Spring Semester course

CH31010: Mass Transfer II

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L1: Basic concepts on Humidification – Dehumidification

Course Outline

[SM] Humidification/Dehumidification, Cooling towers, Spray Chambers, Principles of air conditioning.

[RM] Drying: Theory and mechanism of drying, Batch and continuous drying.

[RM] Liquid-Liquid Extraction.

[RM] Leaching.

[SM] Adsorption and Ion Exchange.

[SM] Membrane Separations.

Reference / text books:

- Mass Transfer Operations by R. E. Treybal
- Unit Operations of Chemical Engineering by W. L. McCabe, J. C. Smith and P. Harriott
- Coulson, J.F. Richardson's Chemical Engineering, Volume 1 & 2 by J. M. Coulson, J.F. Richardson, J. R. Backhurst and J. H. Harker
- Transport Processes and Unit Operations by C.J. Geankoplis

What is humidification?

Layman terms:

Humidification is the process of constituting the water-vapor content in a gas.

Engineering interpretation:

The process of adding the moisture or water vapor to the air without changing its dry bulb (DB) temperature is called as humidification process.

❖ In actual practice, pure humidification process is not possible, since the humidification is always accompanied by cooling or heating of the air.

What is dehumidification?

Reverse of humidification.

Both heat & mass transfer occurs (and influence) any humidification operation.

Applications of humidification operation

Major / important:

- Humidification of gases for controlled drying of wet solids
- Dehumidification and cooling of gas in air conditioning
- Gas cooling with the help of water
- Cooling of liquid (e.g. water) before reuse

Terminologies and definitions

- **Dry-bulb temperature (DBT):** It is true temperature of air measured (or, any non-condensable and condensable mixture) by a thermometer freely exposed to air, but shielded from radiation and moisture. This is normal air temperature.

Wet Bulb temperature (WBT)

It is the steady-state temperature attained by a small amount of evaporating water in a manner such that the sensible heat transferred from the air to the liquid is equal to the latent heat required for evaporation.

It is the temperature read by a thermometer covered in water-soaked cloth over which air is passed. At 100% relative humidity, the wet-bulb temperature is equal to the air temperature (dry-bulb temperature) and is lower at lower humidity. It is defined as the temperature of the air cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat supplied by the air itself.

- The wet bulb temperature of the air is always less than (or at most equal) to the dry bulb temperature of air.
- It is the lowest temperature achievable by evaporating water into the air to bring the air to saturation.

Factors that influence the WBT

- Dry bulb temperature of air T_G
- Humidity, Y'
- Air velocity
- Shape of the thermometer bulb (insignificant)

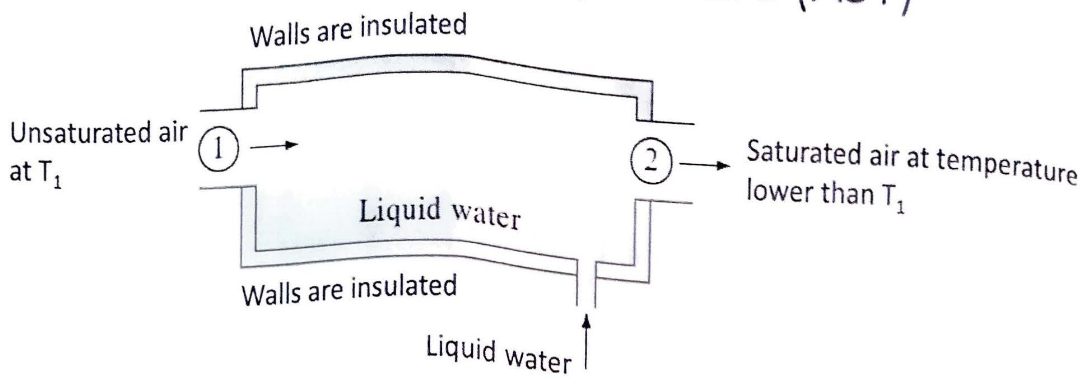
Dew Point temperature (DP)

It is a temperature

- at which a vapor-gas mixture must be cooled (at constant humidity) to become saturated.
- to which the ambient air must be cooled to reach 100% relative humidity assuming there is no further evaporation into the air

The dew point of a saturated gas equals the gas temperature.

Adiabatic saturation temperature (AST)



As the air flows over the water, some of the water evaporates adiabatically gaining the latent heat required for evaporation from the stream of air. So, the temperature of the air-stream decreases and moisture content of the air increases due to this adiabatic evaporation. This continues until a point where the air cannot hold any more moisture.

This temperature when air says 'No vacancy for moisture' is called adiabatic saturation temperature. Because, the unsaturated air is brought to saturation adiabatically.

Here enthalpy of inlet air, $H_i = C_H(T_G - T_{as}) + \lambda_s Y'$

Enthalpy of exit air, $H_o = \lambda_s Y_s'$

At equilibrium, $H_i = H_o$

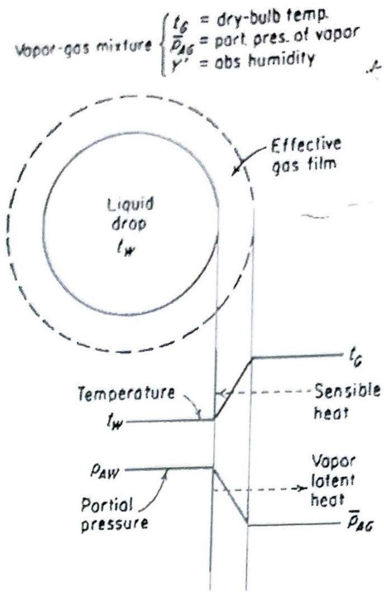
$$\text{So, } C_H(T_G - T_{as}) + \lambda_s Y' = \lambda_s Y_s'$$

$$\Rightarrow T_G - T_{as} = \frac{\lambda_s}{C_H}(Y_s' - Y')$$

C_H : sp. heat cap. of the humid air (air-water vap. mix) @ const. pressure (J/kg. K)

Relationship between WBT & DBT

Consider a drop of liquid immersed in a rapidly moving stream of unsaturated vapor-gas mixture. If the liquid is initially at a temperature higher than the gas DP, the vapor pressure of the liquid will be higher at the drop surface than the partial pressure of vapor in the gas, and the liquid will evaporate and diffuse into the gas. The latent heat required for the evaporation will at first be supplied at the expense of the sensible heat of the liquid drop, which will cool down. As soon as the liquid temperature is reduced below the DBT of the gas, heat will flow from the gas to the liquid, at an increasing rate as the temperature difference becomes larger. Eventually the rate of heat transfer from the gas to the liquid will equal the rate of heat requirement for the evaporation, and the temperature of the liquid will remain constant at some low value, the wet-bulb temperature t_w.



$$q_s = h_G(t_G - t_w) \quad \& \quad N_A = k_G(\bar{p}_{A,G} - p_{A,w})$$

Now, $q_s + \lambda_w M_A N_A = 0$

$$\Rightarrow h_G(t_G - t_w) + \lambda_w M_A k_G(\bar{p}_{A,G} - p_{A,w}) = 0$$

$$\therefore t_G - t_w = \frac{\lambda_w M_A k_G(\bar{p}_{AG} - p_{AW})}{h_G} = \frac{\lambda_w M_A \bar{P} k_G (Y'_w - Y')}{h_G} = \frac{\lambda_w (Y'_w - Y')}{h_G / K_Y}$$

Lewis relationship

For flow of gases past cylinder (such as wet bulb thermometers) and single sphere, the vapour-gas systems are correlated by:

$$\frac{h_G}{C_H K_Y} = \left(\frac{Sc}{Pr}\right)^{0.567} = Le^{0.567}$$

For air-water vapour systems $\frac{h_G}{K_Y}$ as measured is 950 J/kg.K

For low to moderate humidity air, C_H = 1005 J/kg.K

So, for air-water vapour system, $\frac{h_G}{C_H K_Y} = Le \sim 1$ and $Sc \sim Pr$

This implies for air-water vapour systems, WBT and AST are equal ! but this is *not* the case for most other systems.

Difference of WBT and AST

Both of these are the temperatures when the rate of latent heat of vaporization extracted from bulk water becomes equal to the rate of sensible heat transfer from air to water.

- WBT is reached when there is large amount of air and small amount of water while AST is reached when small amount of air and larger amount of water.
- When WBT is reached the temperatures of water and air are different (temperature of water lower than that of air) while when AST is reached temperatures of water and air leaving are same.
- AST is either equal to or lower than WBT (equal in air-water system and unequal in other liquid-gas systems).
- When AST is reached air becomes saturated with water while when WBT is reached there is considerably no change in the humidity of air.
- AST is reached in adiabatic saturator while WBT is reached in wet wick thermometer.
- AST requires adiabatic conditions that heat is exchanged only between the passing air and water inside the adiabatic saturator while WBT requires heat exchange with surrounding air in open.
- AST is the maximum limit up to which temperature of water can be lowered by evaporation at any given dry bulb temperature and pressure in adiabatic conditions while WBT is the maximum limit up to which the temperature of water can be lowered by evaporation in open.
- AST is the equilibrium Temperature while the WBT is the steady state temperature.

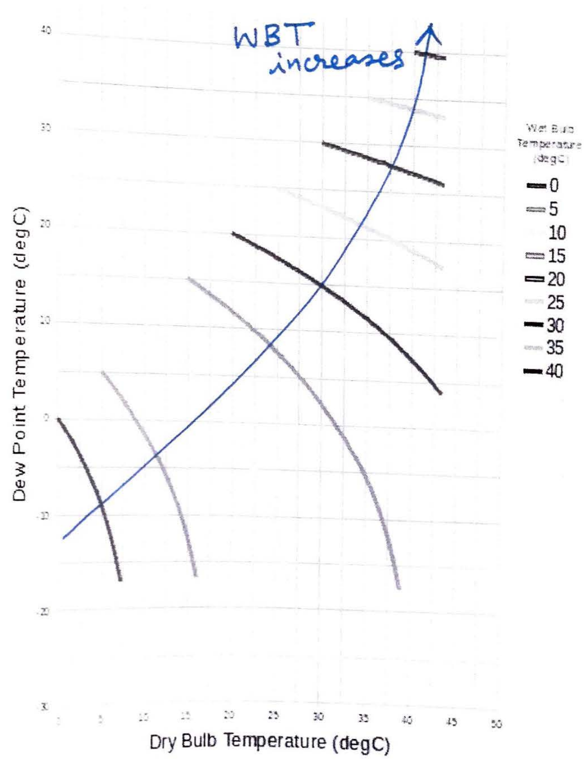
Dry Bulb / Wet Bulb / Dew Point Temperature

In general,

$$DBT \geq WBT \geq DP$$

In the fully saturated condition (100% RH) all three are equal.

Knowledge of any two of these temperature can be used to determine the other.



(Absolute) humidity

It is the direct measurement of moisture content in a gas.

$$Y = \frac{y_A}{y_B} = \frac{\bar{p}_A}{\bar{p}_B} = \frac{\bar{p}_A}{p_t - \bar{p}_A} \frac{\text{moles A}}{\text{moles B}}$$ (in terms of moles)

$$Y' = Y\frac{M_A}{M_B} = \frac{\bar{p}_A}{p_t - \bar{p}_A} \frac{M_A}{M_B} \frac{\text{mass A}}{\text{mass B}}$$ (in terms of mass)

For air-water vap. system, A: water vap. and B: air

It is occasionally called '***Grosvenor humidity***' after the name of the inventor

Percent Humidity (percent saturation)

It is the relation between absolute humidity to that of saturation humidity at that temperature and pressure.

$$\% \text{ Humidity} = \frac{Y'}{Y'_s} \times 100$$

$Y' \rightarrow$ absolute humidity of air

$Y'_s \rightarrow$ humidity of air saturated with water vap. @ same T & P

$$\therefore Y'_s = \frac{P_A^v}{P - P_A^v} \frac{M_{wat}}{M_{air}} \quad \text{and} \quad P_A^v = 12 - \frac{3985}{T - 40}$$ (T in K)

(Antoine equation)

Relative humidity (RH)

It is the ratio of partial pressure of water vapor ($\bar{p}_A$) in air at a given temperature to the vapor pressure of water (p_A) at the dry bulb temperature of air.

$$\% \, RH = 100 \frac{\bar{p}_A}{p_A}$$

Relative humidity does not 'explicitly' give the moisture content of a gas, but gives the 'degree of saturation' of the gas at a given temperature (DBT).

Humid volume

The humid volume, v_H is defined as the volume of unit mass of dry air with accompanying water vapor at a given temperature and pressure.

$$v_H = \left(\frac{1}{M_a} + \frac{Y'}{M_w}\right) 22.14 \, \frac{T_G + 273}{273} \, \frac{1.013 \times 10^5}{P_t}$$

where v_H is in m^3/kg

T_G is DBT of air in °C

P_t is the pressure of air in Pa

For dry air : $Y' = 0$ and for saturated air $Y' = Y_s'$

Humid heat

The humid heat, c_H is the heat energy required to raise the temperature of unit mass of air with the accompanying water vapor by one (1) degree at constant pressure.

$$C_H = 1.005 + 1.88Y' \quad kJ/(kg \text{ of dry air})\cdot K$$

first part of right hand side is heat capacity of dry air in kJ/kg.K and second part is heat capacity of water vapor in kJ/kg.K.

Enthalpy

The enthalpy of a vapor-gas mixture is the sum of the relative enthalpies of gas and vapor content.

$$H' = C_H(T_G - T_0) + \lambda_w Y'$$

$$= (1.005 + 1.88Y')(T_G - T_0) + 2260Y'$$

where λ_w is the latent heat of vapourization of water

H : kJ/kg of air-water vap. mixture