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RESEARCH ARTICLE

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A parametric simulation on the effect of the rejected brine temperature on the performance of multieffect distillation with thermal vapour compression desalination process and its environmental impacts

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Abstract

Multieffect distillation with thermal vapour compression (MED–TVC) is one of the most attractive thermal desalination technologies for the production of freshwater. Several mathematical models were presented in the open literature to analyse the steady-state performance of such process. However, these models have several limitations and assumptions. Therefore, there remains the challenge of having a reliable model to accurately predict the performance of the MED process. Thus, this research attempts to resolve this challenge by rectifying the shortcomings of the models found in the literature and create a new one. The robustness of the developed model is evaluated against the actual data of Umm Al-Nar commercial plant situated in UAE. In seawater desalinisation, a large amount of high-salinity stream (brine) is rejected back into the sea. This paper investigates the influence of the rejected (exit) brine temperature on the system performance parameters of MED–TVC process. Specifically, these parameters are considered as total heat consumption, gain output ratio, freshwater production, heat transfer area and performance ratio. Also, the particular parameters of TVC section of the entrainment ratio, compression ratio and expansion ratio are also addressed. Moreover, a critical evaluation of the influence of the rejected brine temperature on the seawater is also embedded.

KEYWORDS

environmental impact, mathematical modelling, MED–TVC, model validation, rejected brine temperature, seawater desalination

1 | INTRODUCTION

In the recent years, a considerable expansion has been considered for the seawater desalination plants to overcome the shortage of freshwater. Coupling thermal vapour compression (TVC) to multieffect distillation (MED) system is becoming an attractive option owing to its significant role in reducing the energy consumption as well as the increase in the system's efficiency.[1] Interestingly, coupling the TVC section to MED lessens the requirement of the external steam because a portion of the distillate is entrained by the TVC section from the last effect and therefore can be utilised as a motive steam.[2] Thus, the energy consumption and associated capital and operating costs are significantly minimised.[3] As a matter of fact, energy consumption is considerably influenced by the operating conditions and geometry of thermo-compressor.[1]

However, one of the main existing concerns of MED–TVC process is the disposal of high-concentration stream (brine) into water resources, which entails an environmental challenge. Broadly speaking, the amount of brine discharged back into the sea from MED process is huge, which could hold negative effects on the marine ecosystems.

It is important to investigate the impact of the operating parameters of MED–TVC on the system performance indicators, namely, gain out ratio, performance ratio (PR), total production of distilled water, heat transfer area (HTA) and total heat consumption. This would allow the operators to design the process within a set of appropriate parameters.

Several studies were explored to investigate the sensitivity of the operating parameters on the performance of MED–TVC desalination systems-based models developed. Several successful examples are described in the following;

Ji *et al.*[4] introduced a theoretical model for a single-effect TVC desalination system to investigate the effect of the operating conditions variation on the performance of the process. This includes the impact of the temperature of the intake seawater and mass flow rate of the cooling water. It was found that in order to increase the efficiency of a desalination plant, the amount of cooling water has to be increased.

Kamali *et al.*[5] presented a mathematical model for MED–TVC system to study the influence of the temperature of steam, number of effects, HTA and concentration factor on the PR. In this context, PR is the quantity of freshwater distilled by condensing 1 kg of steam at 2,330 kJ/kg, which is the average value of the latent amount of heat at the temperature of steam. The results showed that the increase of the HTA, number of effects and concentration factor reflect an increase in the PR. However, any decrease of the temperature of the steam would increase the PR.

Another mathematical model was developed by Ameri *et al.*[6] for MED–TVC system to analyse the effect of different design parameters, for example, number of effects, steam pressure of the inlet, temperature difference across the effects and the seawater temperature of the feed on the system indicators such as the PR, the flow rate of the cooling water and the specific HTA (SHTA). It is worthy to mention that specifying the SHTA is essential to evaluate the dimensions that would help to assess the construction costs of the thermal desalination plant. The results affirmed that an increase in the steam pressure of the inlet leads to an increase in the PR and the SHTA while the flow rate of the cooling water decreases.

A mathematical model was presented by Shen *et al.*[7] for MED–TVC system to explore the effect of the steam parameters on the performance of MED–TVC desalination plant. The results concluded that the gained output ratio (GOR) could be increased as a result of an increase of the steam pressure. GOR can be defined as the quantity of freshwater produced in the plant over the quantity of steam consumed. Furthermore, the increase in the suction vapour temperature causes a reduction in the specific energy consumption and the SHTA while the GOR increases with the rise of the suction vapour temperature.

Bin Amer[8] introduced a comprehensive mathematical model of the MED–TVC desalination process. A sensitivity analysis of the operating parameters and optimisation were carried out. The results deduced the optimal design and operating conditions of MED–TVC varied between 8.2 and 22.9 for four and 16 effects with top brine temperature (TBT) between 56°C and 69.5°C, respectively.

A mathematical model for once-through multistage flash (MSF) desalination process was presented by Roy *et al.*[9] The impact of the TBT on the performance of the process was explored. Furthermore, the effect of the rejected (exit) brine temperature on the SHTA and the PR was also involved. The results showed that the increase in TBT results in an increase in the PR. A reduction in exit brine temperature causes an increase in the PR and specific HTA.

More recently, a detailed model for MED–TVC desalination process was developed by Filippini *et al.*[10] on the basis of a hybrid system of reverse osmosis (RO) and MED processes. Specifically, the MED and TVC section models were adapted from El-Dessouky and Ettouney[2] and Darwish *et al.*, [11] respectively. This model specifically aided to evaluate the thermodynamic properties of the MED–TVC system as a function of salinity, fouling and temperature. A simple comparison was made for the model's predictions with respect to other published models. This mainly included the GOR at different steam temperatures. Results showed that the model was able to predict the performance of MED system with high accuracy owing to its low divergences against observational data as compared with the other tested models and taking into consideration high detailed phenomena in the MED–TVC process. However, the overlooking of

TVC section was one of the disadvantages, and the contribution of the TVC section was not examined.

This paper focuses on enhancing the model of Filippini *et al.*[10] for MED–TVC desalination process to quantify the necessity of a robust model. Unlike Filippini *et al.*, [10] our new model is validated for both MED and TVC parts of the system. To represent the consistency of the improved model of this study, it has been decided to carry out a validation against the real plant data of Umm Al-Nar (located in the UAE).

In addition, note that all the approved studies in MSF, MED and MED–TVC have been based on a fixed value of the rejected (disposed stream) brine temperature that are usually between 10°C and 15°C above the inlet sweater temperature.[8–10,12]

Although the impact of exit brine temperature on the marine life and environment is known to some extent, until to date, the impact of exit brine temperature on the GOR, PR, freshwater production (M_d), total heat consumption (HC) and HTA have not been explored yet. Furthermore, the impact of exit brine temperature on the TVC design parameters including the entrainment ratio (Ra), compression ratio (CR) and expansion ratio (ER) has not been considered in the past. These are the important aspects that will be focused on/addressed in this work.

2 | PROCESS DESCRIPTION

A conventional MED–TVC system is mainly composed of a number of effects (n), feed preheaters, a condenser, flashing boxes and a TVC as shown in Figure 1. MED can be designed in different configurations on the basis of flow direction of the heating steam and evaporating brine. These configurations are parallel feed, forward feed and backward feed. In this respect, parallel feed type is the most commonly used.[12] Both brine and vapour flow are in the same direction in this configuration, and feed seawater (M_f) is separated into set of parallel streams in order to be used as a feed for each effect. In this configuration, the feed enters the system at seawater temperature T_w and specifically introduced into the condenser where an increase of its temperature occurs from T_w to T_f. Therefore, a selected portion of M_f leaves the condenser at T_f as it exchanges heat with the vapour produced in the last effect. A large amount of M_f is rejected back into the sea as cooling water (M_{cw}), whereas the remaining amount of M_f is equally divided between the effects. Excess amount of heat enters the system by the hot motive; thus, the cooling water is used to remove this heat. The feed seawater is sprayed in the effects perpendicularly.

A quantity of the vapour generated in the last effect is compressed and entrained by the motive steam, which goes through the TVC section from the external source. This compressed vapour is introduced into the tube side of the first effect and is used as heating source to increase the temperature of the feed seawater. Condensation of heating steam takes place inside the tubes, which then warms up the feed seawater to the TBT (T_1). This temperature is the boiling temperature of the first effect. Amount of vapour (D_1) is generated through evaporating portion of the feed, which enters the second effect as heat medium at temperature and pressure lower than the temperature and pressure of $n-1$ effect. The temperature of the vapour (T_{v1}) is lower than T_1 by a marginal value. This is known as boiling point elevation (BPE). The vapour formed flow through the demister for the purpose of removing any entrained brine droplets. The vapour is introduced into the second effect (next effect) where it acts as a heating medium once it passes the demister.

The unevaporated brine flows from the first effect into the second effect at a lower pressure. There are two mechanisms behind the formation of vapour inside effects 2 to n: first, by boiling the brine and, second, by

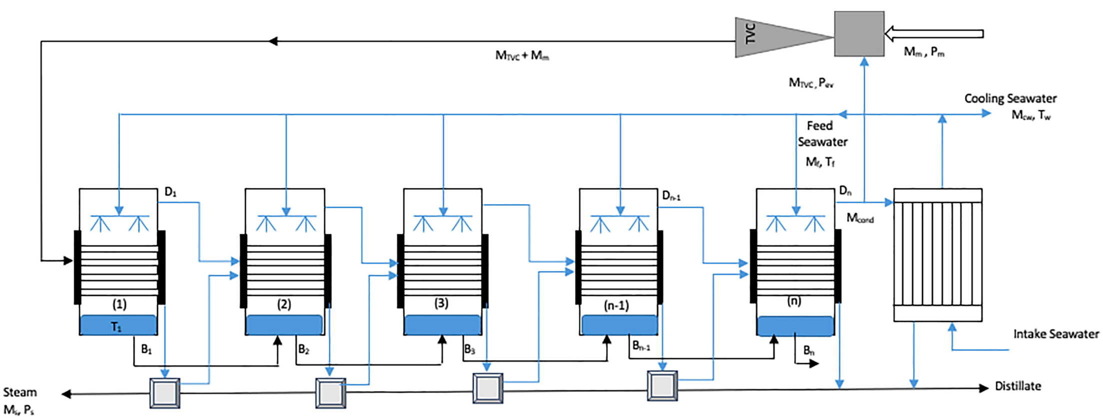

FIGURE 1 Parallel multieffect distillation with thermal vapour compression (MED–TVC) system with n number of effects

flashing the brine that originates from the first effect. The process of flashing occurs in the second effect and continues to the last effect. As a result, a portion of the vapour is generated. Flashing boxes are used to recover the heat from the condensed freshwater. Note that the temperature of vapour generated by flashing is lower than the condensation temperature of distillate by non-equilibrium allowance (NEA). The vapour is formed by flashing and boiling in the flashing box, and the last effect is passed to the condenser. Moreover, proper venting must be provided for the preheaters and the condenser to remove any noncondensable gases (NCGs). Basically, these gases are impeding the heat transfer process as well as increasing the pressure. In order to compress the NCGs to the atmosphere, the vent for the final condenser has to be coupled to a steam ejector. The steam ejector creates vacuum that is maintained on the last effect and hence the unevaporated brine flow from effect n to $n + 1$.

3 | IMPROVED MODELLING OF MED–TVC PROCESS

The implication of the MED–TVC process in seawater desalination depicts their characteristic as an economic desalination process in comparison with other thermal processes such as MSF.[13] This in turn has requested a wide interest in developing the related models, which can be used to explore the effect of operating conditions and to predict the perfect conditions that will give the optimum performance with regard to its high quality and quantity of freshwater.

Filippini *et al.*[10] were able to evaluate the temperature profiles of the plant, which included the distillate temperature, brine temperature and feed temperature. Note that Filippini *et al.*[10] included the thermal load and the recovery ratio in their model. In this regard, the recovery ratio is the quantity of distillate obtained from 1 kg of seawater. Moreover, Filippini *et al.*[10] model included the specific heat consumption (SHC) but without considering the heat consumed in the TVC section. Also, Filippini *et al.*[10] used both PR and GOR to express the MED performance that has not been noticed in the previous modelling of MED–TVC system by others. This is attributed to the unsuitability of GOR to account the enthalpy drop of the steam supplied compared with PR as claimed by Filippini.[14] Up to this point, GOR is the amount of freshwater produced over the amount of steam used as external utility, whereas the PR is the quantity of freshwater produced by condensing 1 kg of steam at an average latent heat at steam temperature, that is, 2,330 kJ/kg. For completeness of the proposed model in this work, both GOR and PR are included. However, Filippini *et al.*[10] focused on the MED section (while validating the model) without considering the existence of the TVC section. Having said that, neglecting the TVC section results in minimising the robustness of the model developed to accurately predict the process performance. It is meaningful to mention that TVC section has been proven by several researchers as an important part of MED system. For instance, the entrainment process of the TVC section minimises the requirement of an external steam utility by reusing vapour as the heating medium. Hence, it is plausible to expect a reduced energy consumption.[7] Also, an increase in the ER of TVC section would increase the entrainment ratio, and this causes a reduction in the flow rate of the entrained vapour. Thus, this would lead to a reduction in the freshwater production and GOR.[15] Furthermore, El-Dessouky and Ettouney[2] showed that lower compression ratio corresponds to a higher PR at low boiling temperatures and high motive steam pressures. Therefore, it is important to update the model of Filippini *et al.*[10] despite its high consistency in validation of the MED section but not the TVC section with literature data. The next section illustrates the characteristics of the new improved model of this study.

3.1 | Assumptions

A set of plausible assumptions were considered to develop the new steady-state model of MED–TVC system as illustrated below,

1. Distillate product is salt free; that is, $x_d = 0$.
2. Fixed temperature difference across each effect of 4°C.
3. Equal flow rate across each effect.
4. Thermodynamic losses are negligible.
5. The external utility provides saturated steam and leaves as saturated liquid.
6. The NEAs and pressure drops are negligible.
7. The effects of NCGs are neglected.
8. The falling film evaporation on the tube surfaces where seawater is sprayed onto them is not considered.

In this context, the following set of equations has been newly considered to build the proposed model. This in turn would highlight the improvements made on the model developed by Filippini *et al.*[10] for the MED–TVC system.

- The modified equation of Bin Amer[8] has been considered to estimate the entrainment ratio in the TVC section, which is commonly used in several literature models as follows

$$R_a = 0.235 \frac{(P_s)^{1.19}}{(P_{ev})^{1.04}} (\mathrm{ER})^{0.015}. \quad (1)$$

Entrainment ratio is denoted by R_a, pressure of saturated steam at temperature T_s is denoted by P_s, pressure of saturated entrained vapour is indicated by P_{ev} and ER is the expansion ratio.

It is important to mention that Filippini *et al.*[10] have used different equations to estimate the entrainment ratio on the basis of temperature and pressure correction factors. These equations have been proved to be minimising the accuracy in predicting the entrainment ratio as will be shown in Section 4.

- The ER is calculated by using the formula of El-Dessouky and Ettouney.[2] This would compensate the shortcoming of Filippini *et al.*[10] owing to ignoring the validation of TVC section.

$$\mathrm{ER} = \frac{P_m}{P_{ev}}. \quad (2)$$

P_m (kPa) is the motive steam pressure.

- Most interestingly, SHC is considered as a main characteristic of the thermal desalination technologies.[16] Broadly speaking, the SHC is necessary to evaluate the system performance including TVC section. In this respect, Equation 3 is adapted from Al-Mutaz and Wazeer[12] to properly evaluate the SHC for the entire MED–TVC process

$$Q_d = \frac{M_s \lambda_m}{M_d}. \quad (3)$$

Q_d (kJ/kg) is the SHC considering the TVC section. Also, M_s and M_d (kg/s) are the steam flow rate and distillate flow rate, respectively. It is also worthy to mention that the SHC has been considered by Filippini *et al.*[10] for MED only without taking into account the heat consumption of TVC section.

λ_m (kJ/kg) is the motive steam latent heat calculated from the latent heat of vaporisation $\lambda(T_s)$ (kJ/kg) at steam temperature (T_s) and the latent heat of the outlet condensate at saturated liquid λ_{oc} (kJ/kg) as presented in the following equation:

$$\lambda_m = \lambda(T_s) - \lambda_{oc}. \quad (4)$$

In this respect, λ_{oc} can be calculated using the following correlation of Bin Amer[8]:

$$\lambda_{oc} = -0.033635409 + 4.208t(1) - 0.0000263129t(1)^2 - 0.000011221t(1)^3. \quad (5)$$

$t(1)$ is the feed temperature after the first preheater (°C).

Thus, this study provides an improved model of MED–TVC system associated with the model developed by Filippini *et al.*[10] The model is coded and solved using the gPROMS software.[17]

3.2 | Model equations

The comprehensive model for MED–TVC developed by Filippini *et al.*[10] is given in Tables 1 and 2 with the thermodynamic correlations in Table 3. The model equations were built based on a sequence of mass and energy balances around the MED effects, TVC, condenser and flash chambers.

4 | MODEL VALIDATION

The model predictions and the simulation data of Filippini *et al.*[10] are compared against the established data of the commercial Umm Al-Nar plant located in Abu Dhabi in the UAE as presented in Table 4.

Table 5 shows a considerable difference between the prediction of the proposed model and Filippini *et al.*[10] in terms of entrainment ratio of TVC section, although the compression ratios were close. This is mainly attributed to relaxing the ER of the TVC section by Filippini *et al.*,[10] which is not the case of the new proposed model. However, the new proposed model is able to estimate the ER despite the fact that this value is not reported for Umm Al-Nar in literature and Filippini *et al.*[10] model did not consider it. Sadri *et al.*[15] assessed the influence of the ER on the GOR and the total production of freshwater. Hence, it is important to include the ER to study the performance of MED–TVC. On the other hand, both the proposed and Filippini *et al.*[10] models are similar to predict the GOR, PR, M_d and SHTA. Note that Alasfour *et al.*[18] have not reported the value of SHTA for Umm Al-Nar plant.

It is noteworthy that the improved model calculates the value of the entrainment ratio of the desalination plant with a relative error of 7.1% compared with 31% of Filippini *et al.*[10] model when compared with real plant data.

TABLE 1 MED system model equations (adapted from Filippini *et al.*[18])

No.	Explanation	Equation	Unit
1	Flow rate of the feed	$M_f = \frac{M_s\,\lambda(T_s)}{Q_{\text{sensible}} + Q_{\text{latent}}}$	kg/s
2	Evaluation of sensible heat (first effect)	$Q_{\text{sensible}} = M_f \int_{t_1}^{T_1} cp(T_1, x_1)\,dT$	kJ/s
3	Latent heat used to vaporise a portion of the distillate in the first effect	$Q_{\text{latent}} = D_1\,\lambda(T_{v1})$	kJ/s
4	Temperature drop per effect (first attempt)	$\Delta T = \frac{T_s - T_b}{n}$	°C
5	Temperature drop among the effects equal to the increase in the temperature among the preheaters (first attempt)	$\Delta T = \Delta t$	°C
6	Temperature of the feed (first effect) after $n-1$ preheater	$t_1 = tn + (n-1)\,\Delta t$	°C
7	Vapour phase temperature	$T_v = T - \text{BPE}(T, x)$	°C
8	Flow rate of flashed distillate	$D_{\text{flash},i} = \alpha B_{i-1}$	kg/s
9	Fraction of rejected brine by flashing	$\alpha = \frac{c_p\,(T_{\text{mean}} x_{\text{mean}})\Delta T}{\lambda(T_{\text{mean}})}$	-
10	Mean temperature	$T_{\text{mean}} = \frac{T_1 + T_b}{2}$	°C
11	Mean salinity	$x_{\text{mean}} = \frac{x_f + x_b}{2}$	ppm
12	Distillate fraction by evaporation	$\beta = \frac{\alpha\left[x_b(1-\alpha)^n - x_f\right]}{(x_b - x_f)\left[1-(1-\alpha)^n\right]}$	-
13	Flow rate of evaporated distillate	$D_{i,\text{boiled}} = \beta M_D$	kg/s
14	Total distillate	$D_i = D_{i,\text{boiled}} + D_{i,\text{flashed}}$	kg/s
15	Rejected brine flow rate	$B_i = B_{i-1} - D_i$	kg/s
16	Evaluation of salinity profiles	$x_i = \frac{x_{i-1} B_{i-1}}{B_i}$	ppm
17	Area of evaporators	$A_{ev,i} = \frac{Q_i}{U_{ev,i}\Delta T_{ev,i}}$	m^2
18	Heat load of *i*th effect	$Q_i = D_{\text{boiled},i-1} - \lambda(T_{v,i-1})$	kJ/s
19	Temperature difference in evaporators	$\Delta T_{ev,i} = \Delta T - \text{BPE}_{i-1}$	°C
20	Thermal load of the external steam in the first effect	$Q_s = M_s \lambda(T_s) = A_{ev1} 1\ Uev_1\,(T_s - T_1)$	kJ/s
21	Evaluation of preheater area	$M_f \int_{t_{i+1}}^{t_i} cp(t, x_f)\,dt = U_{ph,i} A_{ph,i}\,\Delta t_{\log,i}$	m^2
22	Logarithmic temperature drop in preheaters	$\Delta t_{\log,i} = \frac{\Delta t}{\log\left(\frac{T_{vi} - t_{i+1}}{T_{vi} - t_i}\right)}$	°C
23	Area of final condenser	$Q_{\text{COND}} = U_{\text{COND}} A_{\text{COND}} \Delta T_{\log,\text{COND}}$	m^2
24	Heat load in final condenser	$Q_{\text{COND}} = D_n\,\lambda(T_{vn})$	kJ/s
25	Logarithmic temperature drop in final condenser	$\Delta T_{\log,\text{COND}} = \frac{t_n - T_w}{\log\left(\frac{T_{vn} - T_w}{T_{vn} - tn}\right)}$	°C
26	Gained output ratio	$\text{GOR} = \frac{M_d}{M_s}$	-
27	Gained output ratio (TVC)	$\text{GOR} = \frac{M_d}{M_s}$	-
28	Performance ratio	$\text{PR} = \text{GOR}\frac{2{,}330\ \text{kJ/kg}}{\lambda(T_s)}$	-
29	Performance ratio (TVC)	$\text{PR} = \text{GOR}_{\text{TVC}}\frac{2{,}330\ \text{kJ/kg}}{\lambda(T_s)}$	-
30	Equalising of exchange areas procedure	$A_{\text{ev mean}} = \frac{\sum_{i=0}^{n} A_{ev,i}}{n}$	m^2
31		$A_{\text{ev mean}} - \frac{Q_i}{U_{ev,i}\Delta T_{ex,i}} = 0$	-
32		$\Delta T_i = \Delta T_{ex,i} - \text{BPE}_i$	°C
33		$T_i = T_{i-1} - \Delta T_i$	°C
34		$T_{vi} = T_i - \text{BPE}(T_i, X_i)$	°C
35		$\Delta A_{ev} = \frac{\max(A_{ev}(2{:}10)) - \min(A_{ev}(2{:}10))}{A_{\text{ev mean}}} * 100$	%
36	Flow rate of the vapour entrained (TVC section)	$M_{\text{TVC}} = M_s - M_m$	kg/s
37	Flow rate of the vapour in the final condenser	$M_{\text{cond}} = D_n - M_{\text{TVC}}$	kg/s

Abbreviations: MED, multieffect distillation; TVC, thermal vapour compression.

TABLE 2 TVC section model equations (adapted from El-Dessouky and Ettouney[2])

No.	Description	Equation	Unit
1	Pressure at vapour temperature	$P_{\mathrm{v}} = P_{\mathrm{crit}} e^{\left(\frac{T_{\mathrm{crit}}}{T_{\mathrm{vn}}} + 273.15\right)^{-1} \sum_{j=1}^{8} f_j}$	bar
2	Pressure at steam temperature	$P_{\mathrm{s}} = P_{\mathrm{crit}} e^{\left(\frac{T_{\mathrm{crit}}}{T_{\mathrm{s}}} + 273.15\right)^{-1} \sum_{j=1}^{8} f_j}$	bar
3	Compression ratio	$\mathrm{CR} = \frac{P_{\mathrm{v}}}{P_{\mathrm{s}}}$	-
4	Motive steam flow rate	$M_{\mathrm{m}} = M_{\mathrm{s}} \frac{R_{\mathrm{a}}}{1 + R_{\mathrm{a}}}$	kg/s
5	Motive steam temperature	$T_{\mathrm{m}} = 42.6676 - \frac{3892.7}{\log\left(\frac{P}{1,000}\right) - 9.48654}$	°C

Note: Coefficient: f1 = −7.4192; f2 = 0.29721; f3 = −0.1155; f4 = 0.00868; f5 = 0.00109; f6 = −0.0043; f7 = 0.00252; f8 = −0.00052.
Abbreviation: TVC, thermal vapour compression.

TABLE 3 Thermodynamic correlations of MED system (adapted from El-Dessouky and Ettouney[2])

	No.	Equation	Comment
Boiling point elevation	1	$w = x \cdot 10^{-5}$ (w/w%)	Correlation valid in the range: 1% $< w <$ 16%, 10°C $< T <$ 180°C
	2	$\mathrm{BPEa} = 8.325 \cdot 10^{-2} + 1.883 \cdot 10^{-4} T + 4.02 \cdot 10^{-6} T^2$	
	3	$\mathrm{BPEb} = -7.625 \cdot 10^{-4} + 9.02 \cdot 10^{-5} T - 5.2 \cdot 10^{-7} T^2$	
	4	$\mathrm{BPEc} = 1.522 \cdot 10^{-4} - 3 \cdot 10^{-6} T - 3 \cdot 10^{-8} T^2$	
	5	$\mathrm{BPE} = \mathrm{BPEa} \cdot w + \mathrm{BPEb} \cdot w^2 + \mathrm{BPEc} \cdot w^3$	
Specific heat at constant pressure	6	$s = x \cdot 10^{-3}$ (g/kg)	Correlation valid in the range: 200,00 ppm $< x <$ 160,000 ppm, 20°C $< T <$ 180°C
	7	$\mathrm{cpa} = 4206.8 - 6.61697 s + 1.2288 \cdot 10^{-2} s^2$	
	8	$\mathrm{cpb} = -1.1262 + 5.4178 \cdot 10^{-2} s - 2.2719 \cdot 10^{-4} s^2$	
	9	$\mathrm{cpc} = 1.2026 \cdot 10^{-2} - 5.3566 \cdot 10^{-4} s + 1.8906 \cdot 10^{-6} s^2$	
	10	$\mathrm{cpd} = 6.8777 \cdot 10^{-7} + 5.3566 \cdot 10^{-6} s - 4.4268 \cdot 10^{-9} s^2$	
	11	$\mathrm{cp} = \frac{\mathrm{cpa} + \mathrm{cpb}.T + \mathrm{cpc}.T^2 + \mathrm{cpd}.T^3}{1,000} \quad \left(\frac{\mathrm{kJ}}{\mathrm{kg}.^{\circ}\mathrm{C}}\right)$	
Latent heat of evaporation	12	$\lambda = 2501.89715 - 2.40706 \cdot T + 1.19221 \cdot 10^{-3} T^2 - 1.5863 \cdot 10^{-5} T^3$	-
Global heat exchange coefficients	13	$U_{\mathrm{ev}} = 1.9695 + 1.2057 \cdot 10^{-2} T - 8.5989 \cdot 10^{-5} T^2 - 2.5651 \cdot 10^{-7} T^3$	-
	14	$U_{\mathrm{cond}} = U_{\mathrm{ph}} = 1.7194 + 3.2063 \cdot 10^{-3} T + 1.597 \cdot 10^{-5} T^2 - 1.9918 \cdot 10^{-7} T^3$	-

TABLE 4 Design and operating condition of Umm Al-Nar plant (taken from Alasfour *et al.*[18])

Number of effects	6
Top brine temperature (°C)	61.8
Temperature of brine in the last effect (°C)	42.8
Temperature of feed seawater (°C)	40
Temperature of cooling seawater (°C)	30
Temperature drop in each effect (°C)	3.80
Motive pressure (kPa)	2,500
Motive steam flow rate (kg/s)	10.6 × 2

In terms of the compression ratio, both Filippini *et al.*[10] model and our model are within 2%. Note that this parameter was not presented in literature for the real plant. Referring to Table 5, both the compression ratio of the proposed model and Filippini *et al.*[10] are higher than 1.81, and they are within the optimal range for the compression ratio of 1.81 to 3.68 as stated by Bin Amer.[8]

Regarding the system performance, which critically denotes the SHC, it is clearly seen that the proposed model is able to predict this parameter, although this parameter is not reported in literature for Umm Al-Nar. Also, Filippini *et al.*[10] model has not clearly specified the

TABLE 5 Comparison of MED–TVC system against actual data of Umm Al-Nar plant

Reported or calculated parameters	Umm Al-Nar (taken from Alasfour *et al.*[18])	Prediction by Filippini *et al.*[10] model	This work
TVC entrainment ratio	1.36	1.97	1.27
TVC expansion ratio	Not reported	Not considered	305.04
TVC compression ratio	Not reported	2.89	2.95
System performance			
Specific heat consumption (kJ/kg)	Not reported	Not considered for MED+TVC. Only considered for MED	391.23
Gained output ratio (GOR)	8.81	8.73	8.73
Performance ratio (PR)	Not reported	8.85	8.85
Freshwater production (kg/s)	184.20	183.92	183.92
Specific heat transfer area (m^2 s/kg)	Not reported	351.14	351.14

Abbreviations: MED, multieffect distillation; TVC, thermal vapour compression.

SHC owing to relaxing the TVC section. The SHC reflects the energy consumption characteristics of the MED–TVC desalination systems.[7] The GOR of the system is predicted by both models, which is very close to that of the real plant. In terms of the PR, there is a similarity in predicting the PR of the plant, although the value of the PR is not reported in the literature for the real plant. Similarly, the value of the SHTA is not reported. However, both models were able to predict the value of the SHTA. Thus, it can be said that these models are able to predict the SHTA. It is worth noting that determining the SHTA is necessary to assess the dimensions, and in turn, this aids to evaluate the construction costs of the desalination plant.[19]

Finally, the freshwater production was similarly predicted by both competitive models with a very small deviation from the actual data.

Therefore, it is fair to say that the proposed model was able to predict the actual data of the desalination plant closer than did Filippini *et al.*[10] The marginal discrepancy between the comparative data might be due to those assumptions made in the proposed model. However, this model can be improved further by involving the correlation of the film evaporation[20] (Assumption no. 8) to precisely reduce the convergence between the model predictions and plant data.

5 | RESULTS AND DISCUSSION

Table 6 depicts the input parameters used to study the impact of the rejected brine temperature on the performance of MED–TVC system. This includes the TBT that ranges between 60°C and 70°C. Basically, the temperature range is taken similar to what considered in several MED–TVC systems based on TBT of lower than 75°C to avoid scaling problem.[12] Moreover, the rejected (exit) brine temperature ranges between 42°C and 54°C. This is also considered based on the authors' knowledge of the exit brine temperature on the MED–TVC performance. Also, the number of effects is similar to that of Al-Jubail desalination plant in the Kingdom of Saudi Arabia,[8] whereas the temperature of the feed, the temperature of the cooling water, and the motive pressure are similar to those of Umm Al-Nar desalination plant situated in the UAE.[18] The feed salinity used in this simulation is similar to the salinity of the Arabian Gulf at the ambient conditions.[21]

The impact of changing the exit brine temperature of MED–TVC process on the PR, HC, freshwater production, HTA and the GOR is discussed in detail in the next sections. Also, the particular parameters of TVC section of the entrainment ratio, compression ratio and ER are also evaluated.

TABLE 6 Input parameters to perform the study

Variable	Typical value	Reference
Number of effects	8	Bin Amer[8]
Rejected (exit) brine temperature (°C)	42–54	Assumed
Top brine temperature (°C)	60–70	Assumed
Feed seawater temperature (°C)	40	Alasfour *et al.*[18]
Cooling water temperature (°C)	30	Alasfour *et al.*[18]
Cooling water flow rate (kg/s)	100	Assumed
Feed salinity (ppm)	45,000	Dawoud and Al Mulla[21]
Motive pressure (kPa)	2,500	Alasfour *et al.*[18]
Motive steam temperature (°C)	219.5	Assumed

5.1 | Effect of rejected brine temperature on PR and HTA at different TBTs

Figure 2 shows the variation of the HTA and PR as a function of an increase in the exit brine temperature from 42°C to 54°C at three different TBTs of 60°C, 65°C and 70°C. This illustrates that any increase in the rejected brine temperature requires a higher HTA. At higher exit brine temperature, the HTA of the evaporator increases owing to an increase in the entrained vapour pressure, and the condenser HTA decreases owing to an increase in the load of the condenser, which is mainly attributed to the reduction in the amount of vapour being condensed. Note that the increase in the area of the evaporators is more prominent compared with the decrease in the area of the condenser. Therefore, the resultant would be an increase in the HTA.

The lowest TBT of 60°C has resulted in the highest increase in the HTA from 0.83 to 4.13 m^2. However, an increase in the HTA from 0.83 to 2.97 m^2 is noticed at the highest TBT of 70°C. Moreover, the PR steadily decreases as a result to increasing the rejected brine temperature from 42°C to 54°C. In other words, Figure 2 confirms the highest PR at the lowest rejected brine temperature for any given value of TBT. This is due to the increase in the flow rate of the feed at low values of the rejected brine temperature. Moreover, the PR is slightly decreasing owing to increasing TBT, which can be ascribed to the fact that higher TBT corresponds to higher temperature drop across the effects. However, at higher rejected brine temperature, the temperature drop is less as it can be seen in Figure 3.

5.2 | Effect of rejected brine temperature on total heat consumption

One of the main features of the MED–TVC systems is the evaluation of the HC.[7] Figure 4 shows that the HC linearly increases as a consequence to the increase of the exit brine temperature at TBT of 60°C. Statistically, a noticeable increase in the HC from 0.46 to 2.4 kJ/s when the rejected brine increases from 42°C to 52°C is noticed. Basically, increasing the rejected brine temperature leads to a higher vapour pressure. Therefore, the quantity of steam required to compress the vapour at higher vapour pressures and higher rejected brine temperature is steadily increased. Moreover, the latent heat of vaporisation increases with the increase of the vapour pressure correspondingly. The rise in the rate of the vaporisation is more pronounced than the decreasing rate of the motive steam. Thus, the net result is the increase in the total consumption.

5.3 | Effect of rejected brine temperature on total freshwater production and GOR

Figure 5 shows the variation of the GOR and freshwater production as a function of the rejected brine temperature at fixed TBT of 60°C. This in turn shows a high sensitivity of the total freshwater production to the variation of the rejected brine temperature. In this regard, it decreases from 629.0 kg/s at 42°C to 121.5 kg/s at 54°C. This can be ascribed to the decrease in the flow rate of the steam provided in the first effect that accompanying with a decrease in the flow rate of the feed as a consequence to increase the temperature of the rejected brine and finally leads to minimise the freshwater production. It is noteworthy to mention that the temperature difference between steam and brine in the considered effect is fixed at 4°C (Assumption no. 2). Consequently, a rapid degradation in the freshwater production from the first stage to the last one is expected.

It is obvious that increasing the temperature of the rejected brine from 42°C to 54°C can significantly reduce the GOR from 7.2 to 4.8. Therefore, as the amount of freshwater produced is decreased with the increase of rejected brine temperature, the GOR is decreased.

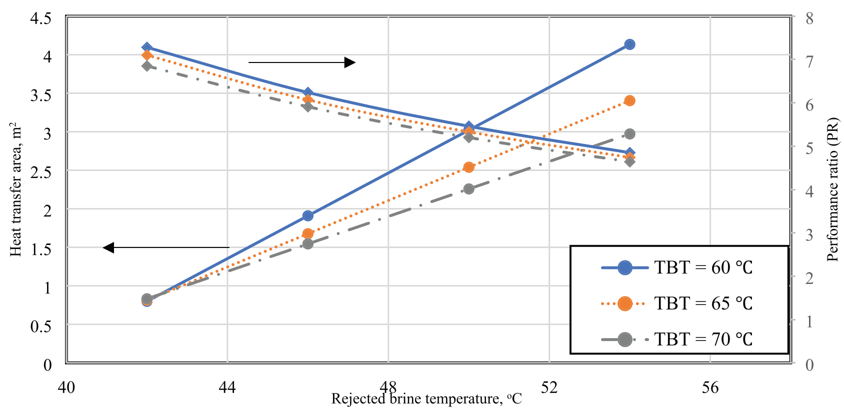

FIGURE 2 Effect of rejected brine temperature on performance ratio (PR) and heat transfer area at different top brine temperatures (TBTs)

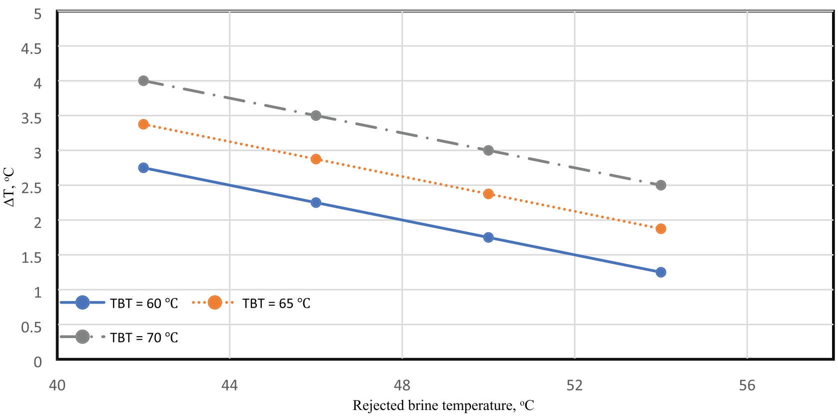

FIGURE 3 Variation of the temperature drop between the effects when the rejected brine temperatures are varied at different top brine temperatures (TBTs)

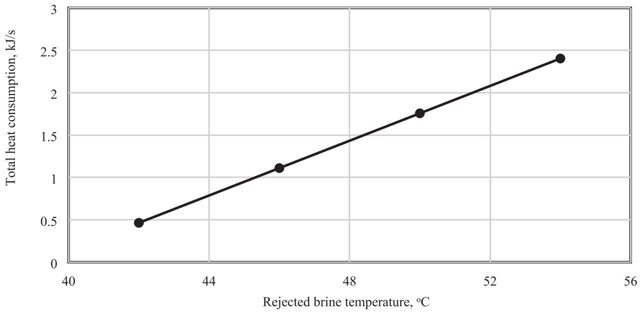

FIGURE 4 Effect of rejected brine temperature on total heat consumption at top brine temperature (TBT) of 60°C

Up to this point, the above impacts of the rejected (exit) brine temperature on the performance indicators of the MED–TVC process are straightforward and significant.

5.4 | Effect of rejected brine temperature on TVC section parameters

The TVC section parameters involve the entrainment ratio, the compression ratio and the ER. These parameters have been proven as the main parameters in modelling the TVC section in literature.[7] In this respect, the entrainment ratio can be defined as the ratio between the motive steam flow rate to the entrained vapour flow rate. The compression ratio is defined as the ratio between the pressure of the saturated steam at the temperature of vapour to the pressure of saturated steam at steam temperature. The ratio between the pressure of the motive steam to the pressure of the entrained vapour is known as the ER.

Figure 6 illustrates the effect of increasing the rejected brine temperature from 42°C to 54°C on the entrainment ratio at fixed TBT of 60°C. This affirmed that any increase in the rejected brine temperature causes a reduction in the entrainment ratio from 1.28 to 0.76. As mentioned earlier, the increase of the rejected brine temperature causes a retardation in the motive steam flow rate, which results in a reduction in the entrainment ratio.

The behaviour of the compression ratio as a function of the rejected brine temperature at fixed TBT of 60°C is illustrated in Figure 7. Results showed that the compression ratio decreases from 3 to 1.81 as the rejected brine temperature rises from 42°C to 54°C. This is due to the increase in the discharge vapour at low exit brine

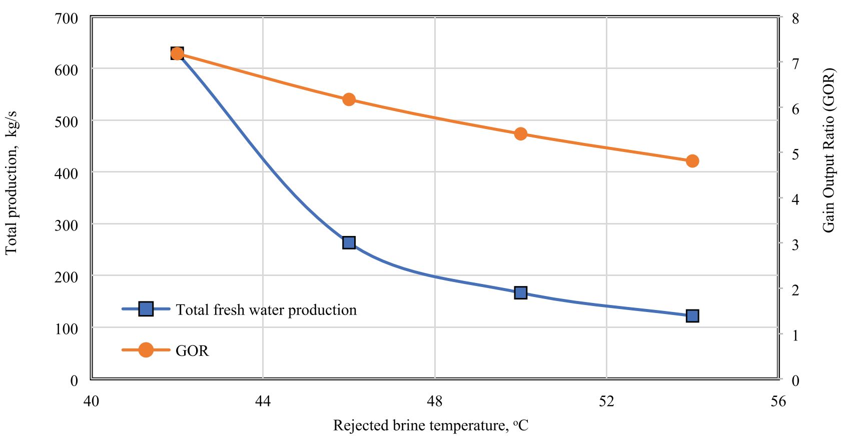

FIGURE 5 Effect of temperature of the rejected brine on total freshwater production and gained output ratio (GOR) at top brine temperature (TBT) 60°C

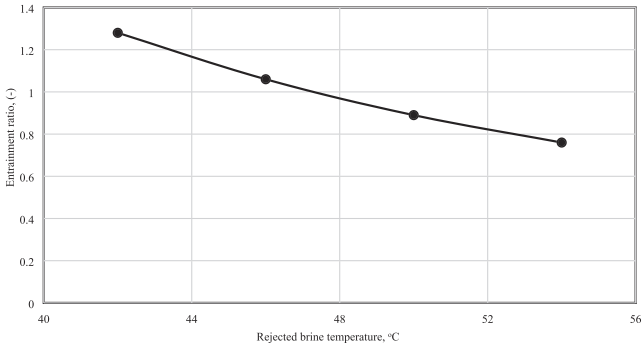

FIGURE 6 Effect of rejected brine temperature on entrainment ratio at fixed top brine temperature (TBT) of 60°C

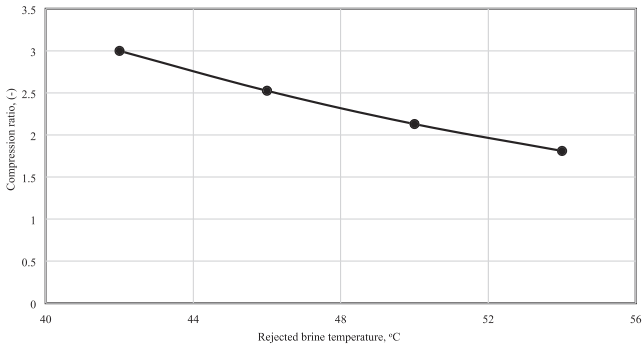

FIGURE 7 Effect of rejected brine temperature on compression ratio at fixed top brine temperature (TBT) of 60°C

temperatures, which reflects high values of compression ratio. As a matter of fact, the compression ratio cannot be lower than 1.81 as can be seen in Figure 7. This is in line with the statements provided by Bin Amer[8] and El-Dessouky and Ettouney.[2] Thus, under the conditions presented in Table 6 and at TBT of 60°C, the compression ratio cannot be lower than 1.81.

Figure 8 shows the influence of increasing the exit brine temperature on the ER at fixed TBT of 60°C. The pressure of the entrained vapour increased as the rejected

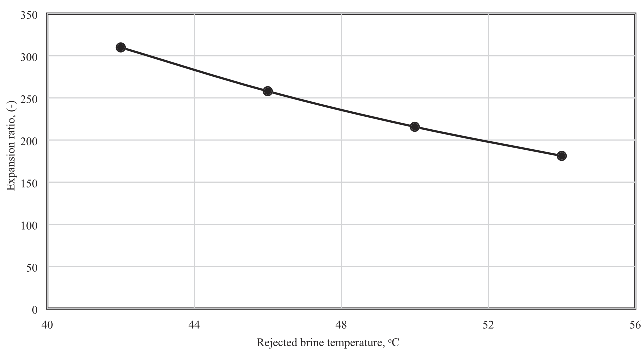

FIGURE 8 Effect of rejected brine temperature on expansion ratio at fixed top brine temperature (TBT) of 60°C

brine temperature increased. Hence, the ER decreases. The disadvantage of the reduction the ER is the decrease in the entrainment ratio. Consequently, this would also lead to decrease in the freshwater production and GOR.

6 | IMPACT OF THE REJECTED BRINE TEMPERATURE ON THE ENVIRONMENT

Indeed, desalination technologies including thermal MED–TVC system are the most attractive and economic option available to produce potable water. Therefore, a wide expansion of thermal and membrane technologies can be noticed around the globe to meet the growing demand of water. However, there is a controversial issue towards these technologies and its passive impact on the environment. This is specifically including the disposing of high-salinity streams without an efficient treatment. Therefore, this issue requires a comprehensive analysis in order to eliminate or at least mitigate it.[22] More importantly, the United Nations (UN) warns of increasing the amount of toxic brine.[23]

Mickley[24] discussed in detail the different approaches associated with the brine disposal produced from the desalination plants. This comes with three suggestions: dispose the brine into the land, deep well injection and discharge into the sea. It has arguably mentioned that the option of disposing brine into the sea would be the most socially, economically, technically or environmentally feasible option for large desalination plants.[25] However, the brine produced from all the desalination plants represents 141.5 m^3/day, which is roughly 50% greater than the total quantity of the freshwater produced.[23] Furthermore, Jones *et al.*[23] affirmed that 6% of the seawater is desalinated using MED process compared with 12% as rejected brine disposed into the sea. Moreover, Ahmed *et al.*[26] estimated that the cost of disposing the brine represents approximately 5% to 33% of the total cost of the desalination process. Therefore, it seems that the option of disposing brine into sea would be an overwhelming option of equivocal consequences.

The impact of increasing the temperature of the discharged brine is significant on the growth of the marine species due to its effect on the marine temperature. In this respect, Dawoud and Al Mulla[21] stated that the seawater temperature in the Gulf is about 35°C at the ambient conditions. However, the continuous disposal of brine into the sea can increase the seawater temperature by around 7°C to 8°C. Furthermore, Cotruvo *et al.*[27] claimed that the brine disposed from the MED process is 5–25°C higher than the seawater temperature. Hiscock *et al.*[28] mentioned that plankton and fish are most likely to be the first species that would be affected from the changes in the seawater temperature. Furthermore, the rate of the chemical and biological processes relies on temperature. Thus, the oxygen content of water is highly affected by the temperature as the oxygen levels becomes lower when the temperature rises.[29] Also, the metabolic rates of marine organisms and rate of photosynthesis by aquatic plant are influenced as result of any variation in the seawater temperature as a consequence to discharge the brine.[30] More recently, Son *et al.*[31] tested the integration of MED and an adsorption cycle (MED-AD), which elaborates the possibility of operating the last effect of the MED system at lower than 9.0°C.

7 | CONCLUSIONS

A steady-state mathematical model for MED–TVC desalination system is presented. This model would offer a powerful modelling tool for future studies especially for sensitivity and optimisation studies.

For any desalination plant, the temperature of the rejected (exit) brine is one of the major concerns. Specifically, the increase in the rejected brine temperature results in a reduction in flow rate of the motive steam, and this would lead to cause a reduction in the GOR and total freshwater produced while the SHTA and SHC increase. The reduction in the TVC section parameters would reduce the freshwater production and GOR. Thus, operating the MED–TVC system with high rejected brine temperature would limit the performance of the plant. The study concludes that the low exit brine temperature not only protects the environment but also improves the plant performance significantly.

NOMENCLATURE

A_{ev}	exchange area of ith evaporator (m^2)
$A_{ph,i}$	exchange area of ith preheater (m^2)
A_{COND}	exchange area of final condenser (m^2)
$A_{ev,mean}$	mean exchange area of evaporators (m^2)
$A_{ph,mean}$	Mean exchange area of preheaters (m^2)
B_i	brine rejected by the ith effect (kg/s)
CR	compression ratio in the steam ejector (–)
D_i	total distillate produced in ith effect (kg/s)
$D_{boil,i}$	distillate produced by boiling in ith evaporator (kg/s)
$D_{flash,i}$	distillate produced by flashing in ith flashing box (kg/s)
ER	expansion ratio (–)
E_s	specific energy consumption (kJ/kg)
GOR	gained output ratio (–)
M_b	rejected brine flow rate (kg/s)
M_{COND}	flow rate of steam in the final condenser (kg/s)
M_d	distillate from MED process (kg/s)
M_f	water intake in the first effect (kg/s)
M_m	motive steam flow rate (kg/s)
M_s	total steam flow rate (kg/s)
M_{cw}	intake water flow rate (kg/s)
M_{TVC}	vapour flow rate entrained in TVC section (kg/s)
n	number of effects of MED process (–)
P_v	pressure of saturated steam at temperature T_v (kPa)
P_s	pressure of saturated steam at temperature T_s (kPa)
P_{ev}	pressure of saturated entrained vapour (kPa)
P_{crit}	critical pressure of water (kPa)
P_m	motive steam pressure (kPa)
PR	performance ratio (–)
Q_{COND}	thermal load in final condenser (kW)
Q_d	specific heat consumption (SHC) (TVC section considered) (kJ/kg)
$Q_{sensible}$	sensible heat used in first effect (kJ/kg)
Q_{latent}	latent heat used in first effect (kJ/kg)
Q_i	thermal load at ith evaporator (kW)
Q_s	thermal load of steam (kW)
R_a	entrainment ratio (–)
SHTA	specific heat transfer area (m^2 s/kg)
t_i	feed temperature after ith preheater (°C)
t_n	feed temperature after final condenser (°C)
T_1	top brine temperature (T_{top}) (°C)
T_b	temperature of rejected brine (°C)
T_s	steam temperature (°C)
T_{vi}	temperature of the vapour phase in ith effect (°C)
T_w	temperature of the cooling water (°C)
T_{mean}	mean temperature of the system (°C)
T_m	motive steam temperature (°C)
T_{crit}	critical temperature of water (°C)
$\Delta T_{ev,i}$	driving force for heat exchange in ith evaporator (°C)
$\Delta T_{log,i}$	driving force for heat exchange in ith preheater (°C)
$\Delta T_{log,cond}$	driving force for heat exchange in final condenser (°C)
ΔT_i	temperature drop between two evaporators (°C)
Δt_i	temperature increase between two preheaters (°C)
$U_{ev,i}$	global heat exchange coefficient in ith evaporator (kW/m^2 °C)
$U_{ph,i}$	global heat exchange coefficient in ith preheater (kW/m^2 °C)

U_{cond} global heat exchange coefficient in final condenser (kW/m^2 °C)
x_i salinity in ith evaporator (ppm or w/w%)
x_b salinity in rejected brine (ppm or w/w%)
x_f salinity in the feed (ppm or w/w%)
x_{mean} mean salinity in the system (ppm or w/w%)

Greek

α fraction of rejected brine from previous effect flashed in the associated preheater (–)
β fraction of total distillate boiled in each evaporator (–)
λ latent heat of evaporation (kJ/kg)

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