



Modeling of a desalination unit by evaporation coupled with solar thermal energy

Modelado de una unidad de desalinización por evaporación acoplada con energía solar térmica

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Abstract

This work aims to develop a dynamic phenomenological model of a solar thermal desalination system operating via atmospheric pressure evaporation, designed for isolated regions with water scarcity. A system of differential equations was formulated to describe the mass and energy balance and evaluate heat and mass transfer phenomena. The model simulation was performed in Python to analyze the behavior of variables in the desalination process, such as water level, salt concentration, temperature, and desalinated water production. The results show that it is possible to evaporate 26.67% of the salt water supplied within one hour. In addition, it assessed the condensation capacity, in which all the steam was condensed. The study stands out for its sustainable approach, integrating solar thermal energy and its operational simplicity, making it suitable for remote locations.

Keywords: Thermal desalination, dynamic modeling, evaporation.

Resumen

El objetivo de este trabajo es desarrollar un modelo fenomenológico dinámico de un sistema de desalinización solar térmica que funciona mediante evaporación a presión atmosférica, diseñado para regiones aisladas con escasez de agua. Para describir el balance de masa y energía y evaluar los fenómenos de transferencia de calor y masa, se formuló un sistema de ecuaciones diferenciales. La simulación del modelo se llevó a cabo en Python para analizar el comportamiento de variables del proceso de desalinización, tales como el nivel de agua, concentración de sal, temperatura y producción de agua desalinizada. Los resultados muestran que es posible evaporar el 26,67 % del agua salada suministrada en una hora. Asimismo, se evaluó la capacidad de condensación, en la que se produjo la condensación de todo el vapor. El estudio destaca por su enfoque sostenible, que integra la energía solar térmica, y por su sencillez operativa, lo que lo hace adecuado para ubicaciones remotas.

Palabras clave: Desalinización térmica, modelización dinámica, evaporación.

INTRODUCTION

The planet Earth has about 70% of its surface covered by water, with an estimated volume of almost 1,4 billion km^3 , a resource essential for life and human activities. However, 97,5% of this water is salt water, and only 0,3% of the freshwater is available on the surface, in liquid form and relatively easy to access, in rivers and lakes. The uneven distribution of water resources, along with the worsening of climate change, makes water scarcity a major problem, especially in arid and semi-arid regions. Furthermore, over the last 100 years, global water consumption has increased sixfold, with a growing rate of about 1% per year [1].

Desalination emerges as one possible solution to the lack of potable water, mainly because salt water is abundant and widely available in oceans and underground reservoirs worldwide. The desalination process can be carried out using various methods, which are mainly classified into two groups: membrane or thermal methods. However, both methods present implementation challenges due to the high cost, the main issue being high energy consumption. Given this, new technologies have been explored to overcome this limitation, such as renewable energy systems coupled with the desalination process [2].

Renewable-energy-powered desalination systems have proven effective in making desalination plants viable, as evidenced by the growing number of such systems in recent years. Among renewable energy sources, solar energy is the most prominent and is widely studied. This source has the advantage of providing both electricity and heat, applicable to different desalination methods [3]. Furthermore, solar energy has relatively low cost, easy implementation, and high availability in arid and semi-arid regions [4].

The work of Cunha and Pontes [5] presents the modeling of a thermal desalination plant using the Multi-effect Distillation (MED) process, coupled with solar thermal collectors and a thermal energy storage system. The study evaluated the viability of applying the system in a semi-arid region of Brazil, highlighting its use as a clean, decentralized alternative for remote communities. The proposed process with a production capacity of $72m^3/day$ was modeled and estimated to have a water cost of US\$4,95 m^3 , proving to be financially feasible [5].

The study by Farné [6] presents a Solar Desalination Geoassisted Continuous (SDGC) system, based on evaporation processes. The model operates in a thermally insulated, low-pressure tank, where salt water is heated by heat exchangers coupled with solar thermal energy and condensed on metal sheets. The system can produce up to 4.000 kg/day of desalinated water under ideal conditions [6]. The work initially sought to standardize the system, focusing on functionality and effectiveness, leaving optimization for future studies. The experimental research by [7] assessed the performance of trays made of different materials (aluminum, polished AISI 304 stainless steel, chromed and unpolished) for the condensation process in a single-stage desalination system with a controlled heat source. The results show that the aluminum tray produced 0,406 mL/kJ of desalinated water per energy supplied and reduced the water's electrical conductivity by more than 97%, making it suitable for consumption. The study highlighted the importance of the material's thermal conductivity and surface roughness in the condensation process [7]. In addition to these studies, there are several others with different systems, either membrane or thermal, coupled with various renewable energy sources [8]. However, there are still few applications in small communities and remote locations.

The present work aims to develop a phenomenological dynamic model of a solar thermal desalination system based on atmospheric-pressure evaporation to support experimental development. Thus, the process eliminates the need for electrical energy and direct heating of salt water by solar collectors, thereby reducing the need for frequent maintenance and specialized labor for operation. This makes the system more viable for application in isolated regions.

PROCESS DESCRIPTION AND MATHEMATICAL MODELING

The studies by Cunha and Pontes [5] and Paixão, Quirino, Fialho, Americano da Costa, and Pontes [9] describe the system of a solar thermal energy desalination plant with indirect heating in three parts. First, the solar collector heats the working fluid using solar radiation and subsequently transfers this heat to the salt water in the desalination unit. The working fluid is usually water, as it has a high heat capacity. The second section consists of the thermal storage tanks that store hot water to keep the process running during periods without sunlight. Finally, the desalination unit is of the MED (Multi-effect Distillation) type, a thermal desalination method in which salt water is heated and evaporated in a series of chambers, with the vapor from each chamber used to heat the next chamber, thereby reducing energy consumption [5], [9].

This study proposes a similar system with a single-stage desalinators, given the lower production capacity. Figure 1 illustrates the desalination system, which consists of a reservoir that stores the saltwater. This water is heated by a coil through which the working fluid coming from the collectors circulates, providing heat for the water's evaporation. The steam rises and exchanges latent heat with the sloped ceiling, so that the condensed water droplets fall into a gutter where they are collected. The process occurs in a semi-continuous manner: the salt water starts inside the reservoir without replenishment from an inlet stream, while condensate and vapor occurs continuously removed from the outlet.

Source: The authors.

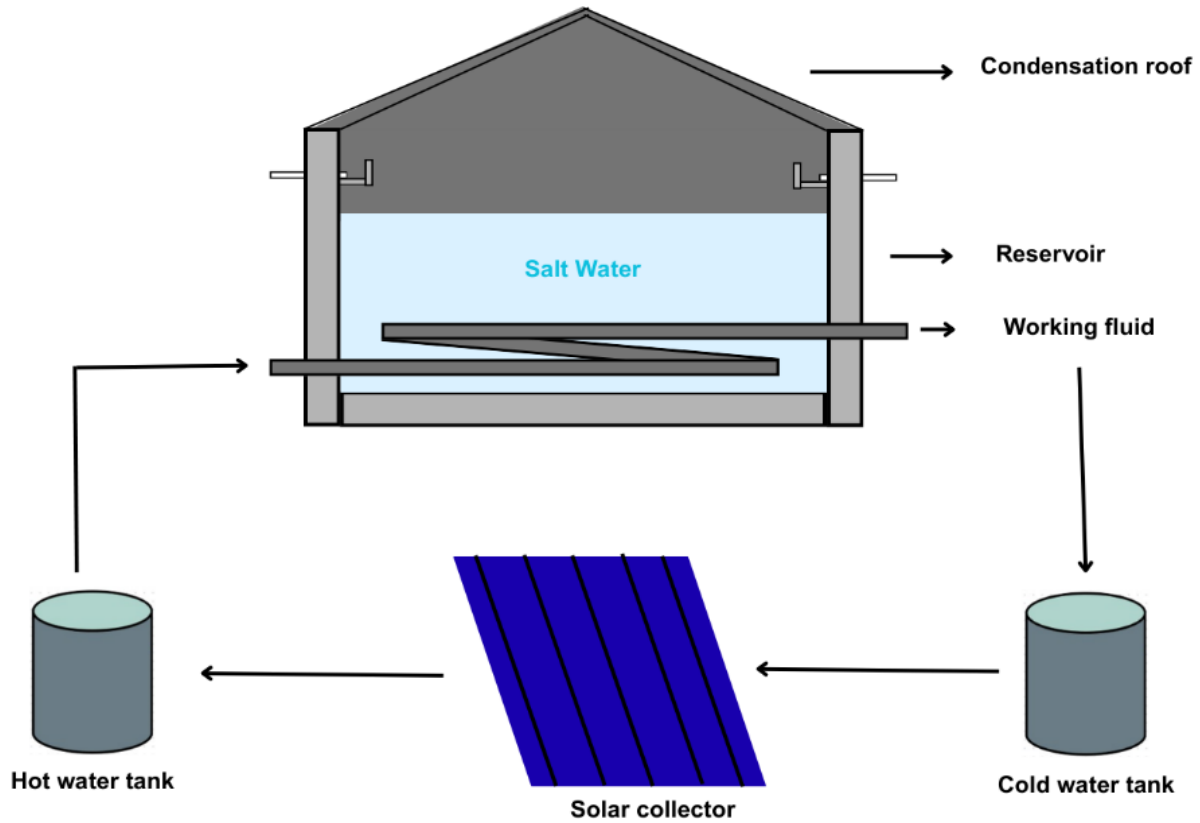


Figure 1. Representation of the studied desalination unit.

The flat plate collectors reach temperatures on the order of 60-70°C, which are therefore insufficient to boil water at atmospheric pressure. Thus, evaporation in the desalinators occurs due to the vapor pressure difference at a given temperature. The concentration gradient between the liquid and vapor phases drives diffusion at the liquid-vapor interface, thereby ensuring the separation of water and brine [10]. The evaporation rate can then be determined by Fick's first law, which, together with the ideal gas law, results in the following equation (1):

$$m_{evaporated} = \frac{-D.M.A}{R.\delta} \left(\frac{y.P}{T^v} - \frac{P_{sat}^{vap}}{T^b} \right) \quad (1)$$

where $m_{evaporated}$ is the mass flow rate of evaporated water (kg/s), D is the diffusivity (m^2/s), M is the molar mass of water (kg/mol), A is the cross-sectional area (m^2), R is the ideal gas constant (kJ/mol.°C), δ is the boundary layer thickness (m), y is the molar fraction of vapor (dimensionless), P is the atmospheric pressure (Pa), T^b is the salt water temperature (°C), T^v is the vapor temperature (°C) and P_{sat}^{vap} is the saturated vapor pressure (Pa) determined by the Antoine equation (2) [11]:

$$P_{sat}^{vap}(T) = 10^{16,3872 - \frac{3885,70}{230,170 + T}} \quad (2)$$

The vapor temperature is found by adjusting the salt water temperature with the specific Boiling Point Elevation (BPE) for saline solutions, given by equation (3):

$$T^v = T^b - BPE$$

$$BPE = C^b \left(E + FC^b + G(C^b)^2 \right)$$

$$E = 8,325 \cdot 10^{-2} + 1,883 \cdot 10^{-4} \cdot T^v + 4,02 \cdot 10^{-6} \cdot (T^v)^2$$

$$F = -7,625 \cdot 10^{-4} + 9,02 \cdot 10^{-5} \cdot T^v - 5,2 \cdot 10^{-7} \cdot (T^v)^2$$

$$G = 1,522 \cdot 10^{-4} - 3 \cdot 10^{-6} \cdot T^v - 3 \cdot 10^{-8} \cdot (T^v)^2 \quad (3)$$

It is also necessary to adjust the diffusivity as a function of temperature variation, equation (4):

$$D = D_0 \left(\frac{T}{T_0} \right)^{1,75} \quad (4)$$

The model was inspired by [9], who developed a phenomenological dynamic model for the MED. The following hypotheses are considered for the system modeling: Water density is constant and independent of temperature; there is no accumulation in the vapor phase; heat losses to the environment are significant. Salt is not carried over into the vapor phase; the heating rate of the system is constant due to the thermal storage system, which absorbs fluctuations in irradiation over a one-hour interval.

The mass balance of the liquid phase relates the variation in the quantity of salt water level in the reservoir with respect to time, equation (5):

$$\frac{dh^b}{dt} = \frac{-m_{evaporated}}{\rho^b \cdot A} \quad (5)$$

where h^b is the height of salt water in the desalinators (m), t is the time (s), $m_{evaporated}$ is the mass flow rate of evaporated water (kg/s), ρ^b is the density of salt water (kg/m³) and A is the cross-sectional area (m²).

The energy balance of the liquid phase is determined by the heat rate from the hot tank, heat loss to the environment, and the water that evaporates and leaves the liquid phase. The equation is rearranged as a function of the salt water temperature, according to equation (6):

$$\frac{dT^b}{dt} = \frac{1}{b} \cdot \left(\frac{Q_E - Q_P + m_{evaporated}(H^b - H^v)}{\rho^b \cdot A \cdot h^b} \right) - \frac{a}{b} \cdot \left(\frac{C^b \cdot m_{evaporated}}{h^b \cdot \rho^b \cdot A} \right) \quad (6)$$

where T^b is the salt water temperature (°C), t is the time (s), a is the partial derivative of the brine enthalpy with respect to salt concentration (%(m/m).kJ/kg.s), b is the partial derivative of the brine enthalpy with respect to temperature (kJ.°C/kg.s), Q_E is the heat rate coming from the hot tank (kJ/s), Q_P is the heat loss rate to the environment (kJ/s), H^b is the brine enthalpy (kJ/kg), H^v is the vapor enthalpy (kJ/kg), h^b is the height of salt water in the desalinators (m), $m_{evaporated}$ is the mass flow rate of evaporated water (kg/s), ρ^b is the density of salt water (kg/m³) and A is the cross-sectional area (m²).

The brine enthalpy is a function of the temperature and the salt concentration of the water, equation (7) [13]:

$$\begin{aligned} H^b(C^b, T^b) = & \{141,355 + 4202,07 \cdot T^b - 0,535 \cdot (T^b)^2 \\ & [-2,34825 \cdot 10^4 + 3,15183 \cdot 10^5 \cdot C^b \\ & + 2,80269 \cdot 10^6 \cdot (C^b)^2 - 1,44606 \cdot 10^7 \cdot (C^b)^3 \\ & + 0,004 \cdot (T^b)^3 - C^b \cdot + 7,82607 \cdot 10^3 T^b - 44,1733 \cdot (T^b)^2 + 0,21394 \cdot (T^b)^3 \\ & - 1,99108 \cdot 10^4 \cdot C^b \cdot T^b + 2,77846 \cdot 10^4 \cdot (C^b)^2 \cdot T^b \\ & + 97,2801 \cdot C^b \cdot (T^b)^2] \} \cdot 10^{-3} \end{aligned} \quad (7)$$

The partial derivative of the brine enthalpy relative to concentration (a), given by equation (8):

$$\begin{aligned} a = \left(\frac{\partial H^b}{\partial C^b} \right)_T = & [2,34825 \cdot 10^4 - 2 \cdot 3,15183 \cdot 10^5 \cdot C^b - 3 \cdot 2,80269 \cdot 10^6 \cdot (C^b)^2 \\ & + 4 \cdot 1,44606 \cdot 10^7 \cdot (C^b)^3 - 7,82607 \cdot 10^3 T^b + 44,1733 \cdot (T^b)^2 - 0,21394 \cdot (T^b)^3 \\ & + 2 \cdot 1,99108 \cdot 10^4 \cdot C^b \cdot T^b - 3 \cdot 2,77846 \cdot 10^4 \cdot (C^b)^2 \cdot T^b - 2 \cdot 97,2801 \cdot C^b \cdot (T^b)^2] \cdot 10^{-3} \end{aligned} \quad (8)$$

The partial derivative of the brine enthalpy relative to temperature (b), given by equation (9):

$$\begin{aligned} b = \left(\frac{\partial H^b}{\partial T^b} \right)_{C^b} = & [4202,07 - 2 \cdot 0,535 \cdot T^b + 3 \cdot 0,004 \cdot (T^b)^2 - 7,82607 \cdot 10^3 \cdot C^b \\ & + 2 \cdot 44,1733 \cdot T^b \cdot C^b - 3 \cdot 0,21394 \cdot (T^b)^2 \cdot C^b + 1,99108 \cdot 10^4 \cdot (C^b)^2 \\ & - 2,77846 \cdot 10^4 \cdot (C^b)^3 - 2 \cdot 97,2801 \cdot T^b \cdot (C^b)^2] \cdot 10^{-3} \end{aligned} \quad (9)$$

The heat loss to the environment (Q_P), given by equation (10):

$$Q_P = U \cdot A_{total} \cdot (T^b - T_{amb}) \quad (10)$$

The component balance (salt) that accumulates in the single stage of the desalinator is given by equation (11):

$$\frac{dC^b}{dt} = \frac{C^b \cdot m_{evaporated}}{h^b \cdot \rho^b \cdot A} \quad (11)$$

where C^b is the salt concentration in the salt water (%(m/m)), t is the time (s), h^b is the height of salt water in the desalinator (m), $m_{evaporated}$ is the mass flow rate of evaporated vapor (kg/s), ρ^b is the density of salt water (kg/m³), and A is the cross-sectional area (m²).

The mass balance in the vapor phase, given that there is no accumulation, is given by equation (12):

$$m^v = m_{evaporated} - m^l \quad (12)$$

Where m^v is the mass of vapor that does not condense on the desalinator roof and m^l is the condensed mass on the roof, which is recovered from the desalinator.

The energy balance in the vapor phase is given by equation (13):

$$m_{evaporated} H^b = m^v H^v + m^l H^l + U \cdot A_{cond} \cdot (T^v - T_{amb}) \quad (13)$$

Where H is the enthalpy (kJ/kg), the superscripts b , v and l represent the brine, vapor [12] and liquid [13] phases, respectively, U is the overall heat transfer coefficient (kW/m²°C), A_{cond} is the area of the roof and walls where heat loss to the environment occurs, and T_{amb} is the ambient temperature (°C). In this manner, it is possible to calculate the mass flow rate of condensed liquid and the non-condensed vapor by equation (14) of the mass balance in the vapor phase.

$$m^l = \frac{U \cdot A_{cond} \cdot (T^v - T_{amb}) + m_{evaporated} (H^v - H^b)}{(H^v - H^l)} \quad (14)$$

The parameters for the model are presented in Table 1. The operational and initial conditions, adopted from [9] and [6], are summarized in Table 2 and Table 3, respectively.

Table 1. Parameters for the desalinator model.

Parameters	Variables	Values	Units
ρ^b	Salt water density	975	Kg/m ³
D_0	Diffusivity at initial temperature	$2,6 \cdot 10^{-6}$	m ² /s
M	Molar mass of water	$1,8 \cdot 10^{-2}$	Kg/mol
P	Atmospheric Pressure	101325	Pa
R	Ideal gas constant	8,314	J/mol.°C

Table 1. Parameters for the desalinator model. (continued)

Parameters	Variables	Values	Units
U	Overall heat transfer coefficient	9,97	W/m ² °C
A	Desalinator cross-sectional area	1	m ²
A_{cond}	Condensation area	1,2	m ²
δ	Boundary Layer Thickness	0,001	m

Source: The authors.

Table 2. Process variables for the desalinator.

Symbols	Variables	Values	Units
T_{amb}	Ambient temperature	25	°C
Q_E	Heat Supplied to the desalinator	100	kJ/s
y	Vapor fraction	0,01	-

Source: The authors.

Table 3. Initial conditions for the desalinator model.

Symbols	Variables	Values	Units
$C^b (t = 0)$	Salt water concentration	0,035	%(m/m)
$T^b (t = 0)$	Salt water Temperature	25	°C
$h^b (t = 0)$	Salt water height	0,5	m
$m^l (t = 0)$	Condensed water	0	kg
$m^v (t = 0)$	Non-condensed water	0	kg

Source: The authors.

The system of differential equations was implemented in Python and solved using the 4th -order Runge-Kutta method via the native `solve_ivp` function over a one-hour interval.

RESULTS

This study developed dynamic modeling of a desalination unit coupled with a solar thermal system based on atmospheric pressure evaporation. The desalinator considered a 1 m² stainless steel area with a reservoir evaporation water volume of 500 L. The initial conditions are a salt-water height of 0,5 m, a concentration of 0,035%(m/m), and an ambient temperature of 25°C. The hot water heat rate was estimated according to [9], based on an irradiation of 1000 W/m² at peak time, with 50 collectors each with an area of 2 m² and a flow rate of 1 kg/s, yielding a value of 100 kJ/s. An operating time of 1 hour was considered.

Figure 2 presents the variation of the salt water height as a function of time. It is possible to verify a reduction in the desalinator's water level, as expected. Initially, a slope is observed as the temperature increases, until it stabilizes and the evaporation rate approaches a constant value. During one hour of operation, the height reduced from 0,5 m to 0,367 m, with an approximate

evaporation of 130 kg of desalinated water.

Source: The authors.

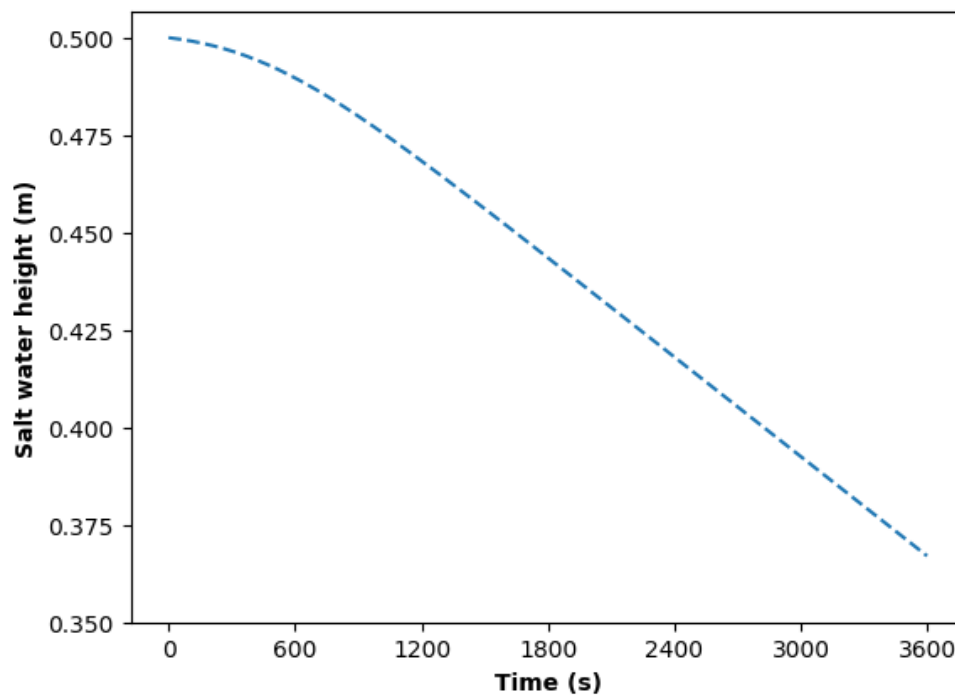


Figure 2. Variation in salt water height over time.

Figure 3 presents the evolution of the concentration in the desalination unit. Since there is no salt inlet or outlet, the concentration increases due to water evaporation. The final salt concentration in the brine was 0,048% (m/m).

Source: The authors.

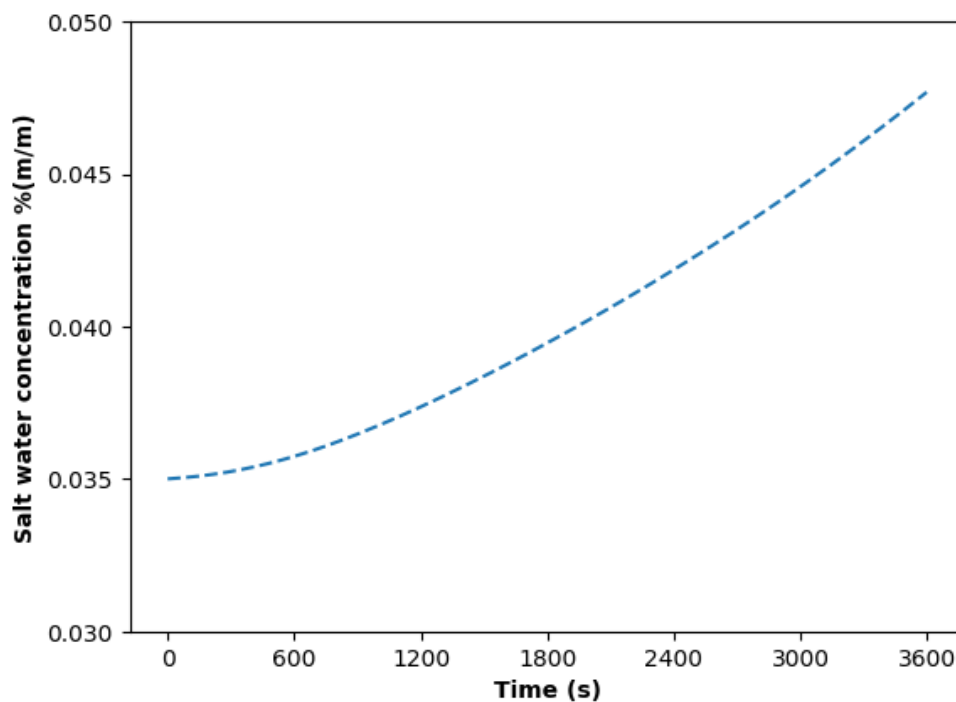


Figure 3. Variation in salt concentration in salt water over time.

Figure 4 presents the results of the salt water temperature variation over time. The heat supplied initially is used for both evaporation and energy accumulation, in the form of sensible heat through the temperature increase. This energy is transferred via heat exchange between the heated working fluid and the salt water. When the temperatures equilibrate, the heat supply ceases. The temperature stabilizes around 49°C, indicating an equilibrium between the heat derived from solar energy and the losses to the environment and those due to evaporated water leaving the system.

Source: Authors own elaboration.

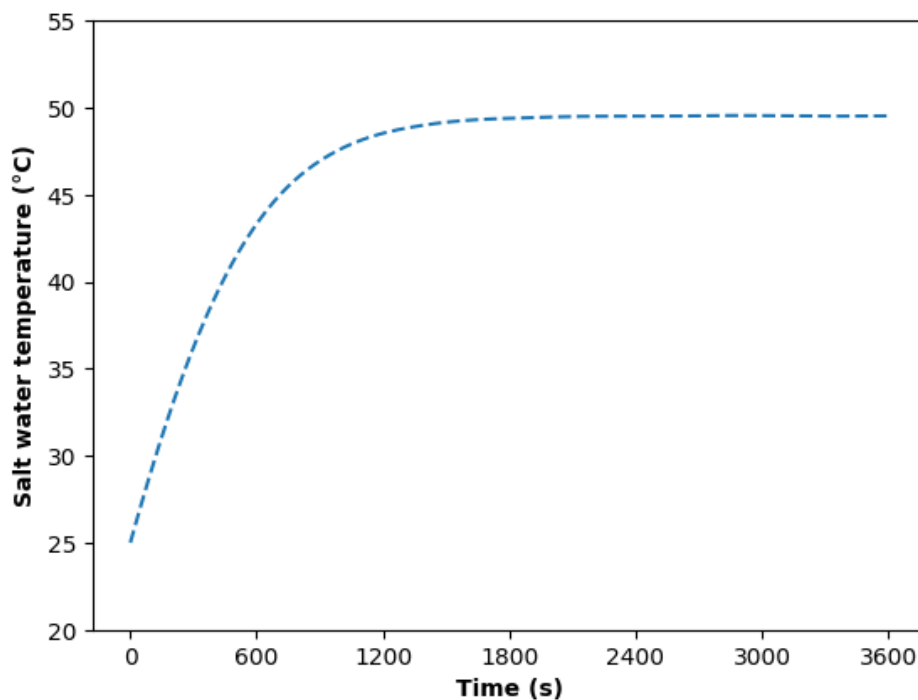


Figure 4. Variation in salt water temperature over time.

Figure 5 presents the results for desalination unit water production and for the desalinator's roof capacity to dissipate latent heat from the generated vapor into the environment. The thermal conductivity of the stainless steel was considered to be $15 \text{ W/m} \cdot ^\circ\text{C}$, with a thickness of $0,005 \text{ m}$, and the convective heat transfer coefficient of the air was considered to be $10 \text{ W/m}^2 \cdot ^\circ\text{C}$, representing natural convection. Thus, the condensation process managed to condense all the vapor, resulting in an approximate production of 130 kg of desalinated water.

Therefore, the results show an expected behavior and the condenser managed to condense the generated vapor.

Source: The authors.

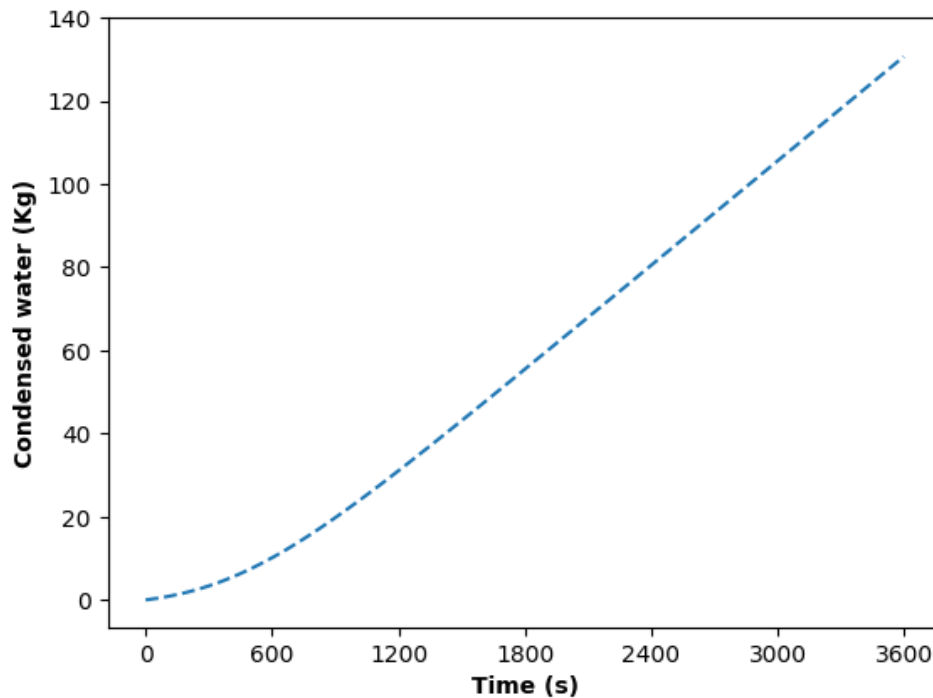


Figure 5. Graph of condensed water in the desalination process.

CONCLUSION

This study developed a phenomenological dynamic model of a solar thermal desalination system based on atmospheric-pressure evaporation, demonstrating its technical viability for isolated regions and eliminating the need for electrical energy and heating from other auxiliary sources. Therefore, the model can present lower energy, operational, and maintenance costs. The simulation results indicate that the system can continuously produce desalinated water and exhibits an efficient evaporation rate. Furthermore, the condensing surface capacity to convert all generated vapor into liquid water was confirmed.

The mathematical model, composed of coupled differential equations, adequately described the behavior of the system variables over time, including variations in water level, salt concentration, and saltwater temperature. The parameters and initial conditions based on previous studies ensured the consistency of the results. Therefore, in future work, a prototype will be built to experimentally verify the model, confirming and strengthening its outcomes through comparison with real data.

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