Week 4

Gas-vapor mixtures

Air conditioning processes

Today's Outline

- Gas-vapor mixtures
- Key definitions and measures

Gas-vapor Mixtures

- At temperatures below the critical temperature, gas phase is called a vapor e.g. a gaseous state close to saturation region – possible condensation
- Previously, we looked at mixtures of gases, hence temperatures greater than critical temperature, thus single phase
- Now two-phase mixture i.e. gas-vapor mixture
- Air-water-vapor mixture is most common
- Air conditioning (AC) – primary application

Dry and atmospheric air

- Air is N2, O2, etc.
- Usually contains some water vapor i.e. moisture
- This is called atmospheric air
- Dry air is air with no water vapor
- Treat **air as mixture of water vapor and dry air** with amount of water vapor changing due to condensation and evaporation from oceans, lakes, rivers, etc.

Modeling Dry Air

- For AC applications, T ranges from -10 to 50 C
- In this range, **air can be treated as ideal gas**
- Also c_p=1.005 kJ/kg-K constant (< 0.2% error)
- With T=0 C as a reference we have:

DRY AIR

T,°C	c_p,kJ/kg·°C
–10	1.0038
0	1.0041
10	1.0045
20	1.0049
30	1.0054
40	1.0059
50	1.0065

$$h_{da} = c_p T = (1.005 kJ/kg - C)T \quad (kJ/kg)$$

$$\Delta h_{da} = c_p \Delta T = (1.005 kJ/kg - C)\Delta T \quad (kJ/kg)$$

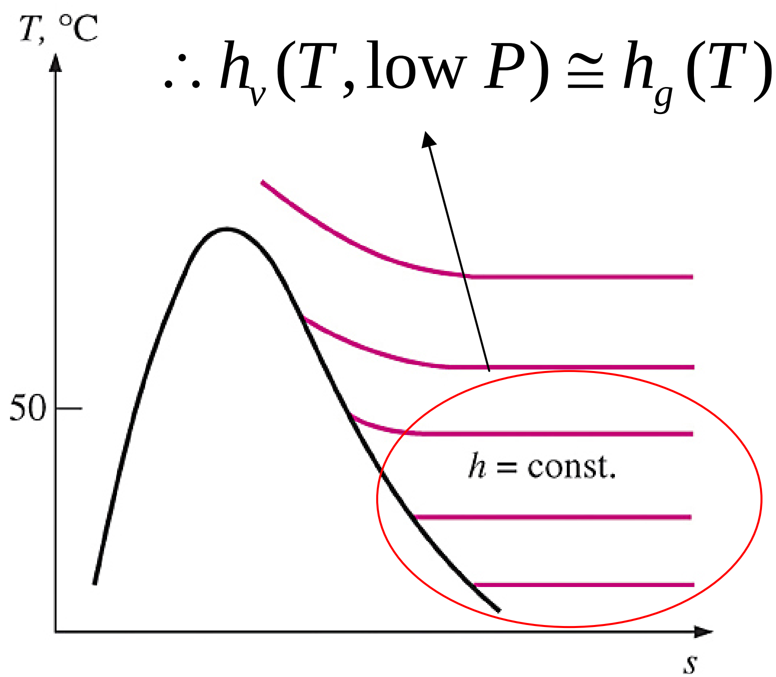
Modeling Water Vapor (in air)

- Also, **water vapor below 50 C (12.3kPa) can be treated as ideal gas**.
- So water vapor in air behaves as if it existed alone and obeys Pv=RT, e.g. P_v is so low (<10kPa) (compare to steam power plant application with pressure high so no IG!)
- So atmospheric air modeled as ideal gas mixture with: $P = P_a + P_v$ with water vapor as IG

Enthalpy evaluation

$$h = const \rightarrow T = const.$$

$$\therefore h_v(T, \text{low } P) \cong h_g(T)$$



WATER VAPOR

	h_g, kJ/kg		Difference,
T, °C	Table A-4	Eq. 14-4	kJ/kg
−10	2482.1	2482.7	−0.6
0	2500.9	2500.9	0.0
10	2519.2	2519.1	0.1
20	2537.4	2537.3	0.1
30	2555.6	2555.5	0.1
40	2573.5	2573.7	−0.2
50	2591.3	2591.9	−0.6

$$h_g(T) \cong 2500.9 + 1.82T \quad (kJ/kg) \quad (T \text{ in } C)$$

$$h_g(T) \cong 1060.9 + 0.435T \quad (Btu/lbm) \quad (T \text{ in } F)$$

Specific Humidity of Air

- How much water vapor is in air?
- Absolute or specific humidity (humidity ratio):

$$\omega = \frac{m_v}{m_a} = \frac{P_v V / R_v T}{P_a V / R_a T} = \frac{P_v / R_v}{P_a / R_a} = \frac{P_v M_v}{P_a M_a} = 0.622 \frac{P_v}{P_a}$$

$$\omega = 0.622 \frac{P_v}{P - P_v}$$

- How much water vapor is in mixture relative to amount of dry air present? How "wet" is air?
- Note:

$$\omega = 0 \text{ dry air; add moisture } \omega \uparrow \Rightarrow \text{ saturated air}$$

Relative Humidity of Air

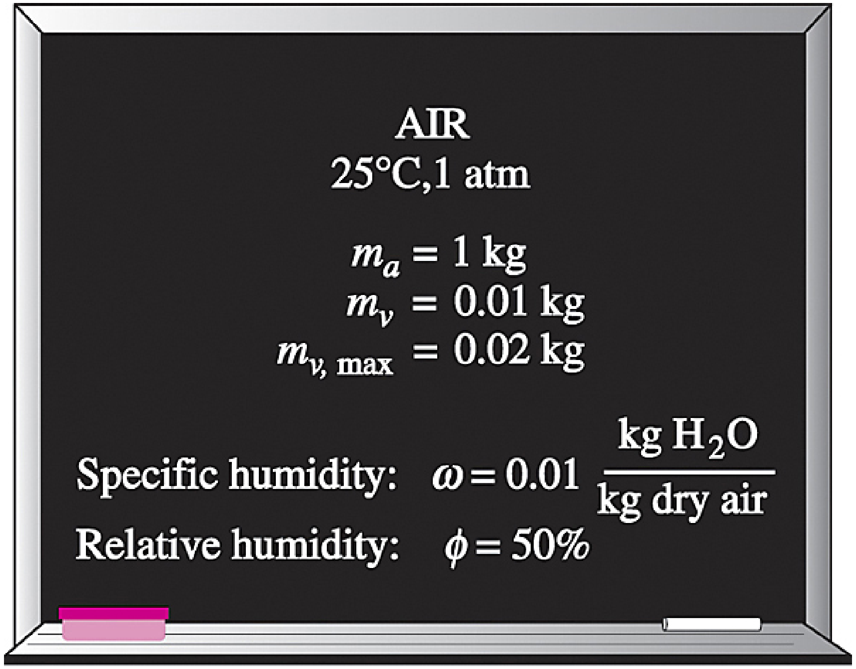
- Comfort depends on how much moisture air can hold relative to maximum amount of moisture air can hold at same temperature
- This leads to relative humidity:

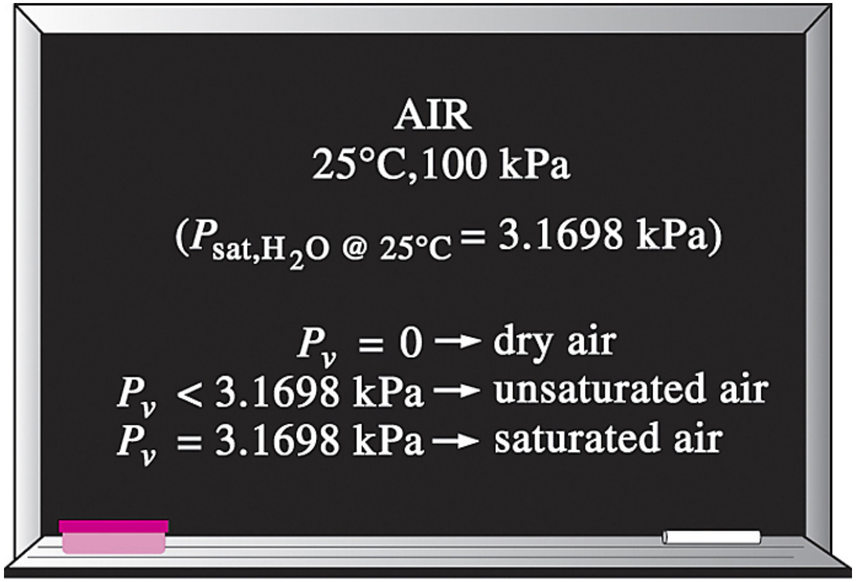
$$\phi = \frac{m_v}{m_g} = \frac{P_v V / R_v T}{P_g V / R_a T} = \frac{P_v / R_v}{P_g / R_a} = \frac{P_v}{P_g} \text{ with } P_g = P_{\substack{sat \\ @T}}$$

$$\phi = \frac{\omega P}{(0.622 + \omega) P_g} \quad \text{and} \quad \omega = \frac{0.622 \phi P_g}{P - \phi P_g}$$

$$\phi = 0 \text{ dry air; } \phi = 1 \text{ saturated air;}$$

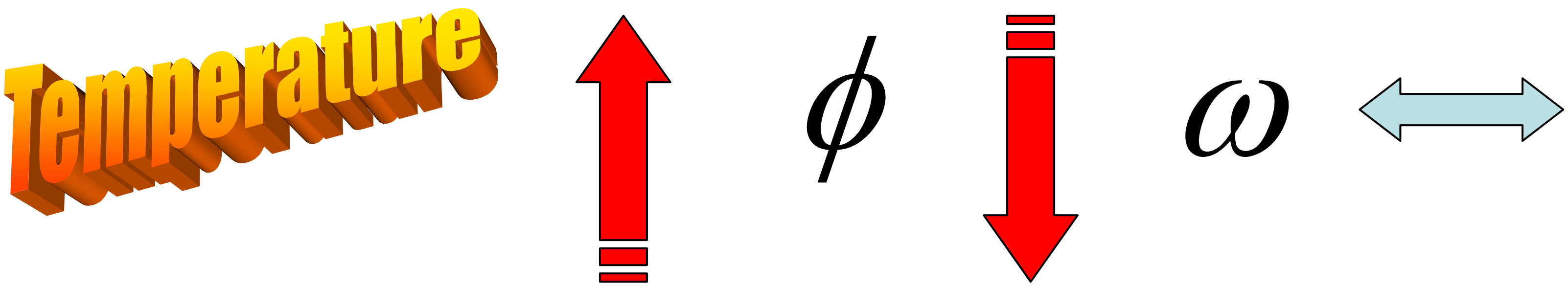
Specific and Relative Humidity of Air





Effect of temperature

- Amount of moisture air can hold depends on temperature e.g. $P_g=f(T)$
- Relative humidity of air changes with temperature while specific humidity remains constant with temperature



Enthalpy

- Atmospheric air is a mixture of dry air and water vapor. Hence,

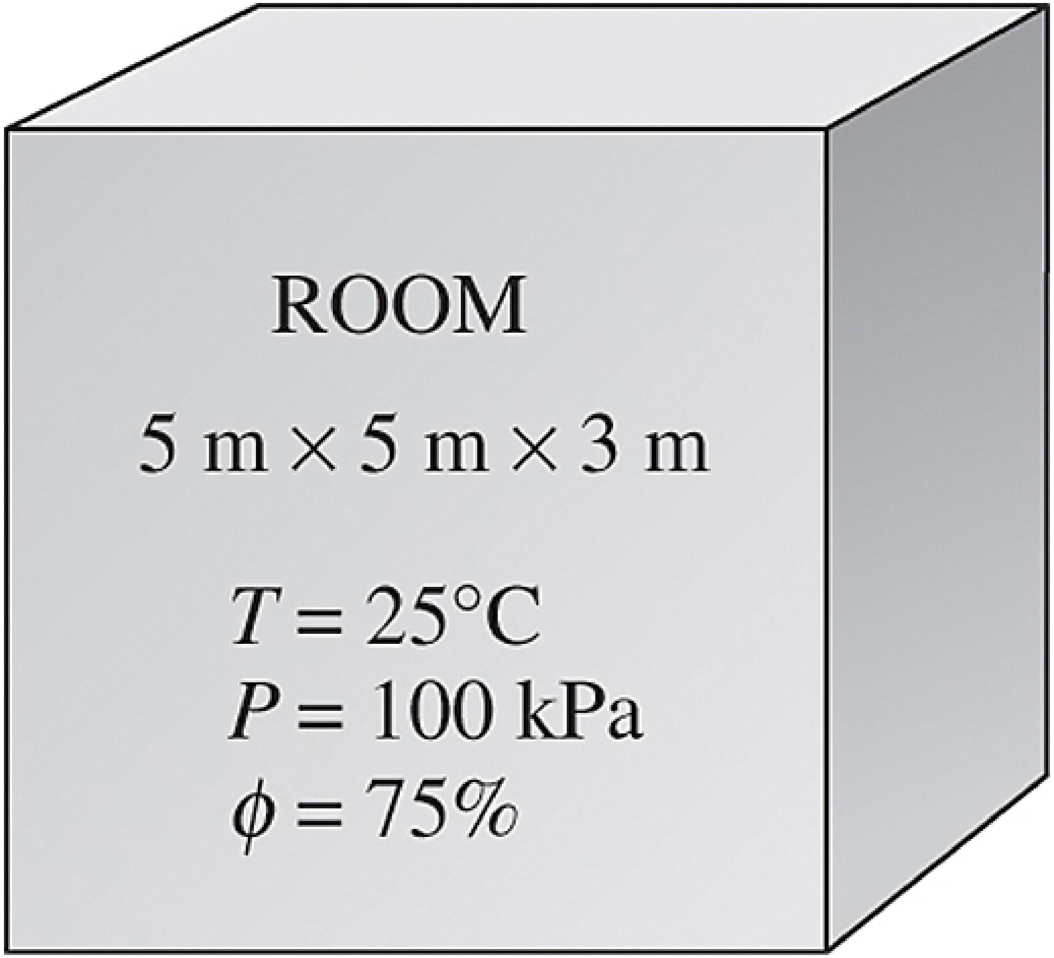
$$H = H_a + H_v = m_a h_a + m_v h_v$$

$$\div m_a \rightarrow h = \frac{H}{m_a} = h_a + \frac{m_v}{m_a} h_g = h_a + \omega h_v$$

$$h = h_a + \omega h_g$$

- Ordinary temperature of atmospheric air is often called dry-bulb temperature for distinction

Example 14-1

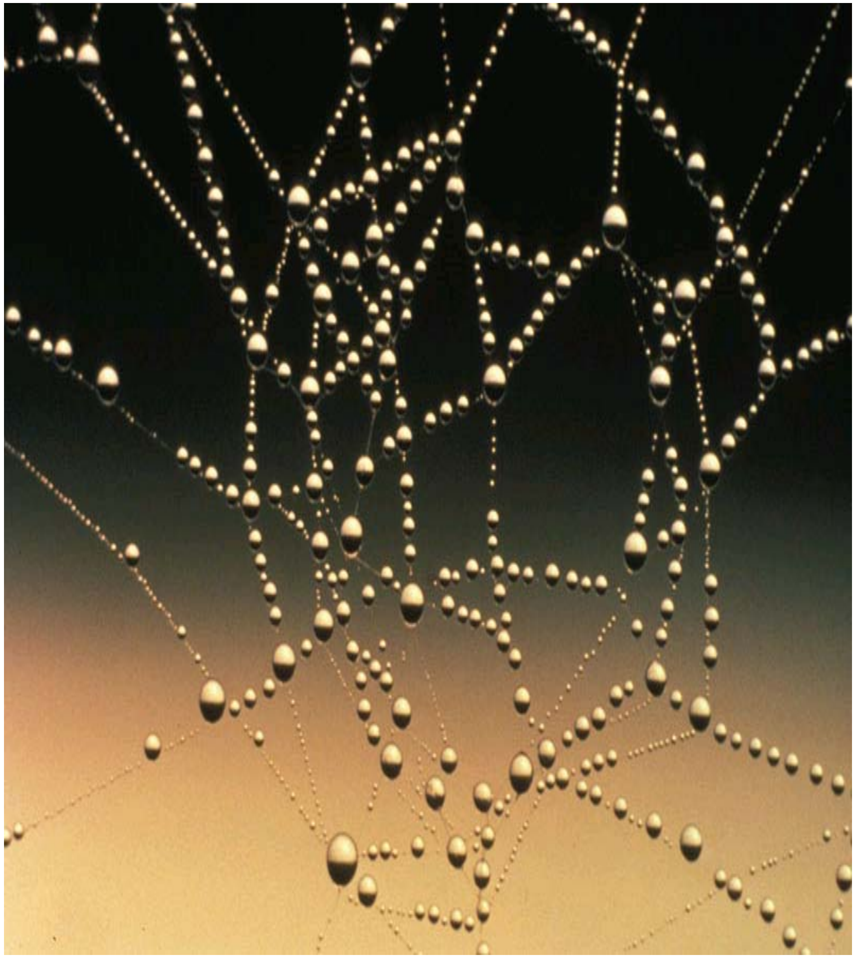


Example 14-1

Example 14-1

Condensation

- Summer mornings grass is wet but no rain? Moisture in air condenses on cool surface
- During day water vaporizes
- At night, as temperature decreases, so does moisture capacity of air, that is, relative humidity goes up
- Eventually, amount of moisture air can hold equals amount of moisture in air e.g. air becomes saturated with moisture
- Any further decrease in temperature will lead to condensation ie. dew formation

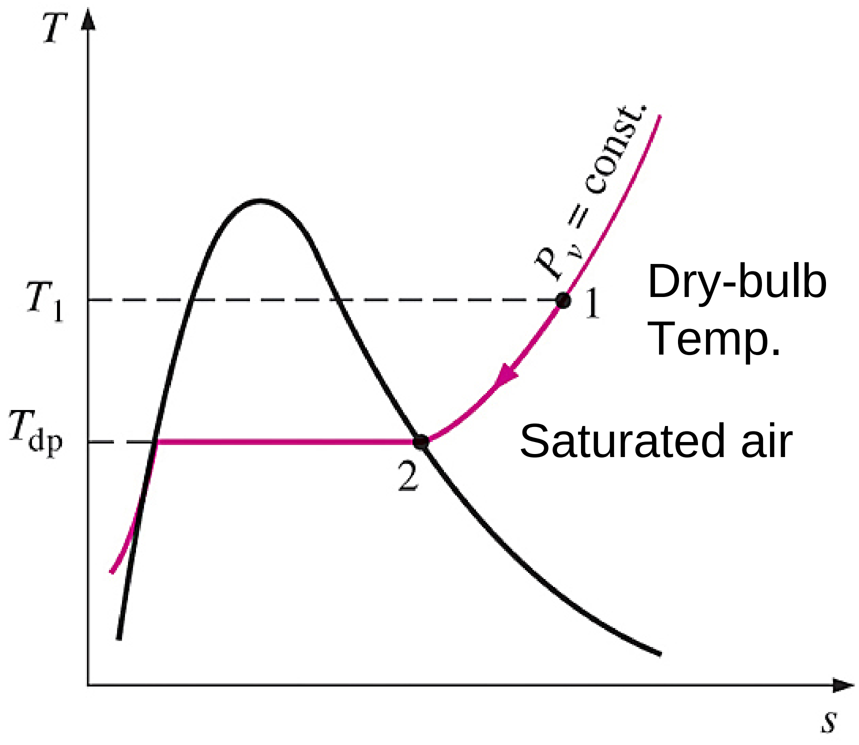


Dew-point Temperature

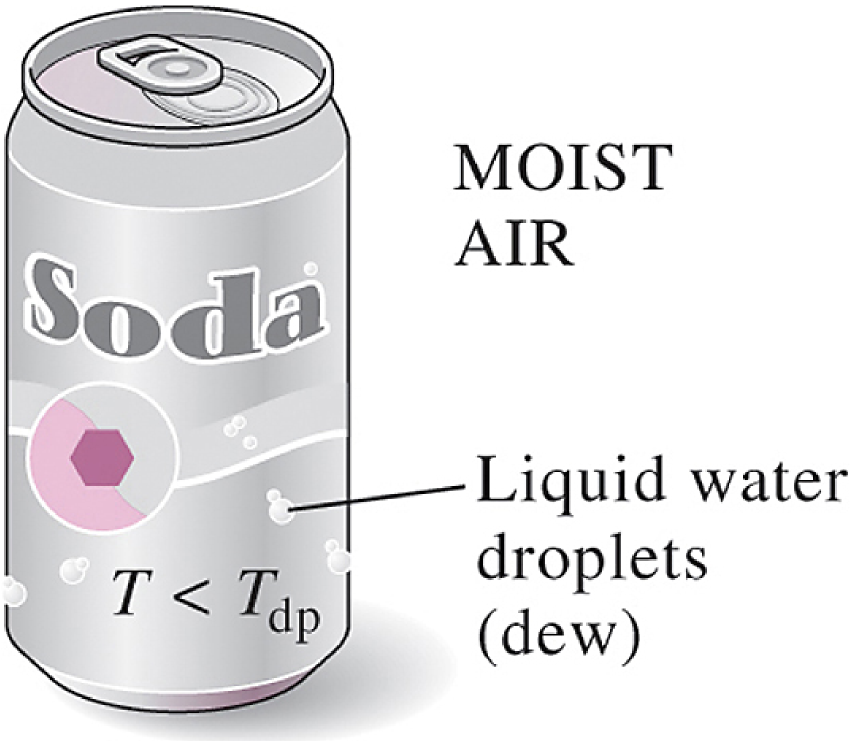
- Temperature at which condensation begins if air is cooled at constant pressure

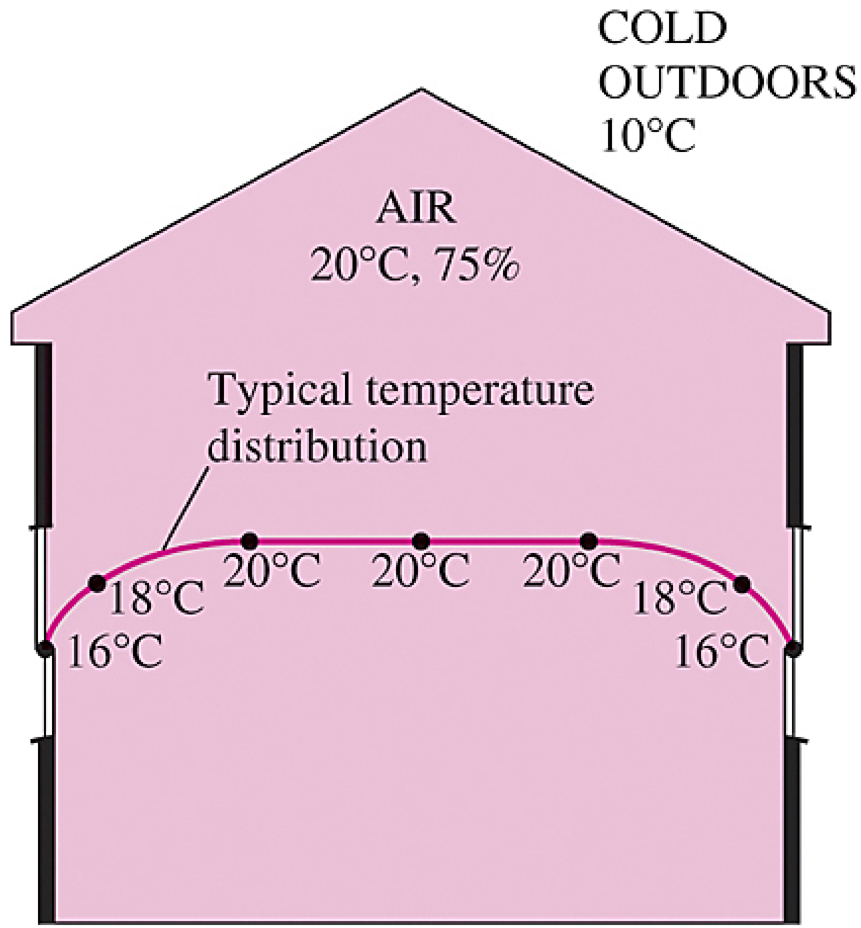
$$T_{DP} = T_{sat\,@\,P_v}$$

- Further cooling, some vapor condenses out
- Less vapor so vapor pressure decreases



Examples


Soda
$T < T_{dp}$
MOIST AIR
Liquid water droplets (dew)


COLD OUTDOORS 10°C
AIR 20°C, 75%
Typical temperature distribution
16°C
18°C
20°C
20°C
20°C
18°C
16°C

Example 14-2

Summary

- Air-water vapor mixtures in AC applications can be modeled as ideal gas mixture
- Specific or absolute humidity measures how much moisture is in the air absolutely
- Relative humidity measures how much much moisture is in the air compared to maximum amount it can hold at given T
- Mixture enthalpy is mass-weighted average of air and water enthalpies – ideal gas applies
- Dew-point temperature is temperature at which condensation occurs as air is cooled at constant pressure

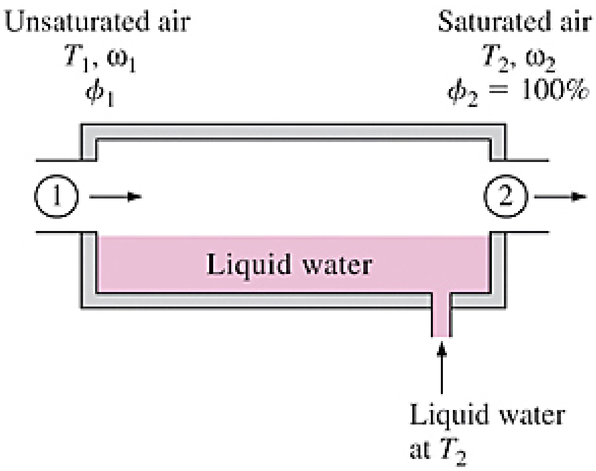
Today's Outline

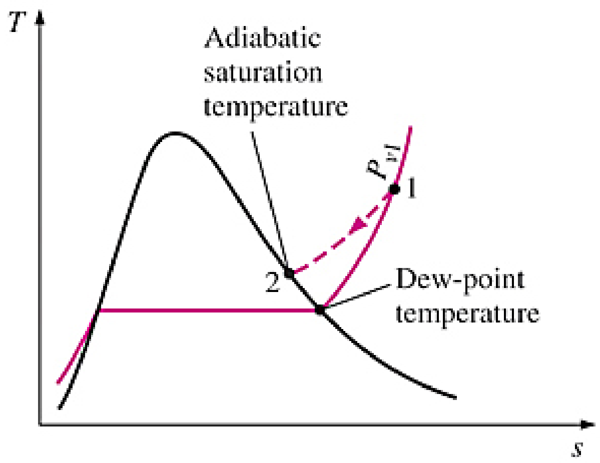
- Adiabatic saturation
- Wet-bulb temperature
- Psychrometric chart

Adiabatic Saturation Process

- How do we determine specific and relative humidity? Seek to relate to P, T meas.
- One way is related to adiabatic saturation process
- What is the adiabatic saturation process?

Adiabatic Saturation Process





- Long insulated channel with pool of water
- Steady stream of unsaturated air with specific humidity and temperature known
- Some water evaporates and mixes with airstream inc. moisture and dec. temp.
- Channel long enough so saturated air exits at adiabatic saturation temp. T_2
- Supply water at T_2 to maintain steady state; No Q, W, KE, PE

Governing Equations

- 2-inlet, 1-exit, steady flow
- Mass conservation

$$\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a \qquad \dot{m}_{w_1} + \dot{m}_f = \dot{m}_{w_2} \rightarrow \omega_1 \dot{m}_{a_1} + \dot{m}_f = \dot{m}_a \omega_2$$

$$\therefore \dot{m}_f = \dot{m}_a (\omega_2 - \omega_1)$$

- Energy conservation

Energy Conservation

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_{a_1} h_1 + \dot{m}_f h_{f_2} = \dot{m}_a h_2 \rightarrow \dot{m}_{a_1} h_1 + \dot{m}_a (\omega_2 - \omega_1) h_{f_2} = \dot{m}_a h_2$$

$$\div \dot{m}_a \rightarrow h_1 + (\omega_2 - \omega_1) h_{f_2} = h_2$$

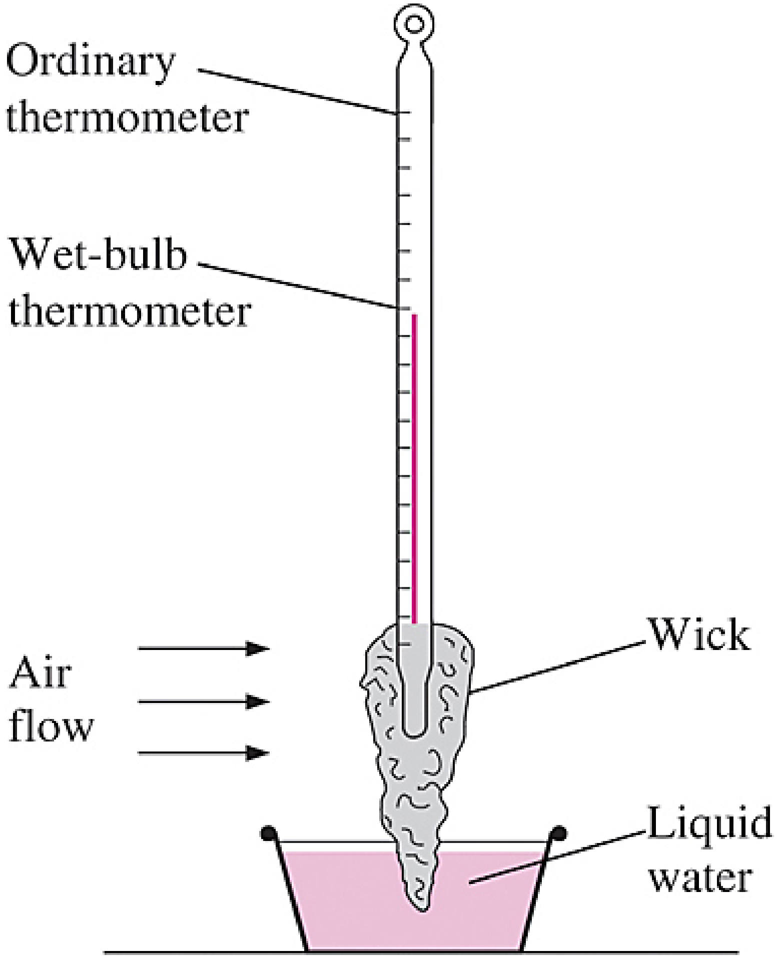
$$(c_p T + \omega h_g)_1 + (\omega_2 - \omega_1) h_{f_2} = (c_p T + \omega h_g)_2$$

$$\omega_1 = \frac{c_p (T_2 - T_1) + \omega_2 h_{fg_2}}{h_{g_1} - h_{f_2}}; \quad \omega_2 = \frac{0.622 P_{g\,2}}{P_2 - P_{g\,2}}$$

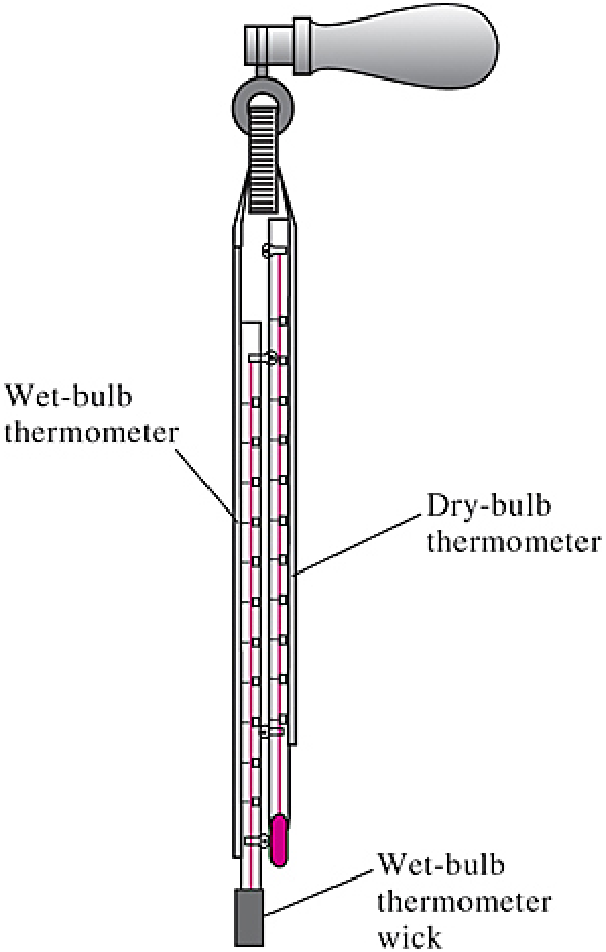
Practical Issues

- Thus, measuring P, T at inlet and exit of adiabatic saturator will allow determination of relative and specific humidity at inlet
- Requires a long channel to reach saturation conditions – not practical
- Using similar principle, above analysis still holds

Wet-bulb thermometer



Sling psychrometer

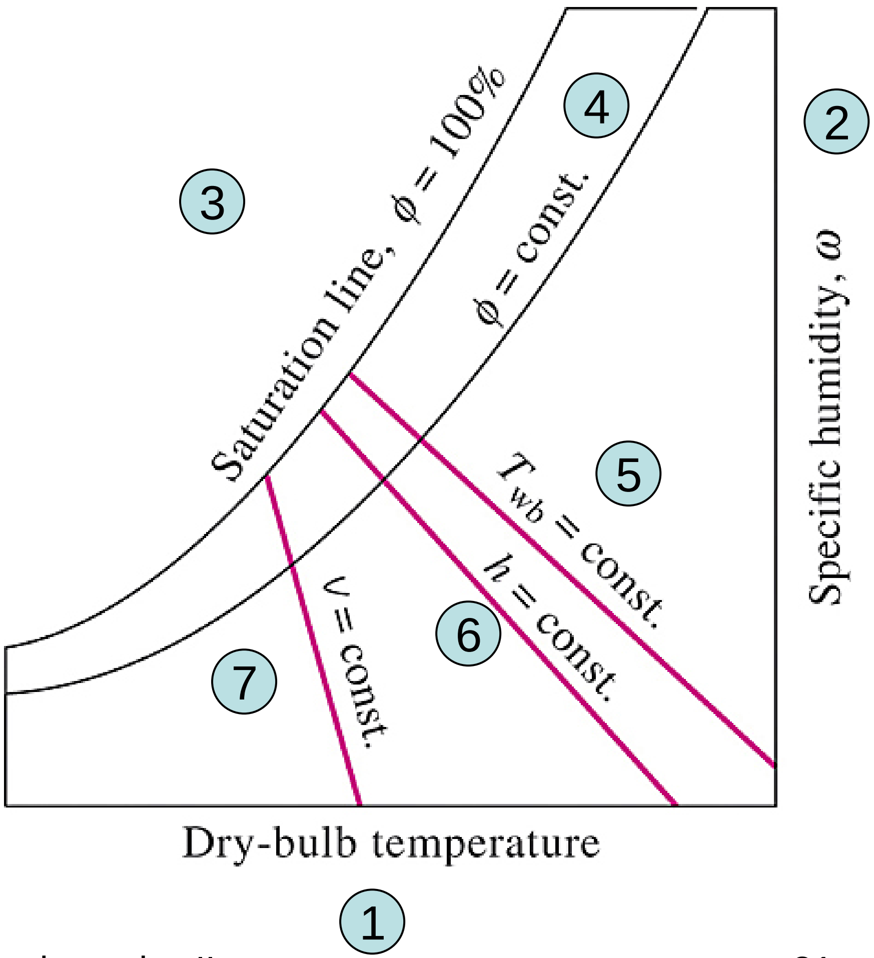


Example

Example

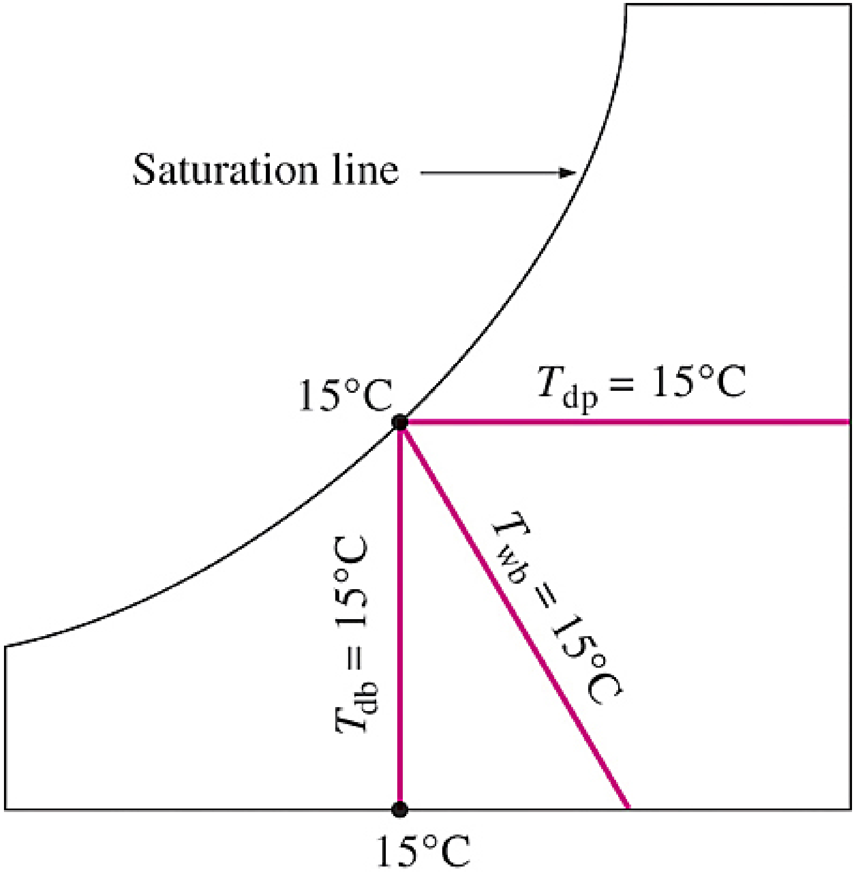
Psychrometric Chart

- State of atmospheric air fixed by 2 indep. Intensive properties
- Remaining properties can be computed using previous equations
- It is convenient to plot the solutions to these equation in chart form for a given pressure



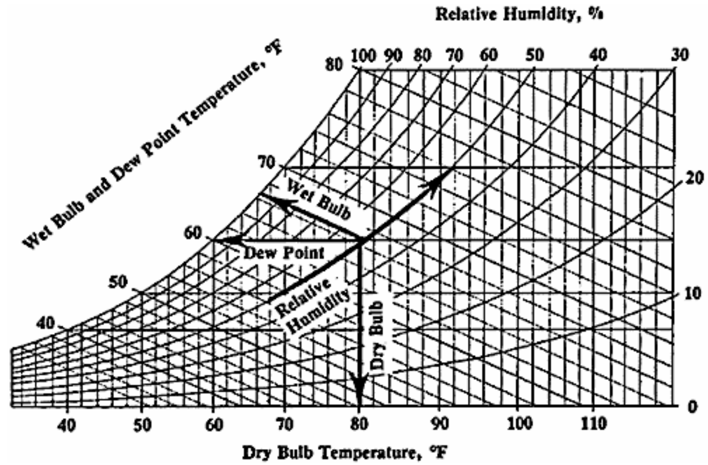
Saturated Air

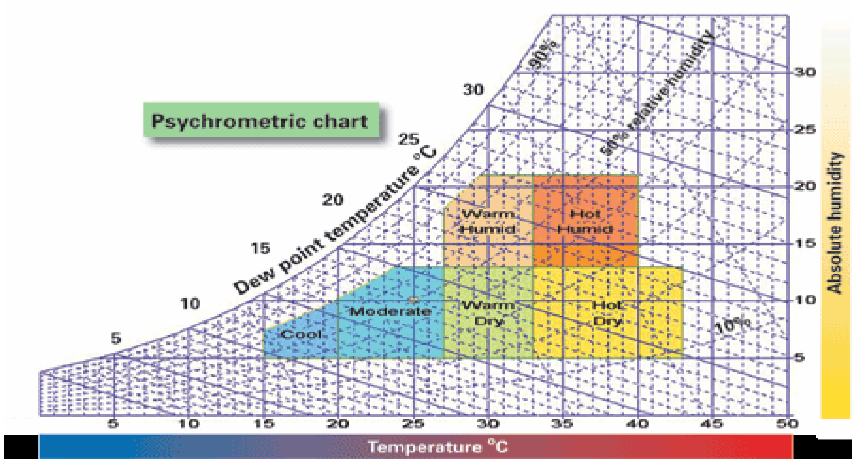
- $T_{DB}=T_{WB}=T_{DP}$ for sat. air
- Visualizing AC process
  - Heating/cooling horizontal line
  - Any vertical movement implies changes in moisture level



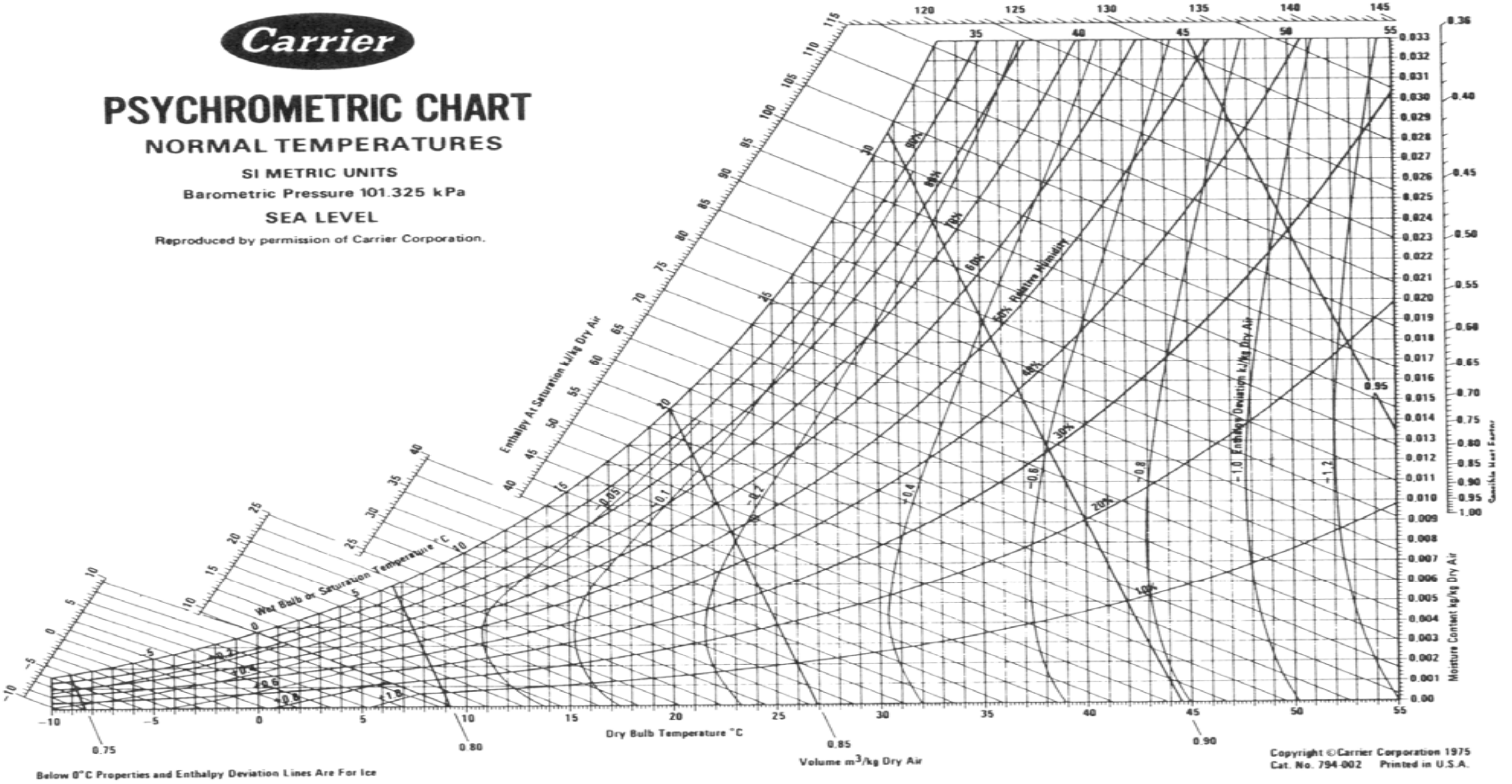
Simplified Psychrometric Charts

- Dry-bulb temperature – temperature of air determined by ordinary thermometer
- Wet-bulb temperature – temperature of air due to evaporative cooling effect
- Dew-point temperature – condensation temperature due to constant pressure cooling
- Relative humidity – ratio of how much moisture is in air compared to how much air can hold at same temperature (pressure)
- Specific humidity – ratio of how much moisture to how much dry air

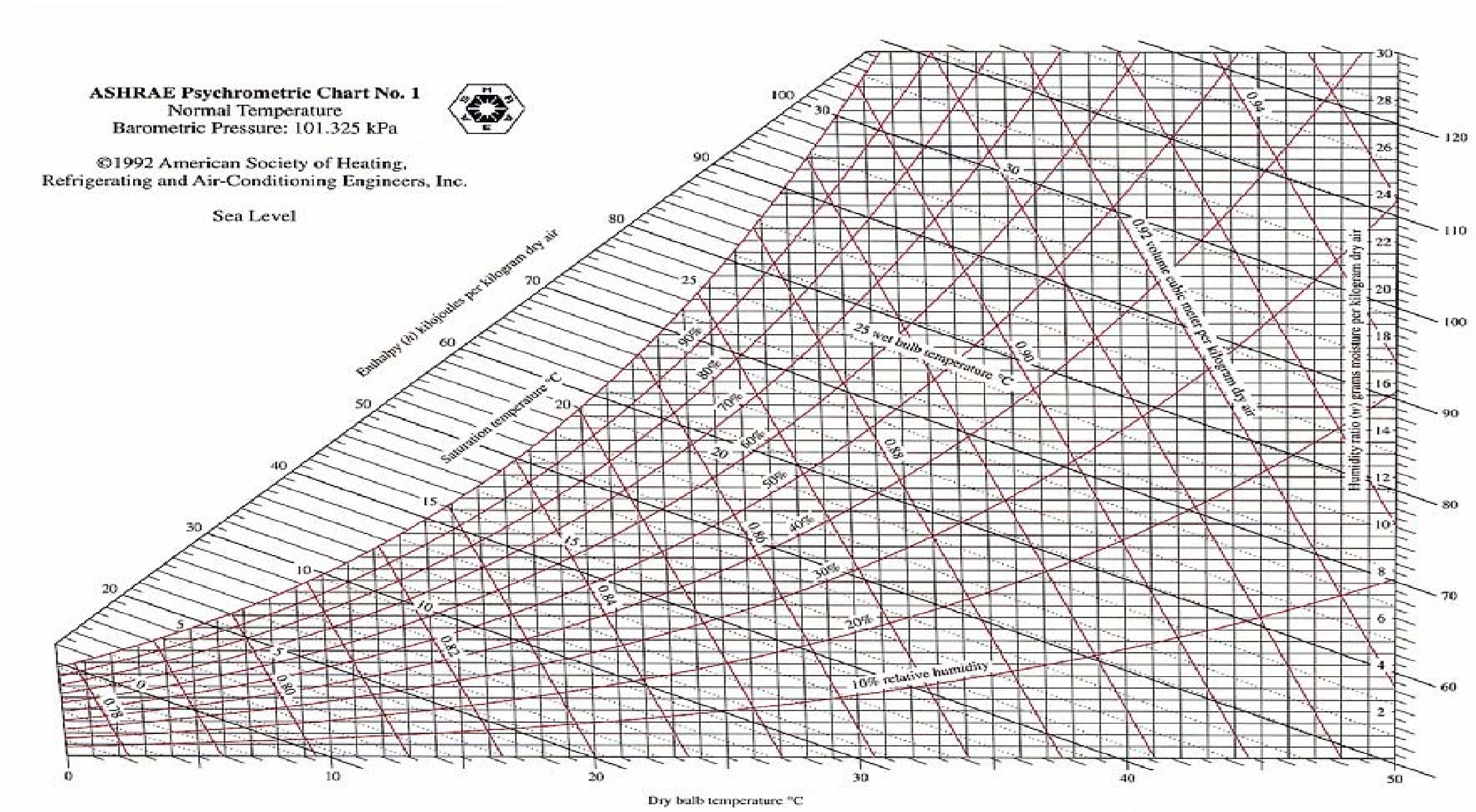




Detailed Psychrometric Chart

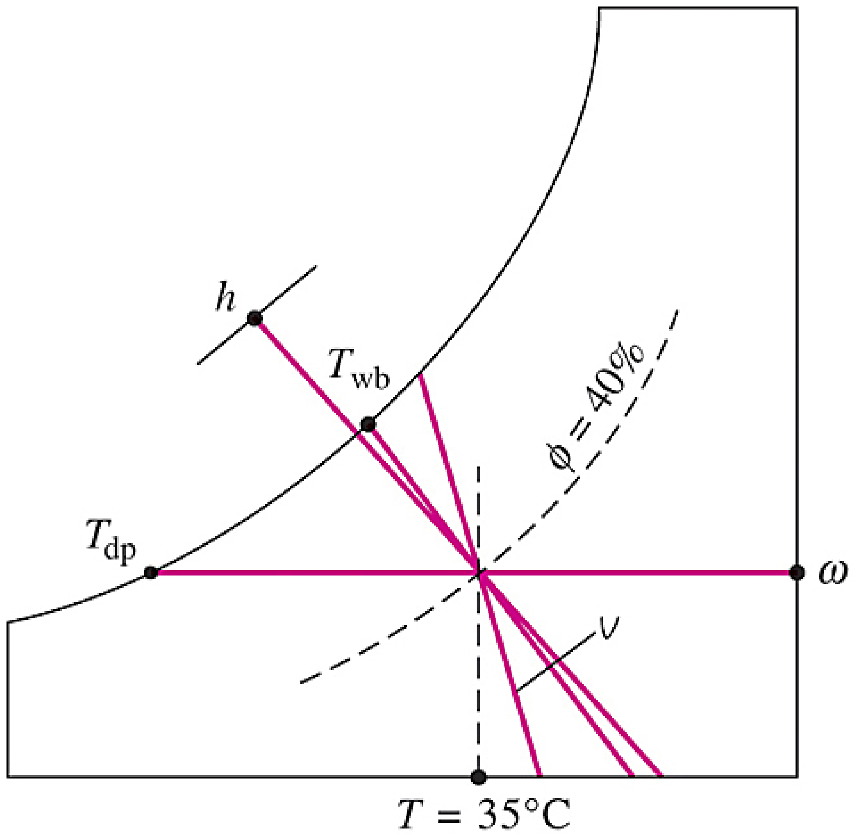


Detailed Psychrometric Chart



Example 14-4

- Consider a room that contains air at 1 atm, 35 C, and 40% relative humidity. Using the psychrometric chart, determine (a) specific humidity, (b) enthalpy, (c) wet-bulb temperature, (d) dew-point temperature, and (e) specificl volume of air.



Example 14-4

Summary

- Adiabatic saturation process produces saturated air and introduces wet-bulb temperature – theoretically useful to determine unknown humidity of wet air stream; practically limited
- Psychrometric chart useful to visualize AC processes and determine/fix states

Today's Outline

- Human comfort and air conditioning
- Air conditioning processes
  - Simple heating/cooling
  - Heating with humidification
  - Cooling with dehumidification
  - Evaporative cooling
  - Adiabatic mixing of airstreams

Human Comfort and Air Conditioning

- Human beings want to feel comfortable ie. Not too hot or too cold; not to sticky (humid) and not too dry.
- As engineers it is our duty to help people feel comfortable – besides it keeps us employed☺
- We cannot change the weather but we can change the climate in a confined space by conditioning the air i.e. air conditioning

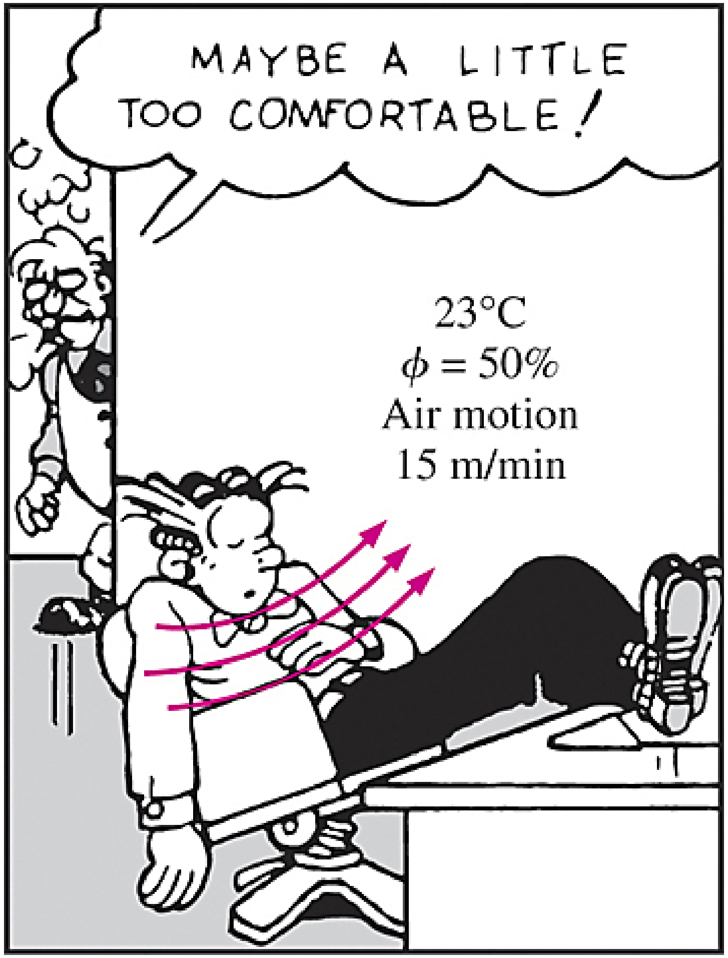
Human Body

- Human body is a heat engine i.e. energy input – energy output
- Comfortable environments are where body can dissipate waste heat effectively

Human Body and Discomfort

- Cold environment – body loses more heat than it normally generates - discomfort
  - Body cuts down circulation (pale)
  - Put barriers in path of heat (clothes, blankets)
  - Raise heat generation in body (exercise)
  - Reduce surface area for heat transfer (cuddle up)
- Hot environment – body can't dissipate enough heat – discomfort
  - Dress lightly
  - Don't exercise
  - Fan to replace hot air near our bodies with cooler air
  - Sweating (evaporative cooling – tbd)

Human Body and Comfort

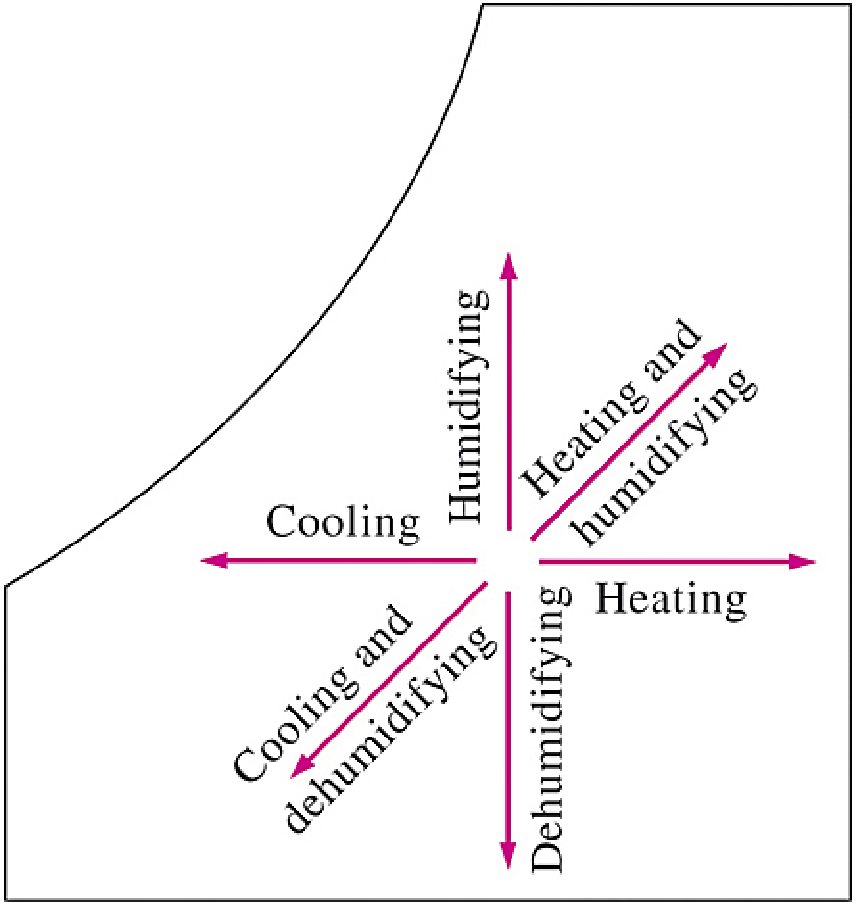


- Comfort depends on
  - Dry-bulb temperature
  - Relative humidity
  - Air motion
- In general, we are comfortable between:
  - ❑ Temps. ~ 22 and 27 C (72 and 80 F)
  - ❑ 40 and 60% relative humidity
  - ❑ Slight air motion to remove heat and moisture but not too strong to notice i.e. wind-chill factor

Air Conditioning

- Processes to “fix” temperature and humidity:
  - Simple heating (raising temperature)
  - Simple cooling (lowering temperature)
  - Humidifying (adding moisture)
  - Dehumidifying (removing moisture)
  - Or a combination
- How do these processes look on a psychrometric chart?

AC and Psychrometric Chart



- Heating or cooling we have **specific humidity is constant**
- Air is typically
  - Heated and humidified in the winter
  - Cooled and dehumidified in the summer

Governing Equations

- Most AC processes are steady, hence:

DRY AIR MASS: $\sum \dot{m}_{a,i} = \sum \dot{m}_{a,e}$

WATER MASS: $\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e}$

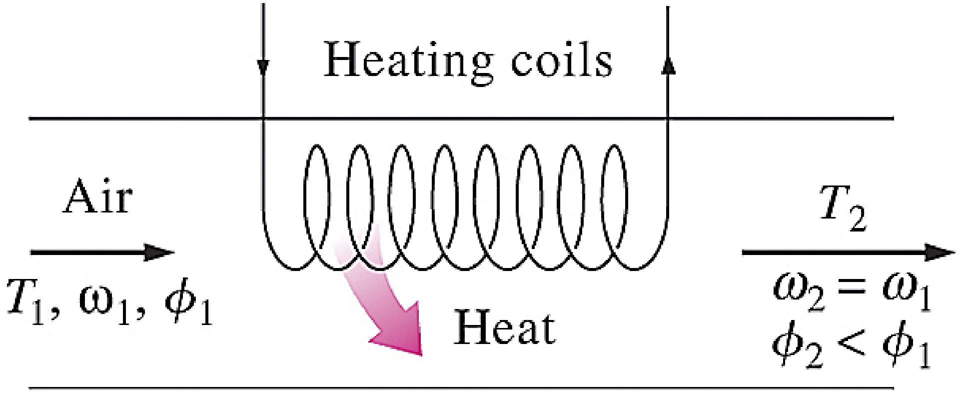
or $\sum \dot{m}_{a,i}\omega_i = \sum \dot{m}_{a,e}\omega_e$

ENERGY: $\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$

- Changes in KE and PE and work of fan is typically negigible

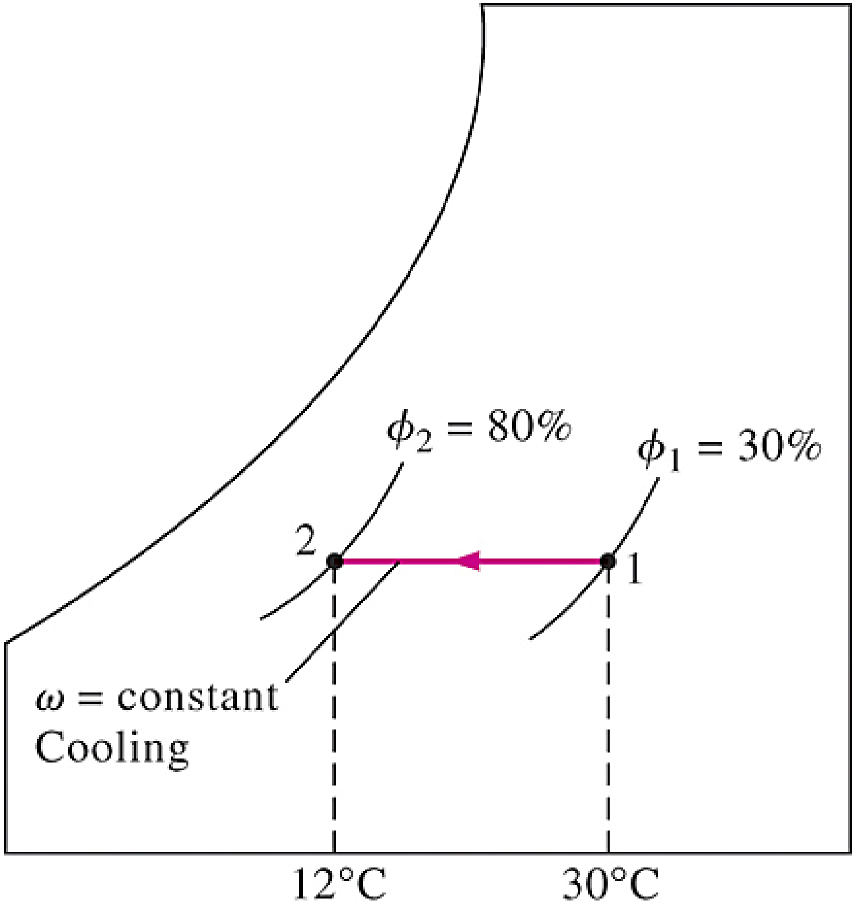
Simple Heating and Cooling

- **Heating:** Stove, heat pump, or electric resistance heater
  - Air is heated by circulating it through a duct with tubing for hot gases, wires, etc.
  - Specific humidity is constant with no moisture added or removed from air



Heating/cooling and Psych chart

- Note: Relative humidity *decreases* during heating because moisture capacity of air increases with temperature
- As a result, relative humidity of heated air might be uncomfortable leading to dry skin, breathing problems, inc. in static electricity.
- Cooling – pass air over coils through which a refrigerant flows
- Note: Dry-bulb temperature decreases and relative humidity *increases*



Heating/cooling and governing equations

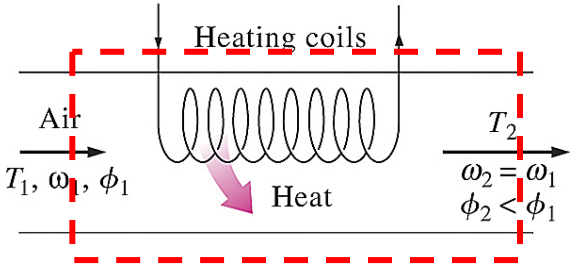
$$\sum \dot{m}_{a,i} = \sum \dot{m}_{a,e} \rightarrow \dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_a$$

$$\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e}$$

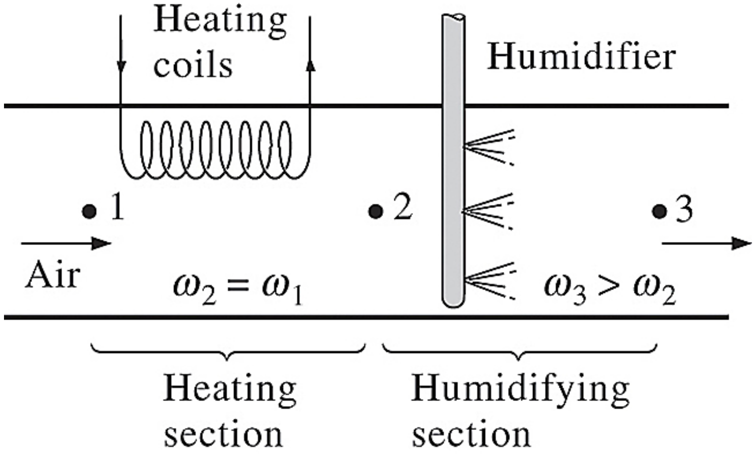
$$\text{or } \sum \dot{m}_{a,i}\omega_i = \sum \dot{m}_{a,e}\omega_e \rightarrow \omega_1 = \omega_2$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \rightarrow \dot{Q} = \dot{m}_a (h_2 - h_1)$$

$$q = h_2 - h_1 \text{ (enthalpies per unit mass d.a.)}$$



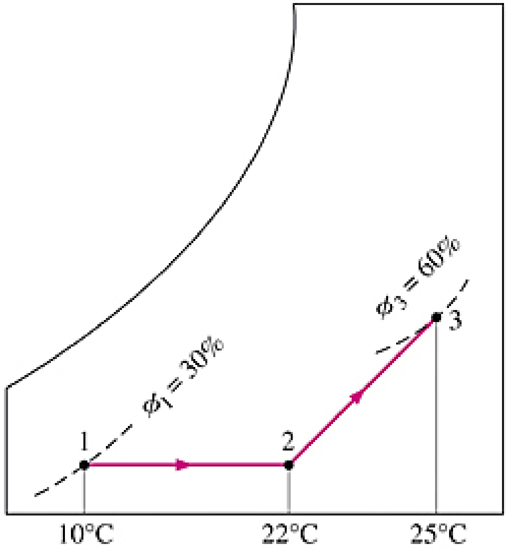
Heating with humidification

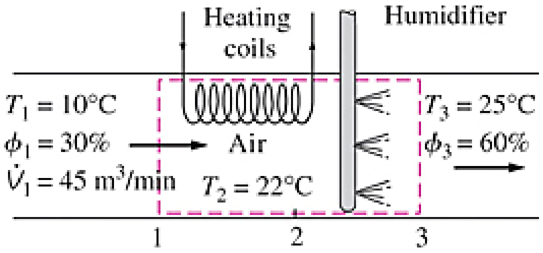


- **Goal:** Eliminate problems with low relative humidity from simple heating by humidifying air
- **Humidifier:** If steam then addition heating $T_3 > T_2$; if spraying water than cooling $T_{3<} T_2$ so air heated to higher temp. in heater section

Example 14-5

- An AC system is to take in outdoor air at 10 C and 30% relative humidity at steady rate of 45 m3/min and to condition it to 25 C and 60% relative humidity. The outdoor air is first heated to 22 C in heating section and then humidified by injection of hot steam in humidifying section. Assuming entire process takes place at 100 kPa, determine (a) rate of heat supply in heating section and (b) mass flow rate of steam required in humidifying section.





Example 14-5

Example 14-5

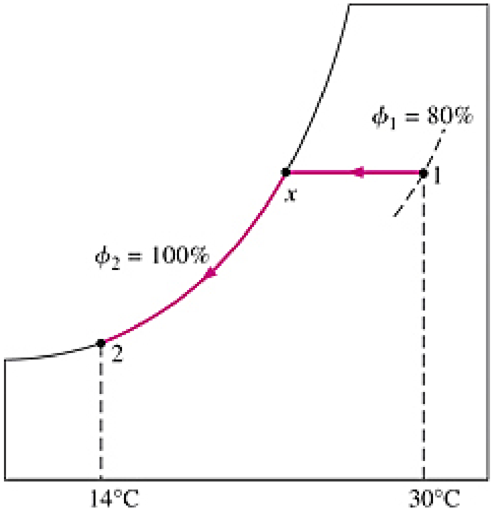
Example 14-5

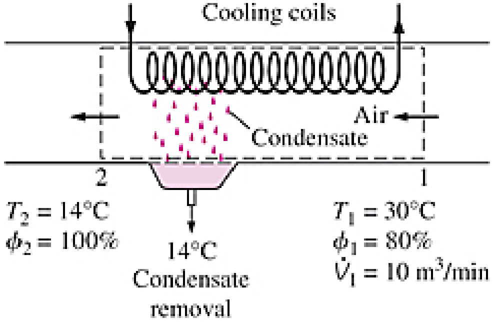
Cooling with dehumidification

- Recall specific humidity is constant for simple cooling but relative humidity increases
- May need to dehumidify air to improve comfort level
- Involves cooling air below its dew-point temperature (to make water condense out)

Example 14-6

- Air enters a window AC at 1 atm, 30 C, and 80% relative humidity at rate of 10 m3/min, and leaves as saturated air at 14 C. Part of the moisture in the air that condenses during the process is also removed at 14 C. Determine rates of heat and moisture removal from the air.





Example 14-6

Example 14-6

Summary

- AC processes involve controlling temperature and humidity of moist air via some combination of heating/cooling, humidification/dehumidification
- Thermodynamic analysis involves steady multiple stream mass/energy balances
- Must account for mixture properties