

Mass transfer

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What is mass transfer?

Mass transfer is the net movement of mass from one location, usually meaning stream, phase, fraction or component, to another. Mass transfer occurs in many processes, such as diffusion, absorption, evaporation, drying, precipitation, membrane filtration, and distillation.

The driving force for mass transfer is usually a difference in chemical potential. In a single phase system where temperature and pressure are uniform, the difference in chemical potential is due to the variation in concentration of each species

It forms the basis for separation processes. It is used in reaction engineering, separations engineering, heat transfer engineering, and many other sub-disciplines of chemical engineering like electrochemical engineering.

Classification of mass transfer operations

Phases in contact	Mass transfer operations
Liquid-Liquid	Extraction, Liquid thermal diffusion
Liquid-Solid	Dissolution, Crystallization
Liquid-Vapor	Distillation
Liquid-Gas	Gas absorption
Solid-Vapor	Sublimation, Adsorption
Solid-Solid	Solid diffusion
Gas- Gas	Gas diffusion, Thermal diffusion
Solid-Liquid-Solid	Leaching
Solid-Liquid-Vapor	Adsorption

Mass transfer coefficient

$$k_c = \frac{\dot{n}_A}{A \Delta c_A}$$

Where,

k_c is the mass transfer coefficient m/s

\dot{n}_A is the mass transfer rate [mol/s]

A is the effective mass transfer area [m²]

Δc_A is the driving force concentration difference [mol/m³].

This (k_c) can be used to quantify the mass transfer between phases, immiscible and partially miscible fluid mixtures (or between a fluid and a porous solid). Quantifying mass transfer allows for design and manufacture of separation process equipment.

Mass transfer equipment's

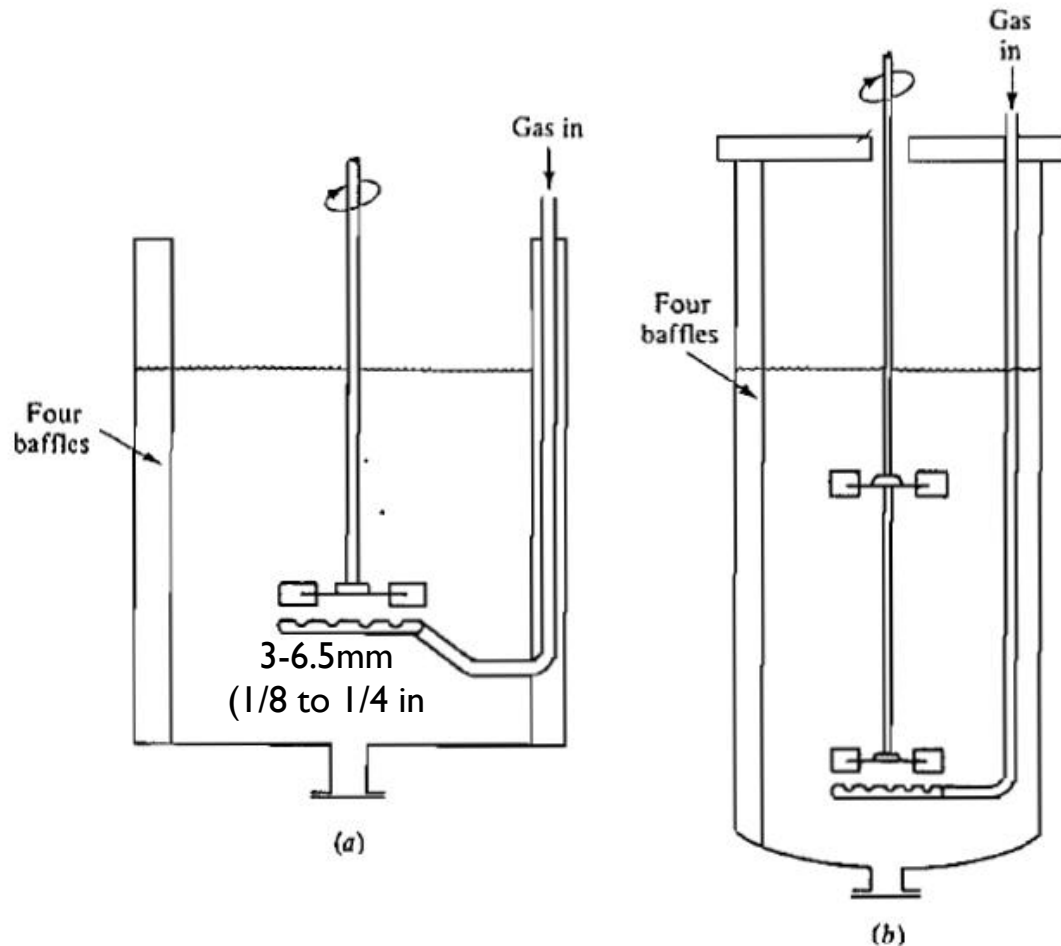
➤ Gas dispersed

- Agitated vessels
- Tray towers
- Bubble cap trays

➤ Liquid dispersed

- Venturi scrubbers
- Wetted wall towers
- Spray towers & spray chambers
- Baffle towers & shower trays
- Packed towers

AGITATED VESSEL



Used for dispersing small quantities into liquid on a batch or semi batch process. Also useful for cases where the liquid contains a suspended solid.

Mechanically agitated vessel for gas liquid contact (a) standard and (b) multiple impellers for deep tank.

Propellers

A propeller is a fan which propels a fluid by pushing against it: it converts rotational motion into linear motion. An impeller is a rotor that produces a sucking force and is part of a pump. A propeller is always open, and an impeller is always closed, as it draws fluid.

The turbine extracts energy from a moving fluid, while the other two add energy to a moving fluid. That means the turbine uses mechanical energy to give electrical energy and the fan or propeller uses electrical energy to give mechanical force.

Common propeller & impellers

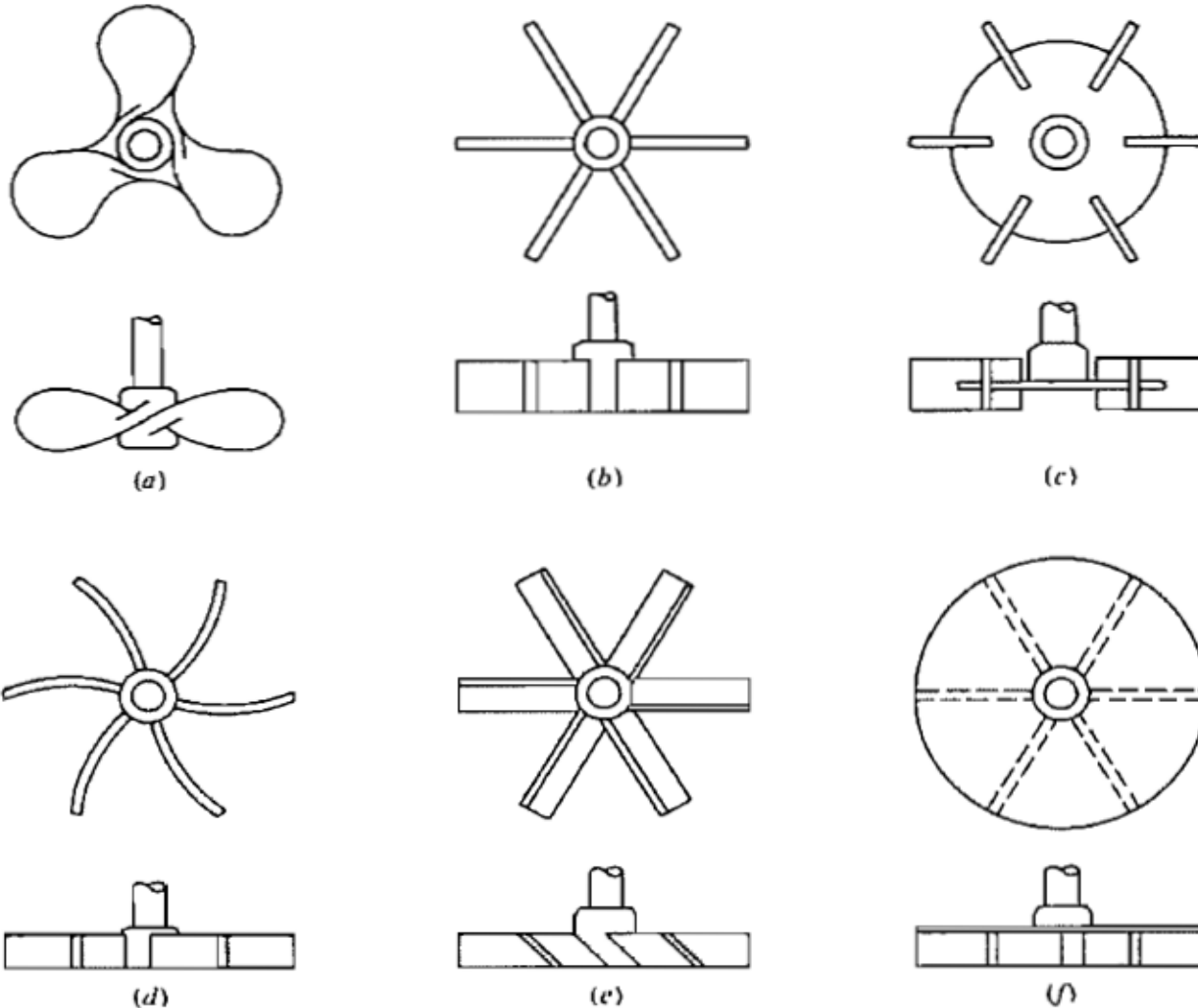


Figure 6.3 Impellers, with typical proportions: (a) marine-type propellers; (b) flat-blade turbine, $w = d_i/5$, (c) disk flat-blade turbine, $w = d_i/5$, $d_d = 2d_i/3$, $B = d_i/4$; (d) curved-blade turbine, $w = d_i/8$; (e) pitched-blade turbine, $w = d_i/8$; and (f) shrouded turbine, $w = d_i/8$.

Propeller pitch

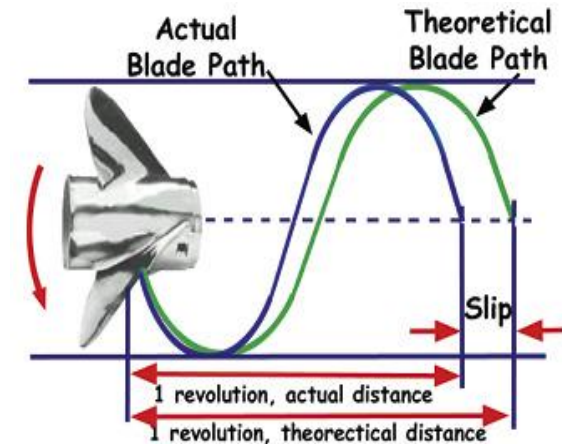
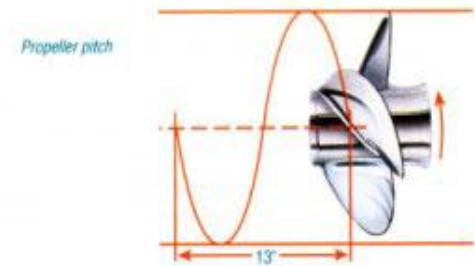
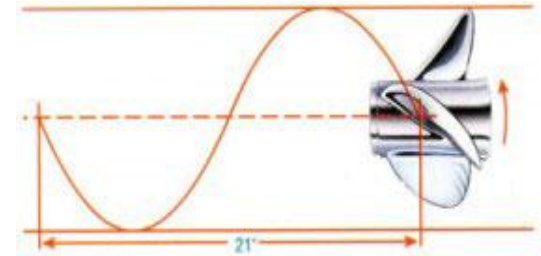
- Propeller pitch is the distance that a propeller theoretically advances or moves during one revolution.

$$\text{Geometric pitch} = \left(\frac{4}{3}\right) \pi D \tan \beta$$

where D diameter in inches, and β is blade angles

- The square pitch propeller has a pitch ratio of 1:1 which means for each rotation fluid is moved forward by an amount equal to its diameter.

- Propeller slip refers to the difference between the theoretical distance a propeller should travel based on its pitch and the actual distance it travels through the water. Slip can be caused by various factors like hull condition, propeller condition, current, wind, and waves.

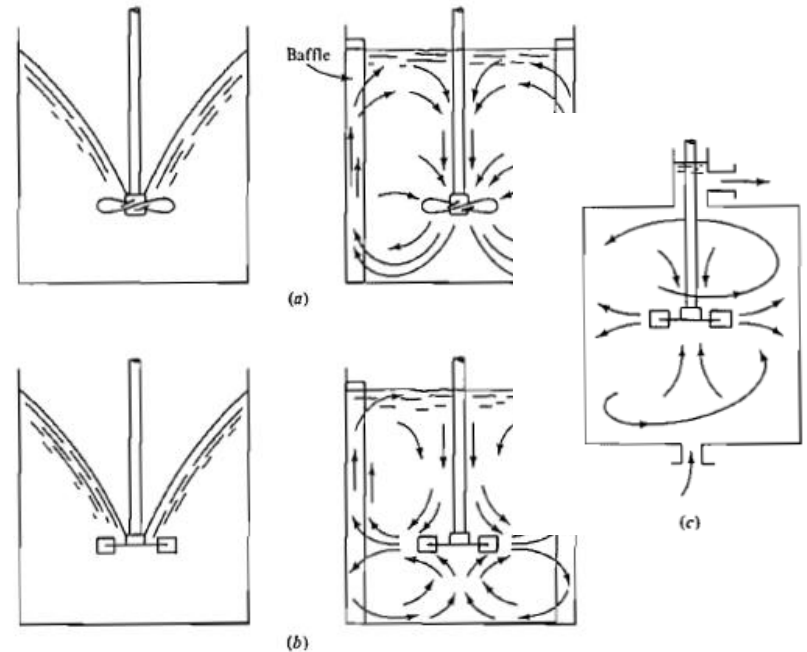


Vortex formation

A vortex is a region in a fluid in which the flow revolves around an axis line, which may be straight or curved. Vortices form in stirred fluids, and in smoke rings, whirlpools in the wake of a boat, and the winds surrounding a tropical cyclone, tornado.

Effect of vortex:

- Reduces the degree of agitation and mixing
- Gas entrainment
- Erosion of pipe and fittings
- Pressure drop

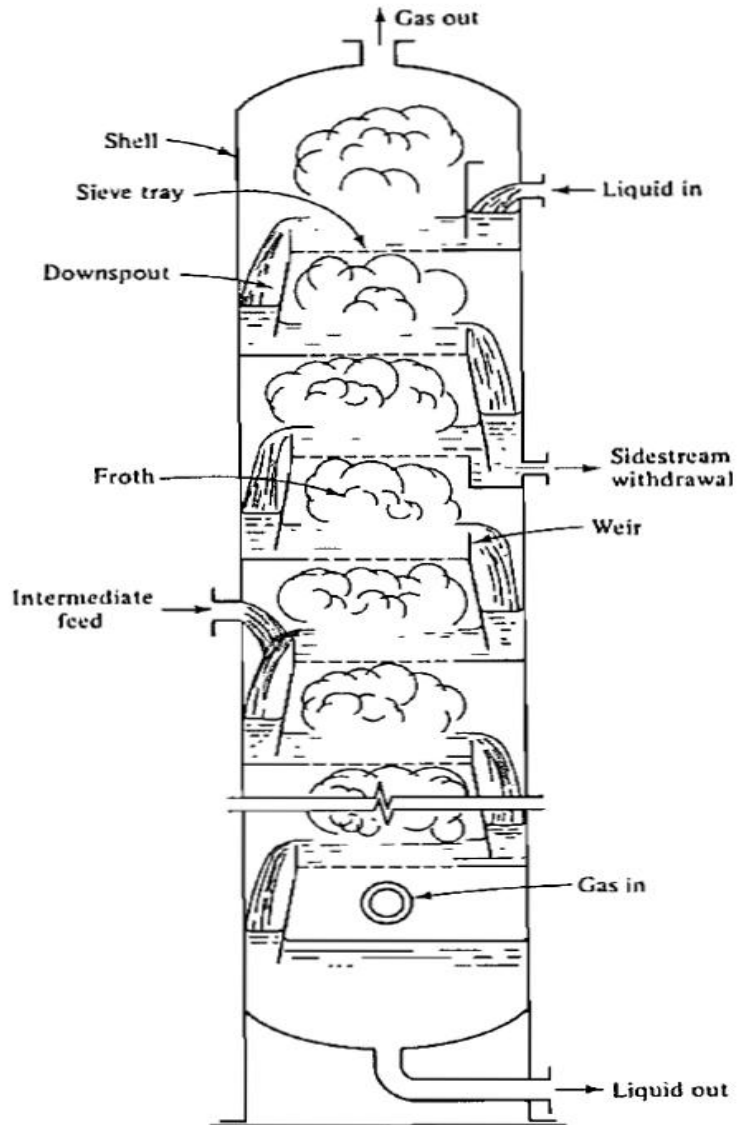


Liquid agitation pattern in gas-liquid interface with and without baffles (a) marine impeller (b) disc flat bed turbine (c) in a full vessel without gas-liquid interfaces (continuous) without baffle.

Prevention of vortex

- Open tanks with gas-liquid interfaces
 - Operation in the laminar range for the impeller. (not in practice)
 - Off centre location of the impeller on a shaft entering the vessel at an angle to the vessel axis. (common, mostly used for small scale)
 - Installation of baffle. (most common, standard baffle width is $T/12$)
- Closed tank, operated full, with no gas-liquid surface. This is specially convenient for cases where liquid flows continuously through the vessel. A circular flow pattern is super imposed upon the axial flow directed toward the centre of the impeller.

Tray tower



Tray towers are vertical cylinders in which the liquid and gas are contacted in stepwise fashion on trays or plate.

Major section:

- Shell & trays
- Tray spacing
- Tower diameter
- Downspouts
- Weirs
- Liquid flow

Schematic section through sieve tray tower

Recommended general conditions and dimension for tray towers

1. Tray spacing

Tower diameter T		Tray spacing t	
m	ft	m	in
1 or less	4 or less	0.15	6 minimum
1-3	4-10	0.50	20
3-4	10-12	0.60	24
4-8	12-24	0.75	30
		0.90	36

2. Liquid flow

- a. Not over $0.015 \text{ m}^3/(\text{m diam}) \cdot \text{s}$ ($0.165 \text{ ft}^3/\text{ft} \cdot \text{s}$) for single-pass cross-flow trays
- b. Not over $0.032 \text{ m}^3/(\text{m weir length}) \cdot \text{s}$ ($0.35 \text{ ft}^3/\text{ft} \cdot \text{s}$) for others

3. Downspout seal

- a. Vacuum, 5 mm minimum, 10 mm preferred ($\frac{1}{4}$ – $\frac{1}{2}$ in)
- b. Atmospheric pressure and higher, 25 mm minimum, 40 mm preferred (1–1.5 in)

Recommended general conditions and dimension for tray towers

4. Weir length for straight, rectangular weirs, cross-flow trays, $0.6T$ to $0.8T$, $0.7T$ typical

Weir length W	Distance from center of tower	Tower area used by one downspout, %
$0.55T$	$0.4181T$	3.877
$0.60T$	$0.3993T$	5.257
$0.65T$	$0.2516T$	6.899
$0.70T$	$0.3562T$	8.808
$0.75T$	$0.3296T$	11.255
$0.80T$	$0.1991T$	14.145

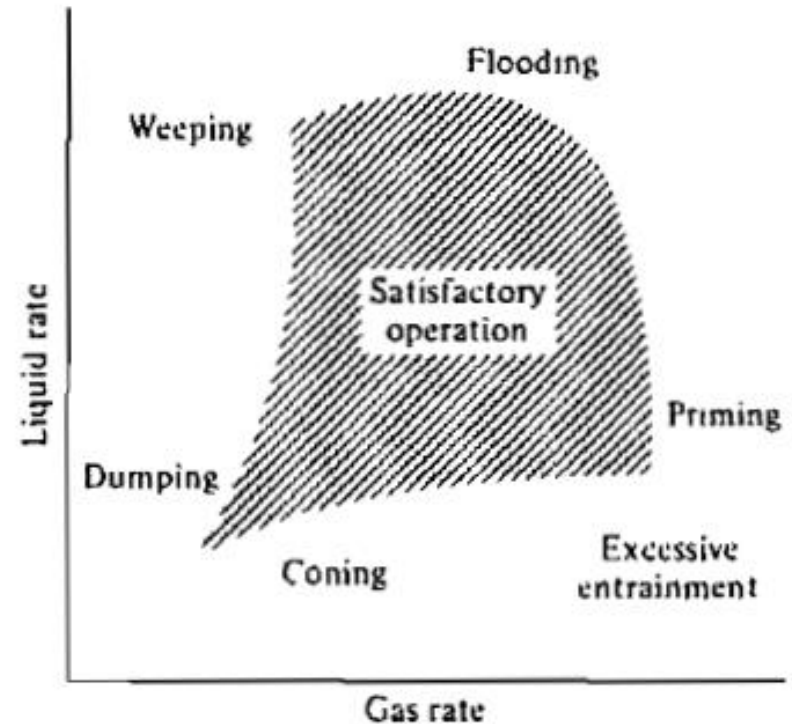
5. Typical pressure drop per tray

Total pressure	Pressure drop
35 mmHg abs	3 mmHg or less
1 std atm	$500\text{--}800\text{ N/m}^2$ ($0.07\text{--}0.12\text{ lb}_f/\text{in}^2$)
$2 \times 10^6\text{ N/m}^2$	1000 N/m^2
$300\text{ lb}_f/\text{in}^2$	$0.15\text{ lb}_f/\text{in}^2$

Operating challenges in tray tower

I. Entrainment

- Entrainment of droplets of liquid in rising gas stream
- At high gas velocities, when gas bubbles through the liquid, small droplets of liquid will be carried by the gas to tray above.
- This reduces mass transfer and tray efficiencies.

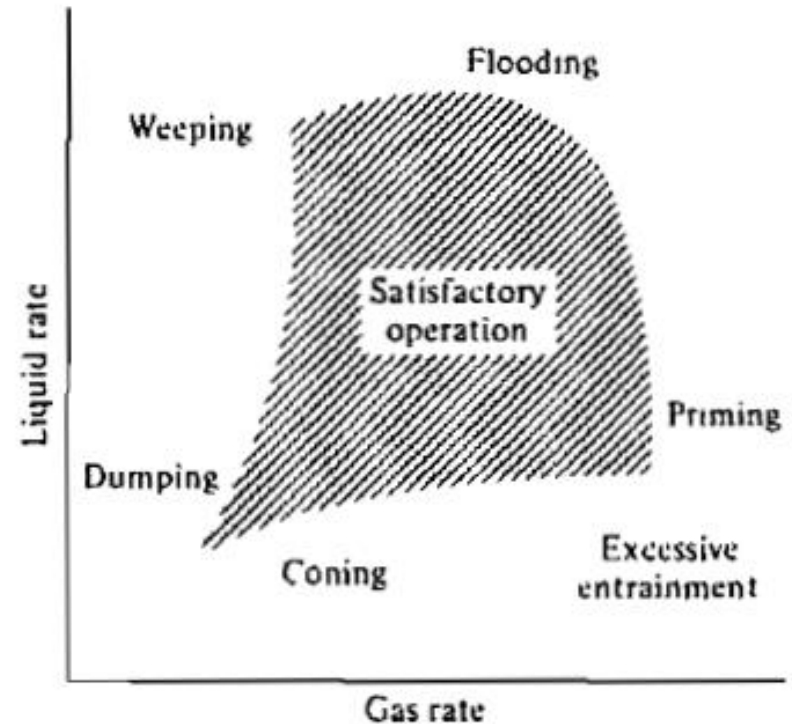


Operating characteristics of tray tower

Operating challenges in tray tower

2. Priming

- This is the exaggerated condition of entrainment
- Due to high gas flow rate, liquid from the bottom trays are carried away along with the gas from one tray to the tray above.
- Liquid handling load and gas pressure drop increases

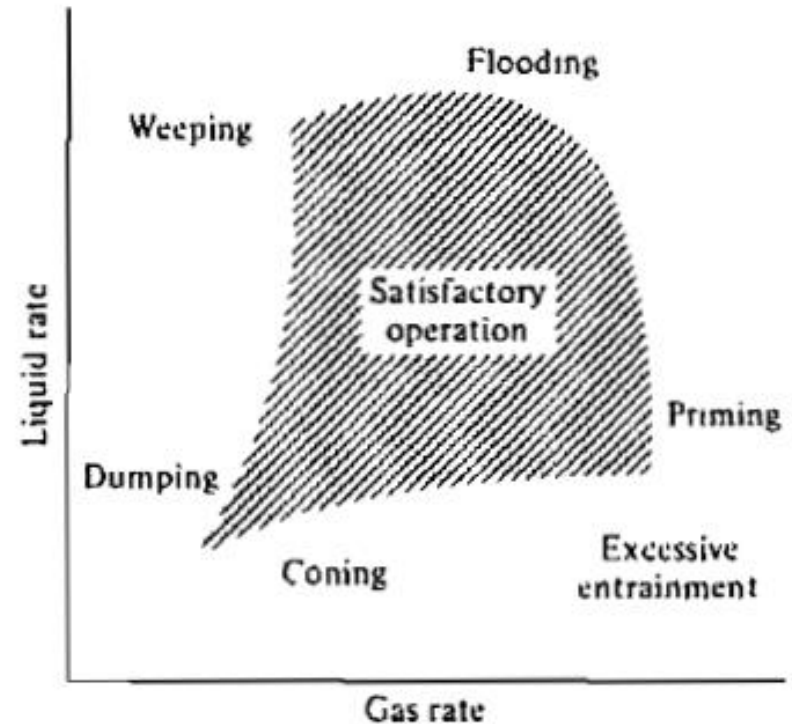


Operating characteristics of tray tower

Operating challenges in tray tower

3. Flooding

- At large liquid depths on the tray and high gas velocities
- Due to increases rate of flow either gas or liquid, large pressure difference in the space between trays is created
- This reduces mass transfer and tray efficiencies.



Operating characteristics of tray tower

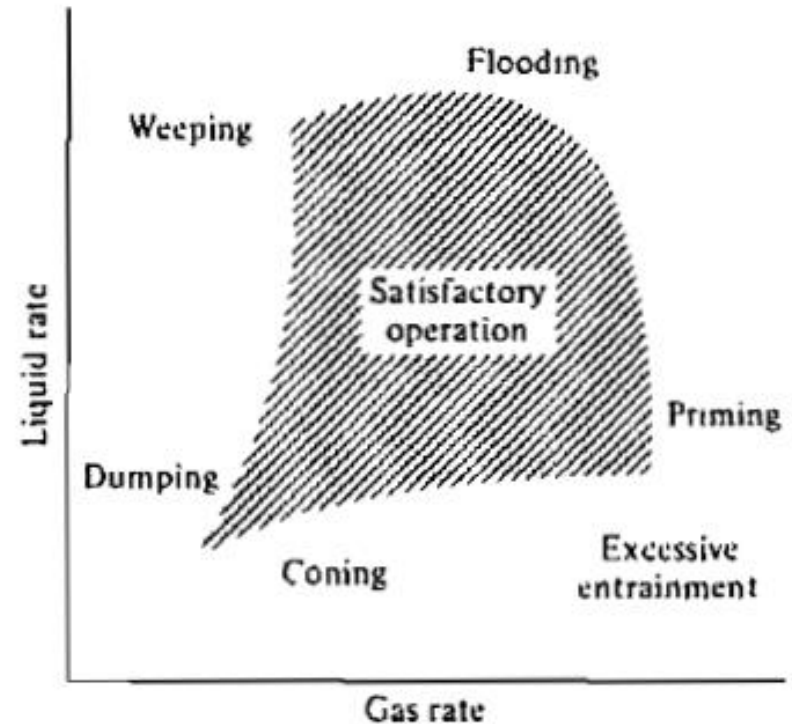
Operating challenges in tray tower

4. Weeping

- At low gas velocity
- Most of the liquid may rain down through the opening of the tray

5. Dumping

- At very low gas rates, none of the liquid reaches the downspout.

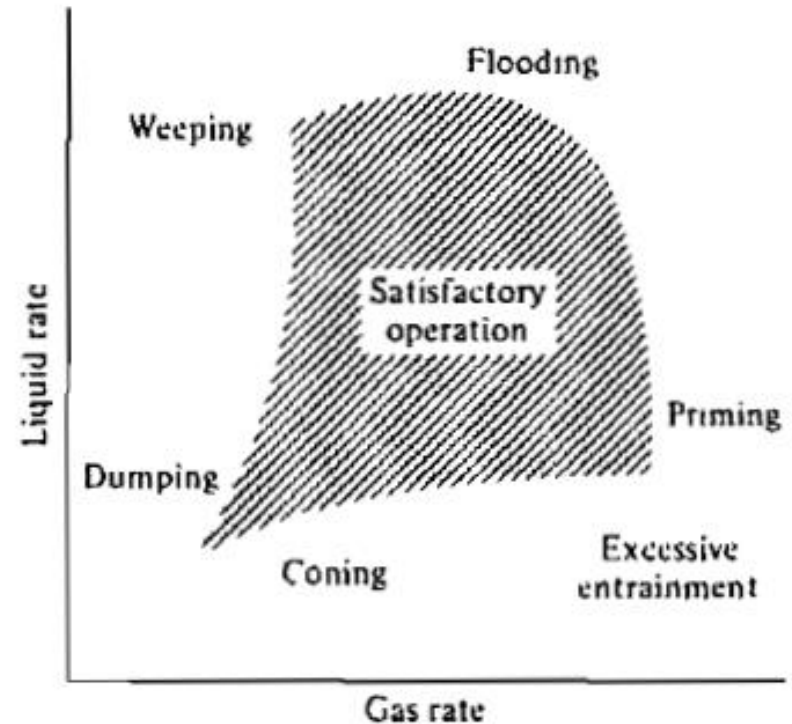


Operating characteristics of tray tower

Operating challenges in tray tower

6. Coning

- If the liquid rate is too low
- The gas rising through the opening of the tray and may push the liquid away
- Causes poor contact between gas and liquid



Operating characteristics of tray tower

Column efficiency

The overall efficiency is the ratio of the number of ideal plates needed in an entire column to the number of actual plates. For examples, if six ideal plates are called for and the plate efficiency is 60%, then the number of actual plates $6/.60=10$.

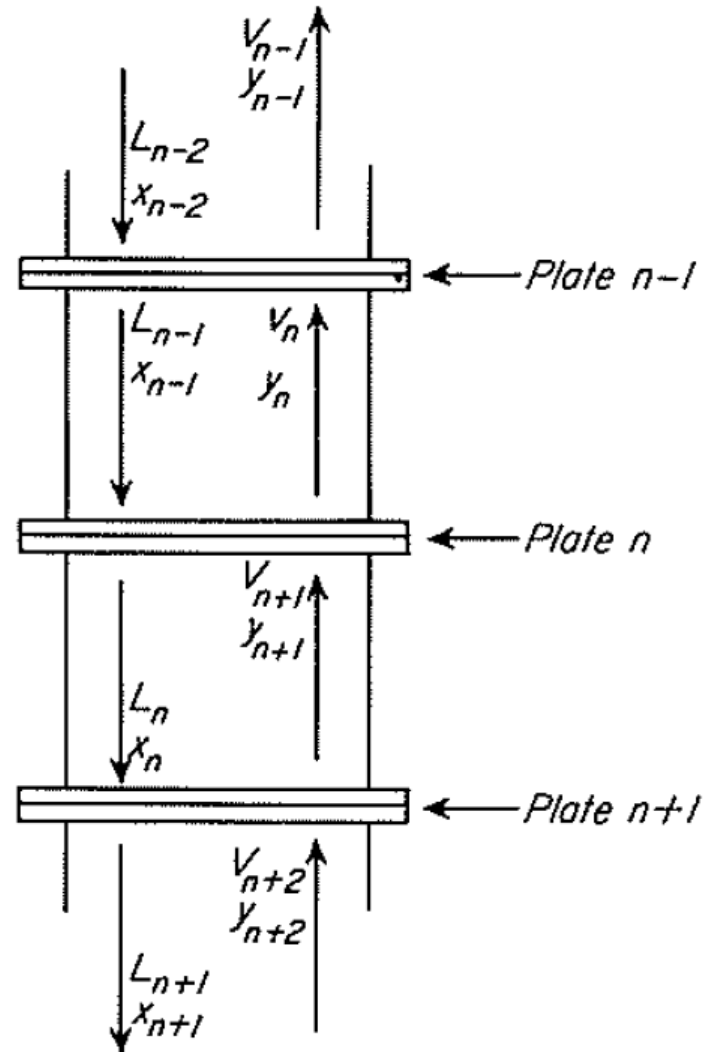


Plate efficiency

The *Murphree efficiency*¹⁰ η_M is defined by

$$\eta_M = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}} \quad (18.66)$$

where y_n = actual concentration of vapor leaving plate n

y_{n+1} = actual concentration vapor entering plate n

y_n^* = concentration of vapor in equilibrium with liquid leaving downpipe from plate n

The *local efficiency* η' is defined by

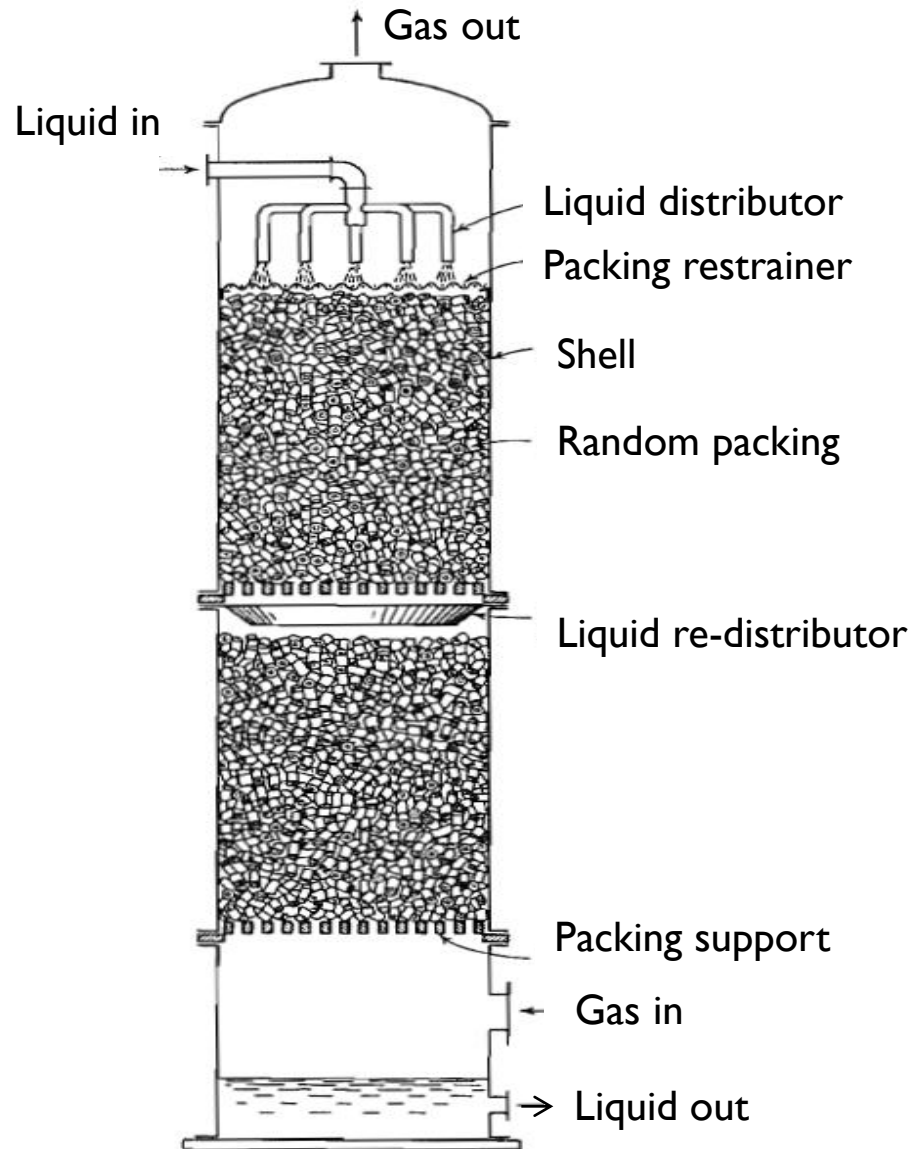
$$\eta' = \frac{y'_n - y'_{n+1}}{y'_{en} - y'_{n+1}} \quad (18.67)$$

where y'_n = concentration of vapor leaving specific location on plate n

y'_{n+1} = concentration of vapor entering plate n at same location

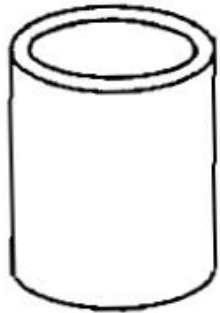
y'_{en} = concentration of vapor in equilibrium with liquid at same location

Packed tower

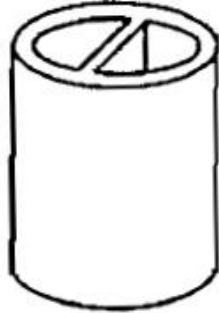


Packing materials

Random packing



(a)



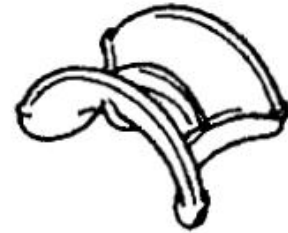
(b)



(c)



(d)



(e)



(f)



(g)

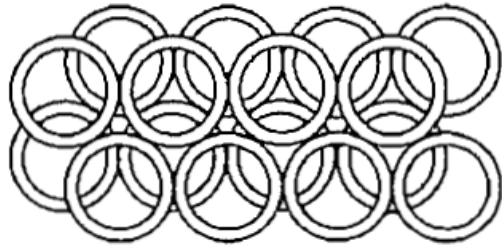
Advantages:

Less expensive,
Lower liquid
holdup

Example: Some random packings; (a) Raschig ring (b) Lessing ring (c) Partition ring (d) Berl saddle (e) Intalox saddle (f) Tellerette and (g) Pall ring

Packing materials

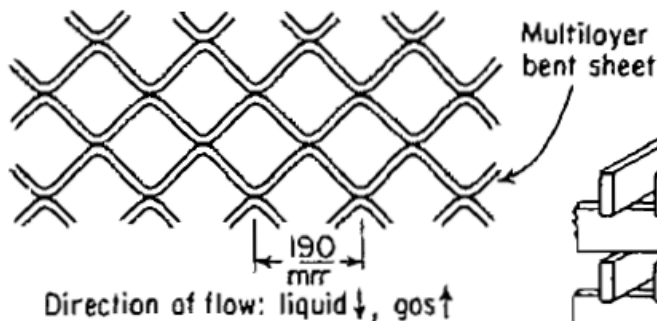
Regular packing



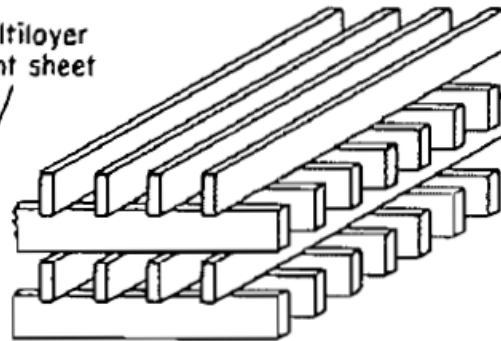
(a)



(b)



(c)



(d)

Advantages:

higher efficiency,
Lower energy
consumption,
increased
capacity, lower
pressure drop.

Example: Some regular or stacked packings; (a) raschig ring, stacked staggered (b) Double spiral ring (c) Section through expanded metal lath packings (d) Wood grids

Characteristics of Packing materials

- Provide for large interfacial surface between liquid and gases to ensure good surface contact.
- The packing must permit passage of large volume of fluid through small tower cross section without loading or flooding and with low pressure drop for the gas.
- Be chemically inert to fluid being processed.
- Have structural strength to permit easy handling and installation.
- Represent low cost.

Difference between packed column and plate tower

Packed column	Plate tower
Easy separation	Difficult separation
Required less column diameter	Required more column diameter
Less pressure drop	More pressure drop
Can not be used for solid suspensions	Can bear certain amount of solid
Can be used in case of foaming	Can not be used in case of foaming
Corrosive fluid can be handled	Used for non-corrosive fluid