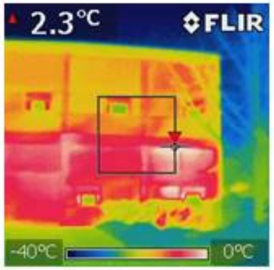
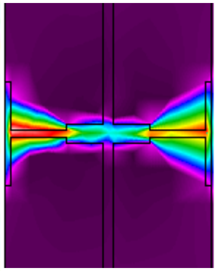
CAE 331/513
Building Science
Fall 2016





Week 7: October 4, 2016
Finish psychrometric equations

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Scheduling update

- Instead of coming to class on Thursday (Oct 6th), I would like you to attend my lecture at 1:45 pm in MTCC Auditorium

Talk title: "Outdoor pollutant penetration through building envelopes"

- You are already registered: http://events.r20.constantcontact.com/register/event?oeidk=a07ed4dw98b70b651d5&llr=ykrp4sdab

Psychrometric equations summary (SI units)

$$pV = nRT$$

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

$$W = 0.622 \frac{p_w}{p - p_w} \quad [\frac{\mathrm{kg_w}}{\mathrm{kg_{da}}}]$$

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

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

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

$$R_i = \frac{R}{MW_i}$$

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

where

$$\begin{aligned} C_8 &= -5.800\,220\,6 \text{ E+03} \\ C_9 &= 1.391\,499\,3 \text{ E+00} \\ C_{10} &= -4.864\,023\,9 \text{ E-02} \\ C_{11} &= 4.176\,476\,8 \text{ E-05} \\ C_{12} &= -1.445\,209\,3 \text{ E-08} \\ C_{13} &= 6.545\,967\,3 \text{ E+00} \end{aligned}$$

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 summary (SI units)

Wet bulb temperature (iterative solver):

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

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

Specific volume:

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

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

where

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

Specific enthalpy:

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

*where T is in °C

Obtaining these data from ASHRAE Tables

ASHRAE HoF Ch. 1 (2013) Table 2 gives us W_s, v_{da} , v_s , h_{da}, and h_s directly at different temperatures:

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressu

Temp., °C	Humidity Ratio	Specific Volume, m^3/kg_{da}			Specific Enthalpy, kJ/kg_{da}		
t	W_s, kg_w/kg_{da}	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s
15	0.010694	0.8159	0.0140	0.8299	15.087	27.028	42.115
16	0.011415	0.8188	0.0150	0.8338	16.093	28.873	44.966
17	0.012181	0.8216	0.0160	0.8377	17.099	30.830	47.929
18	0.012991	0.8245	0.0172	0.8416	18.105	32.906	51.011
19	0.013851	0.8273	0.0184	0.8457	19.111	35.107	54.219
20	0.014761	0.8301	0.0196	0.8498	20.117	37.441	57.558
21	0.015724	0.8330	0.0210	0.8540	21.124	39.914	61.037
22	0.016744	0.8358	0.0224	0.8583	22.130	42.533	64.663

Obtaining these data from ASHRAE Tables

ASHRAE HoF Ch. 1 (2013) Table 3 gives us p_{ws} at different temperatures:

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg_w Sat. Liquid v_i/v_f	Specific Volume, m^3/kg_w Evap. v_{ig}/v_{fg}	Specific Volume, m^3/kg_w Sat. Vapor v_g	Specific Enthalpy, kJ/kg_w Sat. Liquid h_i/h_f	Specific Enthalpy, kJ/kg_w Evap. h_{ig}/h_{fg}	Specific Enthalpy, kJ/kg_w Sat. Vapor h_g
3	0.7581	0.001000	168.013	168.014	12.60	2493.80	2506.40
4	0.8135	0.001000	157.120	157.121	16.81	2491.42	2508.24
5	0.8726	0.001000	147.016	147.017	21.02	2489.05	2510.07
6	0.9354	0.001000	137.637	137.638	25.22	2486.68	2511.91
7	1.0021	0.001000	128.927	128.928	29.43	2484.31	2513.74
8	1.0730	0.001000	120.833	120.834	33.63	2481.94	2515.57
9	1.1483	0.001000	113.308	113.309	37.82	2479.58	2517.40
10	1.2282	0.001000	106.308	106.309	42.02	2477.21	2519.23

Revisit example from a previous class

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

Find the following using psychrometric equations (SI units):

(a) the humidity ratio, W

(b) dew point temperature, T_{dew}

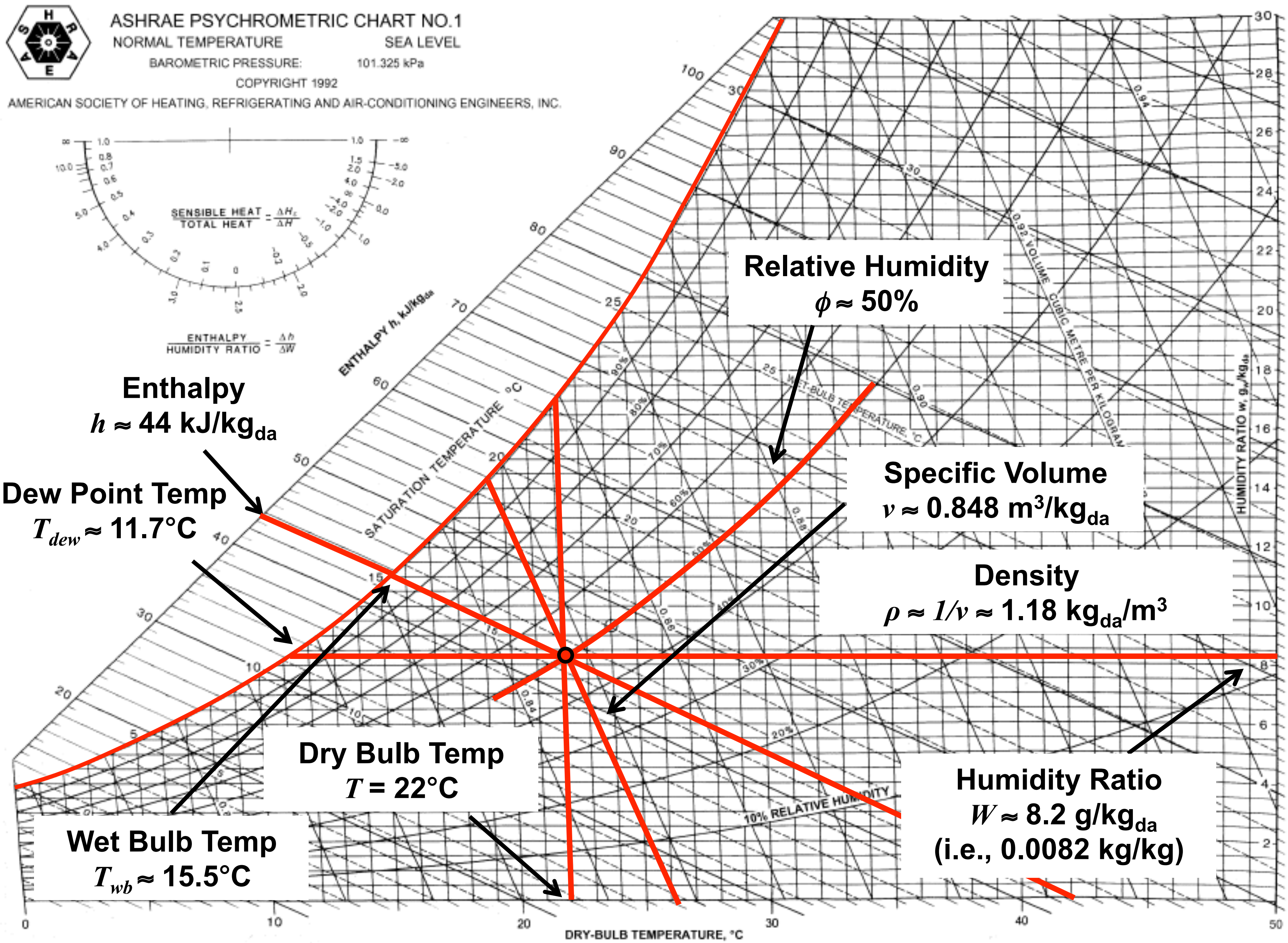
(c) wet-bulb temperature, T_{wb}

(d) enthalpy, h

(e) specific volume, v

(f) density, ρ

(g) degree of saturation, μ


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/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE °C
VOLUME CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kg da
DRY-BULB TEMPERATURE, °C
Enthalpy
$h \approx$ 44 kJ/kg$_{da}$
Dew Point Temp
$T_{dew} \approx$ 11.7°C
Relative Humidity
$\phi \approx$ 50%
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 a previous class

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) degree of saturation, μ

(c) relative humidity, ϕ

(d) enthalpy, h

(e) specific volume, v

(f) density, ρ

(g) wet bulb temperature, T_{wb}

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

- From previous:

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

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

$$p_{ws@T=30°C} = 4.2467\,kPa$$

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

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:

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

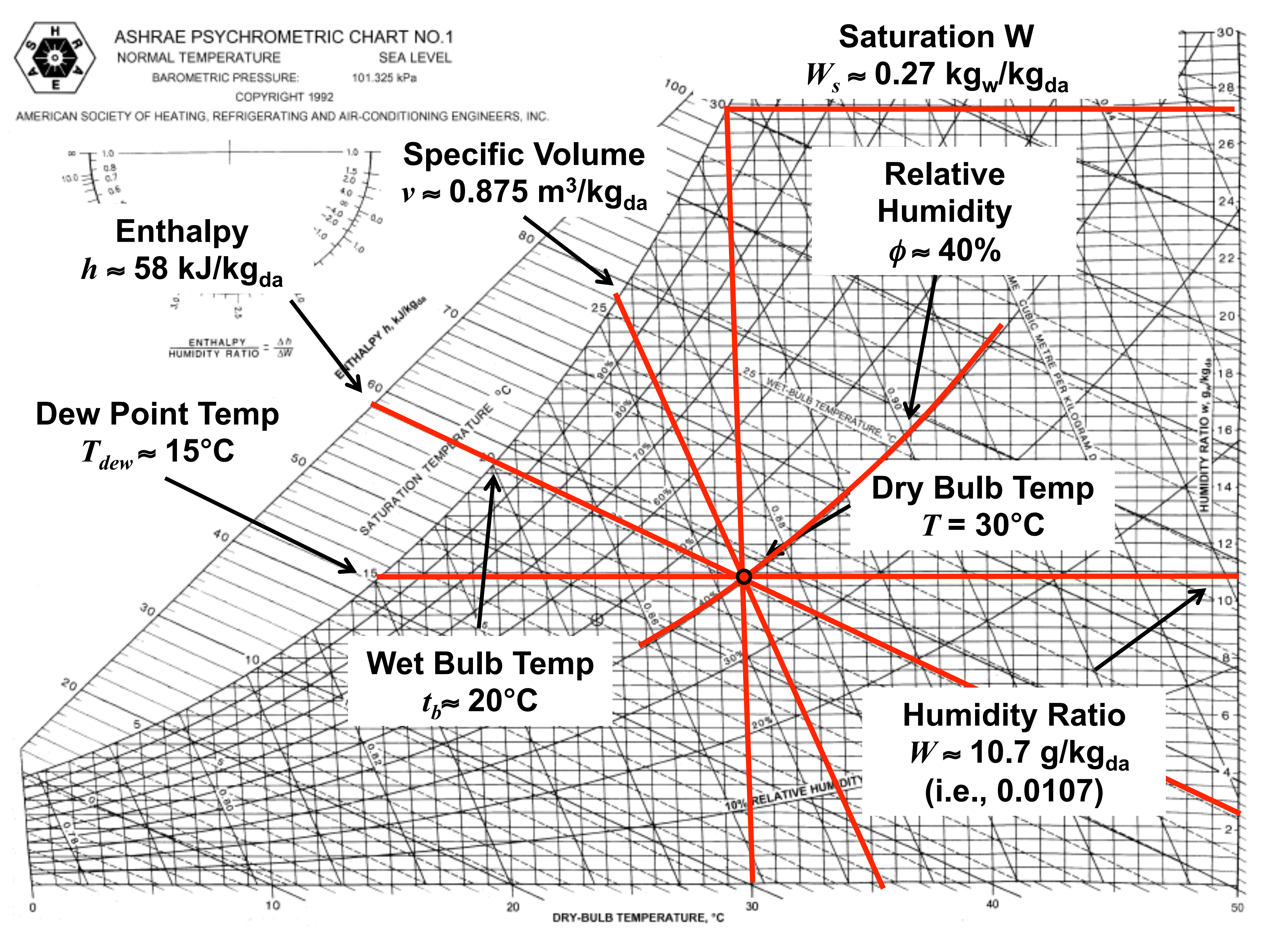
where: $T = 30°C$ $\quad W_{s@T_{wb}=?} = 0.622 \left. \frac{p_{ws}}{p - p_{ws}} \right|_{@T_{wb}=?}$

$T_{wb} = ?°C$

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)

$$\boxed{T_{wb} = 20.1°C}$$



ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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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 h, kJ/kg$_{da}$
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE °C
CUBIC METRE PER KILOGRAM
HUMIDITY RATIO w, g$_w$/kg$_{da}$
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C

IP units example

Moist air exists at 68°F dry-bulb temperature with 50% RH at sea level

Find the following using psychrometric equations (IP units):

(a) the humidity ratio, W

(b) the saturation humidity ratio, W_s

(c) degree of saturation, μ

(d) specific volume, v

(e) density, ρ

(f) enthalpy, h

Why is this stuff helpful?

PSYCHROMETRIC PROCESSES

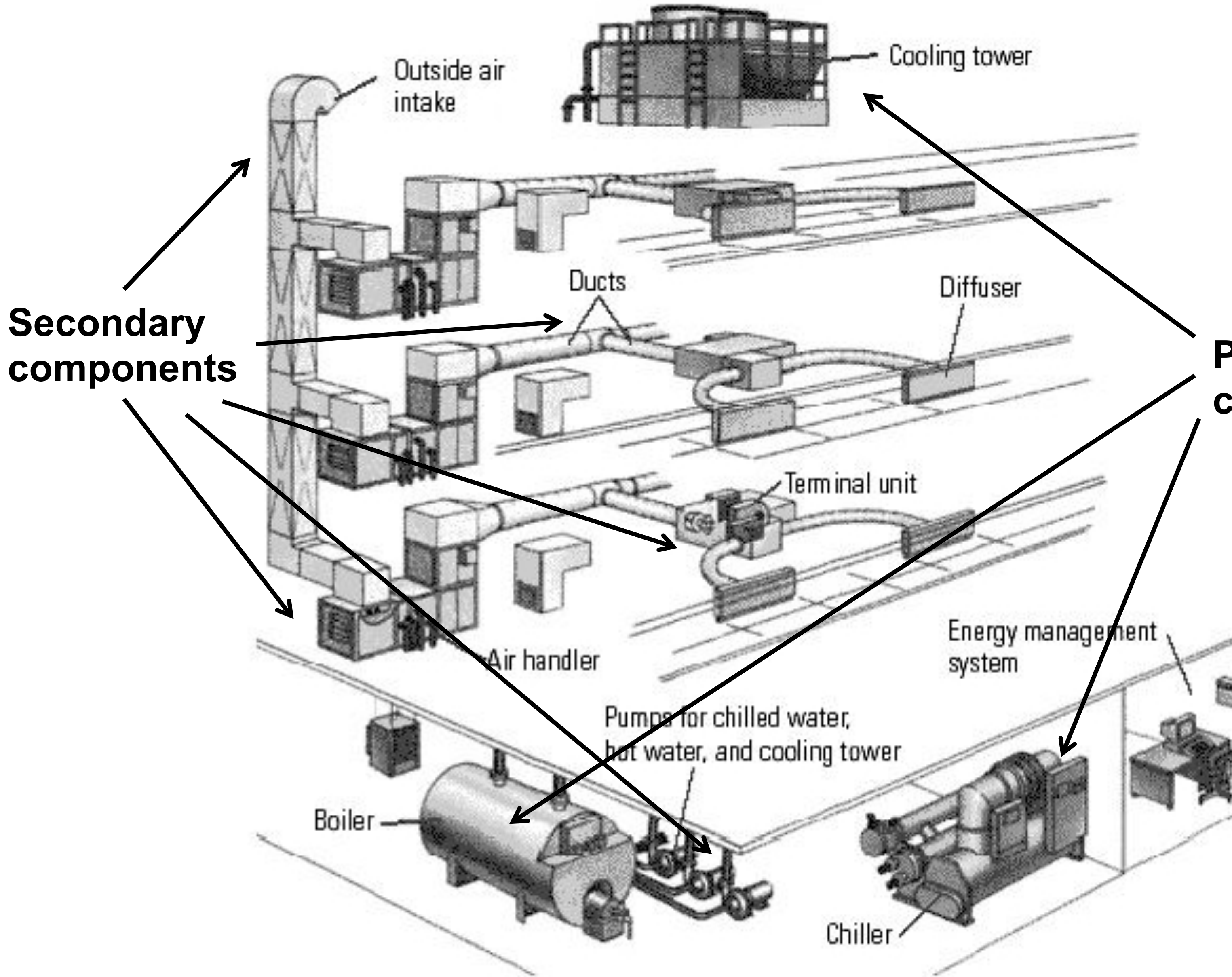
Use of the psychrometric chart for *processes*

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:

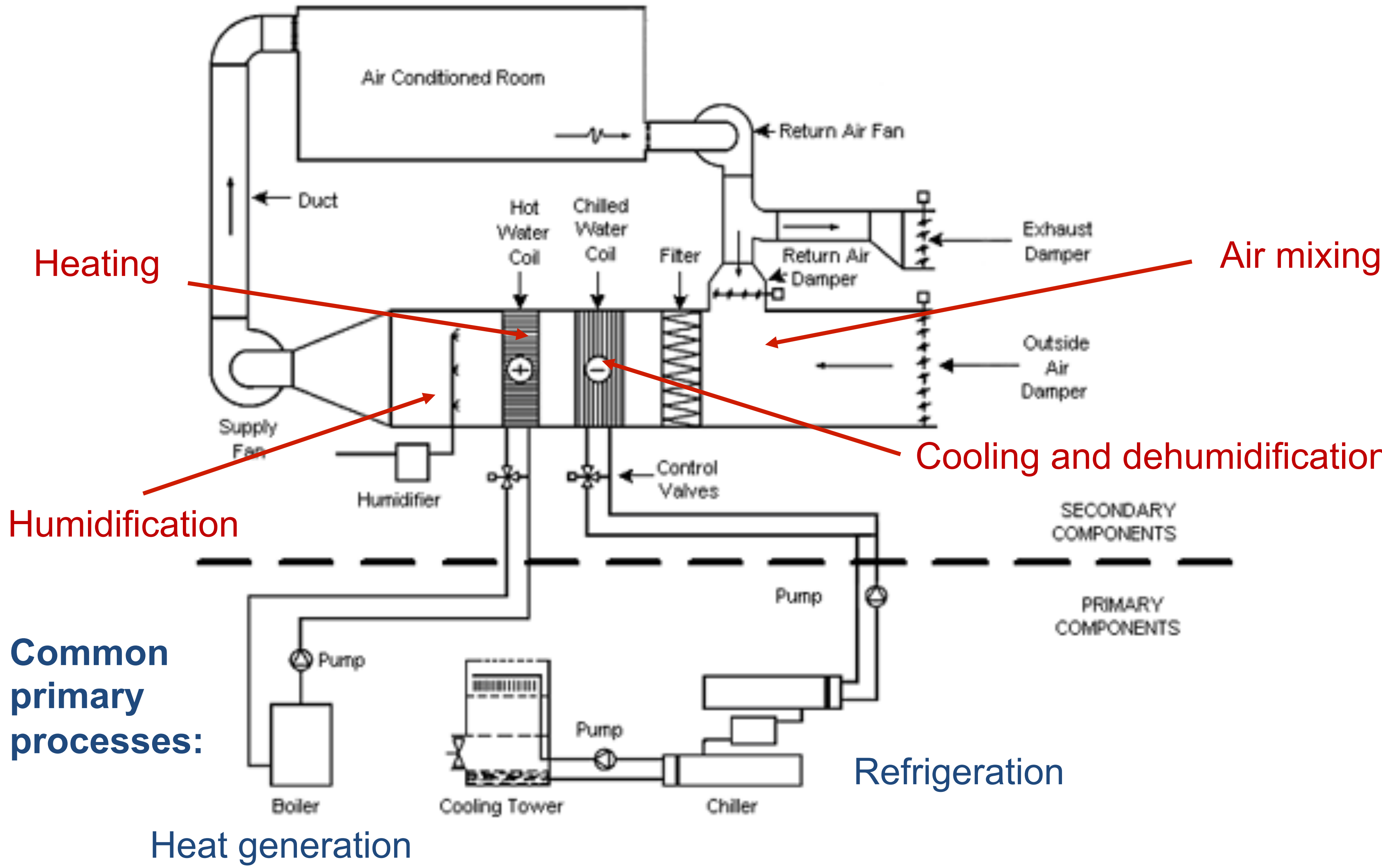
- Sensible cooling or heating
- Warming and humidification of cold, dry air
- Cooling and dehumidification of warm, humid air
  - Sensible + latent cooling
- Evaporative cooling
- Mixing of airstreams

Typical components of an HVAC system



Typical HVAC *processes*

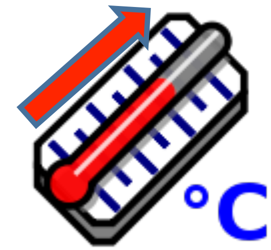
Some common psychrometric processes:



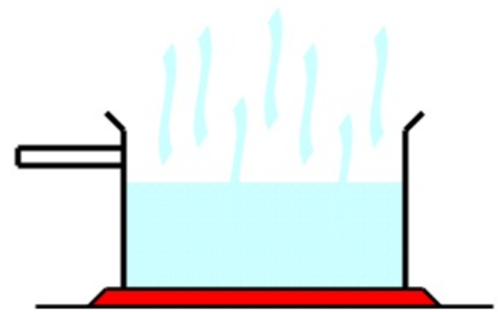
Common primary processes:

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

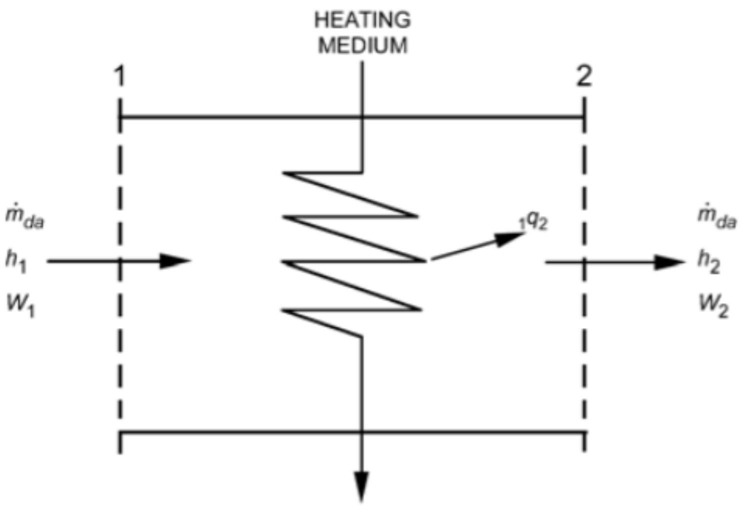


Fig. 2 Schematic of Device for Heating Moist Air

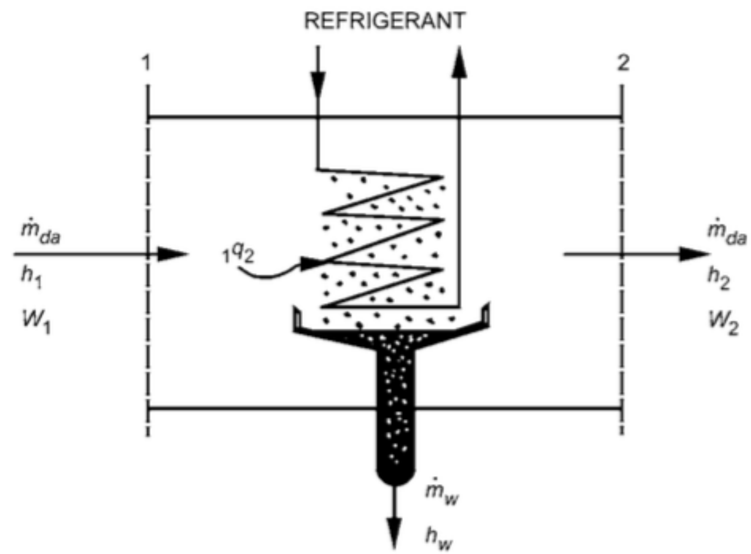


Fig. 3 Schematic of Device for Cooling Moist Air

Generic equations for both heating and cooling processes:

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

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

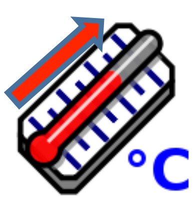
Sensible heat transfer equation

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

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



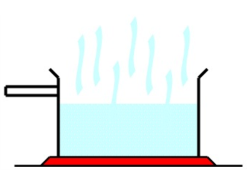
Latent heat transfer equation

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

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})

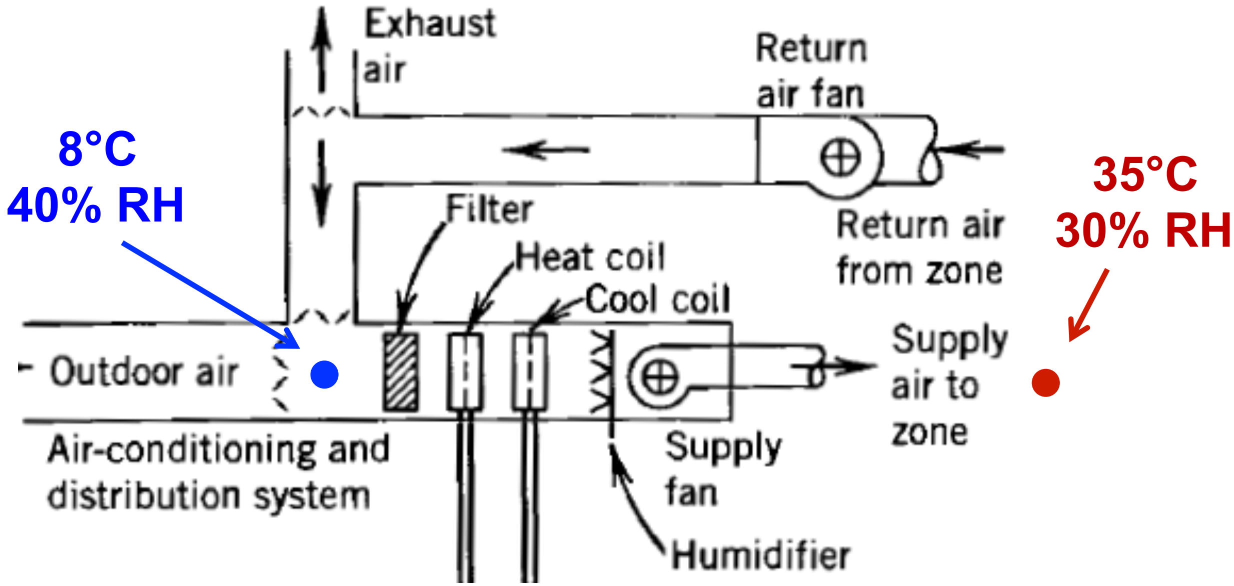
For humidification: $Q_{latent} > 0$

For dehumidification: $Q_{latent} < 0$



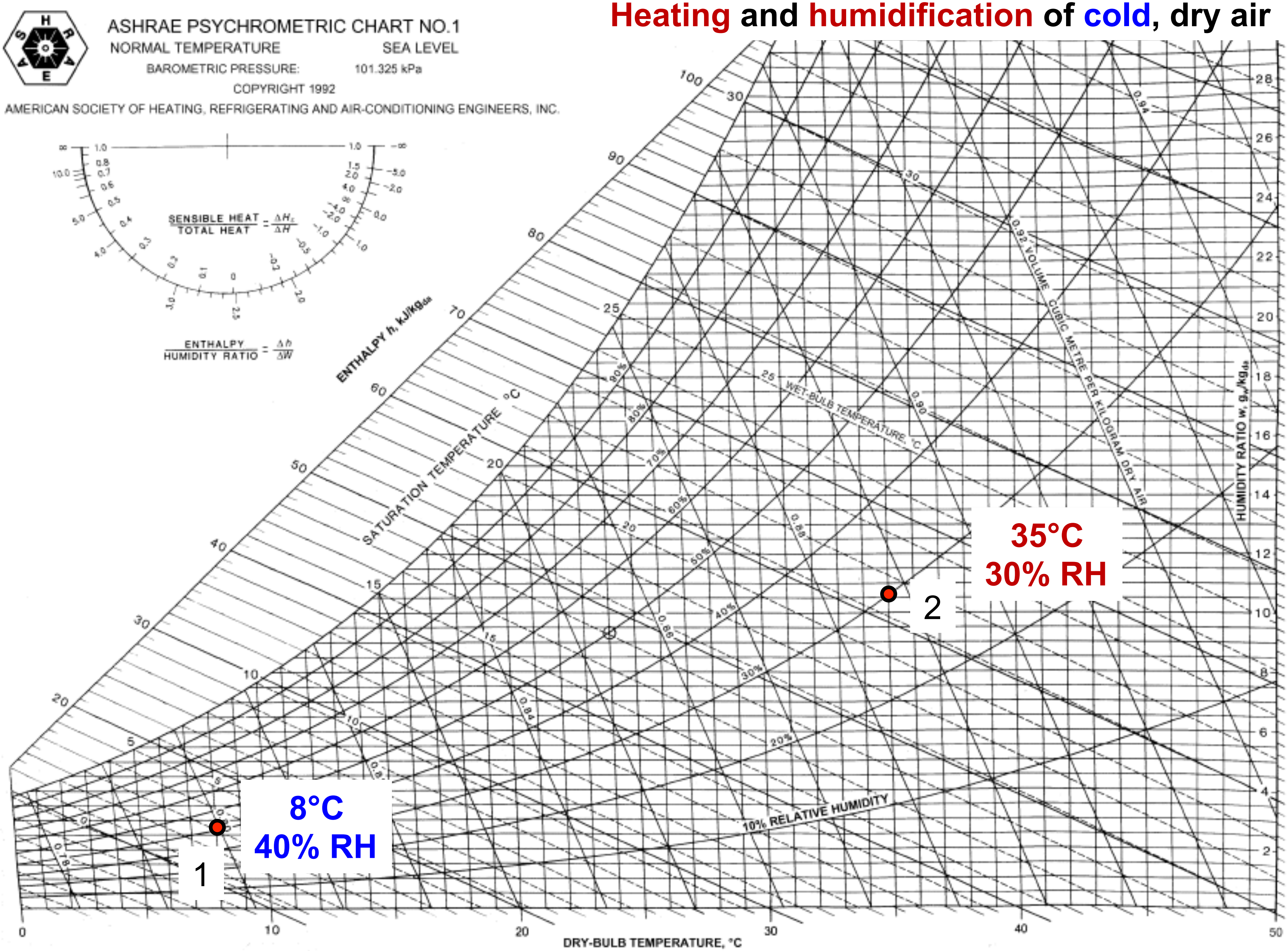
Heating and humidification of cold, dry air

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

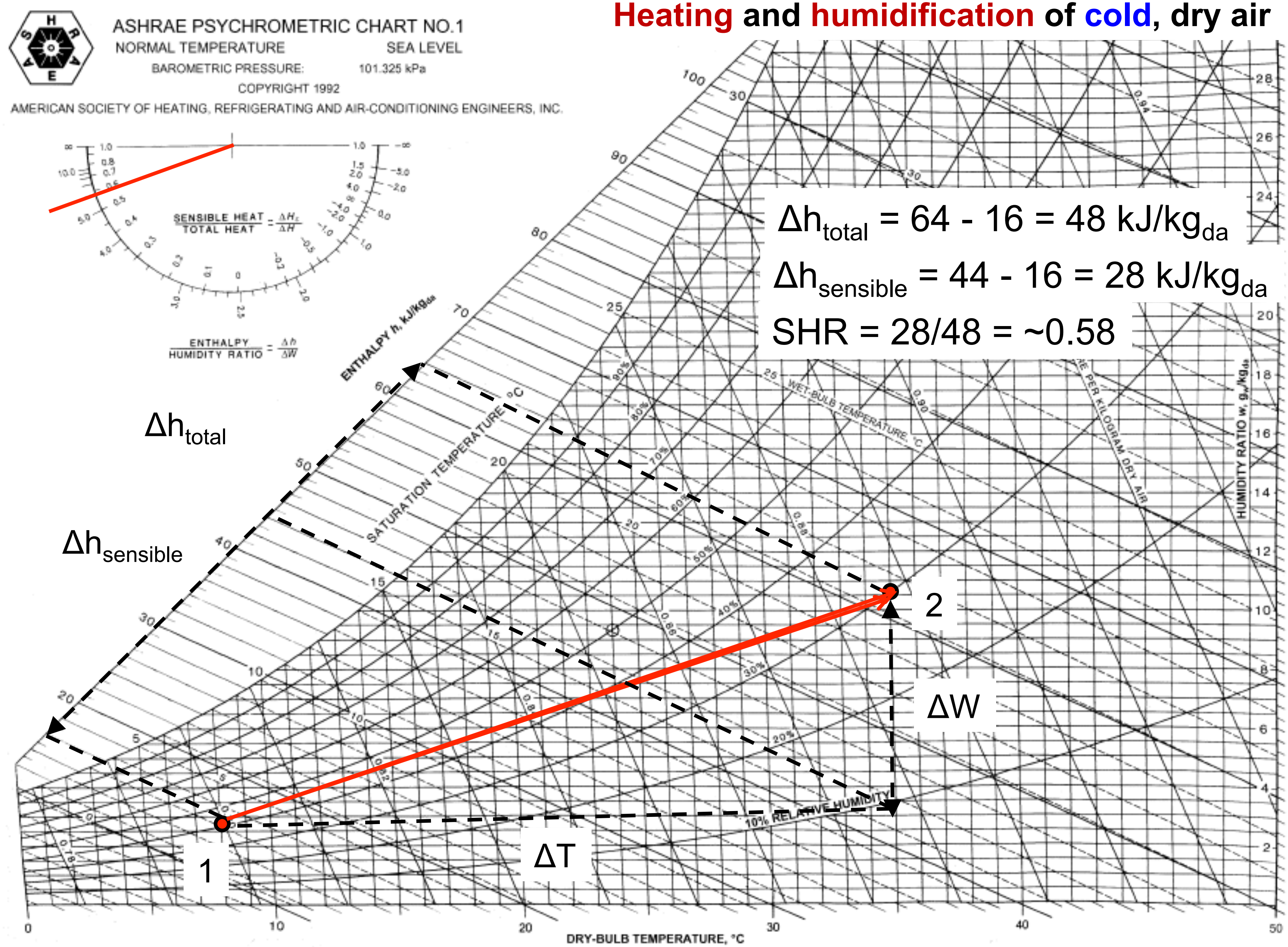


Q1: What is the enthalpy change required?
Q2: What is the total rate of heat transfer if the airflow rate is 10 m^3/s?
Q2: What is the split between sensible and latent transfer?

Heating and humidification of cold, dry air



Heating and humidification of cold, dry air



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

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

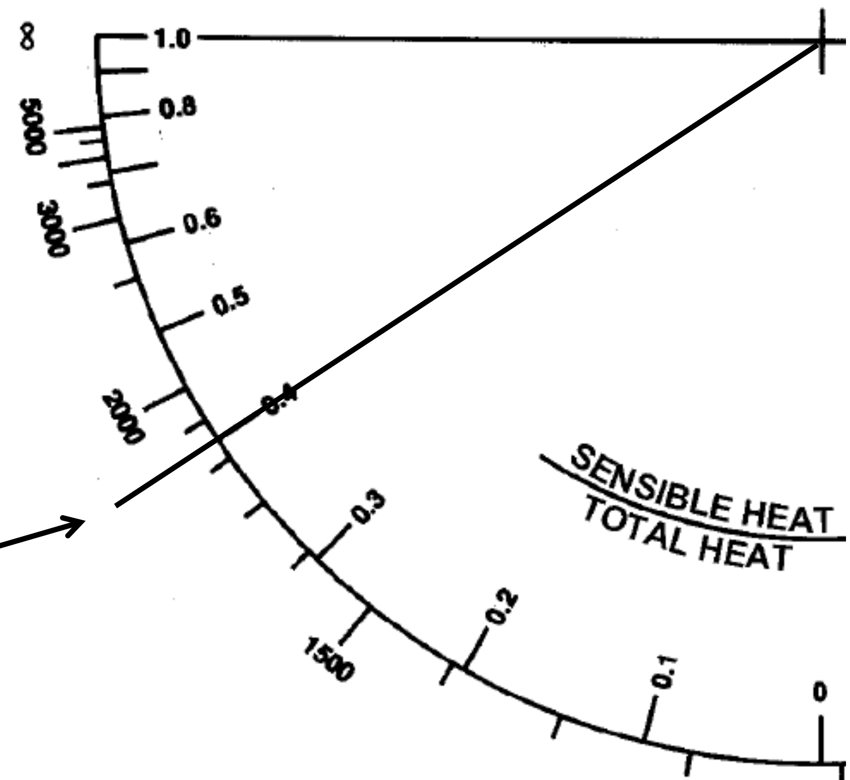
$SHR = 28/48 = \sim 0.58$

Sensible heat ratio (SHR)

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

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

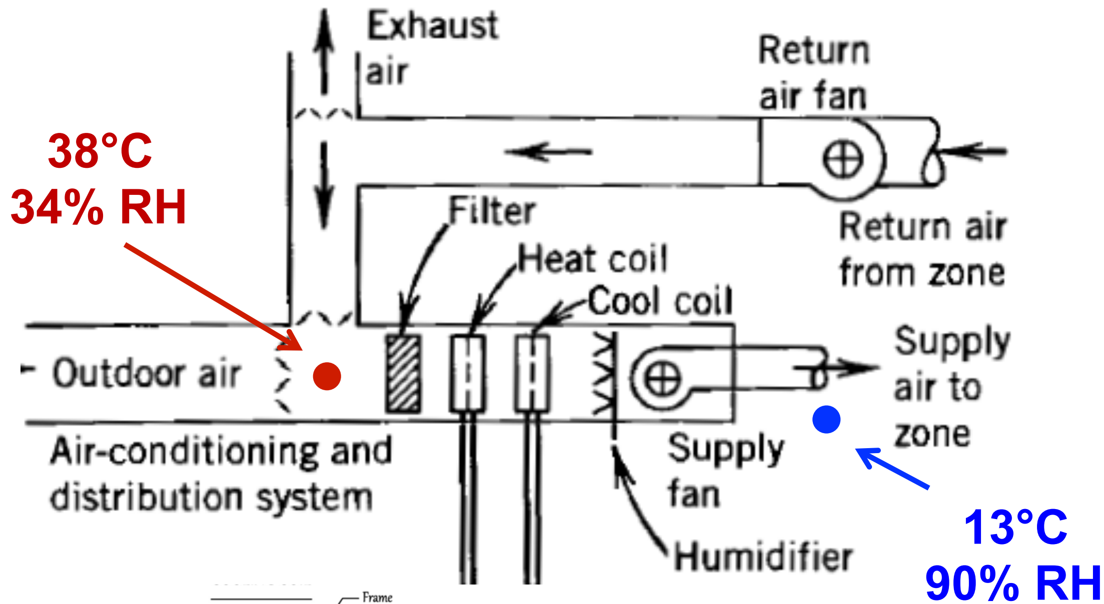
- Allows for understanding sensible load relative to latent load

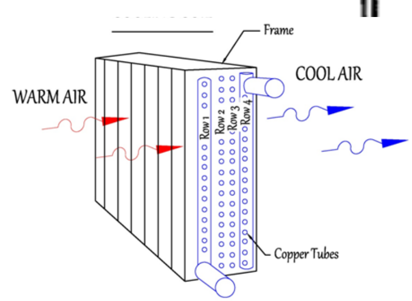


Here is a process
with an SHR ≈ 0.4

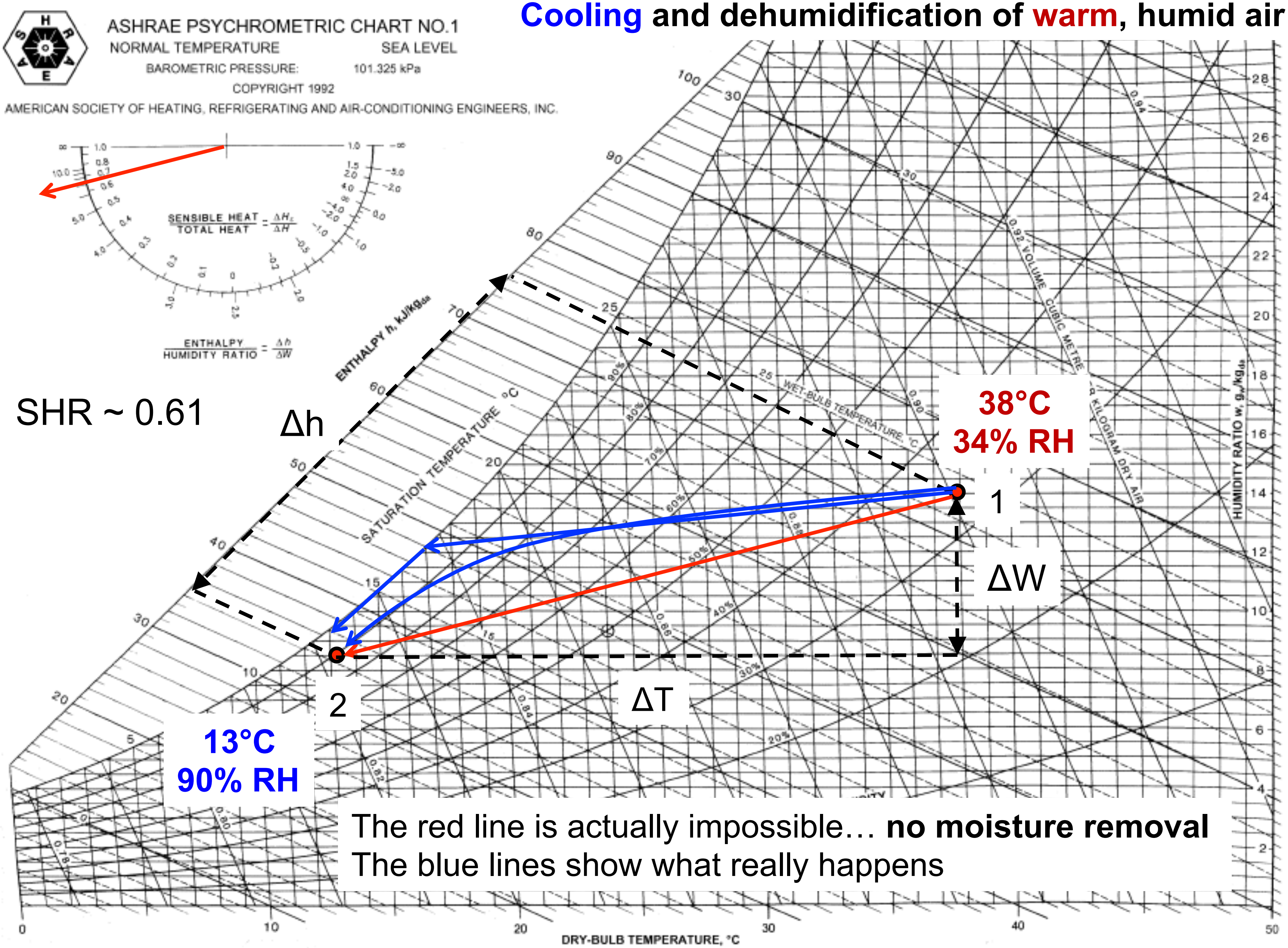
Cooling and dehumidification of **warm**, humid air

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





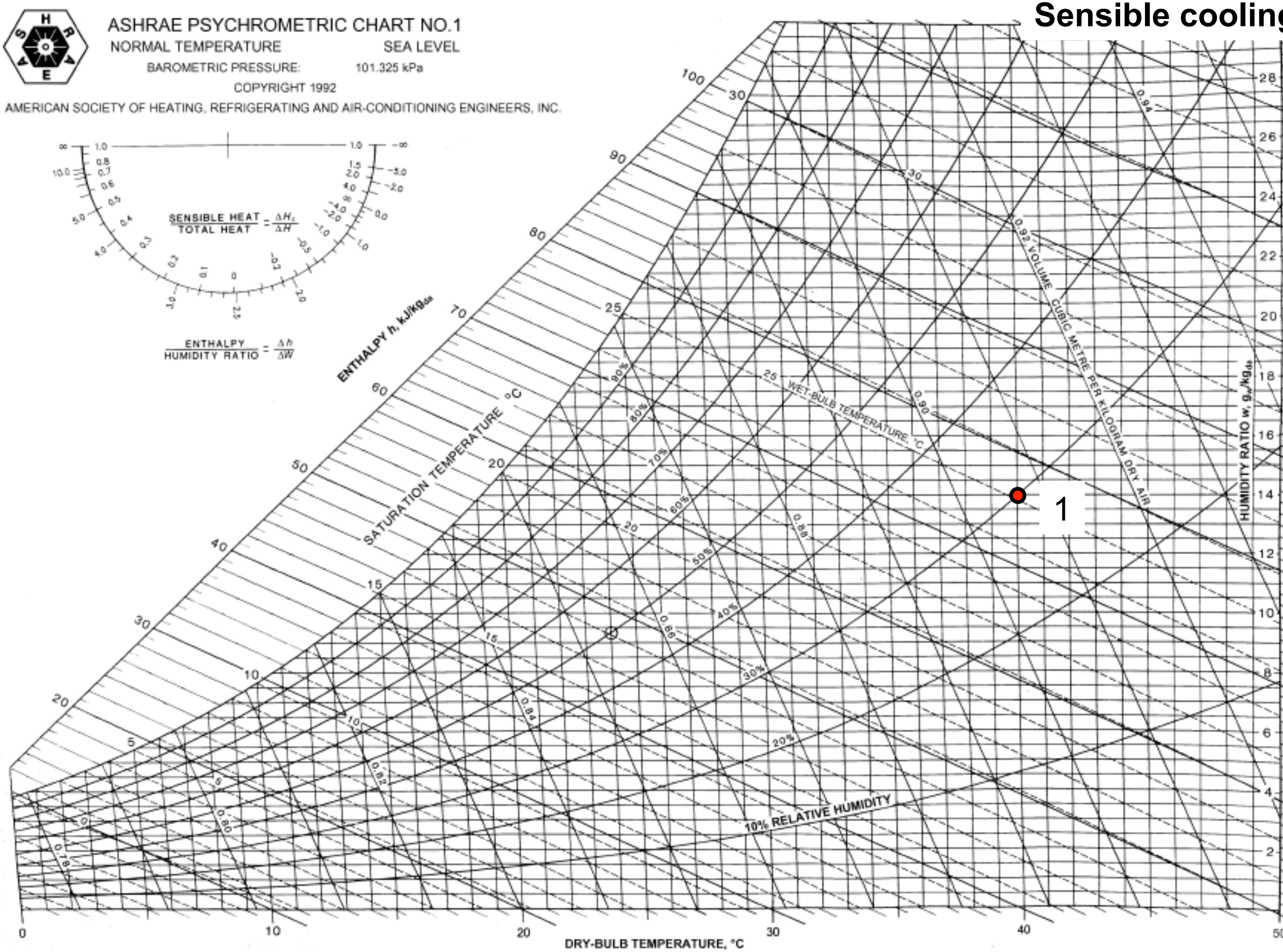
Cooling and dehumidification of warm, humid air



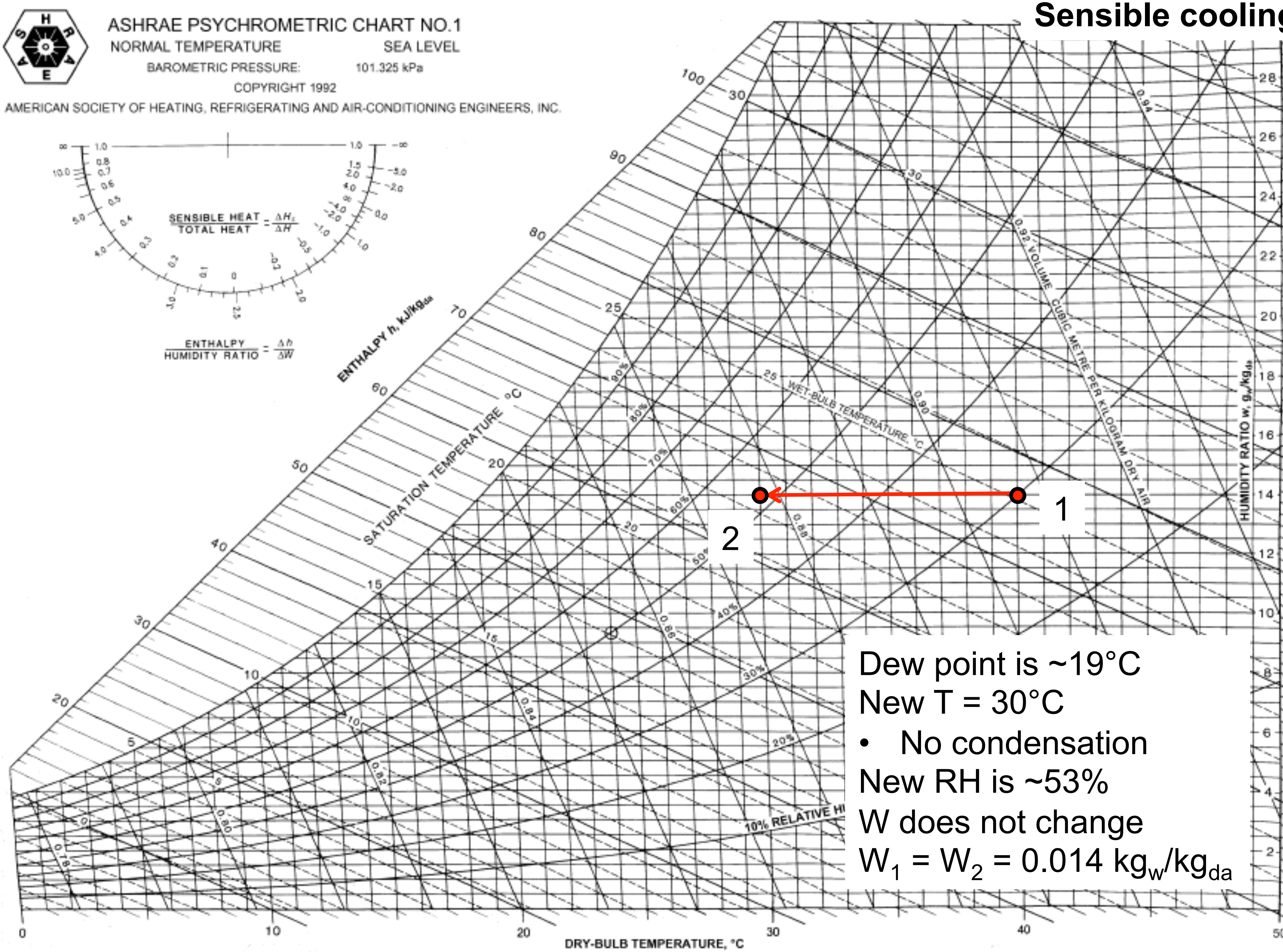
Example: *Sensible* cooling

- 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

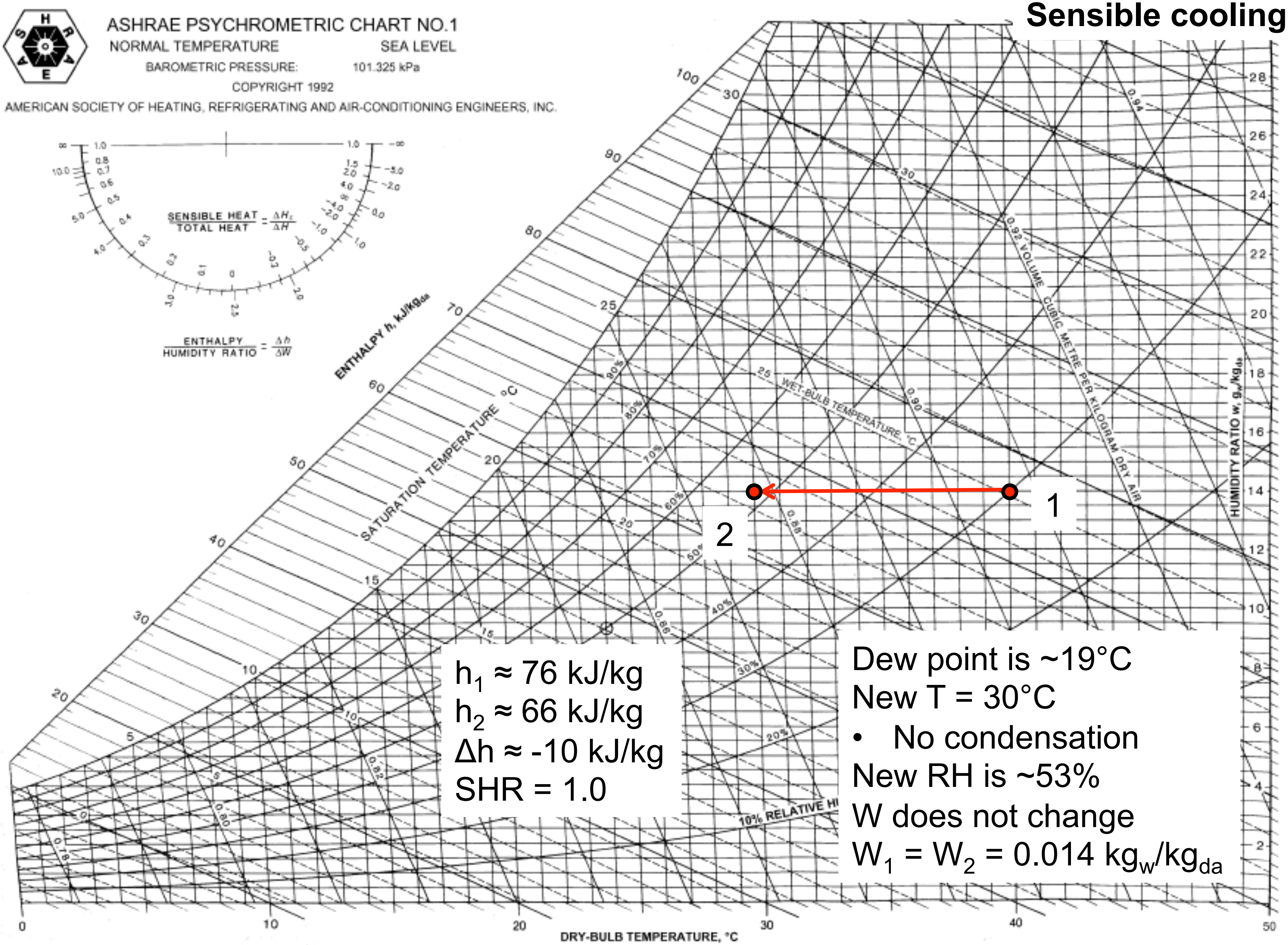
- No condensation

New RH is ~53%

W does not change

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

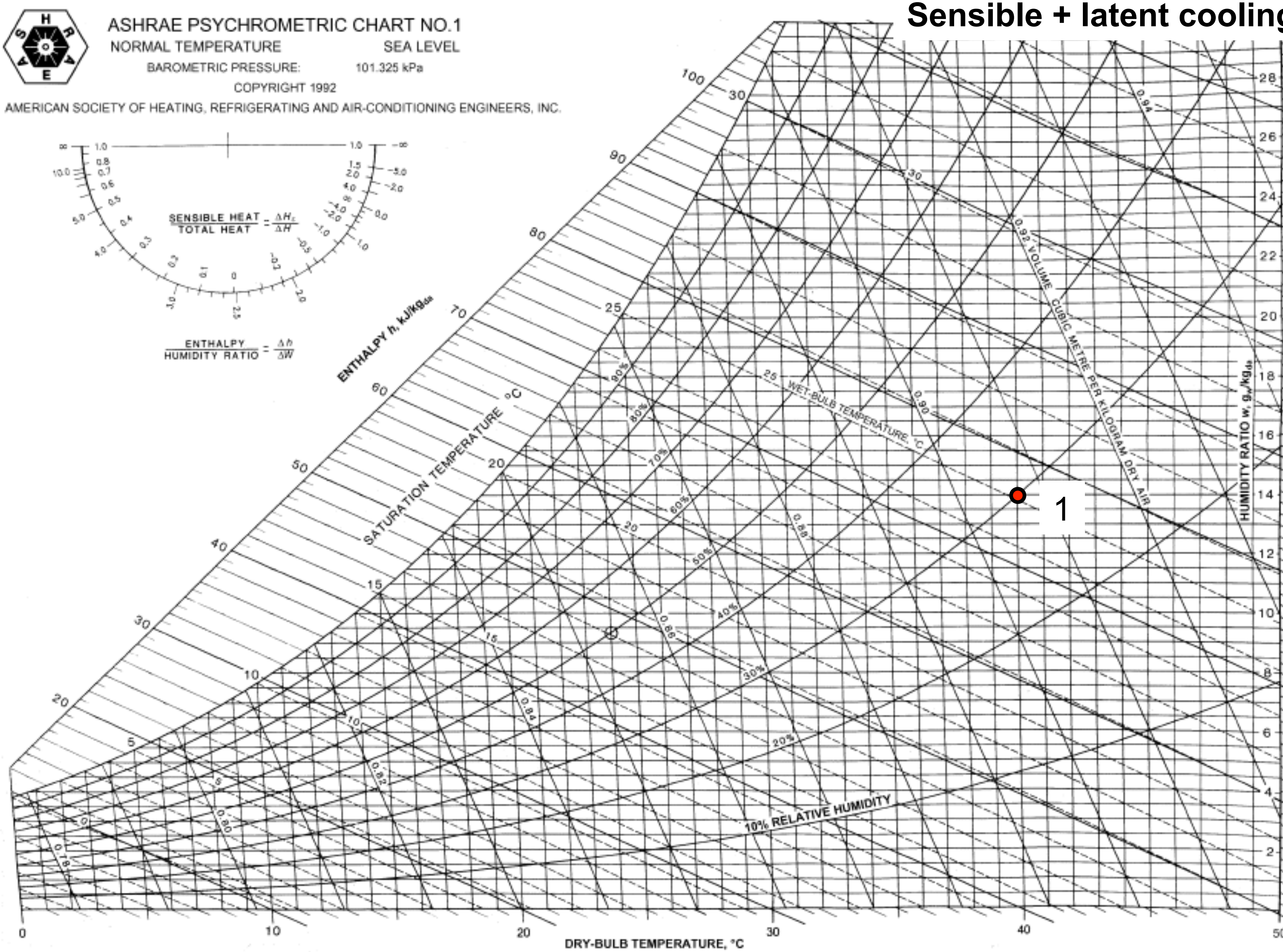
Sensible cooling



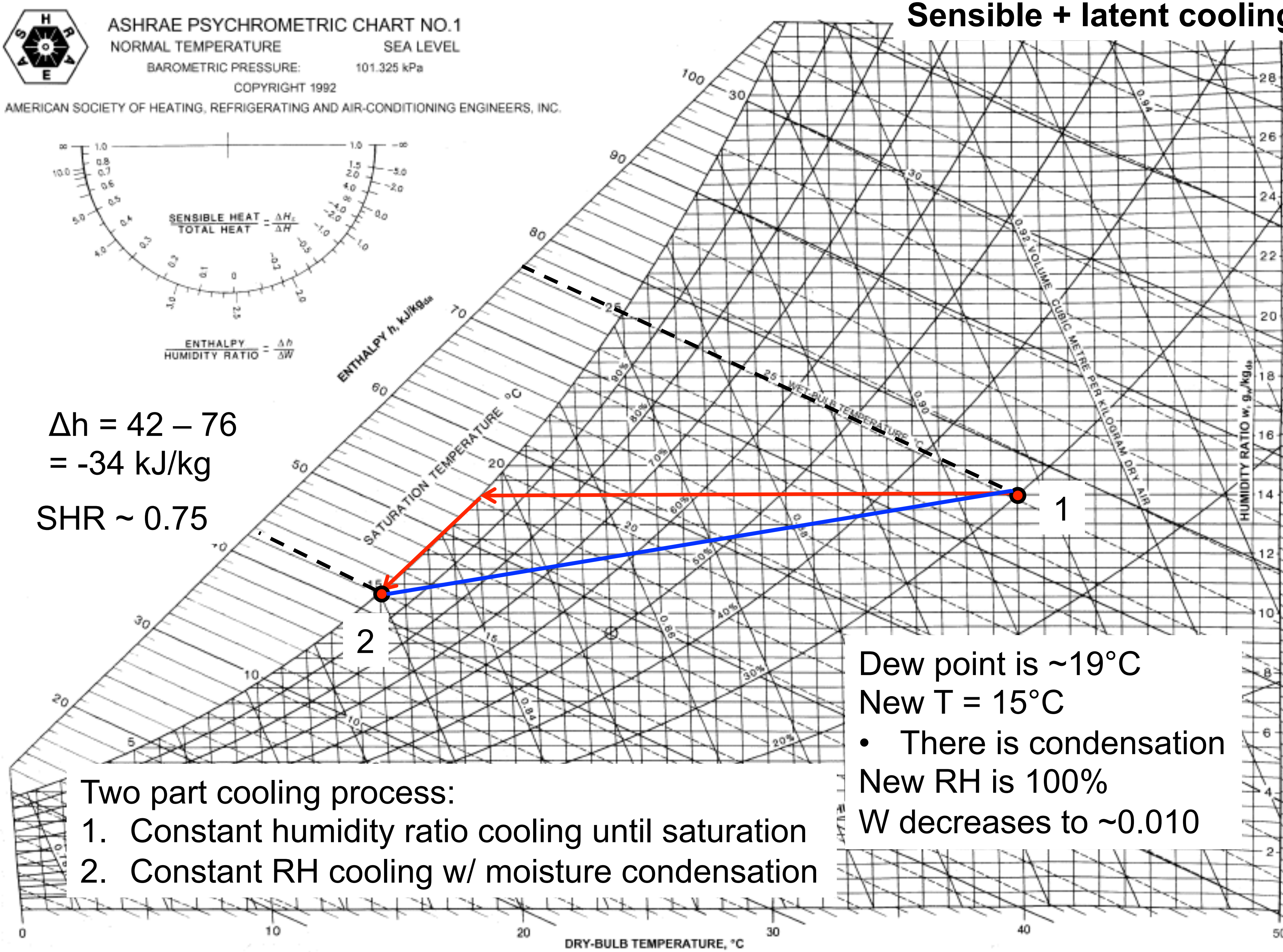
Example: ***Sensible*** **+** ***latent*** **cooling**

- 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

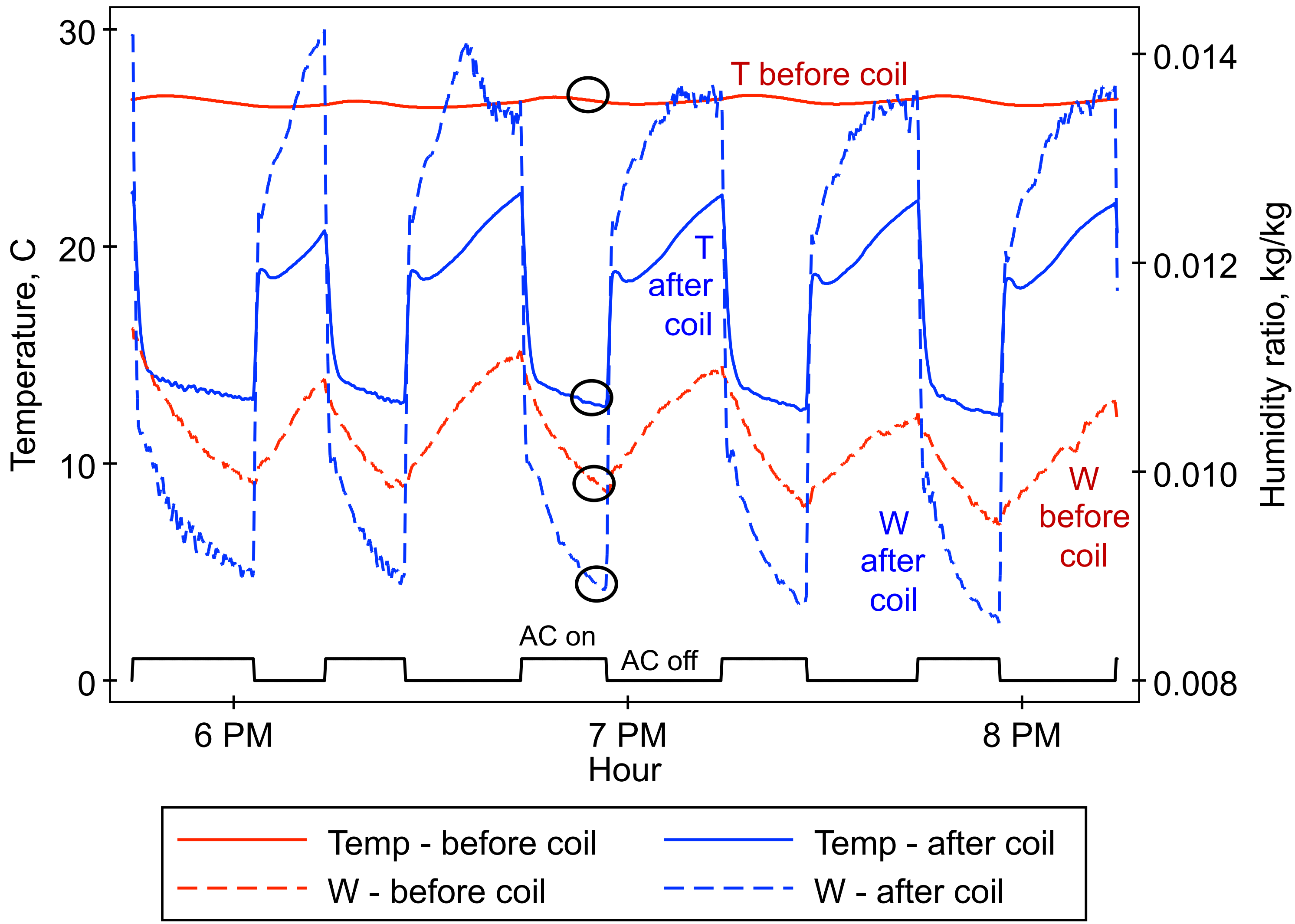
SHR ~ 0.75

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

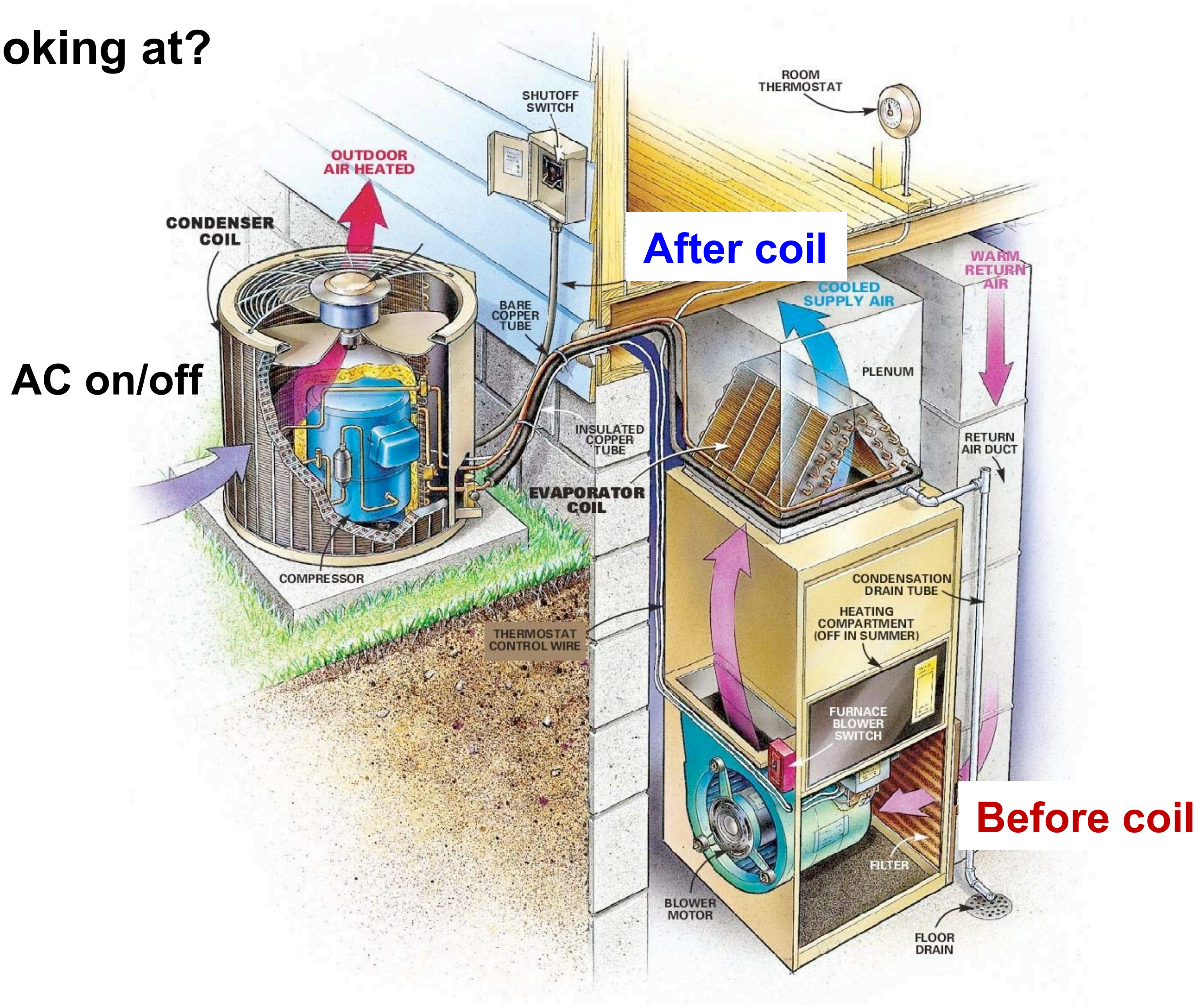
Real data: ASHRAE RP-1299
Energy implications of filters

Temperature and humidity ratio differences across AC coils in homes



Real data: ASHRAE RP-1299
Energy implications of filters

What are we looking at?



Sensible + latent cooling