# Heat Transfer Equipment
# Evaporator

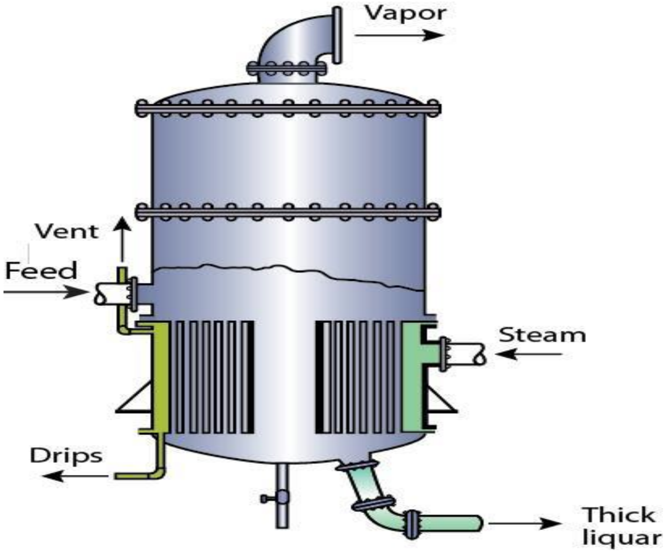
Evaporation is the removal of solvent as vapor from a solution. The aim is to concentrate a non-volatile solute, such as organic compounds, inorganic salts, acids or bases from a solvent. Common solutes are caustic soda, caustic potash, sodium sulfate, sodium chloride, phosphoric acid, and urea. The most common solvent in most of the evaporation systems is water. Evaporation is normally stopped before the solute starts to precipitate in the operation of an evaporator.

## TYPE OF EVAPORATORS

Evaporator consists of a heat exchanger for boiling the solution with special provisions for separation of liquid and vapor phases. Most of the industrial evaporators have tubular heating surfaces. The tubes may be horizontal or vertical, long or short; the liquid may be inside or outside the tubes.

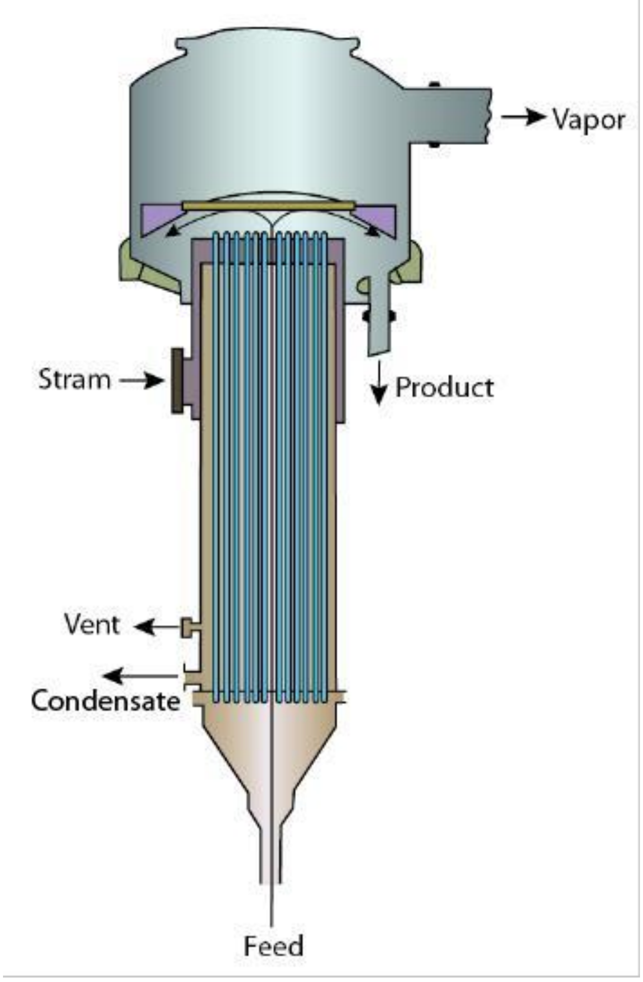
### *2.1. Short-Tube Vertical Evaporators*

***Short-tube vertical evaporators*** are the oldest but still widely used in sugar industry in evaporation of cane-sugar juice. These are also known as ***calandria*** evaporators. It became so common in process industry that this evaporator is sometimes known as ***standard evaporator***. Short-tube vertical evaporators consist of a short tube bundle (about 4 to 10 ft in length) enclosed in a cylindrical shell. This is called calandria. The feed is introduced above the upper tube sheet and steam is introduced to the shell or steam chest of the calandria. The solution is heated and partly vaporized in the tubes. The central tube in a calandria is of longer diameter. Typically it's downcomer area is taken as 40 to 70% of the total cross sectional area of tubes. The circulation rate through the downcomer/downtake is many times the feed rate. The flow area of the downtake is normally approximately equal to the total tubular flow area.



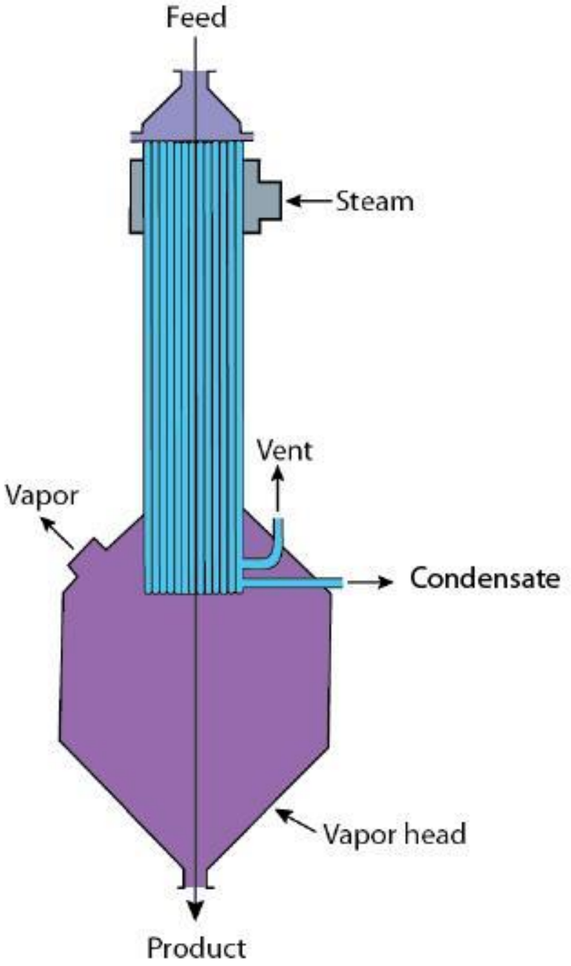
## *Long-Tube Vertical Evaporators*

This is another most widely employed natural circulation evaporator because it is often the cheapest per unit of capacity. The long vertical tube bundle is fixed with a shell that extends into a larger diameter vapor chamber at the top (**Figure 3.2**). The long-tube vertical (LTV) evaporator consists of one pass shell and tube heat exchanger. In this type of evaporator, the liquid flows as a thin film on the walls of long (from 12 to 30 feet in length) and vertical heated tube. Both rising film and falling types are used. Tube length usually varies from 20 to 65 ft. The main advantage of this type of evaporators is higher heat transfer rate. The feed enters at the bottom and the liquid starts boiling at lower part of the tube. The LTV evaporators are commonly used in concentrating black liquors in the paper and pulp industries.



## *Falling Film Evaporators*

In a falling film evaporator, the liquid is fed at the top of the tubes in a vertical tube bundle. The liquid is allowed to flow down through the inner wall of the tubes as a film. As the liquid travels down the tubes the solvent vaporizes and the concentration gradually increases. Vapor and liquid are usually separated at the bottom of the tubes and the thick liquor is taken out. Evaporator liquid is recirculated through the tubes by a pump below the vapor-liquid separator. The distribution of liquid in the inner wall of the tubes greatly affects the performance of this type of evaporator. The falling film evaporator is largely used for concentration of fruit juices and heat sensitive materials because of the low holdup time. The device is suitable for scale-forming solutions as boiling occur on the surface of the film.



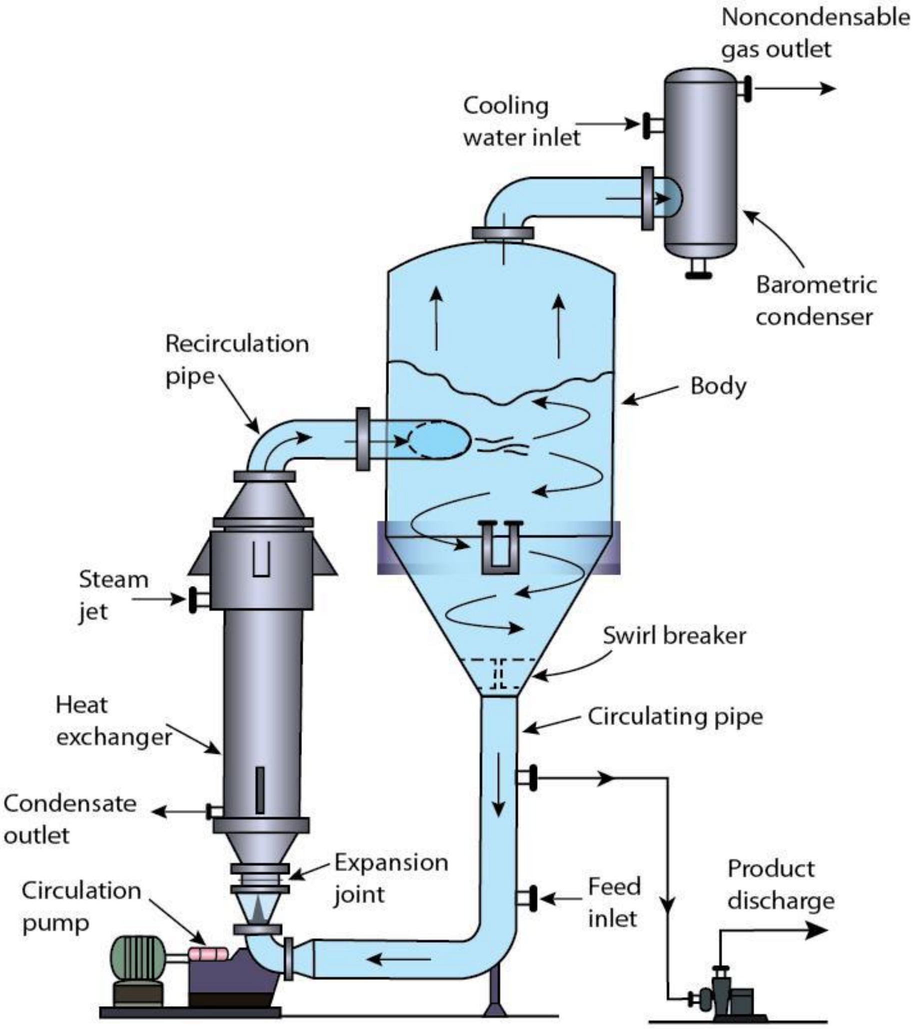
## *Forced Circulation Evaporators*

Forced circulation evaporators are usually more costly than natural circulation evaporators. However the natural circulation evaporators are not suitable under some situations such as:

- highly viscous solutions due to low heat transfer coefficient
- solution containing suspended particles and for heat sensitive materials

All these problems may be overcome when the liquid is circulated at high velocity through the heat exchanger tubes to enhance the heat transfer rate and inhibit particle deposition. Any evaporator that uses pump to ensure higher circulation velocity is called a forced circulation evaporator. The main components of a forced circulation evaporator are a tubular shell and tube heat exchanger (either horizontal or vertical), a flash chamber (separator) mounted above the heat exchanger and a circulating pump.

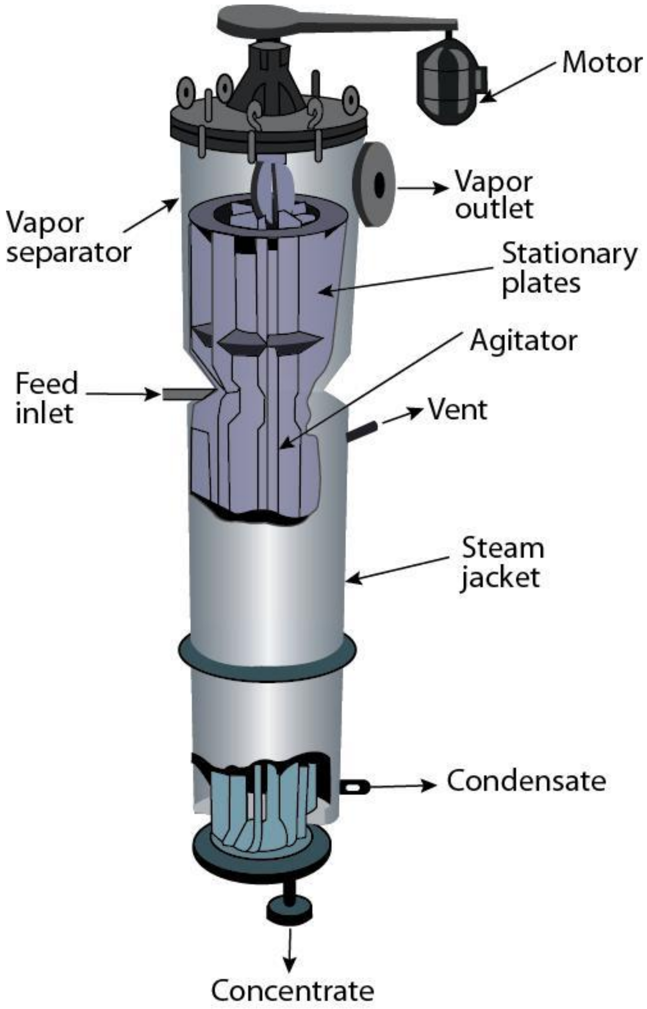
The solution is heated in the heat exchanger without boiling and the superheated solution flashes off (partially evaporated) at a lower pressure are reduced in the flash chamber. The pump pumps feed and liquor from the flash chamber and forces it through the heat exchanger tubes back to the flash chamber. Forced circulation evaporator is commonly used for concentration of caustic and brine
solutions and also in evaporation of corrosive solution.



## *Agitated Thin Film Evaporator*

Agitated thin film evaporator consists of a vertical steam-jacketed cylinder and the feed solution flows down as a film along the inner surface of large diameter jacket. Liquid is distributed on the tube wall by a rotating assembly of blades mounted on shaft placed coaxially with the inner tube. The blades maintain a close clearance of around 1.5 mm or less from the inner tube wall.

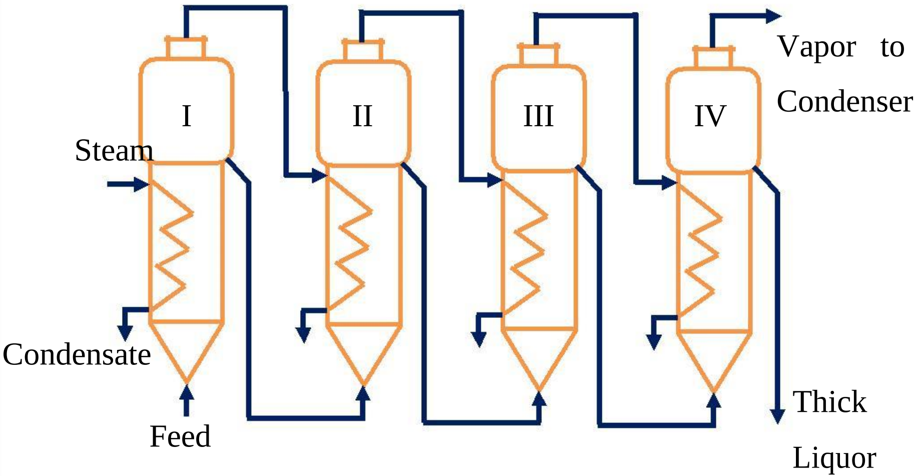
The main advantage is that rotating blades permits handling of extremely viscous solutions. The device is suitable to concentrate solutions having viscosity as high as up to 100 P.



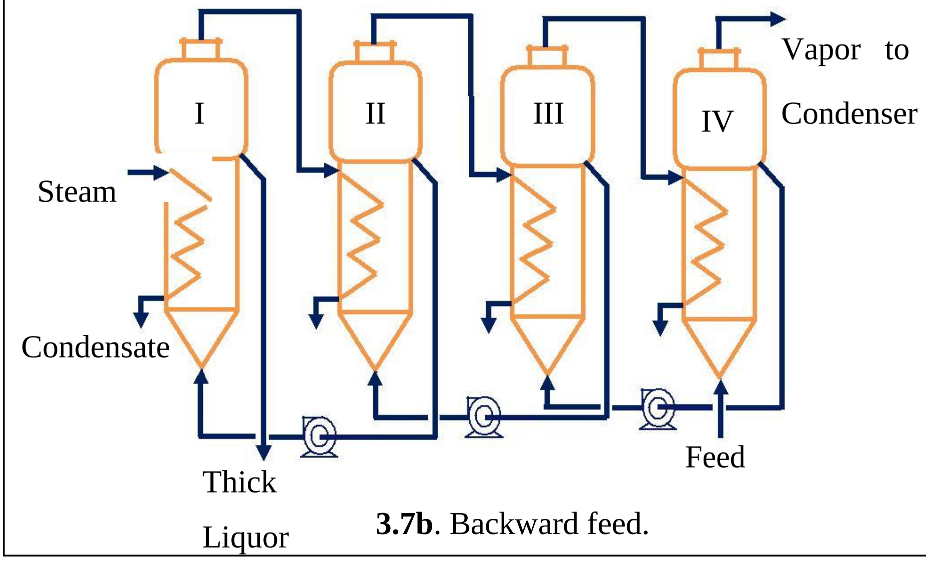
## MULTIPLE EFFECT EVAPORATORS

Evaporators are classified by the number of *effects*. In case of a *single-effect* evaporator, the vapor from the boiling liquor is condensed and the concentrated product is withdrawn from the bottom of the evaporator. Although the operation is simple, the device does not use steam efficiently. Typically 1.1 to 1.3 kg of steam is required to evaporate 1 kg of water.

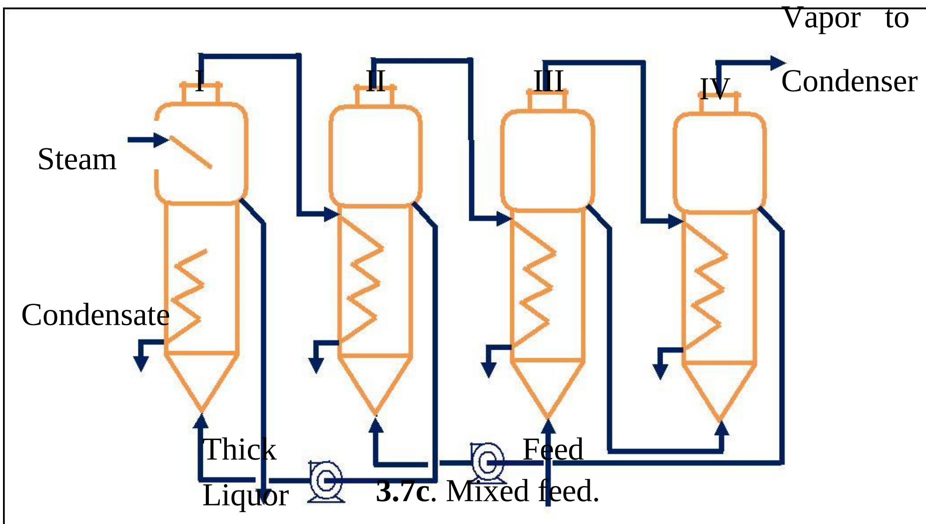
The steam consumption per unit mass of water evaporated can be increased by putting more than one evaporator in series such that the vapor from one evaporator is used in the second evaporator for heating. The vapor from the second evaporator is condensed and the arrangement is called *double-effect* evaporators. The heat from the vapor generated in the first evaporator is used in the second evaporator. Evaporation of water is nearly doubled in double effect evaporation system compared to single effect per unit mass of steam used. Additional effects can be added in series in the same way to get a *triple-effect* evaporator, *quadruple-effect* evaporator and so on. There are several configurations based on feeding arrangement.



**3.7a**. Forward feed.



**3.7b**. Backward feed.



**3.7c**. Mixed feed.

# 4. PERFORMANCE OF EVAPORATORS (CAPACITY AND ECONOMY)

The performance of a steam-heated evaporator is measured in terms of its capacity and economy. Capacity is defined as the number of kilogram of water vaporized per hour. Economy (or steam economy) is the number kilogram of water vaporized from all the effects per kilogram of steam used. For single effect evaporator, the steam economy is about 0.8 (<1). The capacity is about *n*-times that of a single effect evaporator and the economy is about 0.8*n* for a *n*-effect evaporators. However, pumps, interconnecting pipes and valves are required for transfer of liquid from one effect to another effect that increases both equipment and operating costs.

## *Boiling point elevation (BPE)*

Most evaporators produce concentrated liquor having a boiling point considerably higher than that of pure solvent (or water). This phenomenon is called boiling point elevation (BPE). BPE occurs as the vapor pressure of a solution (usually aqueous solution) is less than that of pure solvent at the same temperature. Boiling point of a solution is a colligative property. It depends on the concentration of solute in the solution for a pair of solute and solvent.

BPE of the concentrated liquor reduces the effective temperature driving force compared to the boiling of pure solvent. Equilibrium vapor generated from a solution exhibiting boiling point elevation is superheated with respect to vapor generated during boiling of pure solvent. The vapor is generated at the solution boiling point, which is higher than the pure component boiling point. The vapor, however, is solute free, so it won’t condense until the extra heat corresponding to the elevation is removed, thus it is superheated. Therefore the BPE of the concentrated solution must be known for evaporator design.

**Design problem**

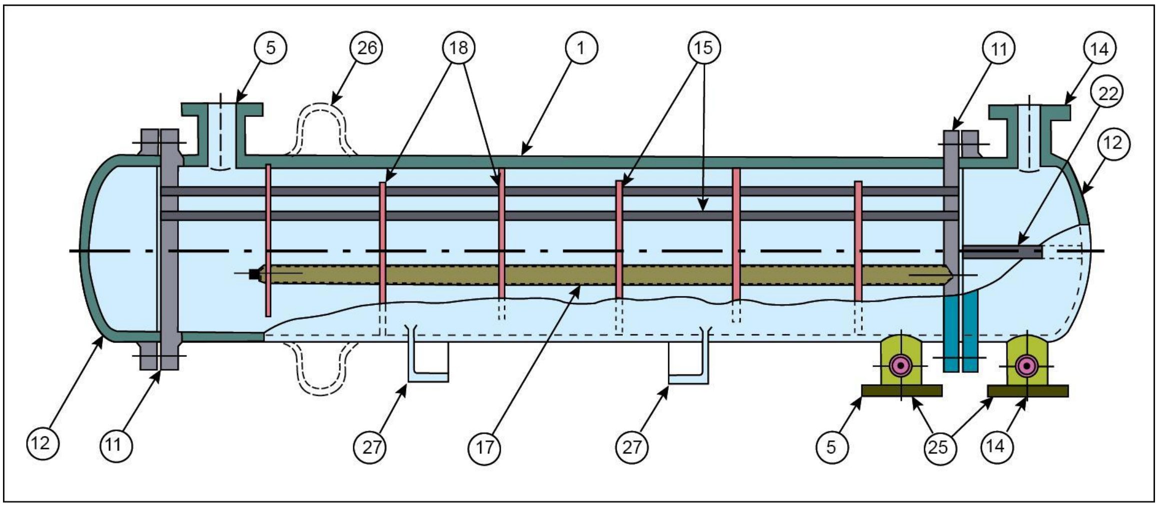
A 5% aqueous solution of a high molecular weight solute has to be concentrated to 40% in a forward-feed double effect evaporator at the rate of 8000 kg.h$^{-1}$. The feed temperature is 40°C. Saturated steam at 3.5 kg.cm$^{-2}$ is available for heating. A vacuum of 600 mm Hg is maintained. Calculate the area requirements, The overall heat transfer coefficients are 550 kcal.h$^{-1}$m$^{-2}$ °C$^{-1}$ in the first and the last effect respectively. The specific heat of the concentrated liquor is 0.87 kcal.kg$^{-1}$°C$^{-1}$.

# Heat Exchangers

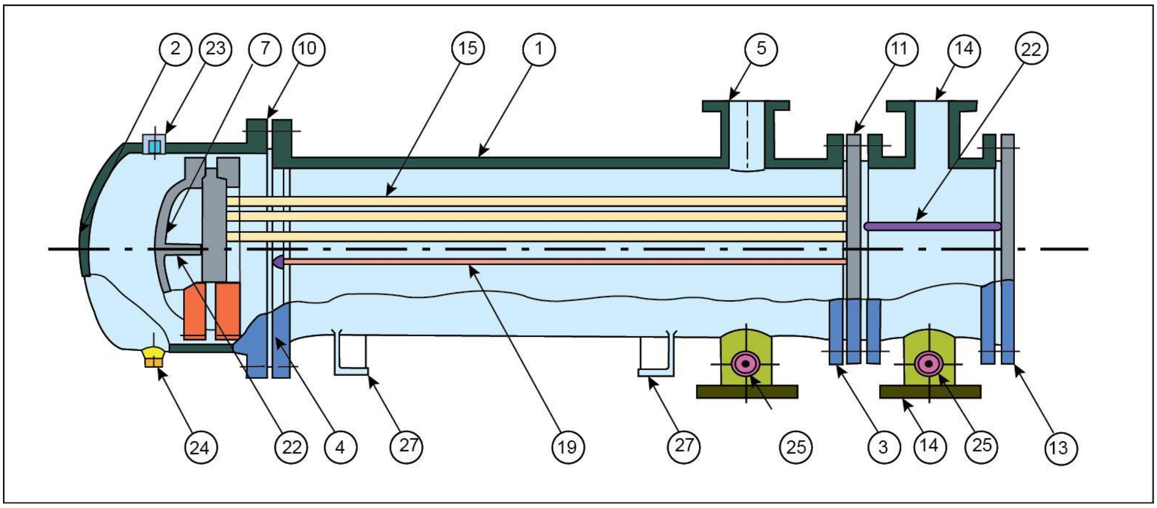
## *Classification of heat exchangers*

Transfer of heat from one fluid to another is an important operation for most of the chemical industries. The most common application of heat transfer is in designing of heat transfer equipment for exchanging heat from one fluid to another fluid. Such devices for efficient transfer of heat are generally called Heat Exchanger.

**Fixed tube-sheet exchanger**: The simplest and cheapest type of shell and tube exchanger is with fixed tube sheet design. In this type of exchangers the tube sheet is welded to the shell and no relative movement between the shell and tube bundle is possible (**Figure 1.2**).



**Removable tube bundle:** Tube bundle may be removed for ease of cleaning and replacement. Removable tube bundle exchangers further can be categorized in floating-head and U-tube exchanger.



## Fouling Considerations

The most of the process fluids in the exchanger foul the heat transfer surface. The material deposited reduces the effective heat transfer rate due to relatively low thermal conductivity. Therefore, net heat transfer with clean surface should be higher to compensate the reduction in performance during operation. Fouling of exchanger increases the cost of (i) construction due to oversizing, (ii) additional energy due to poor exchanger performance and (iii) cleaning to remove deposited materials. A spare exchanger may be considered in design for uninterrupted services to allow cleaning of exchanger. The effect of fouling is considered in heat exchanger design by including the tube side and shell side fouling resistances.

## Selection of fluids for tube and the shell side

| *Tube-side fluid* | *Shell-side fluid* |
|---|---|
| Corrosive fluid | Condensing vapor (unless corrosive) |
| Cooling water | Fluid with large temperature difference (>40°C) |
| Fouling fluid | |
| Less viscous fluid | |
| High-pressure steam | |
| Hotter fluid | |

# Process Design Procedure

**Step #1.** Obtain the required thermophysical properties of hot and cold fluids at the **caloric temperature or arithmetic mean temperature**.

**Step #2.** Perform energy balance and find out the heat duty ( $Q$ ) of the exchanger.

**Step #3.** Assume a reasonable value of overall heat transfer coefficient ($U_{o,assm}$). The value of $U_{o,assm}$ with respect to the process hot and cold fluids

**Step #4**. Decide tentative number of shell and tube passes ( $n_p$ ). Determine the LMTD and the correction factor $F_T$ ($F_T$ normally should be greater than 0.75 for the steady operation of the exchangers. Otherwise it is required to increase the number of passes to obtain higher $F_T$ values.

**Step #5**. Calculate heat transfer area ($A$) required:

**Step #6**. Select tube material, decide the tube diameter (ID= $d_i$ , OD = $d_o$ ), its wall thickness (in terms of BWG or SWG) and tube length ( $L$ ). Calculate the number of tubes

( $n_t$ ) required to provide the heat transfer area ($A$): $n_t = \frac{A}{\pi d_o L}$

Calculate tube side fluid velocity, $u = \frac{4\dot{m}(n_p/n_t)}{\pi \rho d_i^2}$

If $u$ <1 m/s, fix $n_p$ so that, $\mathrm{Re} = \frac{4\dot{m}(n_p/n_t)}{\quad} \geq 10^4$

Where, $m$, $\rho$ and $\mu$ are mass flow rate, density and viscosity of tube side fluid. However, this is subject to allowable pressure drop in the tube side of the heat exchanger.

**Step #7**. Decide type of shell and tube exchanger (fixed tubesheet, U-tube etc.). Select the tube pitch ($P_T$), determine inside shell diameter ( $D_s$ )

**Step #9**. Assign fluid to shell side or tube side (a general guideline for placing the fluids is summarized in **Table 1.4**). Select the type of baffle (segmental, doughnut etc.), its size (i.e. percentage cut, 25% baffles are widely used), spacing ( $B$ ) and number. The baffle spacing is usually chosen to be within 0.2 $D_s$ to $D_s$ .

**Step #10**. Determine the tube side film heat transfer coefficient ( $h_i$ ) using the suitable form of Sieder-Tate equation in laminar and turbulent flow regimes. Estimate the shell-side film heat transfer coefficient ( $h_o$ ) from: Select the outside tube (shell side) dirt factor ( $R_{do}$ ) and inside tube (tube side) dirt factor. Calculate overall heat transfer coefficient ($U$) based on the outside tube area

# Design Problem

150000 lb per hour of kerosene will be heated from 75 to 120°F by cooling a gasoline stream from 160 to 120°F. Inlet pressure will be 50 psia for each stream and the maximum pressure drop of 7 psi for gasoline and 10 psi for kerosene are permissible. Published fouling factors for oil refinery streams should be used for this application. Design a shell and tube heat exchanger for this service.