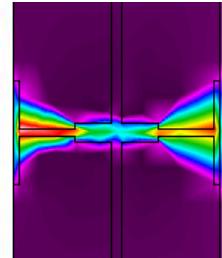
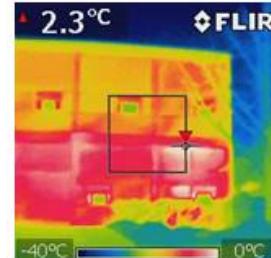


CAE 331/513

Building Science

Fall 2017



October 5, 2017
Psychrometrics (equations)

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Graduate student projects (CAE 513 only)

- Expectations document on BB now
 - Individual projects
 - Literature review
 - Some modeling and/or measurement
 - Conference-type paper submission
- Due dates for deliverables:
 - Tuesday, October 17: Project topic via email
 - Thursday, November 30: Final report submission

Graduate student projects: Topic suggestions

- Energy questions
 - Efficiency of radiant vs. central forced air heating/cooling?
 - Efficiency of different air distribution systems (e.g., overhead/UFAD)
 - Net zero energy/carbon design/operation
 - Electrical metering and power draw signatures
- HVAC systems
 - Heat pumps, geothermal, energy recovery, absorption chillers, cogeneration
- Green building rating systems
 - LEED, Green Globes, EnergyStar, Living Building, BREEAM, 189.1
- Moisture
 - Dampness, fungal growth, remediation, buffering capacity
- IAQ/IEQ
 - Thermal comfort, aerosols, ventilation, VOCs
- Other
 - Electrical, lighting, plumbing, acoustics
- Tools you can use:
 - Energy simulation, MATLAB modeling, measurements in BERG Lab

Last time

Introduced Psychrometrics and several key terms:

1. Dry bulb temperature
2. Vapor pressure
3. Saturation
4. Relative humidity
5. Absolute humidity (or humidity ratio)
6. Dew point temperature
7. Wet bulb temperature
8. Enthalpy
9. Density
10. Specific volume



ASHRAE PSYCHROMETRIC CHART NO. 1

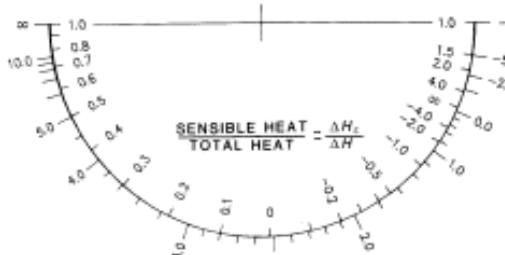
NORMAL TEMPERATURE

SEA LEVEL

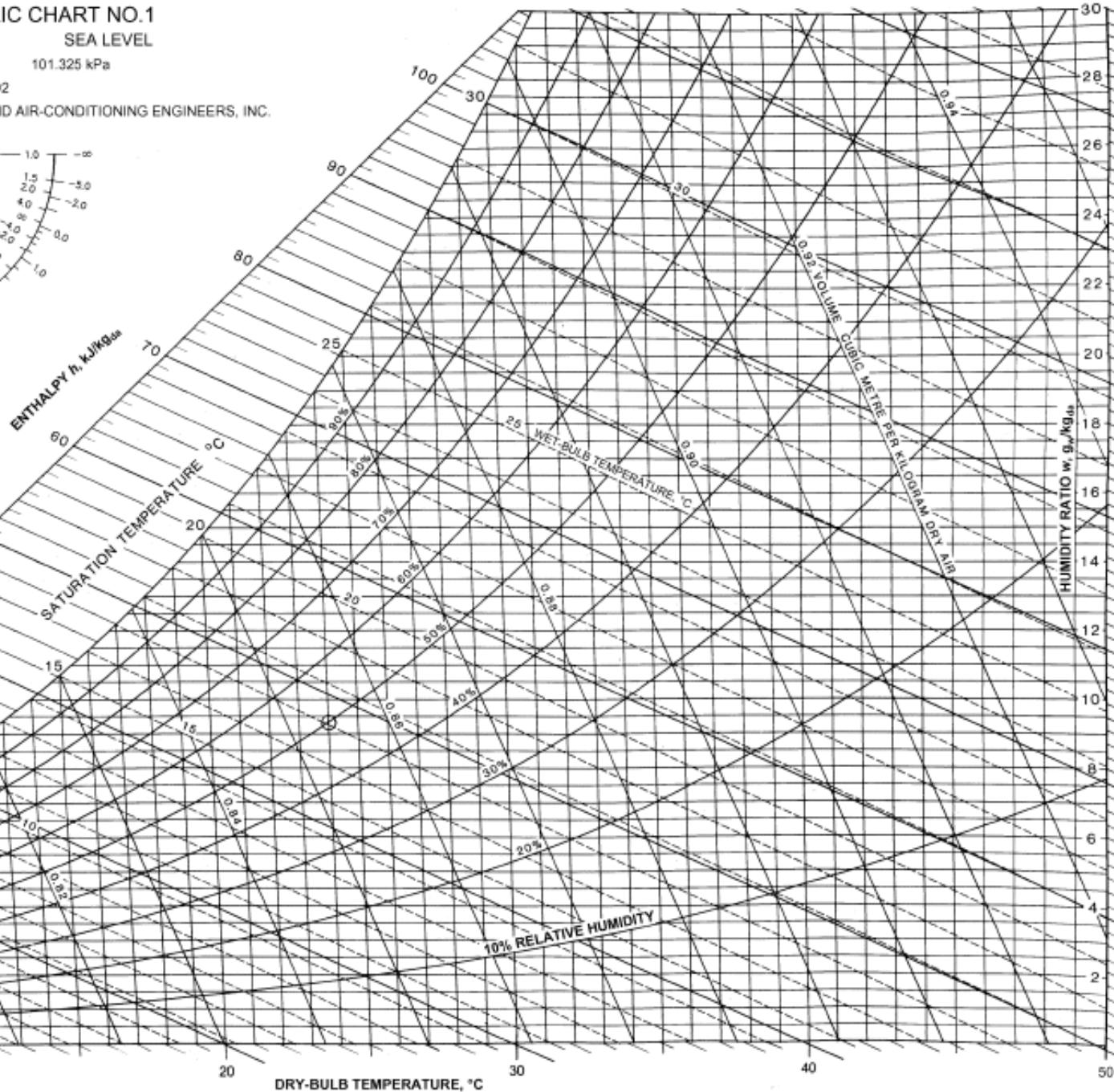
BAROMETRIC PRESSURE: 101.325 kPa

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$$\text{ENTHALPY } h, \text{ kJ/kg} = \frac{\Delta h}{\Delta W}$$

**SI chart**



ASHRAE PSYCHROMETRIC CHART NO.1

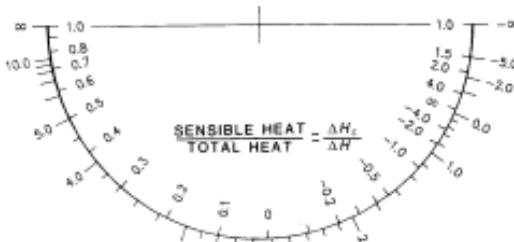
NORMAL TEMPERATURE

SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa

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$$\text{ENTHALPY } h, \text{ kJ/kg}_{\text{da}}$$

Enthalpy
 $h \approx 44 \text{ kJ/kg}_{\text{da}}$

Dew Point Temp
 $T_{\text{dew}} \approx 11.7^\circ\text{C}$

Dry Bulb Temp
 $T = 22^\circ\text{C}$

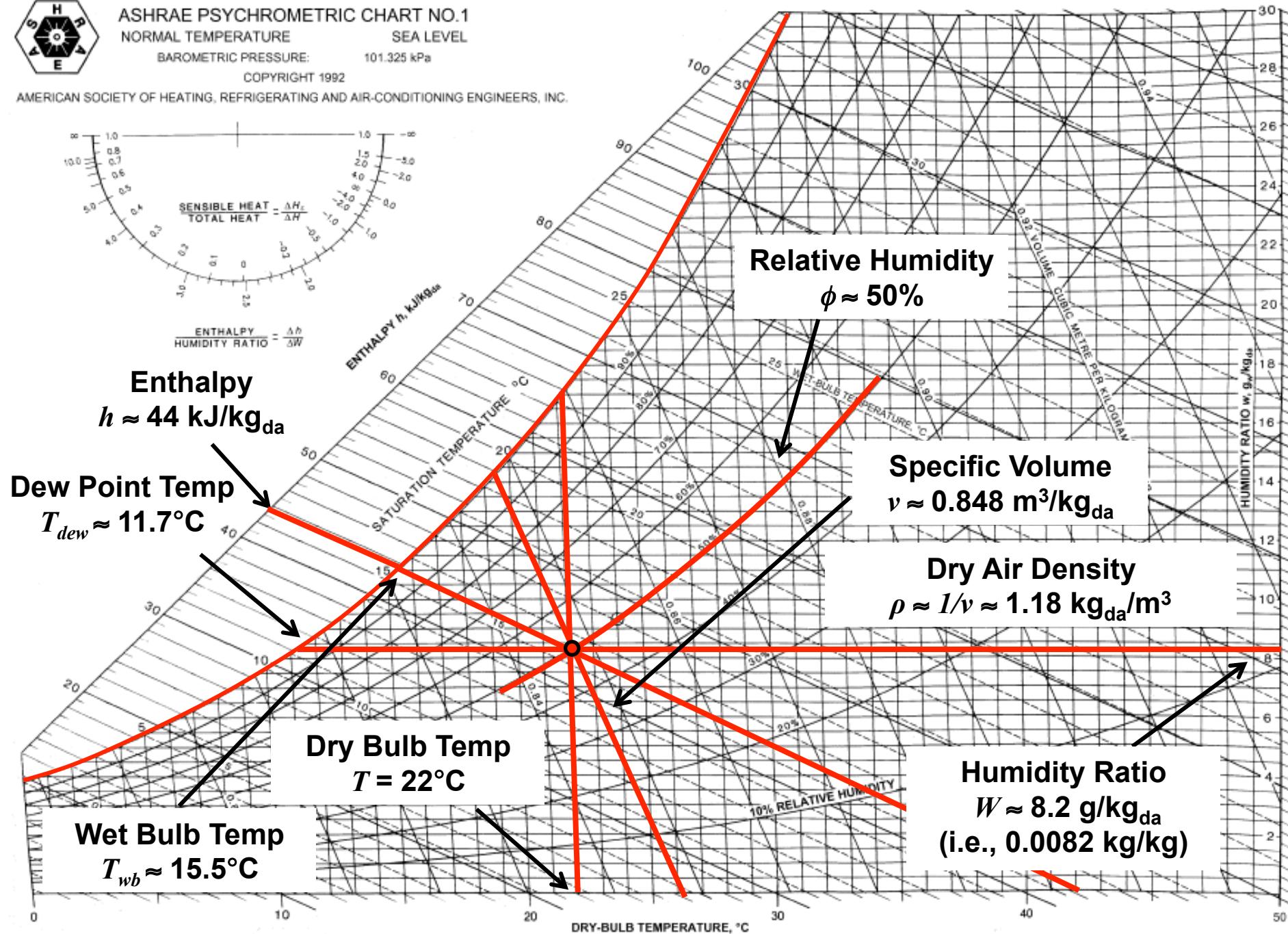
Wet Bulb Temp
 $T_{\text{wb}} \approx 15.5^\circ\text{C}$

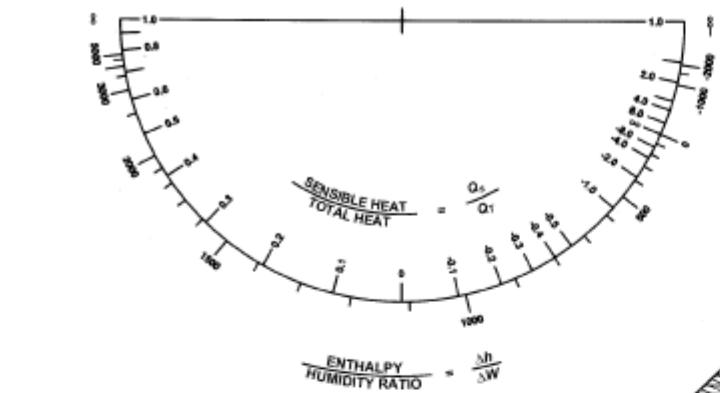
Relative Humidity
 $\phi \approx 50\%$

Specific Volume
 $v \approx 0.848 \text{ m}^3/\text{kg}_{\text{da}}$

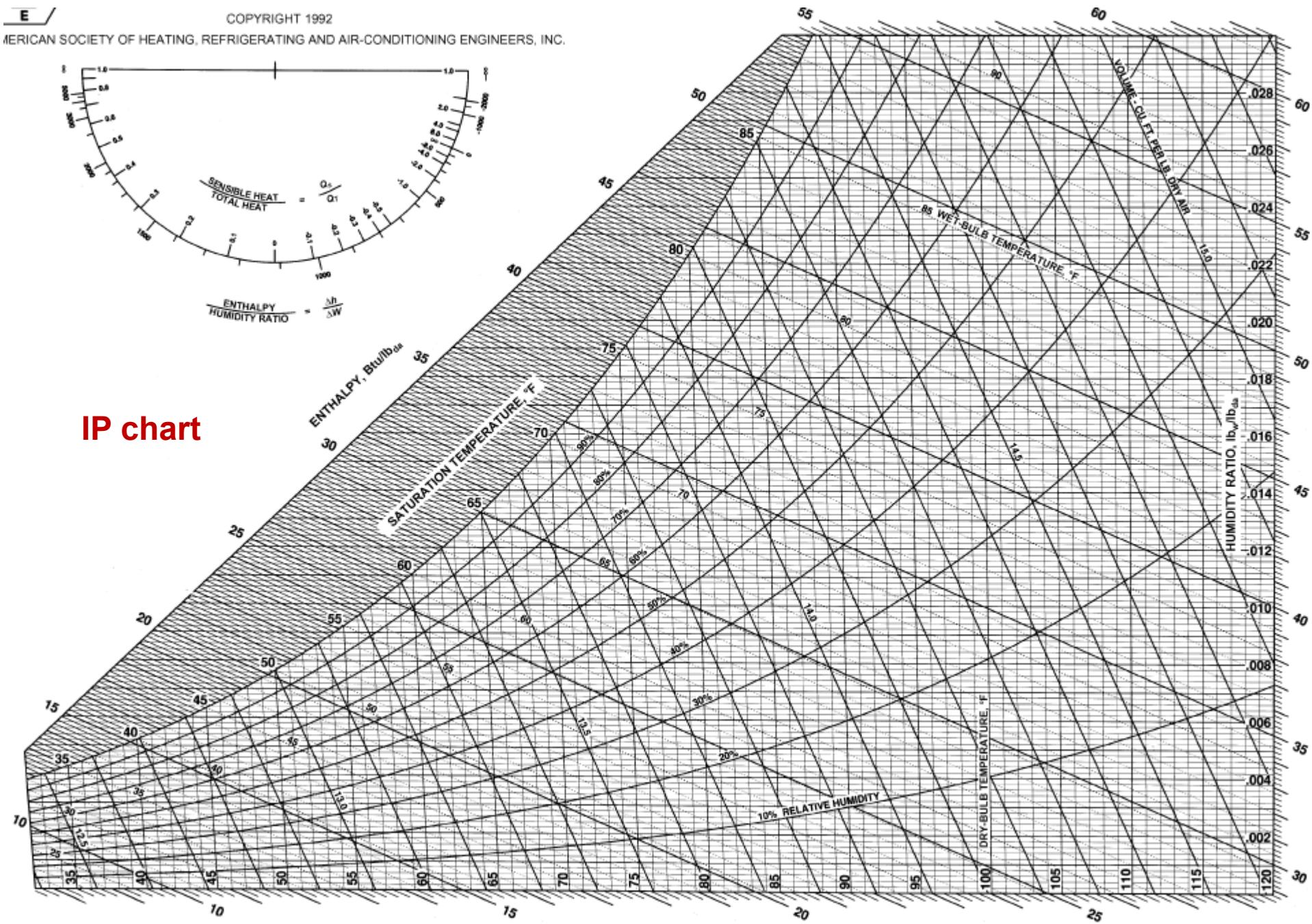
Dry Air Density
 $\rho \approx 1/v \approx 1.18 \text{ kg}_{\text{da}}/\text{m}^3$

Humidity Ratio
 $W \approx 8.2 \text{ g/kg}_{\text{da}}$
(i.e., 0.0082 kg/kg)





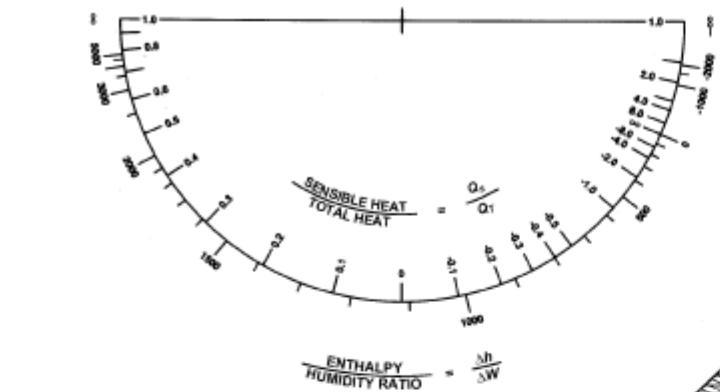
IP chart



E

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Enthalpy
 $h \approx 30 \text{ Btu/lb}$

Dew Point Temp
 $T_{dew} \approx 40^\circ\text{F}$

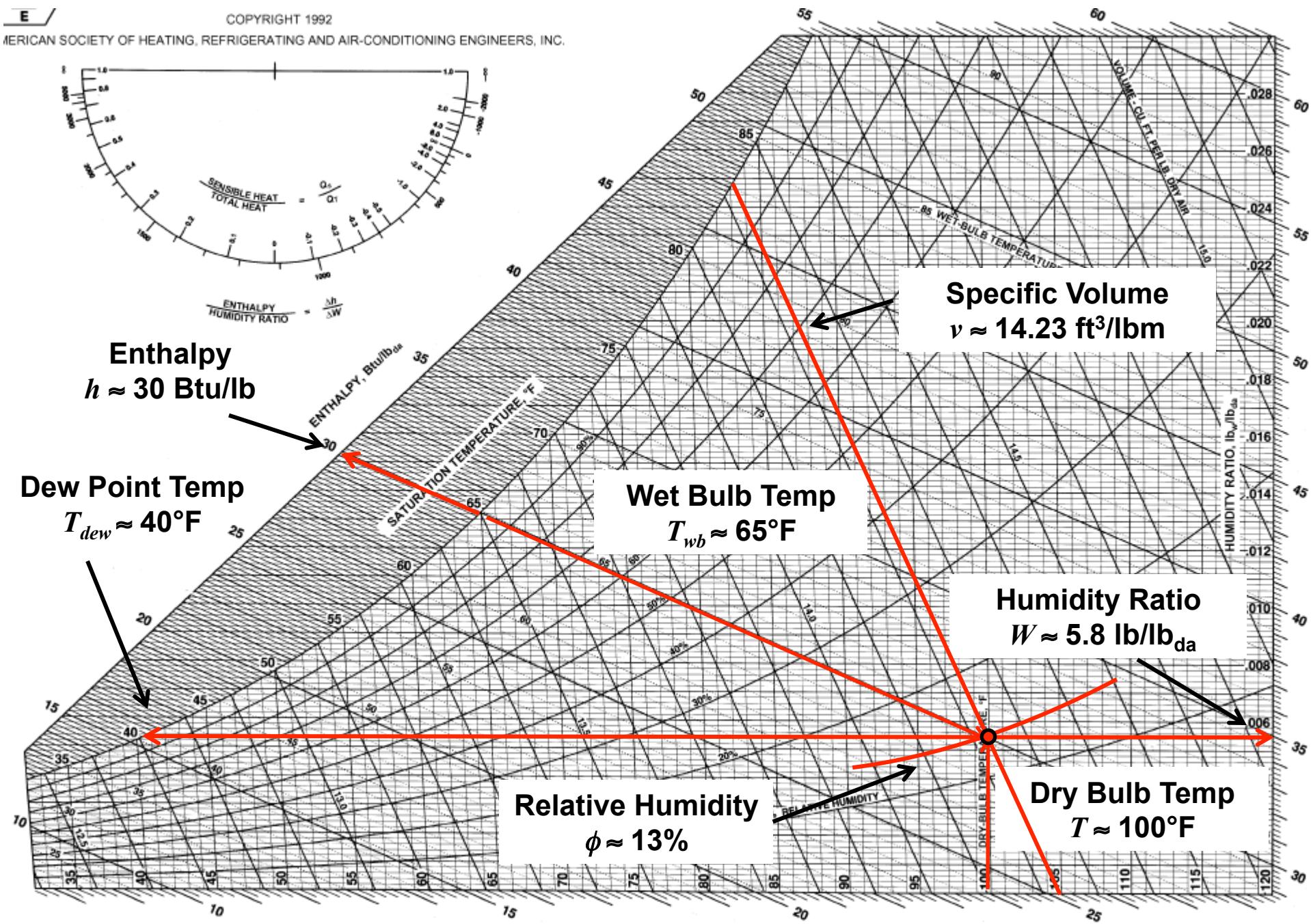
Wet Bulb Temp
 $T_{wb} \approx 65^\circ\text{F}$

Relative Humidity
 $\phi \approx 13\%$

Specific Volume
 $v \approx 14.23 \text{ ft}^3/\text{lbm}$

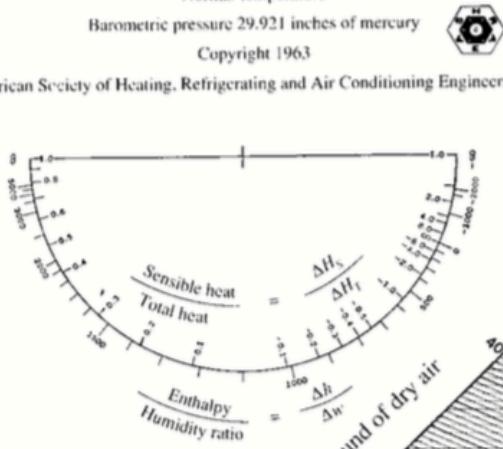
Humidity Ratio
 $W \approx 5.8 \text{ lb/lb}_{da}$

Dry Bulb Temp
 $T \approx 100^\circ\text{F}$

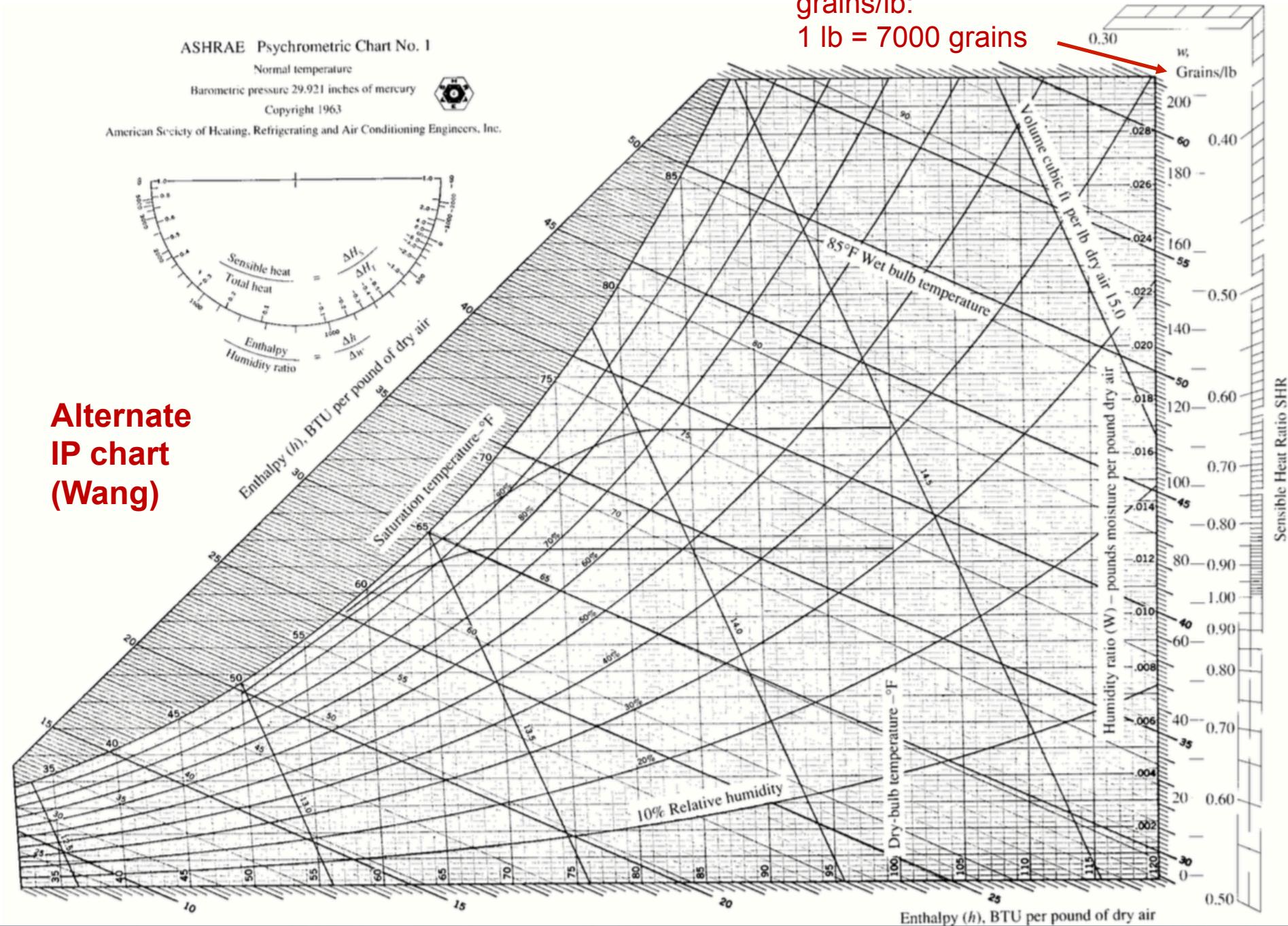


ASHRAE Psychrometric Chart No. 1
 Normal temperature
 Barometric pressure 29.921 inches of mercury
 Copyright 1963
 American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

grains/lb:
 1 lb = 7000 grains



Alternate IP chart (Wang)



PSYCHROMETRIC EQUATIONS

Specifying the state of moist air



In order to specify the state of moist air, we need total atmospheric pressure, p , the air temperature, T , and at least one other property

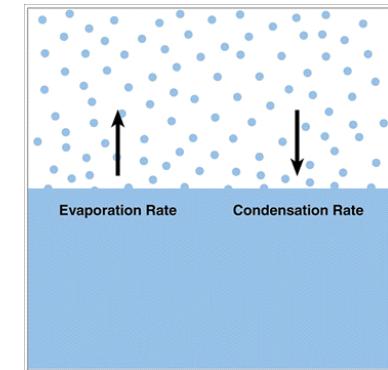
- W , ϕ , h , p_w , or T_{dew}
- We can use the psychrometric chart
- We can also use the **underlying equations** for greater accuracy and automation
- All equations are in ASHRAE 2013 Handbook of Fundamentals Chapter 1

Remember: Vapor pressure and Saturation

- Air can hold moisture (i.e., **water vapor**)
- **Vapor pressure** is the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases

p_w

*Units of pressure, Pa or kPa
(aka “**partial pressure**”)



- The amount of moisture air can hold in vapor form before condensation occurs is dependent on temperature
 - We call the limit **saturation**

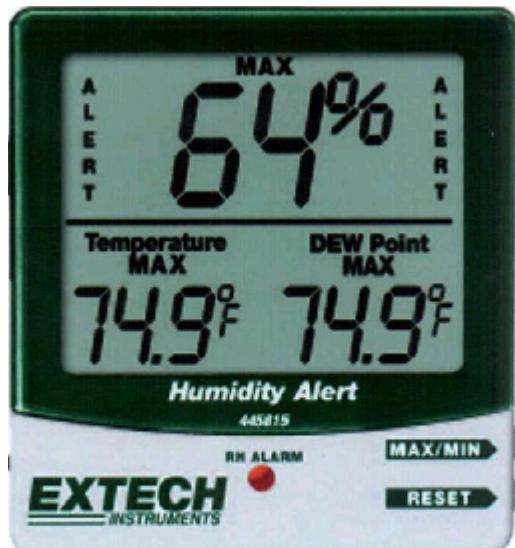
p_{ws}

*Units of pressure, Pa or kPa
(aka “**saturation vapor pressure**”)



Relative humidity, ϕ (RH)

- The relative humidity ratio, ϕ , is the mole fraction of water vapor (x_w) relative to the water vapor that would be in the mixture if it were saturated at the given T and P (x_{ws})
 - We can also describe RH by partial pressures (ideal gas)
- Relative humidity is a common measure that relates well to how we perceive moisture in air



$$\phi = \left[\frac{x_w}{x_{ws}} \right]_{T,P} = \frac{p_w / p_{tot}}{p_{ws} / p_{tot}} = \frac{p_w}{p_{ws}}$$

p_{ws} for $0^{\circ}\text{C} < T < 200^{\circ}\text{C}$ (SI units)

For p_{ws} , the saturation pressure over **liquid water**:

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

where

$$C_8 = -5.800\ 220\ 6 \times 10^3$$

$$C_9 = 1.391\ 499\ 3 \times 10^0$$

$$C_{10} = -4.864\ 023\ 9 \times 10^{-2}$$

$$C_{11} = 4.176\ 476\ 8 \times 10^{-5}$$

$$C_{12} = -1.445\ 209\ 3 \times 10^{-8}$$

$$C_{13} = 6.545\ 967\ 3 \times 10^0$$

Unit

p_{ws} = saturation pressure, Pa

T = absolute temperature, K = $^{\circ}\text{C} + 273.15$

Note:

These constants are only for SI units
IP units are different

*We will use this equation for most conditions in building science (above 0°C)

p_{ws} for $-100^{\circ}\text{C} < T < 0^{\circ}\text{C}$ (SI units)

For p_{ws} , the saturation pressure over **ice**:

$$\ln p_{ws} = \frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 T^4 + C_7 \ln T$$

where

$$C_1 = -5.674\ 535\ 9 \text{ E+03}$$

$$C_2 = 6.392\ 524\ 7 \text{ E+00}$$

$$C_3 = -9.677\ 843\ 0 \text{ E-03}$$

$$C_4 = 6.221\ 570\ 1 \text{ E-07}$$

$$C_5 = 2.074\ 782\ 5 \text{ E-09}$$

$$C_6 = -9.484\ 024\ 0 \text{ E-13}$$

$$C_7 = 4.163\ 501\ 9 \text{ E+00}$$

Units:

p_{ws} = saturation pressure, Pa

T = absolute temperature, K = $^{\circ}\text{C} + 273.15$

Note:

These constants are only for SI units
IP units are different

Humidity ratio, W (SI units)

- The humidity ratio, W , is ratio of the mass of water vapor to mass of dry air in a given volume
 - We use W when finding other mixture properties
 - Note 1: W is small ($W < 0.03$ for most real building conditions)
 - Note 2: W is sometimes expressed in grains/lb where 1 lb = 7000 grains (I don't use this but you will in CAE 464 HVAC Design)

$$W = \frac{m_w}{m_{da}} = \frac{MW_w x_w}{MW_{da} x_{da}} = 0.622 \frac{x_w}{x_{da}}$$

Units:
[$\frac{\text{kg}_w}{\text{kg}_{da}}$]

$$x_{da} = \frac{P_{da}}{P_{da} + P_w} = \frac{P_{da}}{P_{tot}}$$
$$x_w = \frac{P_w}{P_{da} + P_w} = \frac{P_w}{P_{tot}}$$

Humidity ratio, W (SI units)

- The humidity ratio, W , is ratio of the mass of water vapor to mass of dry air in a given volume
 - We use W when finding other mixture properties
 - Note 1: W is small ($W < 0.03$ for most real building conditions)
 - Note 2: W is sometimes expressed in grains/lb where 1 lb = 7000 grains (I don't use this but you will in CAE 464 HVAC Design)

$$W = 0.622 \frac{x_w}{x_{da}} = 0.622 \frac{p_w / p_{tot}}{p_{da} / p_{tot}} = 0.622 \frac{p_w}{p_{da}} = 0.622 \frac{p_w}{p_{tot} - p_w}$$

where: $p_{tot} = p_{da} + p_w = 101,325 \text{ Pa}$ @ sea level

Saturation humidity ratio, W_s (SI units)

- At a given temperature T and pressure P there is a maximum W that can be obtained
- If we try to add any more moisture, it will just condense out
 - It is when the partial pressure of vapor has reached the saturation pressure
- This maximum humidity ratio is called the saturation humidity ratio, W_s
 - From our previous equation we can write:

$$W_s = 0.622 \frac{p_{ws}}{p_{da}} = 0.622 \frac{p_{ws}}{p_{tot} - p_{ws}}$$

UNITS
[$\frac{\text{kg}_w}{\text{kg}_{da}}$]

Degree of saturation, μ (SI units)

- The degree of saturation, μ (dimensionless), is the ratio of the humidity ratio W to that of a saturated mixture W_s at the same T and P
 - Note that μ and ϕ are not quite the same
 - Their values are very similar at lower temperatures but may differ a lot at higher temperatures

$$\mu = \left[\frac{W}{W_s} \right]_{T,P}$$

$$\mu = \frac{\phi}{1 + (1 - \phi)W_s / (0.6295)}$$
$$\phi = \frac{\mu}{1 - (1 - \mu)p_{ws} / p_{tot}}$$

Specific volume, ν , and density, ρ (SI units)

- The specific volume of moist air (or the volume per unit mass of air, m^3/kg) can be expressed as:

$$\nu = \frac{R_{da} T}{P_{da}} = \frac{R_{da} T}{P_{tot} - P_w} = \frac{R_{da} T(1 + 1.6078W)}{P_{tot}}$$

$$\nu \approx 0.287042(T + 273.15)(1 + 1.6078W) / p_{tot}$$

where

ν = specific volume, $\text{m}^3/\text{kg}_{da}$

t = dry-bulb temperature, $^\circ\text{C}$

W = humidity ratio, $\text{kg}_w/\text{kg}_{da}$

p = total pressure, kPa

- If we have ν we can also find moist air density, ρ (kg/m^3):

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

Enthalpy, h (SI units)

- The enthalpy of a mixture of perfect gases equals the sum of the individual partial enthalpies of the components
- Therefore, the enthalpy (h) for moist air is:
$$h = h_{da} + Wh_g$$

h = enthalpy for moist air [kJ/kg]

h_g = specific enthalpy for saturated water vapor (i.e., h_{ws}) [kJ/kg_w]

h_{da} = specific enthalpy for dry air (i.e., h_{ws}) [kJ/kg_{da}]

- Some approximations:
$$h_{da} \approx 1.006T \quad h_g \approx 2501 + 1.86T$$

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

*where T is in °C and h is in kJ/kg

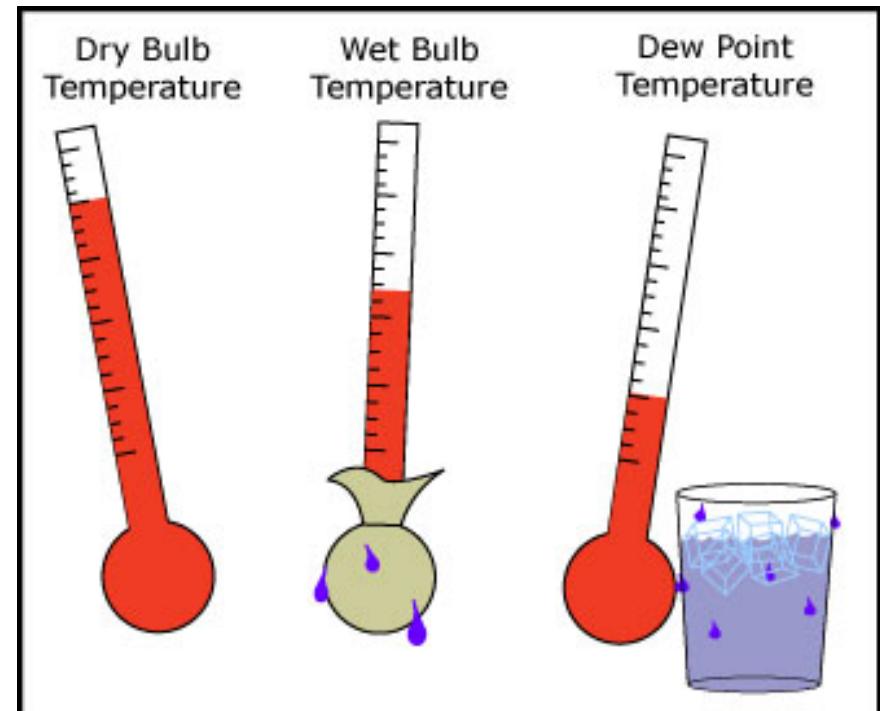
Remember: 3 different temperatures T , T_{dew} , and T_{wb}

The standard temperature, T , we are all familiar with is called the **dry-bulb** temperature, or T_d

- It is a measure of internal energy

We can also define:

- **Dew-point temperature**, T_{dew}
 - Temperature at which water vapor changes into liquid (condensation)
 - Air is maximally **saturated** with water vapor
- **Wet-bulb temperature**, T_{wb}
 - The temperature that a parcel of air would have if it were cooled to saturation (100% **relative humidity**) by the evaporation of water into it
 - ✓ The energy needed to evaporate liquid water (heat of vaporization) is taken from the air in the form of sensible heat and converted to latent heat, which lowers the temperature at constant enthalpy



Units of Celsius, Fahrenheit, or Kelvin

Dew-point temperature, T_{dew}



The dew point temperature, T_{dew} , is the air temperature at which the current humidity ratio (W) is equal to the saturation humidity ratio (W_s) at the same temperature

$$\text{i.e., } W_s(p, T_{dew}) = W$$

When the air temperature is lowered to the dew-point at constant pressure, the relative humidity rises to 100% and condensation occurs

T_{dew} is a direct measure of the humidity ratio W since $W = W_s$ at $T = T_{dew}$



ASHRAE PSYCHROMETRIC CHART NO.1

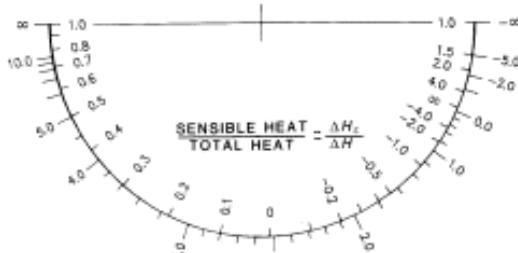
NORMAL TEMPERATURE

SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa

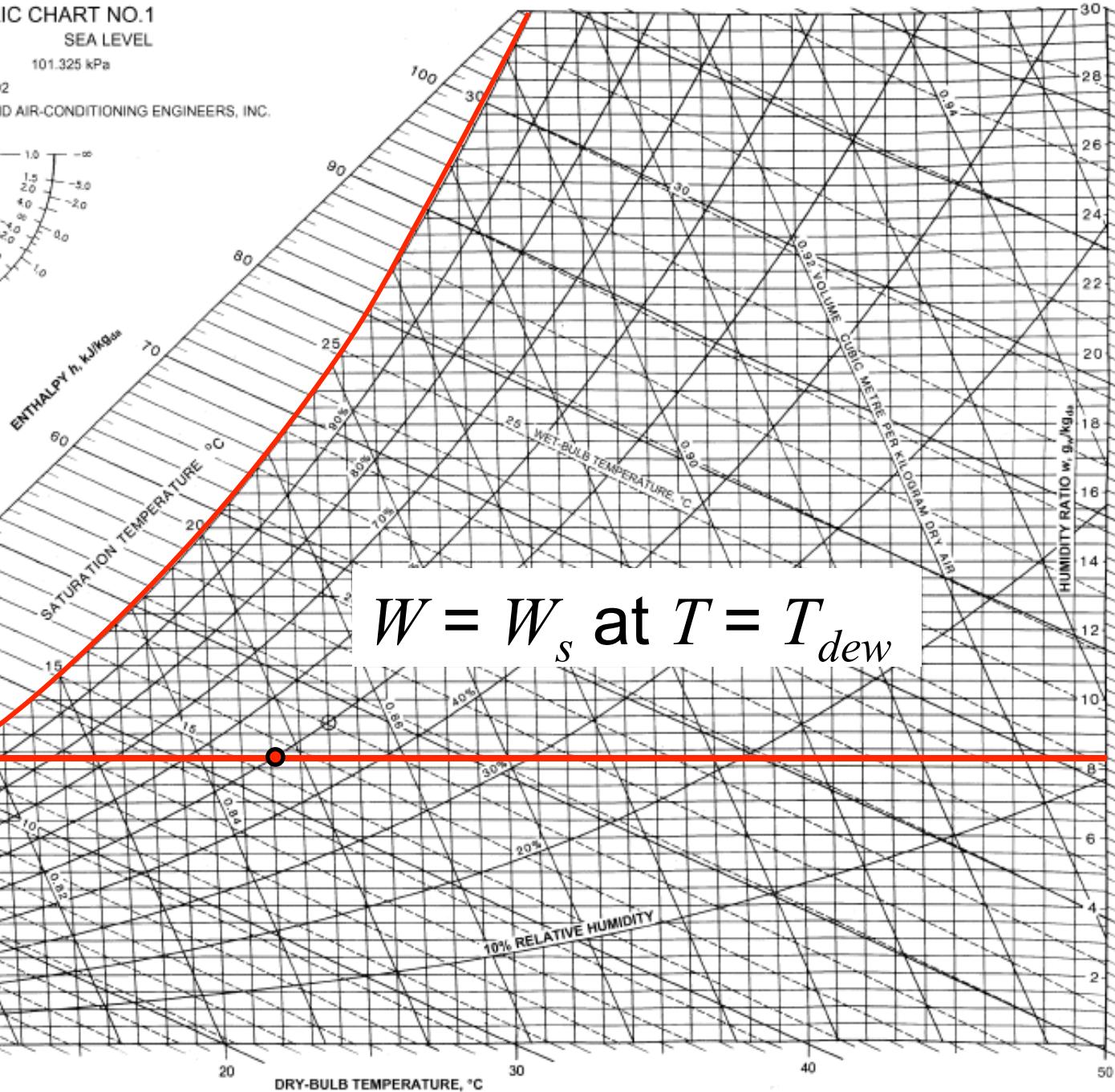
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$$\text{SENSIBLE HEAT} = \frac{\Delta H_s}{\Delta H}$$

$$\text{ENTHALPY} = \frac{\Delta h}{\text{HUMIDITY RATIO}} = \frac{\Delta h}{\Delta W}$$

**Dew Point Temp**

$$T_{dew} \approx 11.7^\circ\text{C}$$

Dew-point temperature, T_{dew} (SI units)

- Dew-point temperature, T_{dew}

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

$\alpha = \ln p_w$

p_w = water vapor partial pressure, kPa

$C_{14} = 6.54$

$C_{15} = 14.526$

$C_{16} = 0.7389$

$C_{17} = 0.09486$

$C_{18} = 0.4569$

Note:

These constants are only for SI units
IP units are different

Wet-bulb temperature, T_{wb} (SI units)

- Wet-bulb temperature, T_{wb}
- Requires **iterative solving**... find the T_{wb} that satisfies the following equation (above freezing):

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

- And for T below freezing:

$$W = \frac{(2830 - 0.24T_{wb})W_{s@T_{wb}} - 1.006(T - T_{wb})}{2830 + 1.86T - 2.1T_{wb}} = \text{actual } W$$

*Where T_{wb} and T are in Celsius

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 Pressure

Temp., °C <i>t</i>	Humidity Ratio W_s , kg _w /kg _{da}	Specific Volume, m ³ /kg _{da}			Specific Enthalpy, kJ/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 <i>t</i>	Absolute Pressure p_{ws} , kPa	Specific Volume, m^3/kg_w			Specific Enthalpy, kJ/kg_w		
		Sat. Liquid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Sat. Liquid h_i/h_f	Evap. h_{ig}/h_{fg}	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 last class

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

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, ν
- (f) density, ρ

Also:

- (g) degree of saturation, μ

Psychrometric equations summary (SI units)

$$pV = nRT$$

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

$$W = 0.622 \frac{p_w}{p - p_w} \left[\frac{\text{kg}_w}{\text{kg}_{da}} \right] \quad \rho = \frac{m_{da} + m_w}{V} = \frac{1}{v} (1 + W)$$

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

$$p_v = \frac{p}{\rho} = RT \quad R_i = \frac{R}{MW_i}$$

Dew point temperature:

Between dew points of 0 and 93°C,

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

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

Below 0°C,

where

$$C_8 = -5.800\ 220\ 6 \times 10^3$$

$$C_9 = 1.391\ 499\ 3 \times 10^0$$

$$C_{10} = -4.864\ 023\ 9 \times 10^{-2}$$

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$$C_{13} = 6.545\ 967\ 3 \times 10^0$$

p_{ws} = saturation pressure, Pa

T = absolute temperature, K = °C + 273.15

where

t_d = dew-point temperature, °C

$\alpha = \ln p_w$

p_w = water vapor partial pressure, kPa

$C_{14} = 6.54$

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Psychrometric equations summary (SI units)

Wet bulb temperature (iterative solver):

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

*Where T_{wb} and T are in Celsius

Specific volume:

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

$$v \approx 0.287042(T + 273.15)(1 + 1.6078W) / p \quad \text{where}$$

Specific enthalpy:

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

*where T is in $^{\circ}\text{C}$

v = specific volume, $\text{m}^3/\text{kg}_{da}$

t = dry-bulb temperature, $^{\circ}\text{C}$

W = humidity ratio, $\text{kg}_w/\text{kg}_{da}$

p = total pressure, kPa



ASHRAE PSYCHROMETRIC CHART NO.1

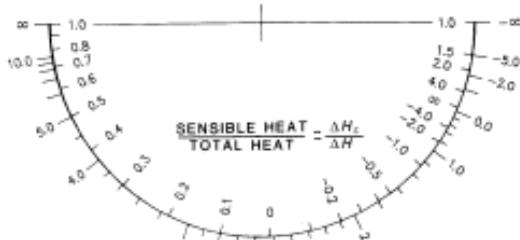
NORMAL TEMPERATURE

SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa

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$$\frac{\text{ENTHALPY}}{\text{HUMIDITY RATIO}} = \frac{\Delta h}{\Delta W}$$

Enthalpy
 $h \approx 44 \text{ kJ/kg}_{\text{da}}$

Dew Point Temp
 $T_{\text{dew}} \approx 11.7^\circ\text{C}$

Relative Humidity
 $\phi \approx 50\%$

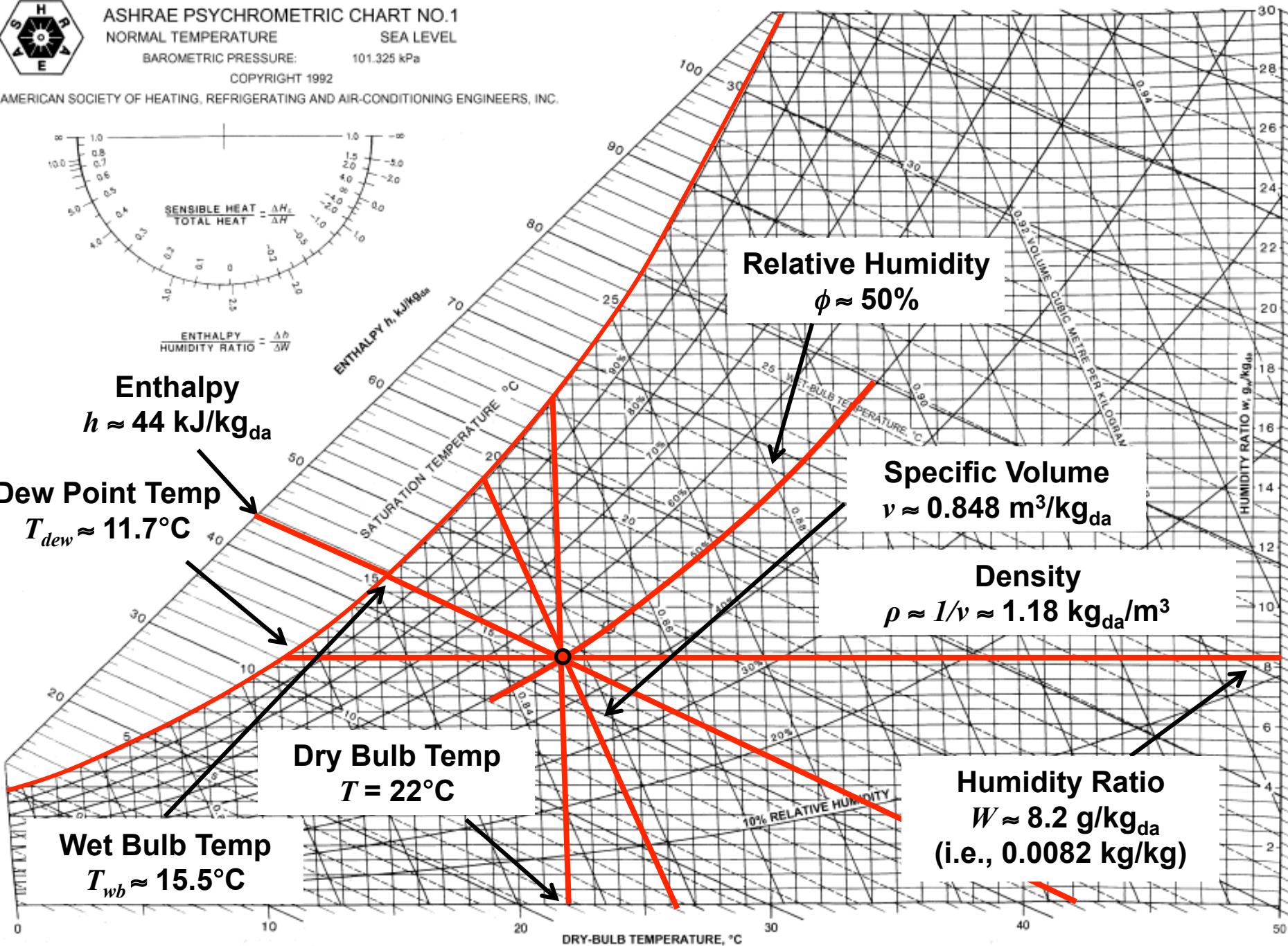
Specific Volume
 $v \approx 0.848 \text{ m}^3/\text{kg}_{\text{da}}$

Density
 $\rho \approx 1/v \approx 1.18 \text{ kg}_{\text{da}}/\text{m}^3$

Dry Bulb Temp
 $T = 22^\circ\text{C}$

Wet Bulb Temp
 $T_{\text{wb}} \approx 15.5^\circ\text{C}$

Humidity Ratio
 $W \approx 8.2 \text{ g/kg}_{\text{da}}$
(i.e., 0.0082 kg/kg)



Revisit another example from last 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, ν
- (f) density, ρ
- (g) wet bulb temperature, T_{wb}

Humidity ratio

$$W = 0.622 \frac{p_w}{p - p_w} \Big|_{@T=30^\circ C}$$

Assume $p = 101.325 \text{ kPa}$ (sea level)

- For a known $T_{dew} = 15^\circ \text{C}$, 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

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

$$W_{@T=30^\circ C} = W_{s@T=15^\circ C} = 0.622 \frac{p_{ws}}{p - p_{ws}} \Big|_{@T=15^\circ C}$$

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



$$W_{@T=30^\circ C} = W_{s@T=15^\circ C} = 0.622 \frac{1.7057}{101.325 - 1.7057} = 0.01065 \frac{\text{kg}_w}{\text{kg}_{da}}$$

Degree of saturation

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

$$W_{s@T=30^{\circ}C} = 0.622 \frac{p_{ws}}{p - p_{ws}} \Big|_{@T=30^{\circ}C}$$

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

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

$$p_{ws@15^{\circ}C} = 4.2467 \text{ kPa}$$

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

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

Relative humidity

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

- From previous:

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

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

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

Enthalpy

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

*where T is in °C

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

Specific volume and density

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

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

$$v \approx 0.873 \frac{m^3}{kg_{da}}$$

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

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: $T = 30^\circ C$

$T_{wb} = ?^\circ C$

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

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)

$$T_{wb} = 20.1^\circ C$$

*Where T_{wb} and T are in Celsius



ASHRAE PSYCHROMETRIC CHART NO.1

NORMAL TEMPERATURE

SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa

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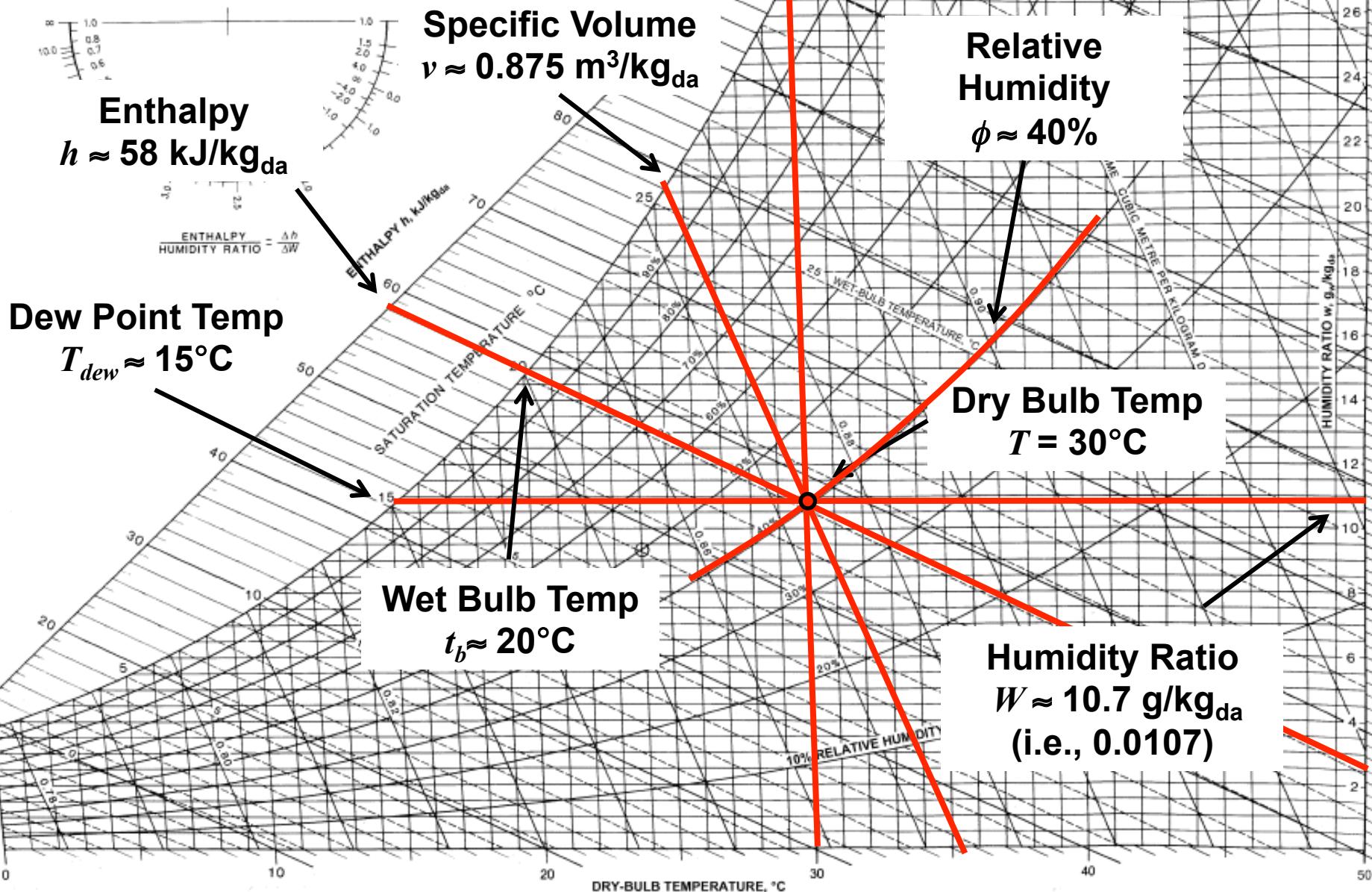


Enthalpy
 $h \approx 58 \text{ kJ/kg}_{\text{da}}$

$$\frac{\text{ENTHALPY}}{\text{HUMIDITY RATIO}} = \frac{\Delta h}{\Delta W}$$

Dew Point Temp
 $T_{\text{dew}} \approx 15^\circ\text{C}$

Specific Volume
 $v \approx 0.875 \text{ m}^3/\text{kg}_{\text{da}}$



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

HW 3 assigned

- HW 3 assigned on Blackboard last time
 - Building an Excel-based psychrometric calculator
 - Due Tuesday October 10
- Next time: psychrometric *processes*