4 HUMIDIFICATION OPERATION

Mass Transfer II

Cooling of warm water is done by direct contact of air in cooling towers. There is four major application of air water contacting.

1. Water cooling: Air-water contacting is done mostly for the purpose of cooling the warm water before it can be reused.

2. Humidification: Air having a specified moisture content is necessary for some process applications – for example, in the drying of a solid under controlled condition.

   The process of increasing the moisture content of air is called 'humidification'. A humidifier is also used at the inlet of an air- ventilating system.

3. Dehumidification: Moist warm air may be relieved of a part of its moisture by contacting with water at a lower temperature. Dehumidification has use in air conditioning.

4. Gas cooling: A hot air stream can be cooled conveniently in contact with water. However, its content changes in the process.

Each of the above operation involves 'simultaneous transfer of heat and mass'.

(a) once-through cooling

(b) a cooling water curcuit.
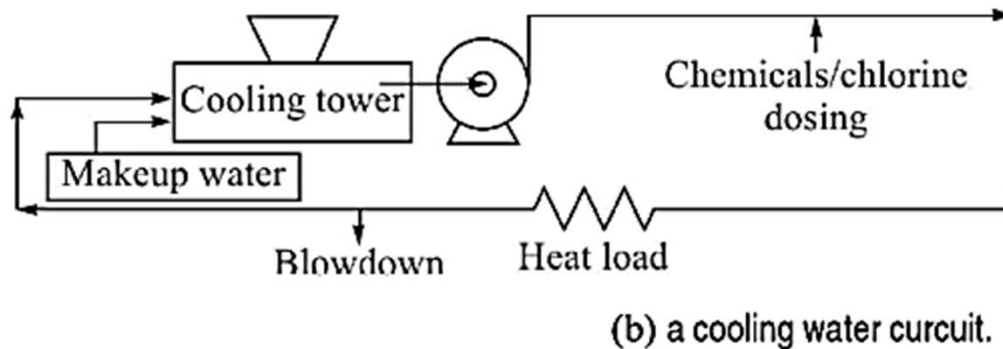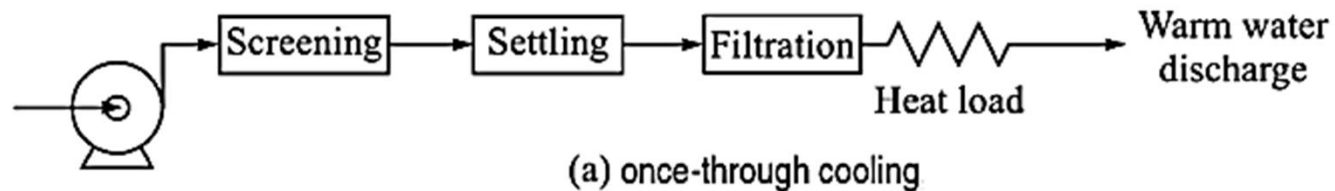
Humidification operation is a classical example for an interphase transfer of mass and energy.

Vapor-Liquid Equilibrium and Enthalpy for a Pure Substance

The equilibrium vapor-pressure characteristics of liquid are important for these operation.

Vapor-pressure curve

Every liquid exerts an equilibrium pressure, the vapor pressure, to an extent depending upon the temperature.

When the vapor pressure of a liquid are plotted against the corresponding temperatures, a curve like TBDC results.

The vapor-pressure curve for each substance is unique, but each exhibits similar characteristics shown in figure.

Point T — Triple Point

Point C — Critical Point

For common liquids such as water, many refrigerants and others, the vapor-pressure-temperature curve are available.

However, for most of liquids these curve are approximated by Clausius-Clapeyron equation, which relate the slope of the vapor-pressure curve to the latent heat of vaporization.

$$\frac{dp}{dT} = \frac{\lambda'}{T(v_G - v_L)}$$

Where v_G and v_L are molal specific volumes of the saturated vapor and liquid, respectively, and λ' is the molal latent heat.
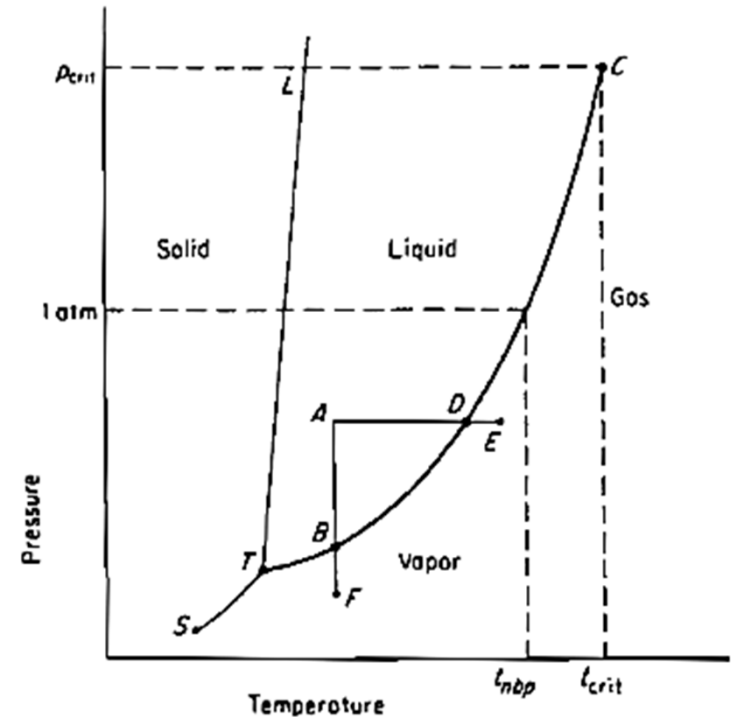
As a simplification neglect the υ_L in comparison with υ_G and express the latter by the ideal gas law

$$d \ln p = \frac{dp}{p} = \frac{\lambda' \, dT}{RT^2}$$

If λ' can be considered reasonably constant over a short range of temperature

$$\ln p = -\frac{\lambda'}{RT} + \text{const}$$

Equation suggest that plot between ln p vs 1/T will be straight for short temperature range.

Reference Substance Plot

Equation rewritten for a second substance, a reference substance at the same temperature

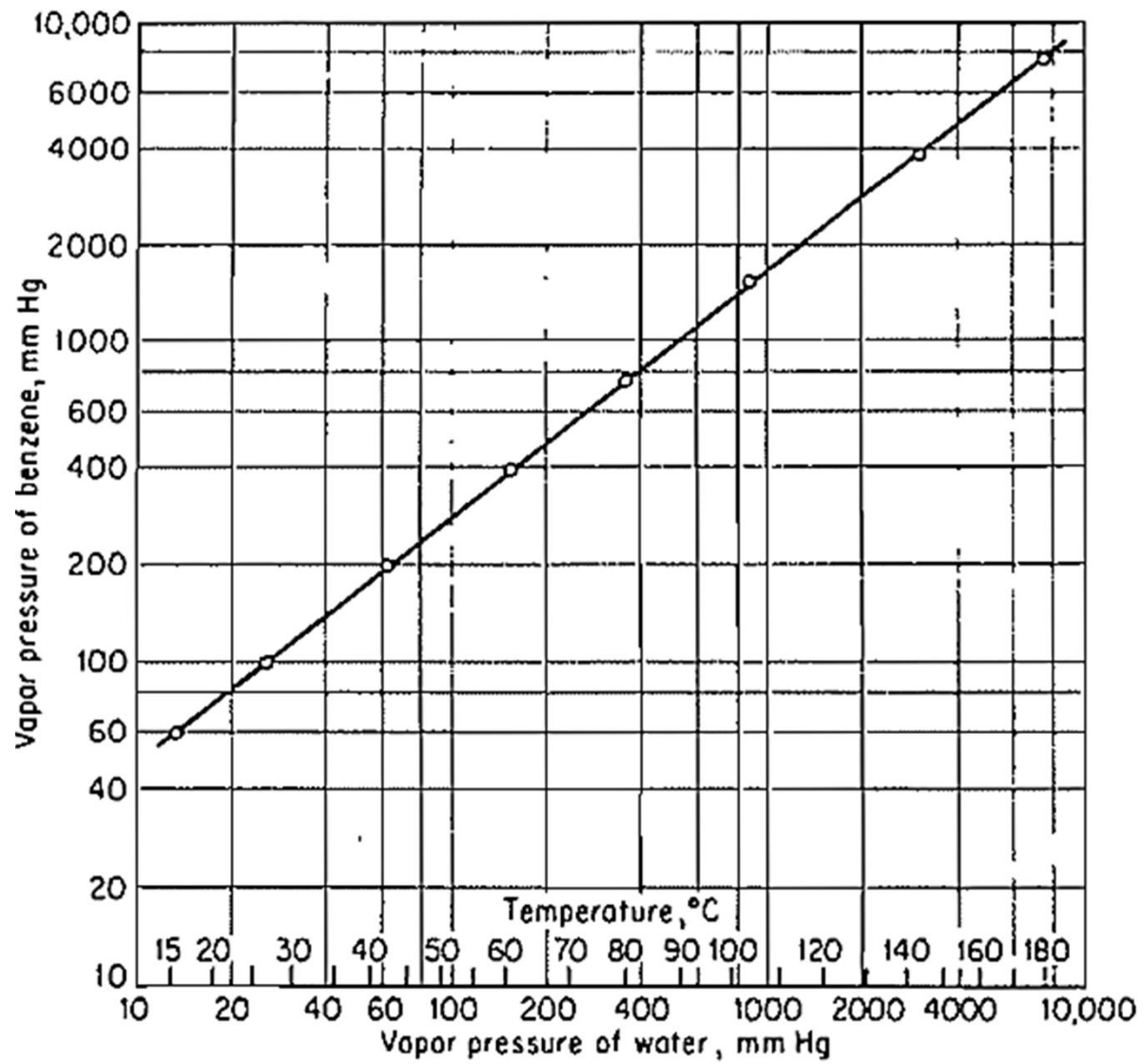$$d \ln p_r = \frac{\lambda'_r \, dT}{RT^2}$$

Where subscript r denotes the reference substance. Dividing the equation

$$\frac{d \ln p}{d \ln p_r} = \frac{\lambda'}{\lambda'_r} = \frac{M\lambda}{M_r \lambda_r}$$

After integration

$$\log p = \frac{M\lambda}{M_r \lambda_r} \log p_r + \text{const}$$

Linear graph between log p vs log p_r where vapor pressure are taken at same temperature.

Enthalpy

The sum of the internal energy U of a substance (the total energy residing in the substance owing to the motion and relative position of the constituent atoms and molecules) and the product of pressure and volume of the substance is defined as the enthalpy of the substance.

$$H = U + pv$$

Graphical representation of relative enthalpy of a typical substance in all three state is shown in figure.

For a liquid or vapor, the slope of the constant-pressure lines at any temperature is termed the heat capacity.

The lines are not strictly straight, so that the heat capacity changes with temperature.

Sensible heats are readily calculated as

$$H_1 - H_2 = C(t_1 - t_2)$$
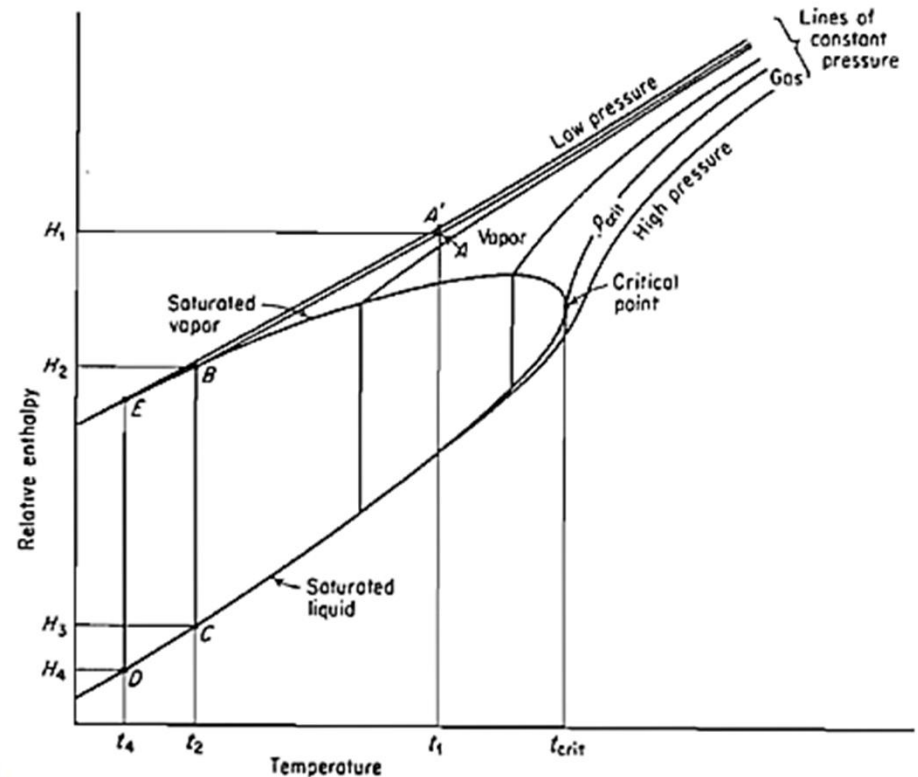
Vapor-Gas Mixture

A substance **A** relatively near its condensation temperature at the prevailing pressure is termed as Vapor.

A substance **B** above the critical point or relatively superheated is termed as Gas.

Molal Absolute Humidity

It is defined as the moles of vapor carried by a unit mole of vapor free gas.

$$Y = \left(\frac{y_A}{y_B}\right) = \left(\frac{p_A}{p_B}\right) = \left[\frac{p_A}{(P_t - p_A)}\right] = \frac{\text{moles of A}}{\text{moles of B}}$$

When the quantities y_A and y_B are expressed in mass, then it is called mass absolute humidity (Y') or Grosvenor humidity.

$$Y' = Y \cdot \left(\frac{M_A}{M_B}\right) = \left[\frac{p_A}{(P_t - p_A)}\right]\left(\frac{M_A}{M_B}\right) = \frac{\text{mass of A}}{\text{mass of B}}$$

Saturated Absolute Humidity (Y$_S$)

When the vapor-gas mixture is saturated, then the partial pressure becomes equal to the vapor pressure of that substance.

$$Y_S = \frac{P_A}{P_B} = \left[\frac{P_A}{(P_t - P_A)}\right]$$

When the quantities are expressed in mass

$$Y_S' = \left(\frac{P_A}{P_B}\right)\left(\frac{M_A}{M_B}\right) = \left[\frac{P_A}{(P_t - P_A)}\right]\left(\frac{M_A}{M_B}\right)$$

Both saturated humidities become infinite at the boiling point of the liquid at the prevailing total pressure.

Unsaturated Vapor-Gas Mixtures

If the partial pressure of the vapor in a vapor-gas mixture is for any reason less than the equilibrium vapor pressure of the liquid at the same temperature, the mixture is unsaturated.

Dry bulb temperature

This is the temperature of a vapor-gas mixture as ordinarily determined by immersion of a thermometer in the mixture.

Relative Humidity or Relative Saturation (% RH)

It is normally expressed in percentage. If p_A is the partial pressure under a given condition and P_A is the vapor pressure at any dry bulb temperature of the mixture then,
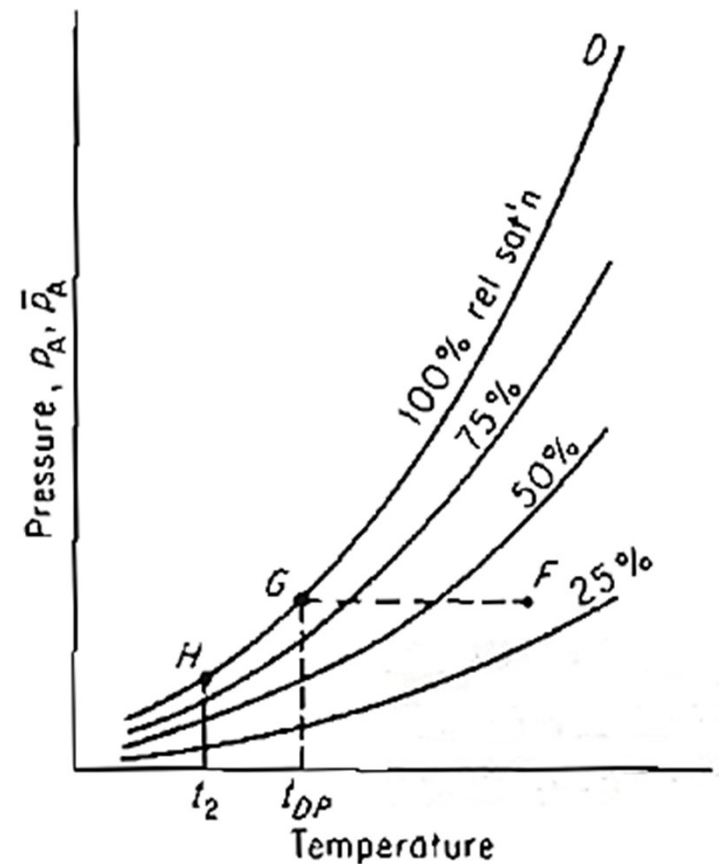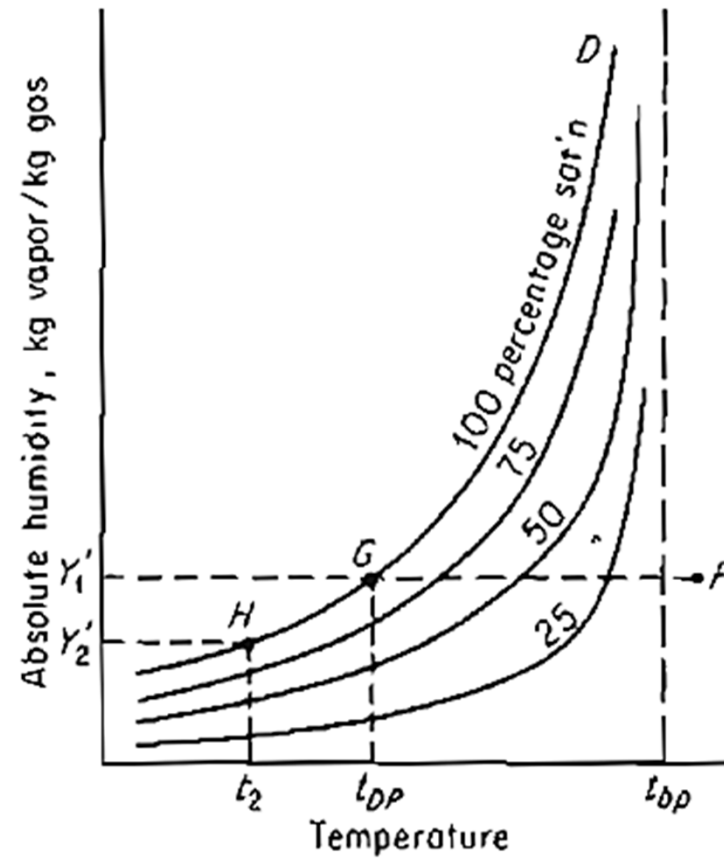
$$\% \ RH = \left(\frac{p_A}{P_A}\right) \times 100$$

Percentage Saturation or Percentage Humidity (H_p)

It is defined as the percentage of humidity under given condition to the humidity under the saturated condition.

Saturated values are computed at the dry bulb temperature of the mixture.

$$H_p = \left(\frac{Y}{Y_s}\right) \times 100$$

Dew Point

This is the temperature at which a vapor-gas mixture becomes saturated when cooled at constant total pressure out of contact with a liquid.

For Example: If an unsaturated mixture such as that at F is cooled at constant pressure out of contact with liquid, the path of the cooling process follows the line FG, the mixture becoming more nearly saturated as the temperature is lowered, and fully saturated at t_{DP}, the dew-point temperature.

Humid Volume

The humid volume v_H of a vapor-gas mixture is the volume of unit mass of dry gas and its accompanying vapor at the prevailing temperature and pressure.

For a mixture of absolute humidity Y' at t_G and p_t, total pressure, the ideal gas law gives the humid volume as

$$v_H = \left(\frac{1}{M_B} + \frac{Y'}{M_A} \right) 22.41 \frac{t_G + 273}{273} \frac{1.013 \times 10^5}{p_t} = 8315 \left(\frac{1}{M_B} + \frac{Y'}{M_A} \right) \frac{t_G + 273}{p_t}$$

Where v_H is in m³/kg, t_g in degree Celsius, and p_t in N/m².

Humid Heat

The humid heat CS is the heat required to raise the temperature of unit mass of gas and its accompanying vapor one degree at constant pressure.

For a mixture of absolute humidity Y',

$$C_S = C_B + Y'C_A$$

Provided neither vaporization nor condensation occurs, the heat in BTU required to raise the temperature of a mass of WB dry gas and its accompanying vapor an amount Δt will be

$$Q = W_B C_S \Delta t$$

Enthalpy

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

For a gas at a dry bulb temperature of t_G, with a humidity of Y', the enthalpy relative to the reference state t_0 is,

$$H' = \text{Enthalpy of gas} + \text{Enthalpy of vapour component}$$
$$= C_B (t_G - t_0) + Y'[C_A (t_G - t_{DP}) + \lambda_{DP} + C_{A,L} (t_{DP} - t_0)]$$

Where λ_{DP} is latent heat of vaporization at dew point and $C_{A,L}$ is specific heat of component A (vapor) in liquid phase.

This expression can further be simplified as low pressures are normally encountered in humidification operations.
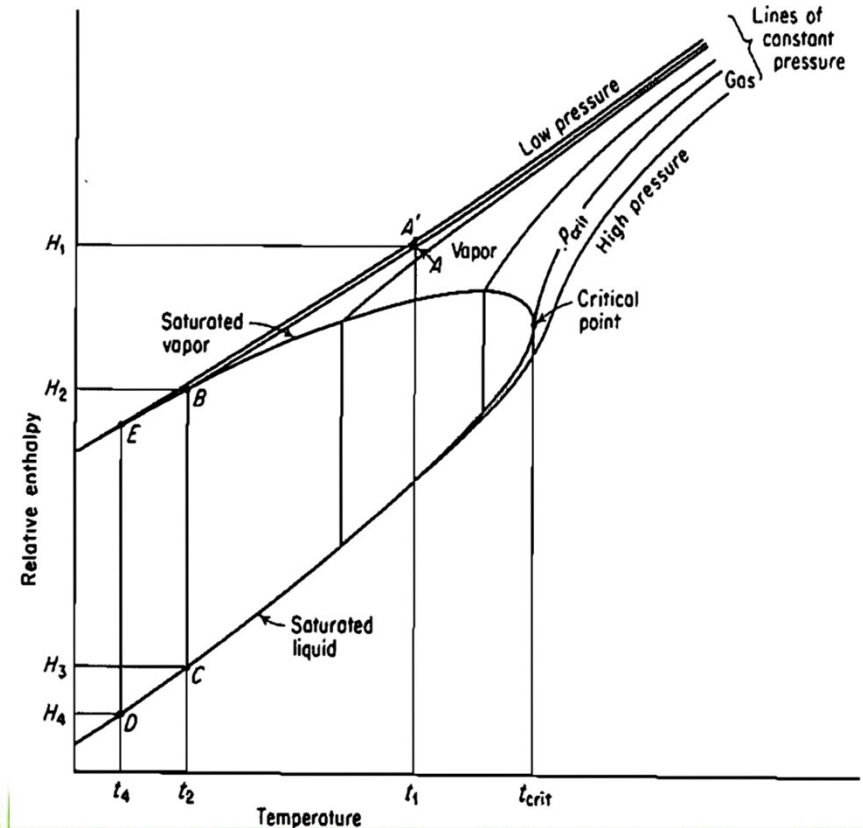
The vapor enthalpy can then be computed by following the path A'ED and

Becomes, per unit mass of vapor, $C_A(t_g - t_0) + \lambda_0$ is the latent heat of vaporization at the reference temperature.

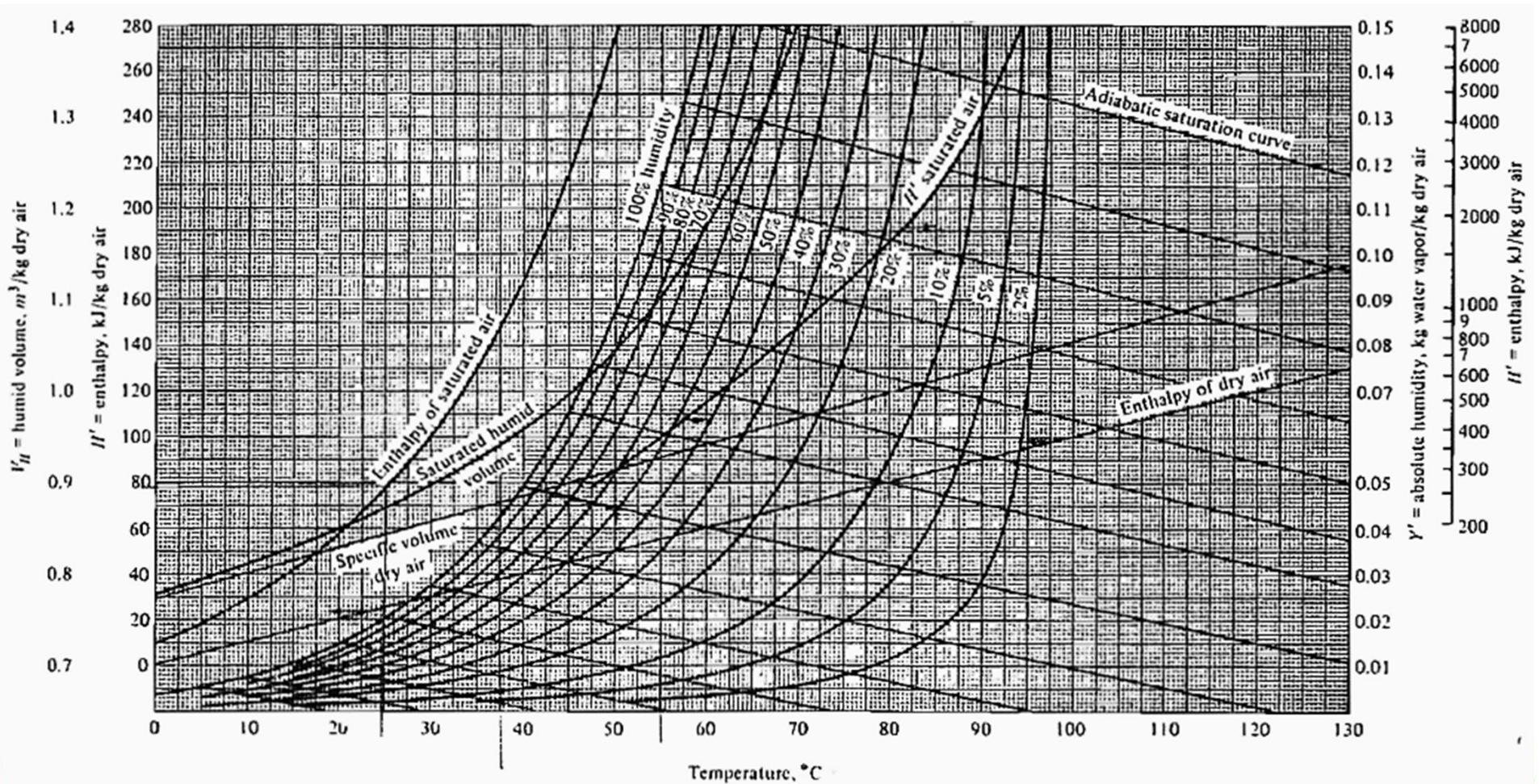The enthalpy of the mixture, per unit mass of dry gas, is then

$$H' = C_B (t_G - t_0) + Y' [C_A(t_G - t_0) + \lambda_0]$$
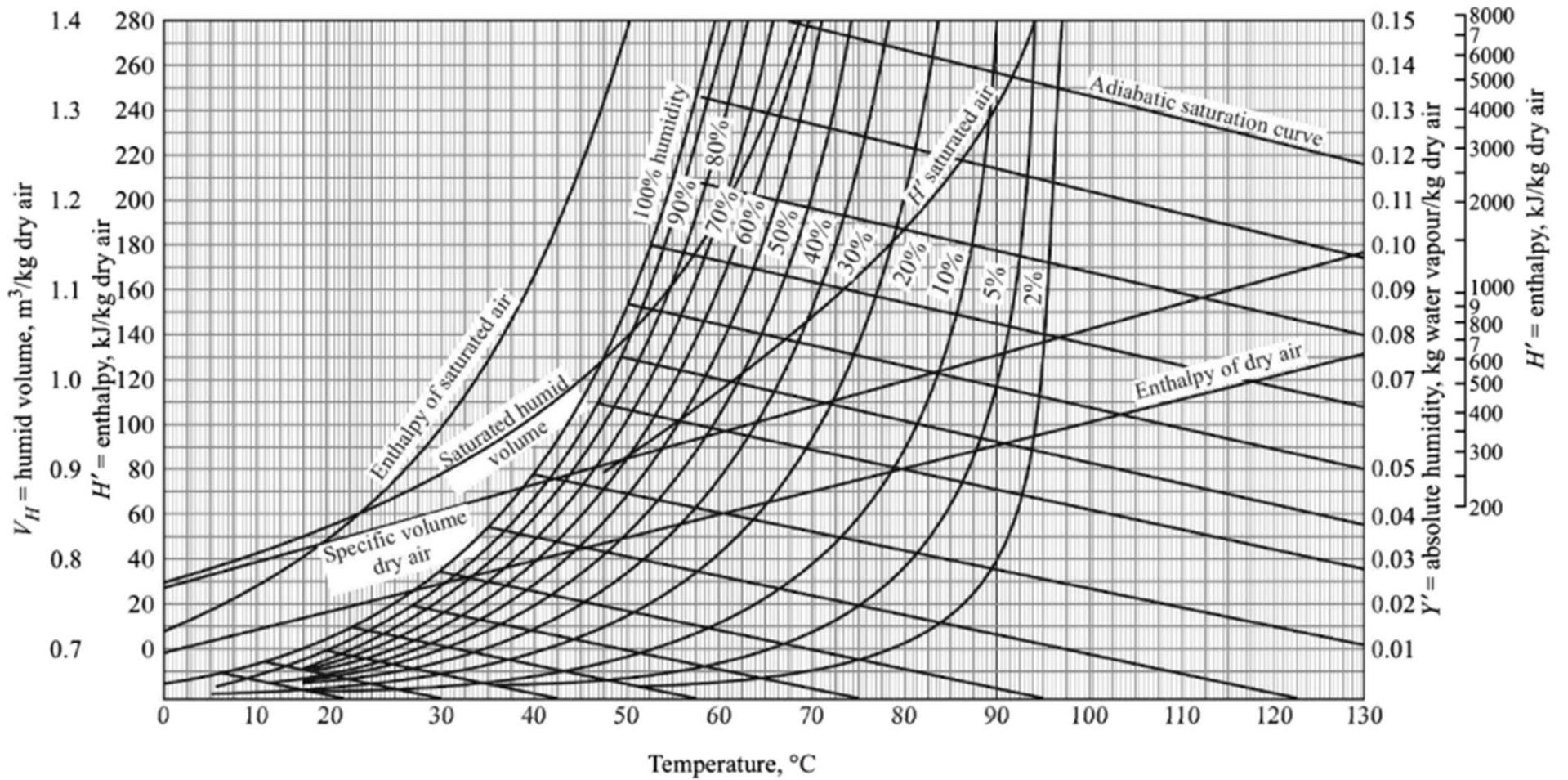$$= C_S (t_G - t_0) + Y'\lambda_0$$

The System Air-Water

A typical psychometric chart is shown in Figure from which the various properties of air water system can be obtained. Alternatively, the equation given above can be used.

Adiabatic Saturation Curves

Consider a system as shown in Figure. A feed stream of gas is contacted with a liquid spray and as a result of diffusion and heat transfer between the gas and liquid, the gas leaves the system humidified and temperature different from those at the entrance.
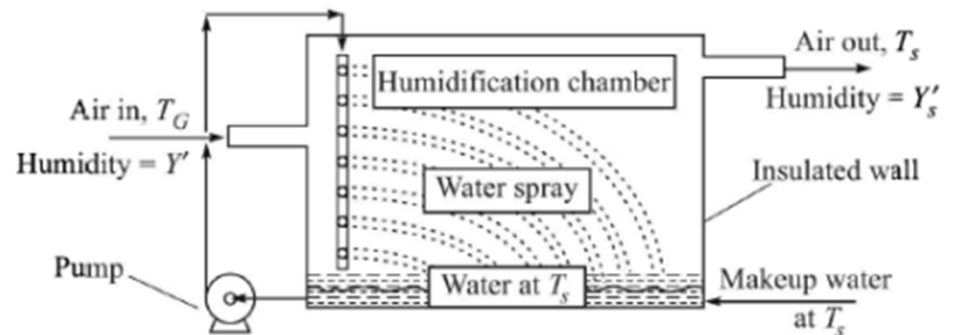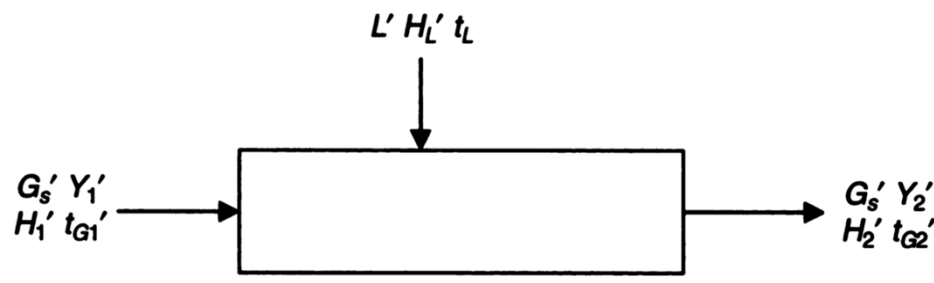
Assuming the operation to be adiabatic. A mass balance for substance A gives

$$L' = G_S' (Y_2' - Y_1')$$

Enthalpy balance yields

$$G_S' H_1' + L' H_L = G_S' H_2'$$

i.e.

$$H_1' + (Y_2' - Y_1') H_L = H_2'$$

Using the definition of enthalpy equation is modified as

$$C_{S1}(t_{G1} - t_0) + Y_1'\lambda_0 + (Y_2' - Y_1')C_{A,L}(t_L - t_0) = C_{S2}(t_{G2} - t_0) + Y_2'\lambda_0$$

If the gas mixture leaving the system is fully saturated and hence the various quantities are denoted as t_{as}, Y'_{as}, H_{as} and if the liquid enters at t_{as}, equation becomes

$$[C_B (t_{G1} - t_0) + Y'_1 C_A (t_{G1} - t_0)] + Y'_1 \lambda_0 + [Y'_{as} - Y'_1] C_{A,L} (t_{as} - t_0)$$
$$= [C_B (t_{as} - t_0) + Y'_{as} C_A (t_{as} - t_0)] + Y'_{as} \lambda_0$$

By subtracting $Y'_1 C_A t_{as}$ from both sides and further simplifying, we get equation as

$$(C_B + Y'_1 C_A) (t_{G1} - t_{as}) = C_{S1} (t_{G1} - t_{as})$$
$$= (Y'_{as} - Y'_1) [C_A(t_{as} - t_0) + \lambda_0 - C_{A,L}(t_{as} - t_0)]$$

i.e.
$$C_{S1} (t_{G1} - t_{as}) = (Y'_{as} - Y'_1)(\lambda_{as})$$

or
$$(t_{G1} - t_{as}) = (Y'_{as} - Y'_1) \left(\frac{\lambda_{as}}{C_{S1}} \right)$$

This is the equation of a curve on the psychrometric chart, the "adiabatic saturation curve" which passes through the points (Y'_{as}, t_{as}) on the 100 percent saturation curve and (Y'_1, t_{G1}).
Since the humid heat C_{S1} contains the term Y'_1, the curve is not straight but slightly concave upward.

For any vapor-gas mixture there is an adiabatic-saturation temperature t_{as} such that if contacted with liquid at t_{as}, the gas will become humidified and cooled.

If sufficient contact time is available, the gas will become saturated at (Y'_{as}, t_{as}) but otherwise will leave unsaturated at (Y'_2, t_{G2}), a point on the adiabatic-saturation curve for the initial mixture.

Wet Bulb Temperature (WBT)

It is the steady state temperature attained by a small amount of liquid evaporating into a large amount of unsaturated vapor-gas mixture.

To measure the wet bulb temperature, a thermometer or an equivalent temperature measuring device such as a thermocouple is covered by a wick which is saturated with pure liquid and immersed in a stream of moving gas having a definite temperature and humidity. The ultimate temperature attained is called wet bulb temperature and will be less than the dry bulb temperature (if the gas is unsaturated).

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 dew point, the vapor pressure of the liquid will be higher at the drop surface than the partial pressure of the vapor in the gas.

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 then cool down.

As soon as the liquid temperature is reduced below the dry-bulb temperature of the gas, heat will flow from the gas to the liquid, at an increasing rate as the temperature difference becomes larger.

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.

The mechanism of the wet-bulb process is essentially same as adiabatic saturation except humidity of the gas is assumed not to change during the process.

A drop of liquid shown in figure, at the steady state condition humidity of vapor gas mixture is not measurably affected by the evaporation because mass of the gas is so large as it passes the drop.

Since both heat and mass transfer occur simultaneously.
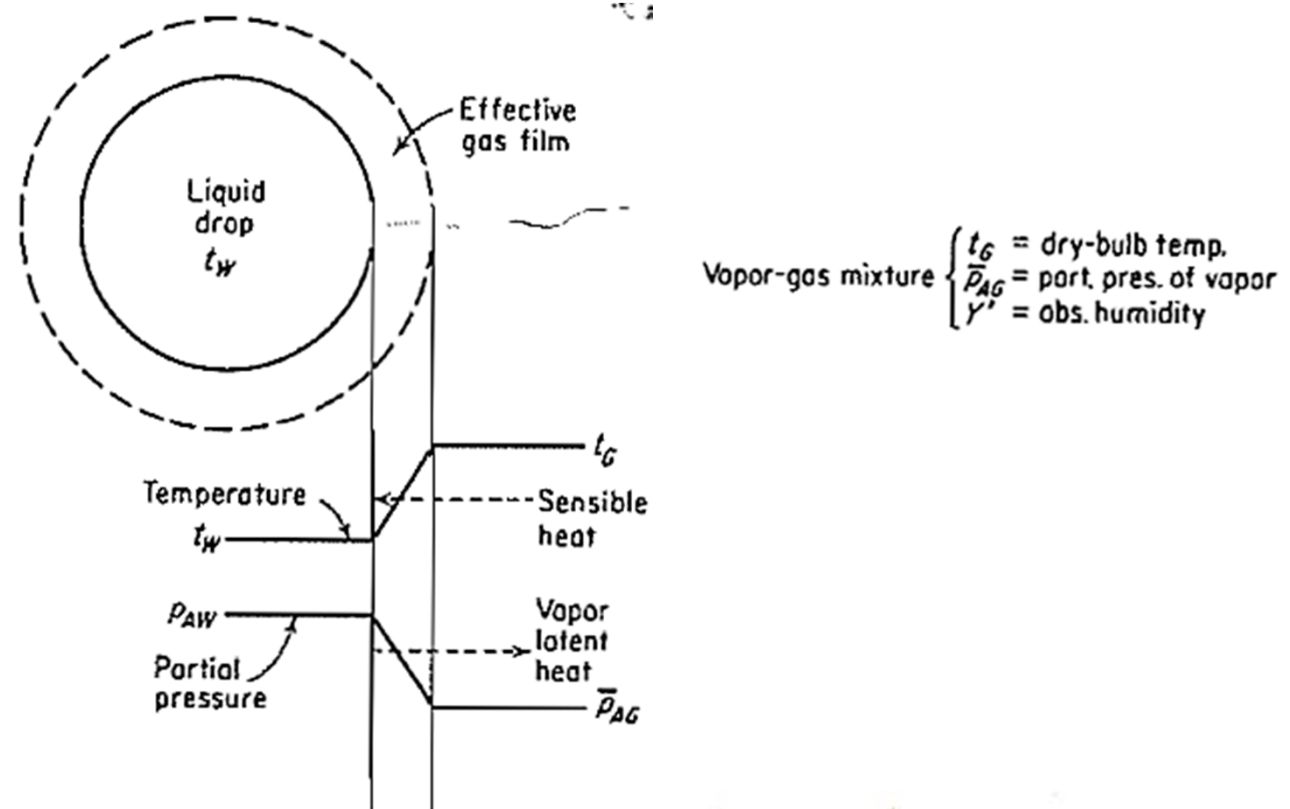
The total heat release at the interface q_t must include the effect produced due to latent heat of evaporation, when the transferred mass passes through the interface.

Equation
$$q_t = q_s + \lambda_A N_A + \lambda_B N_B$$

applies with $q_t = 0$ since no heat passes through the gas-liquid interface, and $N_B = 0$. Therefore

$$q_s = \frac{N_A M_A C_A}{1 - e^{-N_A M_A C_A / h_G}}(t_G - t_w) \approx h_G(t_G - t_w)$$

Approximation of the right-hand side is usually satisfactory since the rate of mass transfer is small. Further

$$N_A = F \ln \frac{1 - p_{A,w}/P_t}{1 - \bar{p}_{A,G}/P_t} \approx k_G(\bar{p}_{A,G} - p_{A,w})$$

Approximation on the right is usually satisfactory since N_A is small [N_A is negative if q_s is taken to be positive]. $p_{A,w}$ is the vapor pressure of A at t_w. Put these value in the above equation.

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

Where λ_w is the latent heat at the wet-bulb temperature per unit of mass. From this

$$t_G - t_w = \frac{\lambda_w M_A k_G (p_{A,\,w} - p_{A,\,G})}{h_G} = \frac{\lambda_w M_B \bar{p}_{B,\,M} k_G (Y'_w - Y')}{h_G}$$

Where $\bar{p}_{B,\,M}$ is the average partial pressure of the gas. Since $M_B \bar{p}_{B,\,M} k_G = k_Y$

Equation becomes

$$t_G - t_w = \frac{\lambda_w (Y'_w - Y')}{h_G / k_Y}$$

$t_G - t_w$ is the wet-bulb depression. The above equation can be used to calculate the wet-bulb temperature if h_G and $k_{Y'}$ are known or estimated using a suitable correlation. The quantities t_w and Y'_w are related through the vapor pressure equation.

However, the psychometric data show that under moderate conditions the ratio of the heat and the mass transfer coefficient, $h_G / K_{Y'} = 0.227$ kcal/kg °C.

For air-water vapor system, this is again equal to the humid heat of moist air C_s at moderate humidities.

$$\frac{h_G}{k_Y C_S} \approx 1$$

The above equation is known as Lewis relation.

For flow of gases past cylinders, such as wet-bulb thermometers, and past single spheres, the results for 18 vapor-gas systems are well correlated by

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

For dilute mixtures, where C_s = C_B, and with Pr for air taken as 0.707, equation becomes

$$\frac{h_G}{k_Y} = 1223\ Sc^{0.567}$$

Adiabatic saturation equation and wet bulb equation are identical. The adiabatic saturation curve (line) and the wet bulb temperature (line) merge in the case of air-water system only since Lewis number is unity for that system.

For other systems, these lines are different.