

Course Code: NFE-131

Course Title: Unit Operation in Food Industries

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EVAPORATION

Frequently in the food industry a raw material or a processed food contains more water than is required in the final product. When the foodstuff is a liquid, the easiest method of removing the water, in general, is to apply heat to evaporate it. Evaporation is thus a process that is often used by the food technologist.

The basic factors that affect the rate of evaporation are the:

- rate at which heat can be transferred to the liquid,
- quantity of heat required to evaporate each kg of water,
- maximum allowable temperature of the liquid,
- pressure at which the evaporation takes place,
- changes that may occur in the foodstuff during the course of the evaporation process.

Considered as a piece of process plant, the evaporator has two principal functions, to exchange heat and to separate the vapour that is formed from the liquid.

Important practical considerations in evaporators are the:

- maximum allowable temperature, which may be substantially below 100°C.
- promotion of circulation of the liquid across the heat transfer surfaces, to attain reasonably high heat transfer coefficients and to prevent any local overheating,
- viscosity of the fluid which will often increase substantially as the concentration of the dissolved materials increases,
- tendency to foam which makes separation of liquid and vapour difficult.

THE SINGLE EFFECT EVAPORATOR

The typical evaporator is made up of three functional sections: the heat exchanger, the evaporating section, where the liquid boils and evaporates, and the separator in which the vapour leaves the liquid and passes off to the condenser or to other equipment. In many evaporators, all three sections are contained in a single vertical cylinder. In the centre of the cylinder there is a steam heating section, with pipes passing through it in which the evaporating liquors rise. At the top of the cylinder, there are baffles, which allow the vapours to escape but check liquid droplets that may accompany the vapours from the liquid surface.

A diagram of this type of evaporator, which may be called the conventional evaporator, is given in Fig. 8.1. In the heat exchanger section, called a calandria in this type of evaporator, steam condenses in the space surrounding the tubes and the liquid being evaporated boils on the inside of the tubes and in the space above the upper tube plate.

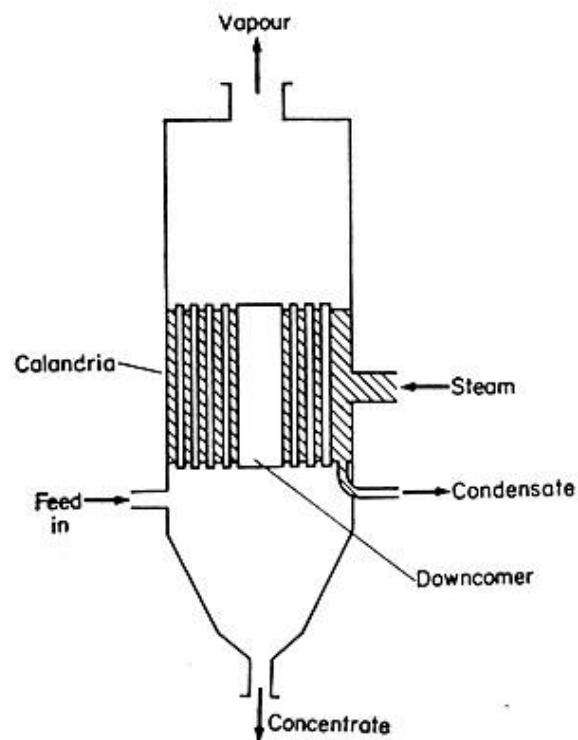


Figure 8.1 Evaporator

The resistance to heat flow is imposed by the steam and liquid film coefficients and by the material of the tube walls. The circulation of the liquid greatly affects evaporation rates, but circulation rates and patterns are very difficult to predict in any detail. Values of overall heat transfer coefficients reported for evaporators are of the order of $1800\text{-}5000 \text{ Jm}^{-2}\text{s}^{-1}\text{°C}^{-1}$ for the evaporation of distilled water in a vertical tube evaporator with heat supplied by condensing steam.

However, with dissolved solids in increasing quantities as evaporation proceeds leading to increased viscosity and poorer circulation, heat transfer coefficients in practice may be much lower than this. As evaporation proceeds, the remaining liquors become more concentrated and because of this the boiling temperature rises. The rise in the temperature of boiling reduces the available temperature drop, assuming no change in the heat source. And so the total rate of heat transfer will drop accordingly. Also, with increasing solute concentration the viscosity of the liquid will increase, often quite substantially, and this affects circulation and the heat transfer coefficients leading again to lower rates of boiling.

Yet another complication is that overall heat transfer coefficients have been found to vary with the actual temperature drop, so that the design of an evaporator on theoretical grounds is inevitably subject to wide margins of uncertainty.

Perhaps because of this uncertainty, many evaporator designs have tended to follow traditional patterns of which the calandria type of Fig. 8.1 is a typical example.

Vacuum Evaporation

For the evaporation of liquids that are adversely affected by high temperatures, it may be necessary to reduce the temperature of boiling by operating under reduced pressure. The relationship between vapour pressure and boiling temperature, for water, is shown in Fig. 7.2. When the vapour pressure of the liquid reaches the pressure of its surroundings, the liquid boils. The reduced pressures required to boil the liquor at lower temperatures are obtained by mechanical, or steam jet ejector, vacuum pumps, combined generally with condensers for the vapours from the evaporator. Mechanical vacuum pumps are generally cheaper in running costs but more expensive in terms of capital than are steam jet ejectors. The condensed liquid can either be pumped from the system or discharged through a tall barometric column in which a static column of liquid balances the atmospheric pressure. Vacuum pumps are then left to deal with the non-condensibles, which of course are much less in volume but still have to be discharged to the atmosphere.

Heat Transfer in Evaporators

Heat transfer in evaporators is governed by the equations for heat transfer to boiling liquids and by the convection and conduction equations. The heat must be provided from a source at a suitable temperature and this is condensing steam in most cases. The steam comes either directly from a boiler or from a previous stage of evaporation in another evaporator. Major objections to other forms of heating, such as direct firing or electric resistance heaters, arise because of the need to avoid local high temperatures and because of the high costs in the case of electricity. In some cases, the temperatures of condensing steam may be too high for the product and hot water may be used. Low-pressure steam can also be used but the large volumes create design problems.

Calculations on evaporators can be carried out combining mass and energy balances with the principles of heat transfer.

EXAMPLE 8.1. Single effect evaporator: steam usage and heat transfer surface

A single effect evaporator is required to concentrate a solution from 10% solids to 30% solids at the rate of 250kg of feed per hour. If the pressure in the evaporator is 77kPa absolute, and if steam is available at 200kPa gauge, calculate the quantity of steam required per hour and the area of heat transfer surface if the overall heat transfer coefficient is $1700\text{Jm}^{-2}\text{s}^{-1}\text{C}^{-1}$.

Assume that the temperature of the feed is 18°C and that the boiling point of the solution under the pressure of 77kPa absolute is 91°C . Assume, also, that the specific heat of the solution is the same as for water, that is $4.186 \times 10^3\text{Jkg}^{-1}\text{C}^{-1}$, and the latent heat of vaporization of the solution is the same as that for water under the same conditions.

From steam tables (Appendix 8), condensing temperature of steam at 200kPa gauge (300kPa abs.) is 134°C and latent heat 2164kJkg^{-1} ; the condensing temperature at 77kPa (abs.) is 91°C and latent heat is 2281kJ kg^{-1} .

Mass balance (kg h^{-1})

| | Solids | Liquids | Total |
|-------------|--------|---------|-------|
| Feed | 25 | 225 | 250 |
| Product | 25 | 58 | 83 |
| Evaporation | | | 167 |

Heat balance

Heat available per kg of steam

$$\begin{aligned} &= \text{latent heat} + \text{sensible heat in cooling to } 91^\circ\text{C} \\ &= 2.164 \times 10^6 + 4.186 \times 10^3(134 - 91) \\ &= 2.164 \times 10^6 + 1.8 \times 10^5 \\ &= 2.34 \times 10^6 \text{ J kg}^{-1} \end{aligned}$$

Heat required by the solution

$$\begin{aligned} &= \text{latent heat} + \text{sensible heat in heating from } 18^\circ\text{C to } 91^\circ\text{C} \\ &= 2281 \times 10^3 \times 167 + 250 \times 4.186 \times 10^3 \times (91 - 18) \\ &= 3.81 \times 10^8 + 7.6 \times 10^7 \\ &= 4.57 \times 10^8 \text{ J} \end{aligned}$$

Now, heat from steam = heat required by the solution,

Therefore quantity of steam required per hour

$$\begin{aligned} &= (4.57 \times 10^8) / (2.34 \times 10^6) \\ &= 195 \text{ kg h}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Quantity of steam/kg of water evaporated} &= 195/167 \\ &= \underline{1.17 \text{ kg steam/kg water.}} \end{aligned}$$

Heat transfer area

Temperature of condensing steam = 134°C .

Temperature difference across the evaporator = $(134 - 91) = 43^\circ\text{C}$.

Writing the heat transfer equation for q in Js^{-1} ,

$$\begin{aligned} q &= UA \Delta T \\ (4.57 \times 10^8) / 3600 &= 1700 \times A \times 43 \\ A &= 1.74 \text{ m}^2 \end{aligned}$$

$$\text{Area of heat transfer surface} = \underline{1.74 \text{ m}^2}$$

It has been assumed that the sensible heat in the condensed steam (cooling from 134°C to 91°C) is recovered, and this might in practice be done in a feed heater. If it is not recovered usefully, then the sensible heat component, about 8%, should be omitted from the heat available, and the remainder of the working adjusted accordingly.

Condensers

In evaporators that are working under reduced pressure, a condenser, to remove the bulk of the volume of the vapours by condensing them to a liquid, often precedes the vacuum pump. Condensers for the vapour may be either surface or jet condensers. Surface condensers provide sufficient heat transfer surface, pipes for example, through which the condensing vapour transfers latent heat of vaporization to cooling water circulating through the pipes. In a jet

condenser, the vapours are mixed with a stream of condenser water sufficient in quantity to transfer latent heat from the vapours.

EXAMPLE 8.2. Water required in a jet condenser for an evaporator

How much water would be required in a jet condenser to condense the vapours from an evaporator evaporating 5000kg h^{-1} of water under a pressure of 15cm of mercury? The condensing water is available at 18°C and the highest allowable temperature for water discharged from the condenser is 35°C .

Heat balance

The pressure in the evaporator is 15cm mercury = $Z\rho g = 0.15 \times 13.6 \times 1000 \times 9.81 = 20 \text{ kPa}$.

From steam tables (Appendix 8), condensing temperature of water under pressure of 20 kPa is 60°C and the corresponding latent heat of vaporization is 2358 kJ kg^{-1} .

$$\begin{aligned} \text{Heat removed from condensate per kilogram} \\ &= 2358 \times 10^3 + 4.186 \times 10^3 \times (60 - 35) \\ &= 2.46 \times 10^6 \text{ J kg}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Total heat removed from condensate per hour} \\ &= 5000 \times 2.46 \times 10^6 \text{ J} \end{aligned}$$

$$\begin{aligned} \text{Heat taken by cooling water} \\ &= 4.186 \times 10^3 \times (35 - 18) \\ &= 7.1 \times 10^4 \text{ J kg}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Quantity of cooling water per hour} \\ &= (5000 \times 2.46 \times 10^6) / 7.1 \times 10^4 \\ &= \underline{1.7 \times 10^5 \text{ kg}} \end{aligned}$$

EXAMPLE 8.3. Heat exchange area for a surface condenser for an evaporator

What heat exchange area would be required for a surface condenser working under the same conditions as the jet condenser in Example 8.2, assuming a U value of $2270 \text{ J m}^{-2} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}$, and disregarding any sub-cooling of the liquid.

The temperature differences are small so that the arithmetic mean temperature can be used for the heat exchanger (condenser).

$$\begin{aligned} \text{Mean temperature difference} \\ &= (60 - 18)/2 + (60 - 35)/2 \\ &= 33.5^\circ\text{C}. \end{aligned}$$

The data are available from the previous Example, and remembering to put time in hours.

$$\begin{aligned} \text{Heat removed from condensate} &= \text{Heat transferred to water} \\ &= UA\Delta T \\ 5000 \times 2.46 \times 10^6 &= 2270 \times A \times 33.5 \times 3600 \\ A &= 45 \text{ m}^2 \\ \text{Heat transfer area required} &= \underline{45 \text{ m}^2} \end{aligned}$$

This would be a large surface condenser so that a jet condenser is often preferred.

MULTIPLE EFFECT EVAPORATION

An evaporator is essentially a heat exchanger in which a liquid is boiled to give a vapour, so that it is also, simultaneously, a low-pressure steam generator. It may be possible to make use of this, to treat an evaporator as a low pressure boiler, and to make use of the steam thus produced for further heating in another following evaporator called another *effect*.

Consider two evaporators connected so that the vapour line from one is connected to the steam chest of the other as shown in Fig. 8.2, making up a two effect evaporator.

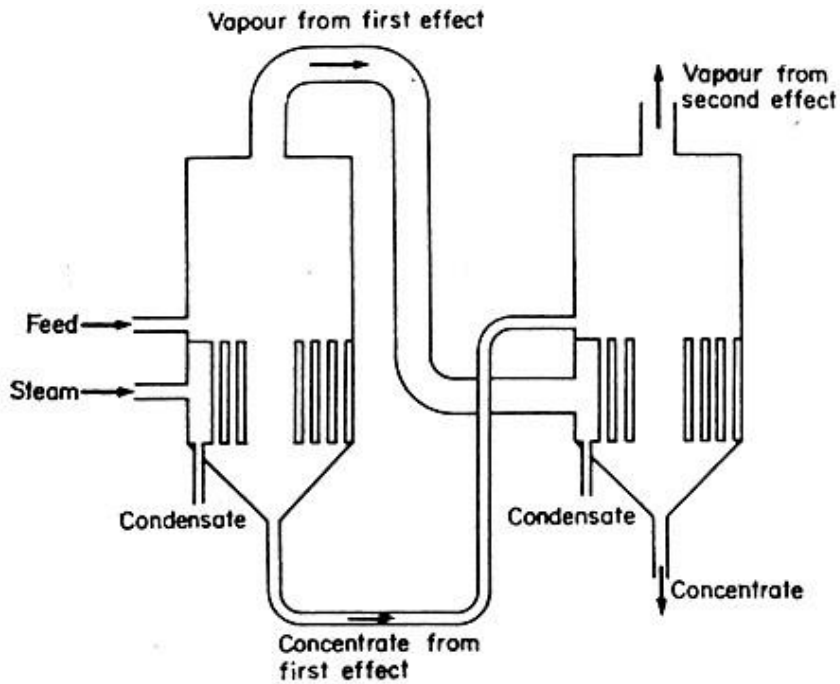


Figure 8.2 Double effect evaporator – forward feed

If liquid is to be evaporated in each effect, and if the boiling point of this liquid is unaffected by the solute concentration, then writing a heat balance for the first evaporator:

$$q_1 = U_1 A_1 (T_s - T_1) = U_1 A_1 \Delta T_1 \quad (8.1)$$

where q_1 is the rate of heat transfer, U_1 is the overall heat transfer coefficient in evaporator 1, A_1 is the heat transfer area in evaporator 1, T_s is the temperature of condensing steam from the boiler, T_1 is the boiling temperature of the liquid in evaporator 1 and ΔT_1 is the temperature difference in evaporator 1 = $(T_s - T_1)$.

Similarly, in the second evaporator, remembering that the "steam" in the second is the vapour from the first evaporator and that this will condense at approximately the same temperature as it boiled, since pressure changes are small,

$$q_2 = U_2 A_2 (T_1 - T_2) = U_2 A_2 \Delta T_2$$

in which the subscripts 2 indicate the conditions in the second evaporator.

If the evaporators are working in balance, then all of the vapours from the first effect are condensing and in their turn evaporating vapours in the second effect. Also assuming that heat losses can be neglected, there is no appreciable boiling-point elevation of the more concentrated solution, and the feed is supplied at its boiling point,

$$q_1 = q_2$$

Further, if the evaporators are so constructed that $A_1 = A_2$, the foregoing equations can be combined.

$$U_2/U_1 = \Delta T_1/\Delta T_2. \quad (8.2)$$

Equation (8.2) states that the temperature differences are inversely proportional to the overall heat transfer coefficients in the two effects. This analysis may be extended to any number of effects operated in series, in the same way.

Feeding of Multiple Effect Evaporators

In a two effect evaporator, the temperature in the steam chest is higher in the first than in the second effect. In order that the steam provided by the evaporation in the first effect will boil off liquid in the second effect, the boiling temperature in the second effect must be lower and so that effect must be under lower pressure.

Consequently, the pressure in the second effect must be reduced below that in the first. In some cases, the first effect may be at a pressure above atmospheric; or the first effect may be at atmospheric pressure and the second and subsequent effects have therefore to be under increasingly lower pressures. Often many of the later effects are under vacuum. Under these conditions, the liquid feed progress is simplest if it passes from effect one to effect two, to effect three, and so on, as in these circumstances the feed will flow without pumping. This is called *forward feed*. It means that the most concentrated liquids will occur in the last effect. Alternatively, feed may pass in the reverse direction, starting in the last effect and proceeding to the first, but in this case the liquid has to be pumped from one effect to the next against the pressure drops. This is called *backward feed*. Because the concentrated viscous liquids can be handled at the highest temperatures in the first effects, it usually offers larger evaporation capacity than forward feed systems, but it may be disadvantageous from the viewpoint of product quality.

Advantages of Multiple Effect Evaporators

At first sight, it may seem that the multiple effect evaporator has all the advantages, the heat is used over and over again and we appear to be getting the evaporation in the second and subsequent effects for nothing in terms of energy costs. Closer examination shows, however, that there is a price to be paid for the heat economy.

In the first effect, $q_1 = U_1 A_1 \Delta T_1$ and in the second effect, $q_2 = U_2 A_2 \Delta T_2$. We shall now consider a single-effect evaporator, working under the same pressure as the first effect $q_s = U_s A_s \Delta T_s$, where subscript s indicates the single-effect evaporator.

Since the overall conditions are the same, $\Delta T_s = \Delta T_1 + \Delta T_2$, as the overall temperature drop is between the temperature of the condensing steam in the first effect and the evaporating temperature in the second effect. Each successive steam chest in the multiple effect evaporator condenses at the same temperature as that at which the previous effect is evaporating.

Now, consider the case in which $U_1 = U_2 = U_s$, and $A_1 = A_2$. The problem then becomes to find A_s for the single-effect evaporator that will evaporate the same quantity as the two effects.

From the given conditions and from eqn. (8.2),

$$\Delta T_1 = \Delta T_2$$

and
$$\begin{aligned} \Delta T_s &= \Delta T_1 + \Delta T_2 = 2\Delta T_1 \\ \Delta T_1 &= 0.5\Delta T_s \end{aligned}$$

Now
$$\begin{aligned} q_1 + q_2 &= U_1 A_1 \Delta T_1 + U_2 A_2 \Delta T_2 \\ &= U_1 (A_1 + A_2) \Delta T_s / 2 \\ &= U_s (A_1 + A_2) \Delta T_s / 2 \end{aligned}$$

but
$$q_1 + q_2 = q_s$$

and
$$q_s = U_s A_s \Delta T_s$$

so that
$$\begin{aligned} U_s (A_1 + A_2) \Delta T_s / 2 &= U_s A_s \Delta T_s \\ (A_1 + A_2) / 2 &= 2A_1 / 2 = A_s \end{aligned}$$

That is
$$A_1 = A_2 = A_s$$

The analysis shows that if the same total quantity is to be evaporated, then the heat transfer surface of each of the two effects must be the same as that for a single effect evaporator working between the same overall conditions. The analysis can be extended to cover any number of effects and leads to the same conclusions. In multiple effect evaporators, steam economy has to be paid for by increased capital costs of the evaporators. Since the heat transfer areas are generally equal in the various effects and since in a sense what you are buying in an evaporator is suitable heat transfer surface, the n effects will cost approximately n times as much as a single effect.

Comparative costs of the auxiliary equipment do not altogether follow the same pattern. Condenser requirements are less for multiple effect evaporators. The condensation duty is distributed between the steam chests of the effects, except for the first one, and so condenser and cooling water requirements will be less.

The optimum design of evaporation plant must then be based on a balance between operating costs which are lower for multiple effects because of their reduced steam consumption, and capital charges which will be lower for fewer evaporators. The comparative operating costs are

illustrated by the figures in Table 8.1 based on data from Grosse and Duffield (1954); if the capital costs were available they would reduce the advantages of the multiple effects, but certainly not remove them.

TABLE 8.1 STEAM CONSUMPTION AND RUNNING COSTS OF EVAPORATORS

| Number of effects | Steam consumption (kg steam/kg water evaporated) | Total running cost (relative to a single-effect evaporator) |
|-------------------|--|---|
| One | 1.1 | 1 |
| Two | 0.57 | 0.52 |
| Three | 0.40 | 0.37 |

EXAMPLE 8.4. Triple effect evaporator: steam usage and heat transfer surface

Estimate the requirements of steam and heat transfer surface, and the evaporating temperatures in each effect, for a triple effect evaporator evaporating 500 kg h⁻¹ of a 10% solution up to a 30% solution. Steam is available at 200kPa gauge and the pressure in the evaporation space in the final effect is 60kPa absolute. Assume that the overall heat transfer coefficients are 2270, 2000 and 1420 J m⁻² s⁻¹ °C⁻¹ in the first, second and third effects respectively. Neglect sensible heat. Assume no boiling-point elevation, and also equal heat transfer in each effect.

Mass balance (kg h⁻¹)

| | Solids | Liquids | Total |
|-------------|--------|---------|-------|
| Feed | 50 | 450 | 500 |
| Product | 50 | 117 | 167 |
| Evaporation | | | 333 |

Heat balance

From steam tables (Appendix 8), the condensing temperature of steam at 200kPa gauge is 134°C and the latent heat is 2164 kJ/kg⁻¹. Evaporating temperature in final effect under pressure of 60kPa(abs.) is 86°C, as there is no boiling-point rise and latent heat is 2294 kJ/kg.

Equating the heat transfer in each effect:

$$q_1 = q_2 = q_3$$

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3$$

And $\Delta T_1 + \Delta T_2 + \Delta T_3 = (134 - 86) = 48^\circ\text{C}.$

Now, if $A_1 = A_2 = A_3$
then $\Delta T_2 = U_1 \Delta T_1 / U_2$ and $\Delta T_3 = U_1 \Delta T_1 / U_3$
so that $\Delta T_1 (1 + U_1 / U_2 + U_1 / U_3) = 48$

$$\Delta T_1 \times [1 + (2270/2000) + (2270/1420)] = 48$$

$$3.73 \Delta T_1 = 48$$

$$\Delta T_1 = 12.9^\circ\text{C},$$

$$\Delta T_2 = \Delta T_1 \times (2270/2000) = 14.6^\circ\text{C}$$

$$\text{and } \Delta T_3 = \Delta T_1 \times (2270/1420) = 20.6^\circ\text{C}$$

And so the evaporating temperature:

- in first effect is $(134 - 12.9) = 121^\circ\text{C}$; latent heat 2200 kJ kg^{-1} .
- in second effect is $(121 - 14.6) = 106.5^\circ\text{C}$; latent heat 2240 kJ kg^{-1}
- in the third effect is $(106.5 - 20.6) = 86^\circ\text{C}$, latent heat 2294 kJ kg^{-1}

Latent heats from steam tables (Appendix 8)

Equating the quantities evaporated in each effect and neglecting the sensible heat changes, if w_1 , w_2 , w_3 are the respective quantities evaporated in effects 1, 2 and 3, and w_s is the quantity of steam condensed per hour in effect 1, then

$$\begin{aligned} w_1 \times 2200 \times 10^3 &= w_2 \times 2240 \times 10^3 \\ &= w_3 \times 2294 \times 10^3 \\ &= w_s \times 2164 \times 10^3 \end{aligned}$$

The sum of the quantities evaporated in each effect must equal the total evaporated in all three effects so that:

$$\begin{aligned} w_1 + w_2 + w_3 &= 333 \\ w_2 &= w_1 \times (2200/2240) = 0.982 w_1 \\ w_3 &= w_1 \times (2200/2294) = 0.959 w_1 \\ w_s &= w_1 \times (2200/2164) \\ (1 + 0.982 + 0.959) w_1 &= 333 \\ w_1 &= 113 \text{ kgh}^{-1} \\ w_2 &= 111 \text{ kgh}^{-1} \\ w_3 &= 108 \text{ kgh}^{-1} \\ w_s &= 115 \text{ kgh}^{-1} \end{aligned}$$

Steam consumption

It required 115kg steam (w_s) to evaporate a total of 333kg water, that is
0.35kg steam/kg water evaporated

Heat exchanger surface

Writing a heat balance on the first effect:

$$\begin{aligned} \text{Heat to evaporate water per hour} &= \text{Heat supplied} = U_1 A_1 \Delta T_1 \\ (113 \times 2200 \times 1000)/3600 &= 2270 \times A_1 \times 12.9 \end{aligned}$$

$$A_1 = 2.4 \text{ m}^2 = A_2 = A_3$$

$$\text{Total area} = A_1 + A_2 + A_3 = \underline{7.2 \text{ m}^2}.$$

Note that the conditions of this example are considerably simplified, in that sensible heat and feed heating effects are neglected, and no boiling-point rise occurs. The general method remains the same in the more complicated cases, but it is often easier to solve the heat balance equations by trial and error rather than by analytical methods, refining the approximations as far as necessary.

VAPOUR RECOMPRESSION

For economy of steam, another method is to take the vapour and, after compressing it, return it to the steam chest of the evaporator from which it was evaporated.

The compression can be effected either by using some fresh steam at a suitably high pressure in a jet ejector pump, or by mechanical compressors. The use of jet ejectors is the more common. By this means a proportion of the vapours are re-used, together with fresh steam, and so considerable overall steam economy is achieved by reusing the latent heat of the vapours over again. The price to be paid for the recompression can be either in the pressure drop of the fresh steam (which may be wasted through a reducing valve in any case) or in the mechanical energy expended in mechanical compressors. Vapour recompression is similar in many ways to the use of multiple effects. The available temperature in the fresh steam is reduced before use for evaporation and so additional heat exchange surface has to be provided: roughly one stage equals one extra effect.

The temperature of the feed also affects the steam economy of an evaporator. If the feed is not at its boiling point, heat has to be used in raising it to this temperature. A convenient source of this feed pre-heat may be in the vapours from a single effect evaporator; a separate feed pre-heater can be used for this purpose.

BOILING-POINT ELEVATION

As evaporation proceeds, the liquor remaining in the evaporator becomes more concentrated and its boiling point will rise. The extent of the boiling-point elevation depends upon the nature of the material being evaporated and upon the concentration changes that are produced. The extent of the rise can be predicted by Raoult's Law, which leads to:

$$\Delta T = kx \quad (8.3)$$

where ΔT is the boiling point elevation, x is the mole fraction of the solute and k is a constant of proportionality.

In multiple effect evaporators, where the effects are fed in series, the boiling points will rise from one effect to the next as the concentrations rise. Relatively less of the apparent temperature drops are available for heat transfer, although boiling points are higher, as the condensing temperature of the vapour in the steam chest of the next effect is still that of the pure vapour. Boiling-point elevation complicates evaporator analysis but heat balances can still be drawn up

along the lines indicated previously. Often food materials are made up from large molecules in solution, in which boiling-point elevation can to a greater extent be ignored.

As the concentrations rise, the viscosity of the liquor also rises. The increase in the viscosity of the liquor affects the heat transfer and it often imposes a limit on the extent of evaporation that is practicable.

There is no straightforward method of predicting the extent of the boiling-point elevation in the concentrated solutions that are met in some evaporators in practical situations. Many solutions have their boiling points at some concentrations tabulated in the literature, and these can be extended by the use of a relationship known as Duhring's rule. Duhring's rule states that the ratio of the temperatures at which two solutions (one of which can be pure water) exert the same vapour pressure is constant. Thus, if we take the vapour pressure/temperature relation of a reference liquid, usually water, and if we know two points on the vapour pressure/temperature curve of the solution that is being evaporated, the boiling points of the solution to be evaporated at various pressures can be read off from the diagram called a Duhring plot. The Duhring plot will give the boiling point of solutions of various concentrations by interpolation, and at various pressures by proceeding along a line of constant composition. A Duhring plot of the boiling points of sodium chloride solutions is given in Fig. 8.3.

EXAMPLE 8.5. Duhring Plot for sodium chloride solutions

It is found that a saturated solution of sodium chloride in water boils under atmospheric pressure at 109°C. Under a total pressure of 25.4kPa absolute, water boils at 65.6°C and saturated sodium chloride at 73.3°C. From these, draw a Duhring plot for saturated salt solution. Knowing the vapour pressure/temperature relationship for water from Fig. 7.2, find the boiling temperature of saturated salt solution under a total pressure of 33.3kPa absolute.

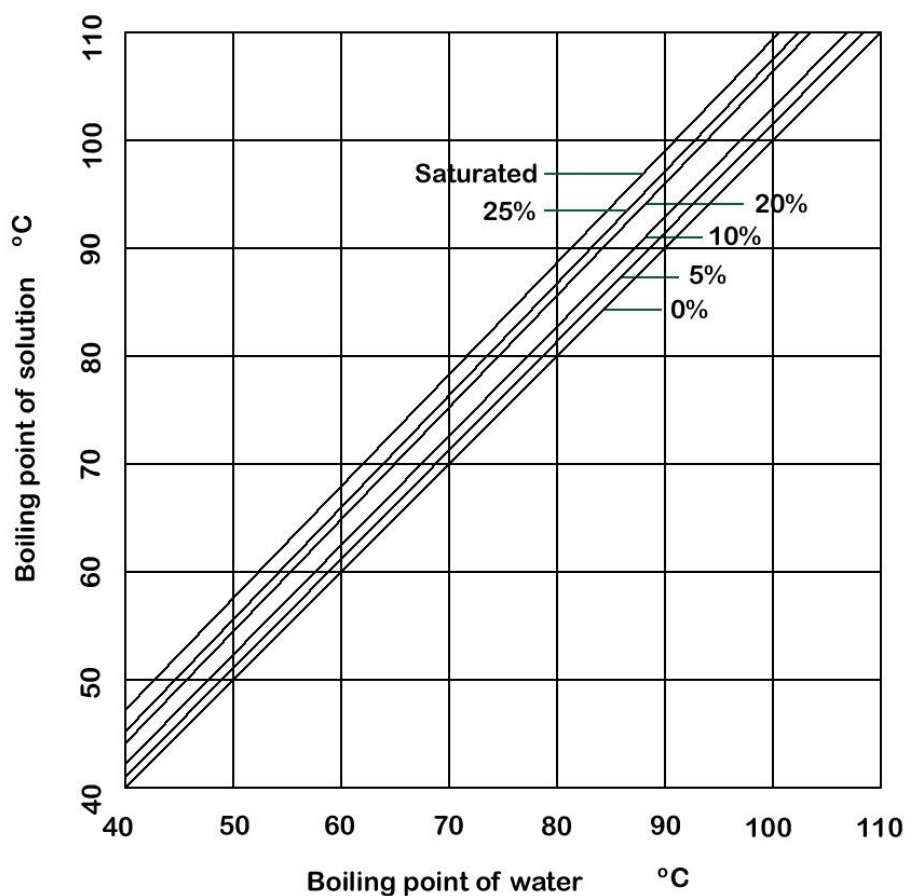


Figure 8.3 Duhring plot for boiling point of sodium chloride solutions

The Duhring plot for salt solution is in Fig. 8.3, and since the line is straight, it may be seen that knowledge of two points on it, and the corresponding boiling points for the reference substance, water, would enable the line to be drawn.

From the line, and using Fig. 7.2 again, it is found that: the boiling point of water under a pressure of 33.3kPa is 71.7°C, we can read off the corresponding boiling temperature for saturated salt solution as 79.4°C.

By finding the boiling points of salt solutions of various concentrations under two pressures, the Duhring lines can then, also, be filled in for solutions of these concentrations. Such lines are also on Fig.8.3. Intermediate concentrations can be estimated by interpolation and so the complete range of boiling points at any desired concentration, and under any given pressure, can be determined.

Latent heats of vaporization also increase as pressures are reduced, as shown for water in Table 7.1. Methods for determining these changes can be found in the literature, for example in Perry (1997).

EVAPORATION OF HEAT SENSITIVE MATERIALS

In evaporators which have large volumes into which incoming feed is mixed, the retention time of a given food particle may be considerable. The average retention time can be obtained simply, by dividing the volume of the evaporator by the feed rate, but a substantial proportion of the liquor remains for much longer than this. Thus with heat sensitive materials a proportion may deteriorate and lead to general lowering of product quality. Many food products with volatile flavour constituents retain more of these if they are evaporated under conditions favouring short contact times with the hot surfaces.

This difficulty is overcome in modern, high flow rate, evaporators; in which there is a low hold-up volume and in which little or no mixing occurs. This can be achieved for solutions of low viscosity by climbing and falling film evaporators, either tubular or plate types. Other examples are plate evaporators, centrifugal evaporators, and the various scraped plate, thin film, evaporators.

EXAMPLE 8.6. Concentration of tomato juice in a climbing film evaporator

Tomato juice is to be concentrated from 12% solids to 28% solids in a climbing film evaporator, 3m high and 4cm diameter. The maximum allowable temperature for tomato juice is 57°C. The juice is fed to the evaporator at 57°C and at this temperature the latent heat of vaporization is 2366kJkg⁻¹. Steam is used in the jacket of the evaporator at a pressure of 170kPa (abs). If the overall heat transfer coefficient is 6000Jm⁻²s⁻¹°C⁻¹, estimate the quantity of tomato juice feed per hour.

Mass balance: basis 100kg feed

| | Solids | Liquids | Total |
|---------|--------|---------|-------|
| Feed | 12 | 88 | 100 |
| Product | 12 | 31 | 43 |

Heat balance

Take heating surface as 3m long x 0.04m diameter.

$$\begin{aligned} \text{Area of evaporator tube } \pi DL &= \pi \times 0.04 \times 3 \\ &= 0.38\text{m}^2 \end{aligned}$$

Condensing steam temperature at 170kPa (abs) = 115°C from Steam Tables.

Making a heat balance across the evaporator

Heat supplied by steam,

$$\begin{aligned} q &= UA\Delta t \\ &= 6000 \times 0.38 \times (115 - 57) \\ &= 1.32 \times 10^5 \text{Js}^{-1} \end{aligned}$$

Heat required per kg of feed for evaporation

$$\begin{aligned} &= \text{water evaporated} \times \text{latent heat} \\ &= 0.57 \times 2366 \times 10^3 \\ &= 1.34 \times 10^6 \text{Jkg}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Water evaporated per second} &= (1.32 \times 10^5) / 1.34 \times 10^6 \\ &= 0.1\text{kg s}^{-1} \end{aligned}$$

$$\text{Rate of evaporation} = 360\text{kg h}^{-1}$$

$$\text{Quantity of tomato juice feed per hour} = \underline{360\text{kg}}$$

EVAPORATION EQUIPMENT

Open Pans

The most elementary form of evaporator consists of an open pan in which the liquid is boiled. Heat can be supplied through a steam jacket or through coils, and scrapers or paddles may be fitted to provide agitation. Such evaporators are simple and low in capital cost, but they are expensive in their running cost as heat economy is poor.

Horizontal Tube Evaporators

The horizontal tube evaporator is a development of the open pan, in which the pan is closed in, generally in a vertical cylinder. The heating tubes are arranged in a horizontal bundle immersed in the liquid at the bottom of the cylinder. Liquid circulation is rather poor in this type of evaporator.

Vertical Tube Evaporators

By using vertical, rather than horizontal tubes, the natural circulation of the heated liquid can be made to give good heat transfer. The standard evaporator, shown in Fig. 8.1, is an example of this type. Recirculation of the liquid is through a large “downcomer” so that the liquors rise through the vertical tubes about 5 - 8 cm diameter, boil in the space just above the upper tube

plate and recirculate through the downcomers. The hydrostatic head reduces boiling in the lower parts of the tubes, which are covered by the circulating liquid. The length to diameter ratio of the tubes is of the order of 15:1. The basket evaporator shown in Fig. 8.4(a) is a variant of the calandria evaporator in which the steam chest is contained in a basket suspended in the lower part of the evaporator, and recirculation occurs through the annular space round the basket.

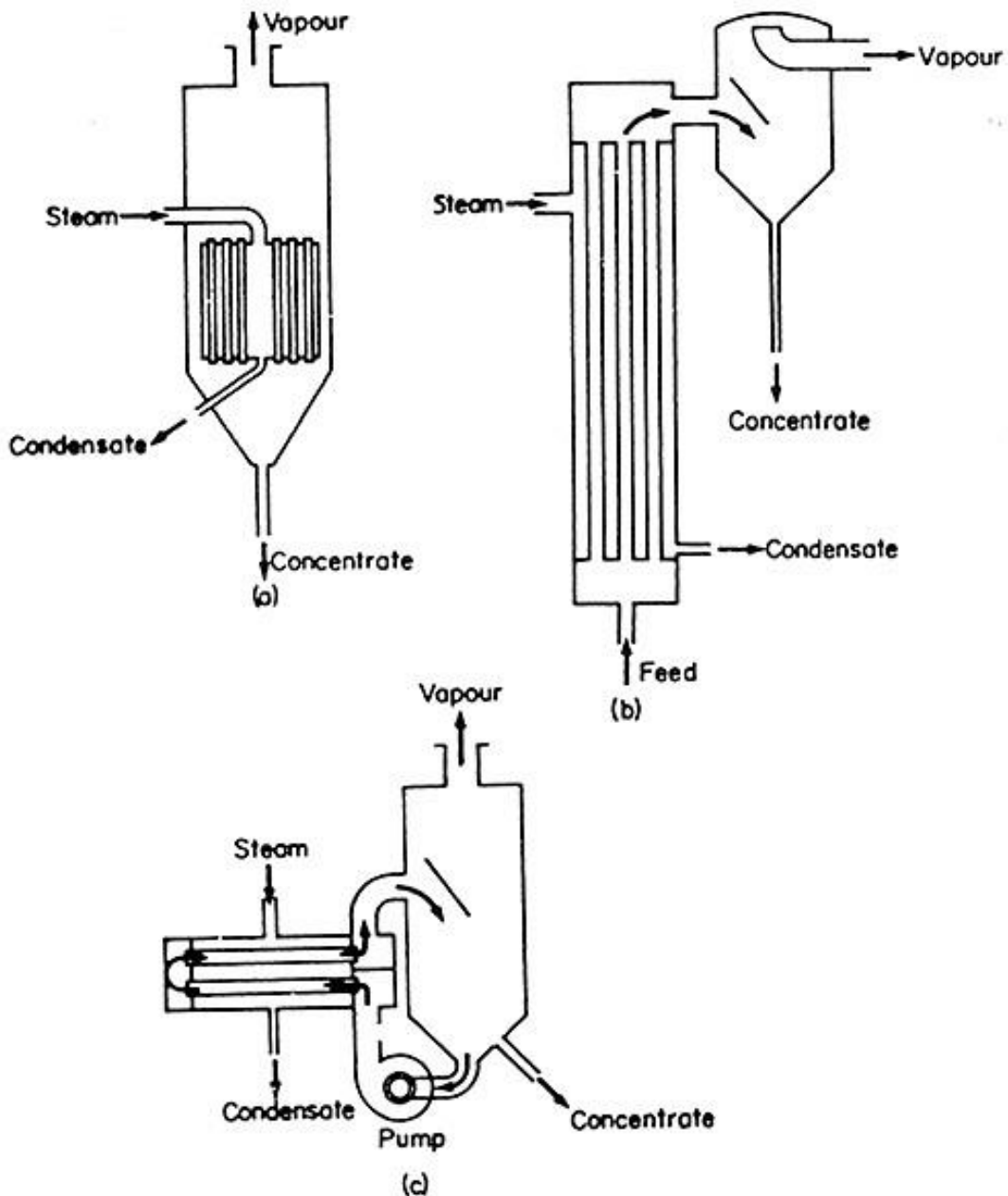


Figure 8.4 Evaporators (a) basket type (b) long tube (c) forced circulation

Plate Evaporators

The plate heat exchanger can be adapted for use as an evaporator. The spaces can be increased between the plates and appropriate passages provided so that the much larger volume of the vapours, when compared with the liquid, can be accommodated. Plate evaporators can provide good heat transfer and also ease of cleaning.

Long Tube Evaporators

Tall slender vertical tubes may be used for evaporators as shown in Fig. 8.4(b). The tubes, which may have a length to diameter ratio of the order of 100:1, pass vertically upward inside the steam chest. The liquid may either pass down through the tubes, called a falling film evaporator, or be carried up by the evaporating liquor in which case it is called a climbing film evaporator. Evaporation occurs on the walls of the tubes. Because circulation rates are high and the surface films are thin, good conditions are obtained for the concentration of heat sensitive liquids due to high heat transfer rates and short heating times.

Generally, the liquid is not recirculated, and if sufficient evaporation does not occur in one pass, the liquid is fed to another pass. In the climbing film evaporator, as the liquid boils on the inside of the tube slugs of vapour form and this vapour carries up the remaining liquid which continues to boil. Tube diameters are of the order of 2.5 to 5 cm, contact times may be as low as 5 -10 sec. Overall heat transfer coefficients may be up to five times as great as from a heated surface immersed in a boiling liquid. In the falling film type, the tube diameters are rather greater, about 8 cm, and these are specifically suitable for viscous liquids.

Forced Circulation Evaporators

The heat transfer coefficients from condensing steam are high, so that the major resistance to heat flow in an evaporator is usually in the liquid film. Tubes are generally made of metals with a high thermal conductivity, though scale formation may occur on the tubes, which reduces the tube conductance. The liquid film coefficients can be increased by improving the circulation of the liquid and by increasing its velocity of flow across the heating surfaces.

Pumps, or impellers, can be fitted in the liquid circuit. Using pump circulation, the heat exchange surface can be divorced from the boiling and separating sections of the evaporator, as shown in Fig.8.4(c). Alternatively, impeller blades may be inserted into flow passages such as the downcomer of a calandria type evaporator. Other forced circulation evaporators are various scraped surface and agitated film evaporators. In one type, the material to be evaporated passes down over the interior walls of a heated cylinder and it is scraped by rotating scraper blades to maintain a thin film, high heat transfer and a short and controlled residence time exposed to heat.

Forced circulation is used particularly with viscous liquids. As the viscosity increases, for example at higher concentrations, mechanical transport across heated surfaces is used to advantage. Methods include mechanically scraped surfaces, and the flow of the solutions over heated spinning surfaces. Under such conditions residence times can be fractions of a minute and when combined with a working vacuum as low as can reasonably be maintained, volatiles retention can be maximized.

Forced circulation may also be worth consideration for expensive heat exchange surfaces when these are required because of corrosion or hygiene requirements. In this case it pays to obtain the greatest possible heat flow through each square metre of heat exchange surface.

SUMMARY

1. Heat and material balances are the basis for evaporator calculations.

- The rate of boiling is governed by the heat-transfer equations.
- For multiple effect evaporators, i.e. two or more evaporators used in series. With two evaporators:

$$q_1 = q_2$$

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2$$

and if A_1 and A_2 are equal

$$\frac{U_2}{U_1} = \frac{\Delta T_1}{\Delta T_2}$$

and these equations can be extended to more than two effects.

- Multiple effect evaporators use less heat than single effect evaporators. For an n-effects evaporator, the steam requirement is approximately 1/n, but requires more heat exchange surface; the heat exchange surface required is approximately n times for the same output.
- Condensers on an evaporator must provide sufficient cooling to condense the water vapour from the evaporator. Condenser calculations are based on the heat transfer equation.
- Boiling-point elevation in evaporators can be estimated using Dühring's rule that the ratio of the temperatures at which two solutions exert the same pressure is constant.
- Special provisions, including short residence times and low pressures to give low boiling points, are necessary when the maximum retention of volatile constituents is important, and when heat sensitive materials are evaporated.

PROBLEMS

- A single effect evaporator is to produce a 35% solids tomato concentrate from a 6% solids raw juice entering at 18°C. The pressure in the evaporator is 20kPa absolute and steam is available at 100kPa gauge. The overall heat transfer coefficient is $440 \text{ Jm}^{-2} \text{ s}^{-1} \text{ } ^\circ\text{C}^{-1}$, the boiling temperature of the tomato juice under the conditions in the evaporator is 60°C, and the area of the heat transfer surface of the evaporator is 12 m^2 . Estimate the rate of raw juice feed that is required to supply the evaporator.
(536 kg h^{-1})
- Estimate (a) the evaporating temperature in each effect, (b) the requirements of steam, and (c) the area of the heat transfer surface for a two effect evaporator. Steam is available at 100kPa gauge pressure and the pressure in the second effect is 20kPa absolute. Assume an overall heat transfer coefficient of 600 and $450 \text{ Jm}^{-2} \text{ s}^{-1} \text{ } ^\circ\text{C}^{-1}$ in the first and second effects respectively. The evaporator is to concentrate $15,000 \text{ kg h}^{-1}$ of raw milk from 9.5 % solids to 35% solids. Assume the sensible heat can be ignored, and there is no boiling-point elevation.
(a) 1st effect 94°C, 2nd effect 60°C (b) 5,746 kg h^{-1} , 0.53 kg steam/kg water (c) 450 m^2)
- A plate evaporator is concentrating milk from 10% solids to 30% solids at a feed rate of 1500 kg h^{-1} . Heating is by steam at 200kPa absolute and the evaporating temperature is 75°C. (a) Calculate the number of plates needed if the area of heating surface on each plate is 0.44 m^2 and the overall heat transfer coefficient $650 \text{ Jm}^{-2} \text{ s}^{-1} \text{ } ^\circ\text{C}^{-1}$. (b) If the plates, after several

hours running become fouled by a film of thickness 0.1mm, and of thermal conductivity $0.1 \text{ Jm}^{-1}\text{s}^{-1}\text{°C}^{-1}$, by how much would you expect the capacity of the evaporator to be reduced?

((a) 50 (b) 13% of its former value)

4. (a) Calculate the evaporation in each effect of a triple effect evaporator concentrating a solution from 5% to 25% total solids at a total input rate of $10,000\text{kg h}^{-1}$. Steam is available at 200kPa absolute pressure and the pressure in the evaporation space in the final effect is 55kPa absolute. Heat transfer coefficients in the effects are, from the first effect respectively, 600, 500 and $350\text{Jm}^{-2}\text{s}^{-1}\text{°C}^{-1}$. Neglect specific heats and boiling-point elevation. (b) Calculate also the quantity of input steam required per kg of water evaporated.
(a) 1st Effect 2707kg h^{-1} , 2nd Effect 2669kg h^{-1} , 3rd Effect 2623kg h^{-1} (b) 0.343 kg kg^{-1})
5. If in Problem 4 there were boiling point elevations of 0.60, 1.50 and 4°C respectively in the three effects starting from the first, what would be the change in the requirement of input steam required per kg water evaporated?
(0.342 kg kg^{-1} compared with 0.343 kg kg^{-1} ; therefore no change)
6. (a) Estimate the minimum quantity of 12°C cooling water required for a jet condenser to condense the 70°C vapours from an evaporator which concentrates 4000kg h^{-1} of milk from 9% solids to 30% solids in one effect. (b) For the same evaporator estimate for a surface condenser, the quantity of 12°C cooling water needed and the necessary heat transfer area if the cooling water leaves at a maximum of 25°C and the overall heat transfer coefficient is $2200 \text{ Jm}^{-2}\text{s}^{-1}\text{°C}^{-1}$ in the condenser.
(a) $130 \times 10^3\text{kg h}^{-1}$ Note in practice this is higher (b) $130 \times 10^3\text{kg h}^{-1}$, 17.3m^2)
7. If in the evaporator of Problem 6, one-half of the evaporated vapour were mechanically recompressed with an energy expenditure of 160 kJ kg^{-1} , what effect would this have on the steam economy, assuming the steam supply was at 100kPa absolute?
(46.6% steam energy saved)
8. A standard calandria type of evaporator with 100 tubes, each 1m long, is used to evaporate fruit juice at 18°C with approximately the same thermal properties as water. The pressure in the evaporator is 80kPa absolute, and in the steam jacket 100kPa absolute. Take the tube diameter as 5 cm and the overall heat transfer coefficient at $440 \text{ Jm}^{-2}\text{s}^{-1}\text{°C}^{-1}$. Estimate the rate of evaporation in the evaporator
(72.5kg h^{-1})