Modeling the Feasibility of Employing Solar Energy for Water Distillation

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Abstract

The world's demand on drinking water has been increasing enormously during the last few decades. Solar distillation may become a potential alternative for water treatment. The feasibility of using solar energy for water distillation was identified by modeling the water temperature profile in a rectangular stainless-steel evaporator tank. Five different heat transfer scenarios were investigated to determine the maximum water temperature that could be achieved. Studied heat transfer modes included either conduction, convection, or radiation under steady or unsteady state conditions. A comparison between the five studied scenarios

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showed that there was a noticeable rise in water temperature in all scenarios. The average temperature rise of the five scenarios was approximately 28 °C and was equivalent to a final water temperature of 53 °C which was kept initially at 25 °C. Results confirmed that the increase in both radiation energy and radiation time would boost-up the water temperature quickly and more efficiently.

Keywords

Water distillation · Solar energy · Radiation · Modeling · Mathematical models · Water treatment · Water purification · Heat transfer · Conduction · Convection · Radiation · Evaporator tank · Temperature · Heat · Energy · Treatment · Solar feasibility · Desalination · Sun energy · Radiation time · Radiation energy · Heat scenario · Transfer mode · Drinking water · Fresh water

Introduction

Fresh water is the most vital element for human existence. Water makes up to 70% of human total body weight, and it is very necessary to increase life quality (Ogbonmwan 2011). However, natural fresh water resources and supplies, such as rainfalls and lakes, are limited in many countries. For example, there is a serious water problem in deserted countries like Saudi Arabia and Jordan (Middle East Area) in which the water demand is exceeding their water supplies due to the limited varieties of natural water resources (Muslih et al. 2010; Jaber and Mohsen 2001). Speaking of water demand world widely, 20% of the world's current population lacks safe drinking water, and it is expected that by 2025, there will be around two billion people facing difficulties in finding fresh water and will live in a scarcity of water. The previous scenario will occur because of the rapid growth in world's population, which consequently will increase the worldwide demand on fresh water (Maddah and Chogle 2017). Hence, there is a growing demand to improve the performance of current water purification technologies and to utilize renewable energies such as solar energy to compensate for the shortage in fresh water supply (Maddah and Chogle 2017; Maddah et al. 2017).

Water treatment or purification process is basically a separation process known as desalination. In a desalination process, salts and other minerals (concentrated brine) are rejected from seawater or brackish water flow in order to have a freshwater stream containing a low concentration of dissolved salts. There is a specific amount of energy that is required by the desalination process in order to be able to separate the excess amounts of salts from saline water. Hence, researchers and scholars are constantly devoting so much time and effort to develop today's available and commercial separation technologies. The common goal is to have an improved separation technology for water desalination with a lower water production cost. Water production costs can be minimized either by decreasing capital costs or by decreasing operation and maintenance (O&M) costs for such a water desalination plant, keeping in mind that energy costs are under O&M category since given energy is usually utilized for plant operation (Khawaji et al. 2008).

The use of direct solar energy for desalinating seawater has been investigated quite extensively in the last few decades. The main reason behind using solar energy for water desalination is that it is free, available, renewable, environmental-friendly, and harmless. Solar desalination or solar distillation process mimics what happens to water in the natural hydrologic cycle: meaning that saline water (seawater or brackish water) is exposed to the sun's rays and gets heated. Produced water vapor comes in contact with a cool surface that is placed within a solar still unit or a water condenser unit. As a result of the condensation process, fresh water droplets accumulate and get collected as a final product. Examples of solar distillation include the greenhouse solar still unit, the traditional boiler/condenser distillation system powered with solar energy, and the solar pond system (basin) (Hamed et al. 1993; El-Nashar 1993; Buros 2000).

Solar stills may not be the optimal choice for solar water distillation because they have a high capital cost and they are vulnerable to weather-related damage. Moreover, variations in the overall efficiency between different solar still designs have been noted in previous studies. Different solar still designs share difficulties in the requirement of a large solar collection area (e.g., 25 hectares land/l000 m^3 of product water/day); and thereafter reducing the feasibility of producing water (Khawaji et al. 2008).

Evaluation of the whole desalination process in such a water distillation plant is important and should be considered carefully to check how the idea is feasible commercially. The following topics are some of the important research areas under the evaluation process of a desalination plant (Khawaji et al. 2008):

- Improvements in the desalination process for salt rejection
- Assessment of the composition of the effluents
- Assessment of the environmental impacts of the effluents

This chapter (study) will focus on evaluating a proposed solar-distillation system for small-scale and mid-scale production of potable water. The objective was to identify the feasibility of using solar energy for water distillation that is known as solar distillation system. In other words, the water temperature profile in a rectangular evaporator tank (assumed geometry) was modeled theoretically for different heat transfer scenarios in order to determine the maximum water temperature that could be reached from solar radiation; knowing the water temperature profile would help us visualizing the feasibility of solar energy for water distillation as well as determining the efficiency of the system.

Water Distillation

Distillation appears to be one of the best practical and economical techniques for water treatment. Distillation technology is a great choice for governments and industries when a mass production of fresh water from high saline water like seawater is required to meet the demand (Saidur et al. 2011).

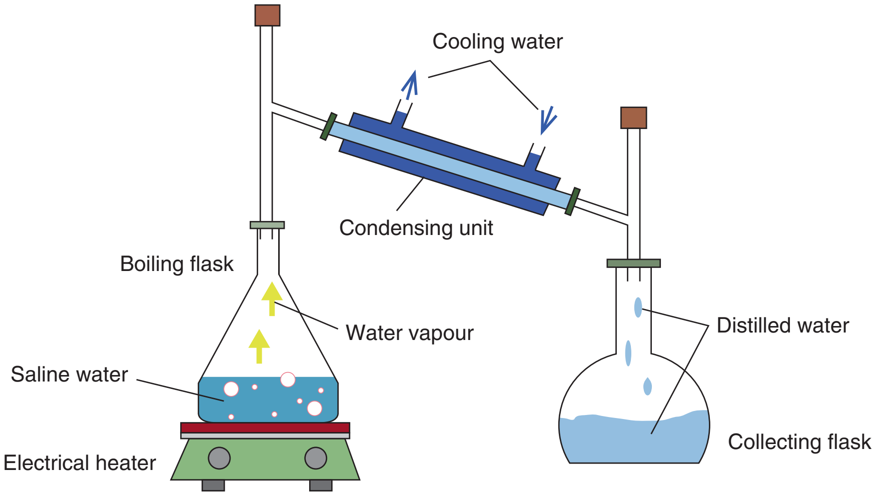


Fig. 1 Simple traditional distillation process (Adapted from Harwood and Moody 1989)

The fundamental principle of any water distillation technique is based on the vaporization/condensation process. Vaporizing (boiling) saline water at 100 °C (or even below) allows water vapors and dissolved gasses to become volatile and to be condensed in a later condensation stage. Minerals and dissolved salts in water are not capable to evaporate easily unless for boiling temperatures above 300 °C. Thus, only pure water vapor (fresh water produced from condensation) will come out while salts and minerals will be left behind (Baker 2000; Johnson et al. 2012).

There are several distillation methods, which were developed for water desalination. Simple traditional distillation method, as shown in Fig. 1, is the most well-known, simple, and basic method to purify water. In this method, the saline water in the boiling flask is boiled by a heat source (electrical heater, natural gas stove, oil stove, solar plat, or direct solar energy) and then evaporated to go toward the condensing unit. The condensing unit is cooled to separate the coming water vapors as pure droplets; the water vapor loses some of its latent heat and changes from being in a vapor phase to be in a liquid phase, which will be collected in the collected flask to have the fresh water product. Traditional distillation method is commonly used in chemical laboratories as well as domestic applications (Harwood and Moody 1989; Cengel and Boles 2002). However, distilling water by the traditional method is very expensive in large-scale applications because traditional distillation method requires a large amount of energy to evaporate the saline water due to the high latent heat of vaporization of water that is about 2257 kJ/kg at 100 °C (Cengel and Boles 2002).

Another distillation method which differs in simplicity, cost, and applications is known as single stage distillation as shown in Fig. 2. The system consists of an evaporator tank, a heating steam coil (heat exchanger), a condenser tank, and a storage tank plus piping connections. Single stage distillation process is somehow similar to the traditional distillation technique. However, single stage distillation

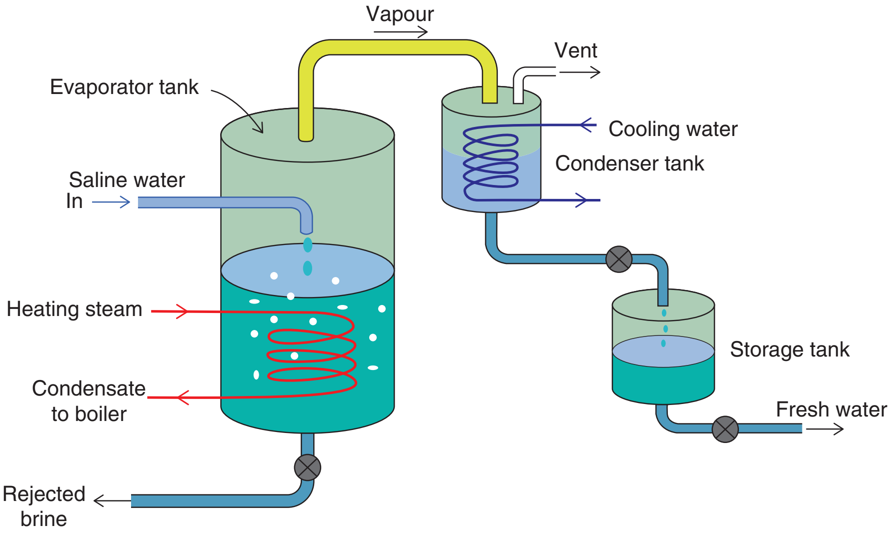


Fig. 2 Single stage distillation process (Adapted from Spiegler 2012)

method is usually a continuous process where simple traditional distillation method is usually in batch mode. The evaporator tank in single stage distillation method follows the same concept as the boiling flask in simple traditional distillation method. The only difference is that energy (heat) source in single stage distillation is obtained from using heating steam coils that act like a heat exchanger between inlets and outlets of both evaporator and condenser tanks (Saidur et al. 2011; Johnson et al. 2012). This method is suitable for saline water distillation in marine application and large laboratories applications. Single stage distillation is the optimal choice for compact size plants and when it is possible to exchange energy for the heating steam coils with other processes of nearby plants and factories (Rahman et al. 2003).

However, multiple effect distillation (MED) system consists of four evaporators, one boiler, and one condenser as shown in Fig. 3. Boiling water in the boiler will generate hot steam that will boil the saline water in the first evaporator. Hot vapors of the first evaporator will go to the second evaporator and will be the heating medium/source to heat and boil the saline water there (Saidur et al. 2011; Johnson et al. 2012).

In multiple stage flash (MSF) method that is shown in Fig. 4, saline water is heated outside the boiling chamber and then gets evaporated in the boiling chamber by lowering pressure. The increase in seawater temperature happens due to the latent heat of condensation flowing from the condensing water vapors. Providing an external low pressure steam, by using a steam turbine, allows the saline water to be heated in the brine heater (El-Nashar 2001). The heated water is then transported into the evaporator flash chambers (stages) which are usually made of multistages and typically contain 19–28 stages in modern large MSF plants (Jambi and Wie 1989).

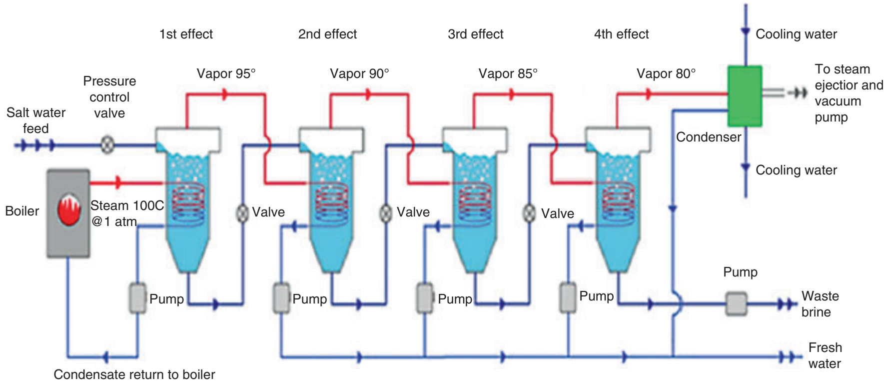


Fig. 3 Multiple effect distillation process (Adapted from Spiegler 2012)

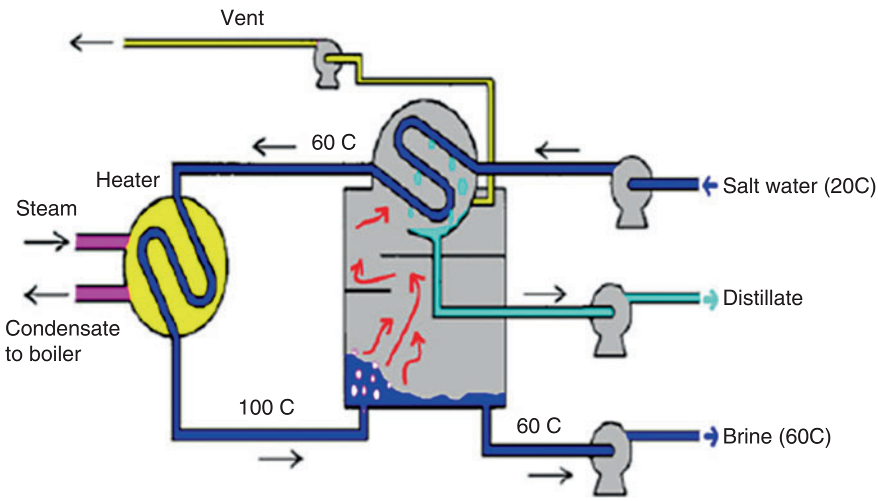
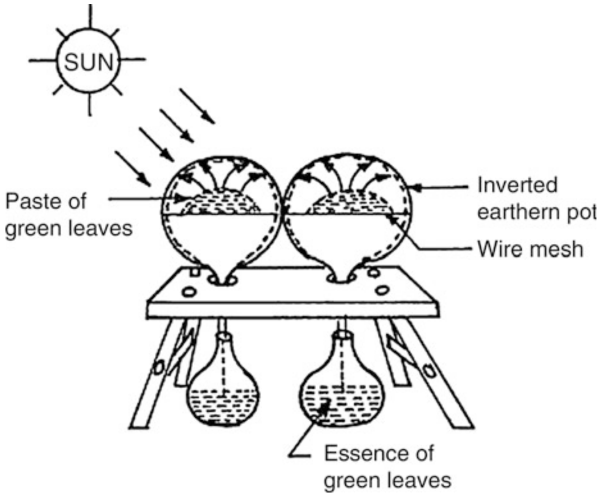


Fig. 4 1-stage flash distillation process (Adapted from; Khawaji et al. 2008)

Both MED and MSF methods require an external source of heat, like crude oil or natural gas that is used to heat up the incoming saline water. MSF process differs from MED by having both heating and boiling processes happening in the same vessel. In 2002, MSF has accounted for 36.5% of the total capacity of established desalination plants for both brackish water and seawater, and it reserved the first place among seawater desalination plants making more than 5000 m^3/day of fresh water (Saidur et al. 2011; Porteous 1983).

Solar distillation is an attractive way for water desalination due to the utilization of a free source of energy that is coming from sun in a form of heat (Saidur et al. 2011). The history of solar distillation started as early as in the fourth century B.C. where Aristotle explored a method to evaporate contaminated water and then

Fig. 5 Historical solar distillation apparatus (Adapted from Tiwari et al. 2003)



condense it to produce fresh water. In 1589, Della Porta utilized the intense heat of solar rays, as shown in Fig. 5, to evaporate water placed in wide inverted earthen pots and then collected the condensate into vases placed underneath (Tiwari et al. 2003). In 1872, a solar water treatment plant was successfully built in Chile and ran for many years to produce fresh water. During World War II, small plastic solar stills were utilized to provide potable water for life rafts floating in the ocean (Saidur et al. 2011).

Solar stills mimic the nature processes for generating rainfall, which are evaporation and condensation (Tiwari et al. 2003). Solar distillation process starts by feeding saline water into a black plate located in the lower portion of the solar distiller (solar still). Water vapor condenses on a cool transparent leaning surface which is usually made of glass or plastic. Pure water droplets are formed and grow up until they become heavy enough to slide down along the leaning surface. Fresh water droplets are collected through special channels located under the leaning surface to be transferred to the product side of the still and thereafter to reach the fresh water tank (Saidur et al. 2011).

Conventional solar stills have various modifications and mode of operations. Hence, solar distillation systems are classified as passive and active solar desalination technologies. Active solar stills operate with an extra-thermal energy that is fed into the passive basin in order to achieve higher evaporation rate (Tiwari et al. 2003). In other words, passive solar stills are direct solar technology while active solar stills are indirect solar technology. Direct solar desalination (passive) requires large land areas and has a relatively low productivity. However, direct solar technology is preferred over the indirect one at a small-scale and mid-scale production due to its relatively low cost and simplicity. Furthermore, the integration of solar thermal energy as a direct technology is suitable for solar desalination applications in remote areas (Qiblawey and Banat 2008). In 2016, Moh'd et al. observed that it was feasible to increase the yield of produced fresh water by developing a hybrid solar-wind water distillation system which consisted of a conventional single basin solar-still and a wind-water heater operating simultaneously. The advantage of the proposed hybrid system was to operate day and night and thereafter increased the quantities of distillate water by three to four folds which could reach up to 5.5 kg/day of distillate water (Moh'd et al. 2016).

Solar Irradiation

The verification of having enough solar energy from sun's irradiation is important to utilize solar energy in water distillation applications. Hickey et al. (1980) carried out an experimental work on the calculations of solar radiation measurements from the earth radiation budget on the Nimbus 7 satellite. The registered mean value of solar radiation was around 1376.0 W/m^2. Another recent study in 2007 reported a solar irradiation mean value of 1368 W/m^2 (Ammann et al. 2007).

Observations of solar irradiance variability have been made in a previous study in 1981 by utilizing active cavity radiometer irradiance monitor on the Solar Maximum Mission satellite. High-precision measurements of total solar irradiance indicated an average value of 1368.31 W/m^2. The irradiance variability magnitude and time scale proposed that there were considerable solar energy amounts within the convection zone in solar active regions (Willson et al. 1981).

However, sustaining solar power at high levels is a challengeable task due to the presence of long-term variations in solar radiation at Earth's surface. It has been reported that there was a linear decrease in the delivered solar power to earth from about the year 1960 to 1990. However, satellite records in the year from 1983 to 2001 revealed an overall increase in solar power at a rate of 0.16 W/m^2 that was approximately 0.10% per year (Pinker et al. 2005). The increase in the delivered solar power might be associated with the increase in human-made greenhouse gases and aerosols, which resulted in developing Earth's absorbance rate (nearly about 0.15 W/m^2). In other words, our planet is absorbing more energy (accumulated) from the sun than it is emitting energy to the space and making a climate change problem due to the high emissions of carbon dioxide.

It is worth mentioning that there is a difference between solar power delivery (required) and solar power accumulation (unwanted). Accumulation of energy in the Earth's atmosphere leads to an increase in the overall Earth temperature, which is related to climate change. However, ensuring the delivery of solar power can be achieved with advanced solar technologies and without energy accumulation (Glaser 1968; Hansen et al. 2005).

There are recent technologies that are efficient enough to convert solar power into usable energy in a cost-effective manner. One example is the parabolic (concave) mirrors that are capable of collecting the sun's energy over a wide area and focus it onto a smaller area on the water surface to intensively heat up the water. The concentrated solar energy on a focus point can easily raise the water temperature above 600 °C when there is a full sun and that is approximately translated as about 100 W/ft^2 (Hameed et al. 2013).

The use of concentrated solar power (CSP) technology, which produces high temperature by concentrating solar energy in a single focal point, along with a solar tracking system to follow the direction of the sun throughout the day was proposed in a previous project by Hameed et al. (2013) in order to easily purify water at a small-scale design and at any remote area (Hameed et al. 2013).

Solar-Distillation Cost Analysis

The water production cost, expressed in $/m^3 of water, depends on both the capital cost of the equipment, the O&M cost including the energy, and the operation and maintenance cost other than energy. Water production cost is obtained by dividing the sum of all costs by the total produced water quantity. Today's industry goal is to produce desalinated water at a low cost of ¢50/m^3 of water and a low cost of power at ¢2/kW h; where ¢ denotes to a US cent (Khawaji et al. 2008).

The O&M cost including the cost of energy is very small or even negligible for solar stills since the energy required for treatment is delivered by solar radiation and there is no need for operating pumps and controls in batch systems (Tiwari et al. 2003). Solar distillation systems are very attractive for small-size applications. The cost of fresh water productivity in solar distillation systems may vary from one place to another depending upon the intensity of solar radiation, the sunshine hours, and the type of still (Tanaka and Nakatake 2006). However, Howe and Tleimat (1974) reported that constructing water treatment plants with a capacity less than 200 m^3/day is the most economical choice when using solar distillation. The development of a solar distillation system is feasibly suitable for water treatment when the weather conditions are favorable and the demand is not too large and less than 200 m^3/day (Fath 1998).

Small communities located in arid environments and with no fresh water sources in the region can save over 30% in total cost by using a solar distillation system rather than transporting water from long distances. The utilization of solar insolation during hot seasons is the most convenient choice in deserted areas to achieve the highest production (Akash et al. 2000).

Kumar and Tiwari (2009) analyzed the life cycle cost of a single-slope passive and a hybrid photovoltaic (PV/T) active solar stills. The estimated distilled water production cost was Rs. 0.70/kg and Rs. 1.93/kg for passive and hybrid (PV/T) active solar stills, respectively, for 30 years lifetime of the systems. Kumar's result is much economical than the cost of producing bottled water in Indian market that is around Rs. 10/kg. The payback periods of the designed passive and active systems were estimated to be in the range of 1.1–6.2 years and 3.3–23.9 years, respectively, with a selling price of distilled water in the range of Rs. 10/kg to Rs. 2/kg. The obtained energy analysis confirmed the energy payback time (EPBT) as 2.9 and 4.7 years, respectively (Kumar and Tiwari 2009; Sampathkumar et al. 2010).

Problem Formulation

A rectangular evaporator tank was considered in the formulation of the heat transfer problem. Specific dimensions and design parameters of the water tank were assigned logically and they are as shown in Table 1. A complete flow chart of the proposed solar-distillation system is shown in Fig. 6. Since Stainless Steel (SS) material is cheap, abundant, and has a low thermal conductivity, it was selected as a construction material for the water evaporator tank. SS low thermal conductivity (k) will keep the absorbed radiation in the evaporator and may reduce the heat loss of sun's thermal energy to the atmosphere (by conduction and through tank boundary-sides).

General Assumptions

The solutions of the formulated problem were carried out based on various general assumptions. The below assumptions allowed us to make the heat transfer problem easier to approach, thereby solvable analytically.

Table 1 Design parameters of the proposed solar-distillation system and their calculated values

Parameter, (Symbol)	Unit	Value	Parameter, (Symbol)	Unit	Value
Radiation energy, (R)	W/m^2	200~1000	Water density, (ρ)	kg/m^3	1000
Radiation time, (t)	hr	2 ~ 10	Water heat capacity, (C_p)	J/kg K	4182
Tank volume, (V)	m^3	61.25	Convective heat transfer coefficient, (h_o)[a]	$W/m^2\ K$	19.36
Cross-section area, (A_c)	m^2	20.4	Conductive heat transfer coefficient, (k)[b]	W/m K	28.5
Surface area, (A_s)	m^2	51	Initial temperature, (T_i)	°C	25
Tank height, (H)	m	3.5	Convective-surrounding temperature, ($T_{\infty 1}$)	°C	30
Tank width, (W)	m	3.5	$\alpha = \frac{A_s}{\rho V C_p}$, ($\alpha$)	m^2 K/J	1.99×10^{-7}
Tank length, (L)	m	5	Water-surrounding temperature ($T_{\infty 2}$)	°C	25
Tank perimeter, (P)	m	17	Radiation-surrounding temperature ($T_{\infty 3}$)	°C	27.5
z-axis differential width, (Δz)	m	3	$m = \frac{P}{A_c\ k}$, (m)	K/W	0.03
Centered z-axis width, (z)	m	1.5	$\sqrt{h_o m} = \sqrt{\frac{h_o\ P}{A_c\ k}}$, ($\sqrt{h_o m}$)	m^{-1}	0.57

[a]Thermal convective coefficients for air and water were averaged and determined from Kurganov 2011; then h_o from Eq. (6)

[b]Thermal conductive coefficient for stainless steel was averaged and determined at 20 °C (Welty et al. 2009)

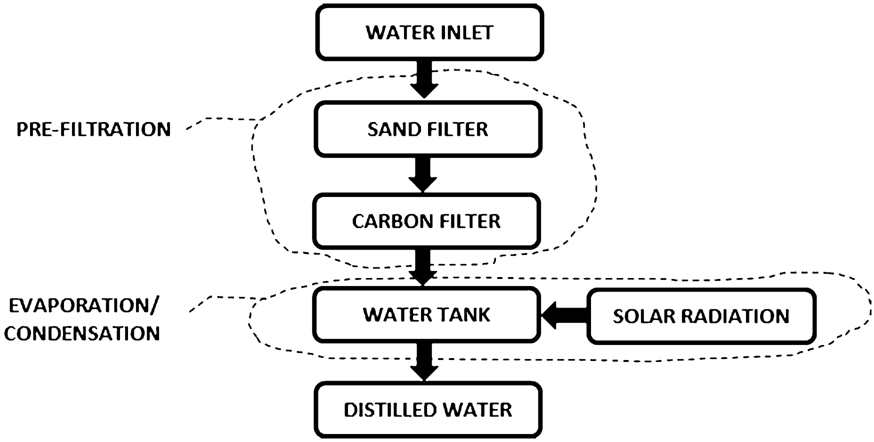


Fig. 6 Solar-distillation system flow chart

1. Water evaporator tank is in a rectangular shape and heat balance is in Cartesian coordinates.
2. One-dimensional heat transfer is considered (z-axis only).
3. Average solar radiation energy ($\mathcal{R}$) is equal 200–1000 W/m^2.
4. No heat generation is involved in the modeling analysis.
5. Water salinity has no effect on the rate of heat transfer and the evaporation of water.
6. Water level in the tank is just as same as the tank depth (height).

The formulated problem of the heat transfer was investigated in different five scenarios. A comparison between the five scenarios was established to find out by how much solar radiation can increase the water temperature. The five studied heat transfer scenarios are shown in Table 2 and named as the following:

1. Radiation with convection
2. Radiation with conduction
3. Unsteady state radiation
4. Unsteady state radiation with convection
5. Radiation with both convection and conduction

Specific Assumptions

Other specific assumptions were assigned for each studied scenario independently to obtain the rise in water temperature easily. As a general rule of thumb, the more we include modes of heat transfer in the equation, the more the result is accurate. However, solving partial differential equations (PDEs) in both space and time would be very difficult and should be solved by advanced mathematical methods

Table 2 The five heat transfer scenarios of the formulated problem

Scenario #	Radiation	Convection	Conduction	Heat generation	Unsteady state
1	√	√	×	×	×
2	√	×	√	×	×
3	√	×	×	×	√
4	√	√	×	×	√
5	√	√	√	×	×

Table 3 Assigned specific assumptions of the different studied scenarios

Scenario #	Assumptions
1	The system is under steady state conditions. No heat transfer by conduction.
2	The system is under steady state conditions. No heat transfer by convection.
3	No heat transfer by conduction. No heat transfer by convection.
4	Neglect heat transfer by conduction since its effect was shown to be low from scenario #2 results. This is because air conductivity to heat is generally very low.
5	The system is under steady state conditions.

or by the aid of engineering programs such as MATLAB. Table 3 demonstrates the specific assigned assumptions for each scenario for the formulated heat transfer problem of the water evaporator tank.

Mathematical Models and Equations

Modeling analysis and formulated heat transfer equations were determined from the general equation of energy balance, Eq. (1). The overall convective heat transfer coefficient (h_o) was calculated from Eq. (6); where h_1 and h_2 are 19.95 W/m^2 K and 650 W/m^2 K which are the convective heat transfer coefficients of air and water, respectively (Kurganov 2011). Water temperature equation of every scenario was obtained in Eq. (5), Eq. (16), Eq. (22), Eq. (31), and Eq. (37) for Scenarios 1, 2, 3, 4, and 5, respectively, Table 4.

Starting from the general energy balance equation (Deen 1998):

$$E_{in} + E_g = E_{out} + E_a \quad (1)$$

Table 4 Obtained water temperature profile equations

#	Scenario	Temperature equation for water
1	Radiation with convection	$T_w = \frac{\mathcal{R}}{h_o} + T_{\infty 1}$
2	Radiation with conduction	$T_w = \frac{\mathcal{R}\ P\ z}{2\ k\ A_c}(W - z) + T_{\infty 3}$
3	Unsteady state radiation	$T_w = \frac{\mathcal{R}\ A_s}{\rho V C_p}\ t + T_i$
4	Unsteady state radiation with convection	$T_w = T_i e^{-(h_o \alpha\ t)} + \left[\frac{1}{h_o}(\mathcal{R} + h_o T_{\infty 1})\right] \times \left[1 - e^{-(h_o \alpha\ t)}\right]$
5	Radiation with both convection and conduction	$T_w = \frac{\mathcal{R}}{h_o} + T_{\infty 1} + \frac{\left\{\mathcal{R} + h_o[T_{\infty 1} - T_{\infty 3}] - \mathcal{R} e^{\left(W\sqrt{h_o m}\right)} + h_o e^{\left(W\sqrt{h_o m}\right)}[T_{\infty 3} - T_{\infty 1}]\right\}}{h_o e^{\left(z\sqrt{h_o m}\right)}\left[e^{\left(W\sqrt{h_o m}\right)} - e^{\left(-W\sqrt{h_o m}\right)}\right]} - \frac{e^{\left(z\sqrt{h_o m}\right)}\left\{\mathcal{R} + h_o[T_{\infty 1} - T_{\infty 3}] - \mathcal{R} e^{\left(-W\sqrt{h_o m}\right)} + h_o e^{\left(-W\sqrt{h_o m}\right)}[T_{\infty 3} - T_{\infty 1}]\right\}}{h_o\left[e^{\left(W\sqrt{h_o m}\right)} - e^{\left(-W\sqrt{h_o m}\right)}\right]}$

Scenario #1

$$E_{in} = E_{out} \tag{2}$$

$$q_{rad} = q_{conv} \tag{3}$$

$$\mathcal{R}\, A_s = h_o\, A_s\, (T_w - T_{\infty 1}) \tag{4}$$

Solving the equation gives:

$$T_w = \frac{\mathcal{R}}{h_o} + T_{\infty 1} \tag{5}$$

Where:

$$h_o = \frac{1}{\left({}^{1}/_{h_1}\right) + \left({}^{1}/_{h_2}\right)} \tag{6}$$

Scenario #2
Now, from Eq. (2)

$$q_{rad} + q_z = q_{z+\Delta z} \tag{7}$$

$$\mathcal{R}\, A_s - k\, A_c \frac{dT_w}{dz}\bigg|_z + k\, A_c \frac{dT_w}{dz}\bigg|_{z+\Delta z} = 0 \tag{8}$$

Where:

$$A_s = P\, \Delta z \tag{9}$$

$$V = A_c\, \Delta z \tag{10}$$

$$\lim_{\Delta z \to 0} \left[\frac{\frac{dT_w}{dz}\big|_{z+\Delta z} - \frac{dT_w}{dz}\big|_z}{\Delta z} \right] = \frac{d}{dz}\left(\frac{dT_w}{dz}\right) = \frac{d^2 T_w}{dz^2} \tag{11}$$

$$\frac{d^2 T_w}{dz^2} = -\frac{\mathcal{R}\, P}{k\, A_c} \tag{12}$$

Solving the ODE gives:

$$T_w = -\frac{\mathcal{R}\, P\, z^2}{2\, k\, A_c} + C_1\, z + C_2 \tag{13}$$

Applying the below boundary conditions:

$$\begin{aligned} &\text{BC1} : z = 0; T = T_{\infty 3} \\ &\text{BC2} : z = W; T = T_{\infty 3} \end{aligned} \tag{14}$$

We get constants:

$$\begin{aligned} C_2 &= T_{\infty 3} \\ C_1 &= \frac{\mathcal{R}\, P\, W}{2\, k\, A_c} \end{aligned} \tag{15}$$

$$T_w = \frac{\mathcal{R}\, P\, z}{2\, k\, A_c}(W - z) + T_{\infty 3} \tag{16}$$

Scenario #3
Now, from Eq. (2)

$$q_{rad} = \rho V C_p \frac{dT_w}{dt} \tag{17}$$

$$\frac{\mathcal{R}\, A_s}{\rho V C_p} = \frac{dT_w}{dt} \tag{18}$$

Solving the ODE gives:

$$T_w = \frac{\mathcal{R}\, A_s}{\rho V C_p}\, t + C_1 \tag{19}$$

Applying the below initial condition:

$$\text{IC} : t = 0; T = T_i \tag{20}$$

$$C_1 = T_i \tag{21}$$

$$T_w = \frac{\mathcal{R}\, A_s}{\rho V C_p}\, t + T_i \tag{22}$$

Scenario #4
Now, from Eq. (1)

$$E_{in} = E_{out} + E_a \tag{23}$$

$$q_{rad} = q_{conv} + \rho V C_p \frac{dT_w}{dt} \tag{24}$$

$$\mathcal{R}\, A_s = h_o\, A_s\, (T_w - T_{\infty 1}) + \rho V C_p\, \frac{dT_w}{dt} \tag{25}$$

$$\frac{dT_w}{dt} + h_o \alpha\, T = \alpha\, (\mathcal{R} + h_o T_{\infty 1}) \tag{26}$$

Where:

$$\alpha = \frac{A_s}{\rho V C_p} \tag{27}$$

Solving the ODE gives:

$$T_w = \frac{1}{h_o}(\mathcal{R} + h_o T_{\infty 1}) + C_1 e^{-(h_o \alpha\, t)} \tag{28}$$

Applying the below initial condition:

$$\text{IC} : t = 0; T = T_i \tag{29}$$

$$C_1 = T_i - \frac{1}{h_o}(\mathcal{R} + h_o T_{\infty 1}) \tag{30}$$

$$T_w = T_i e^{-(h_o \alpha\, t)} + \left[\frac{1}{h_o}(\mathcal{R} + h_o T_{\infty 1})\right] \times \left[1 - e^{-(h_o \alpha\, t)}\right] \tag{31}$$

Scenario #5

Now, from Eq. (2)

$$q_{rad} + q_z = q_{z+\Delta z z} + q_{conv} \tag{32}$$

$$\mathcal{R}\, A_s - k\, A_c \frac{dT_w}{dz}\bigg|_z + k\, A_c \frac{dT_w}{dz}\bigg|_{z+\Delta z} = h_o\, A_s\, (T_w - T_{\infty 1}) \tag{33}$$

$$\lim_{\Delta z \to 0} \left[\frac{\frac{dT_w}{dz}\big|_{z+\Delta z} - \frac{dT_w}{dz}\big|_z}{\Delta z}\right] = \frac{d}{dz}\left(\frac{dT_w}{dz}\right) = \frac{d^2 T_w}{dz^2} \tag{34}$$

$$\frac{d^2 T_w}{dz^2} = \frac{h_o\, P}{k\, A_c}(T_w - T_{\infty 1}) - \frac{\mathcal{R}\, P}{k\, A_c} \tag{35}$$

Solving the ODE in MATLAB with the given below boundary conditions:

$$\begin{aligned} &\text{BC1} : z = 0; T = T_{\infty 3} \\ &\text{BC2} = z = W; T = T_{\infty 3} \end{aligned} \tag{36}$$

We get the solution:

$$T_w = \frac{\mathcal{R}}{h_o} + T_{\infty 1} + \frac{\left\{\mathcal{R} + h_o[T_{\infty 1} - T_{\infty 3}] - \mathcal{R}e^{\left(W\sqrt{h_o m}\right)} + h_o e^{\left(W\sqrt{h_o m}\right)}[T_{\infty 3} - T_{\infty 1}]\right\}}{h_o e^{\left(z\sqrt{h_o m}\right)}\left[e^{\left(W\sqrt{h_o m}\right)} - e^{\left(-W\sqrt{h_o m}\right)}\right]} - \frac{e^{\left(z\sqrt{h_o m}\right)}\left\{\mathcal{R} + h_o[T_{\infty 1} - T_{\infty 3}] - \mathcal{R}e^{\left(-W\sqrt{h_o m}\right)} + h_o e^{\left(-W\sqrt{h_o m}\right)}[T_{\infty 3} - T_{\infty 1}]\right\}}{h_o\left[e^{\left(W\sqrt{h_o m}\right)} - e^{\left(-W\sqrt{h_o m}\right)}\right]} \tag{37}$$

Where:

$$m = \frac{P}{A_c\, k} \tag{38}$$

Results and Discussion

Modeling results allowed us to determine the behavior of the heat transferred from sun radiation into saline water in the evaporator tank. Knowing the temperature profile inside the water tank is very important to estimate the highest achievable water temperature, which will allow us to check for the feasibility of employing solar energy for water distillation.

The effect of solar radiation energy, solar radiation time, and horizontal position in the evaporator tank was studied through modeling analysis. Relations between the previous parameters and the rise in water temperature were considered and discussed thoroughly in the following subsections.

Effect of Solar Radiation on Water Temperature

The effect of solar radiation energy was obvious from the calculated modeling results of the five scenarios. Figure 7 shows the effect of increasing solar radiation energy on water temperature in the five studied scenarios. Obviously, modeled results were determined as expected and that water temperature increased with the increase in solar radiation which indicated a proportional relationship between radiation energy and rise in temperature. Scenario #1 reserved the highest observed temperature of 81.7 °C since it included only radiation and convection (heat transferred into the system) and neglected any heat loss by other modes such as conduction. The addition of a heat loss term by conduction decreased the maximum observed water temperature to 45.9 °C, which is illustrated by Scenario #5. However, including a heat loss by a conduction mean with neglecting convection (scenario #2) showed a slight decrease in the maximum modeled water temperature that was 71.3 °C. A dependent time-radiation system (Scenario #3) and time-

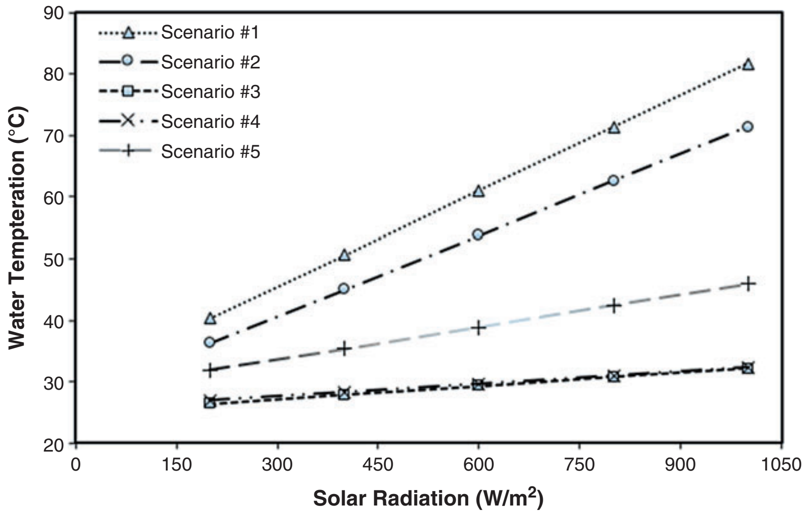


Fig. 7 Effect of solar radiation ($\mathcal{R}$ =200 ~1000 W/m^2) on water temperature rise with a radiation time of (t = 10 h)

radiation-convection system (Scenario #4) showed comparable results that furtherly decreased the observed water temperature to 32.2 °C and 32.3 °C, respectively.

Effect of Radiation Time on Water Temperature

The effect of solar radiation time was obvious from the calculated modeling results of Scenario #3 and Scenario #4 as shown in Fig. 8. Both scenarios showed analogous results, and a proportional relationship between radiation time and rise in water temperature was confirmed. A rise of water temperate of 5.74 °C and 5.79 °C was observed for Scenario #3 and Scenario #4, respectively. The unsteady state situations showed that time-dependent radiation would have lower temperature rise compared to steady state scenarios.

Effect of Position (Horizontal-Axis, z) on Water Temperature

The effect of a selected horizontal position (width) within the evaporator system appeared when there was a conduction term, which accounted for a heat loss from the evaporator tank. It was assumed that there was no effect from the vertical axis (water depth) on the water temperature profile. In other words, the depth of water (tank height) will not affect the distribution of absorbed radiation energy (heat) inside the water tank. It was also assumed that the water depth/level in the tank is just the same as the tank height. Results of Scenario #2 and Scenario #5 in Fig. 9 showed that the peak value of water temperature was observed at the center of the evaporator

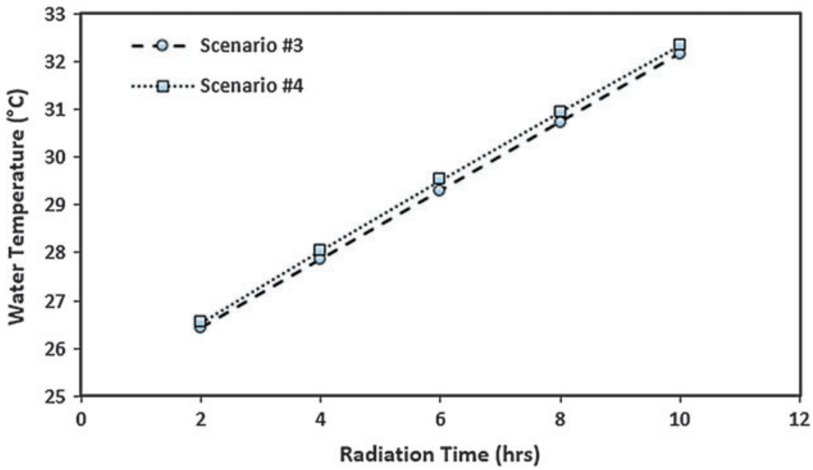


Fig. 8 Effect of solar radiation time ($t = 2$ ~10 h) on water temperature rise with a radiation of ($\mathcal{R} = 1000$ W/m^2)

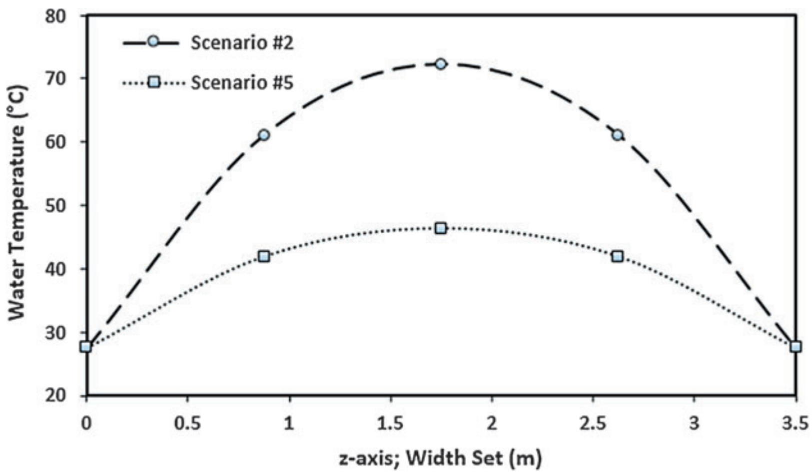


Fig. 9 Effect of horizontal position ($z =$ 0 ~3.5 m) on water temperature rise with a radiation energy of ($\mathcal{R} = 1000$ W/m^2) and a radiation time of (t=10 h)

tank since the heat loss by conduction occurs at the boundary-sides (from the given boundary conditions). The highest modeled water temperatures were 72.24 °C and 46.29 °C for Scenario #2 and Scenario #5, respectively.

Maximum Water Temperature

As noted previously, the maximum observed water temperature within the evaporator tank was 81.7 $^{\circ}$C, which was the result for the case of radiation with convection (Scenario #1) with the assumption of having a radiation energy and radiation time of 1000 W/m^2 and 10 h, respectively. Table 5 shows the highest modeled water temperature values that were calculated in the different studied heat transfer scenarios. The averaged-temperature value of 53 $^{\circ}C$ was calculated from the five scenarios' results, which gave us an approximation on how much would the water temperature rise in real situations. A comparison illustration between the obtained maximum water temperatures of the different studied heat scenarios is shown in Fig. 10.

Solar Radiation Versus Radiation Time

Unsteady state scenarios were analyzed to determine whether solar radiation or radiation time is the much important contributing parameter in the rise of water temperature. Specifically, Scenario #3 results in Fig. 11 showed that the increase in solar radiation from 200 W/m^2 to 1000 W/m^2, under a radiation time of 10 h, caused a maximum rise in water temperature that was equivalent to 5.8 °C. Conversely, for the same scenario (Scenario #3), the increase in radiation time from 2 h to 10 h, under a solar radiation of 1000 W/m^2, caused a maximum rise in water temperature that was equivalent to 5.7 °C. Since the difference between both temperature changes was comparable and was only 0.1 °C less for the latter case, it was concluded that both radiation parameters (solar energy and time) have a similar contribution in raising water temperature.

The same evaluation of the two parameters was carried out for Scenario #4 results that are shown in Fig. 12. A temperature of 5.3 °C was the maximum rise in water temperature due to the increase in solar radiation from 200 W/m^2 to 1000 W/m^2, under a radiation time of 10 h. However, a temperature of 5.8 °C was the maximum rise in water temperature due to the increase in radiation time from 2 h to 10 h, under a solar radiation of 1000 W/m^2. The inclusion of a convection mode in Scenario #4 showed opposite preference to the studied parameters, meaning that radiation time parameter was much important than solar radiation parameter in terms of increasing water temperature. Thus, one may infer that the two parameters may stand little

Table 5 Maximum observed water temperature within the evaporator tank

#	Scenario	Maximum T_w ($^{\circ}C$)
1	Radiation with convection	81.7
2	Radiation with conduction	72.2
3	Unsteady state radiation	32.2
4	Unsteady state radiation with convection	32.3
5	Radiation with both convection and conduction	46.3
–	**Averaged-temperature**	**53**

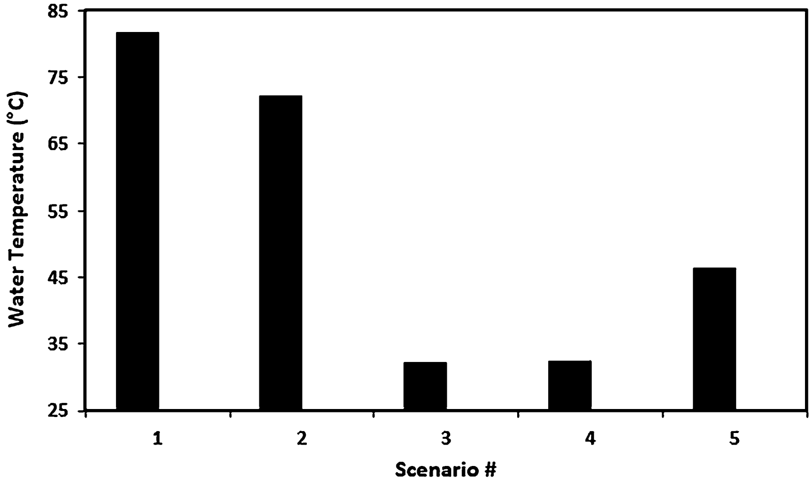


Fig. 10 A comparison analysis of the maximum observed water temperature

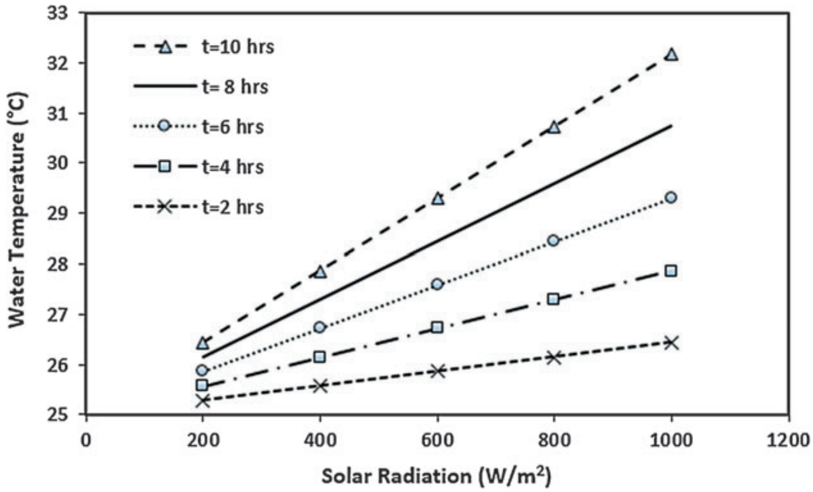


Fig. 11 A comparison analysis between the effect of solar radiation and radiation time (Scenario #3)

differently depending on the studied heat transfer scenario as well as the number of heat transfer modes included in the governing equation.

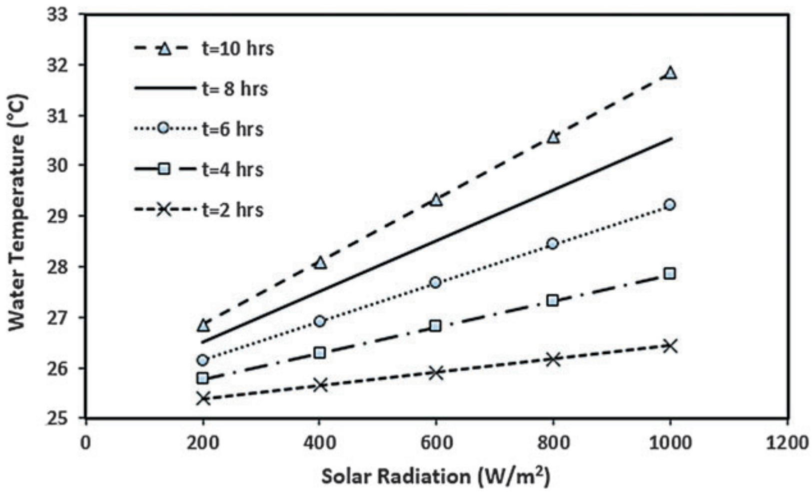


Fig. 12 A comparison analysis between the effect of solar radiation and radiation time (Scenario #4)

Conclusion

The feasibility of using a proposed solar-distillation system was obtained from the general heat equation. Modeling analysis was applied to determine the water temperature profile in a rectangular stainless-steel evaporator tank. Five different scenarios were investigated theoretically to find out the maximum water temperature that could be achieved from solar radiation. The averaged-maximum-water-temperature of the five scenarios was equivalent to 53 °C for water which was kept initially at 25 °C. Results confirmed that there was a proportional relationship between radiation energy and rise in temperature as well as between radiation time and rise in water temperature. The increase in both radiation energy and radiation time would boost-up the water temperature. A comparison analysis between both radiation parameters concluded that solar energy and time have a similar contribution in raising water temperature. Future studies on solar-distillation technologies have to be continued to utilize most of the benefits of solar radiation and to ensure a clean water treatment technology for the coming generations.

Nomenclature

E Energy, W
q Energy flow (generally by conduction unless specified with a subscript), W
A_c Cross section area, m^2
A_s Surface area, m^2
h_o Overall convective heat transfer coefficient, $W/m^2\ K$
h_1 Convective heat transfer coefficient for air, $W/m^2\ K$

h_2	Convective heat transfer coefficient for water, W/m^2 K
T	Temperature, °C
z	Z-axis dimension, m
k	Conductive heat transfer coefficient, W/m K
$\mathcal{R}$	Solar radiation, W/m^2
P	Perimeter, m
V	Volume, m^3
C	Constant
W	Width, m
H	Height, m
L	Length, m
ρ	Water density, kg/m^3
C_p	Water heat capacity, J/kg K
t	Time, s
α	Defined variable in Table 1, m^2 K/J
m	Defined variable in Table 1, K/W

Subscripts

in	into the system
g	generation
out	out of the system
rad	radiation
conv	convection
a	accumulation or storage
w	water
$\infty 1$	convective surrounding
$\infty 2$	water surrounding
$\infty 2$	radiation surrounding
1	first
2	second
i	initial

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