Evaporation System: Types and Design Aspects

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Evaporation is an important unit operation, which is used for solvent removal from a solution, slurry or suspension of solid in a liquid. The purpose is to concentrate a non-volatile solute, such as organic compounds, inorganic salts, acids or bases from a solvent. 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. It has wide application in food processing industries to make concentrates of fruit and vegetable juices. Moreover, in dairy sector, it is used to concentrate the milk. Various design of evaporators is available in market, we have to select the appropriate as per our requirement. If desired design is not available in market we can design the evaporation system as per our requirement.

Type of Evaporators

Evaporator consists of a heat exchanger for boiling the solution with special provisions for separation of liquid and vapour 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.

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 or Robert evaporators. This evaporator was first built by Robert. 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 1 to 3 m 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 its down comer area is taken as 40 to 70% of the total cross sectional area of tubes. The circulation rate through the down comer/down take is many times the feed rate. The flow area of the down take is normally approximately equal to the total tubular flow area.

2. Basket-type Vertical Evaporators

The construction and operational features of basket-type evaporators are very similar to those of the standard evaporator except that the down take is annular. The tube bundle with fixed tube sheets forms a basket hung in the centre of the evaporator from internal brackets. The diameter of the tube bundle is smaller than the diameter of evaporator vessel, thus forming an annular space for circulation of liquid. The tube bundle can be removed for the purpose of cleaning and maintenance and thus basket evaporators are more suitable than standard evaporators for scale forming solutions. The vapour generated strikes a deflector plate fixed close to the steam pipe that reduces entrained liquid droplets from the vapour.

3. 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 vapour chamber at the top. 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 3.6 to 9 m in length) and vertical heated tube. Both rising film and falling types are used. Tube length usually varies from 6 to 20 m. 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.

4. 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. Vapour 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 vapour-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.

5. **Rising or Climbing Film Evaporators**

The LTV evaporator is frequently called a rising or climbing film evaporator. The liquid starts boiling at the lower part of the tube and the liquid and vapour flow upward through the tube. If the heat transfer rate is significantly higher, the ascending flows generated due to higher specific volume of the vapour-liquid mixture, causes liquid and vapour to flow upwards in parallel flow. The liquid flows as a thin film along the tube wall. This co-current upward movement against gravity has the advantageous effect of creating a high degree of turbulence in the liquid. This is useful during evaporation of highly viscous and fouling solutions.

6. **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 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.

7. 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.

8. Gasketed Plate Evaporator

The gasketed-plate evaporator is also called the plate evaporator because the design is similar to that of a plate heat exchanger. A number of embossed plates with four corner openings are mounted by an upper and a bottom carrying bar. The gasket is placed at the periphery of the plates. The interfering gaskets of two adjacent plates prevent the mixing of the fluids and lead the fluid to the respective flow path through the corner opening. The fluids may either flow in series or parallel depending on the gasket arrangement. The heat transfer coefficient is greatly enhanced due to high turbulent flow through narrow passages. This evaporator is suitable for high viscous, fouling, foaming and heat sensitive solutions. This type of evaporators is mainly used for concentration of food products, pharmaceuticals, emulsions, glue, etc.

Design procedure of evaporation system

The latent heat of condensation of the steam is transferred through the heating surface to vaporize water from a boiling solution. Therefore two enthalpy balance equations are required to in order to calculate the rate of solvent vaporization and the rate of required input heat.

Assumptions:

Generally it is possible to solve the energy and the material balance equations analytically by a sequential approach. The following assumptions are made to develop the mass and energy balance equations:-

- There is no leakage or entrainment
- The flow of non-condensable is negligible
- Heat loss from the evaporator system is negligible

From the enthalpy data of the solutions, steam and condensate, the rate of heat input or the rate of steam flow can be calculated. The overall heat transfer coefficient is should be either known from the performance data of an operating evaporator of the same type and processing the same solution or a reasonable value can be selected from the standard. With this information, the required area of heat transfer can be estimated.

Calculate the tube-side and shell-side pressure drop using the method discussed during design of shell and tube exchanger from specified values of the tube length, diameter and the tube layout. If the pressure drop value is more than the corresponding allowable pressure drop, further adjustments in the heat exchanger configuration will be required.

Thermal design

These following equations were used for the calculation-

Mass balance:

$$m_f = m_v + m_p \quad ...1$$

Solid balance:

$$x_f \times m_f = x_p \times m_p \quad ...2$$

Enthalpy balance:

$$\left(m_f \times m_f\right) + (m_s \times m_{vs}) = (m_v \times m_{v1}) + \left(m_p \times m_{p1}\right) + (m_s \times m_{cs}) ...3$$

Where,

m_f = Mass flow rate of feed, kg/h

m_s = Mass flow rate of steam, kg/h

m_v = Mass flow rate of vapour, kg/h

m_p = Mass flow rate of concentrated product, kg/h

x_f = Solid fraction in feed

x_p = Solid fraction in concentrated feed

h_f = Enthalpy of feed, kJ/Kg

h_{vs} = Enthalpy of saturated vapour at temperature t_s, kJ/Kg

h_{v1} = Enthalpy of saturated vapour at temperature t_1, kJ/Kg

h_p = Enthalpy of concentrated product, kJ/Kg

h_{cs} = Enthalpy of condensate, kJ/Kg

Area of heat transfer:

$$q = U\,A\,(t_s - t_1) = (m_s \times h_{vs}) - (m_s \times h_{cs}) \quad ...4$$

Where,

U = Overall heat transfer coefficient, $W/M^2\ {}^0C$

A = Area, m^2

Q = Rate of heat transfer, W

Mechanical Design

Tube Thickness,

$$t_t = \frac{pD}{2fj+p} \quad ...5$$

p = design pressure

D = outer diameter of tube

f = permissible stress

j = joint efficiency (j =1)

Shell thickness,

$$t_s = \frac{pD}{2fj+p} \quad ...6$$

p = design pressure

D = inner diameter of shell

f = permissible stress

j = joint efficiency (j =0.85)

Tube sheet thickness,

$$t_{ts} = fG\sqrt{\frac{0.25p}{f}} \quad ...7$$

f = permissible stress

p = design pressure

G = mean dia of gasket, but we assume it as equal to inner shell dia.

Number of tubes $n = \frac{A}{\pi DL}$ ...8

Where,

A = Surface area for heat transfer, m^2

D = Diameter of tube, m

L = Length of the tube, m

Table 1 presents the values of various design parameters of evaporator, used for computation purpose. Design parameters include mass of feed, mass of concentrated product, mass of vapour; overall heat transfer coefficient, enthalpy of feed, concentrated product, saturated steam, condensed steam, vapour, allowable stress of stainless steel 304, Joint efficiency of tube and shell thickness etc. The enthalpy of feed, product and steam were taken from steam table. These data were used in equations (1), (2) and (3) to compute mass of water vapour, total heat load, required surface area for heat transfer.

Equation (5), (6), and (7) were used to calculate some mechanical parameters include Tube, shell and sheet thickness etc. Joint efficiency of tube and shell thickness was taken as a standard value. The number of tubes was calculated by using equation (8).

Therefore, we can design the desired evaporation system for particular purpose using above design procedure. It will be helpful for all those, who are interested to acquire knowledge of design aspects of evaporation system.

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