

Lecture 6 «Evaporation. Definition of a temperature depression. Evaporation modes. Evaporating devices. Heat and material balances of evaporating devices»

Aim: Describe the evaporation and evaporation modes. Formulate the heat and material balances of evaporating devices.

Lecture summary: *Evaporation* is the process of concentrating solutions by removing the solvent by evaporation while boiling the liquid.

Evaporation is used to increase the concentration of diluted solutions or to separate dissolved substances from them by crystallization.

The peculiarity of the evaporation process is the transition to the vapor state of only the solvent. The boiling point of solutions is always higher than the boiling point of the solvents, it depends on the chemical nature of the solutes and solvents and grows with increasing solution concentration and external pressure.

The difference between the boiling points of the solution t_s and the pure solvent at the same external pressure is called *the temperature depression* Δt_d :

$$\Delta t_d = t - t_{sol} \quad (1)$$

The increase in the boiling point of the solution is also determined by hydrostatic and hydraulic depressions.

The increase in the boiling point due to the hydrostatic pressure of the liquid column in the vertical pipe is called *hydrostatic* depression $\Delta t_{h.d.}$.

The increase in the boiling point of the solution due to the increase in pressure in the apparatus due to hydraulic losses during passage of the secondary vapor through the trap and the outlet of pipeline is called *hydraulic* depression $\Delta t_{hd.d.}$.

The vapor produced by evaporation of the boiling solution is called *secondary*.

When boiling pure water (solvent), the temperature head is equal to the difference between the temperature of the heating steam and the temperature of the boiling water, which is equal to the saturation temperature of the secondary vapor.

When the solution boils, the saturation temperature of the secondary vapor corresponding to the pressure in the apparatus does not change, and the boiling point of the solution increases by the amount of depression. Consequently, the same temperature is lowered by the same magnitude of depression.

Thus, depression causes a loss of temperature head, as a result of which it is called a temperature loss.

Total depression Δt_t is equal to the sum of temperature, hydrostatic and hydraulic depressions:

$$\Delta t_t = \Delta t_d + \Delta t_{h.d.} + \Delta t_{hd.d.} \quad (2)$$

The boiling point of the solution is determined depending on the saturation temperature of the secondary vapor by the formula

$$T_{\text{boil.point of sol.}} = t_{\text{sat.sec.vapor}} + \Delta t_d \quad (3)$$

Evaporation is accompanied by an increase in the density and viscosity of the solution, which leads to a decrease in the heat transfer coefficient [1-3].

Ways of evaporation

Evaporation is made at the expense of heat from the outside, transmitted more often through the surface of heating and less often by direct contact of the solution with the heat carrier.

Water vapor, flue gases, as well as high-boiling liquids and their vapors are used as heat carriers.

The evaporation processes are carried out under vacuum, at elevated and atmospheric pressures. The choice of pressure is related to the properties of the solution to be evaporated and the use of secondary vapor heat.

Evaporation under vacuum has certain advantages before evaporation under atmospheric pressure. When evaporated under reduced pressure, the vacuum in the apparatus is created by condensation of the secondary vapor in the condenser by a vacuum pump. The vacuum evaporation allows to lower the boiling point of the solution, and also to increase the temperature difference between the heating agent and the boiling solution, which makes it possible to reduce the heat exchange surface.

When evaporated under elevated pressure, the resulting secondary steam can be used as a heating agent, for heating or other technological needs.

Evaporating devices

In industry, both single-casing and multi-casing evaporators are widely used. Multi-casing evaporators consist of several (up to four) connected devices. Direct-flow units operate under pressure, dropping from the first housing to the last one.

In such installations, the secondary vapor generated in each previous casing is used to heat the subsequent casing. Fresh steam is heated only by the first case. Secondary steam from the last housing is sent to the condenser (if this housing is under vacuum) or used outside the installation (if the latter housing is working under increased pressure).

Practically the steam consumption (in *kg*) per 1 *kg* of evaporated water is: in a single-casing residue – 1.1; in a two-casing – 0.57; in a three-casing – 0,40; four-casing – 0.30; five-casing – 0,27.

In multiple-unit plants, the same amount of heat is used repeatedly (the heat given off by the heating steam in the first casing), which significantly reduces the amount of fresh steam consumed, i.e. increase the technical and economic parameters of the installation [1-3].

When evaporating small amounts of solutions, horizontal and vertical devices are used, which are boilers equipped with heating jackets and coils for steam and liquid heating or gas heating furnaces.

In the chemical industry, vertical evaporators with natural and forced circulation, as well as film evaporators, were most widely distributed.

The evaporator with a natural circulation of the solution consists of a heating chamber **1** where steam is supplied, plates **2** in which pipes **3** of 2 to 4 m in length are rolled up, a vapor space **4**, a separator **5**, a circulation pipe **6** (Fig. 1).

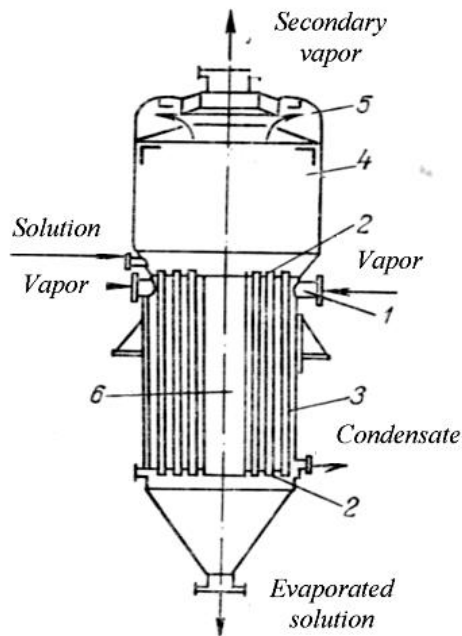


Fig. 1. Evaporator with natural circulation

The evaporated solution circulates through the tubes from the bottom upwards and descends down the circulation pipe. The circulation in the apparatus is due to the difference in the specific gravity of the liquid in the descending circulation pipe and the vapor-liquid emulsion in the boiler tubes. The presence of a vapor space **4** above the solution to be evaporated must ensure a satisfactory separation of the spray of the evaporated solution from the secondary vapor.

Insufficient separation of the spray leads to loss of the solution, and with multi-casing evaporation to contamination of the heating surface of the next housing and the condensate of the secondary vapor. A decrease in the speed of the secondary steam (i.e., an increase in the diameter of the apparatus) and an increase in the height of the vapor space lead to a decrease in the splashwater [3].

Material balance of the evaporation device

The material balance of the evaporation device can be represented by the total number of substances

$$G_1 = G_2 + W \quad (4)$$

and for the dissolved substance

$$G_1 a_1 = G_2 a_2 \quad (5)$$

where G_1 and G_2 – initial and final amount of solution, kg/s; a_1 and a_2 – initial and final concentration of solution in weight fractions; W - amount of evaporated water, kg/s.

The above equations (4) and (5) include five variables, of which some three quantities must be specified. In practical calculations, the following quantities are most commonly

known: the consumption of the initial solution G_1 , its initial concentration a_1 and the required final concentration a_2 of the evaporated solution. Then by the equations (4) and (5) determine the productivity of the device:

over evaporated solution

$$G_2 = \frac{G_1 a_1}{a_2} \quad (6)$$

over evaporated water

$$W = G_1 - G_2 = G_1 \left(1 - \frac{a_1}{a_2}\right) \quad (7)$$

If the flow rate of the initial solution G_1 , its initial concentration a_1 and the amount of evaporated water W are set, then from the material balance equations (4) and (5), it is possible to calculate the final concentration of the solution

$$a_2 = \frac{G_1 a_1}{G_2} = \frac{G_1 a_1}{G_1 - W} \quad (8)$$

and the amount of the final solution

$$G_2 = G_1 - W \quad (9)$$

Thermal balance of the evaporation device

The coming of heat in the evaporation device is composed of heat with the incoming solution $G_{in}c_{in}t_{in}$ and heat, which is given to the apparatus by the heating agent Q .

The heat consumption for evaporation includes: heat carried away by the secondary steam $Wi_{s.s.}$; heat with a leaving solution $G_f c_f t_f$; the heat expended for dehydration Q_d ; loss of heat to the environment Q_l .

Thus, we can write the heat balance equation:

$$Q + G_{in}c_{in}t_{in} = Wi_{s.s.} + G_f c_f t_f + Q_d + Q_l, \quad (10)$$

where c_{in} and c_f – the specific heat capacities of the incoming G_{in} and outgoing G_f solutions, J/(kg·K); t_{in} and t_f – the temperatures of incoming and outgoing solutions, °C; $i_{s.v.}$ – the specific enthalpy of the secondary vapor, at the outlet of the evaporator, J/kg.

The heat of dehydration is the heat input to increase the concentration of the solution and it is equal in magnitude and back to the sign of the heat of vaporization of the solution. Usually, the heat of dehydration is low and therefore not taken into account.

Considering the initial solution as a mixture of the evaporated solution and the water to be evaporated and assuming that the heat capacity c_{in} of the initial solution within the temperature t_{in} to t_f remains constant, we will write down the heat balance of mixing at the boiling point of the solution in the apparatus:

$$G_{in}c_{in}t_{in} = G_f c_f t_f + Wc_w t_f \quad (11)$$

whence

$$G_f c_f t_f = G_{in} c_{in} t_{in} - W c_w t_f \quad (12)$$

where c_w – the average specific heat of water (within the temperature range from 0 °C to t_f), J/(kg·K).

Substituting the value (12) into the heat balance equation (10), we obtain, neglecting Q_d :

$$Q + G_{in} c_{in} t_{in} = W i_{s.s.} + G_{in} c_{in} t_{in} - W c_w t_f + Q_l \quad (13)$$

or

$$Q = G_{in} c_{in} (t_f - t_{in}) + W (i - c_w t_f) + Q_l \quad (14)$$

In this equation, the term $W(i - c_w t)$ is the heat consumption for evaporation of water.

The specific heat capacity of the solution entering into the heat balance equation can be calculated as a function of its concentration a according to the approximate formula

$$c = c_{sol} a + c_w (1 - a), \quad (15)$$

where c_{sol} – the specific heat of an anhydrous solid solute (for two-component solutions).

The heat capacity of solutions (multicomponent) can be calculated from the general formula

$$c = c_1 x_1 + c_2 x_2 + c_3 x_3, \quad (16)$$

where c_1, c_2, c_3 – the heat capacities of the components; x_1, x_2, x_3 – the mass fractions of the components.

In the absence of direct experimental data, the specific heat capacity of a chemical compound can be calculated approximately by the additivity rule:

$$c = \sum_i n_i c_{a,i} / M, \quad (17)$$

where n_i and $c_{a,i}$ – the number of atoms and the atomic heat capacity of the i -th element (Table 1) entering into the chemical compound; M – the molar mass of the compound, kg/kmol.

Table 1 shows the heat capacities of the elements.

Table 1. Atomic heat capacity of elements

Element	The atomic heat capacity of elements for chemical compounds, kJ/(kg·atom·K)		Element	The atomic heat capacity of elements for chemical compounds, kJ/(kg·atom·K)	
	in the solid state	in the liquid state		in the solid state	in the liquid state

C	7.5	11.7	F	21.0	29.3
H	9.6	18.0	P	22.6	31.0
B	11.3	19.7	S	22.6	31.0
Si	15.9	24.3	Rest	26.0	33.6
O	16.8	25.1			

For an approximate calculation of the specific heat capacity of diluted aqueous solutions ($x \leq 0.2$), the heat capacity of the dissolved substance can not be taken into account because of its relative smallness:

$$c = 4,19 \cdot 10^3(1 - x), \quad (18)$$

where $4,19 \cdot 10^3 \text{ J}/(\text{kg} \cdot \text{K})$ – the specific heat of water.

The required flow of heating water vapor ($G_{h.v.}$) for the evaporator is proportional to the required amount of heat:

$$G_{h.v.} = \frac{Q}{(i'' - i')x} = \frac{Q}{r_{h.s}x}, \quad (19)$$

where i'' и i' – the specific enthalpies of dry saturated heating steam and its condensate at the condensation temperature, J/kg; x – the degree of dryness (steam content) of the heating steam (in most cases $x \approx 0.95 \div 0.98$; $r_{h.s.}$ – specific heat of condensation of heating steam, J/kg.

Specific consumption of heating steam (d) characterizes the efficiency of the use of heating steam in relation to the amount of evaporated solvent [1-3]:

$$d = \frac{G_{h.v.}}{W} \quad (20)$$

Questions to control:

1. Show the essence of evaporation and the area of its practical application.
2. Describe the methods of the evaporation process - under vacuum, at atmospheric pressure and under increased pressure.
3. Expand the features of single-casing and multi-casing evaporation, periodic and continuous evaporation.
4. What is meant by secondary steam and extra steam?
5. Explain the principle of operation and the device of the evaporator with natural circulation.
6. Give the equations of material balance of the evaporator.
7. What are the terms in the heat balance equation of the evaporator?

Literature

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