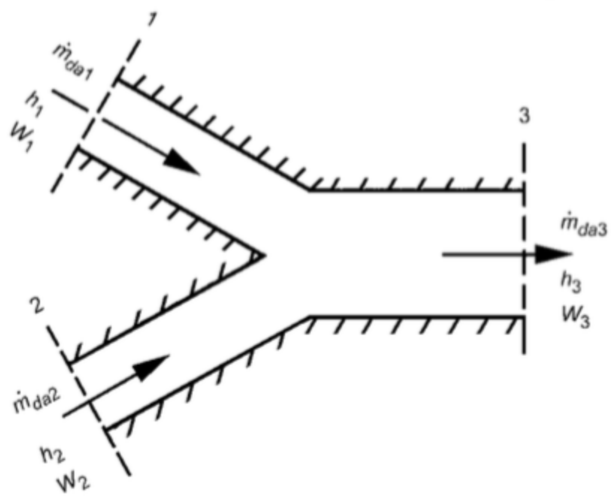
$$W_3 = \frac{\dot{m}_{da1} W_1 + \dot{m}_{da2} W_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

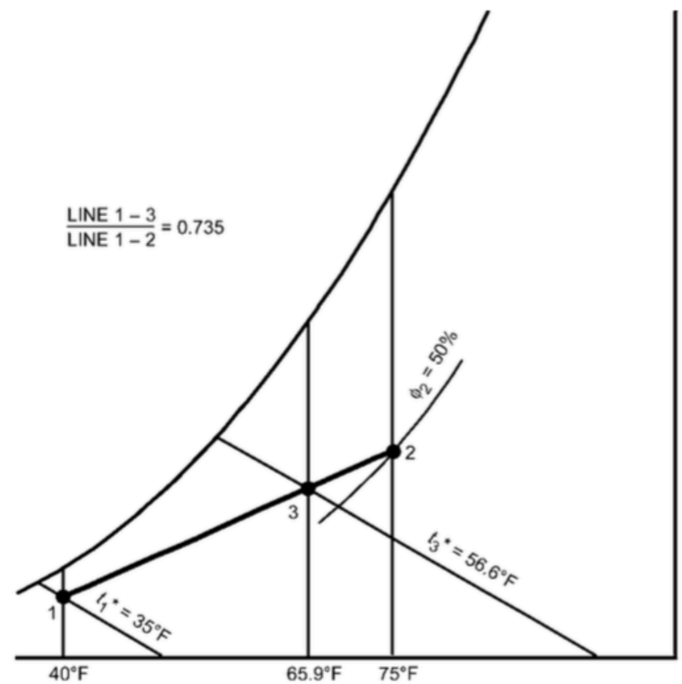
$$h_3 = \frac{\dot{m}_{da1} h_1 + \dot{m}_{da2} h_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

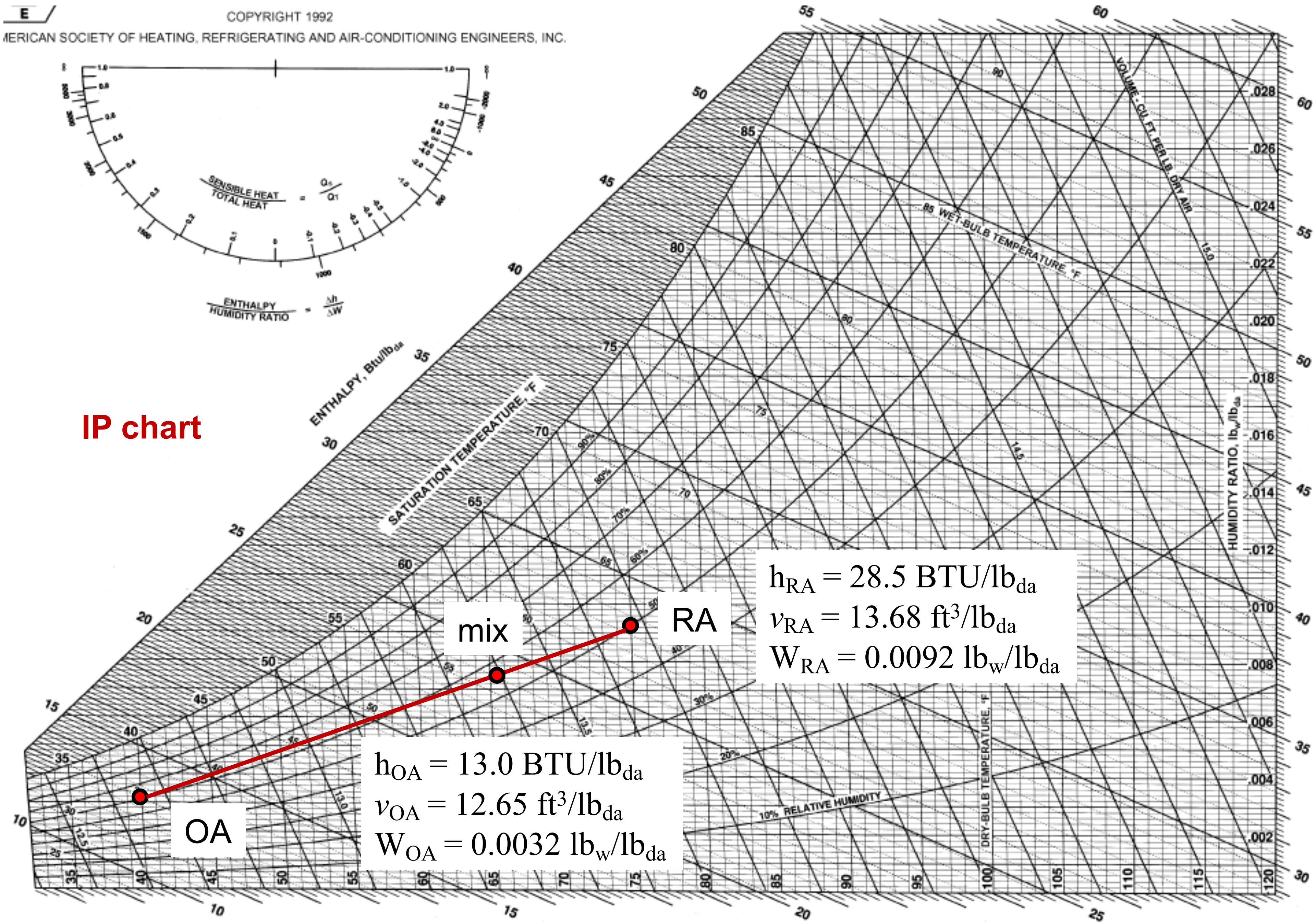


# Example 3: Mixing (IP)

- A stream of 5,000 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
  - Find the dry bulb temperature, humidity ratio, and enthalpy of the resulting mixture

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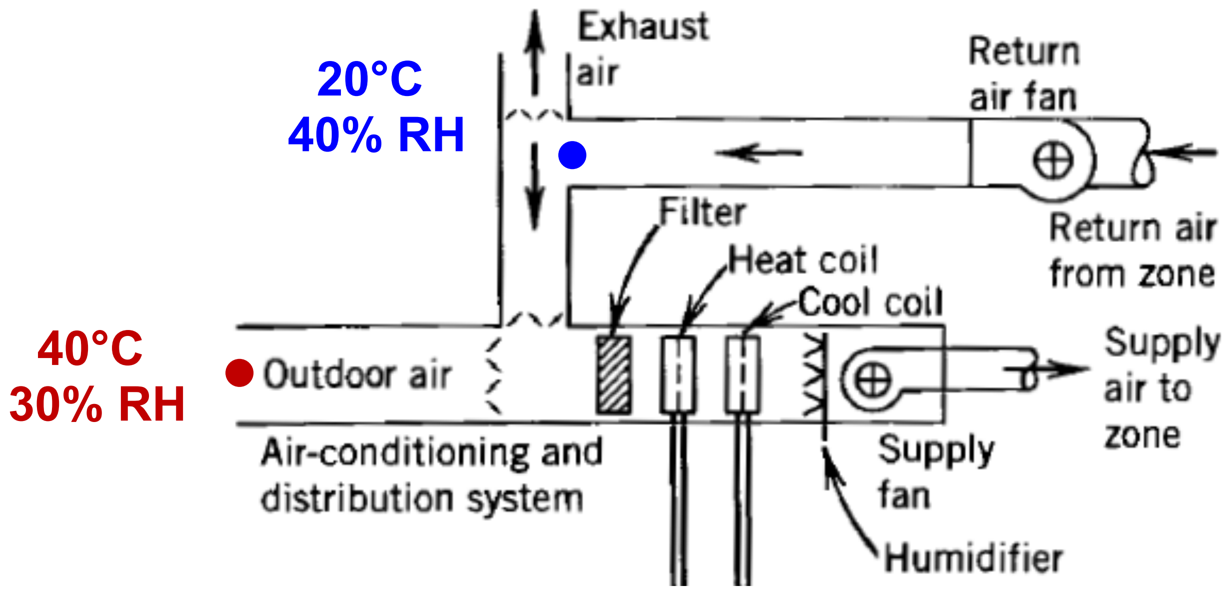
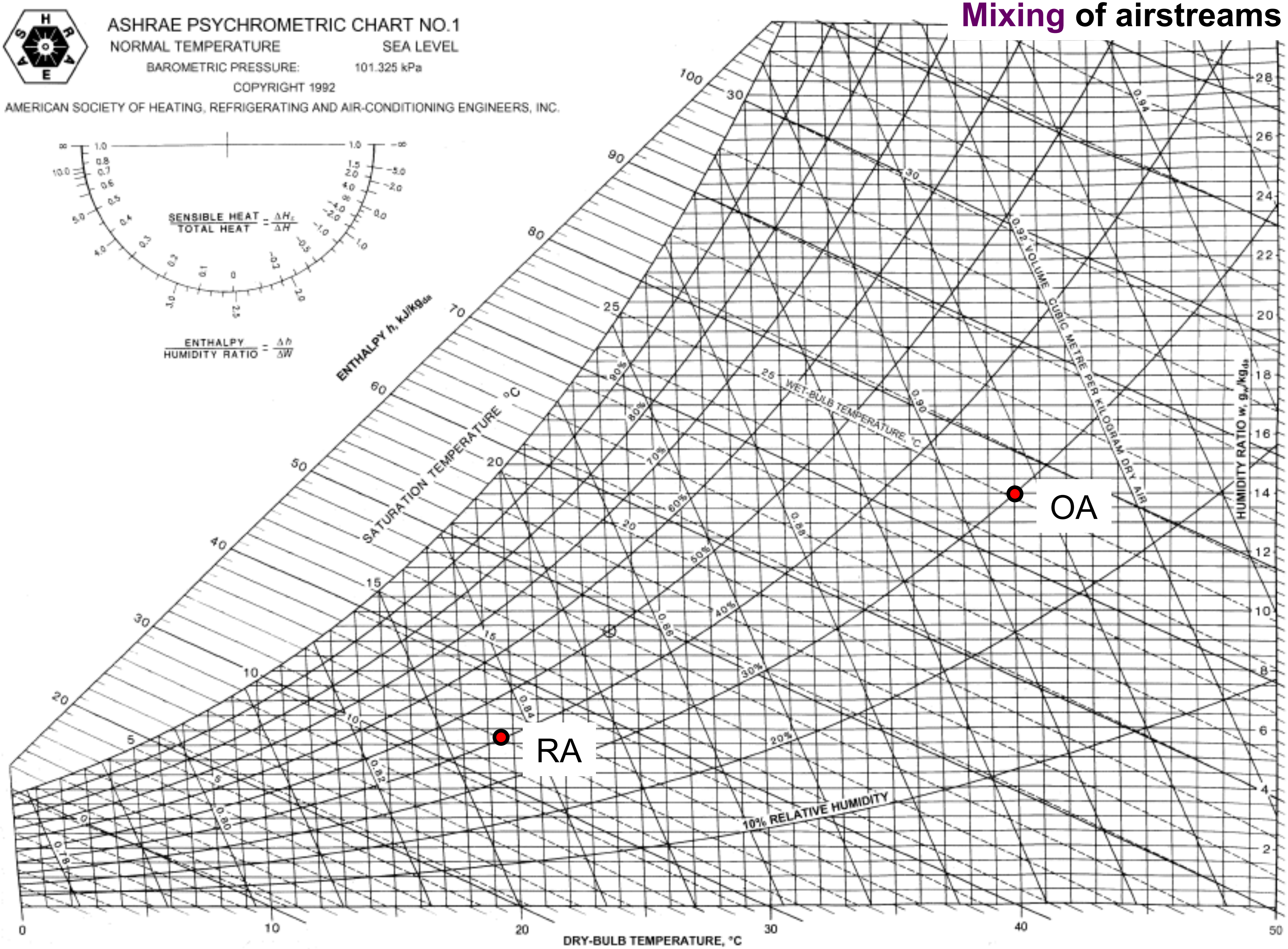
SENSIBLE HEAT / TOTAL HEAT = $Q_S / Q_T$
ENTHALPY / HUMIDITY RATIO = $\Delta h / \Delta W$
IP chart
ENTHALPY, Btu/lb$_{da}$
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME - CU. FT. PER LB. DRY AIR
HUMIDITY RATIO, lb$_w$/lb$_{da}$
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
mix
RA
OA
$h_{RA}$ = 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$_{da}$

# Example 4: Mixing (SI)

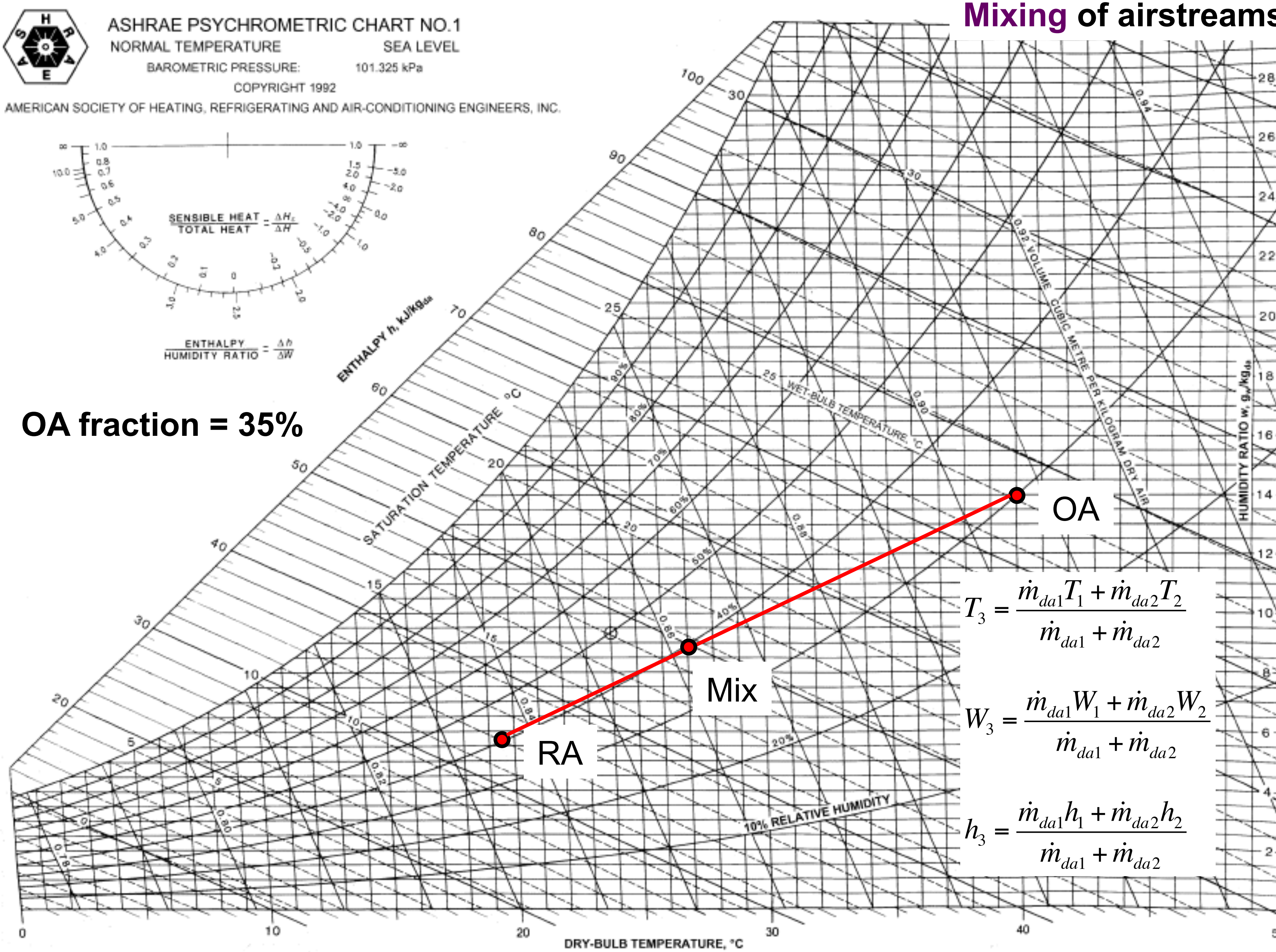
- Hot, humid outdoor air is mixed with recirculated indoor air at an outdoor air mass flow fraction of 35%
  - Q1: What is T, W, RH, and h at the mixed condition?



# Mixing of airstreams



# Mixing of airstreams




**OA fraction = 35%**

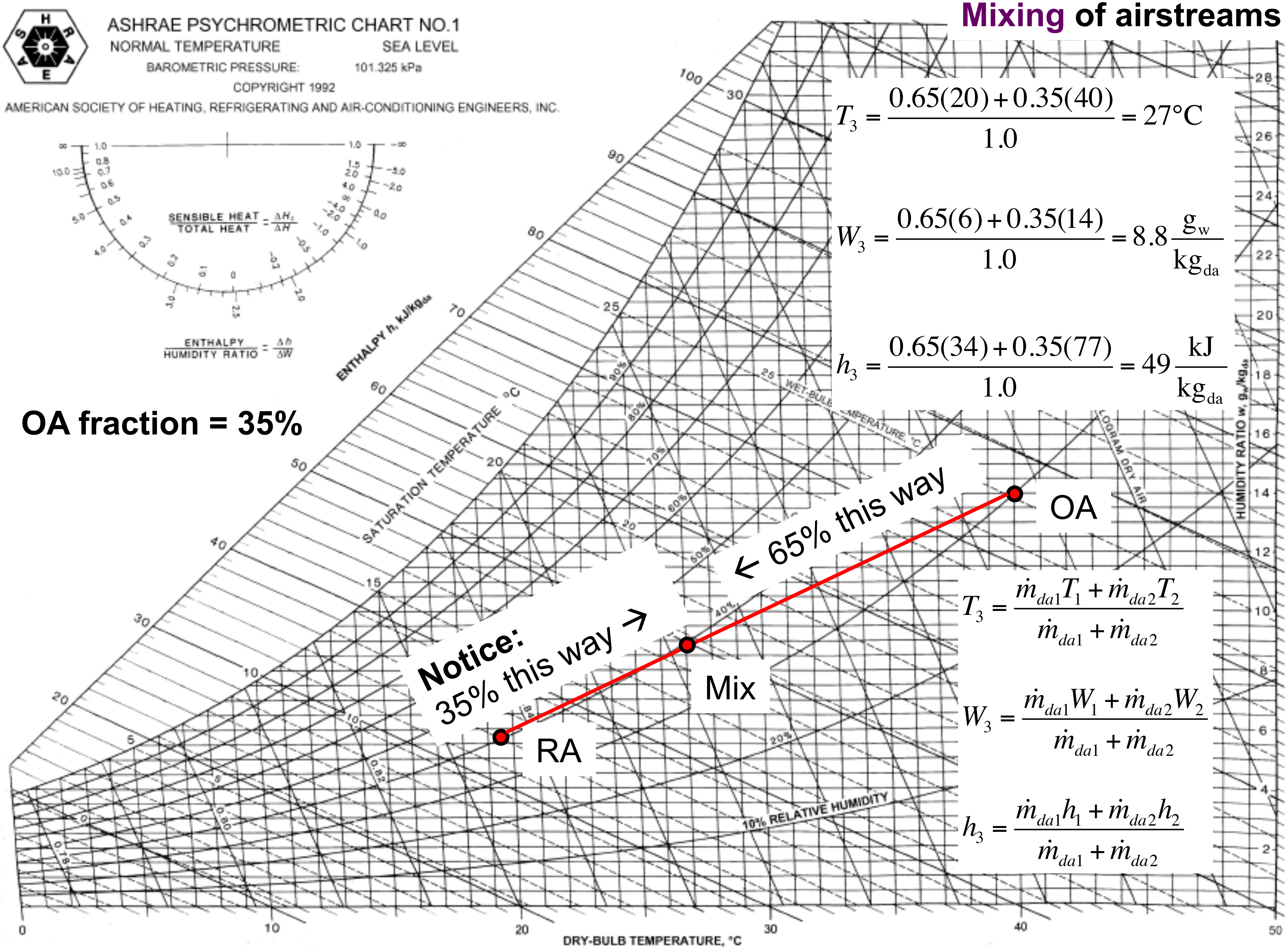
$$T_3 = \frac{\dot{m}_{da1} T_1 + \dot{m}_{da2} T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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

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

# Mixing of airstreams

**OA fraction = 35%**




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

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

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

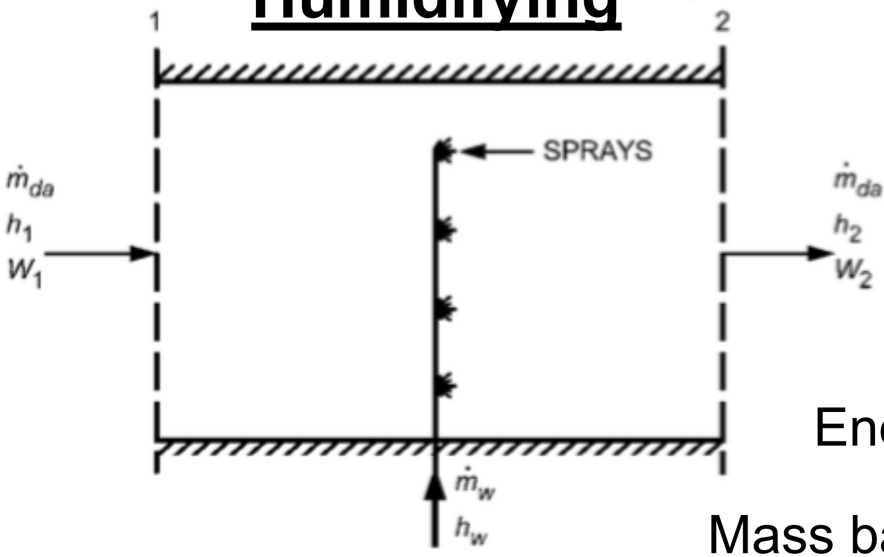
$$T_3 = \frac{\dot{m}_{da1}T_1 + \dot{m}_{da2}T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

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

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

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

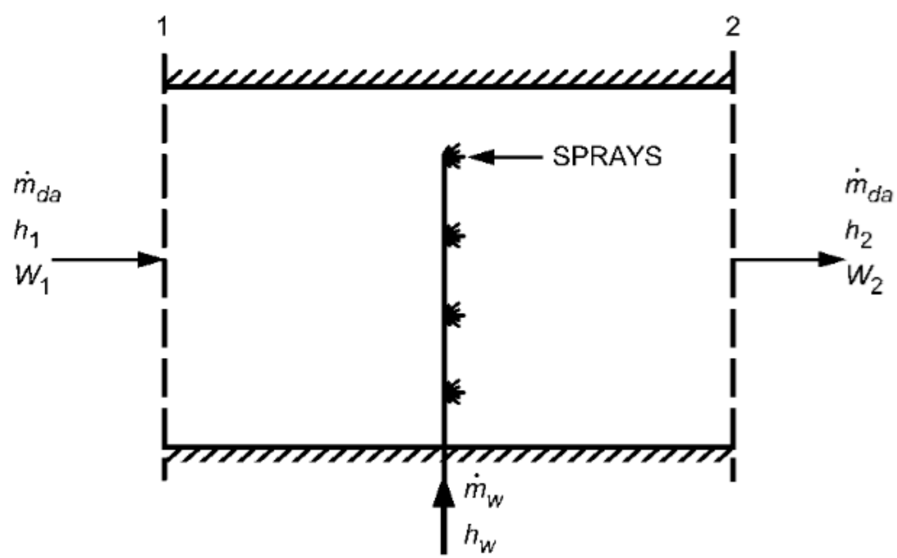
And: $\dot{m}_w h_w = \dot{m}_{da}(h_2 - h_1)$

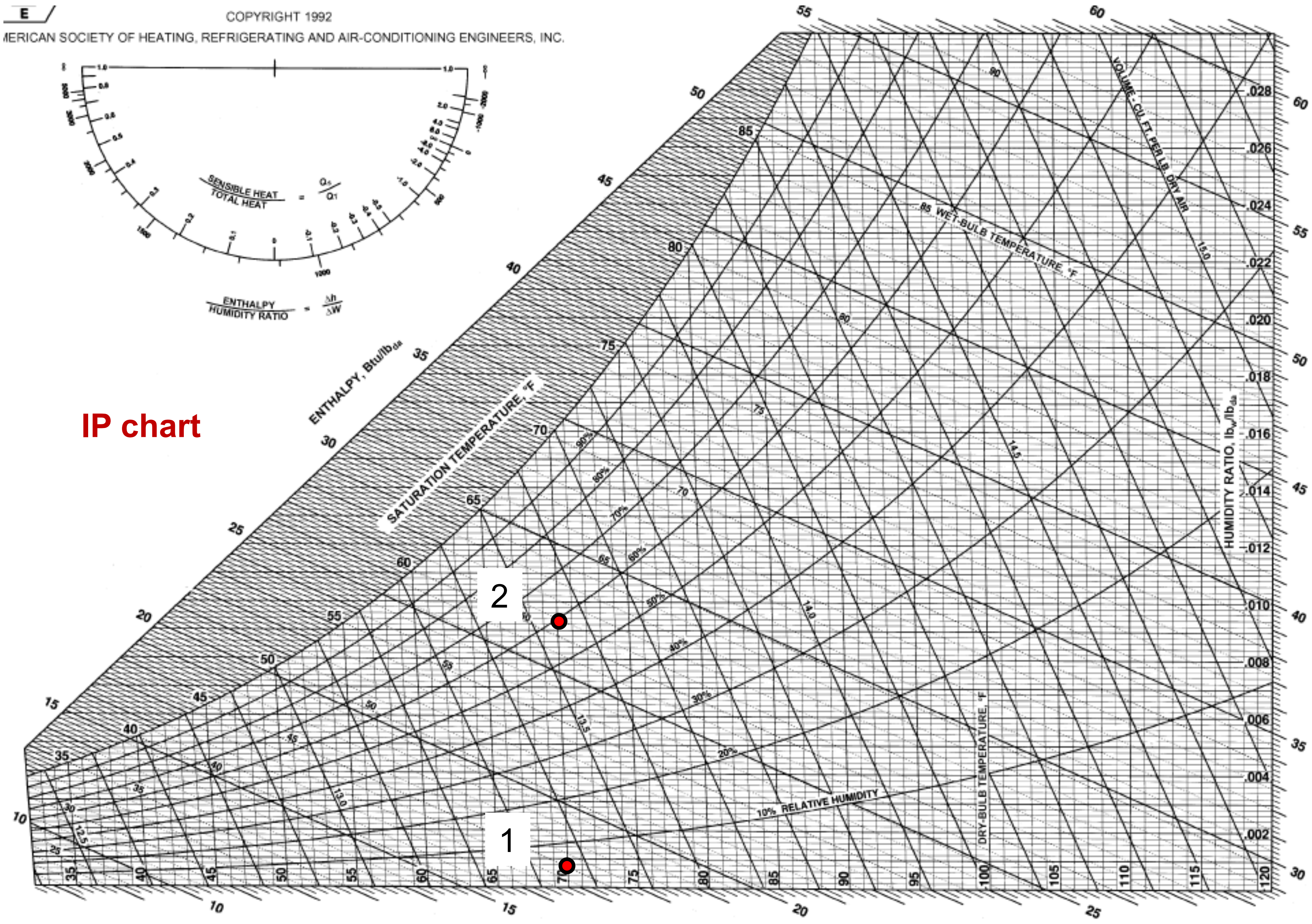
And: $\dfrac{h_2 - h_1}{W_2 - W_1} = \dfrac{\Delta h}{\Delta W} = h_w$

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

# Example 5: Humidification (IP)

- 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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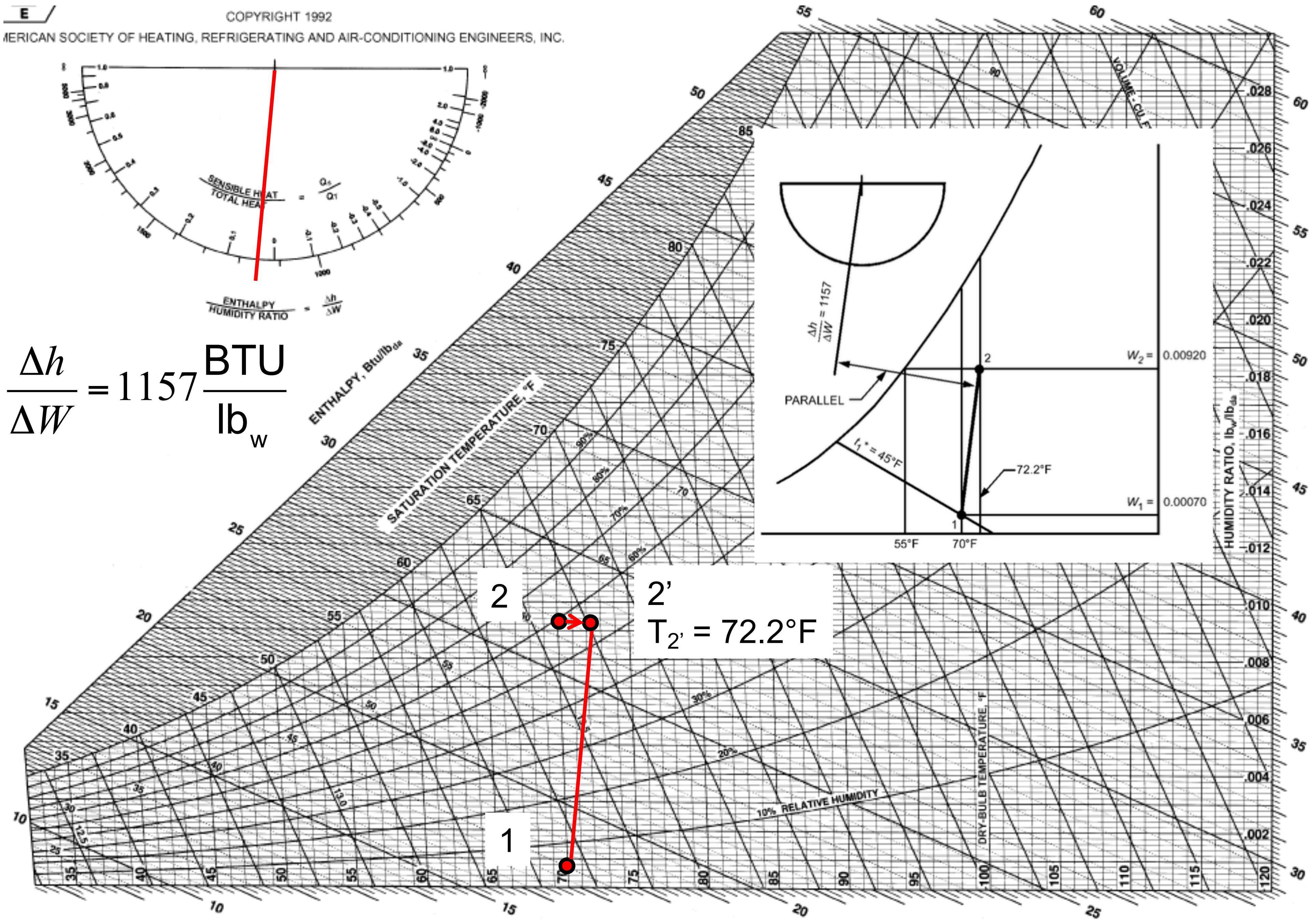
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lb da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb w/lb da
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
2
1

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



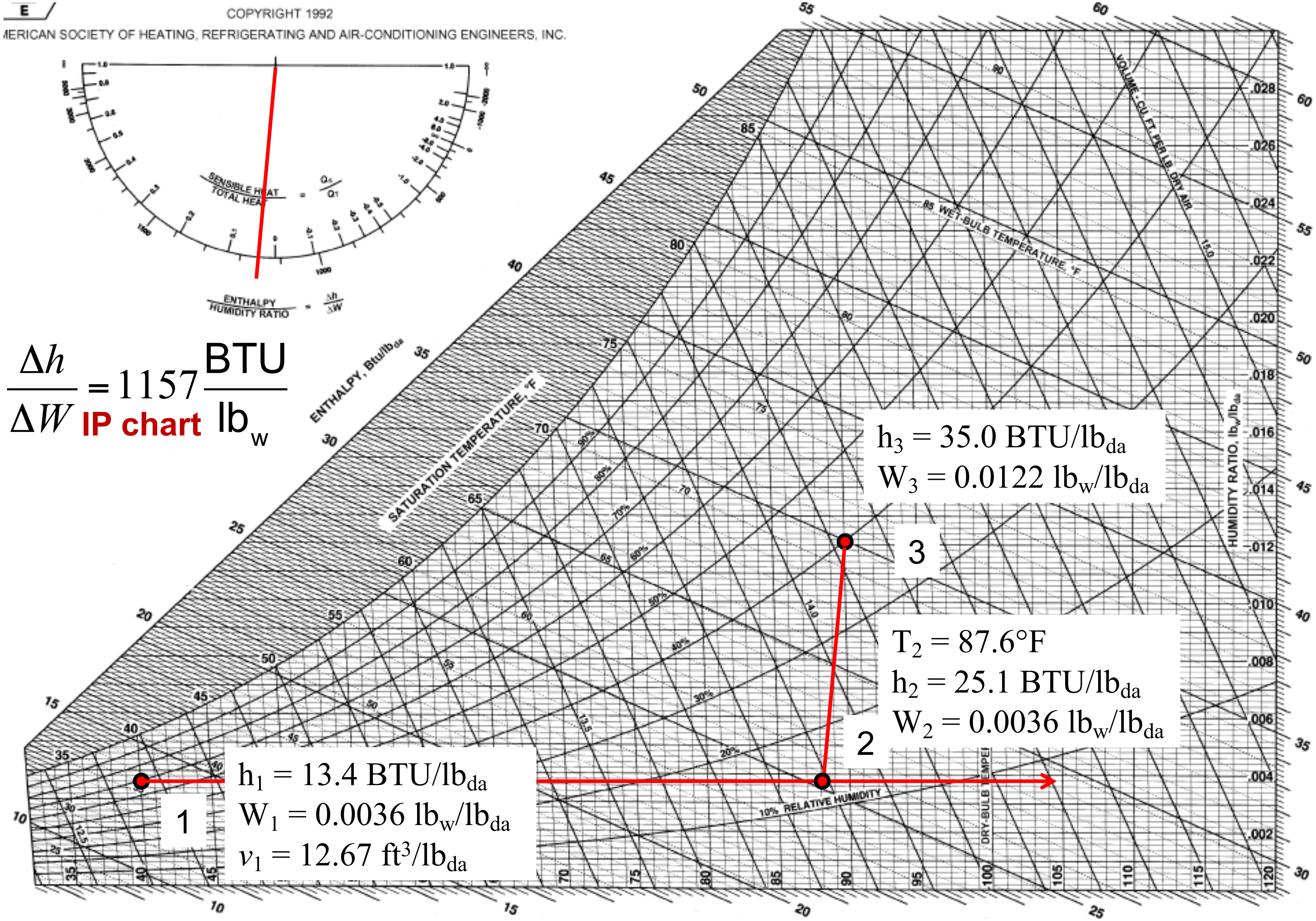
# Example 6: Heating and humidification (IP)

- Moist air is heated and humidified by passing it first over a heating coil and then adding moisture. The moist air enters the system at 40°F dry bulb temperature and 36°F wet bulb temperature at a mass flow rate of 235 $lb_{da}$/min. The humidifier injects saturated steam at 230°F. The moist air exists the system at 90°F dry bulb temperature and 40% RH.

- Locate state 2 on a psychrometric chart and determine the rate of heat addition by the heating coil and the rate of mass addition by the humidifier.

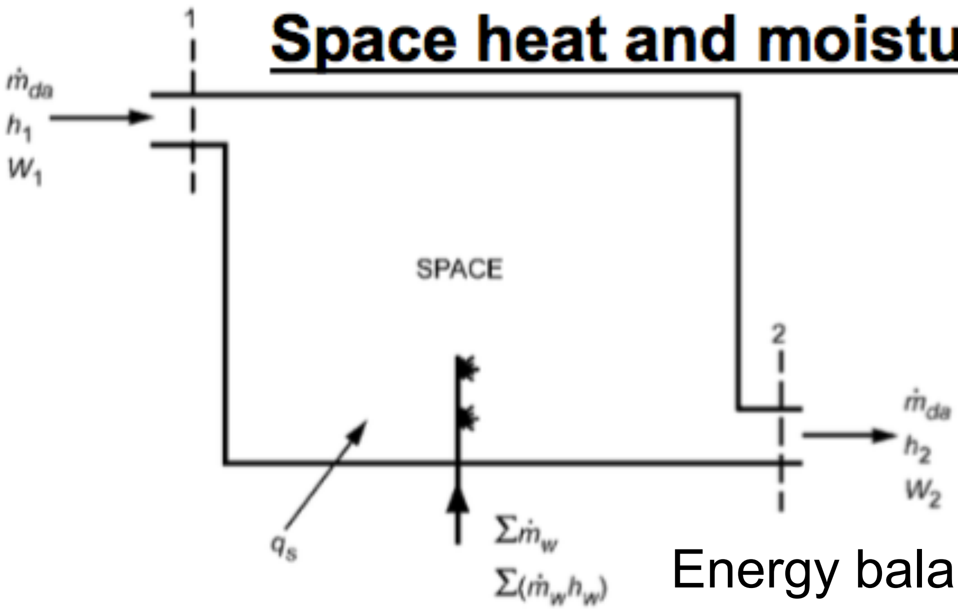
$$\frac{\Delta h}{\Delta W} = 1157 \frac{\text{BTU}}{\text{lb}_w}$$

**IP chart**



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

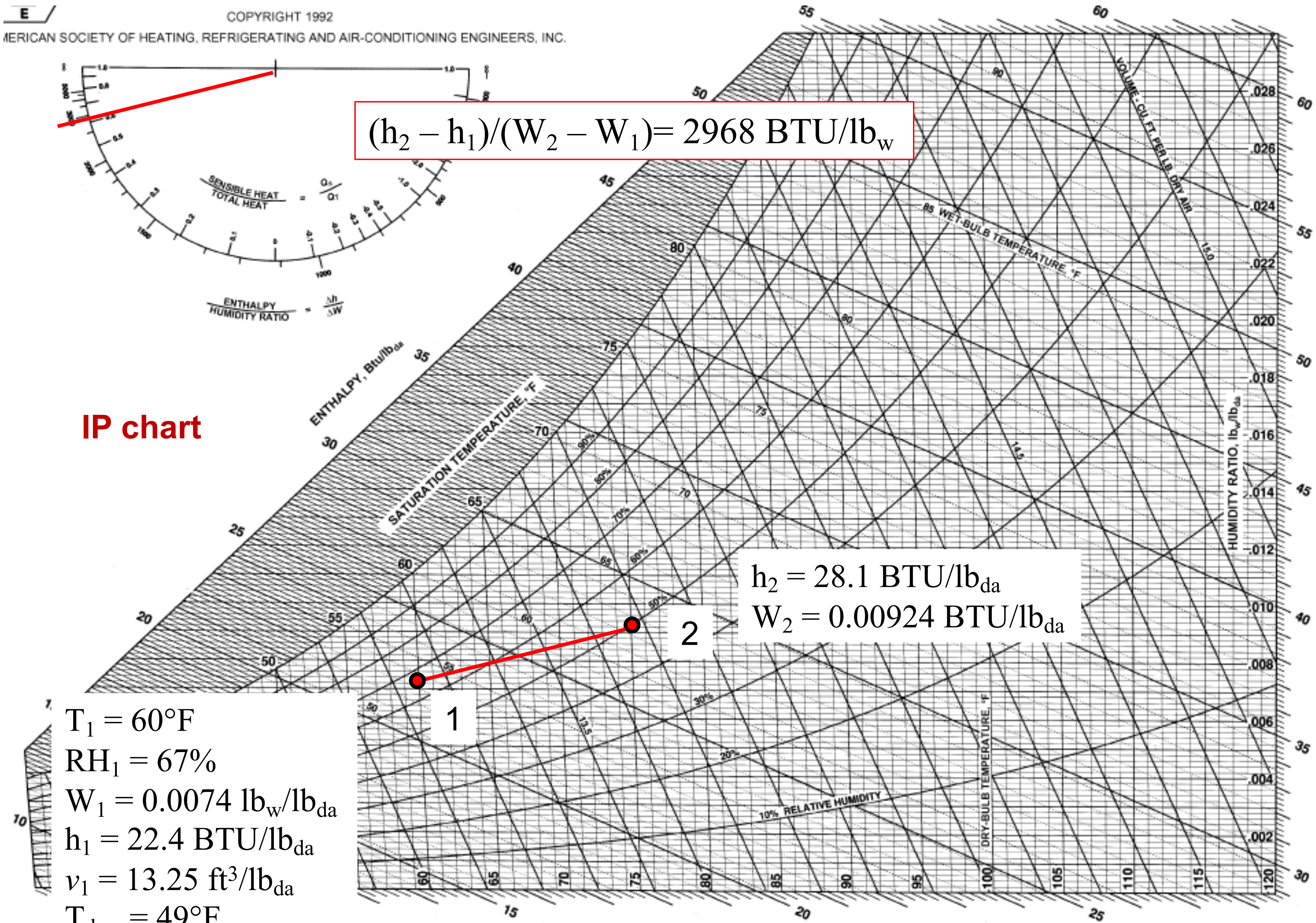
And: $$\frac{\Delta h}{\Delta W} = \frac{\sum \dot{m}_w h_w + Q_{gains}}{\sum \dot{m}_w}$$

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

# Example 7: Space conditioning – cooling (IP)

- The air in a restaurant is to be maintained at 75°F dry-bulb temperature and 50% RH. The load calculations for the restaurant estimate the rate of sensible heat gain to be 178,000 BTU/h. The rate of moisture gain is estimated to be 95 $lb_w$/h with an average enthalpy of moisture ($h_w$) of 1095 BTU/$lb_w$. The supply air temperature is to be 60°F. Assume standard atmospheric pressure.

- Determine the following:
  a) The required dew-point temperature of the supply air
  b) The required volumetric flow rate of supply air (in CFM)




## IP chart

$(h_2 - h_1)/(W_2 - W_1) = 2968$ BTU/lb$_w$

$h_2 = 28.1$ BTU/lb$_{da}$

$W_2 = 0.00924$ BTU/lb$_{da}$

$T_1 = 60°F$

$RH_1 = 67\%$

$W_1 = 0.0074$ lb$_w$/lb$_{da}$

$h_1 = 22.4$ BTU/lb$_{da}$

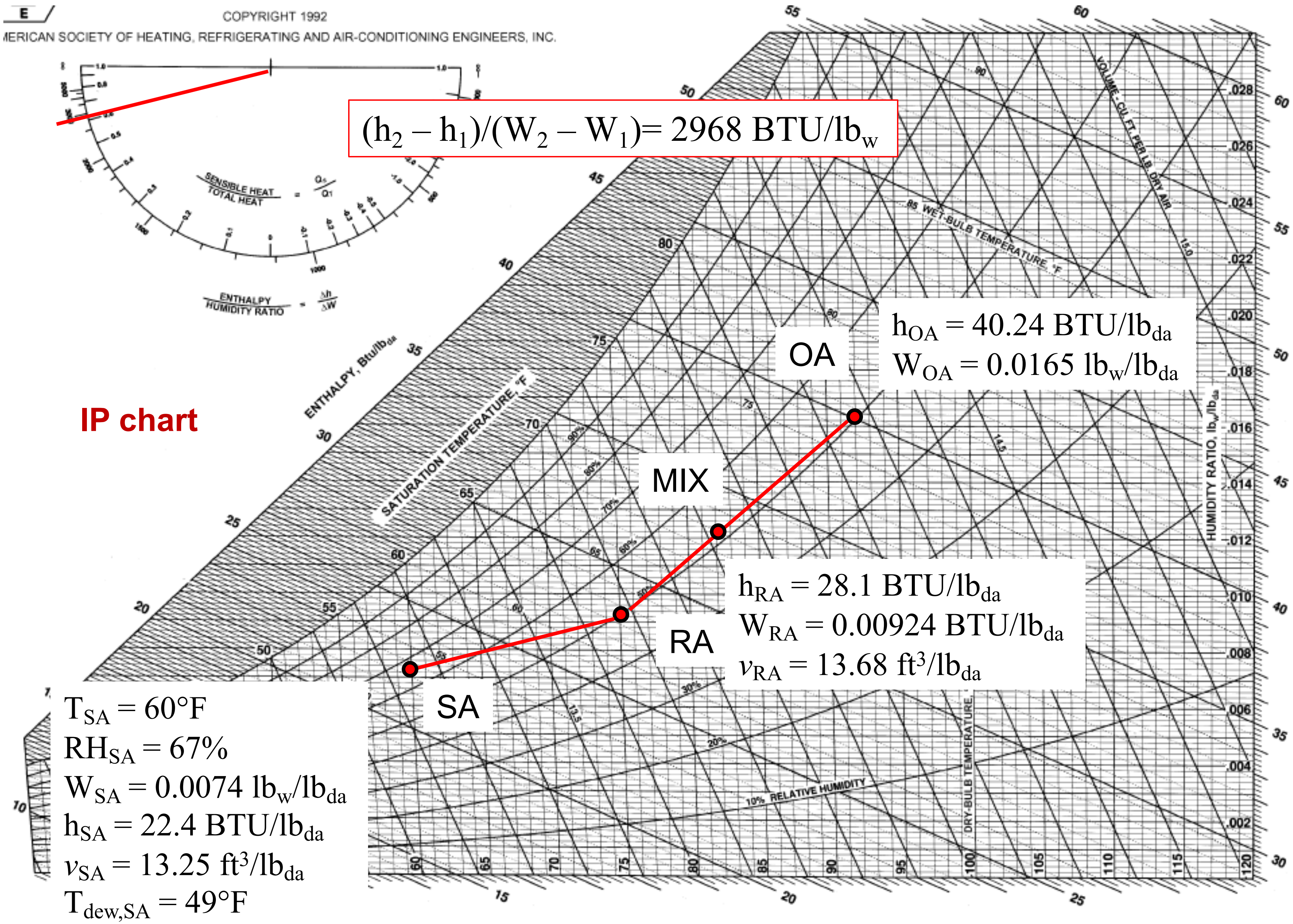
$v_1 = 13.25$ ft$^3$/lb$_{da}$

$T_{dew} = 49°F$

# Example 8: Single-zone space conditioning (IP)

- Assume the restaurant from the previous example is to be served by an air handling unit that mixes outdoor air with recirculated air, then passes the air over a cooling coil to the space. Outside air conditions are 92°F dry bulb and 77°F wet bulb temperatures. The rate of exhaust from the restaurant is 4500 CFM.

- Determine the following:
  a) The mass flow rate of recirculated air
  b) The thermodynamic state of the moist air entering the cooling coil
  c) The refrigeration capacity required



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(h2 – h1)/(W2 – W1)= 2968 BTU/lbw
SENSIBLE HEAT / TOTAL HEAT = Qs/Qt
ENTHALPY / HUMIDITY RATIO = Δh/ΔW
IP chart
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU FT PER LB DRY AIR
HUMIDITY RATIO, lbw/lbda
DRY-BULB TEMPERATURE
10% RELATIVE HUMIDITY
OA
hOA = 40.24 BTU/lbda
WOA = 0.0165 lbw/lbda
MIX
RA
hRA = 28.1 BTU/lbda
WRA = 0.00924 BTU/lbda
vRA = 13.68 ft3/lbda
SA
TSA = 60°F
RHSA = 67%
WSA = 0.0074 lbw/lbda
hSA = 22.4 BTU/lbda
vSA = 13.25 ft3/lbda
Tdew,SA = 49°F