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Investigation of the Solar Water Desalination Efficiency Using Solar Evaporation System

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Abstract
Several types of research have been performed to desalinate the water efficiently. Solar energy, as a low-cost, abundant, and clean energy, has a great potential to alleviate water shortages. Solar water desalination has been considered as an efficient method to utilize in the water desalination process. A solar water evaporation and condensation system are implemented to desalinate water. Solar evaporator system has been proposed and used to produce clean water. High solar energy conversion efficiency requires excellent light absorption, thermal conduction, and water supply performance. Several parameters, such as fluid inlet temperature or inlet velocity, were investigated. The results indicate the best performance in the 1 L/min flow rate and 0.6 m of tube length. Computational fluid dynamics using the COMSOL program was used to analyze the process and find the optimum process conditions.

Keywords: Water, Desalination, Solar System, Fluid Dynamics, CFD, COMSOL.

1. Introduction
Water is one of the vital resources for humans as well as the development of societies (Trenberth et al., 2011; Zhao et al., 2020). Although more than 70% of the earth is covered by water, less than 3% is usable for humans, which is scattered and uneven. Therefore, people in different countries are facing various problems, including diseases and health problems, due to the lack of drinking water. Utilizing water directly or indirectly depends on our activities, such as agricultural, industrial, and domestic (Al-Kharabsheh and Yogi, 2003; Loucks and Beek, 2017). Water resources have declined due to a number of factors such as the increasing industrial and agricultural activities, world population, groundwater salinity, and decline in rainfall. Salty water can be treated by several methods, but each one has its own advantages or disadvantages (Green, 2016; Shahbaz and Ashraf, 2013; Shrivastava and Kumar, 2015). Producing fresh water would consume a huge amount of energy, so this is important to consider an alternative economic desalination water method (Al-Kharabsheh and Yogi, 2003; Esmaeilion, 2020). In this regard, many efforts have been made by researchers to develop water purification technology (Lin et al., 2019; Xu et al., 2019; Yang et al., 2022), including reverse osmosis,

electrodialysis, thermal distillation, and thin-film distillation (Li et al., 2019).

Solar energy has been utilized for several applications, such as water heating, power generation, and water desalination, due to the arrival of photothermal conversion (Hammond, 1972; Lewis, 2016, 2007). The employment of solar energy for water purification has been receiving more and more attention due to the low cost and effectiveness of this method (Cao et al., 2019; Xie et al., 2022). Researchers have made many efforts to increase the efficiency of converting light into thermal energy for water evaporation in solar steam systems (Kong et al., 2022; Lu et al., 2022; Zhao et al., 2020). As a green and economical method, solar water desalination can be implemented as a portable way for water desalination in both rural and urban locations (kalogirou, 2005). In comparison to the traditional methods, such as traditional thermal and membrane-based methods, which required complex substructures, or vent waste gases into the environment, and consume electricity, solar distillation has been recognized as one of the eco-friendly technologies to reduce freshwater famine (Mezher, 2011; Mezher et al., 2011; Service, 2006).

Due to improved evaporation efficiency as a result of extensive solar absorption and improved thermal handling, solar desalination by interfacial evaporation presents remarkable promise for supplying clean water solutions (Bai et al., 2020; Cao et al., 2019). It was found that the temperature difference between the water surface and the glass cover would affect the mass transfer rate (Abdul-Wahab and Al-Hatmi, 2012; Yadav, 1993). Several research groups have studied the effect of occlusion of the solar still to a flat plate solar collector to elevate this temperature (Boukar and Harmim, 2001; Tiwari et al., 1996; Kumar and Tiwari, 1996; Lawrence and Tiwari, 1990). Solar system efficiency would increase with the reduction of pressure due to evaporation at a low temperature while implementing vacuum conditions (Al-Kharabsheh and Yogi, 2003; Fernández and Chargoy, 1990).

A high-efficiency solar distillation system coupled with a solar water heater was designed by El-Agouz et al. to improve the evaporation rate by spraying water at low temperatures. In this study, the maximum daily productivity of the system and the maximum day efficiency in the new desalination system were, respectively, about 9 L/m^2 and 87% (El-Agouz et al., 2014).

In another research, Nkwetta et al. improved the output in a solar still by employing evacuated tubes with heat pipe in the system (Nkwetta et al., 2013).

Hayek et al. compared the efficiency of water in a glass evacuated tube and a heat pipe tube. The obtained results showed the heat pipe evacuated tube had a higher output than the other system (Hayek et al., 2011).

The study of Daghigh and Shafieian on an evacuated tube in a solar water heating system demonstrated that the employment of an evacuated tube gives a higher output water temperature (Daghigh and Shafieian, 2016).

Singh et al. used evacuated tubes with solar still to evaluate the thermal performance and found that the system possessed a higher output compared to evacuated tubes. The highest efficiency was achieved for the system with 0.03 m water depth and 10 evacuated tubes (Singh et al., 2013).

Sampathkumar et al. proved that the heat energy supplied from an evacuated tube increased the basin water temperature and enhanced the output of the solar still (Sampathkumar et al., 2012).

Jowzi et al. modified an evacuated tube system with a bypass tube to attach the bottom of a storage tank to the bottom of the evacuated tube. Their results showed that the modified system removed the stagnant region and increased the thermal efficiency (Jowzi et al., 2019).

Huang et al. experimentally and theoretically demonstrated that the attachment of a heat shield between the absorber plate and the glass tube in an evacuated tube collector reduces heat loss. Their results showed that the thermal efficiency of the system increased by increasing the water flow rate, solar radiation, and ambient temperature (Huang et al., 2019).

According to the literatures, most of the previous works investigated the effect of some parameters such as fluid inlet temperature and inlet velocity on the efficiency of the solar distillation systems.

In this work, a solar system is utilized to evaporate the water under the natural evacuation to water desalination. The effect of various parameters such as tube length, or inlet water flow rate on water desalination has been investigated. Also, computational fluid dynamics[1] implementing Comsol software is used to study transport phenomenon of the desalination process and find the best operation conditions.

2. Experimental

2.1. Solar water desalination setup

To study water desalination with solar energy an evacuated solar system was implemented. The mechanism of desalination in Fig. 1 and the utilized solar desalination system have been shown in Fig. 2 schematically. Several tubes are connected to a manifold, while this manifold acts as a distributor of inlet water to the tubes. There is an annulus structure for each tube, where the inner tube is coated with a light absorbent to absorb maximum solar light energy. The density of water would decrease due to heating with sunlight, where the cold water will enter the evacuated tube. The hot flow will then be passed to a condenser to collect the desalinated water.

[1] Computational Fluid Dynamics (CDF)

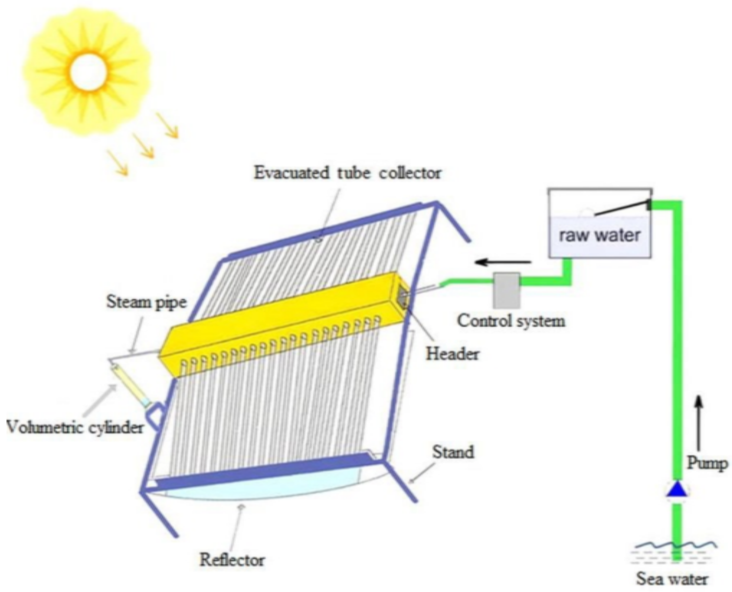

Fig. 1. Schematic of desalination mechanism

The properties of the vacuum tube collectors in the solar desalination systems have been shown in the Table 1. Desalination of salt water in a vacuum is based on the boiling of water at a pressure lower than the atmosphere and as a result, the heat is much lower than normal. So, vacuum tube collectors are used to increase the rate of heat transfer to salt water.

The data were collected for three days in three months at a constant flow rate and tube diameter, while the effect of flow, and tube diameter on the solar water desalination efficiency was also investigated.

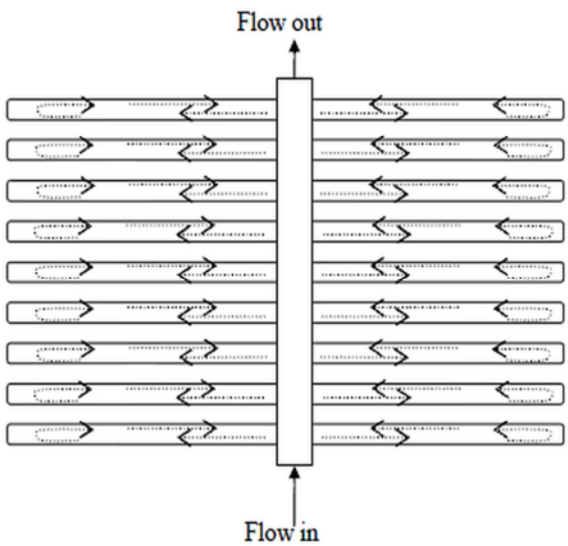

Fig. 2. Schematic of the solar system utilized for water desalination

2.2. Mathematical modeling

Mathematical modeling is performed to evaluate the operating parameter and find the best-operating conditions. By considering a cylindrical energy element for the solar water desalination tube (Fig. 3), the Q_R entered the outer tube and was placed on the surface of the inner tube due to the formation of a gap between the tubes. The below equation can be written

$$\frac{\partial T}{\partial z}=\frac{\rho}{\dot{m}c_p}h\Delta T \quad (1)$$

Where

h, cp, and ṁ, are convective heat transfer coefficient, fluid heat capacity, and mass flow rate, respectively. In order to derive Eq. 1, it was assumed that, 1. There is no conduction heat transfer in the angular (θ), length (Z), and radius (r) directions, 2. Neglected convective heat transfer in the radial (r) and angular (θ) directions. The heat loss in the tube is presented in Fig. 4. Due to its small value, we ignored it.

After integration of both sides of equation 1, the following equation would be written

$$\ln\frac{\Delta T_0}{\Delta T_i}=-\frac{\rho L}{\dot{m}c_p}\bar{h}_L \text{ , } T_s=\text{Constant} \quad (2)$$

2.3. Solution procedure

A developed 1D model using COMSOL multiphysics software has been used to solve Eq. 1 with reported model parameters. A single annular tube of solar desalination system was used to analyze transport phenomenon over the desalination system. The geometry

Table. 1. Properties of the evacuated tube collectors

Length	1800 mm
Outer diameter	58 mm
Inner diameter	47 mm
Weight	8.2 kg
Thickness	2 mm
Material	borosilicate glass
Solar energy adsorbent coating	Aluminum-stainless steel-copper
Vacuum value	More than 3 × 10^5 Pa
Solar energy absorption efficiency	95%
Forest resistance	Up to 35°C
Hail resistance	Up to 35 mm
Wind resistance	Up to 30 m/sec

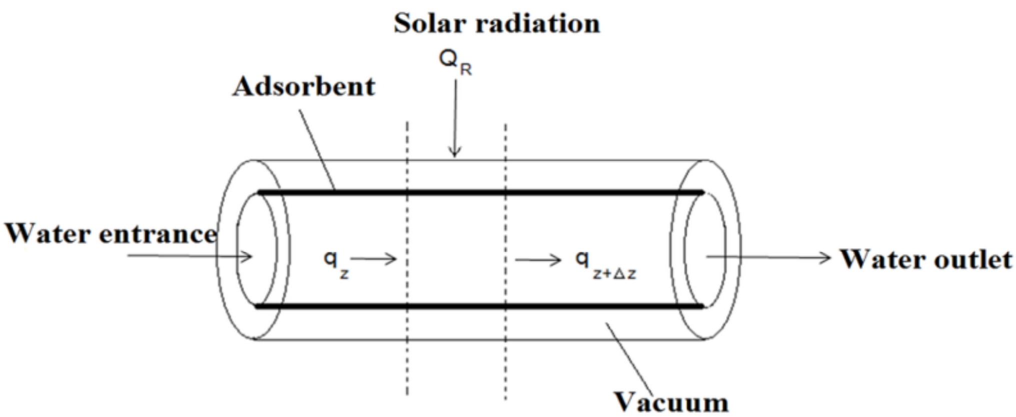

Fig. 3. Mathematical models of solar thermal collectors and selected elements for modeling of the solar system

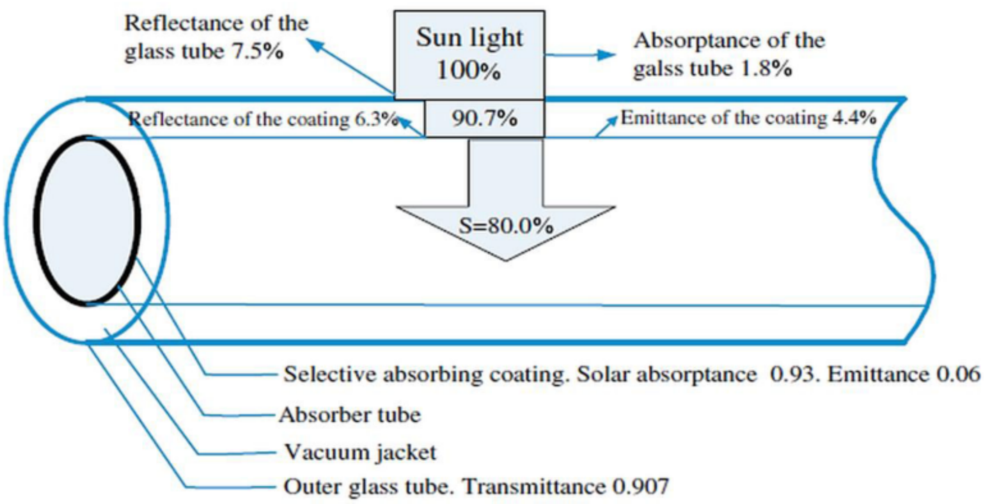

Fig. 4. Heat losses in tube

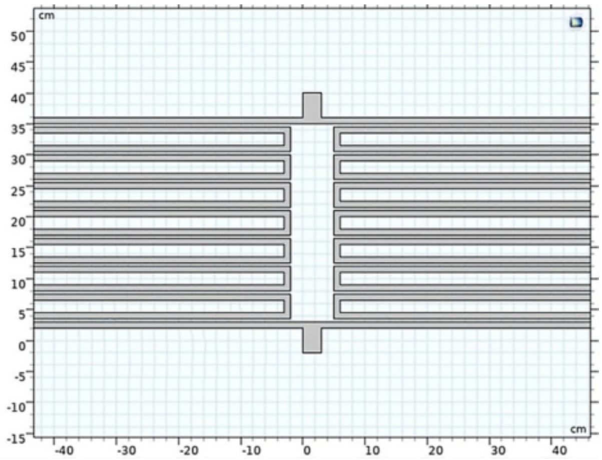

Fig. 5. Geometry of the model

of the model is shown in Fig. 5. After creating the geometry and assigning the physics to the model, the next significant step is to build the mesh. The mesh used for a model geometry plays an instrumental role in how the model is solved, as it determines factors such as, how the geometry is divided, with what shape or element type; the geometry is divided by the size, density, and a number of elements in the geometry. The element quality of these factors directly affect the computation of a problem, including how long it takes a model to solve, the amount of memory required to compute a problem, how the solution is interpolated between nodes, and the accuracy of the solution.

3. Results and discussion

3.1. Effect of initial temperature and inlet velocity

The solar desalination process during a 6.5 h period divided into 30-minute intervals was used to investigate the effect of fluid inlet temperature. The process started at 9:30 am and continued until 4 pm. Figure 6a shows the effect of the initial temperature on the desalination process using a solar system performed in March, April, and May. Accordingly, the same trend for all of the periods in the mentioned three months exists, while a higher water temperature was achieved in the middle of the day (12-1 pm). Besides, the maximum temperature belongs to May (about 62 °C), and the water meets the higher inlet temperature. However, the effect of initial temperature on the heat transfer coefficient and fluid receiving heat was investigated in Fig. 6b and 6c. Accordingly, the convective heat transfer coefficient has increased with an increase in the inlet temperature of water due to a higher vacuum in the tubes. A higher vacuum would lead to an excessive convective heat transfer flux due to the higher speed of the fluid in the tubes. Convective heat transfer coefficient and received heat (kJ/hr) are maximum in May with about 280 W/m^2. °C and 285 kJ/hr, while the minimum of that is in March with about 270 W/m^2. °C and 274 kJ/hr.

The effect of inlet velocity on the solar water desalination is shown in Fig. 7. Generally, due to the increase in the water inlet velocity, outlet temperature has declined. However, no significant change in the outlet temperature is observed by rise in inlet flow from 0.5 to 1 L/min, but the outlet temperature has declined significantly at higher flow rates. Higher flow rates would lead to a drop in the heat received by fluid in the tube due to lower contact time.

- Process modeling

COMSOL multiphysics program was used to study transport phenomenon happening in the solar desalination system tube. For these several inlet temperatures, received heat (radiation heat source) and inlet velocity have been considered the important parameters that affected water desalination. Figure 8a shows the effect of the initial temperature on the outlet temperature, and the convective heat transfer coefficient of the fluid passed a single tube in a constant fluid flow rate. Also, as discussed in the previous section, there is different received heat in different months, so the received heat changes by setting the initial temperature.

Fig. 8a indicates that an increase in the inlet temperature due to receiving higher solar heat depends on the month that it occurs in. Furthermore, the temperature has increased to about 1.4 m of the tube, but after the 1.4 length of the tube, the rise-up temperature rate has declined. For instance, 298.15 K starting temperature ix almost a 310 K final temperature after 1.4 m of the tube. A decline in temperature growth would contribute to lowering heat transfer by an increase in temperature and close to surface temperature. Variation of the convective heat transfer coefficient by tube length is shown in Fig. 8b. Accordingly, a slight increase of convective heat transfer coefficient to about 0.6 m of tube is followed by a sharp increase in heat transfer coefficient due to a decline in temperature difference between the fluid and surface temperature (according to equation 2). However, Fig. 8b indicates a higher heat transfer coefficient (about 600 W/m^2.K for 90 W compared to about 350 W/m^2.K in 70 W received heat) at higher temperature and received head by fluid that may lead to closer fluid and surface temperature.

The effect of tube length and flow rate of fluid on the water desalination solar system was investigated in Fig. 9. According to Fig. 9, due to an increase in received heat, decrease in the flow rate would lead to higher water desalination efficiency. On the other hand, the variation of tube length indicates proper performance in the 1.5 m of tube length (by 334 K final temperature), which may be attributed a higher received heat in this length. Furthermore, by shortening tube length to 1 and 0.5-meter, solar water desalination performance has declined, while the final temperature has reached 315 K

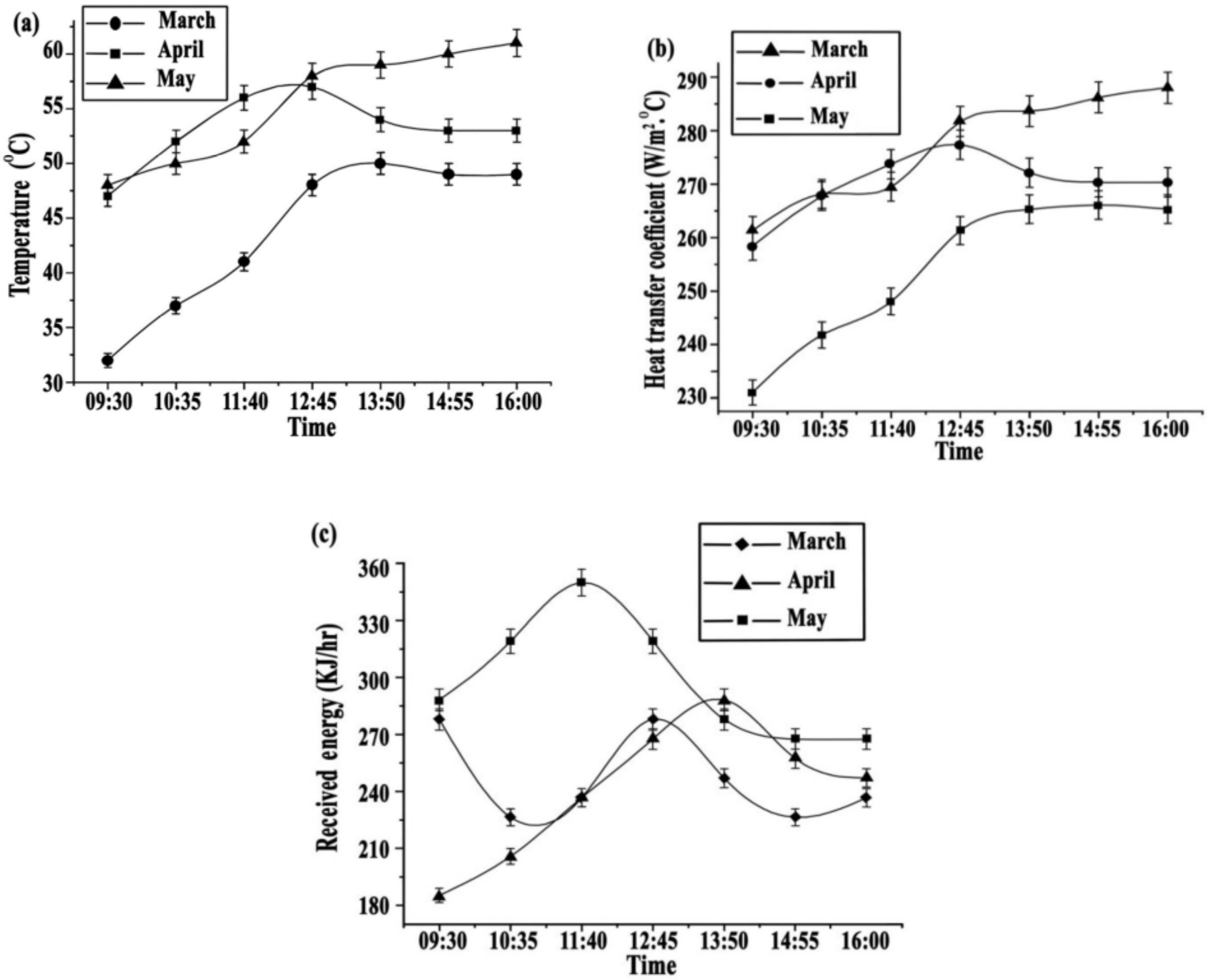

Fig. 6. Effect of time of a) final temperature of the water, b) received heat transfer and c) convective heat transfer coefficient

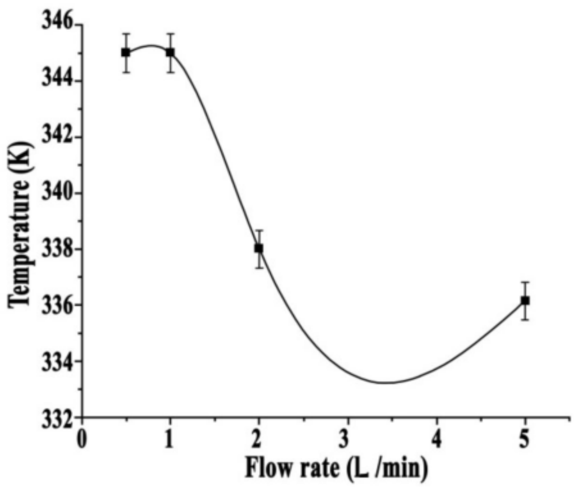

Fig. 7. Relation between temperature and flow rate on the water desalination solar system

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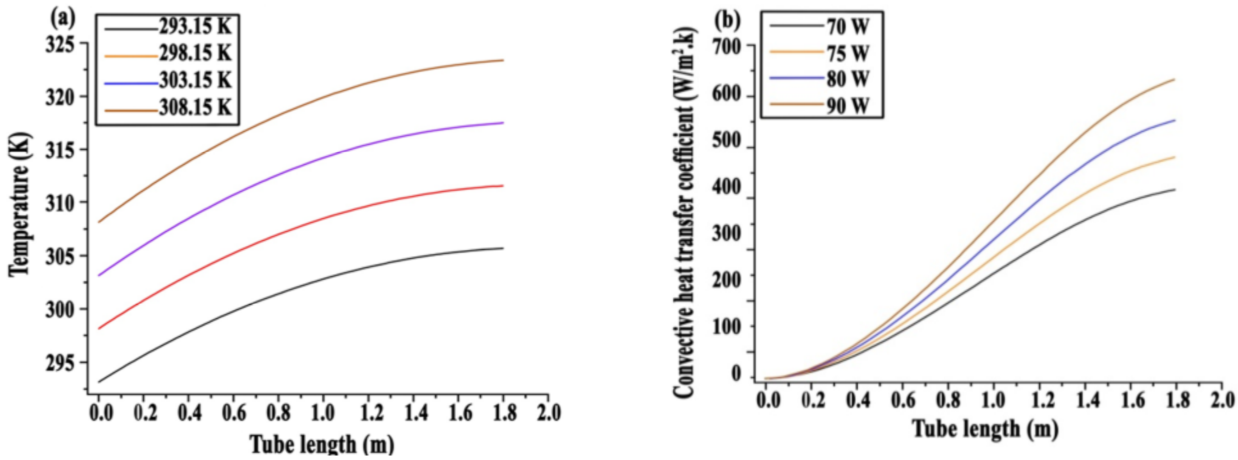

Fig. 8. a) Temperature distribution and b) convective heat transfer coefficient (W/m^2.K) over the tube length in the 0.5 L/min flow rate

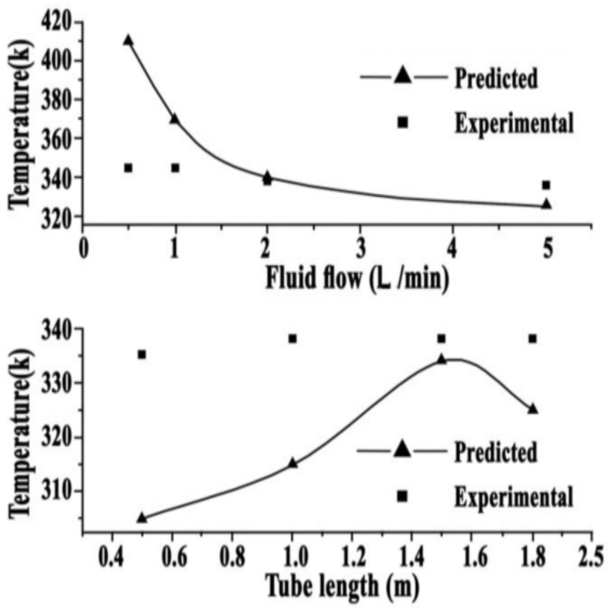

Fig. 9. Effect of tube length and fluid flow on the water desalination performance

and 305, respectively. Results indicate that by decreasing the tube length to about 1 m, solar water desalination performance has not changed significantly.

Furthermore, a comparison of the experimental results and predicted results of variation of tube length and flow rate in the solar water desalination has been made in Fig. 9. The experimental results indicate a performance drop by the lower length of the tube, while the predicted results reveal a significant performance decline by a decrease in the tube length in the constant flow rate. Besides, a similar behavior is observed for the variation of flow rate on the water desalination process, in which both experimental and predicted results reveal an increase in performance. An 80 K increase in fluid temperature was predicted by mathematical modeling over the tube by the decline in the flow rate, while experimental results indicate just a 20 K growth of the outlet temperature of the desalinated fluid.

4. Conclusion

A solar water desalination system was used to desalinate the water at atmospheric pressure for several months of a year. The data were collected in March, April, and May. Results indicate that the performance of the water desalination has been enhanced by moving forward to May, in which the inlet water temperature and received heat was higher compared to the previous months. Also, the variation of tube length and flow rate in the solar water desalination process have been investigated. Results indicate the best performance in the 1 L/min flow rate and 0.6 m of tube length. COMSOL multiphysics program was utilized to study the transport phenomenon that happened in the solar water desalination system. Simulated results revealed better performance by an increase in the received heat and inlet temperature. Also, a better performance by utilizing 1.5 m of the tube in 1 L/min of flow rate. However, results revealed the proper performance of the solar water desalination system that can be used economically and that is environmentally friendly.

5. Acknowledgment

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Nomenclature

C_p	Specific heat capacity
h	Heat transfer coefficient
K	Kelvin temperature scale
L	Length
$\dot{m}$	Mass flow rate
ρ	Density
Q	Volume rate of flow
T	Temperature or Celsius temperature scale

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