



Spring Semester course

CH31010: Mass Transfer II

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L3: Gas Liquid Contact Operations

Types of Gas-Liquid contact operations

Adiabatic operations

Cooling a liquid: Cooling occurs by sensible heat transfer and evaporation, in contact with atmospheric air.

Cooling a hot gas: Direct contact leads to a non-fouling heat exchanger, which is very effective.

Humidifying gas: For controlling the moisture content of air for drying.

Dehumidifying gas: Contact of a warm vapour-gas mix with cold liquid results in condensation of the vapour (e.g. applications in air conditioning, recovery of solvent vapours from gas)

Non-adiabatic operations

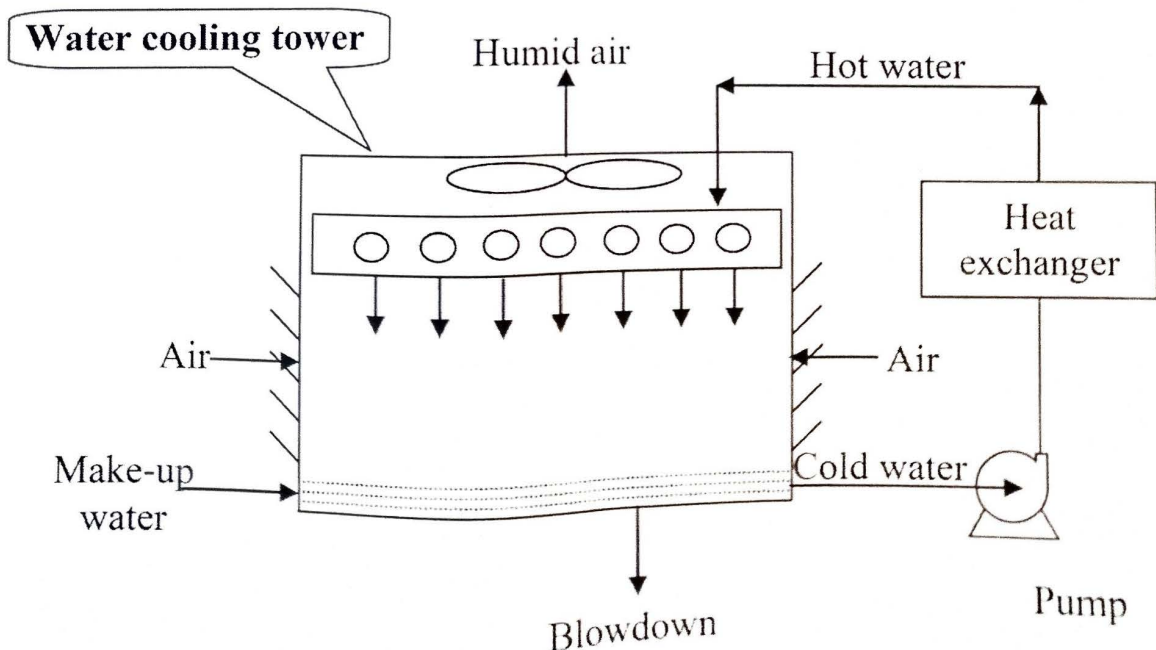
Evaporative cooling: A liquid / gas inside a pipe is cooled by a flowing water film outside, the latter is cooled by contact with air.

Dehumidifying gas: A gas-vapour mix is contacted with refrigerated tubes, and the vapour condenses over the pipes.

Cooling tower

A cooling tower is a special type of heat exchanger in which the warm water and the air are brought in direct contact for '**evaporative cooling**'. It provides a very good contact of air and water in terms of the contact area and mass transfer coefficient of water vapor while keeping air pressure drop low. Enthalpy of air is lower than enthalpy of water. Sensible heat and latent heat transfer take place from water drop to surrounding air.

Thus, cooling is accomplished by sensible heat transfer from water to air and evaporation of a small portion of water. The hot water which is coming from heat exchanger is sprayed at the top of the cooling tower. Air enters through the louvers at the two opposite walls of the cooling tower. During cooling process of water, around 2% water is evaporated. Make water is used to compensate the water loss due to evaporation. Blow-down is there to drain a part of water containing solid deposit. The exit cold water from the cooling tower is used in the heat exchanger or other unit operation.



Factors that affect the performance of cooling water:

Temperature of air

Temperature of incoming water

Contact efficiency between air and water in terms of the mass transfer coefficient

Contact time between air and water

Uniformity of the distribution of the phases within the tower

Air pressure

Contact time between air and water

Types of cooling tower:

Refer to the document "[CT-classification.pdf](#)"

Design/Sizing of a cooling tower

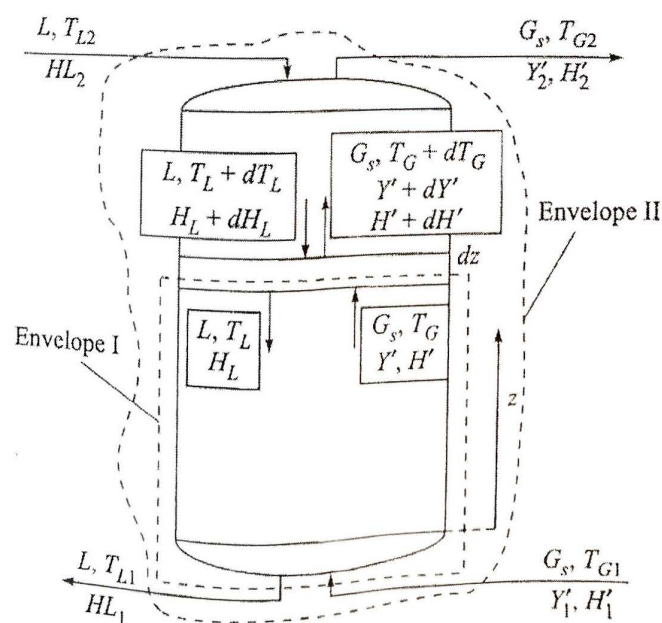
Design specifications:

1. Tower cross-section / diameter
2. Tower height

Assumptions:

- (i) Rate of vaporization is small and loss of feed water is insignificant
- (ii) Adiabatic cooling (no heat exchange through the tower walls)

Mass & Enthalpy balance



Differential enthalpy balance over Δz , $Lc_w dT_L = G_s dH'$

The enthalpy balance over the envelope I gives

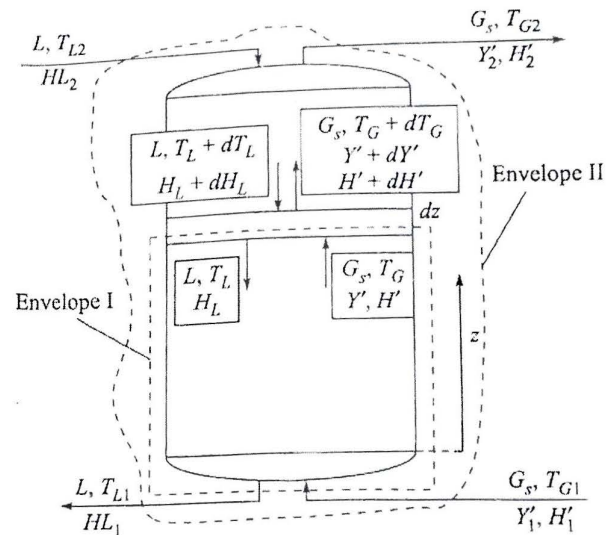
$$Lc_{wL}(T_L - T_{L1}) = G_s(H' - H'_1)$$

Operating line for the air-water contact

Slope of the Operating line: $\frac{c_{wL}L}{G_s}$

Making an enthalpy balance across the entire tower (Envelope II):

$$Lc_{wL}(T_{L2} - T_{L1}) = G_s(H'_2 - H'_1)$$



The rate of transfer of water vapour to air in the differential volume is

$$G_s dY' = k_{Y'} \bar{a} dz (Y'_i - Y')$$

where

$k_{Y'}$ = mass transfer coefficient of water vapour

\bar{a} = specific interfacial area of the air-water contact

Y'_i = humidity of air at the air-liquid interface.

decrease in the temperature of the gas because of sensible heat transfer

$$-G_s c_H dT_G = h_G \bar{a} dz (T_G - T_l)$$

Definition of the enthalpy of the gas: $H' = Y'\lambda_0 + c_H(T - T_0)$

The differential form multiplied by G_s results into

$$\begin{aligned} G_s dH' &= G_s \lambda_0 dY' + G_s c_H dT_G \\ &= G_s \lambda_0 dY' - h_G \bar{a} dz (T_G - T_i) \\ &= -h_G \bar{a} dz (T_G - T_i) + \lambda_0 k_{Y'} \bar{a} dz (Y_i' - Y') \\ &= k_{Y'} \bar{a} dz [(h_G/k_{Y'})(T_i - T_G) + \lambda_0 (Y_i' - Y')] \end{aligned}$$

Using the result $(h_G/k_{Y'}) = c_H$ in the above equation,

$$\begin{aligned} G_s dH' &= k_{Y'} \bar{a} dz [c_H (T_i - T_G) + \lambda_0 (Y_i' - Y')] \\ &= k_{Y'} \bar{a} dz [\{Y_i' \lambda_0 + c_H (T_i - T_0)\} - \{\lambda_0 Y' + c_H (T_G - T_0)\}] \end{aligned}$$

Using the definition of enthalpy of the gas

$$G_s dH' = k_{Y'} \bar{a} dz (H_i' - H')$$

$$\int_{H_1'}^{H_2'} \frac{dH'}{H_i' - H'} = \frac{k_{Y'} \bar{a}}{G_s} \int_0^z dz = \frac{k_{Y'} \bar{a}}{G_s} z$$

Invoking the concept of transfer units, we can define

$$N_{tG} = \int_{H_1'}^{H_2'} \frac{dH'}{H_i' - H'} \quad \text{and} \quad H_{tG} = \frac{G_s}{k_{Y'} \bar{a}}$$

where

N_{tG} = number of gas-enthalpy transfer units

H_{tG} = height of a gas-enthalpy transfer unit.

Height of the packed section, $z = H_{tG} N_{tG}$

Tie lines:

If $h_L \bar{a}$ is the volumetric individual heat transfer coefficient on the water-side of the interface, a differential heat balance equation over a small section of the packing gives

$$Lc_{wL}dT_L = h_L \bar{a} dz(T_L - T_{Li})$$

Using the relations: $Lc_{wL}dT_L = G_S dH' = k_{Y'} \bar{a} dz(H'_i - H')$

You can write: $k_{Y'} \bar{a} dz(H'_i - H') = -h_L \bar{a} dz(T_{Li} - T_L)$

$$\Rightarrow \frac{H'_i - H'}{T_{Li} - T_L} = -\frac{h_L}{k_{Y'}}$$

Alternative form of N_{tG} :

An alternative form of N_{tG} can be obtained by substituting $G_S dH' = L c_{wL} dT_L$

$$Lc_{wL}dT_L = k_{Y'} \bar{a} dz(H'_i - H') \Rightarrow \int_{T_{Li}}^{T_{Lo}} \frac{dT_L}{H'_i - H'} = \frac{k_{Y'} \bar{a}}{Lc_{wL}} \int_0^z dz = \frac{k_{Y'} \bar{a}}{Lc_{wL}} z$$

Steps of the design calculations:

- (a) Specify the inlet and outlet temperatures and the flow rate of warm water. These quantities are governed by the requirement of cooling water in the heat exchangers and other cooling devices in a plant.
- (b) Select the design values of the dry-bulb and the wet-bulb temperature of air at the proposed geographical location of the cooling tower. The relevant data are available at the weather office in the region.
- (c) Draw the 'equilibrium curve', i.e. the saturation-humidity curve. The enthalpy data can be calculated using the vapour pressure equation for water and the physical properties of air and water vapour.
- (d) Locate the lower terminal of the operating line Q on the T_L-H' plane by the point (T_{L1}, H'_1) . This point indicates the condition at the bottom of the tower in the case of water cooling.
- (e) Draw a tangent to the equilibrium line through the point Q . The slope of this tangent gives the ratio of the liquid and the minimum gas flow rates.

- (f) The upper terminal of the operating line is located by the point $P(T_{L2}, H'_2)$. It is the point where the operating line of the slope determined in step (e) meets the vertical line through T_{L2} . It can also be located by calculating the top end enthalpy H'_2 from

$$Lc_{wL}(T_{L2} - T_{L1}) = G_s(H'_2 - H'_1)$$

- (g) Evaluate the integral $\int_{H'_1}^{H'_2} \frac{dH'}{H'_i - H'}$ or $\int_{T_{Li}}^{T_{Lo}} \frac{dT_L}{H'_i - H'}$

This is the number of gas-phase enthalpy transfer units. The volumetric transfer coefficients $k_Y \bar{a}$ and $h_L \bar{a}$ are required for this purpose. As described above, a set of parallel lines (sometimes called *tie lines*) of slope $-h_L \bar{a} / k_Y \bar{a}$ is drawn between the operating line and the equilibrium line. The values of H' and H'_i are taken from the terminals of these lines. The integral is evaluated numerically or graphically.

- (h) The height of the transfer unit is $G_s / k_Y \bar{a}$. The tower height is the product of the number of transfer units (N_{tG}) and the height of each of the units (H_{tG}).

Example problem:

Warm water at 45°C is to be cooled to 30°C by countercurrent contact with air in a tower packed with wood slats. The inlet air has a dry-bulb temperature of 31°C and a wet-bulb temperature of 22°C . The mass flow rate of water is $6000 \text{ kg/m}^2\cdot\text{h}$ and that of air is 1.4 times the minimum. The individual gas-phase mass transfer coefficient is $k_{Y'}\bar{a} = 6000 \text{ kg}/(\text{m}^3)(\text{h})(\Delta Y')$. The volumetric water-side heat transfer coefficient is given by $h_L\bar{a} = 0.059L^{0.51}G_s$, in $\text{kcal}/\text{m}^3\cdot\text{h}\cdot\text{K}$, where L and G_s are mass flow rates of water and air (dry basis).

Determine (a) the dry air flow rate to be used, (b) the height of packing, and (c) the wet-bulb depression at the bottom of the tower.