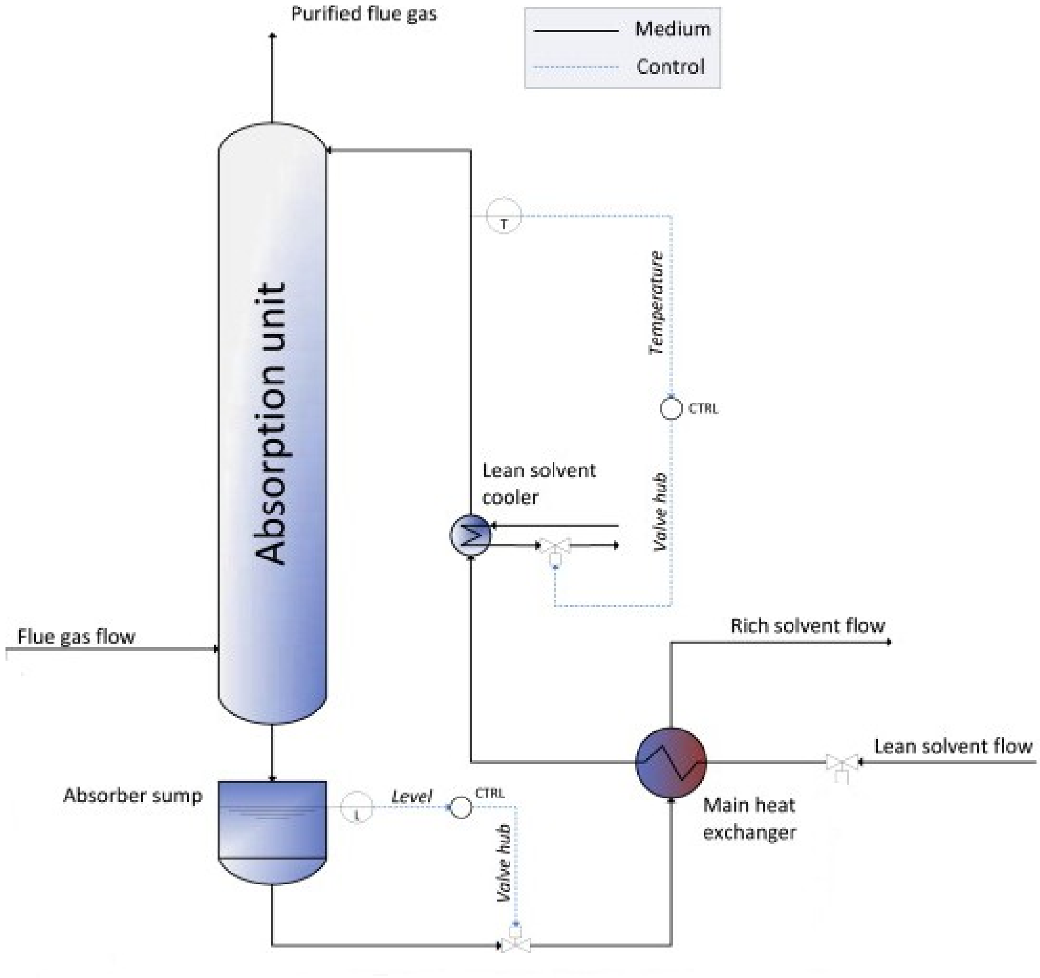
ABSORPTION

- Absorption refers to an operation in which the transfer of material is from a gas phase to a liquid phase. A gas is absorbed by means of liquid in which the solute gas is more or less soluble from its mixture with an inert gas as well as more or less insoluble gas. The liquid is essentially immiscible in the gas phase.
- Removal of solute from the gas mixture by using suitable liquid solvent.
- The separation of ammonia from an air-ammonia mixture by means of water is a typical example of absorption.



<u>**Selection of solvent for absorption and stripping**</u>

(A) Gas Solubility: High solubility of a gas in the solvent is preferred, utilizing low quantity of solvent. Absorbent should not dissolve carrier gas. Similar chemical nature of solute and absorbent (solvent) gives a good solubility. If chemical reaction takes place between solute and solvent, rate of absorption is extremely high. But the reaction should be reversible to recover solvent during desorption.

(B) Volatility: Low volatility or low vapor pressure of the solvent enhances the adsorption operation as solvent loss with carrier gas is very small. Sometimes, a second less volatile solvent is used to recover the first solvent.

(C) Viscosity: For better absorption, a solvent of low viscosity is required. In mechanically agitated absorber, greater amount of power is required for high viscous solvent and flooding is also caused at lower liquid and gas flow rates.

(D) Corrosiveness: Non-corrosive or less corrosive solvent reduces equipment construction cost as well as maintenance cost.

(E) Cost: The solvent should be cheap so that losses will be insignificant and should be easily available.

(F) Toxicity and Hazard: The solvent should be non-toxic, non-flammable, non-hazardous and should be chemically stable.

Types of Absorbers

1. Tray column
2. Packed column

Packing Materials

Packing materials are utilized to provide large interfacial area of contact between two phases. These are made from either of ceramics, metals or plastics. A number of packing materials with

various size, shape and performance are available. These are classified into three types, namely, **dumped or random**, **structured** and **grid**.

The packing materials have following characteristics:

(a) Cost: The cost of the packing materials should be very low.

(b) Surface area: A large interfacial area of contact is always recommended. In that case, pressure drop will be more.

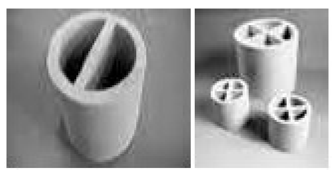
(c) Void volume: A high void volume is needed to maintain low pressure drop.

(d) Fouling resistance: Packing materials should not trap suspended solids present in liquid. Bigger packing materials generally give low fouling resistance.

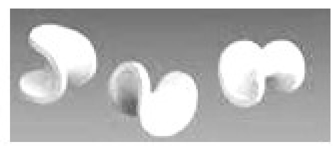
(e) Mechanical strength: Good mechanical strength is desired for choosing packing materials as this will not break or deform during filling or operation.

(f) Uniform flow of streams: Stack of packing materials should have uniform void spaces through which both the streams (gas and liquid) can flow uniformly. Nonuniform flow of streams leads to stagnant liquid pool which in turn gives low mass transfer.

(a) Raschig rings;



(b) Lessing rings and modified Raschig rings (Cross-partition rings)



(c) Berl saddle

(a) Intalox saddle and modification

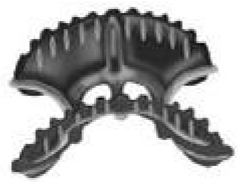
(b) Pall ring and modification

(a) Intalox Metal Tower Packing (IMTP)

(b) Nutter ring

(c) Cascade Mini-Ring (CMR)

(d) Jaeger Tripac



(e) Koch Flexisaddle

(f) Nor-Pac

(g) Hiflow ring

<u>Structured Packings</u>

These materials are used widely as packing materials in packed tower due to low gas pressure drop and improved efficiency. Corrugated metal sheet structured packing and Wire mesh structured packing materials are widely used in the industries.

Mellapak

Flexipak

Montez Corrugated metal sheet

Wire mesh packing

Design of packed tower based on overall mass transfer Coefficient

From overall mass transfer equation, $N_A = K_y(y_{AG} - y_A^*)$ one can write for packed tower as

$N_A = K_y(y - y^*)$

Then,

$$dh = -\frac{G^{/}dy}{K_y \bar{a}(1-y)(y-y^*)}$$

where, y^* is solute concentration in gas phase that is capable of remaining in equilibrium with a liquid having a bulk concentration of x.

Therefore,

where, y^* is solute concentration in gas phase that is capable of remaining in equilibrium with a liquid having a bulk concentration of x.

Therefore,

$$h_T = \int_0^{h_T} dh = \int_{y2}^{y1} \frac{G^{/}dy}{K_y\, \bar{a}(1-y)(y-y^*)}$$

$$= \int_{y2}^{y1} \frac{G^{/}dy}{k_G\, \bar{a}P(1-y)(y-y_i)}$$

$$= \int_{x2}^{x1} \frac{L^{/}dx}{k_L\, \bar{a}(C_{av})(1-x)(x_i-x)}$$

Graphical integration of right hand side of Equation (4.11):

Operating line AB is drawn in xy plane. Any point (x,y) is taken in operating line. A vertical line is drawn upto equilibrium line to get y^*.

$$h_T = \int_{x2}^{x1} \frac{L^{/}dx}{K_x\, \bar{a}(1-x)(x^*-x)} = \int_{y2}^{y1} \frac{G^{/}dy}{K_G\, \bar{a}P(1-y)(y-y^*)} = \int_{x2}^{x1} \frac{L^{/}dx}{k_L\, \bar{a}(C_{av})(1-x)(x^*-x)}$$

Equation 4.7 can be written as

$$h_T = \int_0^{h_T} dh = \int_{y2}^{y1} \frac{G^{/}y_{iBM}\, dy}{k_y \bar{a}\, y_{iBM}\,(1-y)(y-y_i)} = \int_{y2}^{y1} \frac{G^{/}(1-y)_{iM}\, dy}{k_y \bar{a}\,(1-y)_{iM}\,(1-y)(y-y_i)}$$

where, $y_{iBM} = (1-y)_{iM} = \dfrac{(1-y_i)-(1-y)}{ln\frac{(1-y_i)}{(1-y)}}$

$$h_T = \frac{G^{/}}{k_y \bar{a}\,(1-y)_{iM}} \int_{y2}^{y1} \frac{(1-y)_{iM}\, dy}{(1-y)(y-y_i)}$$

As, $\frac{G^{/}}{k_y \bar{a}\,(1-y)_{iM}}$ remains constant at the packing section though G/ varies. This quantity is called 'height if transfer units' (HTU) and designated as H_{tG}. It is important to measure the separation effectiveness of the particular packings for a particular separation process. It also describes the mass transfer coefficient. Larger mass transfer coefficient leads to the smaller value of HTU.

Hence,

$$H_{tG} = \frac{G^{/}}{k_y \bar{a}\,(1-y)_{iM}} = \frac{G^{/}}{k_y^{/} \bar{a}}$$

The integral part of Equation (4.14) is called number of gas phase transfer units as N_{tG}.

$$h_T = H_{tG} \times N_{tG}$$

When overall gas phase mass transfer coefficients are used, the height of the packing is as follows:

$$h_T = \int_{y_2}^{y_1} \frac{G^{/}dy}{K_y \bar{a}\, y_{BM}^{*}\,(1-y)(y-y^{*})} = \frac{G^{/}}{K_y \bar{a}\, y_{BM}^{*}} \int_{y_2}^{y_1} \frac{dy}{(1-y)(y-y^{*})} = H_{toG} \times N_{toG}$$

where, $H_{toG} = \frac{G^{/}}{K_y \bar{a}\, y_{BM}^{*}}$, $N_{toG} = \int_{y_2}^{y_1} \frac{dy}{(1-y)(y-y^{*})}$ and $y_{BM}^{*} = (1-y)_{BM}^{*} = \frac{(1-y^{*})-(1-y)}{ln\frac{(1-y^{*})}{(1-y)}}$.

Define NTU

Height of Packing (z) = NTU x HTU

Where,

NTU = number of transfer units - dimensionless
HTU = height of transfer units - dimension of length

The number of transfer units (NTU) required is a measure of the difficulty of the separation. A single transfer unit gives the change of composition of one of the phases equal to the average driving force producing the change. The NTU is similar to the number of theoretical trays required for tray column. Hence, a larger number of transfer units will be required for a very high purity product.

Height of Transfer Units (HTU)

$\frac{G/}{k_y \bar{a}\ (1-y)_{iM}}$ remains constant at the packing section though G/ varies. This quantity is called 'height if transfer units' (HTU) and designated as H_{tG}. It is important to measure the separation effectiveness of the particular packings for a particular separation process. It also describes the mass transfer coefficient. Larger mass transfer coefficient leads to the smaller value of HTU.

Height Equivalent to Theoretical Plate (HETP)

For a specified separation job, in packed tower, the height of packing is to be determined and in tray tower, numbers of ideal trays are determined. The ratio between packing height to number of trays required for the same separation is called height equivalent to theoretical plate (HETP).

$$HETP = \frac{h_T}{N_T} = \frac{Height\ of\ packing}{Number\ of\ ideal\ trays}$$

Height of packing (Z) = HETP x Number of trays

HETP varies with size and type of packing, flow rate of gas and liquid, concentration of solute, physical and transport properties as well as equilibrium relationship and uniformity of liquid and gas distribution. HETP is used to characterize the packing. A good packing has small HETP.

Absorption Factor

Where A is absorption factor and is defined as $A = L/(mG)$.

Absorption with chemical reaction

In ammonia removal from ammonia air mixture by using water has solvent the chemical reaction will not play an appreciable role.

In the following examples

- removal of NO_x and SO_x from the dust laden gas by using water,
- Removal of CO_2 from industrial flue gas by using sodium hydroxide as solvent, chemical reaction play a vital role.

Henry's Law

A law stating that the mass of a dissolved gas in a given volume of solvent at equilibrium is proportional to the partial pressure of the gas

Where, H is the Henry's constant, is the partial pressure of A in gas phase, is the concentration of component A in the liquid phase.

Stripping or Desorption

- Mass transfer occurs from liquid to gas phase.
- The solute is removed from the liquid solution by contacting with gas.

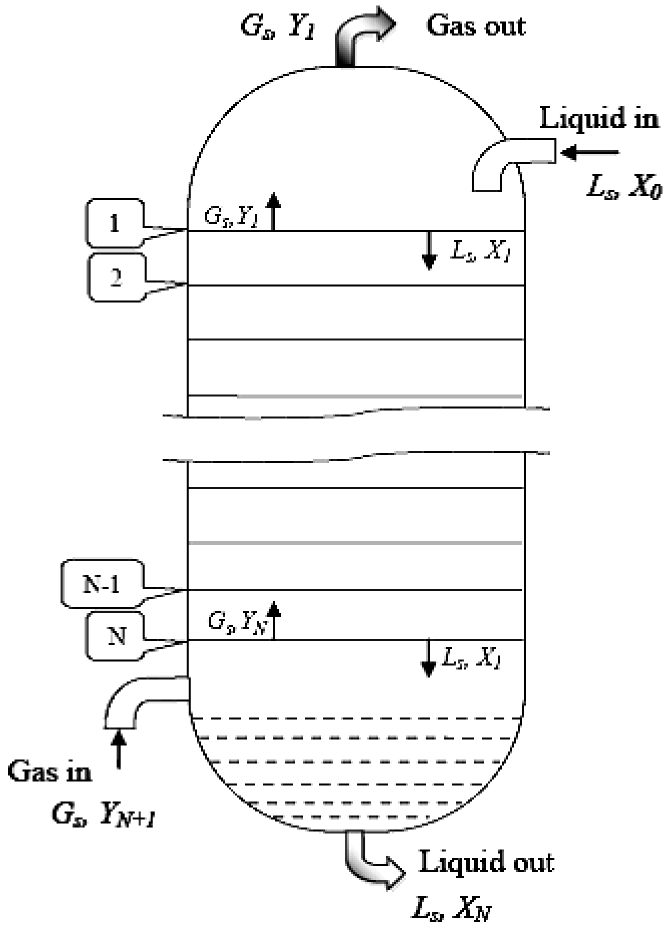
Single stage counter current Unit

G_1, G_2 : molar flow rates of entering and leaving gas

G_S: molar flow rate of inert gas

L_1, L_2 are the molar flow rates of leaving and entering liquid

L_S is the molar flow rate of pure solvent



Where X = Y =

X,Y are the mole ratios of solute to **inert component** in liquid and gas phase respectively

x,y are the mole ratio of solute in liquid and gas phases

Making Material Balance

□□(□□1−□2) =□□□(□1−□2)

STEP-BY-STEP PROCEDURE

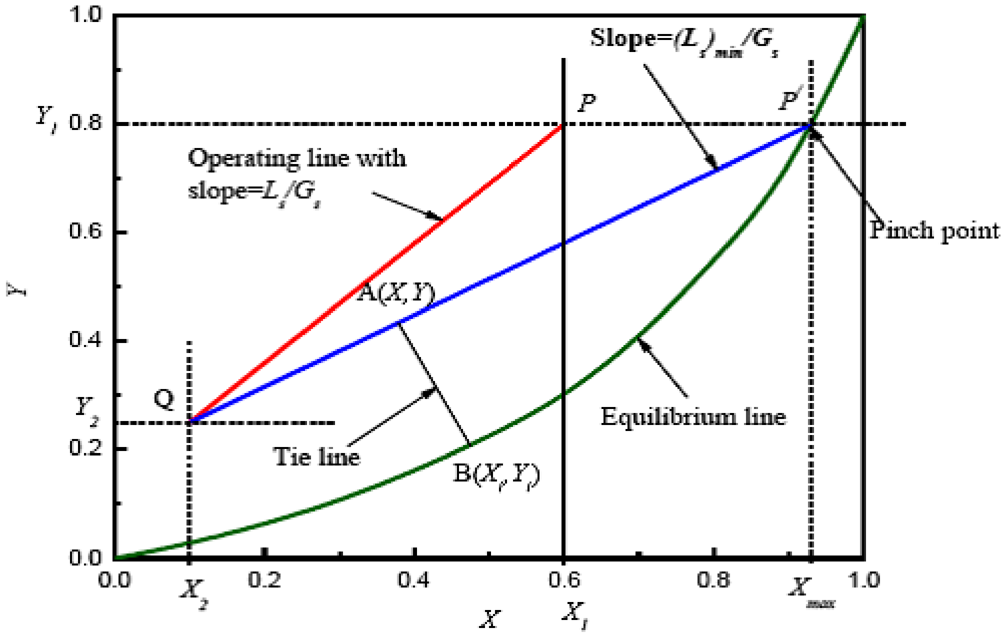
(1) For a particular gas-liquid system, draw equilibrium curve on *X-Y* plane.

(2) Draw operating line in *X-Y* plane (*PQ*) using material balance Equation. Lower terminal *Q* (*X2, Y2*) and upper terminal *P* (*X1, Y1*) are placed in *x-y* plane.

Making Material Balance

$$G_s(Y_1 - Y_2) = L_s(X_1 - X_2)$$

If liquid mass flow rate, *Ls* is not known, minimum liquid mass flow rate *(Ls)min* is to be determined. *Ls* is generally 1.2 to 2 times the *(Ls)min*.



Graphical determination of $(L_s)_{min}$ for absorption.

In the above figure, lower terminal of absorption tower is represented by *Q* (*X2, Y2*); i.e., bottom of the tower. Operating line is *PQ*. If liquid rate is decreased, slope of operating line (*Ls/Gs*) also decreases and operating line shifts from *PQ* to *P'Q* when touches equilibrium line. This perating line is tangent to equilibrium line.

$$\text{Slope of } P^{/}Q = \frac{(L_s)_{min}}{G_s}$$

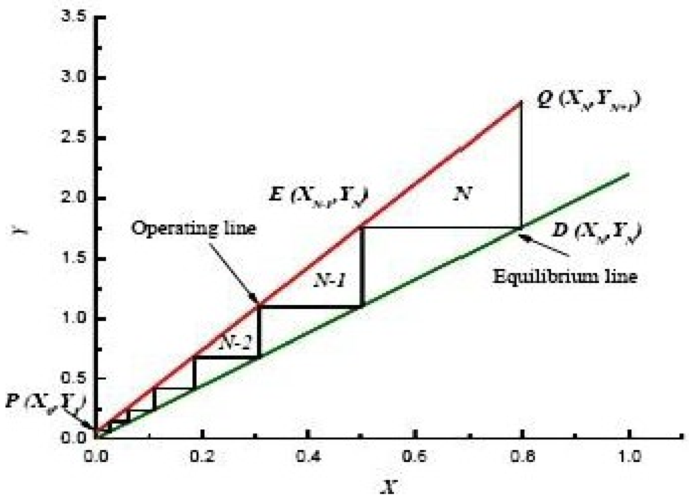
The driving force for absorption is zero at $P^{/}$ and is called "PINCH POINT".

(3) A point *A* (*x, y*) is taken on the operating line. From the known value of k_x and k_y or $k_x\bar{a}$ and $k_y\bar{a}$, a line is drawn with slope of k_x/k_y to equilibrium line, $B(x_i,y_i)$. Line *AB* is called "TIE LINE" and x_i and y_i are known for a set of values of *x* and *y*.

(4) Step (3) is repeated for other points in the operating line to get several (x_i,y_i) sets for $y_1 \geq y \geq y_2$.

(5) Calculate flow rate of gas *G* (kg/h) at each point as $G=G_s(1+y)$.

The following parameters should be known for the determination of "number of stages" (1) Gas feed rate, (2) Concentration of gas at inlet and outlet of the tower, (3) Minimum liquid rate; actual liquid rate is 1.2 to 2 times the minimum liquid rate, (4) Equilibrium data for construction of equilibrium curve now,



Packed Bed Absorber

-
- **HTU =**
-
-
- **Z = No of trays x HETP**

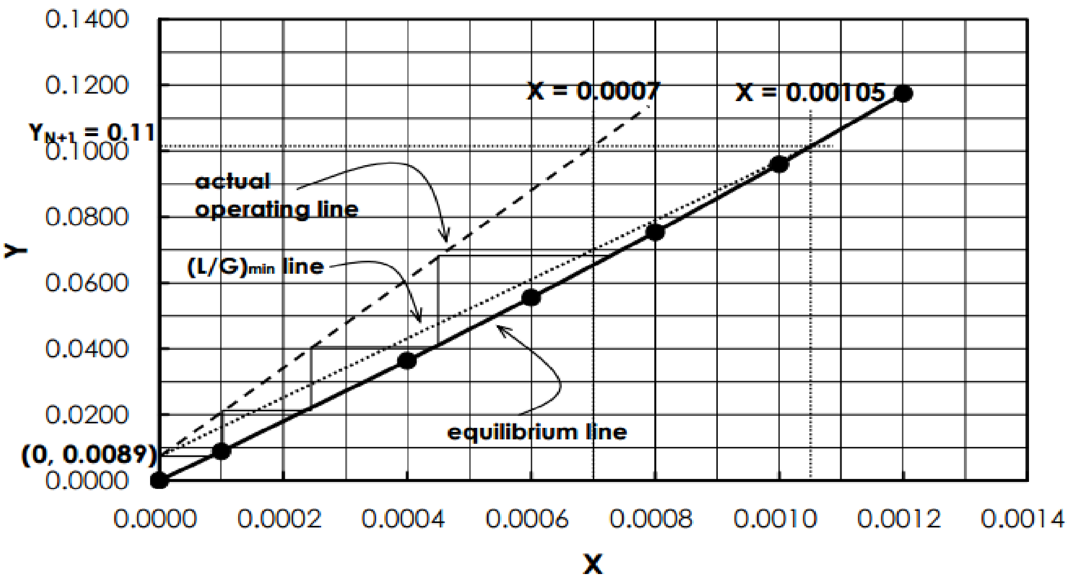
Example

A gas stream containing 90 mol% N_2 and 10% CO_2 is passed through an absorber, in which pure and cool water at 5ºC is used as a solvent The operation is assumed to be isothermal at 5 o C and isobaric at 10 atm The liquid flow rate is 1.5 times the minimum liquid flow rate Determine the number of equilibrium stages required to absorb 92 mol% of CO_2 Given Henry's constant of CO_2 in water at 5ºC of 876 atm/mole fraction.

=

the equilibrium or the y-x data can be computed

x	**0**	**0.0001**	**0.0004**	**0.0006**	**0.0008**	**0.0010**	**0.0012**
y	**0**	**0.00876**	**0.0350**	**0.0526**	**0.0701**	**0.0876**	**0.1051**
X	**0**	**0.0001**	**0.0004**	**0.0006**	**0.0008**	**0.0010**	**0.0012**
Y	**0**	**0.00884**	**0.0363**	**0.0555**	**0.0754**	**0.0960**	**0.1175**



The slope of the min L/G minimum is found to be 97.2

Hence, the slope of the actual operating line is 1.5 times of minimum = 1.5 x 97.2 = 145. 8

$X_1 = 0.0007$

Yields the number of equilibrium stages of ~3.8 = 4

Unit 2 Assignment problems - ABSORPTION

1. NH_3 – air mixture containing 5% NH_3 is scrubbed with water to remove NH_3, 5000 kg/hr of gas mixture is to be processed with 2,00,000 kg/hr of water to reduce NH_3 in the exit gas to 0.15%.Calculate the height of packing required assuming dilute solutions are involved. Equilibrium relation is given by Y = 20 X where X,Y = mole fraction of NH_3 in liquid and vapor. HTU = 2m.
2. SO_2–air mixture containing 8% SO_2 at 20°C and 1 atm is to be scrubbed with water in a sieve plate column. The air and water flow rate is 32.6kg/m^{2}s. If 95% of SO_2 is to be recovered. Calculate the number of theoretical trays required.

   Equilibrium Data at 20°C and 1 atm:

p_A, partial pressure in mmHg of SO_2 gas	12	18.2	31.7	50	69.6	106
C_A, gm of SO_2/100gmof water	2	3.5	5.0	7.5	10.0	20

3. Ammonia is absorbed from gas by using water in a scrubber under atm. Pressure the initial ammonia content is 0.04 kmol / kmol of inert gas. The recovery of ammonia by absorption is 90%. The water enters the tower free from solute. Estimate the concentration of ammonia in the exit stream and number of theoretical stages required?

X	0.005	0.01	0.0125	0.015	0.02	0.027
Y	0.0045	0.0102	0.0138	0.018	0.027	0.039

4. It is desired to absorb 95% ammonia from a feed mixture contain 10% ammonia and rest air. The gas enters at rate of 500kmol/hr. if water is used as solvent at the rate of 1.5 times of the minimum calculate (a) NTU (b) Ls actual (c) height of the tower if HTU = 1m the equilibrium relationship is given by Y=20X

5. A packed tower is designed to recover 98% CO_2 from gas mixture contain 10% CO_2 and 90% air using water. The equilibrium relation is Y=14X where Y is kg CO_2 / kg dry air. And X is kg CO_2 / kg water. The water to gas ratio is kept at 30% more than the minimum value. Calculate height of tower if HTU is 1.25m.

6. A packed tower is used to remove 96 % SO_2 from a stream of air containing 0.0291 mole fraction SO_2. The SO_2 is removed by absorbing it in water which enters the tower with a mass velocity of 0.51 k mol/m^{2}s and the gas stream enters the tower counter currently at the mass velocity of 9.75 X 10^{-3}kmol/m^{2}s. Determine the packed tower height. The following data are available.
   K_x a = 0.94 kmol/m^{3}s, K_ya = 0.0496 kmol/m^{3}s. Slope of the equilibrium line = 28.7

7. A mixture of acetone vapour and air containing 5% by volume of acetone is to be freed of its acetone content by scrubbing it with water in a packed bed absorber. The flow rate of the gas mixture is 700 m^3/hr of acetone-free air measured at NTP and that of water is 1500 kg/hr. The absorber operates at an average temperature of 20°C and a pressure of 101 kPa. The scrubber absorbs 98% acetone. The equilibriumrelation for the acetone vapour-water system is given by: Y* = 1.68X

   Where, Y* = kmol acetone/kmol dry air

X = kmol acetone/kmol water

Calculate: (a) mean driving force for absorption

(b) mass transfer if the overall mass transfer coefficient is k_G = 0.4 kmol of acetone/m^2hr(kmol acetone/kmol dry air)

8. One kilo-mole per unit time of gas consisting of 75% methane and 25% n-pentane vapor at 27 deg C 1atm, is to be scrubbed with 2kmol/unit time of non volatile paraffin oil, molecular weight is 200 entering the absorber free of pentane at 35 deg C. Compute the number of ideal trays for 98% recovery of pentane. The equilibrium data

X	0	0.13	0.18	0.2	0.28	0.33
Y	0	0.1	0.125	0.15	0.2	0.25

9. Ammonia air mixture contain 2% by volume is to be scrubbed with water at 20deg C in a tower packed with 1.27cm Rasching Rings. The water and gas rate are 1170 kg/hr each based on the empty tower cross section. Estimate the height of the tower required if 98% of the ammonia is entering gas is to be absorbed. The tower operates at 1atm. The equilibrium relationship is given by Y = 0.746 X

10. Acetone is to be recovered from a 5 % acetone air mixture by scrubbing with water in a packed tower the liquid rate is 0.85kg/s m^2 and the gas rate is 0.5 kg/s m^2. The overall mass transfer coefficient is 1.5 x 10^{-4} what should be the height of the tower for 98% recovery?

X	0.0099	0.0196	0.0360	0.04
Y	0.0076	0.0156	0.0306	0.0333