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Development and Validation of a Mathematical Model For Multi-Effect Desalination with Thermal Vapor Compressor MED-TVC Desalination Plants

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Annotation

Population growth, industrialization and the resultant increase in water demand has created water shortage, which is now regarded as a global problem due to lack of water in dry regions. Freshwater constitutes only a very small fraction of all water on the Earth, and thus desalination has been a very good solution. Key operational parameters, e.g., feedwater distribution, temperature variations, brine salinity and motive steam conditions are considered by the model. The effect of these factors on the system efficiency and freshwater production was analyzed in detail. The model was proven to be effective for performance prediction by comparing its results with that of previous studies and their data, which showed a strong matching with the accuracy of model.

It is found that the feedwater distribution is optimized to increase the freshwater yield as much as possible while retaining thermal efficiency. Furthermore, the impact that pressure differences, vapor compression, and flashing mechanisms have on the overall system performance is also investigated. These results improve the understanding of how to increase desalination efficiency for both improved heat recovery as well as optimized system design. In this research, contributions are made towards ongoing attempts to develop more sustainable and energy efficient desalination systems. As a usable tool, the proposed model can be used by engineers and researchers to optimize MED-TVC operations, which may include future enhancements of the dynamic system behavior, the MEDTVC integration with renewable energy sources, and hybrid desalination approaches.

Keywords: Water treatment, desalination, MED, mathematical model.

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1. INTRODUCTION

Water is a very important element in our lives, as it is often said that water is the key to life. Water is required for drinking, cleanliness, farming crops, washing dishes, power generation, cooling,

and maintaining the ecological system. Because of these essential uses, the population is expanding [1][2], and for the past two decades, there has been a notable increase in the demand for water. Currently, 15% of the world's population does not have access to clean water, and industrialization and rising water usage have made the water problem a significant global concern in recent years. In arid regions, this problem may lead to other issues. It is important to remember that around 70% of the planet is covered by seas and oceans. Statistics show that freshwater makes up only 3% of the water on Earth, whereas saltwater makes up about 97% [3][4]. Different solutions could be found to address this critical issue, and desalination is one of them. Desalination refers to the removal of fresh water from saline water [5]. The techniques' function based on the idea of phase change, in which water is transformed into vapor and subsequently condensed back into liquid to isolate salts and contaminants. A fundamental necessity for these thermal processes is a reliable and significant heat source, often provided by the combustion of fossil fuels. While effective, this dependence on non-renewable energy sources raises environmental and economic concerns, prompting the exploration of alternative energy solutions for more sustainable desalination. [6][7]. Flash Desalination systems in some places, like the Middle East, because they are low-maintenance, have a simple shape, are easy to use, and have a high heat transfer coefficient, which means they are very thermally efficient. They do not use lot of energy for high updating process; in addition, they have higher performance rati0 [8][9]. A lot of research work has been carried out on MED-TVCs. There have been some who have investigated field investigations and others who have looked at conceptual designs. While a set of mathematical models has been developed, the majority of the research is system simulation and economic evaluation.

Ameri et al. proposed Development of a mathematical model for such a multi-effect desalination system, which would allow the use of gas turbine waste heat to produce drinkable water at a reasonable cost. The model finds the best set of parameters for the system to run by going through all the things that may have an effect on its performance. Results that were achieved are used to base the desalination plant design at Chabahar, Iran [10]. Ameri et al. (2009) made a mathematical model of a multi-effect system that was in a steady state and looked at the thermodynamic performance of the system's indices, such as the number of evaporation effects and the temperature difference between the effects. They did this while controlling the boiler pressure and the temperature of the feed water. [11].

Shakib et al. The model seeks to replicate the kinetic and thermodynamic interactions between the components of desalination and power generation thereby facilitating comprehensive performance analysis and optimization. The paper also integrated power systems and water desalination systems and calculated the feasibility of such a combined system through thermoeconomic evaluation. [12].

A steady state mathematical model to describe shedually the performace of MEDTVQ disalination plant has been provided by Al-Mutaz and Wazeer. Using MATLAB, this mathematical model was developed and solved and was compared with commercial plant data. The design variables are then analyzed in the combined system in terms of efficiency and freshwater production rates as an analysis tool. [13].

Analysis tool is used to analyze the design variables in the combined system in terms of efficiency and freshwater production rates. Thermal, mechanical and heat pumps (adsorption and absorption) belong to vapor-compression systems. [14].

Mazini et al. proposed The model is exemplified by a particular plant situated in Kish Island, Iran, and its validation confirmed that the model can accurately represent the plant across several operational modes. Consequently, the model will be important in identifying optimal design of the MED plant and in designing suitable control of it [15].

Zhou et al presented The model also explains the performance of existing plants and it is also shown that the overall lower exergy destruction and energy consumption is achieved than the conventional MED systems.. [16].

Kouhikamali and Sharifi only focused on the role of MED and studied operating performance in case of constant area zone. They compared the thermocompression of the original design with the same operating conditions analyzed with both numerical simulations and experimental tests, modifying the throat diameter of the thermocompression. They found that the entire efficiency of the modified thermocompression improved [17].

Harandi et al. present a mathematical model of the performance of an integrated system using the waste heat in a gas power plant as source of energy for generation of fresh water from a med tvc unit. Then a response surface model was simulated for maximization of GOR of fresh water and minimization of cost concurrently with NSGA-II algorithm. The high and reasonable efficiency and cost was concluded in comparison. [18].

With the math model that developed in this study, steady state operating conditions, all of the essential elements of the design process of a MED-TVC system were included. This model was evaluated against results of previous research with commercial plants for its validity.

2. PROCESS DESCRIPTION

A representative configuration of a conventional seawater desalination process using a Multi effect Distillation with Thermal Vapor Compression (MED TVC) system is shown in Figure 1. This system is composed mainly of n multiple evaporation effects, a thermal vapor compressor, and a condenser. These units perform together so that freshwater is made via evaporation and condensation of seawater using thermal energy. In MED systems, the feedwater, the brine, or the heating steam exhibit an important role in governing the whole efficiency and the corresponding operation characteristics. In this arrangement, the incoming feedwater is divided into a number of parallel streams, each one can be separately led to the corresponding evaporation effects. Moving on the same axis the brine and vapor streams minimize the possibility to have non-uniform temperature gradients through the effects and makes the thermal control easier. The availability of the water side and the air side pumps makes this configuration amenable to operational flexibility and makes it well suited for integration with variable heat source such as waste heat or renewable energy inputs. [19].

According to Figure 1, the heat emitted by the vapours generated in the final action is absorbed by the seawater feed exiting the condenser at temperature TF. One segment of the feedwater (F) is uniformly distributed among the effects, while the remainder is discharged into the sea as coolant. The cooling water is essential for dissipating the excess heat created by the steam produced in the final effect. The supplied saltwater was sprayed perpendicularly, and the resultant vapor was moving towards areas of lower pressure, often from left to right.[20]

In each effect a wire mesh demister, also called mist separator, is used to catch and eliminate entrained brine droplets. The condensate from first effect is partly recirculated and the remainder is sent to first flashing box. To enable the utilization of brine B1 in the next effect, the brine is transferred through the effects in order to enhance energy recovery. This goes on from one effect to another with lower and lower pressured effects until you get to the last effect.[21]. The two mechanism of vapor generation is through boiling on the surface of the heat transfer tubes and flashing in the liquid mass in effects 2 through n. Furthermore, condensation starts to take place in the second effect and a minute amount of vapor is produced all the way down to the last effect about which flashing occurs in the flashing boxes. One of these flashing boxes is to recover heat from the condensed fresh water [22]. One portion (Mev) is fed to the thermal vapor compressor, and entrained and compressed, as does the remainder to the condenser. Preheating of the incoming

feed saltwater in the condenser by exchanging heat with the condensing vapor where the temperature is increased from Tcw to TF improves the overall system performance.. [23][13].

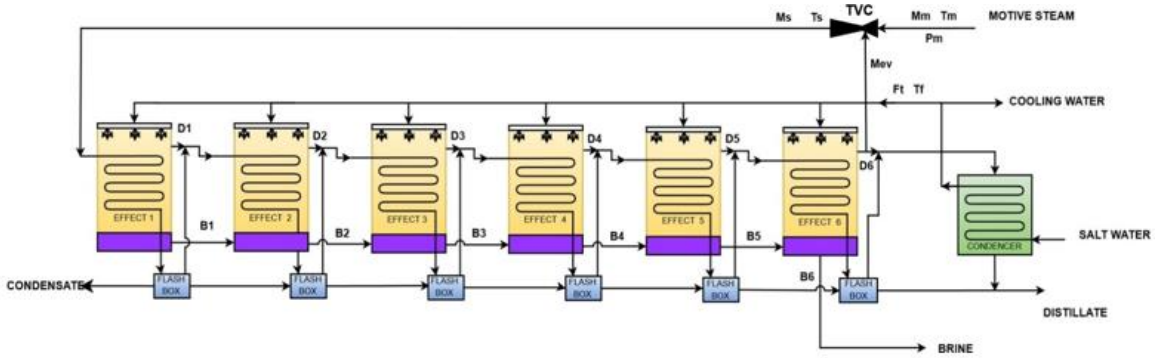

Figure 1. MED-TVC system with six effects

3- METHEODOLOGY

3-1 Assumptions

Mass and energy balance equations were used with the following assumptions to simplify the mathematical calculations and guarantee a correct and effective simulation of the desalination system:

1. The temperature difference was equal for each effect.
2. The distillate was considered salt-free, meaning that the salt concentration in the product (X_D) was zero.
3. The system operates under steady-state conditions.
4. heat capacity of the feed was the same as that of brine and distillate.
5. The feed flow rates were identical for each effect.
6. The boiling point elevation (BPE) was assumed equal across all effects.
7. Negligible thermodynamic losses.

Therefore, we establish some of the simplifying assumptions in order to do some convenient calculations and having a reliable mathematical representation of the desalination system performance

3-2 Mathematical Model

The mathematical model relies on material and energy balances for each component of the system, encompassing the effects, condenser, and thermal vapor compressor (TVC). It utilizes input parameters including top brine temperature, temperatures of the initial and final effects, feedwater flow rate, cooling and feed seawater temperatures, seawater salinity, motive steam flow rate and pressure, as well as the total number of effects. These parameters facilitate the simulation and analysis of the system's performance in a clear and organized manner.

The difference in temperature for each effect was assumed to be equal in this model and was calculated as follows:

$$\Delta T = \frac{(T_1 - T_N)}{(N-1)} \qquad (1)$$

The temperature of the steam from the TVC (T_s) can be calculated as

$$T_S = T_1 + \Delta T \qquad (2)$$

temperature for the effects, calculated as

$$T_{i+1} = T_i - \Delta T \qquad i=2,\ldots,N \qquad (3)$$

The boiling point elevation of BPE is the difference in the boiling point of water at any pressure and the difference because of the amount of dissolved salts in water. The BPE is assumed to be constant for all effects and eq. (4) can determined it [15]:

$$BPE = X_b\left(A + BX_b + CX_b^2\right) \qquad (4)$$

Where:

$$A = \left(8.3251\times10^{-2} + 1.8832\times10^{-4}\,T + 4.021\times10^{-6}\,T^2\right)$$

$$B = \left(-7.6251\times10^{-4} + 9.0201\times10^{-5}\,T - 5.221\times10^{-7}\,T^2\right)$$

$$C = \left(1.5222\times10^{-4} - 3.1\times10^{-6}\,T - 3.1\times10^{-8}\,T^2\right)$$

where T: water temperature in °C and X_b is the salinity of water

The vapor temperature for each effect can be determined as:

$$T_{vi} = T_i - BPE \qquad (5)$$

Salt and water mass balance can be represented as:

$$B_1 = F - D_1 \qquad (6)$$

$$B_i = F + B_{i-1} - D_i \qquad i=2,\ldots,N \qquad (7)$$

$$X_1 = \frac{F}{B_1} X_f \qquad (8)$$

$$X_i = \frac{F}{B_i} X_f + \frac{B_{i-1}}{B_i} X_{i-1} \qquad i=2,\ldots,N \qquad (9)$$

The specific heat capacity of water Cp can be determined by [13]

$$C_P = [a + bT_i + c\,T_i^2 + d\,T_i^3]\times10^{-3} \qquad (10)$$

where:

$$a = \left(4206.790 - 6.61997\,S + 1.22888\times10^{-2}\,S^2\right)$$

$$b = \left(-1.126 + 5.41780\times10^{-2}\,S - 2.272\times10^{-4}\,S^2\right)$$

$$c = \left(1.20261\times10^{-2} - 5.356\times10^{-4}\,S + 1.89059\times10^{-6}\,S^2\right)$$

$$d = \left(6.877\times10^{-7} + 1.5170\times10^{-6}\,S - 4.42681\times10^{-9}\,S^2\right)$$

Where :S is the water salinity in g/kg

For the first effect, the energy balance is:

$$D_1 = \frac{M_s\lambda_s - F\,C_P\,(T_1 - T_f)}{\lambda_1} \qquad (11)$$

where D is the mass flow rate of generated vapor, M_s is the mass flow rate of the ejector outlet stream, and T_f is the temperature of the feedwater, which can be calculated by:

$$T_f = T_N + \Delta T_{cond} \quad (12)$$

In the second effect:

$$D_2 = \frac{D_1 \lambda_1 - F\, C_P (T_2 - T_f) + B_1\, C_P (T_1 - T_2)}{\lambda_2} \quad (13)$$

From effect 3 to effect N, vapor generation occurred from two primary sources. First, the feedwater sprayed onto the evaporator tubes absorbed heat, resulting in partial evaporation. Second, some of the distillate flashed in the flash boxes, which helped to increase the flow of vapour. Thus, for effects 3 through N, the total vapour mass flow rate is calculated by

$$D_i = \frac{(D_{i-1}\lambda_{i-1} + D`_{i-1}\lambda`_{i-1}) - F\, C_P (T_2 - T_f) + B_1\, C_P (T_1 - T_2)}{\lambda_i} \quad (14)$$

The vapor in the flash box mass flow rate (D`) after each effect can be determined by

$$D`_i = \frac{D_{i-1}\, C_P (T_{vi-1} - T`_i)}{\lambda`_i} \quad (15)$$

The flash boxes temperature $T`_i$ after each effect is :

$$T`_i = T_{vi} + NEA_i \qquad i=2,\ldots,N \quad (16)$$

where NEA is the nonequilibrium allowance of the flash boxes, which describes the efficiency of the process in the flash box and is given by [24]:

$$NEA_i = \frac{0.33(T_{vi-1} - T_{vi})}{T_{vi}} \qquad i=2,\ldots,N \quad (17)$$

The total amount of distillate from all effects (D_t) can be expressed as:

$$D_t = D_1 + D_2 + \ldots + D_N = \sum_{i=1}^{N} D_t \qquad i=1,2,\ldots,N \quad (18)$$

The steam ejector performance is mainly defined by two key parameters: compression ratio and expansion ratio. These ratios were determined using the following equations:

$$C_r = \frac{P_s}{P_{ev}} \quad (19)$$

$$E_r = \frac{P_m}{P_{ev}} \quad (20)$$

The method to get the entrainment ratio, Additionally, composite processes are required for that measure. If the entrained fluid is water vapour and the motive stream is known as steam, the empirical model can also be applied: [14]

$$R_a = 0.235 \frac{P_s^{1.19}}{P_{ev}^{1.04}} E_r^{0.015} \quad (21)$$

The entrained steam mass flow rate (M_{ev}) can be calculated as [25]

$$M_{ev} = \frac{M_m}{R_a} \quad (22)$$

It is simple to get the ejector outlet stream flow rate (M_s) by:

$$M_s = M_m + M_{ev} \quad (23)$$

The jet ejector (Mev) entrains a portion of the vapor generated in the final effect (DN), while the remaining portion enters the condenser directly. The vapor from the final effect heats the seawater inside the condenser until the feed seawater's temperature exceeds Tf. Incoming seawater is

mostly released as cooling water, which condenses the vapor created by the final action. The following formula was used to calculate the cooling water mass flow rate:

$$M_{cw} = \frac{(D_N + D_N - M_{ev})\lambda_s}{C_p (T_f - T_{cw})} - M_f \qquad (24)$$

where M_f is the total flow rate of the supplied water. The GOR offers a valuable indication of the effectiveness of the system in producing freshwater relative to energy input. This parameter was calculated as follows:

$$GOR = \frac{D_t}{M_m} \qquad (25)$$

4-RESULTS AND DISSCUSION

4-1 Model Validation

To validate this model must compare the model with actual data from previous research, Al-Mutaz and colleagues create a mathematical model and contrast its output with empirical data.in this work will compare with their results in 3 actual plants: UM ALNAR, Rabigh and Al-Taweelah , that's plants consist of 6 effect , Tables (1,2 and 3) present the comparison and error percentage and show a great agreement between the model and actual data .[13]

Parameter		Actual	Model	Error%
First effect temperature, °C	T_1	61.8	62.05	0.39754
Last effect temperature, °C	T_N	42.8	42.8	0
Temperature difference per effect, °C	ΔT	3.74	3.85	2.84028
Entrainment ratio	Ra	1.36	1.379487	1.4126
Expansion ratio	ER	299.7	292.3703	-2.50699
Compression ratio	CR	3.12	3.15	0.95238
Distill water production, kg/s	D_T	183.2	186.0107	1.51106
Gain output ratio	GOR	8.64	8.774091	1.52827

Table 2. Comparison of MED-TVC Mathematical model against Rabigh plant data

Parameter		Actual	Model	Error%
First effect temperature, °C	T_1	70	70.75	1.05495
Last effect temperature, °C	T_N	49.4	49.4	0
Temperature difference per effect, °C	ΔT	4.1	4.27	3.96481
Entrainment ratio	Ra	1.47	1.478181	0.55345
Expansion ratio	ER	151.4	147.7462	-2.47299
Compression ratio	CR	3.22	3.22	0
Distill water production, kg/s	D_T	56.6	56.97785	0.66315
Gain output ratio	GOR	8.01	8.070517	0.74985

Table 3. Comparison of MED-TVC Mathematical model against Al-Taweelah plant data

Parameter		Actual	Model	Error%
First effect temperature, °C	T_1	63	63.76	1.1964214
Last effect temperature, °C	T_N	44	44	0
Temperature difference per effect, °C	ΔT	3.8	3.95	3.8601303

Entrainment ratio	*Ra*	0.72	0.696968	-3.3046477
Expansion ratio	*ER*	17.8	18.09955	1.655
Compression ratio	*CR*	1.75	1.722222	-1.6129032
Distill water production, kg/s	D_T	192.5	198.8776	3.2068192
Gain output ratio	*GOR*	7.83	8.084457	3.1474862

Another validation for this model with (Ahmedi) model which give in details the parameters in each effect such as distillate flow rate, brine flow rate, temperature and salinity in each effect, and also show great agreement, Figure2 show the comparison between this model and Ahmedi model[5]

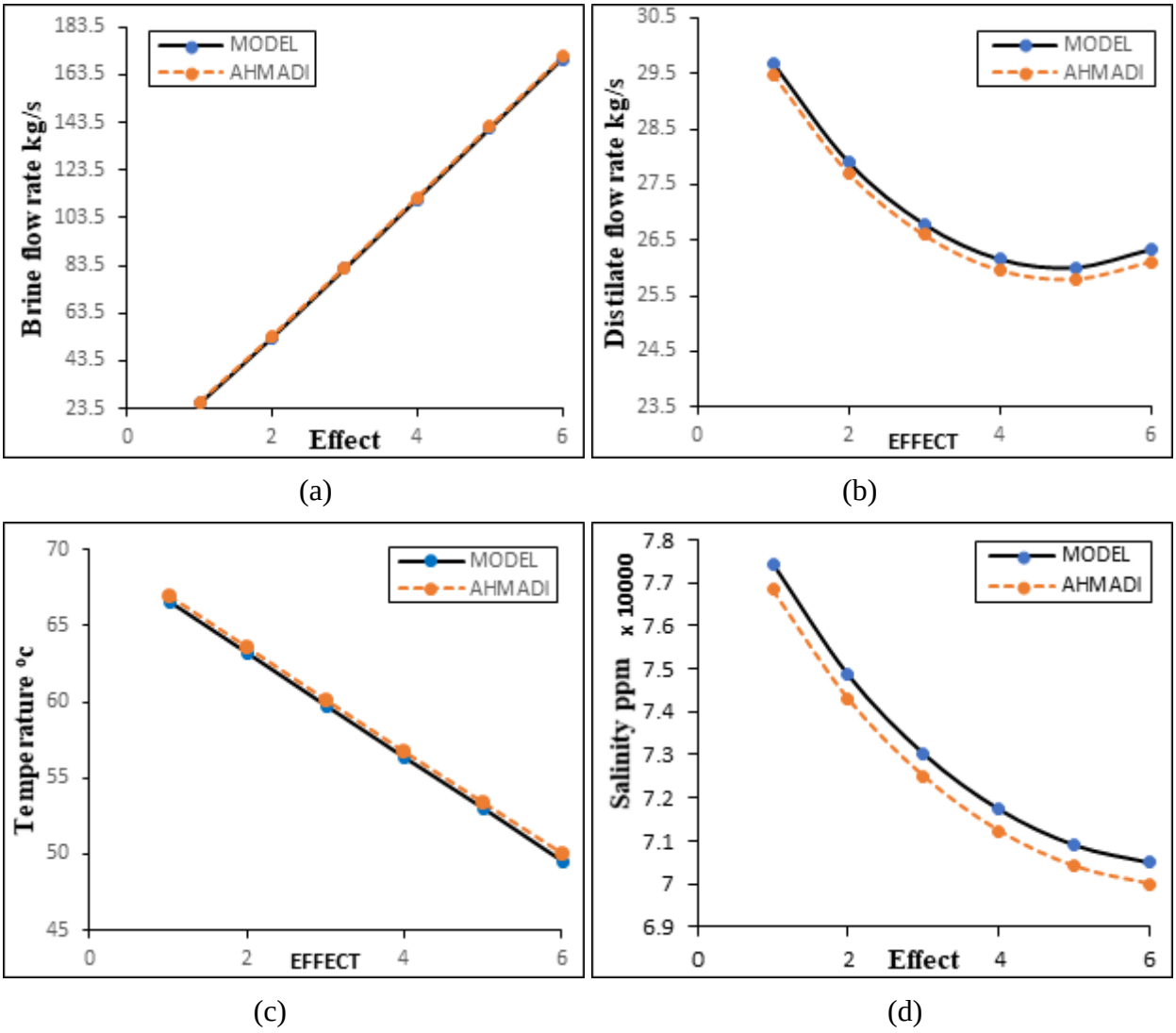

Figure 2. Comparison between this model and Ahmedi model: (a) brine flow rate, (b) distillate flow rate, (c) temperature, (d) salinity

4-2 Feed Flow Rate

In the MED-TVC system, the total seawater intake was divided into two streams: one portion continued to the evaporators after passing through the condenser, while the other was returned to the seawater source called cooling water M_{cw}. The portion that returns to the source is used solely for condensing the vapor produced in the final effect, ensuring efficient heat recovery, and maintaining system stability.

Within the evaporation system, the feedwater was evenly distributed across all evaporators, meaning that each effect received an equal amount of feedwater. The feed flow rate influences several key operational parameters, including the quantity of distilled water produced, brine discharge rate, and salinity concentration in each evaporator.

To analyze these effects, a detailed study was conducted to examine how variations in the feedwater supply to each evaporator affect the system performance. This study focuses on the relationship between the feedwater flow rate, distillate production, brine discharge, and salinity levels at each stage of the evaporation process. Figure 3 illustrates these interactions and provides insights into system behavior under different operating conditions.

Additionally, a case study employing particular input data for the mathematical model is carried out. Table.4 presents the parameters utilized in the analysis, which serve as a foundation for assessing the system's performance and confirming the model's predictions.

Table 4. Input data for case study

Parameter			value
No.of evaporator	---	N	6
steam out of ejector flow	Kg/s	M_s	21.38
steam out of ejector temp	C	T_s	64.7
temp difference between evaporator	C	ΔT	2.45
temp difference in condenser	C	ΔT_{cond}	5
feed salinity	PPM	X_F	36000
motive steam pressure	kpa	P_m	780
compression ratio	---	cr	2
last evaporator temp	C	T_n	50

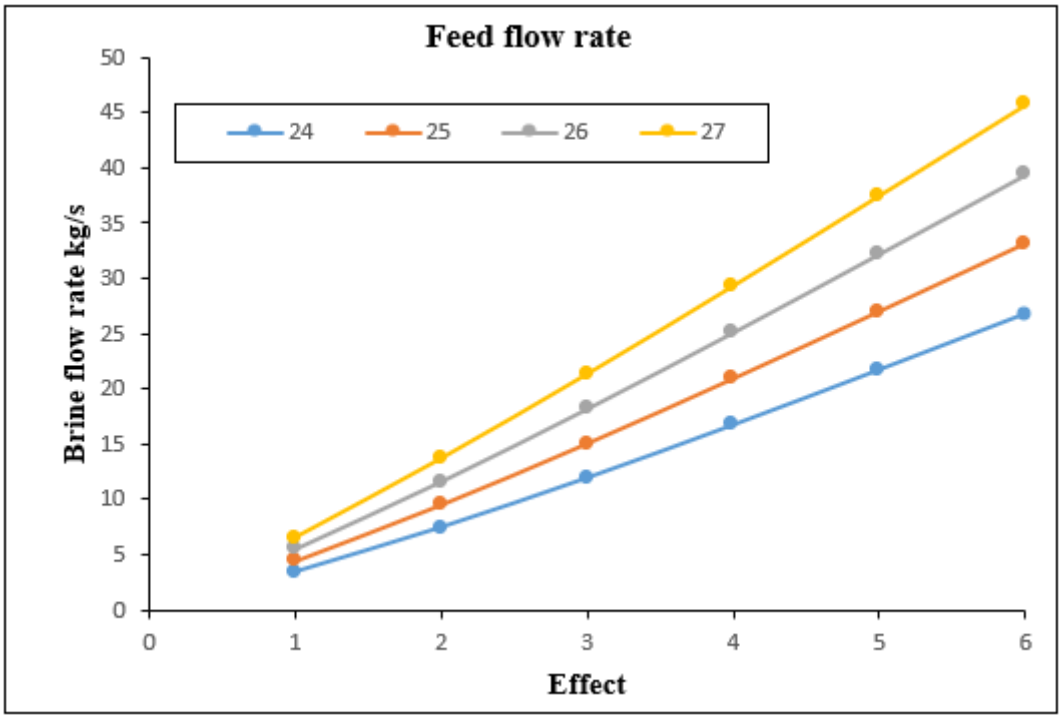

Figure 3 (a) shows that reducing the feedwater flow rate decreases the brine quantity because a greater portion of the feedwater evaporates, resulting in less remaining brine.

Figure 3 (b) shows that as the feedwater flow rate decreased, the distillate yield increased because the available heat was sufficient to evaporate a greater proportion of the feedwater.

Figure 3 (c) shows that the feedwater flow rate reduces brine salinity because the feedwater has a lower salinity than the brine, thereby reducing the overall brine salinity.

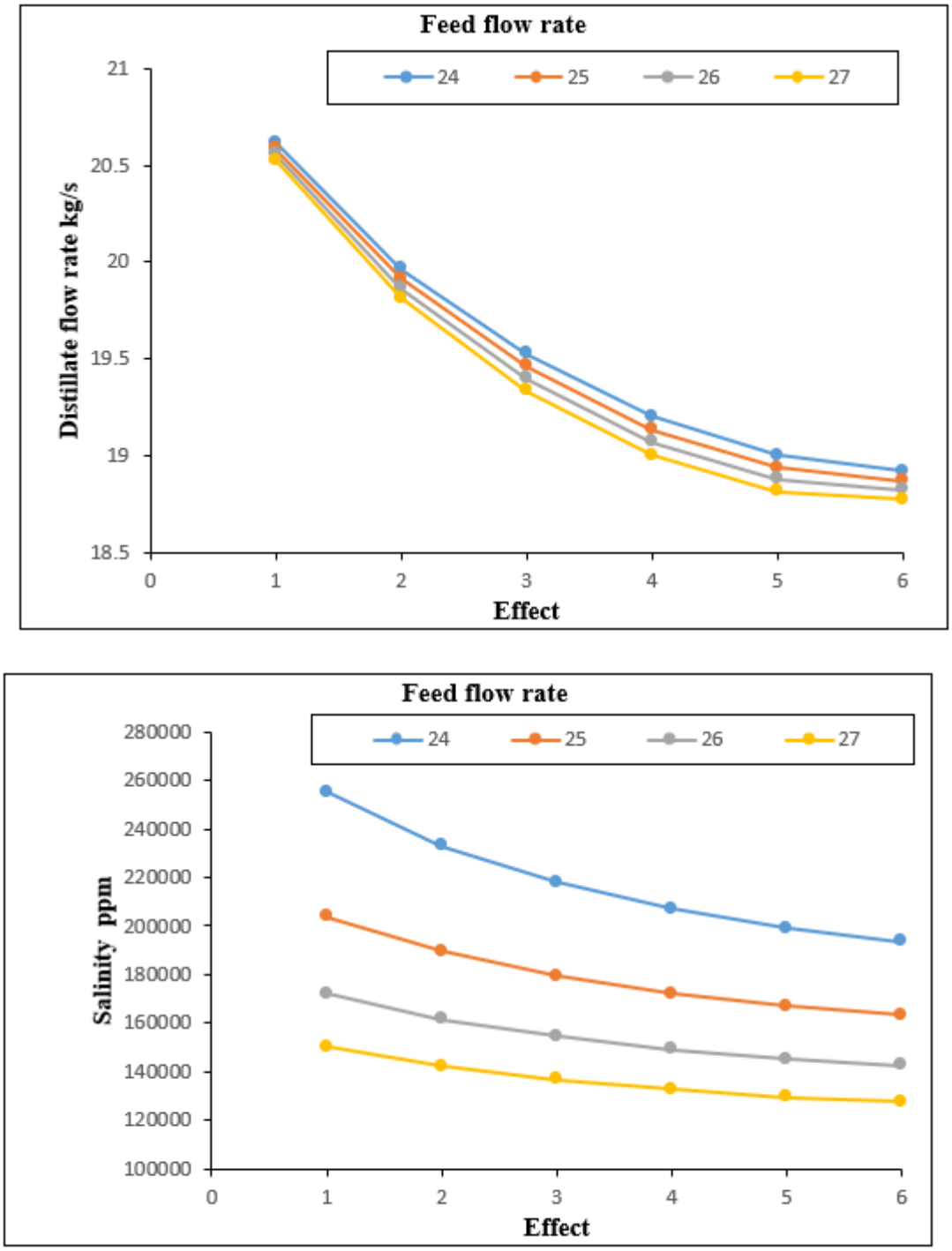

Figure 3. effect of feed flow rate on: (a) brine flow rate, (b) distillate flow rate, (c) salinity

The feedwater flow rate and GOR have an inverse relationship, as seen in Figure 4. The GOR decreases as the feedwater flow rate increases. Higher flow rates limit distillate production efficiency, which lowers yield and, in turn, lowers the total gain output ratio.

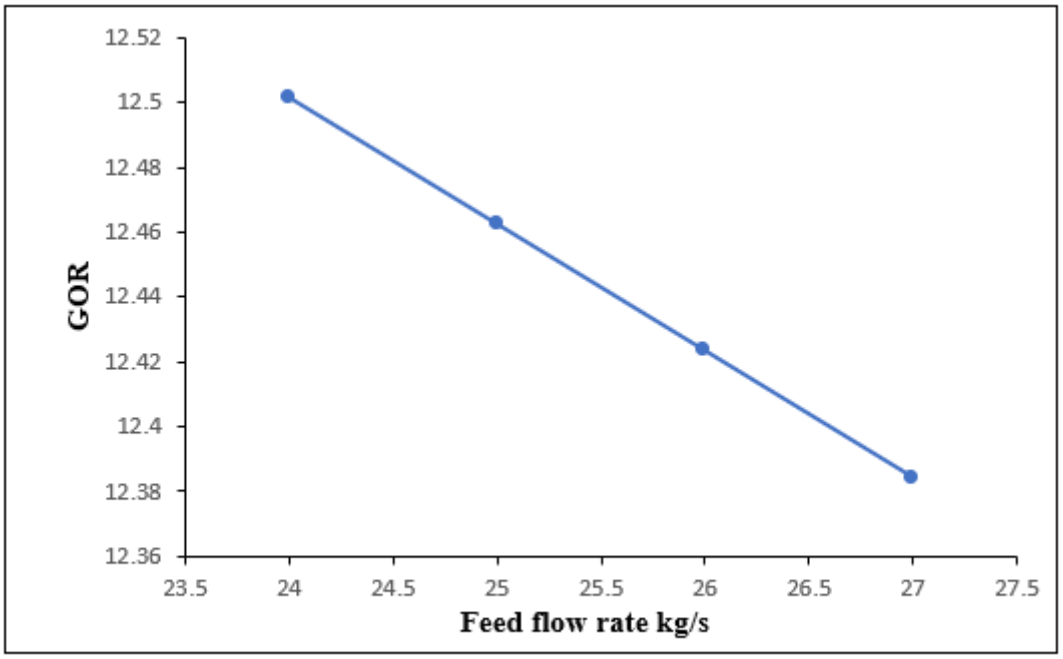

Figure 4. relationship between feedwater flow rate and GOR

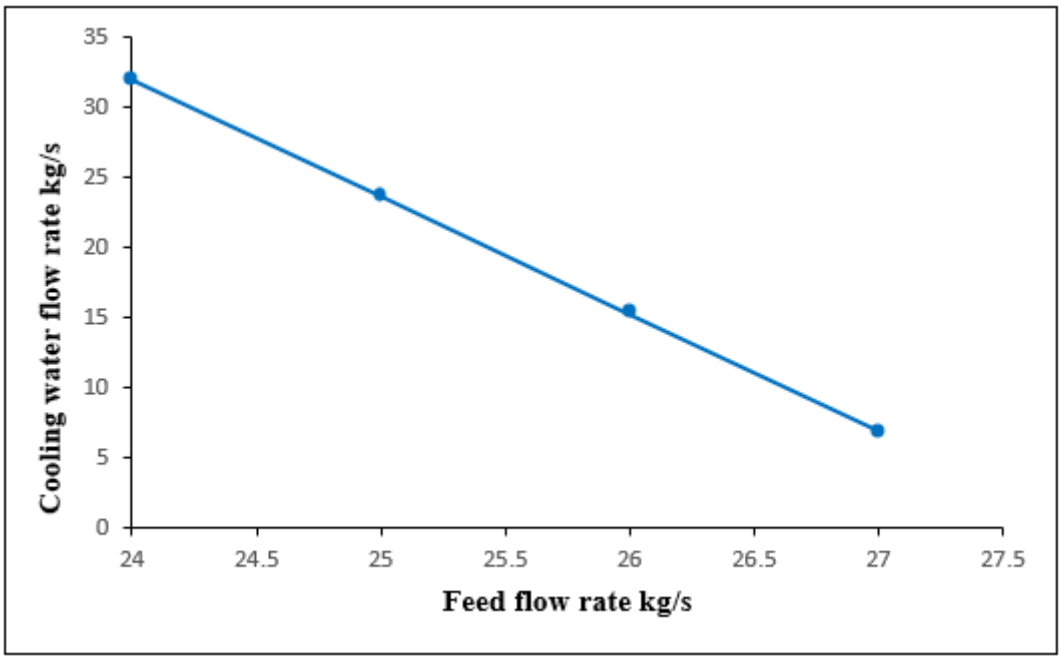

Figure 5. relationship between feedwater flow rate and cooling water flow

Figure 5 show the relationship between the feedwater and cooling water flow rates. The cooling-water flow rate decreased as the feedwater flow rate increased. Higher distillate production from reduced feed water flow rates requires increased cooling water to condense the generated steam.

5-CONCLUSION

In this work, Key design factors like temperature gradients, feedwater distribution, brine salinity, vapor compression were included into the model for a comprehensive knowledge of system behavior. Strong agreement for validation of its dependability for performance evaluation was found when the model predictions were tested against data from past research projects.

This study demonstrates that feedwater distribution has a very important effect on the total desalination process efficiency. We observed that the quantity of feed water fed to each evaporator is directly connected to the amount of distilled water produced, the brine discharge rate and salinity in the system. The properly optimized feedwater flow allows to better utilize the energy, increase freshwater production, and stabilize the system. In addition, key operational parameters, for example, motive steam pressure, compression ratio and temperature drop across the effects, were evaluated with regards to their impact on thermal efficiency.

The study also demonstrated the importance of flashing mechanisms and heat recovery strategies on the system performance. Efficiently controlling the heat exchange processes inside the condenser and flashing boxes will lead to the system reaching the maximum energy recovery in the minimum thermal losses. We found that increasing feedwater flow can lower brine salinity, but above a given threshold, the GOR of the system becomes less as a result and we show that it is necessary to balance feedwater and energy input for efficient performance.

It is demonstrated that the developed mathematical model can assist in evaluation and optimization of MED-TVC desalination systems. Thus, engineers and researchers can deploy this as a reliable way to gauge the design and operational parameters effects, resulting in more efficient and economical desalination plant designs. Additional To further increase energy efficiency and freshwater output, future study might look at hybrid desalination configurations, integrate variable waste heat sources, and extend the model to dynamic operating situations.

REFERENCES

1. M. Kareem Salim, H. S. Sultan, and F. A. Abood, “Performance Evaluation of Single Stage Flash Evaporation Desalination Unit Integrated with a Parabolic Trough Solar Collector for Basrah City Climate, Iraq,” *Basrah journal for engineering science*, vol. 24, no. 1, pp. 97–108, Feb. 2024, doi: 10.33971/bjes.24.1.11.
2. R. Chacartegui, D. Sánchez, N. di Gregorio, F. J. Jiménez-Espadafor, A. Muñoz, and T. Sánchez, “Feasibility analysis of a MED desalination plant in a combined cycle based cogeneration facility,” *Appl Therm Eng*, vol. 29, no. 2–3, pp. 412–417, Feb. 2009, doi: 10.1016/j.applthermaleng.2008.03.013.
3. P. Ahmadi, S. Khanmohammadi, F. Musharavati, and M. Afrand, “Development, evaluation, and multi-objective optimization of a multi-effect desalination unit integrated with a gas turbine plant,” *Appl Therm Eng*, vol. 176, Jul. 2020, doi: 10.1016/j.applthermaleng.2020.115414.
4. I. Tlili, M. Osman, I. Alarifi, H. Belmabrouk, A. Shafee, and Z. Li, “Performance enhancement of a multi-effect desalination plant: A thermodynamic investigation,” *Physica A: Statistical Mechanics and its Applications*, vol. 535, Dec. 2019, doi: 10.1016/j.physa.2019.122535.
5. F. E. Ahmed, R. Hashaikeh, A. Diabat, and N. Hilal, “Mathematical and optimization modelling in desalination: State-of-the-art and future direction,” Nov. 01, 2019, *Elsevier B.V.* doi: 10.1016/j.desal.2019.114092.
6. V. G. Gude, “Energy and water autarky of wastewater treatment and power generation systems,” *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 52–68, May 2015, doi: 10.1016/j.rser.2015.01.055.
7. Mohamad N. Fares, Saleh E. Najim, and Mustafa M. Riza, “Design and Evaluation of a New Desalination System Using Heat Pump,” *Int J Adv Res (Indore)*, vol. 4, no. 3, pp. 1777–1785, 2016.

8. Saeed Daneshmand, Ali Mortaji, and Z. Mortaji, “Investigation and Design Seawater Desalination with Solar Energy,” *Life Sci J*, vol. 9, no. 3, pp. 770–773, 2012.
9. N. M. Al-Najem, M. A. Darwish, and F. A. Youssef, “Thermovapor compression desalters: energy and availability — Analysis of single- and multi-effect systems,” *Desalination*, vol. 110, no. 3, pp. 223–238, Sep. 1997, doi: 10.1016/S0011-9164(97)00101-X.
10. M. Ameri and S. R. Shamshirgaran, “Modeling of Multi-Effect Desalination to Produce Potable Water Using Gas Turbine Flue Gas,” 2008. [Online]. Available: https://www.researchgate.net/publication/268518669
11. M. Ameri, S. Seif Mohammadi, M. Hosseini, and M. Seifi, “Effect of design parameters on multi-effect desalination system specifications,” *Desalination*, vol. 245, pp. 266–283, 2009, doi: 10.1016/j.desal.200.
12. S. E. Shakib, M. Amidpour, and C. Aghanajafi, “Simulation and optimization of multi effect desalination coupled to a gas turbine plant with HRSG consideration,” *Desalination*, vol. 285, pp. 366–376, Jan. 2012, doi: 10.1016/j.desal.2011.10.028.
13. I. S. Al-Mutaz and I. Wazeer, “Development of a steady-state mathematical model for MEE-TVC desalination plants,” *Desalination*, vol. 351, pp. 9–18, Oct. 2014, doi: 10.1016/j.desal.2014.07.018.
14. H. M. Ettouney and H. El-Dessouky, “A simulator for thermal desalination processes,” *Desalination*, vol. 125, no. 1–3, pp. 277–291, Nov. 1999, doi: 10.1016/S0011-9164(99)00148-4.
15. M. T. Mazini, A. Yazdizadeh, and M. H. Ramezani, “Dynamic modeling of multi-effect desalination with thermal vapor compressor plant,” *Desalination*, vol. 353, pp. 98–108, 2014, doi: 10.1016/j.desal.2014.09.014.
16. S. Zhou, L. Gong, X. Liu, and S. Shen, “Mathematical modeling and performance analysis for multi-effect evaporation/multi-effect evaporation with thermal vapor compression desalination system,” *Appl Therm Eng*, vol. 159, Aug. 2019, doi: 10.1016/j.applthermaleng.2019.113759.
17. R. Kouhikamali and N. Sharifi, “Experience of modification of thermo-compressors in multiple effects desalination plants in Assaluyeh in IRAN,” *Appl Therm Eng*, vol. 40, pp. 174–180, Jul. 2012, doi: 10.1016/j.applthermaleng.2012.02.002.
18. H. B. Harandi, A. Asadi, M. Rahnama, Z. G. Shen, and P. C. Sui, “Modeling and multi-objective optimization of integrated MED–TVC desalination system and gas power plant for waste heat harvesting,” *Comput Chem Eng*, vol. 149, Jun. 2021, doi: 10.1016/j.compchemeng.2021.107294.
19. H. Vazini Modabber and M. H. Khoshgoftar Manesh, “4E analysis of power and water cogeneration plant based on integrated MEDTVC and RO desalination units,” *International Journal of Thermodynamics*, vol. 23, no. 2, pp. 107–126, 2020, doi: 10.5541/ijot.616899.
20. I. H. Yilmaz and M. S. Söylemez, “Design and computer simulation on multi-effect evaporation seawater desalination system using hybrid renewable energy sources in Turkey,” *Desalination*, vol. 291, pp. 23–40, Apr. 2012, doi: 10.1016/j.desal.2012.01.022.
21. P. Palenzuela, A. S. Hassan, G. Zaragoza, and D. C. Alarcón-Padilla, “Steady state model for multi-effect distillation case study: Plataforma Solar de Almería MED pilot plant,” *Desalination*, vol. 337, no. 1, pp. 31–42, Mar. 2014, doi: 10.1016/j.desal.2013.12.029.
22. K. M. Bataineh, “Multi-effect desalination plant combined with thermal compressor driven by steam generated by solar energy,” *Desalination*, vol. 385, pp. 39–52, May 2016, doi: 10.1016/j.desal.2016.02.011.

23. H. T. El-Dessouky and H. M. Ettouney, *Fundamentals of Salt Water Desalination*. Amsterdam: Elsevier, 2002.

24. O. Miyatake, K. Murakami, and F. Y. Kawata, “Fundamental experiments with flash evaporation,” *Heat Transf. Jpn. Res*, vol. 2, pp. 89–100, 1973.

25. C. Wen, H. Ding, and Y. Yang, “Performance of steam ejector with nonequilibrium condensation for multi-effect distillation with thermal vapour compression (MED-TVC) seawater desalination system,” *Desalination*, vol. 489, p. 114531, Sep. 2020, doi: 10.1016/j.desal.2020.114531.