THERMAL DESALINATION PROCESSES

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Summary

Desalination processes which involve the evaporation and condensation of water are described. These include multiple-effect boiling, multistage flashing, and vapor compression both mechanical and thermal.

1. Introduction

In distillation seawater is boiled (evaporated) to give off water vapor, which on condensation yields salt-free liquid water. Two widely used desalination processes which make use of this principle are (a) multistage flash distillation and (b) multieffect

boiling. The energy required to drive the process is supplied in the form of thermal energy. The term "multi" implies that multiple reuse of the thermal energy of steam involving the successive processes of evaporation and condensation. Another process, also based on this concept, is vapor compression distillation, which, however, is not as popular as the other two. Here, a compressor or a steam jet ejector supplies the energy to the process.

1.1. Single-effect Boiling

The simplest conceptual scheme for desalination is shown in Figure 1, in which seawater is boiled in an evaporator by condensing steam. The vapor so generated is condensed by heat transfer to a stream of cooling seawater, part of which forms feed to the evaporator. The vapor condenses to pure water, which is the product of desalination.
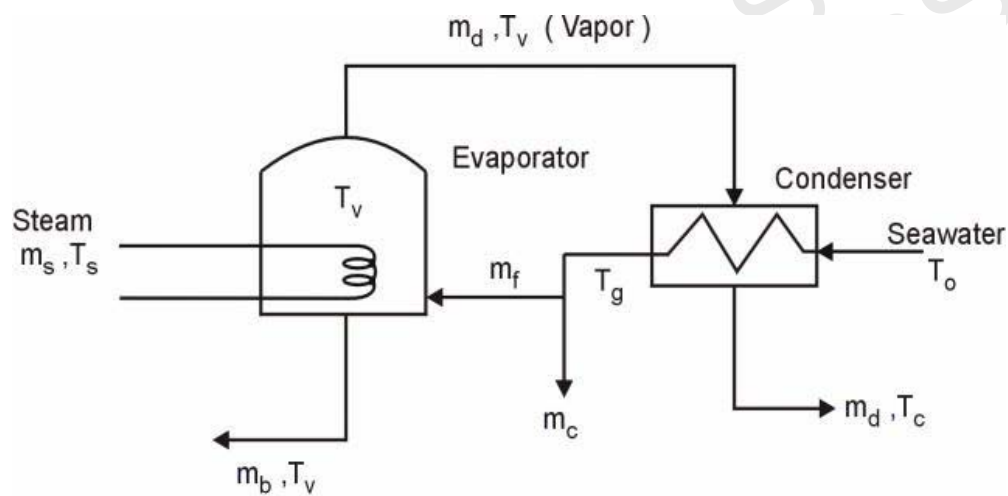

Figure 1. Single-effect boiling.

An overall energy balance of the above process gives the heat input by steam Q:

$$Q = m_d C_d (T_c - T_o) + m_c C_f (T_f - T_o) + m_b C_b (T_v - T_o) + m_f (\Delta H)_{T_o}, \tag{1}$$

where

$$(\Delta H)_{T_O}$$

is the isothermal enthalpy change due to composition changes per unit of feed to the evaporator. The energy balance of the condenser is written as

$$m_d C_v (T_v - T_c) + m_d \lambda_{T_c} = (m_f + m_c) C_f (T_g - T_o). \tag{2}$$

Substituting for $m_c C_f (T_g - T_o)$ from Eq. (2) into Eq. (1),

$$Q = m_d C_d (T_c - T_o) + m_d C_v (T_v - T_c) - m_f C_f (T_g - T_o) + m_d \lambda_{T_c} + m_b C_b (T_v - T_o) + \qquad (3)$$
$$m_f (\Delta H)_{T_o}$$

If the term

$$m_f (\Delta H)_{T_o}$$

is neglected in Eq. (3) and a mean specific heat C is used for all the streams including that of vapor, then it can be approximated to

$$q = \frac{Q}{m_d} \cong \lambda_{T_c} + C\left(\frac{m_f}{m_d}\right)(T_v - T_g), \qquad (4)$$

where q is the heat input per unit mass of product. Furthermore $(T_v - T_g)$ can be considered as the sum of the boiling point elevation (BPE) and terminal difference ΔT_t. Therefore, Eq. (4) can be written as

$$q \cong \lambda_{T_c} + C\left(\frac{m_f}{m_d}\right)(\mathrm{BPE} + \Delta T_t).$$

Ultimately, the above equation can be approximated in terms of the performance ratio R (kilograms of product per 2326 kJ) incorporating the reference value of the latent heat of vaporization λ_r:

$$R \cong \frac{\lambda_r}{\left[\lambda_{T_c} + C\left(\frac{m_f}{m_d}\right)(\mathrm{BPE} + \Delta T_t)\right]} \qquad (5)$$

In Eq. (5), if the magnitudes of different terms are taken as

$C = 4.2$ kJ kg^{-1}°C; BPE = 1°C and $\Delta T_t = 5$°C

and

$m_f / m_d = 2$.

Because in evaporation practice the final concentration is normally not allowed to be more than twice that of the seawater;

$$\lambda_{T_c} \cong \lambda_r = 2326 \text{ kJ kg}^{-1},$$

then the value of R cannot be more than 1 kg 2326 kJ^{-1} in the single-effect evaporation as shown in Figure 1. The major source of irreversibility and, thus, entropy creation in

the single-effect evaporation process is in the wastage of available energy in the leaving streams. This is the motivation for the development of multieffect systems to be described later, in which the available energy is utilized to produce more distillate.

1.2. Single-stage Flashing

An alternative process is shown in Figure 2, in which the feed m_f is further heated by condensing steam in the brine heater. Here, the feed is prevented from boiling by keeping its pressure above the saturation pressure corresponding to its temperature. The feed is then throttled by passing through a valve into the flash chamber which is at a lower pressure. The vapor generated by flashing is condensed, as usual, by heat transfer to a stream of cooling seawater, part of which forms the feed to the brine heater. The condensed vapor (m_d), being pure water, is the product of desalination.
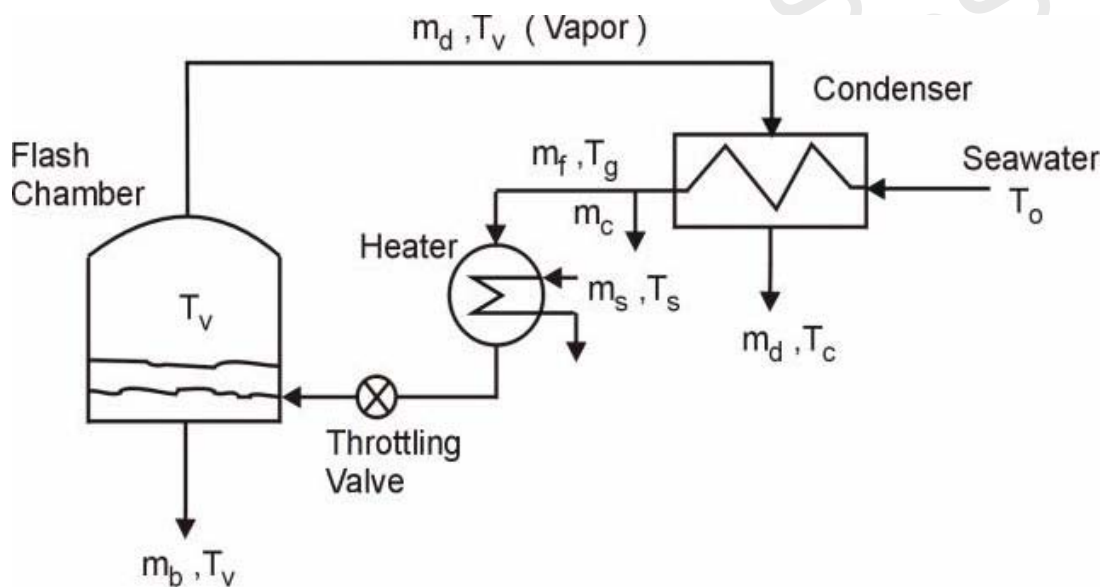

Figure 2. Single-stage flashing.

For the single-stage flashing process, the overall energy balance and the energy balance for the condenser will be the same as given by Eqs (1) and (2), respectively. Hence, Eq. (3) will also express the heat output in this process. However, with flashing there is a basic difference, i.e. the vapor release is now dependent on the feed rate. An energy balance for the flash chamber gives

$$m_f C(T_h - T_c) = m_d C(T_v - T_c) + m_d \lambda_{T_c} + m_b C(T_v - T_c)$$

or

$$m_f C[(T_h - T_v) + (T_v - T_c)] = m_f C(T_v - T_c) + m_d \lambda_{T_c}$$

Finally,

$$\frac{m_f}{m_d} = \frac{\lambda_{T_c}}{(C\Delta T_f)} \tag{6}$$

where $\Delta T_f = T_h - T_v$ is the temperature drop in the flashing process. If in eq. (2), $T_v - T_c = \text{BPE}$ is neglected in Eq. (2), then substituting Eq. (6) into it gives

$$m_c = m_f \left(\frac{\Delta T_f}{T_g - T_o} - 1 \right) \tag{7}$$

Equation (7) shows that, unless $\Delta T_f > T_g - T_o$, no additional cooling water will be required in the condenser. An energy balance on the heater provides heat input per unit product as follows:

$$q = \frac{m_f}{m_d} C(T_h - T_g) = \frac{m_f}{m_d} C(\Delta T_f + \Delta T_t + \text{BPE}) \tag{8}$$

Substituting Eq. (6) into Eq. (8),

$$q = \lambda_{T_c} \left(1 + \frac{\Delta T_t + \text{BPE}}{\Delta T_f} \right)$$

or

$$R = \frac{\lambda_r}{\left[\lambda_{T_c} \left(1 + \frac{\Delta T_t + \text{BPE}}{\Delta T_f} \right) \right]} \tag{9}$$

Here again it is clear from Eq. (9) that in a single stage it is not possible to have a performance ratio of R bigger than one. The highest value of R is obtained when the feed is flashed over the total available temperature range ($T_s - T_o$) after allowing for ΔT_t, BPE, and the seawater temperature rise in the condenser for a finite rate of cooling water. When the available energy from the outgoing streams is to be utilized, ΔT_f has to be small, resulting in $R \cong 0.5$ from Eq. (9). It may be seen from Eq. (5) that single-effect evaporation by boiling can still provide $R \cong 1$.

1.3. Dual-effect Boiling

Compared to a single effect as shown in Figure 1, a further gain in the performance ratio can be obtained by increasing the number of effects in series. A typical dual-effect distillation is shown in Figure 3, in which the vapor generated in the first evaporator is used as a heating medium in another evaporator operating at a lower temperature and pressure. The make-up enters in a backward feed arrangement, i.e. first entering in the effect working under lower pressure and the blow down is discharged from the effect

under higher pressure, having the following flow rates: M for steam, M_f for make-up feed, and M_{d1} and M_{d2} for vapor generated in the first and second effects, respectively.
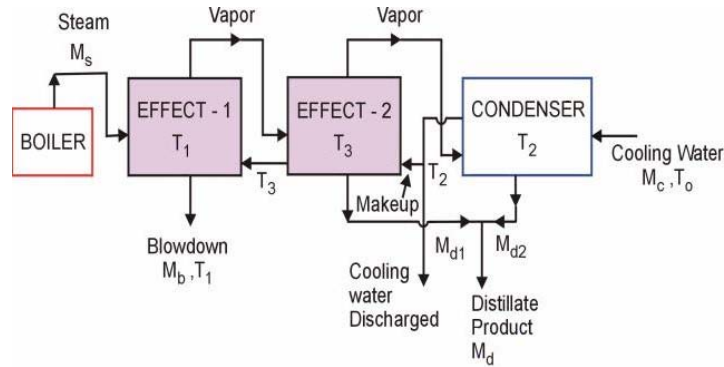

Figure 3. Simple dual-effect distillation.

Energy input into the first effect (condensation of steam) $= M_s\lambda$
Energy input into the second effect (condensation of vapor from first effect) $= M_{d1}\lambda$

Assume the intereffect temperature differences $T_1 - T_3 = T_3 - T_2 = \Delta T$. Furthermore, assume that the specific heat capacity of the liquid C_P and latent heat of vaporization λ do not vary in the range of operation.

Heat balance of the first effect:

$$M_s\lambda = M_{d1}\lambda + (M_f - M_{d2})C_p\Delta T \tag{10}$$

Heat balance of the second effect:

$$M_{d1}\lambda = M_{d2}\lambda + M_f C_p\Delta T \tag{11}$$

Total evaporation:

$$M_d = M_{d1} + M_{d2} \tag{12}$$

Solving Eqs (10) and (11) for M_{d1} and M_{d2} and inserting these values in Eq. (12):

$$M_d = \frac{2M_s\lambda - 2M_f C_p\Delta T - 2M_f (C_p\Delta T)^2 / \lambda}{\lambda - C_p\Delta T} - \frac{M_f C_p\Delta T}{\lambda}.$$

If, in the above equation, the term $(M f C p\Delta T)/\lambda$ is added and subtracted, then

$$M_d = \frac{2M_s\lambda - 4M_f C_p\Delta T}{\lambda - C_p\Delta T} + \frac{M_f C_p\Delta T}{\lambda} \tag{13}$$

Defining the following ratios,

performance ratio (PR) $R = \dfrac{M_d}{M_s}$

and recovery ratio (RR) $R_c = \dfrac{M_d}{M_f}$,

then

$$\frac{M_f}{M_s} = \frac{M_f / M_d}{M_s / M_d} = \frac{R}{R_c}.$$
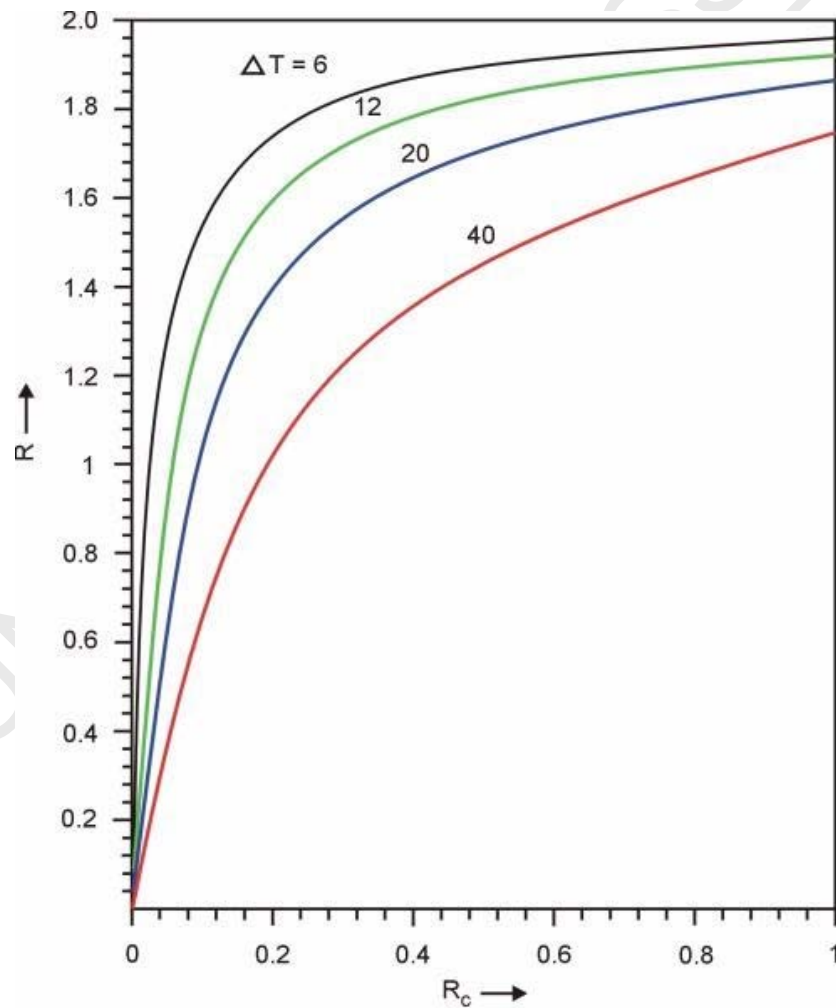

Figure 4. Performance ratios of a dual-effect MEB plant.

Dividing Eq. (13) by M_s, we obtain

$$R = \frac{2}{1 + \left[\dfrac{3}{R_c} - 1 + \dfrac{(C_p \Delta T)}{(R_c \lambda)}\right]\left(\dfrac{C_p \Delta T}{\lambda}\right)}$$

(14)

Equation (14) is plotted in Figure 4 for fixed values of C_p and λ for four different values of ΔT as parameters. It is clear that as ΔT is reduced, R approaches a value of 2.0.

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Bibliography and Suggestions for further study

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