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Economic optimization of the number of effects for the multieffect desalination plant

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ABSTRACT

The multieffect desalination (MED) process is one of the most efficient thermal desalination processes due to its low energy consumption. Due to the recent developments in the desalination industry, latest desalination plants are more cost effective than the older technology-based plants. The primary goal of this paper is to investigate a mathematical model of an MED system in such a way that, it is able to predict the optimum number of effects. The number of effects for a specific plant is a major factor in determining thermal economy and capital amortization. Also the gain output ratio of an MED unit is totally dependent on steam economy and is directly proportional to the number of effects. The total cost of water is dependent on two chief costs: steam cost and capital cost. In this paper, a compromise has been made between these two costs to find optimum number of effects that would produce the minimum sum of the two cost components.

Keywords: Multieffect desalination; Optimization; Economic study; Minimum stages

1. Introduction

Water is one of the most abundant elements on the earth. However, only 3% of the earth's water is fresh, non-saline, held in lakes, rivers, and reservoirs while the remaining 97% is salt water in oceans [1]. Water scarcity is one of the major issues in many regions of the world today [2]. To overcome this problem, desalination of sea water and brackish water is one of the most promising techniques. The most commonly used desalination methods are divided into two main categories: thermal and membrane techniques [3–8]. Multieffect desalination (MED) technology is one of the imperative thermal desalination processes.

MED is the oldest desalination process which is more energy efficient than other thermal desalination processes like multistage flash (MSF) desalination, because it is a low-temperature process and it reduces energy consumption which is required to heat water [9]. This technique is highly reliable and safe. Other advantages of this technology include [10–13]:

(1) Very low electrical energy required compared to the other thermal desalination processes such as MSF.
(2) Can be adapted to any heat source including low grade/low cost heat and hot water to minimize the cost of energy.
(3) Thermodynamically more efficient than MSF, and pressure drops are very low at high volumetric vapor flows.

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(4) Temperature drop per effect is very low (1.5–2.5˚C) due to increase in the heat transfer area and thermodynamic efficiency, which enables it to incorporate large number of effects with a maximum brine temperature of 70˚C.
(5) Low operation and maintenance costs requirements.
(6) Does not require complex pre-treatment systems and operates with different seawater conditions.

MED systems consist of several numbers of evaporators arranged at decreasing level of pressure from the first effect to the last one and an end condenser. Several articles deal with the modeling and optimization of MED systems. Khademi et al. presented the steady-state simulation and optimization of a six-effect evaporator system [14]. In this research, they presented the material and energy balance equations, solution strategy, and optimization of the operating conditions. The effect of feed flow rate, condenser pressure, and feed temperature on the produced water and gain output ratio was studied.

Darwish et al. studied different MED and MSF systems [15]. They developed mathematical models to investigate the effect of different process parameters of the distilled water on the unit cost. The parameters included were specific flow rate of brine, performance ratio (PR), specific heat transfer area, and top brine temperature. Results showed that the conventional MED system has the advantage over MSF system when it operates at low top brine temperature and uses a low-temperature heat source (hot water or steam).

Druetta et al. presented on the mathematical modeling and optimization of MED systems [16]. They developed a highly nonlinear model to analyze the performance of MED system. They studied the simultaneous optimization of the stream-flow patterns, the size of each evaporation unit, and the operating conditions of the MED system. Results showed a good agreement with the real data. Results also showed that the optimization of the flow patterns enhance performance of the system.

N.M. Wade presented the recent developments of the multistage flash (MSF) desalination and MED desalination processes, and compared the costs of water production with the reverse osmosis (RO) process [17]. He concluded that the recent developments in desalination technology and in energy efficiency have led to significant cost savings both in running and capital costs.

Aly and El-fiqi also developed a steady-state mathematical model to investigate both multieffect and multistage desalination systems [18]. They also analyzed the influence of parameters controlling the produced water cost to other operating and design parameters. Results showed that the performance ratio is totally dependent on the number of effects of the system. They investigated that by decreasing the number of effects, specific heat transfer area and performance ratio decreases. So, it is necessary to find optimum number of evaporation effects.

A great number of articles have been published regarding MED system to the best of our knowledge; economic optimization of the number of effects through mathematical modeling has not been presented. So, a mathematical model will be presented in this article to find optimum number of evaporation effects which will give minimum cost for the distillate water. By increasing the number of effects, the running cost decreases but on the other hand, capital cost increases [18–20]. To tackle such problems, a compromise must be found between these two extremes by optimizing the number of effects.

2. Howe's model

For the multieffect desalination (MED) plant, the chief costs are divided into two major categories: capital costs and energy (steam) costs. Howe developed an expression to calculate the total cost in terms of area economy and steam economy which is given below [21]:

$$C = \frac{0.9513 \cdot a \cdot b}{\frac{D}{A}} + \frac{8333 \cdot d \cdot \lambda}{\frac{D}{S}} \quad (1)$$

where C is cost of water in \$/lb, a is capital cost of plant per ft^2 of total heat transfer surface, b is charges on capital cost per annum as a fraction, D is distillate produced in lb/hr, A is heat transfer area in ft^2, d is cost of steam in dollars per million Btu, S is the steam flow rate in lb/hr, 0.9513 is ratio of 8,333 to hours in one year, and 8,333 is pounds of water per kgal.

To get the cost of water in \$/m^3, above equation can be modified as follows:

$$C = \left(\frac{0.9513 \cdot a \cdot b}{\frac{D}{A}} + \frac{8333 \cdot d \cdot \lambda}{\frac{D}{S}}\right) \cdot 0.264 \quad (2)$$

where C is in \$/m^3.

To study the influence of changing the number of effects in the multieffect desalination plant, it is normally considered that D/S = 0.8 n [21]. A mathematical model is presented below to find the value of D/A

as a function of n number of effects using the following assumptions:

- Seawater is supplied to the first effect at its boiling point.
- It is assumed that capacity is constant in this analysis.
- Each effect and condenser have equal heat transfer coefficient and heat transfer area.
- Amount of distillate produced from each effect is same. The overall process based on these assumptions is presented graphically in Fig. 1.

The amount of heat transferred in each effect will be

$$q = D_i \cdot \lambda = U \cdot A_e \cdot \Delta t_m, \quad i = 1, 2, 3, \ldots, n \tag{3}$$

where D_i = distillate produced in each effect, λ = latent heat of distillate, U = overall heat transfer coefficient, A_e = heat transfer area of one effect, and Δt_m = mean temperature difference for heat transfer.

Overall heat transfer coefficient (U_i) can be calculated from the following equation:

$$U_i = \frac{\left(1939.4 + 1.40562 \cdot T_i - 0.0207525 \cdot (T_i)^2 + 0.0023186 \cdot (T_i)^3\right)}{1000} \tag{4}$$

Latent heat of steam input to the MED process and latent heat of distillate in each stage can be obtained by using the following equation:

$$\lambda = 2589.583 + 0.9156 \cdot T - 4.834 \cdot 10^{-2} \cdot T^2 \tag{5}$$

The total production of plant can be found by using the following equation:

$$D = \sum D_i \tag{6}$$

For n number of effects, Eq. (3) can be modified as follows:

$$\sum D_i \cdot \lambda = n \cdot U \cdot A_e \cdot \Delta t_m \tag{7}$$

$$\sum D_i = \left(\frac{n}{\lambda}\right) \cdot U \cdot A_e \cdot \Delta t_m \tag{8}$$

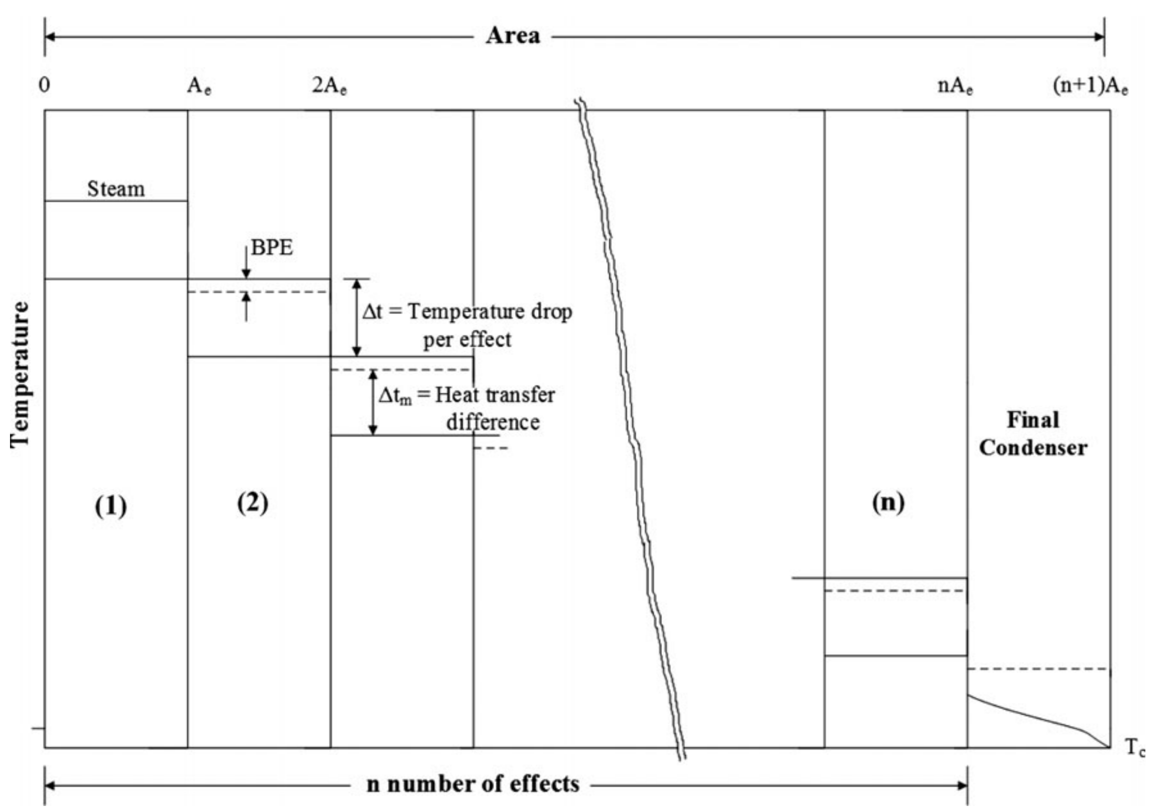

Fig. 1. Temperature profile of an MED system having n effects.

So, Eq. (6) becomes,

$$D = \sum D_i = \left(\frac{n}{\lambda}\right) \cdot U \cdot A_e \cdot \Delta t_m \tag{9}$$

$$\Delta t_m = \Delta t - BPE \tag{10}$$

where Δt is the temperature drop per effect.

By using above expression, Eq. (9) becomes,

$$D = \left(\frac{U \cdot A_e}{\lambda}\right) \cdot (n \cdot \Delta t - n \cdot BPE) \tag{11}$$

The increase in the boiling temperature of water due to the dissolved salts is called boiling point elevation (BPE) which can be calculated by using the following formula [22]:

$$BPE = Xb \cdot [B + (E \cdot Xb)] \cdot (10)^{-3} \tag{12}$$

with

$$B = [6.71 + (6.34 \cdot (10)^{-2} \cdot T_n) + (9.74 \cdot (10)^{-5} \cdot (T_n)^2)] \cdot (10)^{-3}$$

$$E = [22.238 + (9.59 \cdot (10)^{-3} \cdot T_n) + (9.42 \cdot (10)^{-5} \cdot (T_n)^2)] \cdot (10)^{-8}$$

where X_b is the salt concentration of brine in parts per million.

There is no boiling point elevation in the first effect, so the overall temperature difference (ΔT) may be defined as:

$$\Delta T = T_h - T_c = (n+1) \cdot \Delta t - BPE \tag{13}$$

where T_h is the condensing temperature of steam and T_c is the inlet temperature of cooling water.

It is worth mentioning here that the overall temperature difference (ΔT) depends heavily on the seawater temperature during summer which has an impact on both energy and investment costs. To maintain a proper temperature profile along the MED effects, the temperature of seawater is an essential parameter and it is continuously controlled by the plant when entering the condenser. Normally, average value of seawater temperature is provided for analysis.

By rearranging the above equation:

$$n \cdot (n+1) \cdot \Delta t = n \cdot \Delta T + n \cdot BPE \tag{14}$$

$$n \cdot \Delta t = \left(\frac{n}{n+1}\right) \cdot \Delta T + \left(\frac{n}{n+1}\right) \cdot BPE \tag{15}$$

The overall heat transfer area of the plant can be written as:

$$A = (n+1) \cdot A_e \tag{16}$$

By using the values of Eqs. 15 and 16, equation 11 becomes:

$$D = \left(\frac{U}{\lambda}\right) \cdot \left(\frac{A}{n+1}\right) \cdot \left[\frac{n}{n+1} \cdot \Delta T + \frac{n}{n+1} \cdot BPE - n \cdot BPE\right] \tag{17}$$

Or

$$\frac{D}{A} = \frac{U}{\lambda} \cdot \left[\frac{n}{(n+1)^2} \cdot \Delta T + \frac{n}{(n+1)^2} \cdot BPE - \frac{n}{n+1} \cdot BPE\right] \tag{18}$$

$$\frac{D}{A} = \left(\frac{U}{\lambda}\right) \cdot \left(\frac{n}{(n+1)^2}\right) \cdot [\Delta T - n \cdot BPE] \tag{19}$$

So Eq. (2) can be further modified as:

$$C = \left(\frac{0.9513 \cdot a \cdot b}{\left(\frac{U}{\lambda}\right) \cdot \left(\frac{n}{(n+1)^2}\right) \cdot [\Delta T - n \cdot BPE]} + \frac{8,333 \cdot d \cdot \lambda}{0.8 \cdot n}\right) \cdot 0.264 \tag{20}$$

To find the minimum value of number of effects, Eq. (20) can be differentiated with respect to n as follows:

$$(n^2 - 1) + \frac{n \cdot BPE \cdot (n+1)^2}{\Delta T - n \cdot BPE} = (\Delta T - n \cdot BPE) \cdot \left[10949.5 \cdot \left(\frac{U \cdot d}{a \cdot b}\right)\right] \tag{21}$$

3. Results and discussion

3.1. Model validation

The input data has been adopted from Howe's book for model validation [21]. The basic variables which are required to solve the above model are listed in Table 1. It can be seen from equation 20 that latent heat of input steam and distillate of each stage is required to calculate both energy and investment costs which are also given in Table 1. Upon substituting these input parameters into the above model, it gives optimum number of effects nearly equal to 20, which is almost the same as calculated by Howe. It means that 20 is the optimum number that would produce the minimum sum of the investments costs and energy costs. Upon substituting 20 number of effects in Eq. (20), it gives the minimum cost of both components which is equal to 0.133 $/m^3.

3.2. Parametric analysis

It is clear that the optimum number of stages of an MED plant is strongly related to both energy costs and investment costs. At first glance, it seems worthwhile to decrease the specific heat transfer area in the MED system by reducing the number of effects, but on the other hand, this will reduce the performance ratio of the system. From the energy saving point of view, it is good to select the highest possible number of effects because any increase in the number of stages causes an increase in the energy economy. This is true until optimum number of effects reached. So, a compromise is necessary between these two costs to determine the optimum number of effects.

Figs. 2–5 show the parametric study to find optimum number of stages of an MED system at different conditions. Annual charges are kept constant in this analysis. Fig. 2 illustrates the variation of steam cost with changes in the number of effects for fixed capital cost. As can be seen, by increasing the number of effects, the cost of steam decreases at a diminishing rate.

Fig. 3 shows the variation in capital cost by changing the number of effects of an MED system. It is clear

Table 1
Process variables of an MED system [21]

Parameter	Value	Unit
Boiling point elevation (*BPE*)	1.0	℃
Total temperature difference (ΔT)	140	℃
Capital cost of plant (*a*)	64.5	$/m^2
Charges on capital cost per annum (*b*)	14%	–
Cost of steam (*d*)	0.47×10^{-6}	$/kJ
Overall heat transfer coefficient (*U*)	3.4	kW/m^2 K
Latent heat of input steam (λ_s)	2275.5	kJ/kg
Latent heat of stage distillate (λ_d)	2402.7	kJ/kg

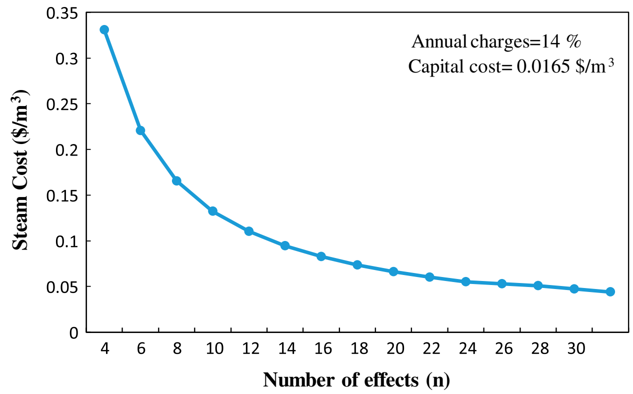

Fig. 2. Variation of steam cost with number of effects.

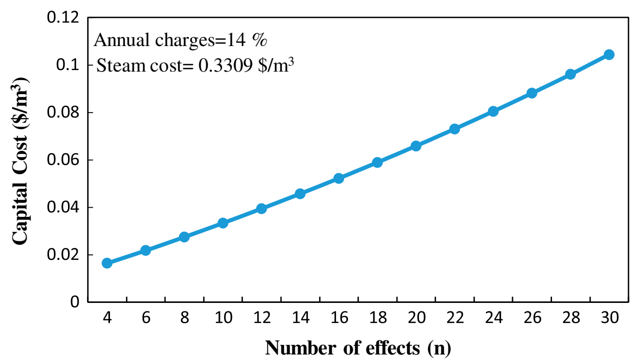

Fig. 3. Variation of capital cost with number of effects.

that the increase in capital investment is nearly linear with the increase in the number of effects.

By increasing the number of effects, stem temperature decreases; the specific heat transfer area of the evaporator/condenser in the MED unit increases, which results in the increment of capital cost. But on the other hand, this will reduce the efficiency of the system because more effects are added into the system which is not necessary. Also, it can be observed from Fig. 4 that specific heat consumption is dependent on the number of effects [23]. With the increase in the number of effects, specific heat consumption decreases drastically. Specific heat consumption is a hyperbolic function of the number of effects as shown in Fig. 4. Thus, it is necessary to find the optimum number of effects.

Fig. 5 shows the influence of number of effects on both capital and steam costs. As a result of steam and capital curves, the third curve representing the sum of the two cost components is also plotted in Fig. 5. Thus, it can be seen that an increase in the number of effects from 11 to 15 would decrease the water cost by almost 0.029 $/m^3. But if a further increase in number

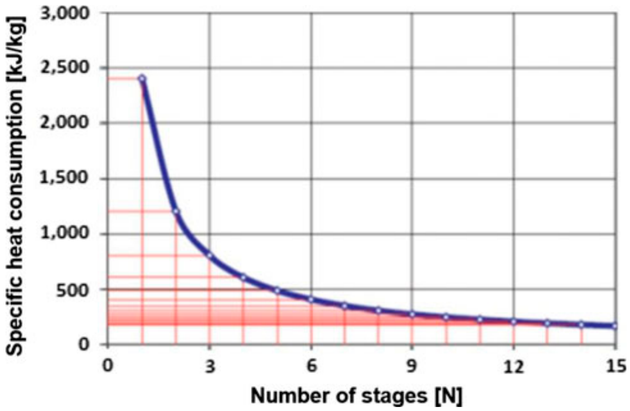

Fig. 4. Variation of specific heat consumption as a function of number of effects of an MED system [23].

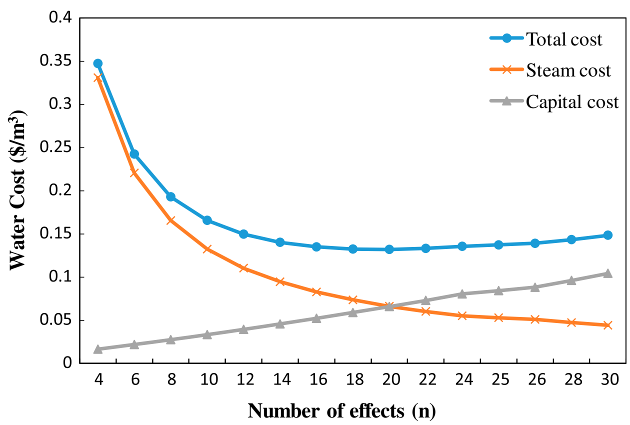

Fig. 5. Variation of steam costs and capital costs with number of effect.

of effects up to 20, it can be seen that the water cost decreases by only an additional 0.0053 $/m^3. It can also be observed from the curves that the minimum overall cost occurs at the point where both thermal and capital costs are almost equal. So, it can be concluded from Fig. 5 that 20 is the optimum number that will give the minimum summation of both costs.

The model presented in this paper can be used to calculate the optimum number of effects for different values of annual charges and steam and capital costs.

4. Conclusion

A mathematical model of an MED system was presented to find the optimum number of effects. The value of optimum number of MED effects is site dependent because capital costs, energy costs, and annual charges are different in different regions of the world. It is not necessary that water cost increases by increasing the number of effects because there is a certain limit for number of effects; beyond that, any increase in number of effects will add extra cost. Optimum number of effects was calculated in this paper by using the Howe's model, that would produce the minimum sum of both steam and capital costs. To ensure that no unnecessary costs have been paid, it is essential to find optimum number of effects.

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Nomenclature

a	—	capital cost of plant, \$/m^2
A	—	heat transfer area, m^2
b	—	charges on capital cost per annum
BPE	—	boiling point elevation, ℃
C	—	total cost of water, \$/m^3
d	—	cost of steam, \$/kJ
n	—	number of effects
D	—	distillate produced, kg/s
q	—	amount of heat transferred in each effect, kJ/s
S	—	steam flow rate, kg/s
T	—	temperature, ℃
ΔT	—	overall Temperature difference, ℃
U	—	heat transfer coefficient, kW/m^2 K
X	—	salt concentration, ppm

Greek symbol

λ	—	latent heat of evaporation, kJ/kg

Subscripts

b	—	brine
c	—	condenser
e	—	effect
h	—	hot
i	—	effect number i
m	—	mean
n	—	last effect

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