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Performance Investigation of a Single Effect Evaporator Desalination Unit: A Simulation Model

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ABSTRACT

This study introduces a performance model for a single-effect evaporation desalination process integrated with a condenser unit. Herein, the proposed desalination unit is developed, designed, and assessed in terms of its performance. The key input parameters used to evaluate system performance conditions include salinity, flow rate, temperature, and evaporator area. Based on the calculations, the model determines the steam temperature and flow rate, which influence the evaporation rate and energy consumption. The end condenser plays a crucial role in condensing vaporized water and maintaining the required temperature and pressure levels. Furthermore, the desalination system was developed using advanced modeling in the MATLAB/Simulink toolbox, which effectively integrates distinct mathematical relations. Sensitivity analysis was performed to assess the impact of brine blowdown temperature and feed mass flow rate on the evaporator performance ratio and productivity, as well as on the condenser power and effectiveness. It provides valuable insights into single-effect evaporation desalination operation, allowing the evaluation of efficiency, optimization of design and operating conditions, and informed decision-making regarding desalination plant performance.

Keywords: Single Effect Evaporator Desalination, Performance Evaluation, Desalination Process, Dynamic Simulation.

NONMENCLATURE

Abbreviations	
E_c	Condenser effectiveness.
h_g	Latent heat of vaporization, kJ/kg.
M_d	Distillate flow rate, kg/s.
PEP	Productivity of the evaporator, m^3/day.
Q_c	Thermal load on the condenser, kW.
S_b	Brine blowdown salinity, kg/kg.
S_f	Feed salinity, kg/kg.
T_f	Feed brine temperature, ^oC.
T_{sea}	Intake seawater temperature, ^oC.
T_v	Vapor temperature, ^oC.

1. INTRODUCTION

Desalination technology plays a crucial role in addressing the global water scarcity challenge. As freshwater resources continue to deplete, it is imperative to explore efficient and sustainable methods for producing potable water from seawater [1]. Over the last thirty years, significant advancements have taken place in the technology, production capacity, and market value of the water desalination sector. In 1995, the number of desalination plants stood at 11,066 with a capacity of 20.3×10^6 m^3/d [2]. Recently, around 16,000 desalination plants have been established worldwide, with an operational capacity of approximately 95.37 million m^3/day and brine production amounting to 141.5 million m^3/day [3]. Consequently, the integration of cutting-edge energy conversion systems is growing in significance. Desalination methods are a highly promising option for providing purified water with minimal energy usage and reduced freshwater expenses.

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[4]. One such process is that single-effect evaporator desalination units are particularly important because of their simplicity and efficiency [5]. Performance investigation is vital for evaluating the effectiveness and efficiency of desalination units, particularly single-effect evaporation systems. This study introduces a simulation model that can be used to assess the performance of such units, offering valuable insights into system design and optimization.

Among the desalination types, the single-effect evaporation desalination process involves heating saline water in an evaporator chamber, causing the liquid phase (water) to vaporize while leaving behind concentrated brine. Key input parameters such as salinity, flow rate, temperature, and evaporator area significantly affect system performance. Higher salinity levels increase energy consumption due to increased boiling point elevation, whereas higher flow rates enhance heat transfer efficiency by reducing the scaling potential on heat exchange surfaces. Steam temperature and flow rate are critical factors influencing the evaporation rate and energy consumption in single-effect evaporation systems [6]. By manipulating these variables within optimal ranges, production capacity can be maximized while minimizing energy requirements.

A single-effect evaporator with a condenser or feed preheater unit not only provides the benefits of energy efficiency and heat recovery but also allows for the efficient removal and collection of the condensed solvent vapor. This additional benefit minimizes solvent loss, ensures better control over the concentration process, and can lead to cost savings by enabling the recycling or reuse of the recovered solvent, further enhancing the system's economic and environmental advantages [7]. Furthermore, the purpose of this study is to understand the factors that influence system performance, such as steam temperature, flow rate, brine blowdown operating conditions, distillate product operating conditions, and end condenser parameters.

Specialized software has been developed to develop, simulate, and enhance various desalination methods. These programs feature a powerful and user-friendly structure. Regardless of the type of simulation being performed, users only need to input the data, and the software will process it uniformly [8]. The MATLAB/Simulink browser is one of the most powerful tools released in recent years. The main aim of this research is to illustrate a built modular computer software for a single-effect evaporator with a condenser unit using MATLAB/Simulink environments.

2. MATERIAL AND METHODS

2.1 The proposed system

The integrated structure is suitable for sweater desalination. Figure 1 illustrates a schematic representation of the envisioned system. The primary components of the system include:

- Single Effect Evaporator.
- Condenser.

A single-effect evaporator with a condenser unit is an evaporator that uses steam to heat a liquid and vaporize it. The vapor is then condensed in a condenser, and the condensate is returned to the evaporator. This process allows the liquid to be concentrated by evaporating some of the solvent.

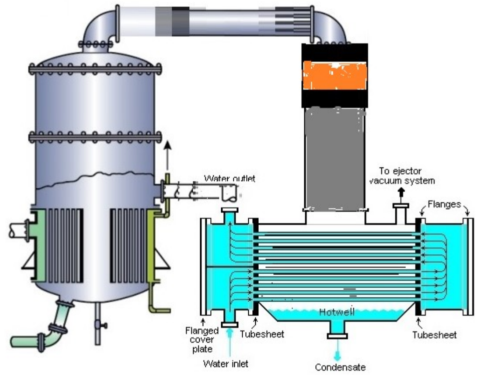

Figure 1. Proposed system units.

2.2 Model simulation & assumptions

Each unit was modeled by applying the fundamental thermodynamic energy balance equations that determine the functioning of each examined technology [2], [6]–[8]. The models have been used and resolved using MATLAB/Simulink software.

Simulink blocks (drag and drop functionality) with relevant connections are included in the generated model according to the adopted design. The system is solved iteratively with various MATLAB command functions contained in each block. Table 1 lists the input and output variables considered in this study.

2.3 Mathematical model

The developed numerical model representing the simulation analysis is described in the following equations. The mathematical approach represents the single-effect evaporator and condenser.

The productivity of the evaporator in m^3/day is obtained as follows [6]:

$$PEP = \frac{(M_d \times 24 \times 3600)}{997} \tag{1}$$

The system performance ratio can be obtained as [7]:

$$P_R = \frac{1 - S_f}{1 - S_b} \quad (2)$$

The thermal load on the condenser, kW, is given as [9]:

$$Q_c = M_d \times h_g \quad (3)$$

The condenser effectiveness is expressed as follows [10]:

$$E_c = \frac{T_f - T_{sea}}{T_v - T_{sea}} \quad (4)$$

Table 1: Data related to the proposed system units [2].

Input parameters	Output parameters
Seawater temperature = 25 °C. Seawater salinity ratio = 42×10^{-3}. Brine blowdown salinity = 70×10^{-3}. Feed mass flow rate = 2.5 kg/s. Brine blowdown boiling temperature = 75 °C. Evaporator area = 85 m^2. End condenser area = 40 m^2.	Brine blowdown flow rate, kg/s. Distillate flow rate, kg/s. Steam temperature, °C. Vapor temperature, °C. Productivity, m^3/day System performance, % Steam mass flow rate, kg/s. Thermal load on the condenser, kW. Preheated feed temperature, °C. Condenser effectiveness, %. Cooling water flow rate, kg/s.

3 RESULTS AND DISCUSSION

To attain the intended performance results, it is crucial to allocate the most appropriate operational parameters. This system representation incorporates all the design factors evaluated in this investigation to establish optimum productivity. Figure 2 shows the productivity of a single-effect evaporator as a function of the brine blowdown boiling temperature and feed mass flow rate. The feed mass flow rate varied from 0.001 to 10 kg/s, and the brine blowdown boiling temperature varied from 40°C to 110°C. As can be seen from the figure, the productivity of the evaporator increases with the feed mass flow rate. This is because a higher feed mass flow rate provides more water to be evaporated. On the other hand, the productivity of the evaporator is limited by the boiling temperature of the feed, and the productivity remains constant as the temperature increases. The maximum productivity of the evaporator in this study was 346.6 m^3/day, which was achieved at a brine blowdown boiling temperature of 110°C and a feed mass flow rate of 10 kg/s. As a result, if high productivity is required, the feed mass flow rate should be increased as much as possible. Nevertheless, it is essential to recognize that this will demand an increased amount of energy to run the evaporator.

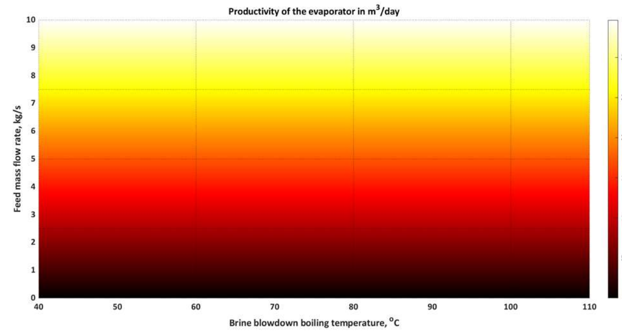

Figure 2. Effect of the brine blowdown temperature and feed mass flow rate on single-effect evaporator productivity.

Figure 3 demonstrates how the efficiency of a single-effect evaporator changes on the basis of two variables: the boiling temperature of the brine blowdown and the rate at which the feed mass flows through it. The graph clearly shows that as the mass flow rate increases, the performance of the evaporator decreases. Similarly, when the boiling temperature of the feed increases, the performance also decreases. The highest performance observed in this study was 0.9972 kg/kg, which occurred when the brine blowdown boiling temperature was 40°C and the feed mass flow rate was 0.001 kg/s. In addition, the graph highlights that the relationship between these factors is nonlinear, with a significant sensitivity to changes in brine blowdown boiling temperature compared to alterations in the feed mass flow rate.

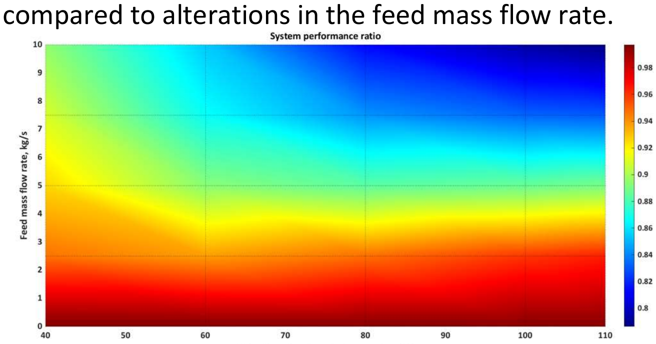

Figure 3. Effect of the brine blowdown boiling temperature and feed mass flow rate on the performance of a single-effect evaporator.

Figure 4 demonstrates the thermal load on a condenser against the brine blowdown boiling temperature and feed mass flow rate, which provides critical insights for condenser design and operation optimization. This indicates that the condenser's thermal load slightly decreases with higher brine blowdown boiling temperatures due to the increased heat removal demands, and conversely increases as the feed mass flow rate rises, owing to greater brine throughput with reduced heat per unit. Moreover, it reveals that at lower temperatures, the thermal load rises rapidly with temperature increments, whereas the rate of increase diminishes at higher temperatures due to changes in water's latent heat of vaporization.

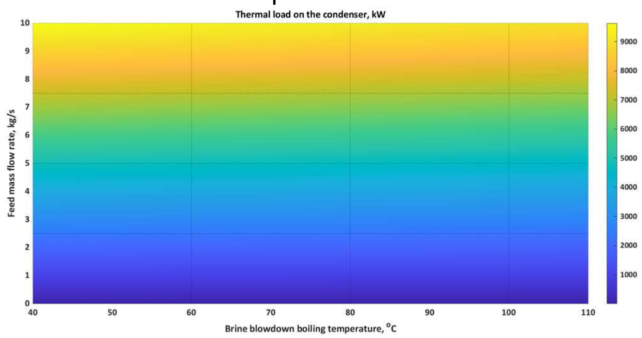

Figure 4. Thermal load variations in the condenser.

In addition, Figure 5 depicts the performance of the condenser with respect to variations in brine blowdown boiling temperature and feed mass flow rate, with productivity measured as distillate mass flow rate per unit feed mass flow rate. Simulation analysis was conducted using a single-effect evaporator under specific conditions, and the graph reveals that performance increases with higher brine blowdown boiling temperatures and decreases with higher feed mass flow rates. This is due to higher temperatures allowing more water to condense to the brine and greater feed rates supplying more water for condensation. In one specific case, the maximum performance achieved was approximately 0.95 at a brine blowdown boiling temperature of 110°C and a feed mass flow rate of 2.5 kg/s.

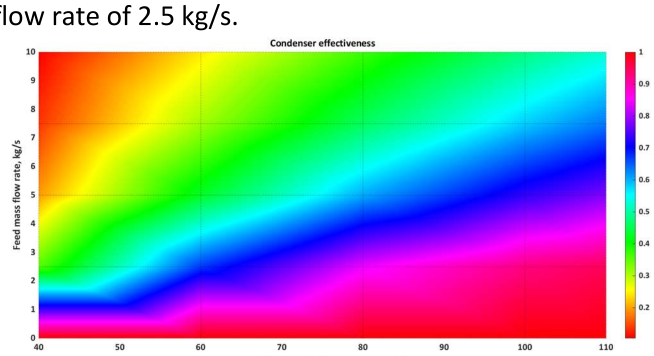

Figure 5. Relationship between boiling temperature, mass flow rate with condenser effectiveness.

Table 2: Data results according to the simulation model.

Single-effect evaporator outputs:	
Steam temperature, °C	86.45
Vapor temperature, °C	74.1
Steam mass flow rate, kg/s	1.059
Brine blowdown flow rate, kg/s	1.5
Distillate flow rate, kg/s	1
Evaporator productivity, m^3/day	86.66
Performance ratio	0.9446
Condenser outputs:	
Condenser thermal power, kW	2324
Cooling water flow rate, kg/s	11.48
Total feed flow rate, kg/s	64.76
Feed brine temperature, °C	10.26
Condenser effectiveness, %	80.98

4 CONCLUSIONS

This study investigates the preliminary simulation analysis of a single-effect evaporator desalination unit coupled with a condenser using MATLAB/Simulink. This research primarily examines the system's performance by analyzing input factors, such as flow rate, brine temperature, and evaporator area. This designed model provides valuable information about critical system performance and productivity factors such as steam temperature, flow rate, brine blowdown characteristics, and condenser parameters. This proposed scheme serves as a significant resource for evaluating efficiency, optimizing design and operating conditions, and making informed decisions regarding the performance of desalination plants.

The results indicate that increased feed mass flow rates lead to improved productivity, although this improvement is limited as the feed boiling temperature increases. Additionally, as both feed mass flow rates and boiling temperatures increase, the performance of the evaporator decreases. This study emphasizes the robust connection between these variables. In conclusion, this study improves the understanding of single-effect evaporator desalination systems and explores ways to improve them, which could be beneficial in tackling concerns related to water scarcity.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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