

Simulation and Parametric Study of a Multiple Effect Distillation with Thermal Vapour Compression

Irnie Azlin Zakaria¹, Siti Mariam Abdul Rahman^{1*}, Edilson Marqueles Chong¹

¹ School of Mechanical Engineering, College of Engineering,
Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA

*Corresponding Author: mariam4528@uitm.edu.my
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Abstract

Desalination plants are widely used in industrial applications, such as oil and gas, food and beverage, and power generation industries, to produce clean water for internal use. This gives industries greater control over their water security. The project aims to simulate the mathematical model for a Multiple Effect Distillation with Thermal Vapour Compression (MED-TVC) with constraints, incorporating mass and energy balances and the seawater's thermodynamic properties. The model was simulated using MATLAB to compare the production rate of clean water and gain output ratio (GOR) with different configurations of the desalination system. Input factors considered in the simulation include seawater to evaporator feed flow rate, seawater intake flow rate, seawater salinity, and seawater temperature. The simulation was validated by comparing it with available data of MED-TVC plants from SIDEM with 98.85% accuracy. Results show that the variation in temperature of each evaporator (increment and reduction from -30% to +50% of initial temperature) influences clean water production. Based on the simulation, the vapour output increases as the evaporator's temperature rises, thus increasing the GOR and total distillate production. These findings highlight the critical role of evaporator temperature in optimizing MED-TVC system performance, providing valuable insights for improving industrial desalination processes.

1. Introduction

As the population and industrial developments grow, the need for clean water resources is surging. Mahadi et al. highlighted the awareness of the importance of desalination and the hazardous effect of brine disposal on the Malaysian ecosystem [1]. Consequently, there is an increasing need for desalination methods that are both sustainable and efficient.

Desalination is a method that separates minerals from water to be used for industrial and human applications [2]. According to a recent journal, industrial processes are the primary consumers of water [3], and by 2030, the demand for it is expected to surpass the current supply by 40% [4]. Baharin & Mohamad [5] also explored renewable energy usage in the desalination process using passive solar energy. One of the solutions to address this water scarcity is integrating a desalination unit into industrial plants, such as a methanol plant. The desalination unit also helps industry by having its water source without being dependent on other sources, which have a risk of interfering with a company's operation when any disruption occurs to the water source. For example, in 2022, Labuan, Malaysia, faced a water supply shortage due to a leakage in the state's main pumping

pipe [6]. This incident disrupted several plants' operations, including PETRONAS Chemicals Methanol Sdn. Bhd. (PCMSB). This situation shows the critical need for a desalination system.

Desalination is a method of separating minerals from water sources such as brackish water, wastewater and seawater. This process is increasingly adopted to produce clean water for human consumption and industrial application [7]. Desalination can be classified into two major categories: non-thermal, also known as membrane, and thermal [8–9]. Within these two categories, different techniques are used to produce clean water. Non-thermal and thermal desalination uses various sources of energy; thermal desalination examples include multi-effect distillation, direct solar distillation, and multiple-flash distillation [10], typically consume heat, while non-thermal desalination such as reverse osmosis, forward osmosis and ionic exchange [11] uses electrical work [12]. When designing modern water desalination plants, the capital and operational costs are the key factors that make thermal-based desalination more appealing than membrane-based desalination [13].

Among the various desalination methods, this research focuses on the Multi-Effect Distillation with Thermal Vapour Compression (MED-TVC) system, as it is more practical and commonly used in industries. Multiple Effect Distillation (MED) stands out due to its high efficiency in energy utilisation and operational effectiveness. MED leverages the principle of utilising vapour from one effect to heat the subsequent effect, thereby minimising the overall energy consumption. This method is particularly advantageous in large-scale desalination and wastewater treatment facilities where energy efficiency is crucial. Thermo Vapour Compression (TVC), a technique that uses mechanical or thermal energy to compress and reuse vapour within the distillation process, offers substantial improvements in energy efficiency. By compressing the vapour generated during the distillation process, TVC systems significantly reduce the thermal energy required for vaporization, lowering operational costs and improving the overall system sustainability.

Numerous research studies have focused on the Multi-Effect Distillation with Thermal Vapor Compression (MED-TVC) system, aiming to optimise its performance, energy efficiency, and economic viability. In 2018, Elsayed et al. [14] focused on identifying optimal operating conditions for MED-TVC systems. The study emphasised that fine-tuning operational parameters could lead to substantial energy savings and cost reductions. This work highlighted the importance of exergy analysis for understanding energy flows and inefficiencies within desalination systems, guiding more sustainable and cost-effective operational strategies.

In 2023, Omid Pilevar et al. [15] developed a dynamic model to assess the performance of MED-TVC systems under various operational conditions, including start-up and steady-state operations, and the impact of ejector malfunctions. The research found that reductions in motive pressure could severely disrupt thermo-compressor performance, leading to a 33% decrease in the Gain Output Ratio (GOR). Additionally, a 10% reduction in motive flow rate or motive vapour pressure could cause significant increases in the saltwater level in the first effect, potentially leading to operational issues such as flooding. This study underscored the importance of maintaining stable operational parameters to ensure efficient and reliable system performance.

Research by Mahdi Abdi-Khanghah et al. [16] focused on developing a comprehensive mathematical model for designing and optimising MED-TVC systems. The model accounted for various factors, including mass and energy balances, thermodynamic equations, and the effects of flashing boxes and pressure losses. This research provided a detailed framework for optimising MED-TVC systems to enhance performance and economic efficiency. The findings highlight the complexity of these systems and the need for thorough, multi-faceted approaches to their design and operation.

These studies collectively provide a deep understanding of the factors influencing the performance of MED-TVC systems, from component-specific optimisations to system-wide design strategies. The research highlights the critical role of precise engineering and operational control in maximising the efficiency and cost-effectiveness of these systems, making significant contributions to the field of desalination technology. In contrast to the previous studies, this study aims to simulate the MED-TVC system using a mathematical model implemented into MATLAB and to determine the impact of altering the evaporators' temperature on the MED-TVC system's performance. Effective simulation of these integrated systems is essential for understanding their behaviour under various operational conditions and designing systems delivering economic and environmental benefits. Our investigation aims to understand how temperature variations affect the performance of the MED-TVC system, intending to contribute to distillation process optimisation and the promotion of sustainable industrial practices in the future.

2. Methodology

The mathematical model for the MED-TVC is based on the energy and mass balance, as well as the thermodynamic properties of seawater. The mathematical model was integrated into MATLAB to simulate the distillate production rate of the MED-TVC system. The simulation's primary focus is on the system's performance and the total production of distillate. Before the simulation, the model was validated using industrial data from a MED-TVC by comparing the simulated total distillate production rate with the actual industrial total distillate production rate. Using the simulator, the configuration of the evaporator's temperature was changed to see the impact of the

evaporator's temperature on the system's performance. Finally, the simulated results obtained from the simulation were analysed to determine the production rate of distillate of the MED-TVC system. Fig. 1 shows the flow of the simulator.

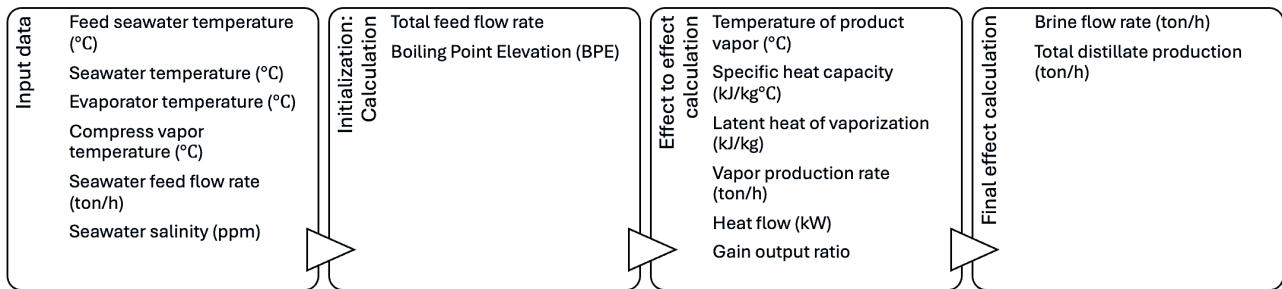


Fig. 1 Simulation flow of MED-TVC

At the end of the simulation, the deviation between simulated and industrial distillate production was calculated together with the other calculated outputs to inspect the differences between simulated and published results.

2.1 System Description

A typical MED-TVC system consists of evaporators, also known as effects, a thermo-compressor and a condenser. Fig. 2 is a simplified illustration of a MED-TVC unit. The system uses thermal and mechanical principles to desalinate water and maximise efficiency. The process works in a sequence of stages known as "effects", where each effect functions at progressively lower pressures and temperatures [14]. The system starts by introducing motive steam, which heats the seawater feed and causes it to evaporate. The first effect generates vapour, which serves as the heating element for the subsequent effect. This process continues with all the remaining effects. Each effect takes advantage of the previous effect's vapour condensation, generating latent heat that allows for additional evaporation in the subsequent effect.

The process is further enhanced by integrating a thermo-compressor into the system. The thermo-compressor's primary role is to compress and entrain a certain amount of the vapour from the last effect by combining it with motive steam at a higher pressure and temperature. The first effect uses recycled compressed vapour as its heat source. The initial effect will then use the recycled compressed vapour as a heating source. Thus, it will increase the MED-TVC's performance and reduce operational costs by reducing the usage of additional motive steam.

Condensation occurs in each effect, and the resulting vapour from each effect is extracted as distillate or distilled water, which is the desired product of the system. The remaining water, which has a higher salinity from each effect, will be discharged as brine. The MED-TVC system's efficiency is determined by the Gain Output Ratio (GOR). GOR is the ratio of distilled water produced to steam consumed. A high value of GOR indicates the system's high efficiency in producing distillate water while minimising energy input.

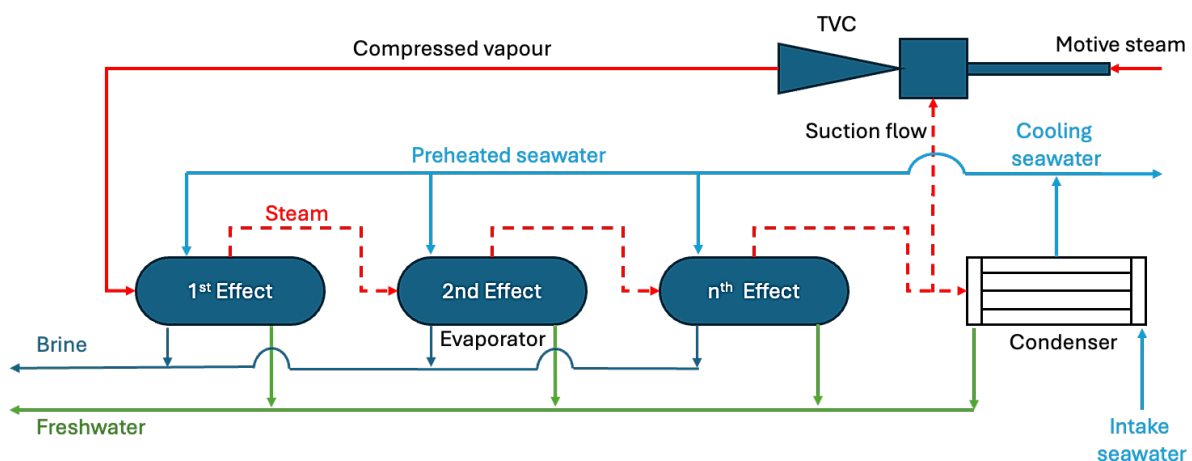


Fig. 2 Schematic illustration of MED-TVC system

2.2 Mathematical Model

For this study, the mathematical model for the MED-TVC system was adapted from existing research. The model applies fundamental mass and energy balances, including assumptions and equations developed by previous studies [14, 16–18] to simulate the system's performance. The model was validated using industrial data. After validation, a parametric study was commenced with varying temperatures. The assumptions are shown in Table 1.

Table 1 Assumptions applied for the model

No	Assumption
1	The system is in a steady state condition.
2	Heat losses are not considered.
3	The Non-Equilibrium Allowance is negligible.
4	Pressure drop during the vapour condensation process is negligible.
5	The latent heat of the vaporization of water depends on temperature.
6	The exchange in the process and the compressor pressure in the compressor respectively are adiabatic.
7	The vapour formed in evaporator, the motive steam, are assumed saturated.
8	The dimension of model of each equipment are not included.
9	The distillate produced is salt free.

The system is assumed to have constant drop of temperature in between each effect and is determined by using Equation (1).

$$\Delta T = \frac{T_1 - T_n}{n - 1} \quad (1)$$

The vapour temperature in an i^{th} effect is determined by using Equation (2).

$$T_{vi} = T_i - BPE_i \quad (2)$$

where BPE_i is the boiling point elevation in ' i^{th} ' effect which is the rise in boiling temperature caused by the dissolved minerals in the water. The feed flow rate is determined by using Equation (3).

$$F_i = \frac{M_f}{n} \quad (3)$$

The energy balance is shown in Equation (4) and Equation (5) to determine the vapour flow rate of each effect.

$$V_{i-1} = \frac{F_i C_{pi} (T_i - T_f) - V_i \lambda_i}{\lambda_{i-1}} \quad (4)$$

$$V_{cv} = \frac{F_1 C_{p1} (T_1 - T_f) - V_1 \lambda_1}{\lambda_{cv}} \quad (5)$$

Equation (6) is the mass balances for each effect of the system.

$$V_n = F_i - B_n \quad (6)$$

The brine flow rate at the final effect is assumed to be the total flow rate of brine divided by the number of effects as shown in Equation (7).

$$B_n = \frac{M_B}{n} \quad (7)$$

The condenser's energy balance is shown in Equation (8).

$$V_{cond} = \frac{C_{pn} (M_f + M_{cw}) (T_f - T_{sw})}{\lambda_n} \quad (8)$$

Equation (9) was used to calculate the latent heat of vaporization in 'ith' effect.

$$\lambda_i = 2589.583 + 0.9156T_i - 4.8343 \times 10^{-2}T_i^2 \quad (9)$$

Equation (10) was used to determine the seawater's specific heat capacity. Equation (11), Equation (12), Equation (13) and Equation (14) were used to compute the parameters for seawater's specific heat capacity.

$$C_{p_i} = (E + FT_i + GT_i^2 + HT_i^3) \times 10^{-3} \quad (10)$$

$$E = 1.2288 \times 10^{-2}X^2 - 6.6197X + 4206.8 \quad (11)$$

$$F = -2.2719 \times 10^{-4}X^2 + 5.4178 \times 10^{-2}X - 1.1262 \quad (12)$$

$$G = 1.8906 \times 10^{-6}X^2 - 5.3566 \times 10^{-4}X + 1.2026 \times 10^{-2} \quad (13)$$

$$H = -4.4268 \times 10^{-9}X^2 + 1.517 \times 10^{-6}X + 6.8777 \times 10^{-7} \quad (14)$$

The temperature of vapour is determined using Equation (15).

$$T_{v_i} = T_i - BPE_i \quad (15)$$

To calculate the boiling point elevation of the 'ith' effect, Equation (16) and its correlation, as shown in Equations (17) and (18), were used.

$$BPE_i = X(J_i + K_iX) \times 10^{-3} \quad (16)$$

$$J_i = (6.71 + 6.34 \times 10^{-2}T_i + 9.74 \times 10^{-5}T_i^2) \times 10^{-3} \quad (17)$$

$$K_i = (22.238 + 9.59 \times 10^{-3}T_i + 9.42 \times 10^{-5}T_i^2) \times 10^{-8} \quad (18)$$

The system's performance is determined by calculating the gain output ratio (GOR) by using Equation (19).

$$GOR = \frac{M_D}{V_M} \quad (19)$$

3. Results and Discussion

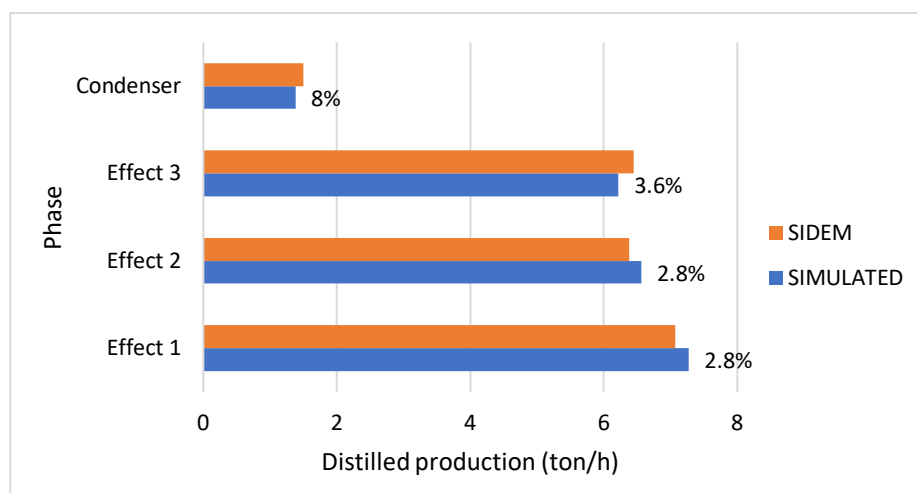
3.1 Model Validation

Before a parametric study can be carried out, the simulation model was verified to determine its accuracy. Industrial data from a MED-TVC system was used to validate the model. First, The Tunisian Chemical Group (GCT) constructed a commercial desalination unit at their phosphoric acid facility, produced by a French company "SIDEM" [18]. SIDEM's unit combines three effects: a thermo-compressor and a condenser. Table 2 shows the operating parameters of SIDEM's MED-TVC.

Fig. 3 depicts the simulated distillate production rate using SIDEM's operating parameters. After simulating the production of distillate, the total distillate production rate of each company was calculated by summing up all the effects of the distillate production rate as well as the condenser's. The simulated total distillate production rate for SIDEM's desalination unit is 21.42 tons/h, which produces a deviation of 1.15% compared to the simulated data. Since the error percentage is below 5% for effect-to-effect output and 8% for condenser output, the simulation model can be used to determine the behaviour of the MED-TVC system with various parameter changes, such as the temperature of the evaporator.

Table 2 The operating parameters of SIDEM's MED-TVC system [18]

	Parameter	Value
Seawater	Salinity, X	39000 ppm
	Temperature, T_{sw}	28 °C
Evaporator / Effect	First evaporator's temperature, T_1	60 °C
	Second evaporator's temperature, T_2	50 °C
	Third evaporator's temperature, T_3	40 °C
Cooling seawater	Cooling seawater flow rate, M_{cw}	160 ton/h
Feed	Feed flowrate, F_i	20 ton/h
Motive steam	Flow rate, V_M	3 ton/h
Distillate	Flow rate, M_D	21.67 ton/h

**Fig. 3** The simulated distillate production rate of the condenser and each effect using SIDEM parameters [adapted from [18]]

3.2 Parametric Study of Model

The temperature of the evaporator is among the critical parameters in determining the energy efficiency and water production of a desalination system. After validating the mathematical model's accuracy with industrial data, a parametric study was conducted by changing the evaporators' temperature with a reduction of 10% and an increment of 10% of the actual evaporator temperature within a range of -30% until +50% from actual operational values of the evaporators' temperature. Fig. 4 shows the simulated heat flow effect of evaporator 1, evaporator 2 and evaporator 3 depending on the variation of the evaporators' temperature. The result shows that as the temperature of the evaporator rises, the heat flow for both the first and second evaporators increases. This is due to the increased temperature differences between evaporators 1 and 2, which results in higher heat transfer [19]. The higher evaporator temperature is associated with a higher vapour production in the first effect. The vapour produced will then boost the water heating in the subsequent stage and eventually increase the freshwater production [19]. Since the temperature of the evaporator increases, the vapour production also increases; hence, the required heat to vaporise the seawater to produce the vapour increases. This was also highlighted in a study by Youssef et al. [20], which found that increasing the evaporator temperature will increase the evaporation rate, leading to a higher vapour production rate. However, an increase in the evaporator temperature is also associated with a higher energy requirement, which will reduce the energy efficiency of the MED-TVC system in total [21]. While that is the case for evaporators 1 and 2, meanwhile, the heat flow needed to produce the original vapour decreases for evaporator 3. This is because the formula used is Equation 6, which is the mass balance for the system. The equation used to determine the amount of vapour produced by evaporator 3 is not dependent on the evaporator's temperature. Thus, the vapour produced by evaporator 3 will not change as the temperature of the evaporator changes.

Fig. 5 depicts the latent heat of vaporisation's behaviour with the variation of evaporators' temperature. The graph shows that increasing the evaporator's temperature reduces the required latent heat of vaporisation. As defined by Li et al. [22], latent heat of vaporisation indicates the required energy to vaporise a certain amount of seawater without changing its temperature. Since the evaporator temperature is already high, the vapour possesses higher thermal energy to break the liquid bond and vaporise. Hence, the latent heat of vaporisation reduces as the evaporator temperature increases. Similar findings were also highlighted by Liu et al., who stated that the rise of the evaporator's temperature will decrease the heat input required for vaporisation due to the increase of the molecular energy at higher temperatures, which resulted in enhanced evaporation rates [23].

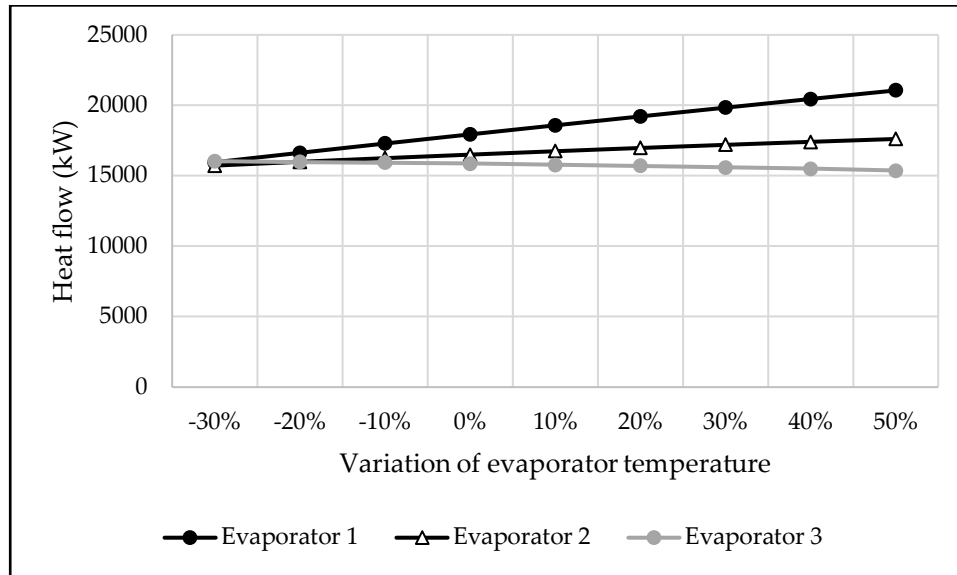


Fig. 4 The simulated heat flow for each evaporator depends on evaporator temperature variation

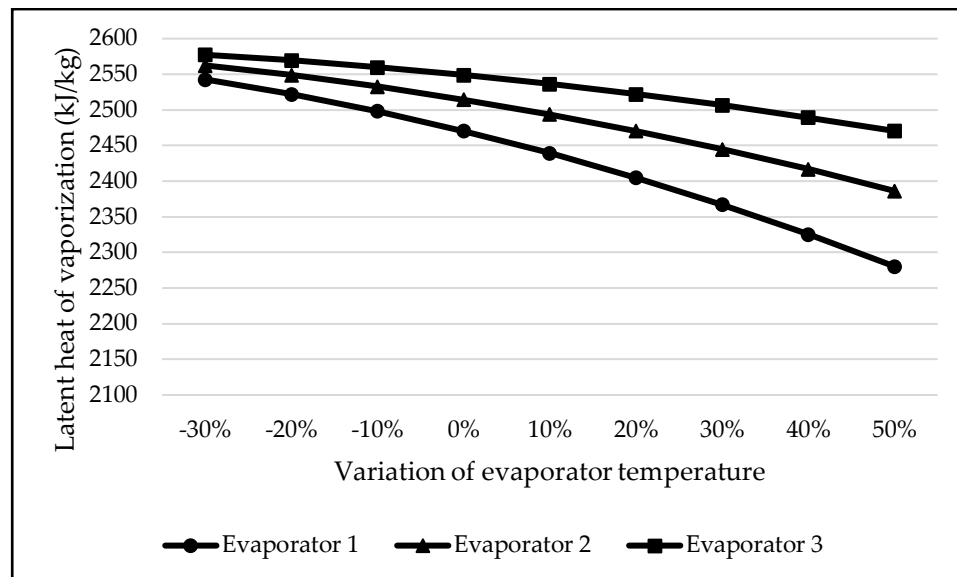


Fig. 5 The simulated latent heat of vaporisation depending on the variation of evaporator temperature

Among the critical results in the desalination system is the GOR, defined as the distillate production ratio over the steam flow rate [1]. Figs. 6 and 7 illustrate the simulated distillate production and GOR with varied evaporator temperature settings. The results show that as the evaporators' temperature rises, the total production rate for the desalination system will increase and vice versa. A study by Duong et al. [24] shows that the distillate production rate improves with enhanced evaporation efficiency due to the rise of evaporator temperature, thus improving the GOR. This means that the required steam reduces as the evaporators' temperature increases for a specific amount of distillate produced. A study shows that preheating water supplied in the condenser will improve heat efficiency, thus improving the GOR for seawater desalination [25]. Furthermore, research by Thabit

et al. [26] highlighted that operating at higher temperatures will increase the recovery rate in desalination plants and improve GOR.

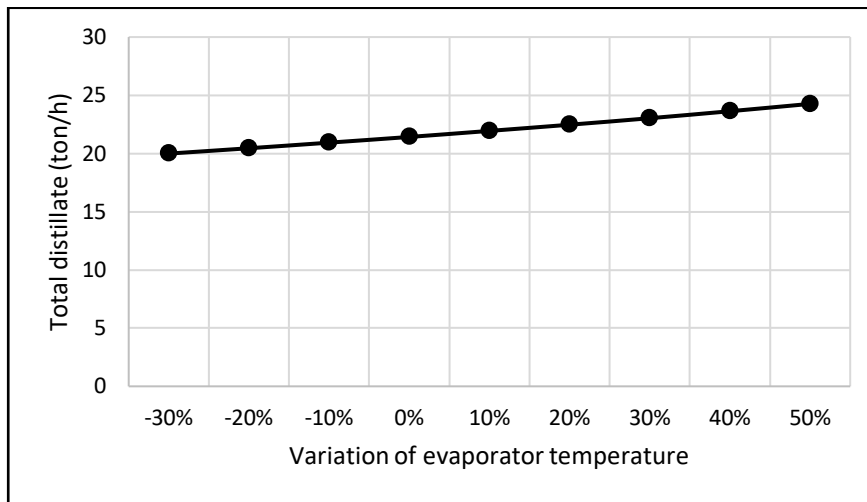


Fig. 6 The simulated total distillate production depending on evaporator temperature variation

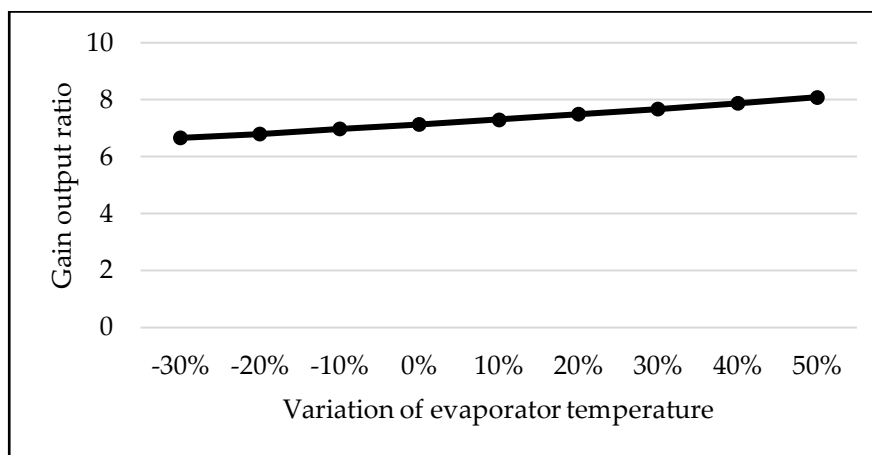


Fig. 7 The simulated gain output ratio with varied evaporator temperatures

In summary, thermodynamics and heat transfer principles can justify the relationship between the evaporators' temperature and the desalination systems' performance. Increasing the evaporator temperature decreases the latent heat of vaporisation, which means it will take less energy to convert seawater into steam; thus, more steam can be produced using the same amount of thermal energy input. Higher evaporator temperature also increases the GOR. This is because the steam's energy is much more efficient, requiring less motive steam to generate more distillate. These principles suggest that increasing the evaporator temperature can optimise the MED-TVC desalination system's performance. Some studies suggest that balancing the benefits with the potential drawbacks, such as energy efficiency, scaling and material stress at higher temperatures, is crucial [27-29].

4. Conclusion

In conclusion, the simulation and parametric study of the MED-TVC system shows that the model predicted the distillate production rate with a minimal error of 1.15%, validating the simulation model's reliability. This study focused on varying the temperature of each evaporator to demonstrate the MED-TVC system's behaviour in terms of its performance. This study demonstrated that increasing the evaporator temperature enhances both the water production and the GOR, which indicates higher efficiency and reduced motive steam consumption per unit of distillate produced. When the evaporator temperature decreases, the opposite effect will occur for total distillate

production and GOR. These findings highlight the critical role of evaporator temperature in optimising MED-TVC system performance, providing valuable insights for improving industrial desalination processes.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Edilson Marqueles Chong, Siti Mariam Abdul Rahman; **data collection:** Edilson Marqueles Chong; **analysis and interpretation of results:** Irnie Azlin Zakaria, Siti Mariam Abdul Rahman, Edilson Marqueles Chong; **draft manuscript preparation:** Edilson Marqueles Chong. All authors reviewed the results and approved the final version of the manuscript.

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