Combined Heat and Mass Transfer

Lec 5: Humidification

Content

Overview and Definitions, Psychrometric (humidity) terminology, Psychrometric (humidity) charts, Some psychrometric processes

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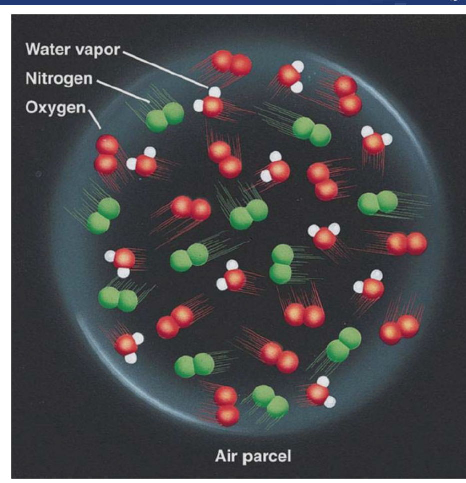
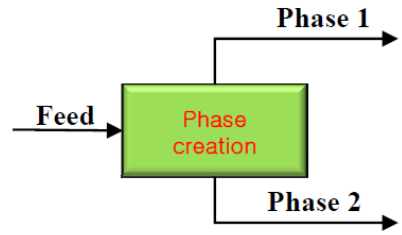
- Overview and Definitions
- Psychrometric (humidity) terminology
- Psychrometric (humidity) charts
- Some psychrometric processes



Principal references: Chapter 9 (Drying) and Chapter 10 (Gas-liquid separation Processes) in C.J. Geankoplis book;
Chapter 19 (Humidification operations) in McCabe et al. book; Chapter 7 (Humidification operations) in Treybal book ;
Chapter 18 Seader & Roper book.

Overview and Definitions

- **Based on phase-creation:**
- Humidification is based on **phase-creation** with Energy-separating agent (ESA)
- It is a **gas-liquid** operations.
- **Gas** is air and **liquid** is pure water.



- **Basic principle:**
  - When a relatively warm liquid water is directly contacted with **unsaturated air**, some of liquid water will vaporize.
  - The liquid temperature will drop mainly because of the latent heat of vaporization.
- **Simply,** water vapor is added to air.
- The reverse of such operation is called **dehumidification** for the removal of water vapor from humid air (warm).

Overview and Definitions

Industrial applications:

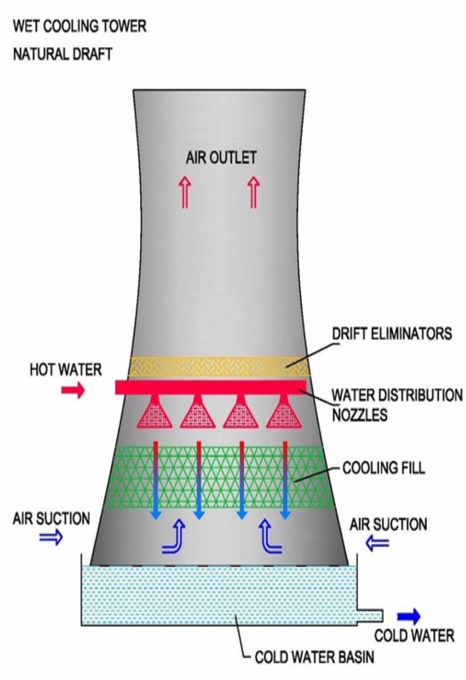
- Humidification/dehumidification are important for **many industrial operations** such as:
  - Humidifying air for control of the moisture content of air in drying or air conditioning.
  - Dehumidifying air where cold water condenses some water vapor from warm air.
  - Water cooling where evaporation of water to the air cools water before reuse (**cooling towers**).

Overview and Definitions

Use to cool the hot water (i. e the used cooling water) comes from heat exchangers or condensers

Cooling of warm water through evaporation by passing cold air in opposite direction (counter-current) -reduce water temperature

- Humidify of the air due to the evaporation of the water-increase air temperature



Within the area of contact between water and air is called an interface

Packing/cooling fill/slats installed inside the cooling tower to increase heat and mass transfer performance

Psychrometric (humidity) terminology

- Remember that water **partial pressure,** ($P_A = y_A P$) is the pressure due to water vapor in the water-air mixture. Where y_A is the mole fraction of water vapor.
- In addition, the water **vapor pressure** (P_{AS}) is the absolute pressure exerted by (molecules of liquid water) on the gas phase in order to escape into the gas; it is a **measure of volatility**.
- The vapor pressure increases with temperature increase.
- The water vapor pressure can be taken from **steam tables** or estimated using, for example, the following **Antoine Eq.**:

$$\ln P_{AS}(\text{bar}) = 11.96481 - \frac{3984.923}{T(\text{K}) - 39.97}$$

Excursion: P_A vs P_{AS}

Vapor Pressure	Partial Pressure
It is exerted by liquid or solid vapor on its condensed phase in equilibrium	It is exerted by individual gases in a non-reactive gas mixture
Well explained by Raoult's Law	Well explained by Dalton's Law
Applicable in solid and liquid phases	Applicable in gaseous phases only
Independent of the surface area or the volume of the system	Calculated using the gases in the same volume
Calculated using the mole fraction of the solute	Calculated using the mole fraction of the gas

Psychrometric (humidity) terminology

- **Psychrometrics** is the study of atmospheric air, which is a mixture of pure air and water vapor at atmospheric pressure
- The pure air portion of an air–water vapor mixture is commonly called dry air; consequently, atmospheric air is said to consist of a mixture of dry air and water vapor.
- The number of possible "degrees of freedom" in a system in equilibrium, as follows:

$$F = C - P + 2$$

where:

F = number of degrees of freedom (number of possible variables)
C = number of components
P = number of phases

Psychrometric (humidity) terminology

- For homogeneous moist air C = 2 and P = 1.
- It follows that the number of independent variables is three, for example, temperature, pressure, and moisture content.
- Psychromerty is most commonly applied to air at atmospheric pressure. In this case, the pressure is not a variable.
- It follows that the state of homogeneous moist air at atmospheric pressure can be defined by two variables: **temperature and moisture content (humidity)**

Psychrometric (humidity) terminology

- **Molal humidity (H_m):** moles of water vapor per unit mole of dry air. This is a direct measure of moisture content:

$$H_m = \frac{p_A}{P - p_A} = \frac{\text{moles of vapor}}{\text{moles of vapor-free (dry) gas}}$$

- **Absolute humidity or simply humidity (H):** mass of water vapor per unit mass of dry air. This is another direct measure of moisture content:

UNITS

$$= \frac{m_A}{m_{da}} = \frac{MW_A p_A}{MW_{da} p_{da}} = \frac{18.02}{28.97}\frac{p_A}{p_{da}} = \frac{18.02}{28.97}\frac{p_A}{P - p_A} \quad \left[\frac{kg_w}{kg_{da}}\right]$$

$$\frac{x_A}{x_{da}} = \frac{p_A}{p_{da}}$$

Psychrometric (humidity) terminology

$$H = \frac{\text{mass of vapor}}{\text{mass of dry gas}} = 0.622\frac{p_A}{P - p_A}$$

- **Saturation humidity (H_s):** absolute humidity at saturation (P_A=P_{AS}):

$$H_S = 0.622\frac{p_{AS}}{P - p_{AS}}$$

- **Percentage humidity or saturation (H_p):** ratio of humidity to the saturation humidity multiplied by 100:

$$H_P = 100\frac{H}{H_S}$$

Psychrometric (humidity) terminology

- **Percentage relative humidity (H_R):** ratio of water vapor partial pressure to its saturation pressure multiplied by 100. It is another measure of the degree of saturation:

$$H_R = 100\frac{p_A}{p_{AS}}$$

- Note that $H_R \neq H_P$ except at saturation

$$H_P = 100\frac{H}{H_S}$$

$$= (100)\frac{18.02}{28.97}\frac{p_A}{P - p_A}\Bigg/\frac{18.02}{28.97}\frac{p_{AS}}{P - p_{AS}} = \frac{p_A}{p_{AS}}\frac{P - p_{AS}}{P - p_A}(100)$$

- **At saturation:** $H_R = H_P$ =100%

EXAMPLE 9.3-1. Humidity from Vapor-Pressure Data

The air in a room is at 26.7°C (80°F) and a pressure of 101.325 kPa and contains water vapor with a partial pressure $p_A = 2.76$ kPa. Calculate the following.

(a) Humidity, H.
(b) Saturation humidity, H_S, and percentage humidity, H_P.
(c) Percentage relative humidity, H_R.

Solution: $p_{AS} = 3.50$ kPa **(from steam tables)**

$$H = \frac{18.02}{28.97}\frac{p_A}{P - p_A} = \frac{18.02(2.76)}{28.97(101.3 - 2.76)} = 0.01742 \text{ kg } H_2O/\text{kg air}$$

$$H_S = \frac{18.02}{28.97}\frac{p_{AS}}{P - p_{AS}} = \frac{18.02(3.50)}{28.97(101.3 - 3.50)} = 0.02226 \text{ kg } H_2O/\text{kg air}$$

$$H_P = 100\frac{H}{H_S} = \frac{100(0.01742)}{0.02226} = 78.3\%$$

$$H_R = 100\frac{p_A}{p_{AS}} = \frac{100(2.76)}{3.50} = 78.9\%$$

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- **Dew point of air-water vapor mixture:**
  - ✓ A temperature at which a vapor-gas mixture must be cooled (**at constant humidity**) to become saturated.
  - ✓ The dew point of a saturated gas equals the gas temperature.
  - ✓ If a vapor-gas mixture is gradually cooled at a constant pressure, the temperature at which it just becomes saturated is also called its dew point
    - In the previous example if the partial pressure is 3.5 kPa. Then, the dew point will be 26.7 °C.
    - In other words, dew point is the temperature to which you must cool the air/vapor mixture to just obtain **H_R=100%** i.e. condensation just starts to occur.

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Psychrometric (humidity) terminology

- **Dry bulb temperature:**
  - ✓ Commonly measured temperature of water-air mixture by a thermometer.
  - ✓ It is true temperature of air measured (or, any non-condensable and condensable mixture) by a thermometer whose bulb is dry.
  - ✓ It indicates the amount of heat in the air and it is directly proportional to the mean kinetic energy of the air molecules.

Psychrometric (humidity) terminology

- **Humid heat of air-water vapor mixture (c_S):** amount of heat required to raise the temperature of 1 kg of mixture by 1 °C:

$$c_S = C_{pB} + H \times C_{pA}$$

Prove this

  - The heat capacity of water is assumed to be constant at , C_{pA} = 1.88 kJ/(kg.K) water vapor.
  - The heat capacity of dry air is assumed to be constant at, C_{pB} = 1.005 kJ/(kg dry air.K). Therefore,

$$c_S \text{ kJ/kg dry air} \cdot \text{K} = 1.005 + 1.88H$$

$$c_S \text{ btu/lb}_m \text{ dry air} \cdot {}^\circ\text{F} = 0.24 + 0.45H$$

Psychrometric (humidity) terminology

- **Humid volume of air-water vapor mixture (v_H):** total volume of 1 kg of the gas mixture at standard pressure and operating temperature (*T*). Using ideal gas law:

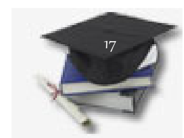
$$v_H \text{ m}^3/\text{kg dry air} = \frac{22.41}{273} T \text{ K} \left(\frac{1}{28.97} + \frac{1}{18.02} H\right)$$

$$= (2.83 \times 10^{-3} + 4.56 \times 10^{-3} H) T \text{ K}$$

$$v_H \text{ ft}^3/\text{lb}_m \text{ dry air} = \frac{359}{492} T ^\circ\text{R} \left(\frac{1}{28.97} + \frac{1}{18.02} H\right)$$

$$= (0.0252 + 0.0405 H) T ^\circ\text{R}$$

Prove this



Psychrometric (humidity) terminology

- **Total enthalpy of air-water vapor mixture (H_y):** total enthalpy per 1 kg of the gas mixture:

$$H_y \text{ kJ/kg dry air} = c_S (T - T_0) + H\lambda_0$$

$$= (1.005 + 1.88 H)(T - T_0 ^\circ\text{C}) + H\lambda_0$$

$$H_y \text{ btu/lb}_m \text{ dry air} = (0.24 + 0.45 H)(T - T_0 ^\circ\text{F}) + H\lambda_0$$

Prove this

where λ_0 is the latent heat of vaporization of water at the base temperature, usually

T_0 =0 ^{o}C : λ_0=2502.3 kJ/kg water

T_0 =32 ^{o}F : λ_0=1075.8 Btu/lbm water

Some approximations $h \approx 1.006T + H(2501 + 1.86T)$

*where *T* is in °C and *h* is in kJ/kg

Psychrometric (humidity) terminology

Wet bulb temperature T_{wb} or T_w

- The wet bulb temperature of air is also measured by the ordinary thermometer, but the only difference is that the bulb of the thermometer is covered by the wet cloth.
- When air/water vapor mixture is not saturated and comes in contact with the wet cloth, some water in the wick evaporates and diffuses into the air and results in cooling the water in the wick.
- As the temperature of the water drops, heat is transferred to the water from both the air and the thermometer;
- The steady state temperature measured by the thermometer is called **as the wet bulb temperature.**

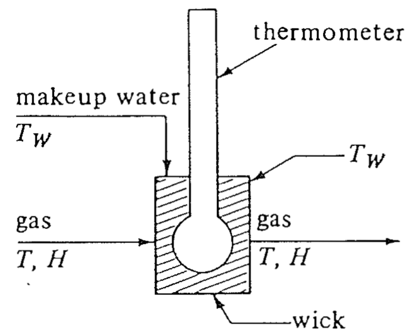
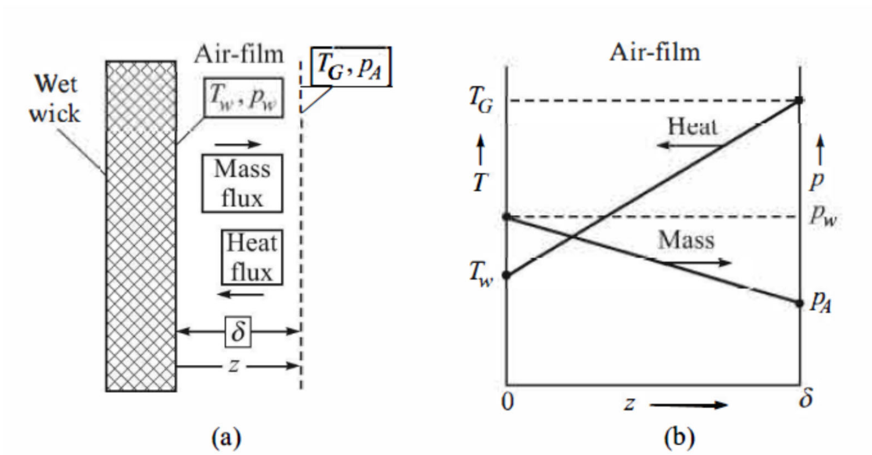


FIGURE 9.3-4. *Measurement of wet bulb temperature.*

Psychrometric (humidity) terminology

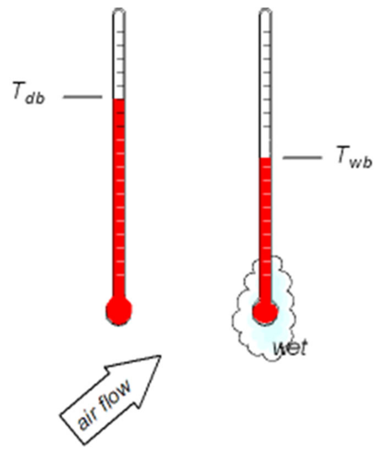


(a) Schematic of the wick and the air-film; (b) the profile of temperature and partial pressure of water vapour in the air-film.

Psychrometric (humidity) terminology

Wet bulb temperature T_{wb} or T_w:

- steady-state non-equilibrium temperature reached when a small amount of water is contacted with a continuous stream of air under adiabatic conditions in a manner such that the sensible heat transferred from the air to the liquid is equal to the latent heat required for evaporation.
- If the moisture content of the air is very low, it will give up more heat to the cloth and the wet bulb temperature of air will also be comparatively lower.
- On the other hand, if the moisture content of air is high it will loose lesser heat and wet bulb temperature will be higher.
- The more is the moisture or water vapor content of the air the more is the wet bulb temperature.



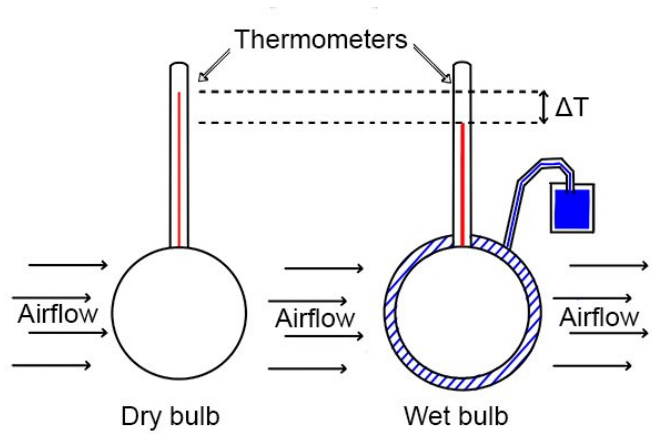
Psychrometric (humidity) terminology

- Thus the wet bulb temperature indirectly indicates the moisture content present in the air or we can say that it is affected by the relative humidity of the air.
- The wet bulb temperature of the air is always less than the dry bulb temperature of air (or at the limit) equal to the dry bulb temperature.
- The difference between the DBT and WBT is called as wet bulb depression.

- Note that the wet bulb temperature is an empirical value (not a property) depending on the kinetics of the measurement, while the adiabatic saturation temperature is a thermodynamic property.

- The wet bulb temperature is affected by: air velocity and the shape, of the thermometer bulb shape, dry bulb temperature of air, humidity of the air.

Psychrometric (humidity) terminology

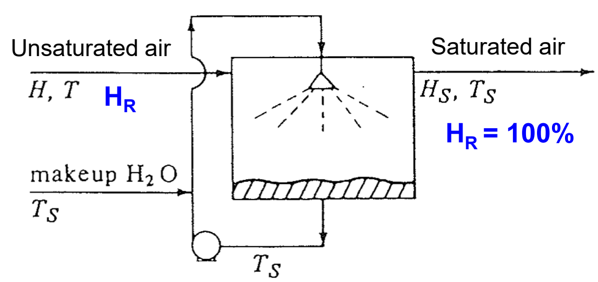


- For saturated air, the dry-bulb, wet-bulb, and dew-point temperatures are identical.
- Thus the dew-point temperature of atmospheric air can be determined by drawing a horizontal line to the saturated curve. (Will be explained in the next section)

Psychrometric (humidity) terminology

Adiabatic saturation temperature T_s:

- If a mass of air is brought to contact with water under adiabatic conditions (no heat transfer with the exterior), the humidity of the air increases until saturation is reached.
- Since there is no external source of heat, water is evaporated using heat from the air itself.
- Consequently, the air is cooled at the same time that it is humidified.
- The process described is called "adiabatic saturation" and the temperature reached at saturation is called the "temperature of adiabatic saturation



Adiabatic Chamber (wall is well-insulated)

Psychrometric (humidity) terminology

Adiabatic saturation temperature T_s:

- Steady-state temperature attained when a continuous stream of air-water vapor mixture is contacted with large amount of water under adiabatic conditions, attains thermal equilibrium and gets saturated with water vapor at that temperature.
- The temperature of adiabatic saturation is a sole function of the initial conditions (temperature and humidity) of the air.
- It follows that the temperature of adiabatic saturation is a thermodynamic property of moist air.
- The process of **adiabatic** saturation follows a straight line on the psychrometric chart **on the constant enthalpy line.**

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Table 18.4 Definitions of quantities useful in psychrometry: A = moisture, B = moisture-free gas, ideal-gas conditions

Quantity	Definition	Relationship	
Absolute, mass humidity	Moisture content of a gas by mass	$\mathcal{H} = \dfrac{M_A p_A}{M_B(P - p_A)}$	(18-5)
Molal humidity	Moisture content of a gas by mols	$\mathcal{H}_m = \dfrac{p_A}{P - p_A}$	(18-6)
Saturation humidity	Humidity at saturation	$\mathcal{H}_s = \dfrac{M_A P_A^s}{M_B(P - P_A^s)}$	(18-7)
Relative humidity (relative saturation as a percent)	Ratio of partial pressure of moisture to partial pressure of moisture at saturation	$\mathcal{H}_R = 100\% \times \dfrac{p_A}{P_A^s}$	(18-8)
Percentage humidity (percent saturation)	Ratio of humidity to humidity at saturation	$\mathcal{H}_P = 100\% \times \dfrac{\mathcal{H}}{\mathcal{H}_s}$	(18-9)
Humid volume	Volume of moisture–gas mixture per unit mass of moisture-free gas	$v_H = \dfrac{RT}{P}\left(\dfrac{1}{M_B} + \dfrac{\mathcal{H}}{M_A}\right)$	(18-10)
Humid heat	Specific heat of moisture–gas mixture per unit mass of moisture-free gas	$C_s = (C_P)_B + (C_P)_A\mathcal{H}$	(18-11)
Total enthalpy	Enthalpy of moisture–gas mixture per unit mass of moisture-free gas referred to temperature, T_o	$H = C_s(T - T_o) + \Delta H_o^{vap}\mathcal{H}$	(18-12)
Dew-point temperature	Temperature at which moisture begins to condense when mixture is cooled	T_{dew}	
Dry-bulb temperature	Temperature of mixture	T_d	
Wet-bulb temperature	Steady-state temperature attained by a wet-bulb thermometer	T_w	
Adiabatic-saturation temperature	Temperature attained when a gas is saturated with moisture in an adiabatic process	T_s	

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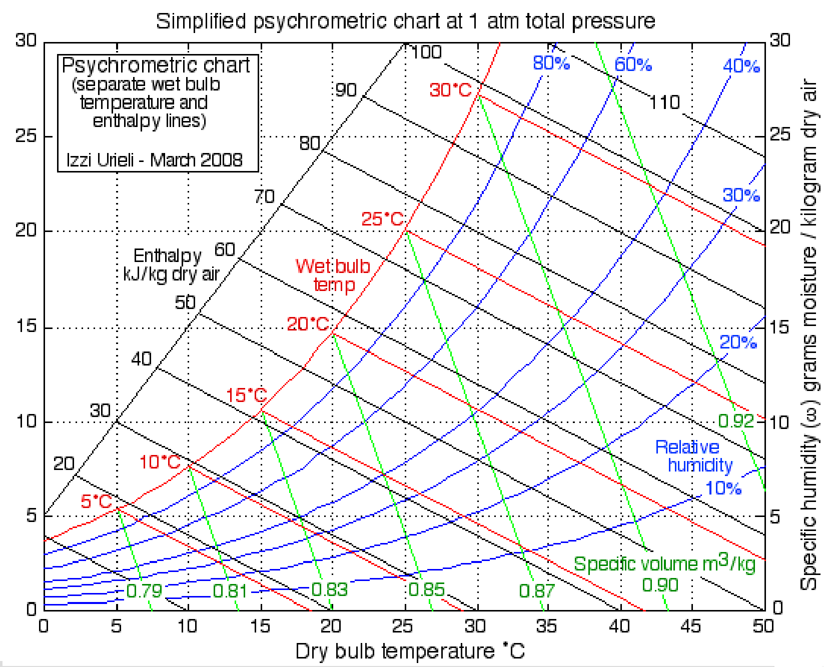
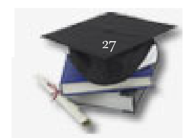
Psychrometric (humidity) charts

- **Visit:** http://www4.uwsp.edu/papersci/biasca/currentpages/





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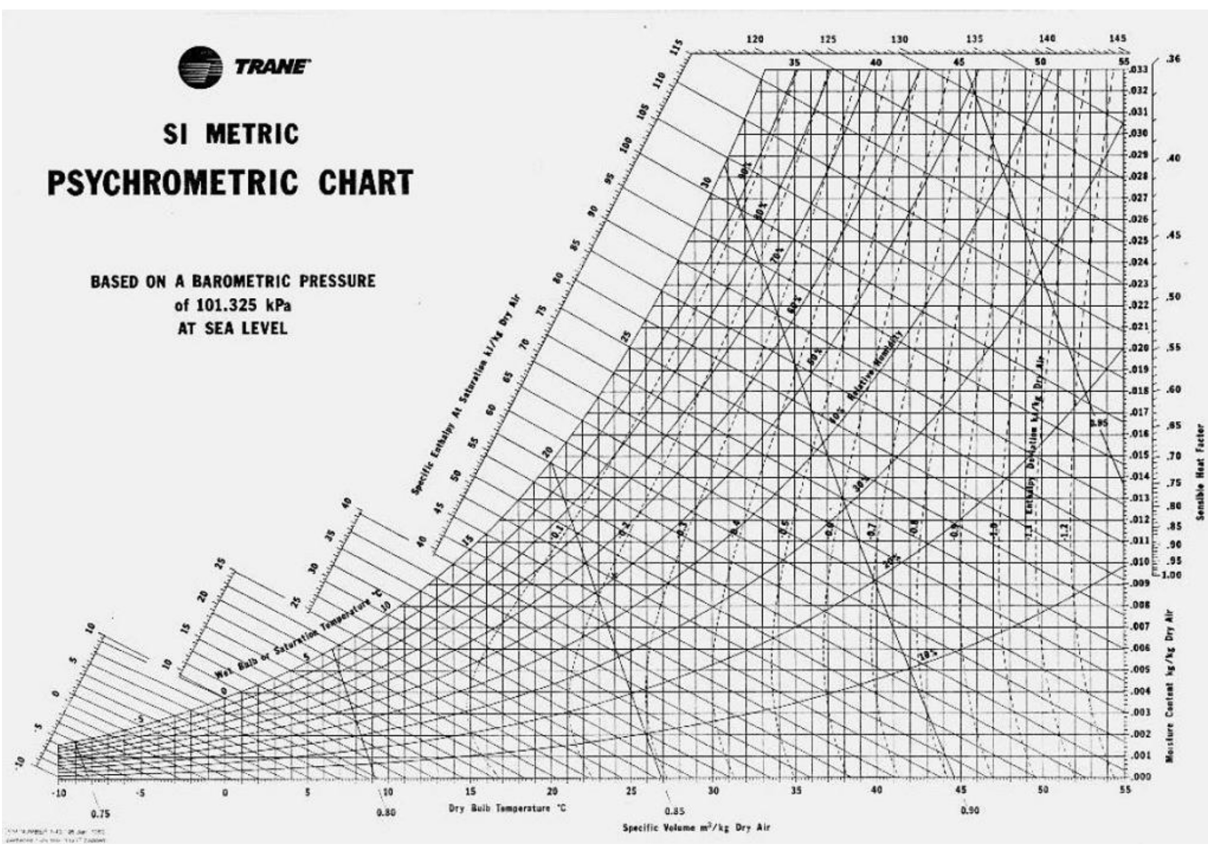
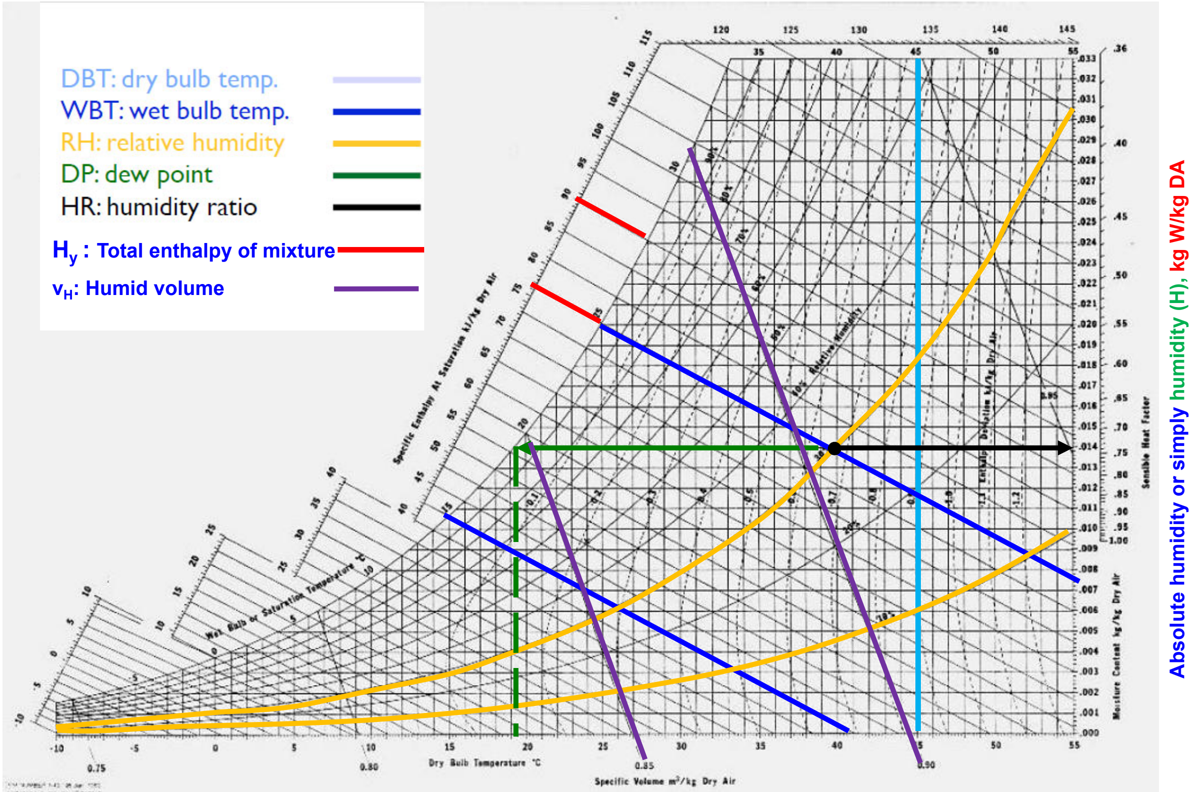
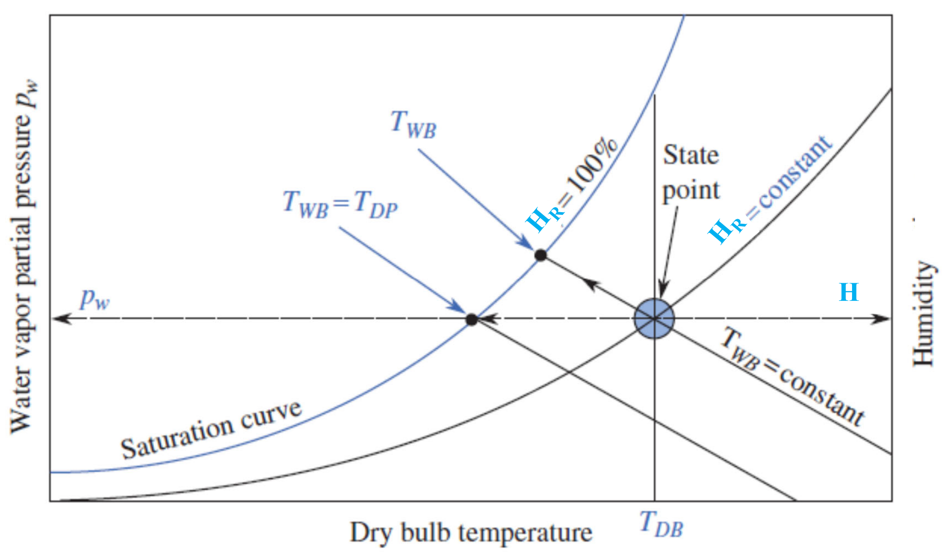
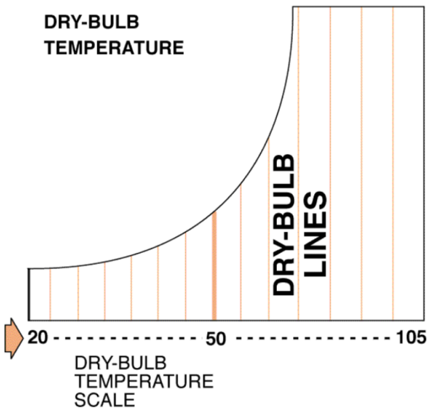


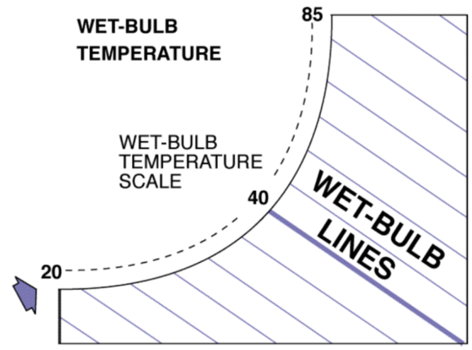


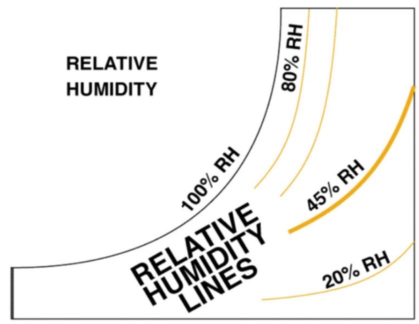
Psychrometric (humidity) charts



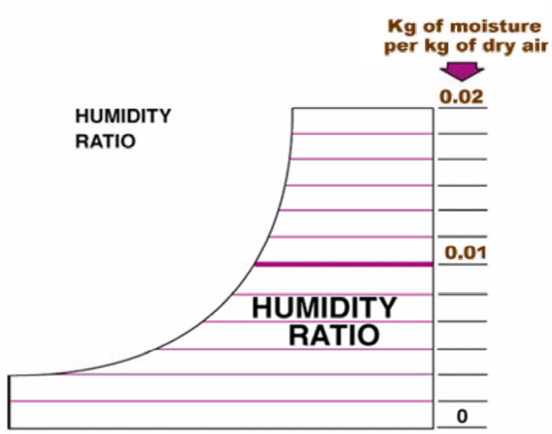
Psychrometric (humidity) chart

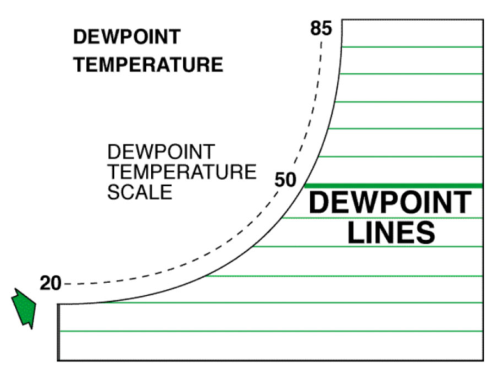




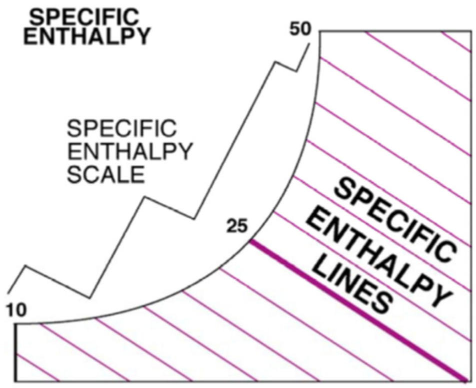


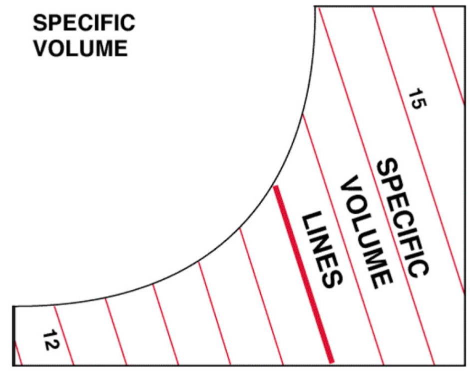
Psychrometric (humidity) chart





Psychrometric (humidity) chart





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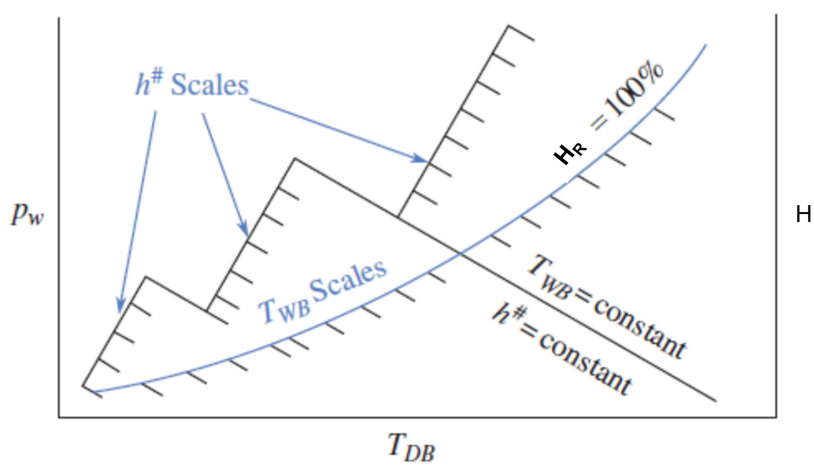
Psychrometric (humidity) chart



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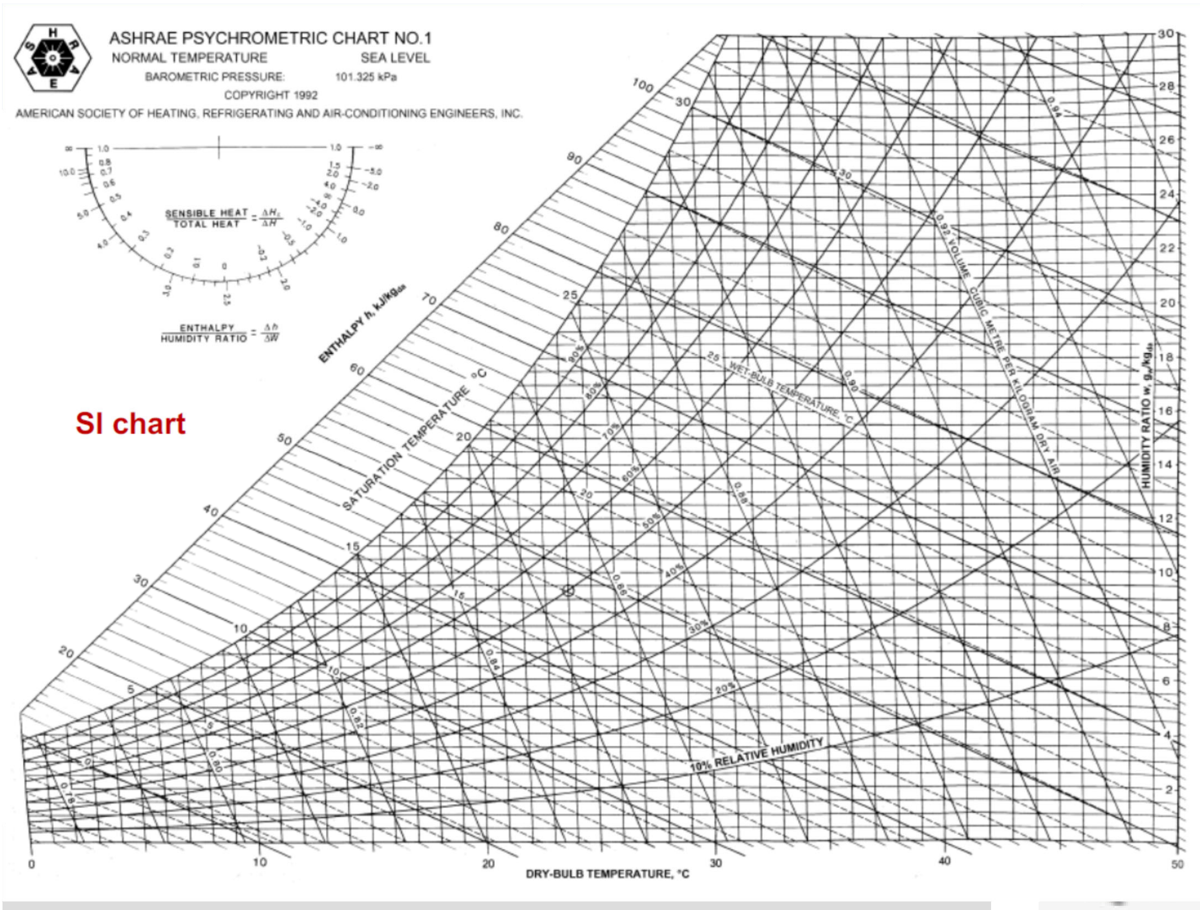
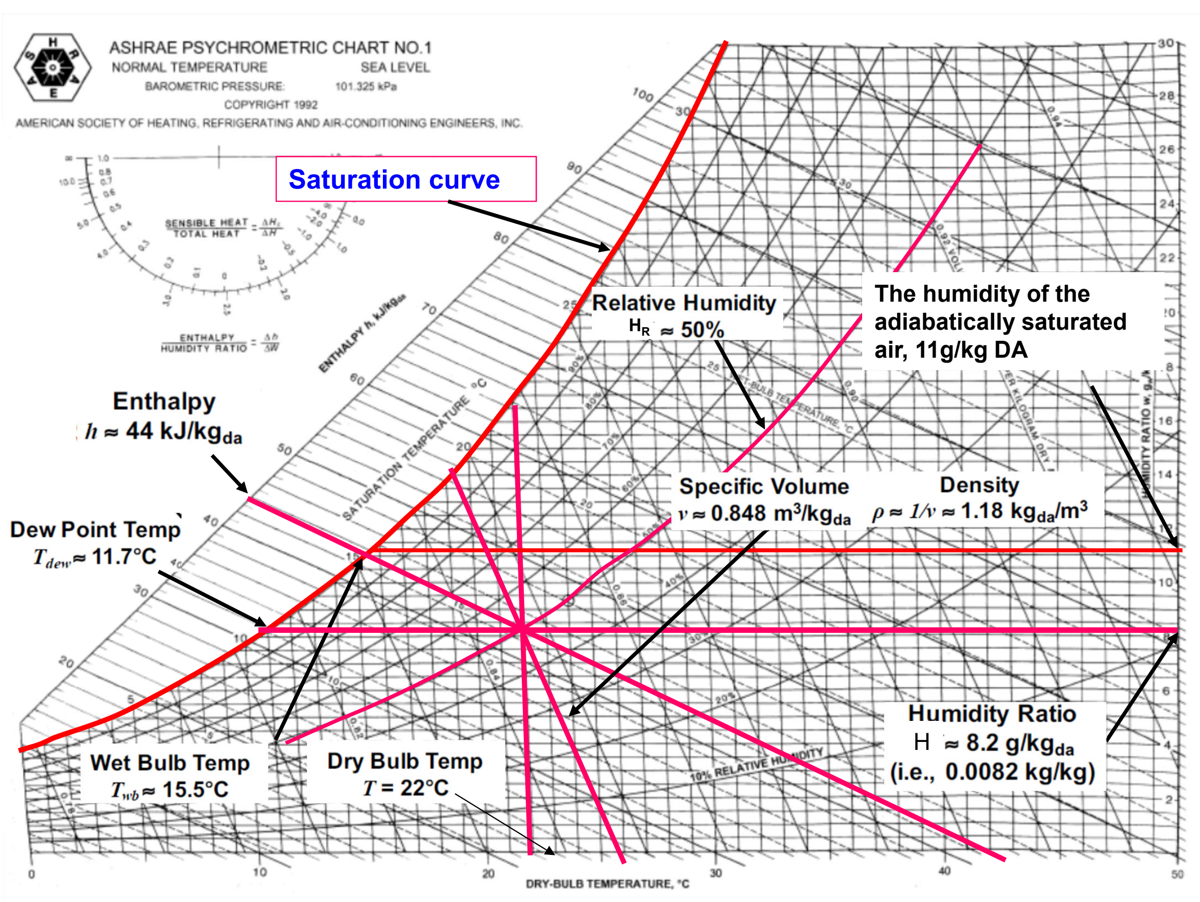

ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
COPYRIGHT 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
SI chart
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g/kg da
DRY-BULB TEMPERATURE, °C


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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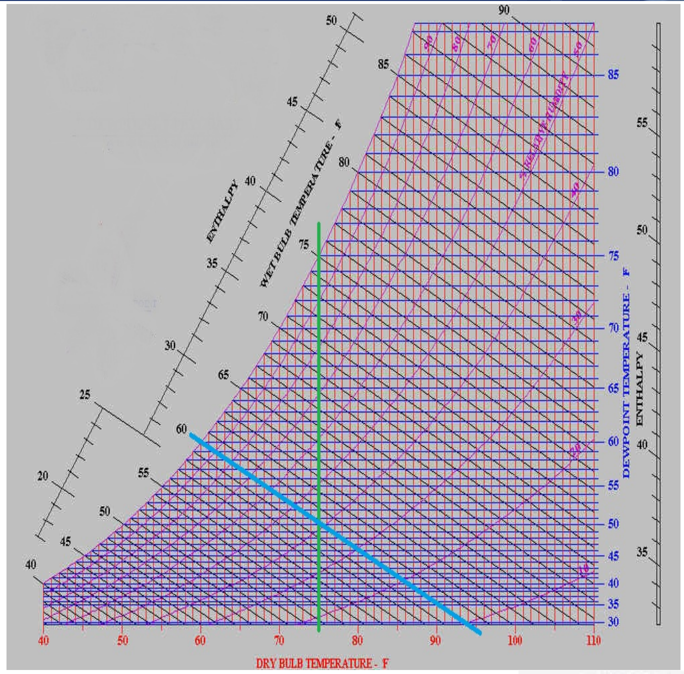
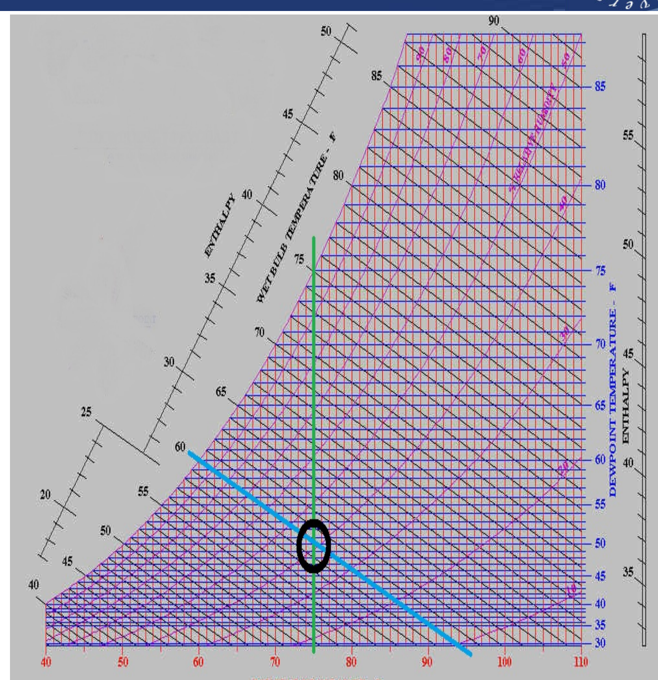
Saturation curve
Relative Humidity
$H_R \approx 50\%$
The humidity of the adiabatically saturated air, 11g/kg DA
Enthalpy
$h \approx 44$ kJ/kg$_{da}$
Dew Point Temp
$T_{dew} \approx 11.7$°C
Specific Volume
$v \approx 0.848$ m^3/kg$_{da}$
Density
$\rho \approx 1/v \approx 1.18$ kg$_{da}$/m^3
Humidity Ratio
H ≈ 8.2 g/kg$_{da}$
(i.e., 0.0082 kg/kg)
Wet Bulb Temp
$T_{wb} \approx 15.5$°C
Dry Bulb Temp
$T = 22$°C
DRY-BULB TEMPERATURE, °C

Psychrometric (humidity) chart

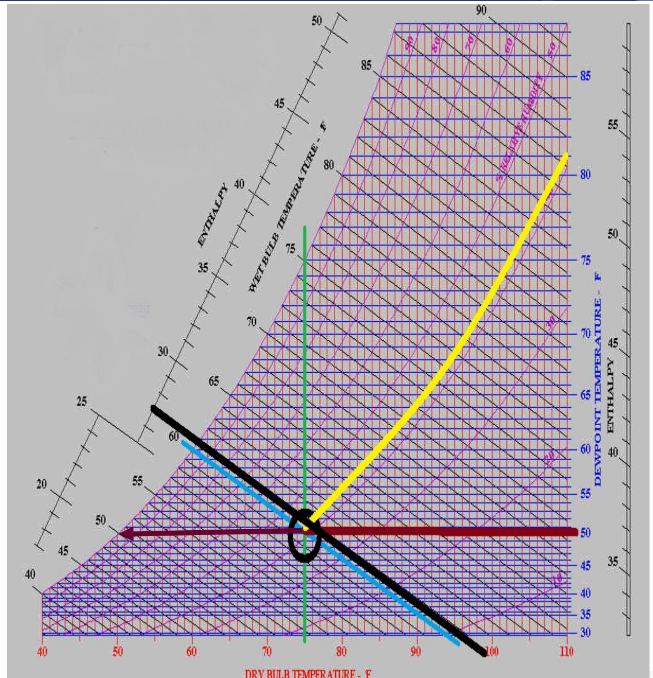
1. Dry bulb temperature 75 DEG F
2. Wet bulb temperature 60 DEG F



Psychrometric (humidity) chart



Psychrometric (humidity) chart



Dewpoint is 50 °F

Relative humidity 42%

Enthalpy 27 btu/lb

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Psychrometric (humidity) chart

Example: Given: T_D = 25°C T_w =20°C, Required: (a) H, (b) T_{dp}, (c) H_R, (d) v, (e) h

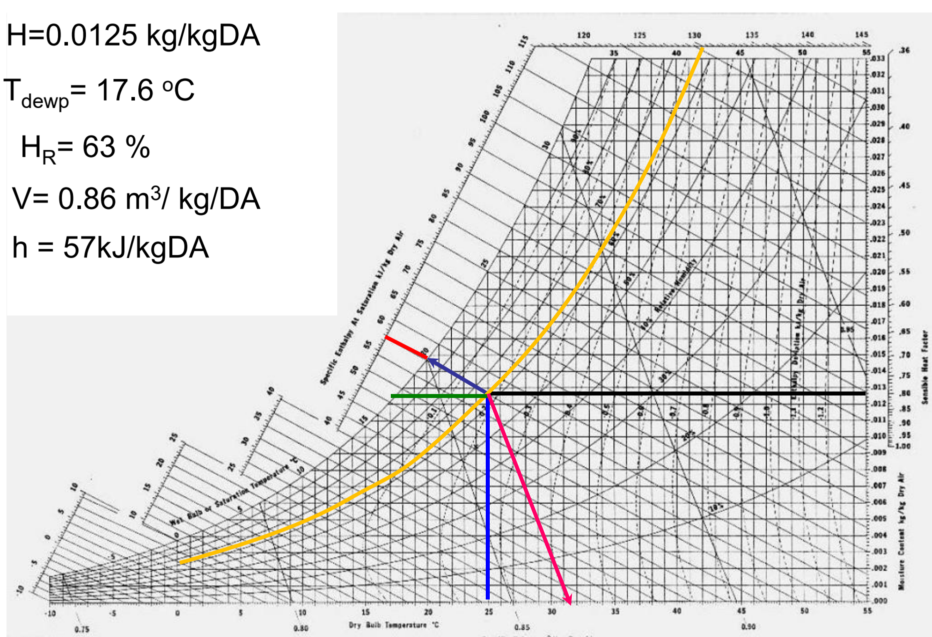
H=0.0125 kg/kgDA

T_{dewp}= 17.6 °C

H_R= 63 %

V= 0.86 m³/ kg/DA

h = 57kJ/kgDA



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Example

EXAMPLE 9.3-2. Use of Humidity Chart

Air entering a dryer has a temperature (dry bulb temperature) of 60°C (140°F) and a dew point of 26.7°C (80°F). Using the humidity chart, determine the actual humidity H, percentage humidity H_P, humid heat c_S, and the humid volume v_H in SI and English units.

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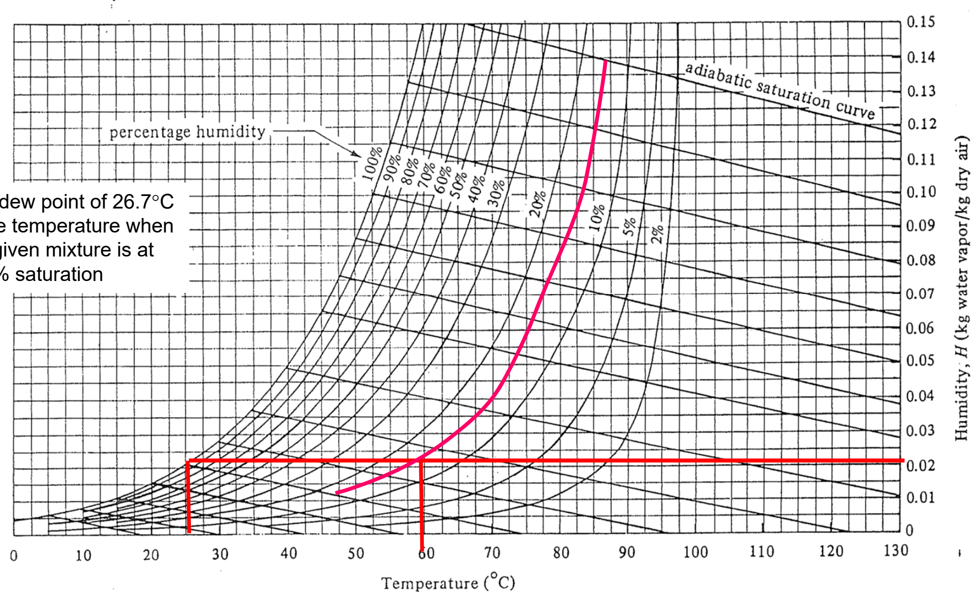
Solution

Solution $H = 0.0225$ kg H_2O/kg dry air $H_P = 14\%$

- The dew point of 26.7°C is the temperature when the given mixture is at 100% saturation



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EXAMPLE 9.3-2.

$$c_S \text{ kJ/kg dry air} \cdot \text{K} = 1.005 + 1.88H$$

$$c_s = 1.005 + 1.88(0.0225)$$
$$= 1.047 \text{ kJ/kg dry air} \cdot \text{K} \quad \text{or} \quad 1.047 \times 10^3 \text{ J/kg} \cdot \text{K}$$

$$c_s = 0.24 + 0.45(0.0225)$$
$$= 0.250 \text{ btu/lb}_m \text{ dry air} \cdot {}^\circ\text{F} \qquad \text{(English)}$$

$$v_H = (2.83 \times 10^{-3} + 4.56 \times 10^{-3} \times 0.0225)(60 + 273)$$
$$= 0.977 \text{ m}^3\text{/kg dry air}$$

In English units,

$$v_H = (0.0252 + 0.0405 \times 0.0225)(460 + 140) = 15.67 \text{ ft}^3\text{/lb}_m \text{ dry air}$$

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EXAMPLE 9.3-3. Adiabatic Saturation of Air

An air stream at 87.8°C having a humidity $H = 0.030$ kg H_2O/kg dry air is contacted in an adiabatic saturator with water. It is cooled and humidified to 90% saturation.

(a) What are the final values of H and T?
(b) For 100% saturation, what would be the values of H and T?

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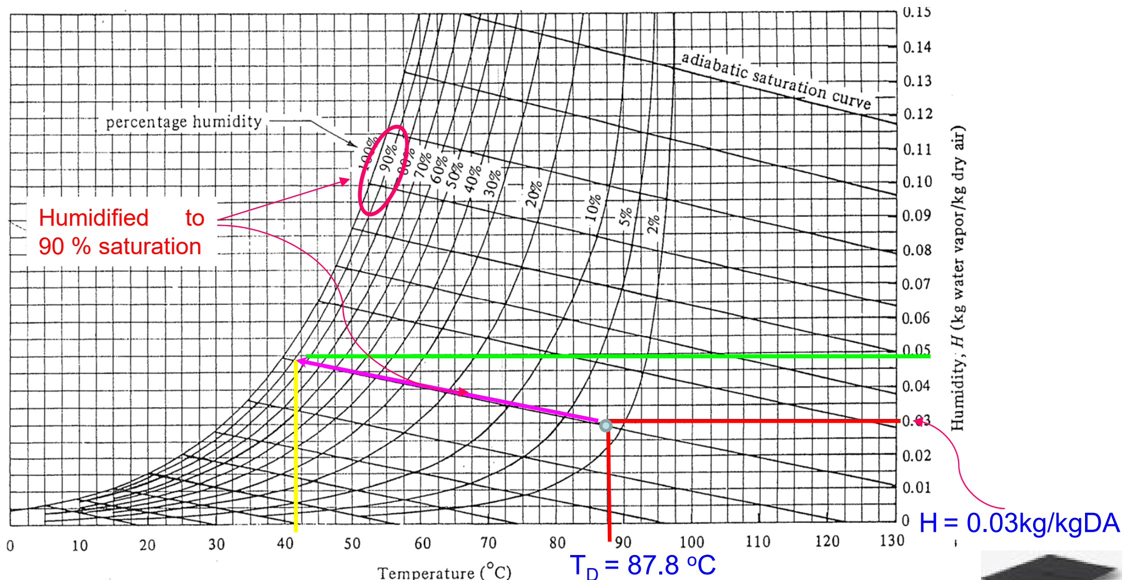
Psychrometric (humidity) chart

Solution: (a) $H = 0.0500 \text{ kg } H_2O/\text{kg dry air} \quad T = 42.5°C$



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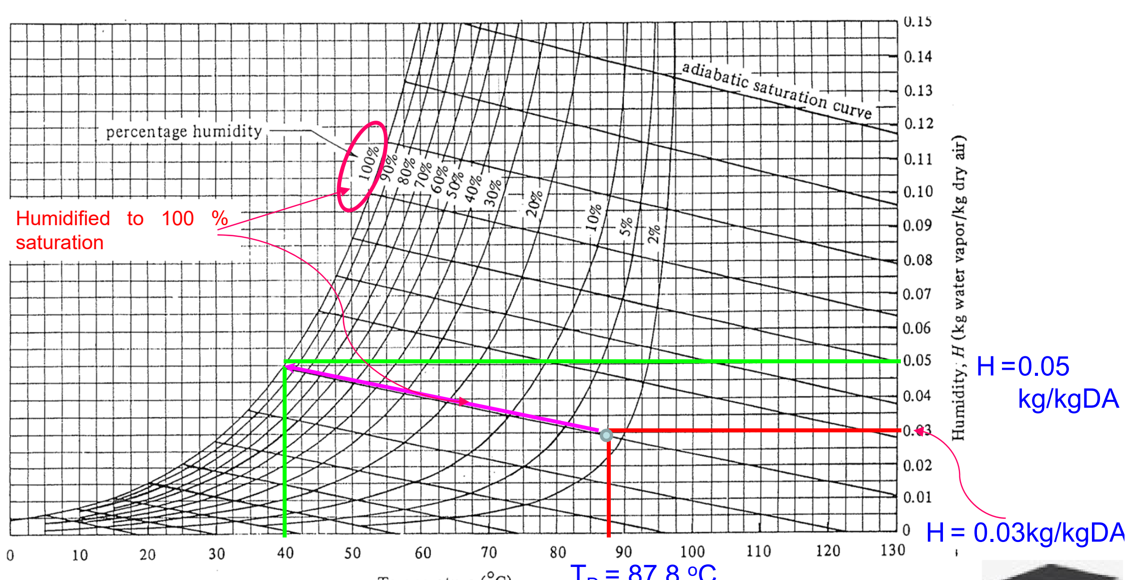
Psychrometric (humidity) chart

Solution: (b) $T = 40.5°C$, $H = 0.0505 \text{ kg } H_2O/\text{kg dry air}$



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Psychrometric (humidity) chart

EXAMPLE 9.3-4. Wet Bulb Temperature and Humidity
A water vapor–air mixture having a dry bulb temperature of $T = 60°C$ is passed over a wet bulb as shown in Fig. 9.3-4, and the wet bulb temperature obtained is $T_W = 29.5°C$. What is the humidity of the mixture?

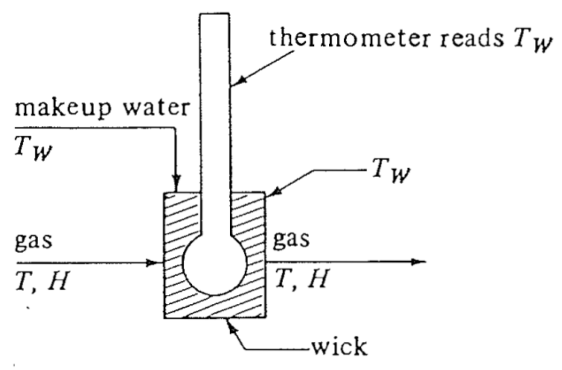

FIGURE 9.3-4. *Measurement of wet bulb temperature.*

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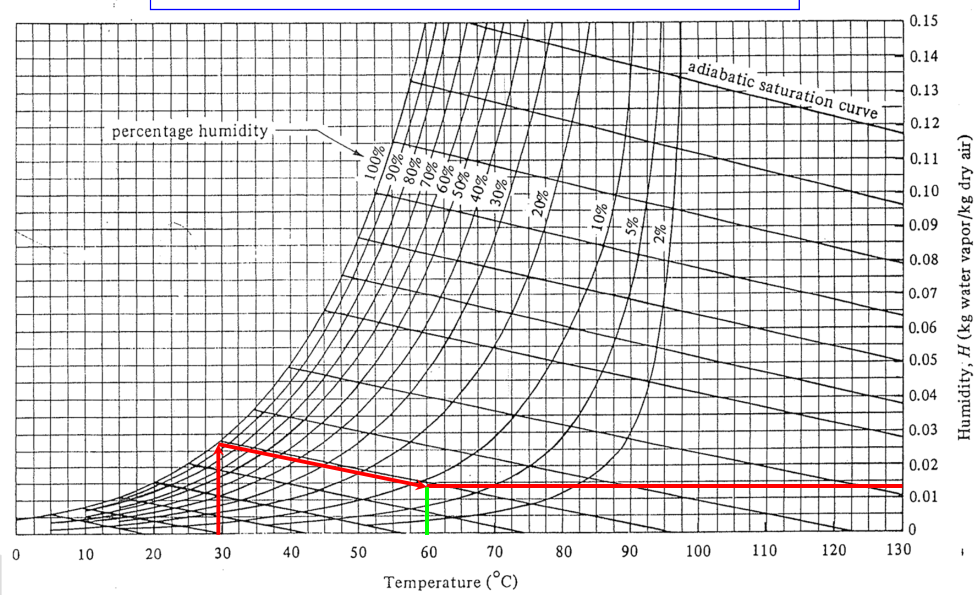
Some psychrometric processes

EXAMPLE 9.3-4.

Solution The wet bulb temperature of 29.5°C can be assumed to be the same as the adiabatic saturation temperature T_S

$T = 60°C$, $H = 0.0135\ kg\ H_2O/kg$ dry air.



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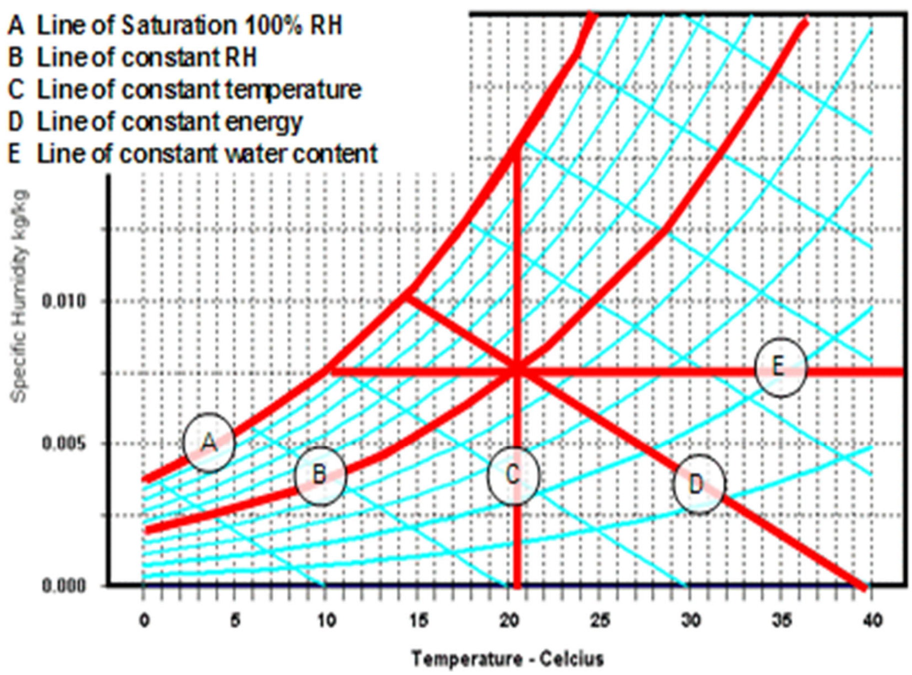
Some psychrometric processes



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Some psychrometric processes

(A) Humidification only

(B) Heating and humidification

(C) Sensible heating only

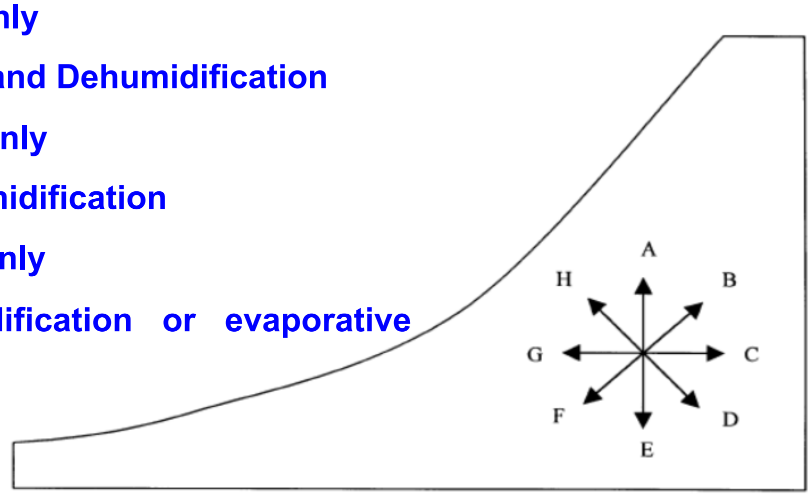
(D) Adiabatic heating and Dehumidification

(E) Dehumidification only

(F) Cooling and dehumidification

(G) Sensible cooling only

(H) Adiabatic humidification or evaporative cooling



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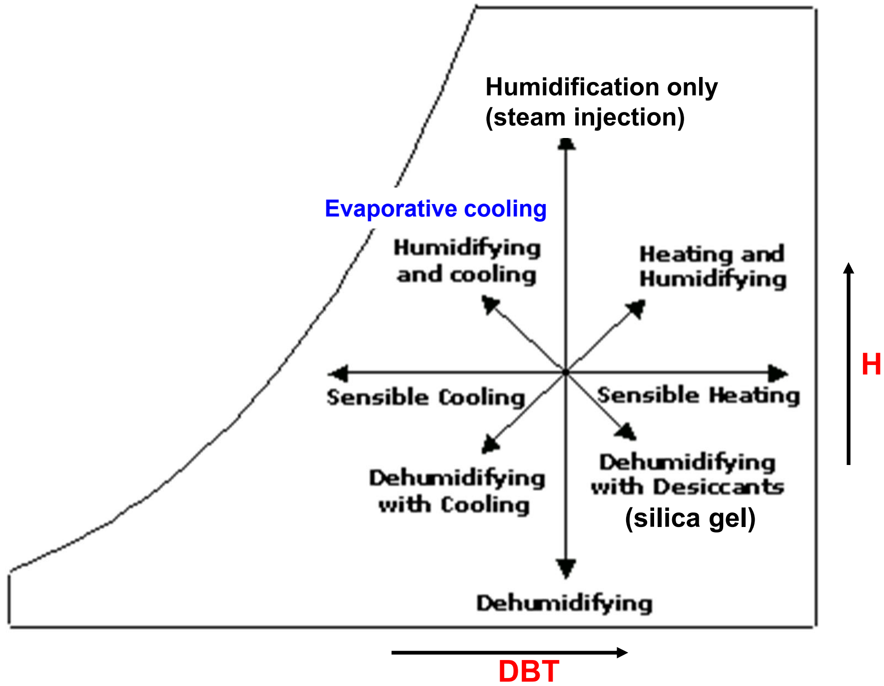
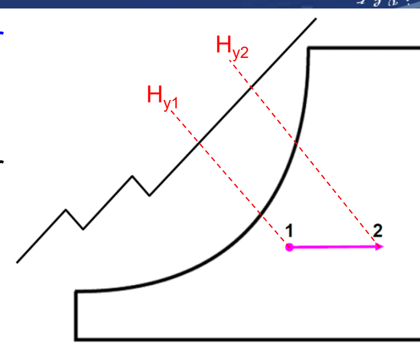
Psychrometric (humidity) charts



Simple Heating and Cooling (Constant H)

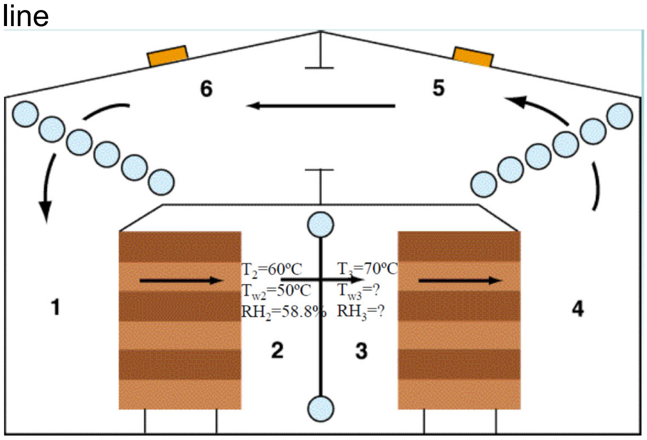
- A psychrometric process that involves the increase or decrease in the temperature of air without changing its humidity ratio
- Example: passing moist air over a room space heater and of kiln air over the heating coils
- The heating process is represented as a horizontal line

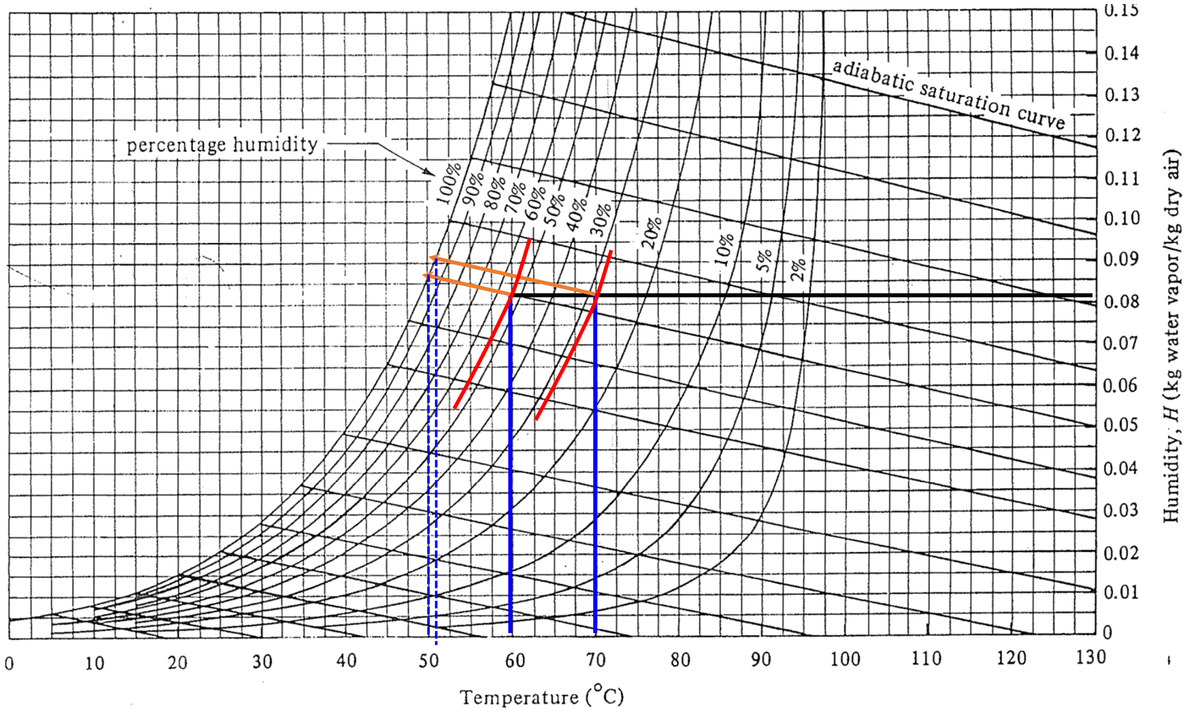


Sensible Heating or Cooling

$$Q = m_a (H_{y2} - H_{y1})$$

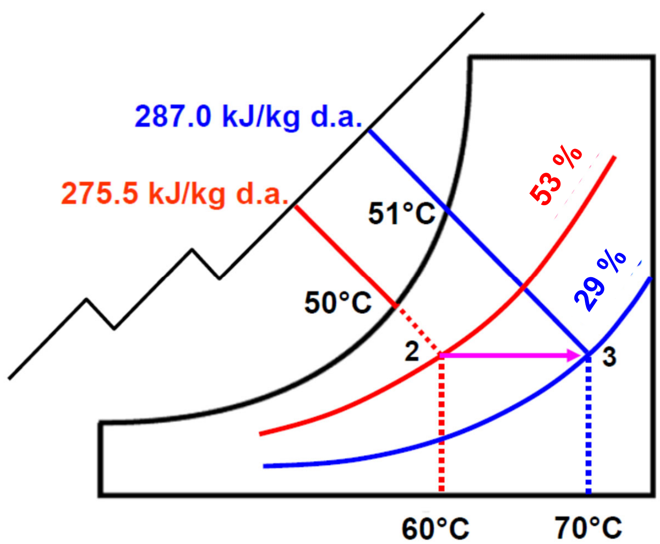
$$= m_a c_s (T_2 - T_1)$$





Simple Heating

Simple Heating and Cooling (Constant H)



Simple Heating

$H_{R1} > H_{R2}$

$H_1 = H_2$

$Q = m_a (H_{y2} - H_{y1})$

$= m_a c_s (T_2 - T_1)$

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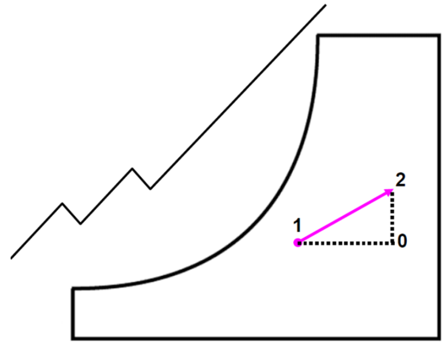
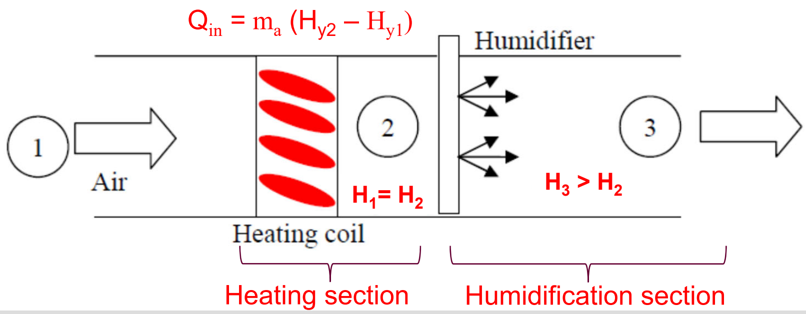
Heating with Humidification

- A psychrometric process that involves the simultaneous increase in both the dry bulb temperature and humidity ratio of the air
- This is accomplished by passing the air first through a heating section and then through a humidifying section.



Heating and Humidifying



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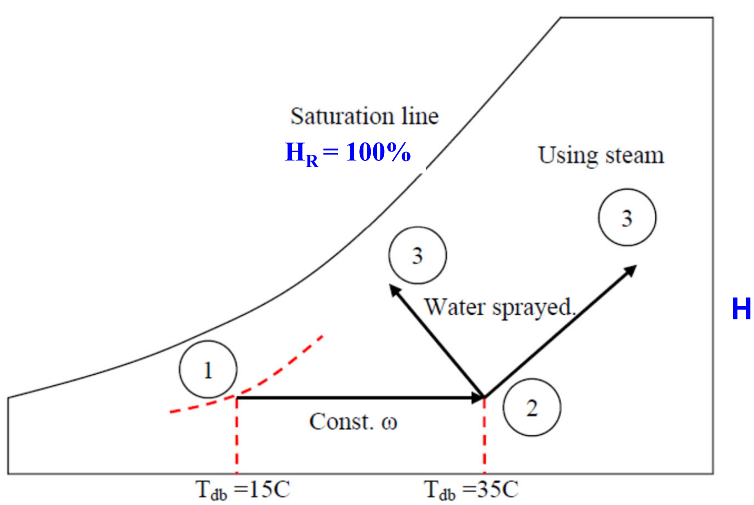
Heating with Humidification



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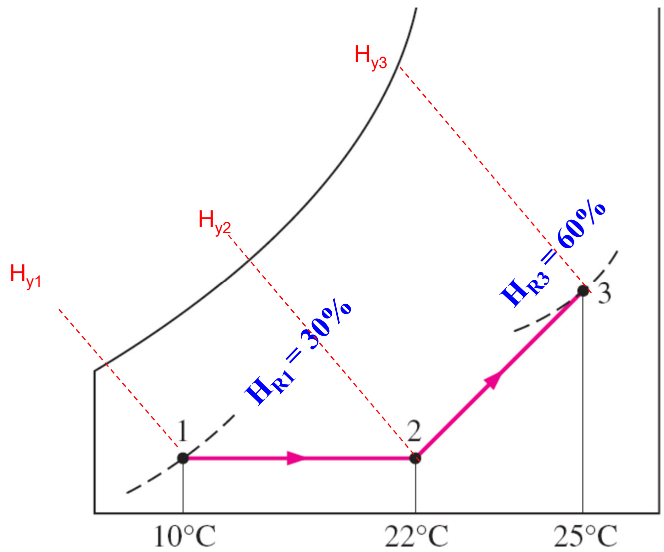
Heating with Humidification



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Example

Two and a half cubic meters of lumber is being dried at 60 °C dry bulb temperature and 52 °C wet bulb temperature. The drying rate of the lumber is 12.5 kg of water/h. If outside air is at 27°C dry bulb temperature and 80% percentage humidity.

a. Classify this psychometric process?

b. How much outside cubic meters of air are needed per minute to carry way the evaporated moisture?

Outside air is at 27°C dry bulb temperature and 80% percentage humidity.

Dried at 60 °C dry bulb temperature and 52 °C wet bulb temperature.

Two and a half cubic meters

The drying rate of the lumber is 12.5 kg of water/h

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Solution

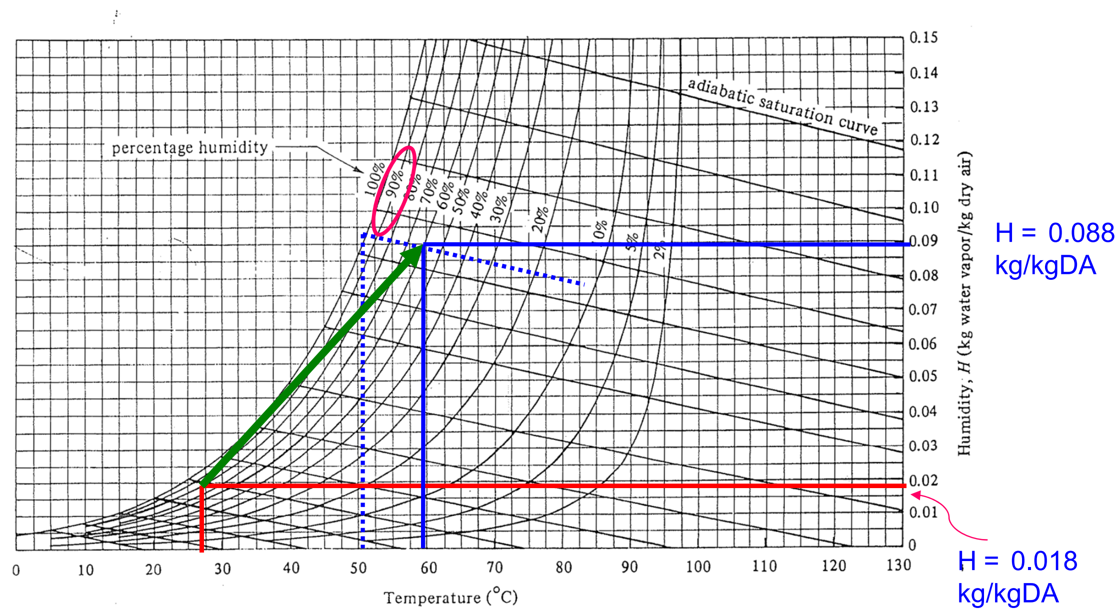


FIGURE 9.3-2. *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*

Solution

a. This is **Heating and humidification process** since it will involves simultaneous increase in both the dry bulb temperature and humidity of the air.

b. ΔH= (**0.088**–0.018) kg/kg dry air = **0.07** kg water/kg dry air

Mass flow rate of dry air = drying rate/ΔH

=12.5 kg of water/h/**0.07** kg water/kg dry air

= **178.6** kg dry air/h

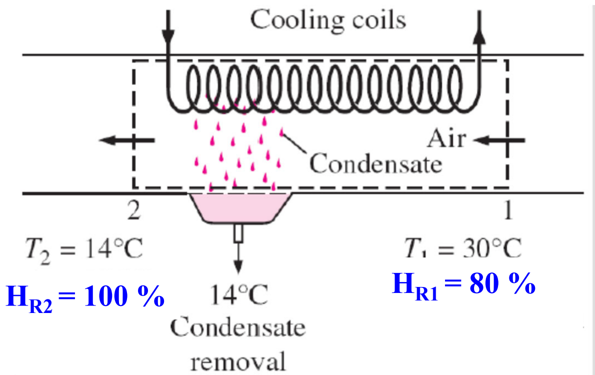
Humid volume, $v_H = [2.83\times10^{-3}+4.56\times10^{-3}(0.018)](27+273)$

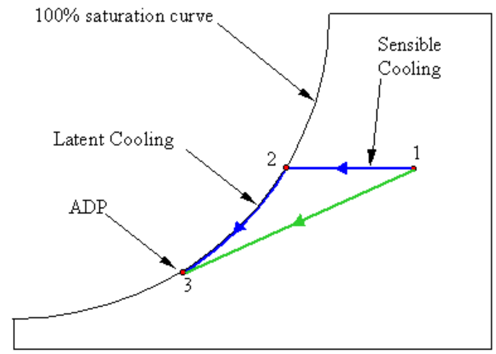
$=0.87\ m^3/\text{kg dry air}$

Volumetric flow rate of air = (**178.6**)(0.87)/60 = **2.59** m^3/min

Cooling with Dehumidification

- A psychrometric process that involves the removal of water from the air as the air temperature falls below the dewpoint temperature

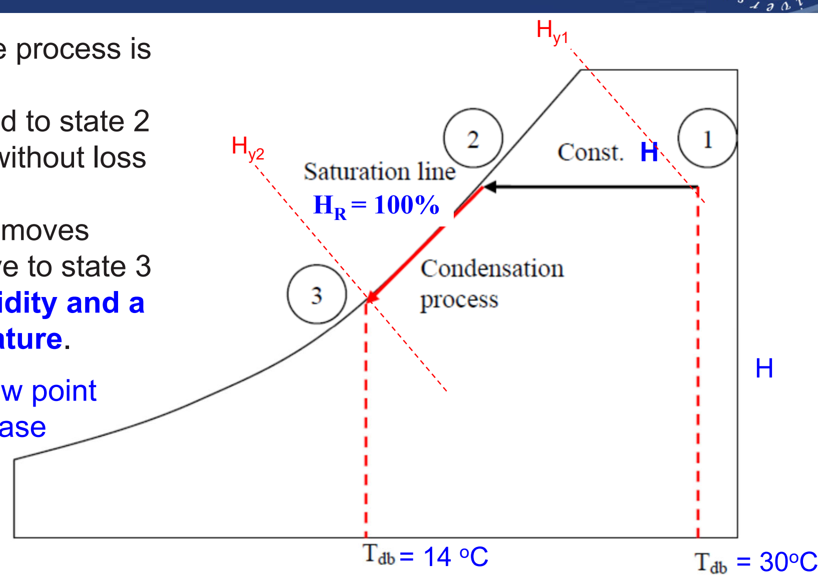




Cooling and Dehumidifying

Cooling with Dehumidification

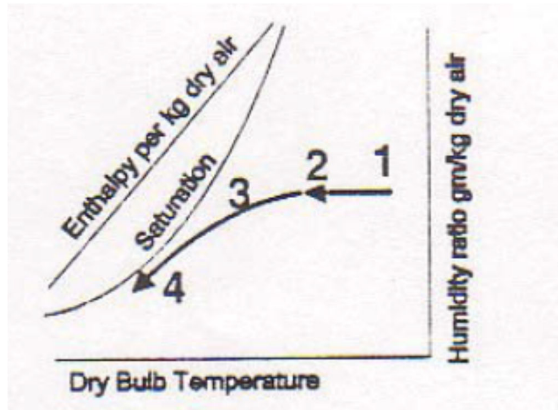
- In the idealized case, the process is shown as 1-2-3
- First the mixture is cooled to state 2 on the saturation curve without loss of water vapor.
- As it is cooled further, it moves down the saturation curve to state 3 which **has a lower humidity and a lower dry bulb temperature**.
- The enthalpy and the dew point temperature of air decrease

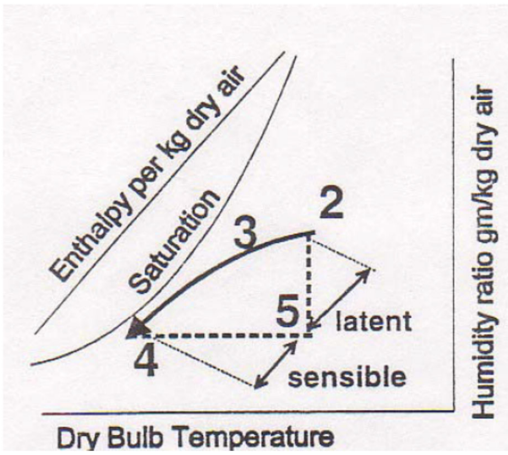


$Q_{out} = m_a (H_{y3} – H_{y1})$

Cooling with Dehumidification

- In the real process, the condensation begins before the saturation curve is reached since the tube wall temperature is normally lower than the dew point temperature.





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Example

Moist air at 50°C dry bulb temperature and 32% relative humidity enters the cooling coil of a dehumidification kiln heat pump system and is cooled to a temperature of 18°C. If the condensate rate is 4 kg water/h. Determine the kW of refrigeration required.

Solution:

This is **Cooling and dehumidification** since it will involves decrease in both the dry bulb temperature and humidity of the air.

Assume the final state at 18 ^{o}C is at saturation (condensation).

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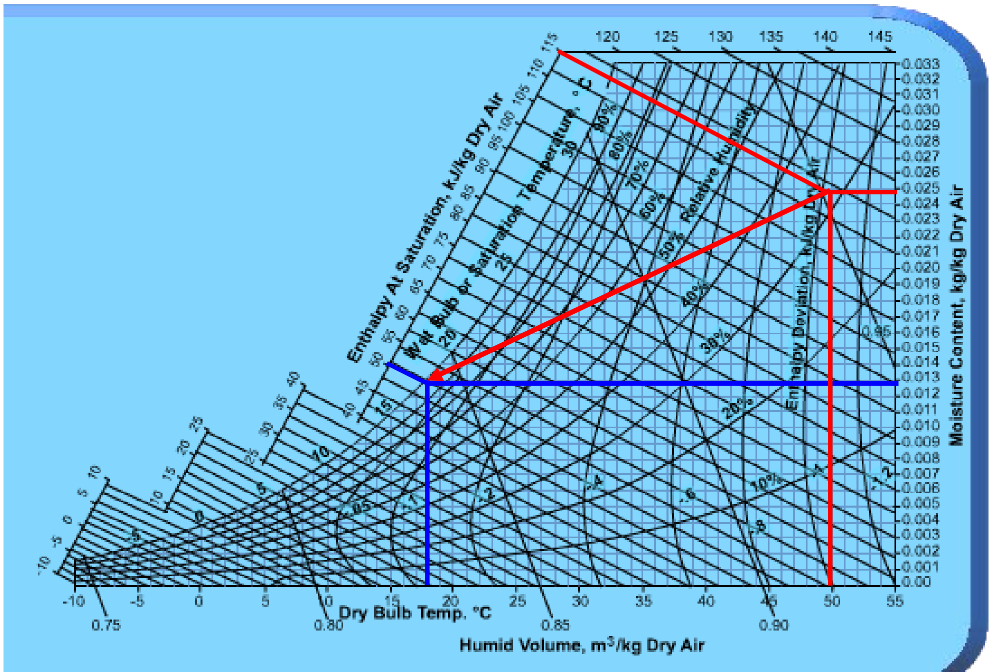
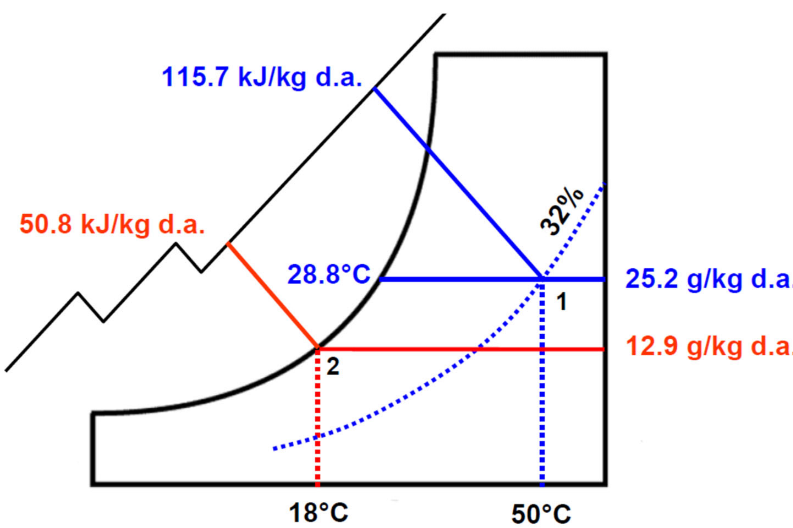
Solution



Solution Cont.d



Solution Cont.d

ΔH = (0.013 -0.025) = -0.012 kg water/kg dry air

Mass flow rate of air = evaporate rate/ ΔH

= - 4/-0.012 = 333.3 kg dry air/h

H_{y1}= 50 kJ/kg dry air

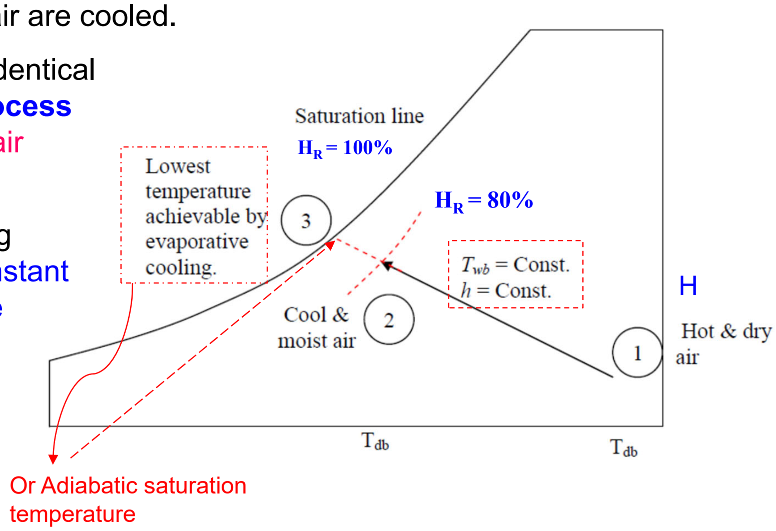
H_{y2}= 115 kJ/kg dry air

ΔH_y = (115– 50)= 65 kJ/kg dry air.

Q = $\Delta H_y \times 333.3 = 65 \times 333.3$ = 21664 kJ /h = 6.0 kW

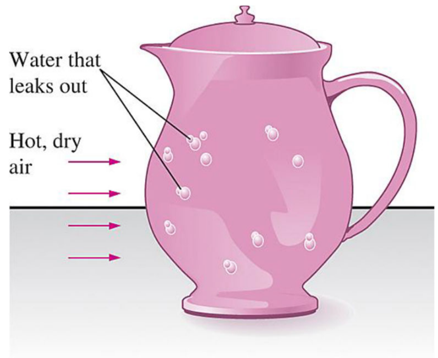
Evaporative Cooling

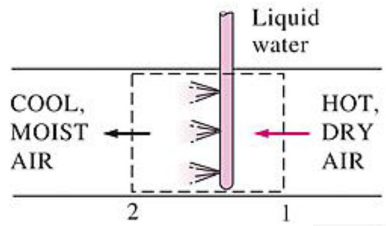
- Evaporative cooling is based on a simple principle: as water evaporates, the latent heat of vaporization is absorbed from the water body and the surrounding air.
- As a result, both water and air are cooled.
- This process is essentially identical **to adiabatic saturation process** that involves the cooling of air without heat loss or gain.
- Thus the evaporative cooling process follows a line of constant wet-bulb temperature on the psychrometric chart.



Evaporative Cooling

- Water in a porous jug left in an open, breezy area cools as a result of evaporative cooling.





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Chemical Dehumidification: Heating and Dehumidification Process

- This process is obtained by passing the air over certain chemicals like alumina and molecular sieves.
- These elements have inherent properties due to which they keep on releasing the heat and also have the tendency to absorb the moisture.
- These are called as the hygroscopic chemicals.

- In actual practice, the **hygroscopic material** are enclosed in the large vessel and the high pressure air is passed inside the vessel through one opening.
- When the air comes in contact with the chemicals the moisture from the air is absorbed and since the chemicals emit heat, the DB temperature of the air increases.

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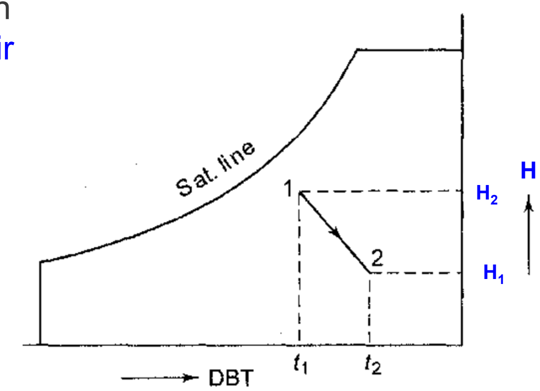
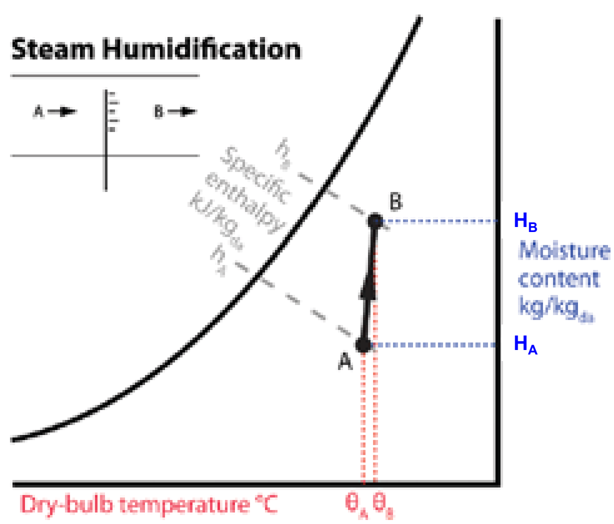
Chemical Dehumidification

- If process is thermally isolated then enthalpy of air remains constant which causes increases in temperature of air as its moister content decreases.
- During the heating and dehumidification process : dry bulb temperature of the air increases while its humidity and dew point decrease.
- The enthalpy and wet bulb temperature are constant



Humidification by steam injection



Adiabatic Mixing

- Mixing processes normally involve no work interactions; thus, one can write (for adiabatic mixing of two streams):

Mass balance on dry air

$$\dot{m}_{a1} + \dot{m}_{a2} = \dot{m}_{a3}$$

Mass balance on water vapor

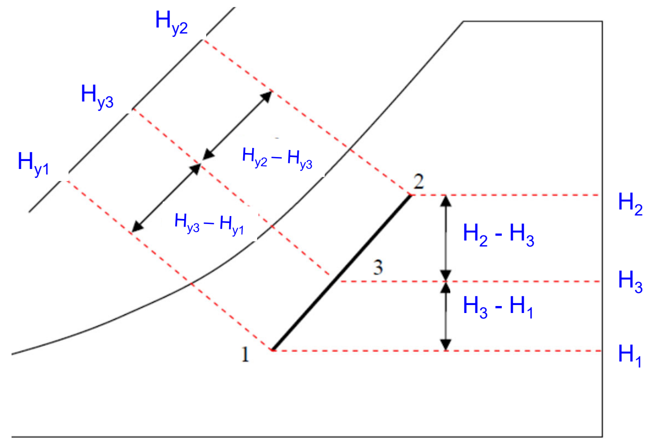
$$\dot{m}_{a1}H_1 + \dot{m}_{a2}H_2 = \dot{m}_{a3}H_3$$

Energy balance

$$\dot{m}_{a1}H_{y1} + \dot{m}_{a2}H_{y2} = \dot{m}_{a3}H_{y3}$$

Hence

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{H_2 - H_3}{H_3 - H_1} = \frac{H_{y2} - H_{y3}}{H_{y3} - H_{y1}}$$



- When two airstreams at states 1 and 2 are mixed adiabatically, the state of the mixture lies on the straight line connecting the two states

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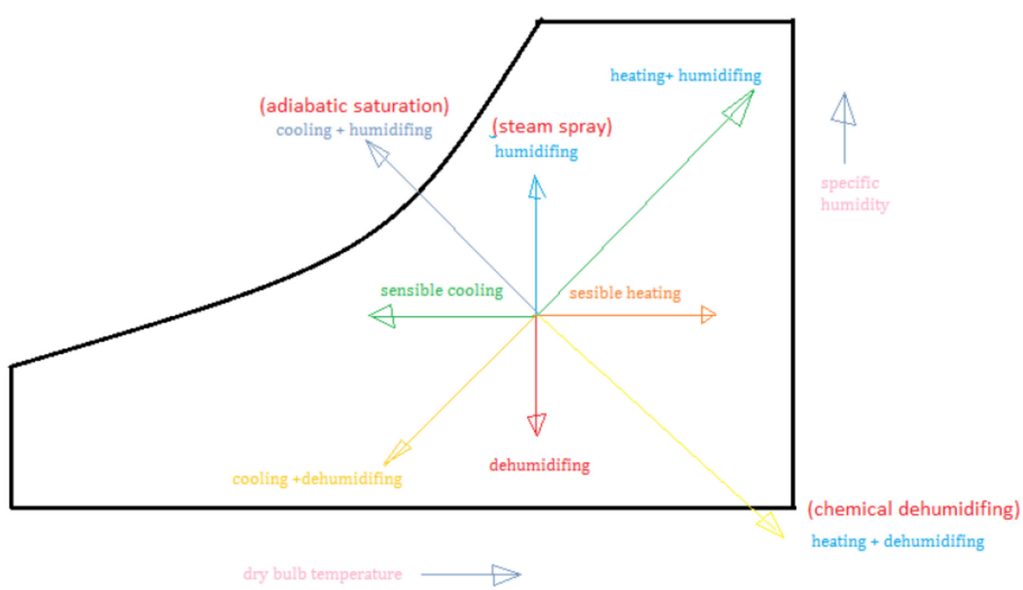
Summary



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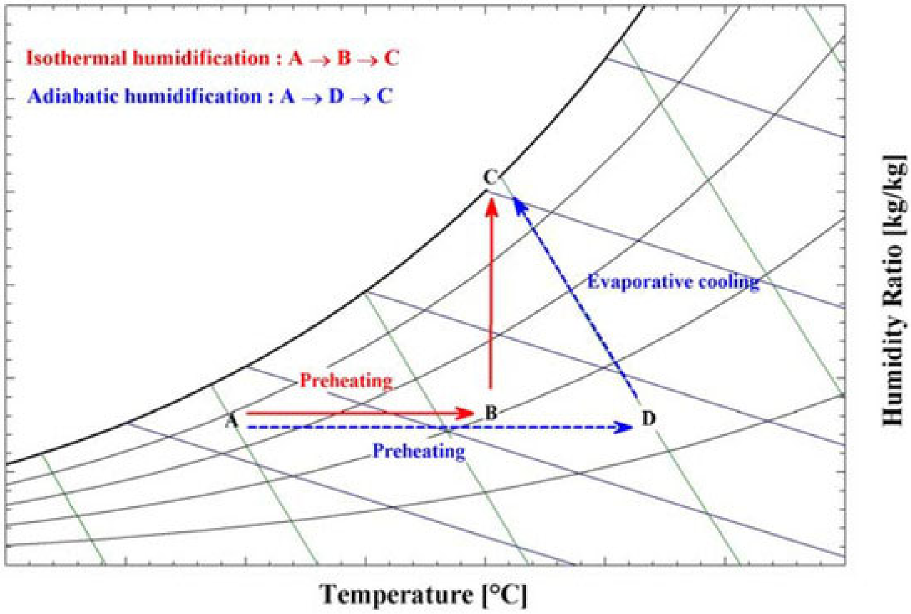
Summary



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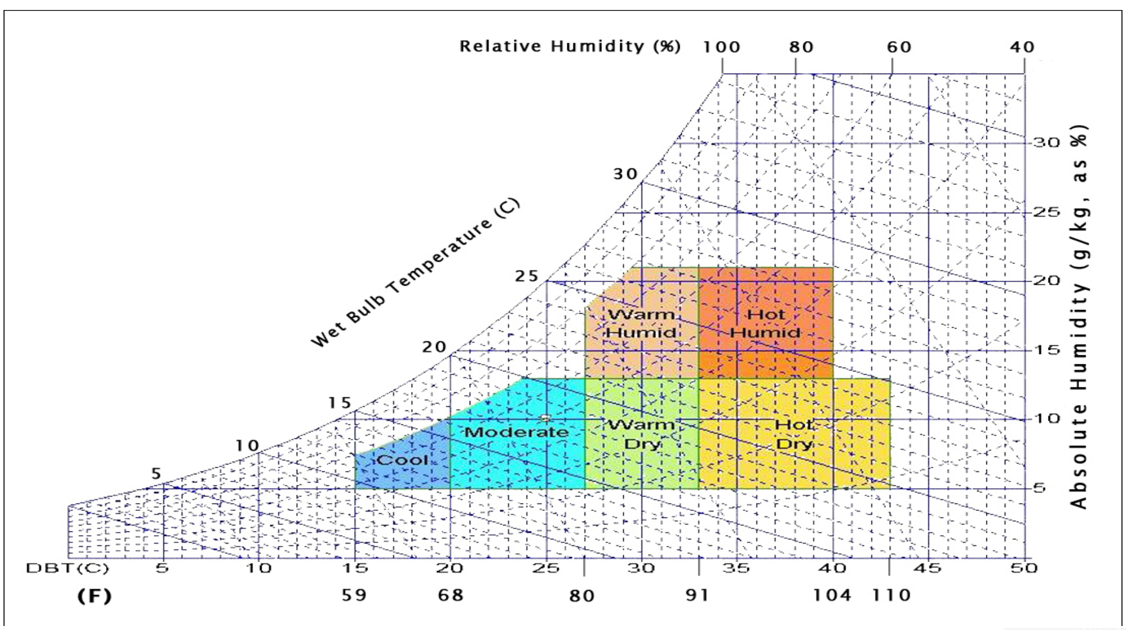
Psychrometric (humidity) chart

Where our ambient location?



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