Gas-liquid contact operations

Direct contact of a gas with a pure liquid may have any of several purpose;

Adiabatic operation

a. Cooling a liquid
b. Cooling a hot gas
c. Humidifying a gas
d. Dehumidifying a gas

Non-adiabatic operation

a. Evaporative cooling
b. Dehumidifying a gas

Adiabatic operations

These are usually carried out in some sort of packed tower, countercurrent flow of gas and liquid.

General relationships will be developed first then particularized for specific operations.

Fundamental relationships

A tower of unit cross-sectional area. A mass balance for substance A over the lower part of the tower (envelop I) is

$$L' - L_1' = G_S'(Y' - Y_1')$$

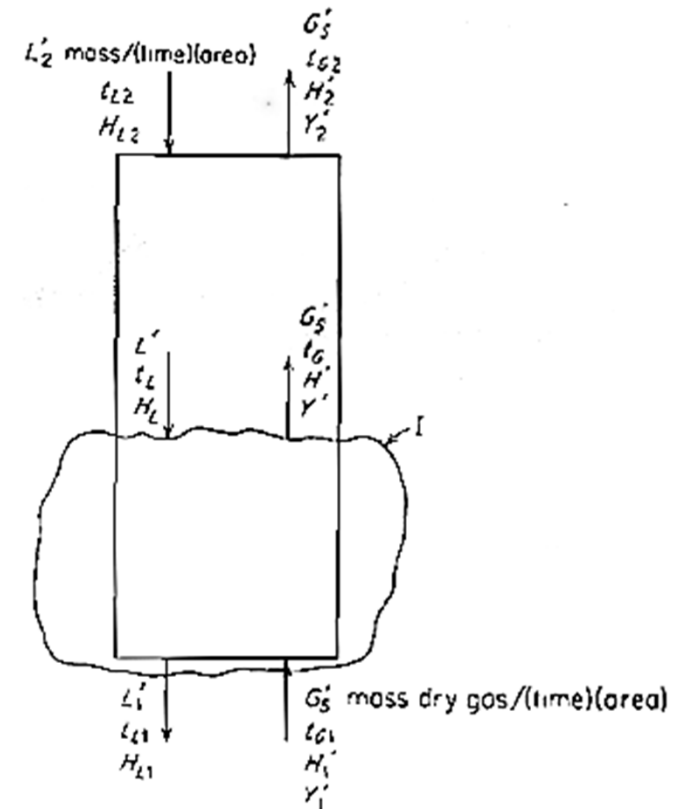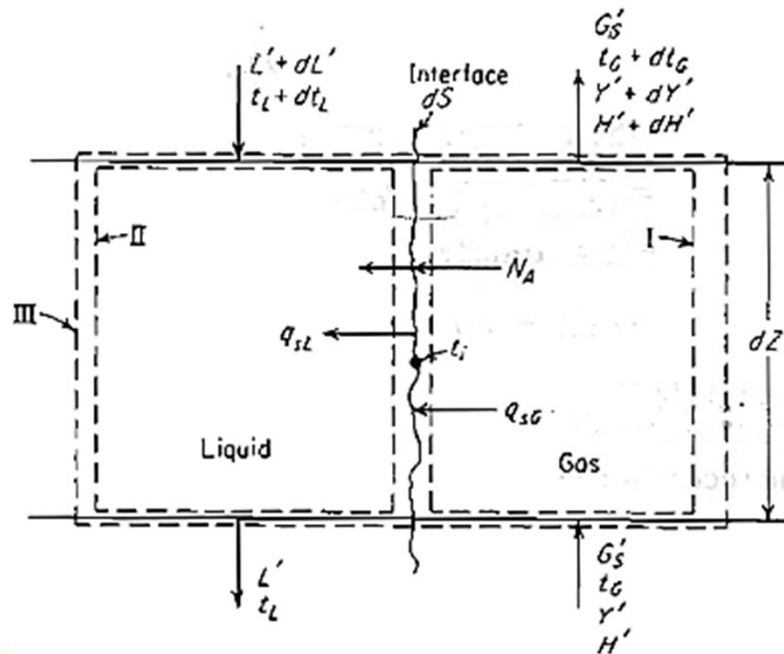$$dL' = G_S' \, dY' \quad \text{Wherein change in humidity of gas dY'}$$

Similarly, an enthalpy balance is

$$L'H_L + G'_S H'_1 = L'_1 H_{L1} + G'_S H'$$

These can be applied for entire column.

A section of the tower of differential height dZ where liquid and gas flowing side by side separated by the gas-liquid interface.

The changes in temperature, humidity, etc., are all differential over this section.

The interfacial surface of the section is dS. If the specific interfacial surface per packed volume is a (not the same as the packing surface a_p), since the volume of packing per unit cross-section is dZ, then dS = a dZ.

If the packing is incompletely wetted by the liquid, the surface for mass transfer a_m, which is the liquid-gas interface, will be smaller than that for heat transfer a_H, since heat transfer may also occurs between the packing and the fluids.

The transfer rates are then;

Mass, mass rate per tower cross-sectional area:

$$N_A M_A a_M \, dZ = M_A F_G \left(\ln \frac{1 - \bar{p}_{A,i}/P_t}{1 - p_{A,G}/P_t} \right) a_M \, dZ = -G_S' \, dY'$$

Sensible heat, as energy rate per tower cross sectional area:

Gas:

$$q_{sG} a_H \, dZ = \frac{N_A M_A C_A}{1 - e^{-N_A M_A C_A / h_G}} (t_G - t_i) a_H \, dZ = h_G' a_H (t_G - t_i) \, dZ$$

Liquid:

$$q_{sL} a_H \, dZ = h_L a_H (t_i - t_L) \, dZ$$

$\bar{p}_{A,i}$ is the vapor pressure of A at the interface temperature t_i, and $\bar{p}_{A,G}$ is the partial pressure in the bulk gas.

h_G' heat transfer coefficient accounts for the effect of mass transfer on heat transfer.

Enthalpy balance around the envelops shown in figure.

Envelop I:

Rate of enthalpy in = $G'_S H'$

Rate of enthalpy out = $G'_S(H' + dH') + (-G'_S\, dY')[C_A(t_G - t_0) + \lambda_0]$

Rate in − rate out = heat transfer rate

$$G'_S H' - G'_S(H' + dH') + (G'_S\, dY')\left[C_A(t_G - t_0) + \lambda_0\right] = h'_G a_H(t_G - t_i)\, dZ$$

dH′ is obtained by differentiation of the below equation and substituted to above equation

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

$$= C_S\, (t_G - t_0) + Y'\lambda_0$$

Then equation reduces to

$$-\, G'_S C_S\, dt_G = h'_G a_H(t_G - t_i)\, dZ$$

Envelop II:

Rate of enthalpy in = $(L' + dL')C_{A,\,L}(t_L + dt_L - t_0) + (-G'_S\, dY')C_{A,\,L}(t_i - t_0)$

Rate of enthalpy out = $L'C_{A,\,L}(t_L - t_0)$

Rate out = rate in + heat transfer rate

$$L'C_{A,L}(t_L - t_0) = (L' + dL')C_{A,L}(t_L + dt_L - t_0) - (G'_S\, dY')C_{A,L}(t_i - t_0)$$
$$+ h_L a_H(t_i - t_L)\, dZ$$

dL' is substituted form equation $dL' = G'_S\, dY'$ in the above equation and the second order differential term dY' dt$_L$ ignored, so equation becomes

$$L'C_{A,L}\, dt_L = (G'_S C_{A,L}\, dY' - h_L a_H\, dZ)(t_i - t_L)$$

Envelop III:
Rate of enthalpy in = $G'_S H' + (L' + dL')C_{A,L}(t_L + dt_L - t_0)$

Rate of enthalpy out = $L'C_{A,L}(t_L - t_0) + G'_S(H' + dH')$

Rate in = rate out (adiabatic operation)
$$G'_S H' + (L' + dL')C_{A,L}(t_L + dt_L - t_0) = L'C_{A,L}(t_L - t_0) + G'_S(H' + dH')$$

dL' and dH' is substituted form equation $dL' = G'_S\, dY'$ and dH' and the term dH' dt$_L$ is ignored, whereupon this becomes and applicable for adiabatic operation.

$$L'C_{A,L}\, dt_L = G'_S\{C_S\, dt_G + [C_A(t_G - t_0) - C_{A,L}(t_L - t_0) + \lambda_0]\, dY'\}$$

Water Cooling with Air

This is most important operation occurs in process industry. Warm water collected through heat exchanger, condensers, and other equipment is cooled by contact with atmospheric air for reuse.

The latent heat of water is so large that only a small amount of evaporation produces large cooling effects.

For air water system Lewis relation applies reasonably well because mass transfer rate and temperature level is low.

So the previous equation can be used in simplified form with some reasonable approximation.

Thus, if sensible heat term is ignored in comparison with the latent heat, then

$$L'C_{A,L}\,dt_L = G_S'C_S\,dt_G + G_S'\lambda_0\,dY' \approx G_S'\,dH \qquad [1]$$

Integrating the equation with assumption that L' is essentially constant (little evaporation). gives.

$$L'C_{A,L}(t_{L2} - t_{L1}) = G_S'(H_2' - H_1')$$

This enthalpy balance can be represented graphically by plotting the gas enthalpy H' against t_L as in figure.

The line ON on the chart represent the equation, and it passes through the points representing the terminal conditions for the two fluids.

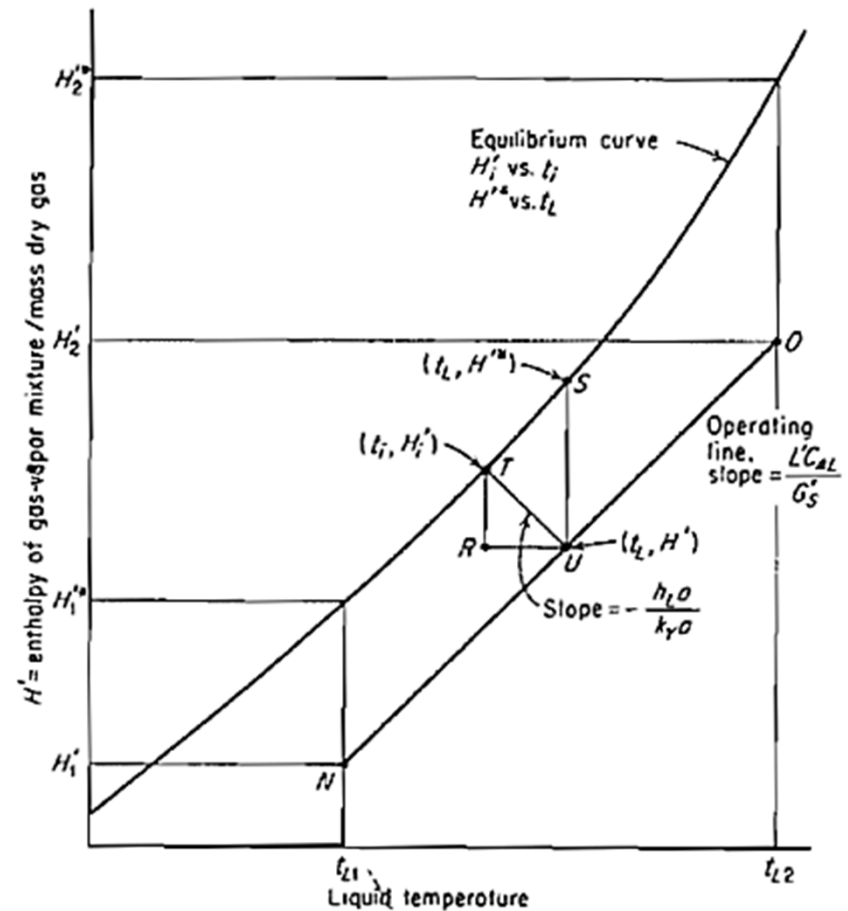As $L'_2 - L'_1$ is small in comparison with L', the line is straight and of slope $L'C_{A,L}/G'_S$.

The equilibrium curve in the figure is plotted for condition of the gas at the gas-liquid interface (enthalpy of saturated gas at each temperature).

If the mass transfer rate is small then

$$G'_S \, dY' = k_Y a_M (Y'_i - Y') \, dZ$$

and equation

$$G'_S C_S \, dt_G = h_G a_H (t_i - t_G) \, dZ$$

When the sensible heat of the transferred vapor is ignored, equation becomes

$$L' C_{A, L}\, dt_L = h_L a_H (t_L - t_i)\, dZ$$

Substituting all the values in equation [1]

$$G_S'\, dH' = h_G a_H (t_i - t_G)\, dZ + \lambda_0 k_Y a_M (Y_i' - Y')\, dZ$$

If $h_G a_H / C_S k_Y a_M = r$, this becomes

$$G_S'\, dH' = k_Y a_M \left[(C_S r t_i + \lambda_0 Y_i') - (C_S r t_G + \lambda_0 Y') \right] dZ$$

For the special case where r = 1 the term in the brackets are gas enthalpies.
r = 1 requires Le = 1 (air-water), and $a_m = a_H = a$
r = 2 have been observed for air-water with low liquid rates
So equation is

$$G_S'\, dH' = k_Y a (H_i' - H')\, dZ$$

In this equation mass transfer coefficient is used with an enthalpy driving force.
Combining all equation and put in equation [1]

$$G_S'\, dH' = k_Y a (H_i' - H')\, dZ = h_L a (t_L - t_i)\, dZ$$

A position in the apparatus corresponding to point U on the operating line, point T represents the interface conditions and the distance TR the enthalpy driving force H'$_i$ –H' within the gas phase.

By making constructions like the triangle RTU at several place along the operating line, corresponding H'$_i$ and H' values can be obtained.

Above equation then provides, assuming $k_y a$ is constant ,

$$\int_{H'_1}^{H'_2} \frac{dH'}{H'_i - H'} = \frac{k_Y a}{G'_S} \int_0^Z dZ = \frac{k_Y a Z}{G'_S}$$

The integral can be evaluated graphically and the packed height Z computed. The enthalpy integral of above equation is sometimes gives another interpretation. Thus,

$$\int_{H'_1}^{H'_2} \frac{dH'}{H'_i - H'} = \frac{H'_2 - H'_1}{(H'_i - H')_{av}} = N_{tG}$$

Where the middle part of the equation is the number of times the average driving force divides into the enthalpy change. This is a measure of the difficulty of enthalpy transfer, called the number of gas-enthalpy transfer units N_{tG}. Therefore,

$$Z = H_{tG} N_{tG}$$

Where the height of a gas-enthalpy transfer unit = $H_{tG} = G'_S / k_Y a.$

H_{tG} is frequently preferred over $k_Y a$ as a measure of packing performance since it is less dependent upon rates of flow and has the simple dimension of length.

However, if the overall driving force and the bulk fluid properties are used, the film conditions are replaced by equilibrium properties and equation becomes

$$N_{tOG} = \int_{H'_1}^{H'_2} \frac{dH'}{H'^* - H'} = \frac{K_Y a Z}{G'_S} = \frac{Z}{H_{tOG}}$$

Dehumidification of Air-Water Vapor

If a warm vapor-gas mixture is contacted with cold liquid so that the humidity of the gas is greater than that at the gas-liquid interface, vapor will diffuse toward the liquid and the gas will be dehumidified.

Sensible heat can be transferred as a result of temperature difference within the system.

The operating line on the gas-enthalpy-liquid-temperature graph will be above the equilibrium curve, the driving force is H' − H'*, and equation for N_{tOG} can be used with this driving force.

Recirculating Liquid-Gas Humidification-Cooling

This is a special case where the liquid enters the equipment at the adiabatic-saturation temperature of the entering gas.

This can be achieved by continuously reintroducing the exit liquid to the contactor immediately, without addition or removal of heat on the way shown in figure.

In such a system, the temperature of the entire liquid will fall to, and remain at, the adiabatic-saturation temperature.

The gas will be cooled and humidified, follow the path of the adiabatic-saturation curve on the psychrometric chart which passes through the entering gas conditions.

Depending upon the degree of

contact, the gas will approach more or less closely equilibrium with the liquid, or its adiabatic-saturation conditions.
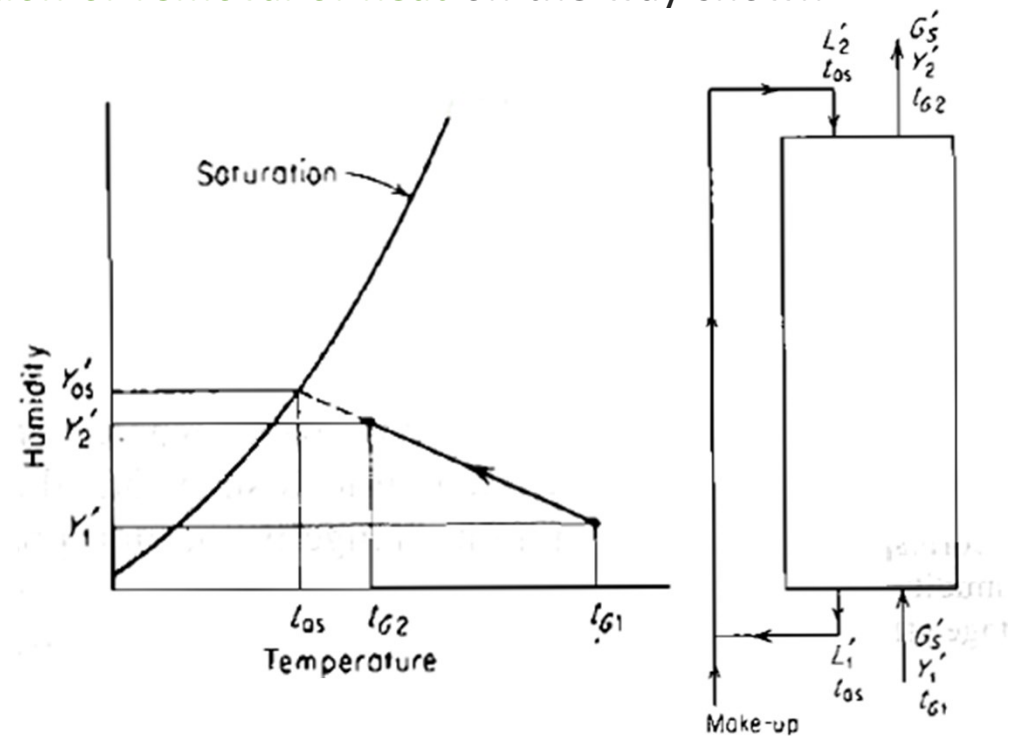
Suppose makeup liquid enters at adiabatic-saturation temperature, minor deviations from this temperature can be ignored because quantity of evaporation is so small relative to the total liquid circulation.

The enthalpy of the gas is practically a function of its adiabatic-saturation temperature, which remain constant throughout the operation.

The enthalpy of the liquid at constant temperature is also constant, so that an operating line would be merely a single point on the equilibrium curve. Therefore, operating diagram cannot be used for design purposes.

The temperature and humidity changes, which lie entirely within the gas phase, can be use shown in figure.

If mass transfer is used as a basis for design, than equation becomes

$$G'_S \, dY = k_Y a (Y'_{as} - Y') \, dZ$$

$$\int_{Y'_i}^{Y'_2} \frac{dY'}{Y_{as} - Y'} = \frac{k_Y a}{G'_S} \int_0^Z dZ$$

Since Y'_{as} is constant,

$$\ln \frac{Y'_{as} - Y'_1}{Y'_{as} - Y'_2} = \frac{k_Y a Z}{G'_S}$$

Equation can be used directly, or it can be rearranged by solving for G'$_s$ and multiplying each side by Y'$_2$ – Y'$_1$ or its equivalent,

$$G'_S(Y'_2 - Y'_1) = \frac{k_Y aZ[(Y'_{as} - Y'_1) - (Y'_{as} - Y'_2)]}{\ln[(Y'_{as} - Y'_1)/(Y'_{as} - Y'_2)]} = k_Y aZ(\Delta Y')_{av}$$

Where (ΔY')$_{av}$ is the logarithmic average of the humidity-difference driving forces at the ends of the equipment. Alternatively,

$$N_{tG} = \frac{Y'_2 - Y'_1}{(\Delta Y')_{av}} = \ln\frac{Y'_{as} - Y'_1}{Y'_{as} - Y'_2}$$

$$H_{tG} = \frac{G'_S}{k_Y a} = \frac{Z}{N_{tG}}$$

Where N$_{tG}$ is the number of gas-phase transfer units and H$_{tG}$ the corresponding height of a transfer unit.

In contacting operation, in one theoretical stage maximum change in one of the phase approaches equilibrium with other.

Since the humidity in adiabatic equilibrium with the liquid is Y'$_{as}$, the Murphree gas-phase stage efficiency is

$$E_{MG} = \frac{Y'_2 - Y'_1}{Y'_{as} - Y'_1} = 1 - \frac{Y'_{as} - Y'_2}{Y'_{as} - Y'_1} = 1 - e^{-k_Y aZ/G'_S} = 1 - e^{-N_{tG}}$$

If heat transfer is used as the basis for design, similar treatment of enthalpy balance equation of envelop I leads to

$$G_S' C_{S1}(t_{G1} - t_{G2}) = \frac{h_G a Z\left[(t_{G1} - t_{as}) - (t_{G2} - t_{as})\right]}{\ln\left[(t_{G1} - t_{as})/(t_{G2} - t_{as})\right]} = h_G a Z (\Delta t)_{av}$$

Where $h_G a$ is the volumetric-heat-transfer coefficient of sensible-heat transfer between the bulk of the gas and the liquid surface.

Nonadiabatic Operation Evaporative Cooling

In evaporative cooling, a fluid is cooled while it flows through a tube. Water flows in a film or spray about the outside of the tube, and air is blown past the water to carry away the heat removed from the tube-side fluid shown in figure.

Advantage is taken of the large heat transfer rate resulting when the spray water is evaporated into the air stream.

The tube-side fluid usually flows through a bank of tubes in parallel shown in next figure.
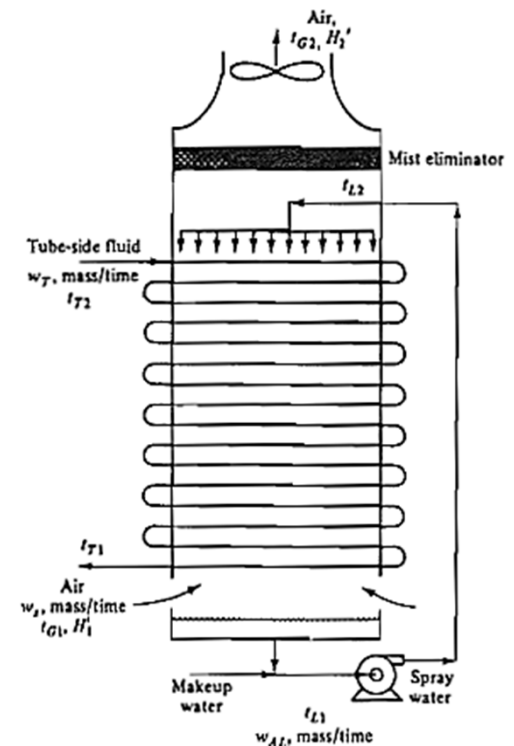
Since the water is recirculated from top to bottom of the heat exchanger, the temperature t_{L2} at which it enters is the same as that at which it leaves, t_{L1}.

While the water temperature does not remain constant as it passes through the device, it does not vary greatly from the terminal value.

The temperature and gas enthalpy profiles through a typical section of the exchanger shown in figure.

(b)

(c)

In the present analysis the heat transfer system will be divided at the bulk water temperature t_L, corresponding to a saturation gas enthalpy $H'_1{}^*$.

The overall heat transfer coefficient U_o based on the outside tube surface, from tube fluid to bulk water, is then given by

$$\frac{1}{U_o} = \frac{d_o}{d_i h_T} + \frac{d_o}{d_{av}} \frac{z_m}{k_m} + \frac{1}{h'_L}$$
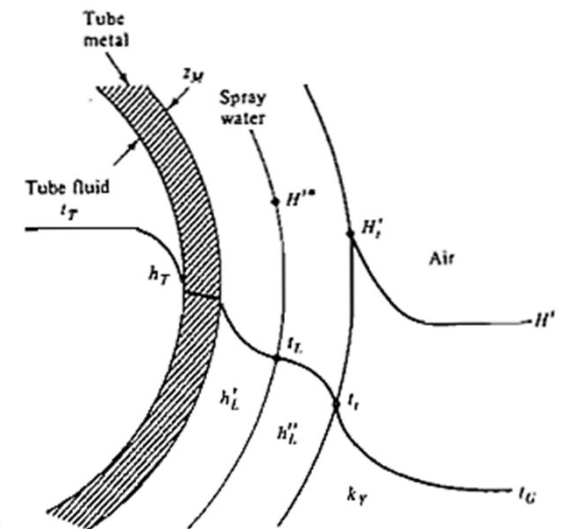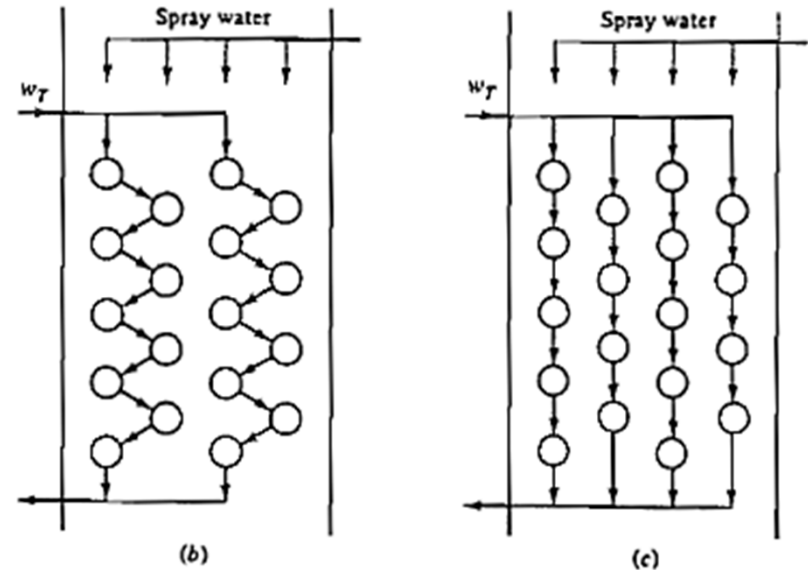
The overall coefficient K_Y for use with gas enthalpies, from $H'_1{}^*$ to H', is

$$\frac{1}{K_Y} = \frac{1}{k_Y} + \frac{m}{h''_L}$$

Where m is the slope of chord such as chord TS on figure

$$m = \frac{H'^* - H'_i}{t_L - t_i}$$

Since the variation in t_L is small, for all practical purpose m can be taken as constant

$$m = \frac{dH'^*}{dt_L}$$

If A_0 is the outside surface of all the tubes, A_0x is the area from the bottom to the level where the bulk water temperature is t_L. Here x is the fraction of the heat transfer surface to that level.

For a differential portion of the exchanger, the heat loss by the tube side fluid is

$$w_T C_T \, dt_L = U_o A_o \, dx(t_T - t_L)$$

whence

$$\frac{dt_T}{dx} = \frac{U_o A_o}{w_T C_T}(t_T - t_L) \qquad [1]$$

The heat lost by the cooling water is

$$w_{A,L} C_{A,L} \, dt_L = K_Y A_o \, dx(H'^* - H') - U_o A_o \, dx(t_T - t_L)$$

or

$$\frac{dt_L}{dx} = \frac{K_Y A_o}{w_{A,L} C_{A,L}}(H'^* - H') - \frac{U_o A_o}{w_{A,L} C_{A,L}}(t_T - t_L) \qquad [2]$$

Heat gained by the air is

$$w_S \, dH' = K_Y A_o \, dx(H'^* - H')$$

$$\frac{dH'}{dx} = \frac{K_Y A_o}{w_S}(H'^* - H') \qquad [3]$$

Subtraction of equation [2] from equation [1] result in

$$\frac{d(t_T - t_L)}{dx} + \alpha_1(t_T - t_L) + \beta_1(H'^* - H') = 0 \qquad [4]$$

Multiplying equation [2] by m and then subtracting equation [3] provides

$$\frac{d(H'^* - H')}{dx} + \alpha_2(t_T - t_L) + \beta_2(H'^* - H') = 0 \qquad [5]$$

Where $$\alpha_1 = -\left(\frac{U_o A_o}{w_T C_T} + \frac{U_o A_o}{w_{A,L} C_{A,L}}\right) \qquad \alpha_2 = \frac{m U_o A_o}{w_T C_T}$$

and $$\beta_1 = \frac{K_Y A_o}{W_{A,L} C_{A,L}} \qquad \beta_2 = -\left(\frac{m K_Y A_o}{w_{A,L} C_{A,L}} - \frac{K_Y A_o}{w_S}\right)$$

Integration of equation [4] and [5], with U_0 and K_Y assumed constant, yields

$$t_T - t_L = M_1 e^{r_1 x} + M_2 e^{r_2 x}$$

$$H'^* - H' = N_1 e^{r_1 x} + N_2 e^{r_2 x}$$

For use with average driving forces, these yields

$$Q = w_T C_T(t_{T2} - t_{T1}) = w_S(H_2' - H_1') = U_o A_o(t_T - t_L)_{av} = K_Y A_o(H'^* - H')_{av}$$

Where

$$(t_T - t_L)_{av} = \frac{M_1}{r_1}(e^{r_1} - 1) + \frac{M_2}{r_2}(e^{r_2} - 1)$$

$$(H'^* - H')_{av} = \frac{N_1}{r_1}(e^{r_1} - 1) + \frac{N_2}{r_2}(e^{r_2} - 1)$$

In these expression r_1 and r_2 are the roots of the quadratic equation

$$r^2 + (\alpha_1 + \beta_2)r + (\alpha_1 \beta_2 - \alpha_2 \beta_1) = 0$$

and

$$N_j = \frac{M_j(r_j + \alpha_1)}{\beta_1} \qquad j = 1, 2$$

These expression permit the design of the evaporative cooler under given values of the various transfer coefficients.

Use standard correlation for h_T for sensible heat change or vapor condensation inside tubes.

|		Equation
Tube OD	19.05 mm	
Arrangement	Centre	$h'_L = (982 + 15.58 t_L)\left(\dfrac{\Gamma}{d_o}\right)^{1/3}$ W/m$^2 \cdot$ K
Pitch	Triangular	
Γ/d_0	1.36 to 3.6 kg H$_2$O/m^2.s	$h''_L = 11\,360$ W/m$^2 \cdot$ K
G'$_S$,min	0.68 to 5 kg/m^2.s	$k_Y = 0.0493\left[G'_{S,\,min}(1 + Y'_{av})\right]^{0.905}$ kg/m$^2 \cdot$ s $\cdot \Delta Y'$
Water temperature t_L	15 to 70°C	
For other tube OD		$Sh = const\ Re^n\ Sc^{n'}$ k_Y can be expected to vary as $G^n d_o^{n-1}$, or in this case as $d_o^{-0.095}$

Equipments

There are various types of equipments available in industries for humidification operations. Conventional packed and tray towers are very effective in these services.
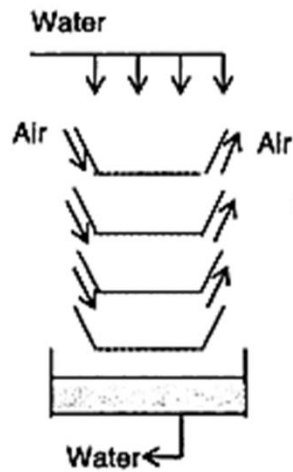
Water Cooling Tower

Typical classification of cooling tower is shown figure. Normally, more than 90 of the tower will have voids such that the pressure drop is very low. tray towers are used for these operation.
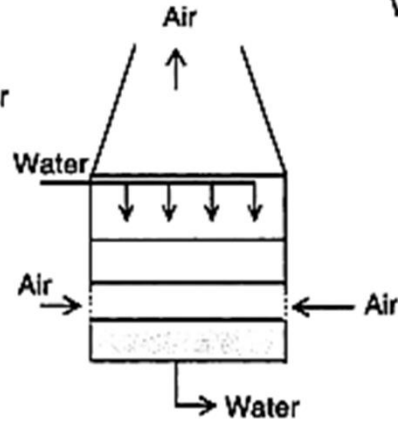
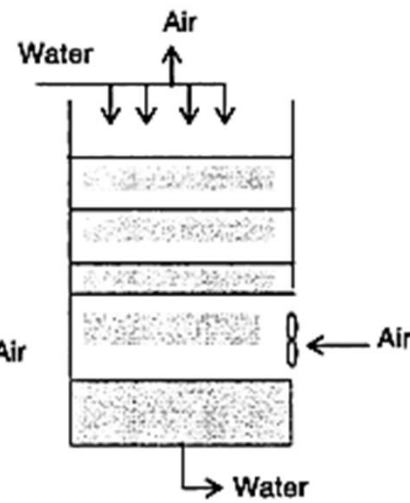Horizontal slats in staggered arrangement is used as internal packing, made of wood or plastic material.
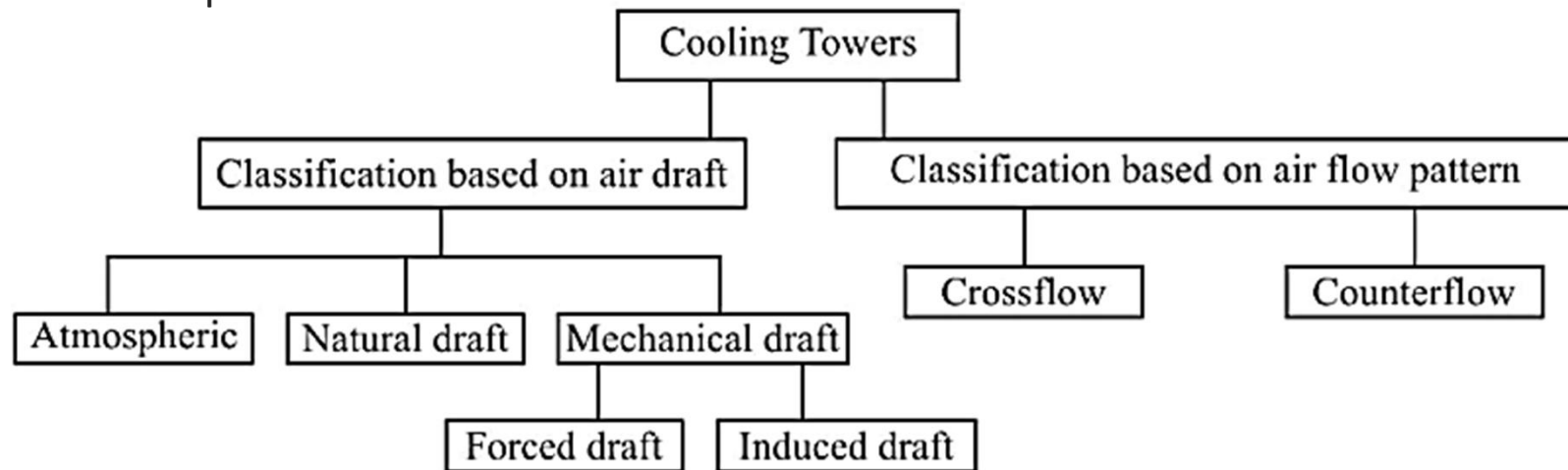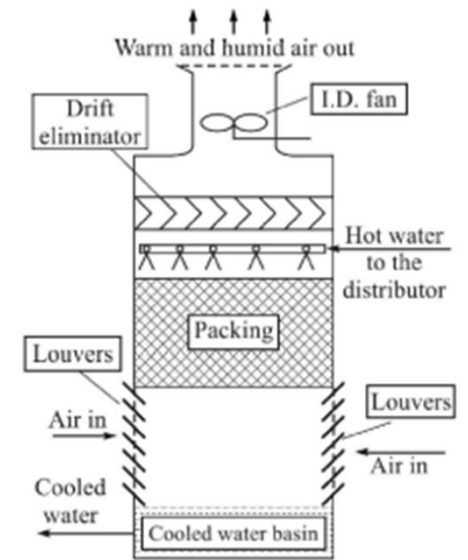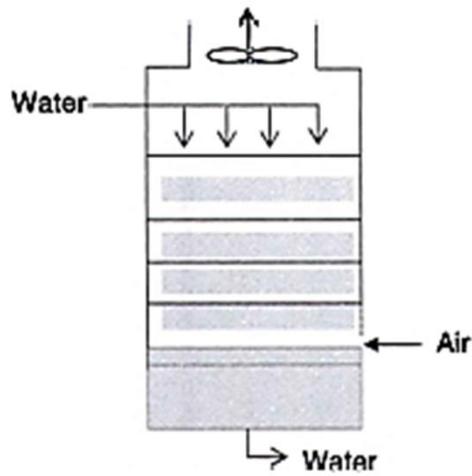

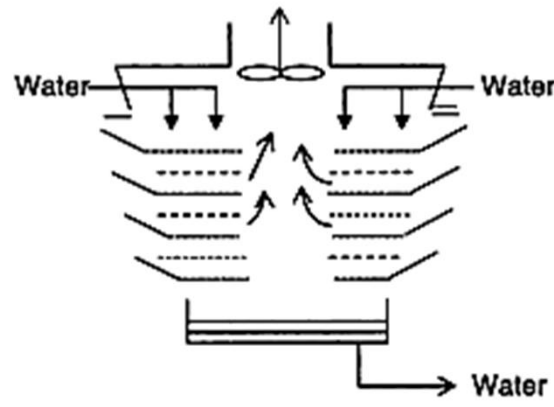Classification of cooling towers.

(a) Atmospheric

(b) Natural draft

(c) Forced draft

(d) Induced draft

(d) Countercurrent draft

(e) Crosscurrent draft

Spray chambers

A typical spray chamber is shown in figure. They are generally used for humidification and cooling operations under adiabatic conditions. They can also used for dehumidification process.

Heaters are provided at the inlet and outlet points of air (for large humidity change). Same thing can be achieved by using hot water in the spray chamber.

Similarly by using water at a low temperature, dehumidification can be achieved.