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Experimental and Analytical Study of a Single Effect Distillation Using Electrical Evaporator Powered by Solar Energy

Saeed J. Almalowi[*]

Mechanical & Manufacturing Engineering Department, Jubail Industrial College, The Royal Commission for Jubail and Yanbu, Jubail, Saudi Arabia
Email: *malouis@rcjy.edu.sa

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Abstract

The experimental and analytical investigation was conducted on a solar-powered single-effect distillation (SED). The evaporator was designed to be an electrical evaporator as opposed to the steam evaporator that existed previously. Using sun-tracking solar panels, the electrical evaporator in the designed distillation unit was powered by solar energy. Approximately 20 kWh was utilized by the small-scale distillation apparatus. This type of design is mobile, so remote areas and countries with fragile economies can utilize it on a small or large scale. Utilizing the principles of energy and mass conservation, the amount of distillate water and power required for a single unit was determined, at the low salinity (2200 PPM) with fixed boiling point temperature ($T_b = 75^\circ\text{C}$), the unit performance is approx. 98.4%. The experimental results and those derived from a mathematical model were compared, and both showed strong accord. Using engineering equation solver (EES) software, a computer program was developed for this research scenario.

Keywords

Distillation, Single, Effect, Solar, Potable, Salt

1. Background

Population expansion necessitates more potable water for consumption, washing, and irrigation. The desalination of seawater has gained widespread use throughout the globe. It is a technology that separates ions and sediments through a series of processes so that potable water is produced. Healthy and safe consumption has become a greater global concern, so desalination is the finest method for desalinating salty water and generating electricity. The majority of water desalination facilities continue to use conventional methods that negatively impact the environment to desalinate water. The Shoaib Power and Desalination Plant is among the most intriguing examples. This plant is the largest of its kind in the globe. This facility is dependent on polluting energy sources for operation. To comply with the vision of the Kingdom of Saudi Arabia, which supports the use of all modern technologies to reduce emissions and pollutants, this facility must rely on renewable energy sources.

Desalination of water is one of the most energy-intensive industrial processes. The dependence of desalination facilities on non-renewable resources such as fossil fuels, which increases the risk of dependence, is the primary issue. Renewable natural resources, such as solar energy, assure a constant supply of potable water. Numerous studies have been conducted on water desalination systems. In his 2014 research paper, J. A. M. D. M. Alves noted that the use of solar energy has existed for centuries and that it is still a developing field. This procedure was designed to produce desalinated water [1]. It was used by converting solar thermal energy into a form that could be directly collected and utilized as solar stills. As technology advanced, one of the more recent systems utilizes solar energy from a solar thermal collection system to power the thermal desalination process. He also asserts that there are multiple ways to utilize renewable energy for beneficial purposes; solar stills are among these technologies.

The water evaporates as the temperature rises, and the vapor condenses on the transparent lid. This method is impractical for large-scale production because it requires extensive space and is more costly than alternative desalination systems. In his investigation, Alves also identified solar ponds as another type of solar desalination system that collects and stores thermal energy. The chemical composition of the system enables solar ponds to store thermal energy. They consist of three levels: The uppermost stratum is known as the convection layer. The stratum in the middle is known as the salinity gradient zone. The stratum beneath is the storage area. As with the lower layer, it is observed that the salinity of the upper layer is constant. However, salinity increases with depth in the middle stratum. Solar ponds are advantageous due to their large storage capacity and the ability to reuse saline in their construction [2] [3]. The global distribution of water resources over decades is depicted in **Figure 1** [4].

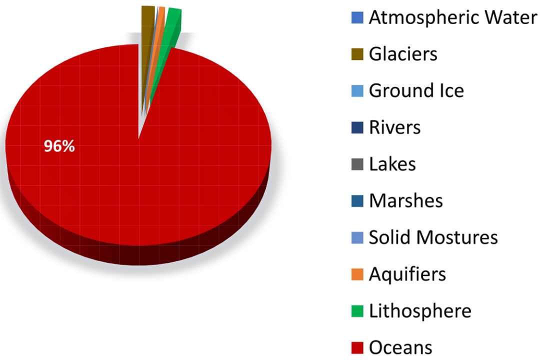


Figure 1. The distribution of water resources.

World population expansion requires cleaner and more abundant water. The population will increase progressively from 1 billion in 1804 to 9 billion in 2050, as shown in **Figure 2** [5].

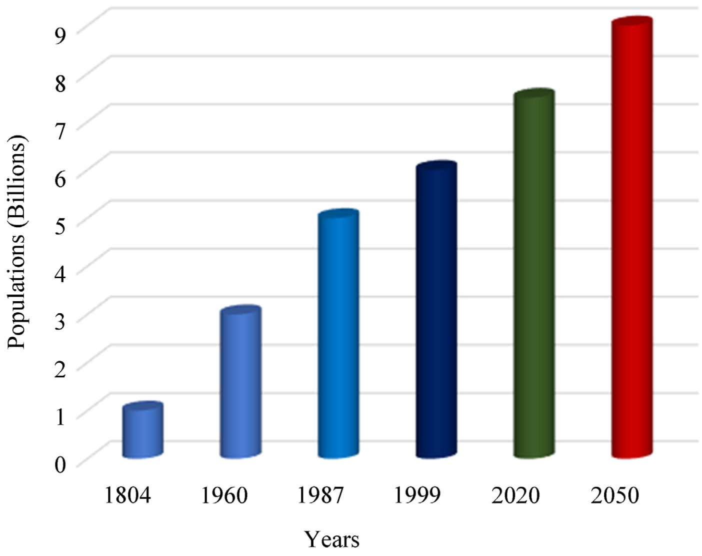


Figure 2. The growth of the world populations over 200 years.

The salinity of water can be classified according to the percentage of salt in parts per million (ppm), as shown in **Table 1** [6].

Table 1. Categories of the water salinity and consumption.

Resources	Salinity (PPM)	Purposes	Consumption (s)	
Rivers and lakes	5 - 1000	Drinking	Type	Amount
Wells	1000 - 3000	Irrigation	Drinking	2 L/day/a person
Seas	3000 - 10,000	N/A	House hold	200 - 400 L/day
Oceans	>10,000	N/A		
Gulfs	>30,000	N/A		

The origins of desalination technology can be traced back to 1800, when desalinization was first used on ships. In 1957, Kuwait constructed its first industrial thermal desalination plant. It was a blinking system with four stages (FSF) [7] [8]. Up until the year 2000, various desalination technologies, including reverse osmosis units (RO), multi-effect desalination (MED), and multi-stages desalination (MSF), were devised, manufactured, and constructed in various nations [9]. The largest MSF in the world, producing approximately 106 m3/day, was established in the Kingdom of Saudi Arabia. [10]. It was constructed in Al-Jubail. **Figure 3** depicts the desalination production capacity of the Gulf states, the United States, and other nations [11].

Fakhra Jabeen et had developed the experimental study to investigate the effect of the rate constant on concentration. They found that the rate constant is not concentration dependent Also, they found that the rate constant for the hydrolysis of ethyl acetate with sodium hydroxide using hydrochloric acid as a catalyst at 27˚C is approximately 0.003 min^{-1} cm [12].

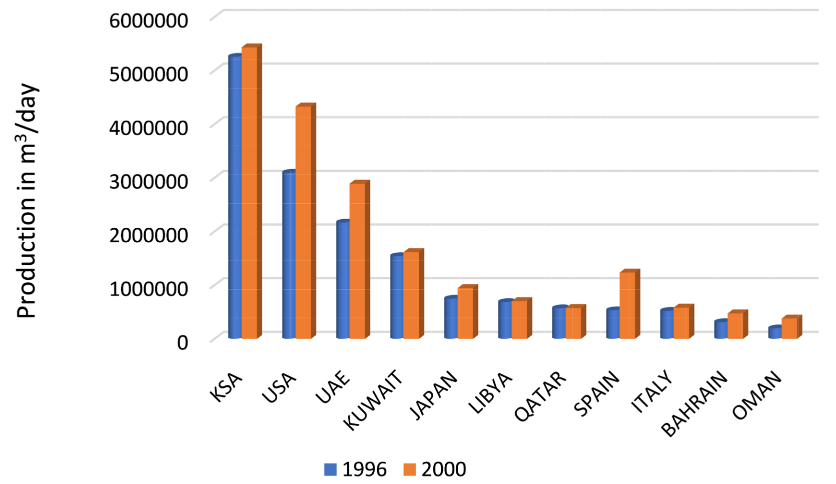


Figure 3. Production in m^3/day in the selected countries.

Also, Fakhra Jabeen et had studied the use of polymer composite membranes in treating wastewater. A brief description of synthesizing these membranes through different routes is given and is reviewed critically [13].

2. Study Methodology

The experimental and analytical investigations for a single-electrical evaporative desalination unit have been examined. The small-scale distillation unit has been designed and manufactured with the following 11 components, as shown in **Figures 4(a)-(b)** and **Figure 5** which consist of an electrical heater (1), four wheels (2), a brine water drainage valve (3), a feed water valve (4), a distillate water tank (5), an upper unit base (6), a condenser unit (7), a feed water tank (8), a glass covering unit (9), a distillate water hose (10) and a brine water drainage hose (11). In **Figure 5**, the schematic diagram depicts all distillation components. The mathematical model was developed using each component's mass and energy conservation. Utilizing the engineering equation solver program. On the evaporation unit and condenser unit, the steady energy and mass balance were implemented.

$$\dot{E}_{in} = \dot{E}_{out} \tag{1}$$

$$\sum_{k=1}^{n} \dot{m}_{i_k} = \sum_{k=1}^{n} \dot{m}_{e_k} \tag{2}$$

Applying the conservation of mass and energy principle on the evaporative unit yields:

$$\dot{m}_f = \dot{m}_d + \dot{m}_b \tag{3}$$

$$\dot{Q}_e + \dot{m}_f h_f = \dot{m}_d h_d + \dot{m}_b h_b \tag{4}$$

Applying the conservation of mass and energy principle on the condenser unit yields:

$$\dot{m}_f h_f + m_d h_c = \dot{m}_{cw} h_{cw} + \dot{m}_d h_d \tag{5}$$

The enthalpies in the energy balance can be represented by the temperature as:

$$\dot{Q}_e + \dot{m}_f C_p T_f = \dot{m}_d C_p T_d + \dot{m}_b C_p T_d \tag{6}$$

$$\dot{m}_f C_p T_f + m_d C_p T_c = \dot{m}_{cw} C_p T_{cw} + \dot{m}_d C_p T_d \tag{7}$$

The design parameters, such as heat transfer surface area are important in this design. The heat transfer area can be evaluated as:

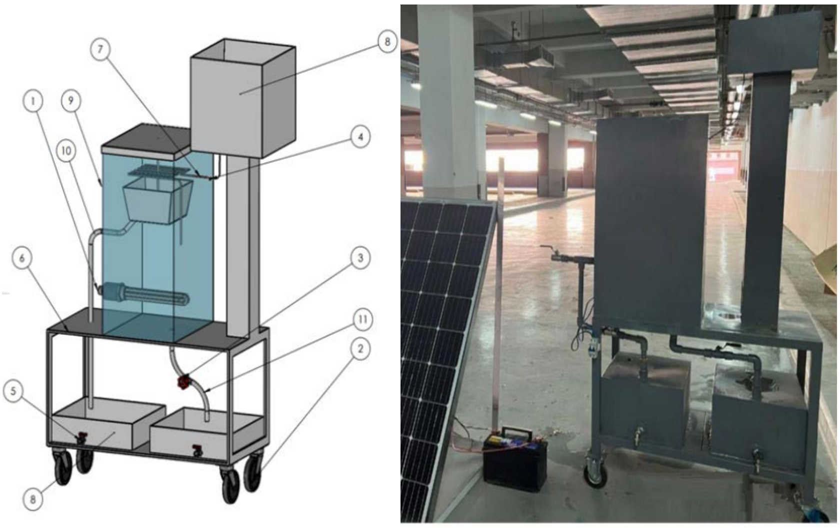
$$A_e = \frac{Q_e}{U_e \left(T_{in} - T_b\right)} \tag{8}$$

$$A_c = \frac{Q_c}{U_e \left(LMTD\right)_c} \tag{9}$$

The performance of this unit can be evaluated by:

$$PR = \frac{Q_d}{Q_e} = \frac{m_d h_d}{IV\Delta t} \tag{10}$$

The DC current (I) and voltage (V) were measured by the multimeter device.



(a)

(b)

Figure 4. (a) Experimental components and (b) experiments demonstration unit.

3. Results and Discussions

Figure 6 illustrates the effect of salinity on the boiling temperature elevation, demonstrating that a higher salinity weight percentage requires a higher boiling point temperature elevation (BPE) in the boiling temperature range (50˚C - 115˚C).

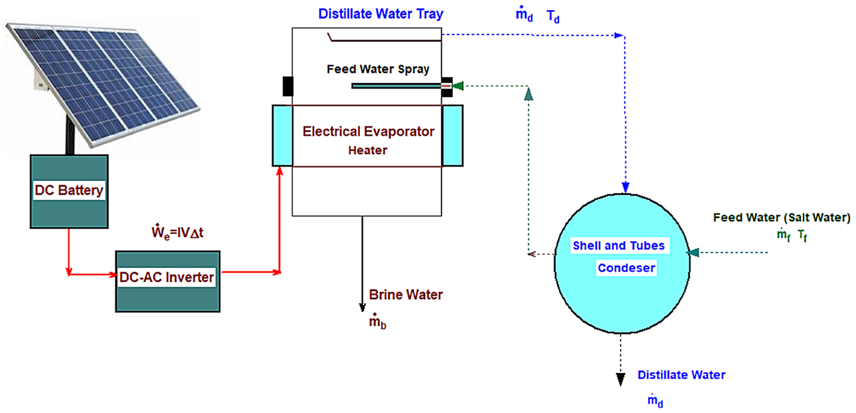


Figure 5. Schematic diagram of a single effect distillation unit.

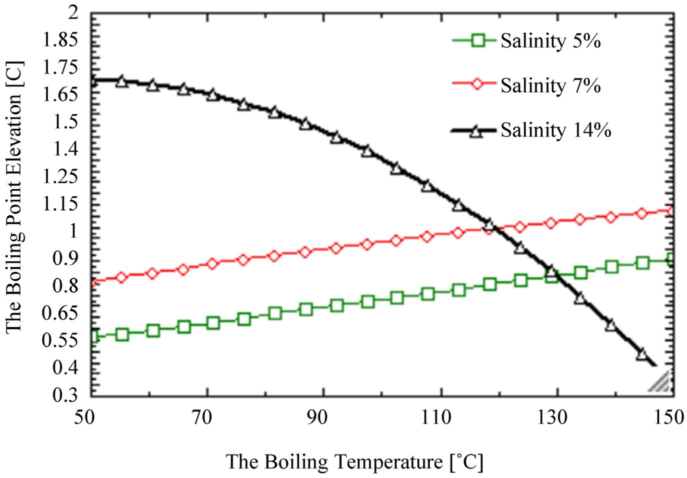


Figure 6. Effect of the salinity percentage on the boiling point elevation for various boiling temperatures.

In addition, the study demonstrates the influence of feed water salinity in parts per million (PPM) (Measured at 4200 PPM, 3200 PPM, and 2200 PPM) on the performance of the unit at varying boiling temperatures. As shown in **Figure 7**, the performance of the unit at the same boiling temperature demonstrates that the law of salinity makes the unit more efficient than those with a higher salinity.

As operational conditions, the temperature of the input water can directly influence the size of the evaporator unit. At the same temperature as the boiling point (T_b), the evaporator unit becomes smaller. When the input water temperature is 40 degrees Celsius, the smallest evaporator size will occur at $T_b = 70$ degrees Celsius as shown in **Figure 8**.

The unit performance ratio of electrical and steam evaporators has been analyzed. As shown in **Figure 9**, the results indicate that the electrical evaporator is more effective than the steam evaporator at the same boiling temperature.

In addition, the study compared the aggregate heat transfer coefficient (U) between the analytical solution and the experimentally determined values. As depicted in **Figure 10**, they exhibit significant agreement.

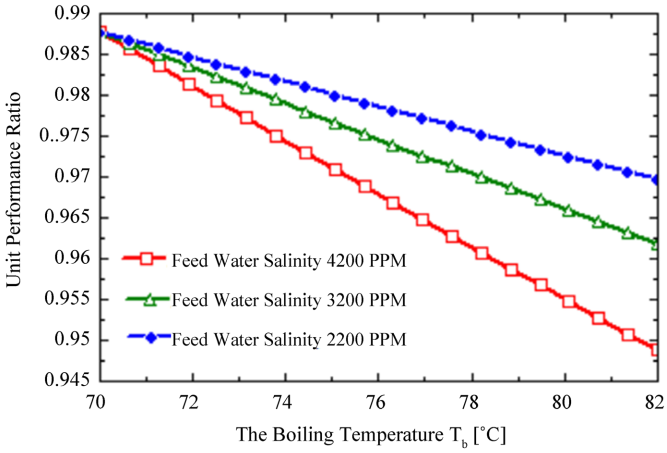


Figure 7. Effect of the feed water salinity on the unit performance for various boiling temperatures.

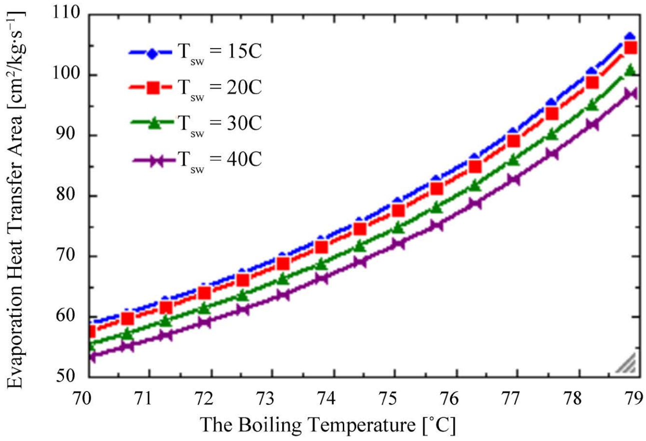


Figure 8. Effect of the feed water temperature (T_{sw}) of the heat transfer area ($cm^2/kg \cdot s^{-1}$).

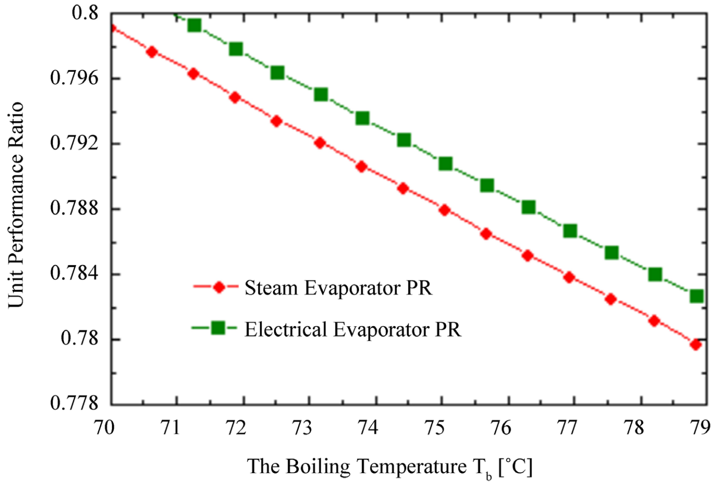


Figure 9. The unit performance ratio (*PR*) of the electrical and steam evaporator.

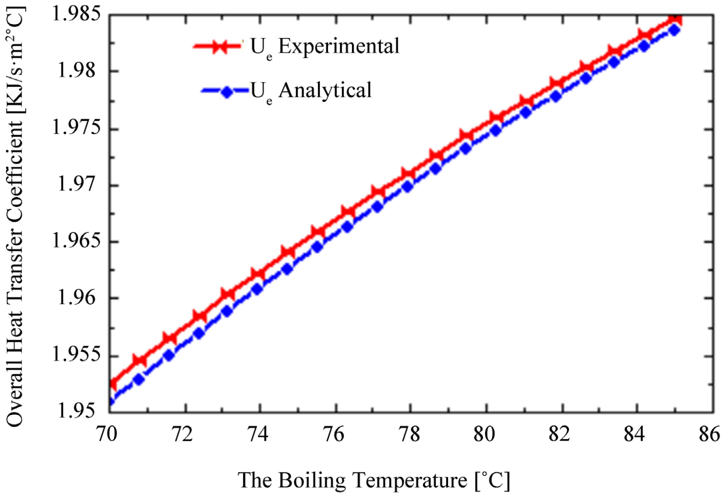


Figure 10. Experimental and analytical comparison of the overall heat transfer coefficient (KJ/cm² s·°C).

4. Conclusion

In this study, the design and operational parameters of a solar-powered single-effect evaporative distillation unit were examined to determine the effect of varying parameters. Important operational parameters included supply water temperature, boiling temperature, and salinity. The study also compares the electrical evaporator unit to the steam evaporator unit. Under identical conditions, the electrical evaporator is more effective than the steam evaporator. At high salinity (4000 PPM) with fixed boiling temperature (T_b = 75°C), the unit performance is 97% which drops to around 2%. In addition to that the unit performance of the electrical evaporator is more efficient than the steam evaporator. Therefore, the solar-powered electrical evaporator distillation unit will be one of the environmentally favorable distillation technologies that contribute to the reduction of global warming.

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Nomenclatures

$\mathbf{U_e}$, $\mathbf{U_c}$	Evaporator and condenser overall heat transfer coefficient (KJ/cm² s·°C), respectively.
PR	Unit performance ratio
T_b	Boiling temperature (°C)
BPE	Boiling point elevation (°C)
$X_{f,b,d}$	Salinity of feed, brine, and distillate water (PPM)
$Q_{e,c,d}$	Evaporator, condenser, and distillate heat transfer (kJ/kg)

Continued

$\dot{m}_{f,d,b}$	Mass flow-rate of feed, distillate, and brine water (kg/s)
$A_{e,c}$	Heat transfer surface area of evaporator and condenser (m^2), respectively.
T_f	Feed water temperature (˚C)
T_d	Distillate water temperature (˚C)
$\dot{\mathbf{W}}\mathbf{e}$	Electrical power (kW)

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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