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Investigation of the Effect of Changing Water Heights on the Performance of a Solar Distillation System Using Crushed Porous Coal Rocks

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Abstract

The solar distillation system becomes necessary to treat the salt water and replace it with pure water, especially in areas of outlying rural. There are many methods that can be followed to improve the distillation system, one of these methods applied in the present work is using crushed porous coal rocks compared with traditional solar distillate systems. The present work included two parts; numerical and experimental. The experimental parts included a set of experiments with and without using crushed porous coal rocks and with changing of the water height above the endothermic surface by (10, 20, and 30) mm. The numerical simulation was carried out by using ANSYS FLUENT programming to solve the governing differential equations (continuity, momentum, and energy) to validate the results of numerical simulation with experimental data. The results proved that using crushed porous coal rocks as an endothermic surface at 10 mm water height was given the best results compared with the traditional solar distillate system, depending on the amount of water collected outside the solar collector.

Keywords: ANSYS FLUENT, solar energy, porous medium, water distillation systems, solar collector designing.

Symbols

a	Permeability
A	Surface collector area, m^2
Aw	Water surface area, m^2
C_F	Inertial Drag Factor
h_{cw}	Convective heat transfer coefficient, W/m^2, °C
h_{ew}	Evaporative heat transfer coefficient, W/m 2 °C
K_v	Air hermal conductivity, W/m^2 °C
L	water latent heat, J/kg
Lv	Dimension of condensing cover, m
P_{ci}	The pressure of saturated vapor at condensation cover temperature, N/m^2
Pr	Prandtl Number
Cp	Specific heat, J/Kg°C
d_f	Ligament Diameter, m
d_p	Pore Diameter, m
g	Acceleration due to gravity, m/s^2
Gr	Grashof number
P_w	Partial saturated vapor pressure at water temperature, N/m^2
$\dot{q}$	Rate of evaporative heats transfer, W/m^2
t	Thickness, mm
T_a	Ambient temperature, °C
T_{ci}	Inner temperature of condensing cover, °C
T_s	Evaporative surface temperature, °C
T_w	Water temperature, °C

1. Introduction

The earth's planet is considered the densest with an overall area of 510.072 million square kilometers. More than 71% of the area is covered by water. Fresh water is occupied about 2.5% of the overall volume of the water while the remaining water is considered brackish water not suitable for drinking, in the present time, the world needs to treat this great shortage of fresh water and find ways to face this great danger [1-3]. In the present decade, multiple methods have been used for the desalination of brackish water, and among these methods is the use of solar distillation, which relies on alternative energy, simple manufacturing technology, and a clear and clean environment. The productivity of the solar still for fresh water is limited, which makes it the only obstacle in using this method [4-5]. When the solar intensity falls on the solar distiller surface, a big part of radiation will penetrate and heat the non-potable water that is still on the heat-absorbing surface. Then water vapor forms on the walls and cover of the solar still, and then it condenses to be collected [6-7]. One of the important methods to increase the solar distillation performance is to motivate the system by using porous coal Rocks as an endothermic surface, which represents a good step toward understanding the

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physics phenomenon of energy transfer to the fluid after absorbing the solar radiation. The crushed porous coal rocks contain pores, which increase the rate of heat transfer as an increase in absorber surface area [8-9]. Most researchers tended to enhance the performance of the solar distiller to increase the productivity of pure drinking water. Muafag [10] studied the important parameters that have affected the enhancement of the water solar still performance such as the basin water depth, design, and operation. The results showed that when the water depth was decreased caused to increase in the pure water productivity and also the solar intensity affected the productivity. Jamal and Siddiqui [11] investigated the effect of water depth in a solar distill basin with two orientations; east-west and from north-south on the evaporative, radiative, and convective heat coefficients between the working fluid and the collector cover surface. Murugavelp et al. [12] designed and operated a single collector basin double slope solar still by comparison between solar energy and the laboratory conditions. The effect of water depth variation was studied and the parameters that have affected the water producticity. The effect of water depth changing in basin solar still by using metal porous media (vertical flax) to improve the solar distillation performance were investigated by Ahmed et al. [13]. Amani et al. [14] designed a solar collector moved in two dimensions to absorb the direct solar energy; heat exchanger and multi-effect distillation system. The simulation of the model was carried out under Iraqi weather conditions. The pure water productivity was changed during the different months depending on the weather conditions. Anburaja et al. [15] designed a solar distillation apparatus whose base has straight edges and grooves. The device was tested by changing inclination angles with the absorber plate to enhance the solar distillation performance. The effect of using an evacuated solar tube collector on the rate of productivity and efficiency of the solar still under climatic conditions was studied by Rafal et al. [16]. Abbas et al. [17] designed a solar distillation apparatus characterized that its four sides were covered with glass. The aim is largest amount of solar radiation to fall on the collector base, which increases the productivity of pure water. Wissam [18] experimentally studied how to improve the performance of the solar still by enlarging the dimensions of the solar still relative to the still base, which provides an additional area for the condensation surface, while using solar panels with the base of the still to increase the heating rate compared to the traditional design. Farhan et al. [19] conducted the experimental and numerical study to investigate the solar performance under weather conditions in Karbala city / Iraq. Qais et al. [20] investigated the important concepts of solar radiation, used methods to describe solar energy, and the methods used to calculate the optimum tilted angle in Jordan northeran. Mowaffaq and Dr. Najim [21] investigated experimentally the effect of various conditions such as water level, basin, and slope angle on the water production rate under Mosul climate conditions. Raed [22] investigated the effect of climate conditions variations such as, wind speed, solar intensity and ambient temperature on the water production rate of solar distillation systems.

The objective of the presented numerical and experimental study is to investigate the effect of using crushed porous coal rocks as an endothermic surface with changes in the water heights above the endothermic surface on the productivity and performance of the solar distillation system under the weather climate conditions of Baghdad, Iraq.

2. Solar Distillation Structure

Figures 1 and 2 show schematically and photographically the two solar water distillation apparatus. The two apparatus were designed and manufactured in Baghdad city (latitude angle of 33.3°). One of the apparatus used crushed porous coal rocks and the other used a traditional flat plate as an endothermic surface. The height of the water above the endothermic surface was changed by (10, 20, and 30) mm. The area of the solar distillation system was 0.9 m^2 where the dimension of the collector basin of (1000×900) mm. The front wall height was 140 mm while the rear wall of 440 mm. The glass cover of the solar distillation (t=2.5 mm) was used to transmit the incidence solar radiation to the heat-absorbent plate and to condense the updraft steam. The glass cover was inclined at 32° from the horizontal axis to ensure most of the solar radiation falls on the collector glass cover. The copper absorber plate (t=9mm) was painted with a met black to absorb more amount of solar radiation. Four sides and bottom of the solar distillation were made from wood (t = 40 mm) to reduce the loss of heat to surrounding. The charcoal was crushed into small rocks about 10 mm approximately to cover the area of the solar collector base. The charcoal behaves as a porous media that used to increase the heat transfer rate to the water as a results increase the endothermic surface area. The comparison between two systems was conducted in August 2022 in Baghdad, Iraq, from 9:00 am to 3:00 pm. The thermocouples of type K were used to measure the water temperatures, inner and outer collector glass cover, water vapor, flat plate, and crushed porous coal rocks. Thermocouples were installed at the outer walls of the collector to measure the loss of heat from the system to ambient. Also, during the experiments, the total solar radiation and diffuse solar radiation on the solar collector were measured.

2.1. Error data analysis

The thoroughness of an experimental data result can be influenced by the two factors: the nature of devices design and measurement precision. The correlation that follows can be used to write the interval of the result's uncertainty w, [23];

$$W_R = \left[\sum_{i=1}^{n}\left(\frac{\partial R}{\partial ai}W\right)^2\right]^{0.5} \qquad (1)$$

Where R is the results and n is the independent parameter summation.

The experimental errors that may have occurred in an independent parameter e are shown in Table 1. These the errors are derived from the measuring instruments as shown below.

Table 1. Experimental error of the used parameters

independent parameter e	result's uncertainty w
Temperature	±0.2 °C
Inclined angle of Cover glass	± 0.1°
Collector dimensions	± 0.4 m
Outer water distillated	± 0. 03 kg

2.2. 2.2. Thermal data analysis [24]

The convection heat transfer rate $\dot{Q}$ can be written by the general following equation, [28];

$$\dot{Q} = h_{cw}\, A(T_s - T_a) \quad (2)$$

The following equation was used to calculate the Nusselt number Nu ;

$$Nu = \frac{h_{cw}\, L_v}{K_v} = c(GrPr)^n \quad (3)$$

The convective heat transfer coefficient h_{cw} can be determined by the below equation;

$$h_{cw} = \frac{K_v}{L_v} c(GrPr)^n \quad (4)$$

The amount of outlet water distilled $\dot{m}$ in kg/hr can be calculated by the following relation;

$$\dot{m} = \frac{\dot{q}\, A_w}{L} \quad (5)$$

Where;

$$\dot{q} = h_{cw}(T_w - T_{ci}) = 0.01623h(P_w - P_{ci}) \quad (6)$$

From equations. (3-6) can be get on the relation;

$$\frac{\dot{m}}{R} = c(GrPr)^n \quad (7)$$

Where;

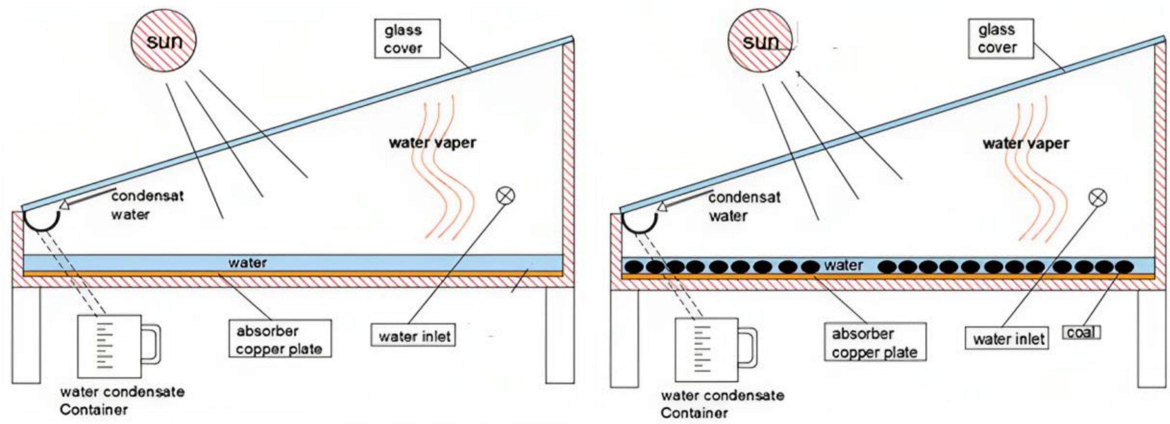
$$R = \frac{0.01623\, K_v}{L\, L_v} A_w(P_w - P_{ci}) \quad (8)$$

After determining the constants c and n in equation (5) by utilizing analysis of linear regressions, the heat transfer coefficient h is assessed from equation (2), which is liberated from different restrictions as contained in following equation, [25]:

$$h_{cw} = 0.884\left[T_w - T_{ci} + \frac{(P_w - P_{ci})(T_w + 273)}{268.9\times10^3 - P_w}\right]^{1/3} \quad (9)$$

Coefficient of heat transfer evaporative can be calculated by the following relation;

$$h_{ew} = 0.01623\frac{K_v}{L_v} c(GrPr)^n \frac{(P_w - P_{ci})}{(T_w - T_{ci})} \quad (10)$$



(a) (b)

Figure 1. Schematic diagram of the solar water distillation apparatus; (a) with flat absorber plate (b) with crushed porous coal rocks

Figure 2. Photographic diagram of the solar water distillation apparatus

3. Numerical Simulations

Figure 3 shows the modeling geometry created and simulated by the ANSYS FLUENT program. The dimensions and boundaries that selected according to the experimental side inputs. Figure 4 indicates the mesh that was formed to simulate the solar distill system with and without crushed porous coal rocks. The mesh was 3D with a quadrilateral mesh type. The nodes and the elements numbers were changed to ±84396 and ± 72352 respectively, relying upon the used water height level and collector endothermic surface. The numerical aspect included modeling the solar distillation system. A three-dimensional model of the condensation and evaporation processes by solar energy was created to solve governing equations (continuity, momentum, and energy). The simulation of the model was carried out in the case of the presence and absence of crushed porous coal rocks as an endothermic porous surface and by changing the water height level located above the endothermic surface. The buoyancy model was simulated by setting gravity to -g in the Y direction. The phases change model and energy equations were activated. RNG k- ϵ model was used to solve the governing equations. The model of radiation was selected in the current work because the glass cover of the collector is transparent. Due to the transparent media of the solar collector roof, the Rosseland with solar tray tracing model was chosen. When the numerical simulation of the coal absorption plate, the term $\vec{S}$ was added to the momentum equation due to the coal is considered a porous material;

$$\vec{S} = -\left(\frac{\mu}{a}\vec{V} + C_F\frac{1}{2}\rho\left|\vec{V}\right|\vec{V}\right) \tag{11}$$

Equation 11 consists two terms; the first represents Darcy term and the second is Forchheimer term a and C_F represent the permeability and the inertial drag factor and can be expressed by the following equations [26];

$$a = \frac{d_p^2\emptyset^3}{150(1-\emptyset)^2} \tag{12}$$

$$C_F = 1.75 - \frac{\rho(1-\emptyset)}{d_p\emptyset^3} \tag{13}$$

Where $\emptyset$ represents the porosity of crushed porous coal rocks and it can be calculated from the following equation [27];

$$\emptyset = 1 - \frac{m}{\rho A d_p} \tag{14}$$

The cell zone for flat plate and crushed porous coal rocks was selected and the boundary conditions of the model were included that temperatures on the lower and upper surfaces were changed depending on the experimental solar radiation intensity which was changed depending on the weather conditions, while the remaining walls were assumed thermally insulated. The glass cover inclines 32° from the horizontal axis. In all instances, the algorithm SIMPLE coupling of the velocity-pressure, an upwind scheme for the turbulence of the kinetic energy and momentum was used as the solution method. Convergence occurs when each of the variables reaches the convergence criterion between 10^{-4} and 10^{-7}, then it can be said that the solution has reached a state of convergence. Table 2 shows the properties of the crushed porous coal rocks l [28].

Table 2. Crushed porous coal rocks properties

Parameters	Values
Porosity (ε)	0.4793
Permeability (K) (m^2)	3.73×10^{-12}
Inertial Resistance Coefficient (C)	4.57×10^{10}
Density (ρ), kg/m^3	1300
Thermal Conductivity (keff.), W/m. °C	0.1998
Specific Heat Capacity (CP), j/kg.°C	1003.3
Average Particle size(d_p), m	0.0026

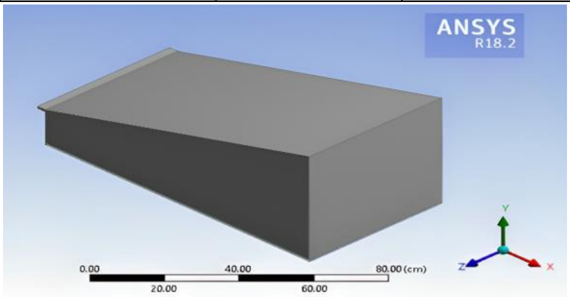


Figure 3. Geometry of the solar water distillation system

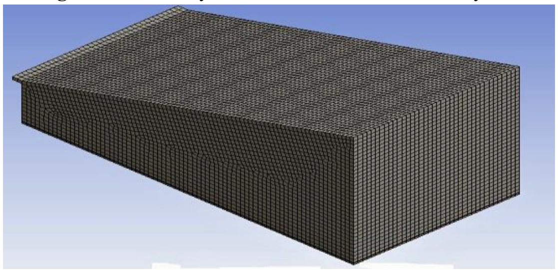


Figure 4. Mesh generation of solar water distillation system

4. Results and Discussion

The numerical and experimental results are presented and analyzed to investigate the effect of using the crushed porous coal rocks as an endothermic surface with varying water height above the endothermic surface on the pure water productivity and solar distillation performance.

Figures 5 and 6 show the behavior of temperature contours for crushed porous coal rock and flat plates at a water height of 1 cm. It's noted from the figure that the magnitude of the level of temperature contours of a traditional flat plate is higher than that of coal rocks absorption plate at the same solar intensity due to the crushed coal rocks containing pores and that leads to an increase in the heat transfer to the water compared to the traditional absorber plate.

Figures 7 and 8 show the solar still streamline for crushed porous coal rock and flat plates at a water height of 1 cm. The figure clears that the circulations lines using a porous coal rocks absorption plate can be given more smooth line towards the glass cover compared to the flat plate. So, this an evidence that the use of crushed porous coal rocks as an endothermic surface gives more turbulence causing to increase in the heat transfer to the exit water condensation region at the same solar intensity.

The vapor friction of water contours for crushed porous coal rock and flat plates at a water height of 1 cm can be seen in Figures 9 and 10. In general, the figure shows that using porous coal rock as an endothermic surface gives high values compared with the flat plate as a result of increasing the transfer of heat from absorber plate cause to the water.

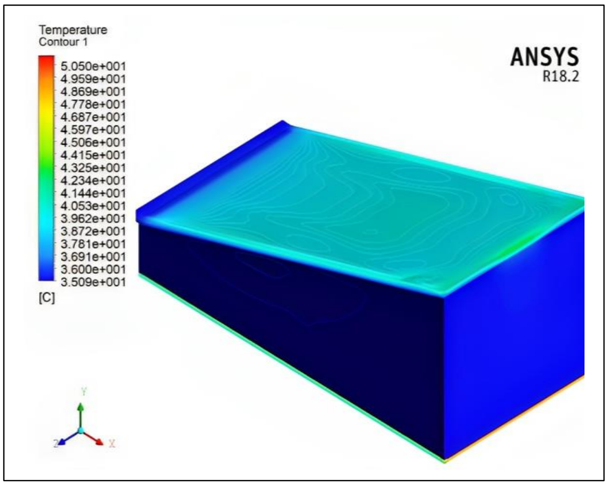


Figure 5. Temperature contours with crushed porous coal rock at 10 mm water height

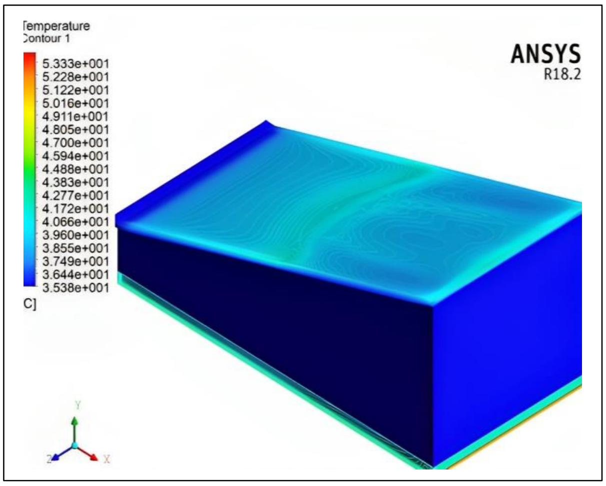


Figure 6. Temperature contours with flat absorber plate at 10 mm water height

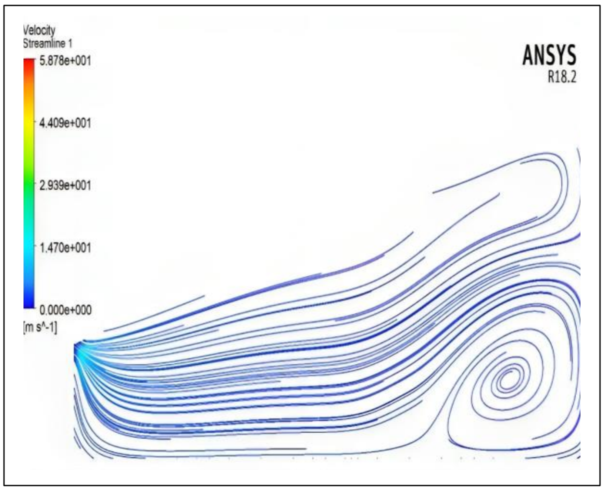


Figure 7. Air Streamline contours with crushed porous coal rock at 10 mm water height

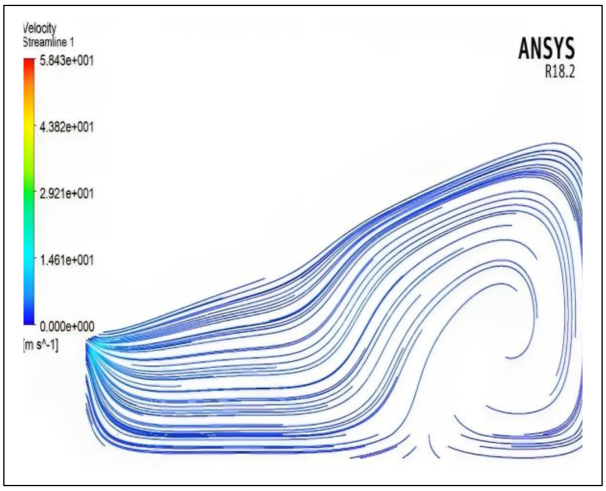


Figure 8. Air Streamline contours with flat absorber plate at 10 mm water height

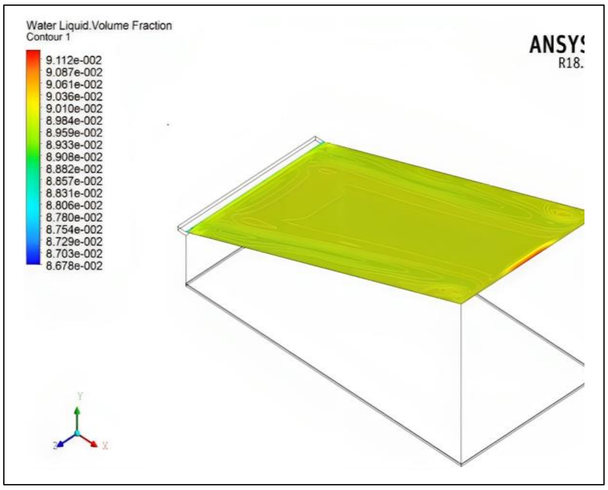


Figure 9. Vapor friction of water contours with crushed porous coal rock at 10 mm water height

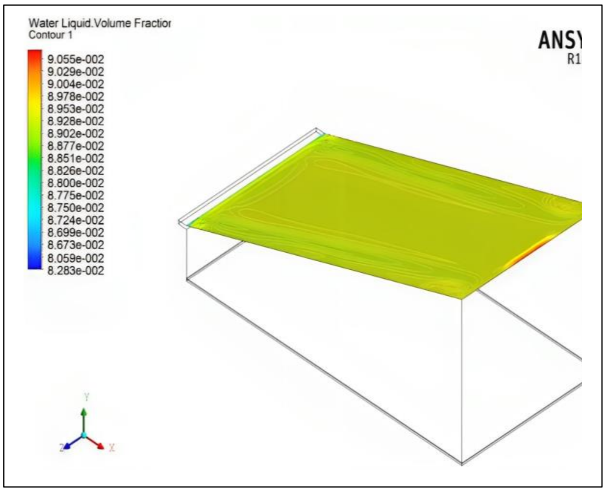


Figure 10. Vapor friction of water contours with flat absorber plate at 10 mm water height

The variation of the solar radiation intensity is presented in figure 11 from 09:00 AM to 03:00 PM on August, 2022. It shows that the solar radiation intensity increases from the early morning to reach its maximum value at 1:00 PM, and then decreased and disappeared at the sunset. The solar irradiance maximum value obtained is 877 W/m^2 at 1:00 PM. It is noted from the figure that the intensity of the solar radiation for the days in which the readings were taken is variable depending on the weather condition for that the day. The variation in solar radiation intensity of the three curves is a small difference of ± 1 to 20 W/m^2.

Figure 12 shows the temperature variation of the solar collector glass, water, and coal rock's absorbent surface with daily time at a water height of 10 mm. It is noted from the figure that the crushed porous coal rocks are higher than the temperature of the cover and water temperatures until approximately 11:00 AM, after which the water temperature becomes as high as possible because the water is penetrated between the porous coal rocks causing to increase the condensation of steam for the cycle as a result of increase the absorber surface area.

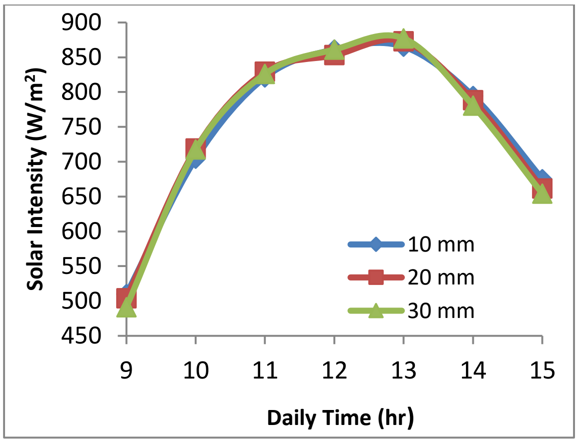


Figure 11. Variation of solar radiation intensity with local time

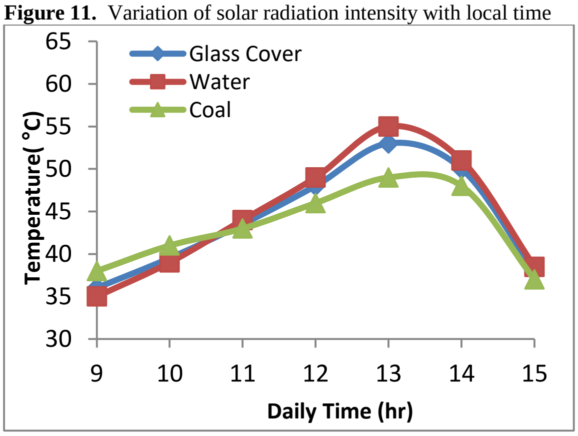


Figure 12. Variation of solar temperature for crushed porous coal rocks

Figures 13 and 14 show the hour daily rate of water produced for crushed porous coal rocks and flat absorber plates at different water heights (10, 20, and 30) mm. It is noted from the figures that the amount of vapor condensed at 10 mm is the highest compared to the rest of the water heights used in this study because the latent heat of evaporation is higher with a 10 mm height of water above the endothermic surface. The reason is due to the volume of water present. Thus, the amount of energy needed to raise its temperature to a higher degree will be lower. Also, it is noted that productivity in the case of using coal rocks gives greater productivity compared to the traditional absorbent plate.

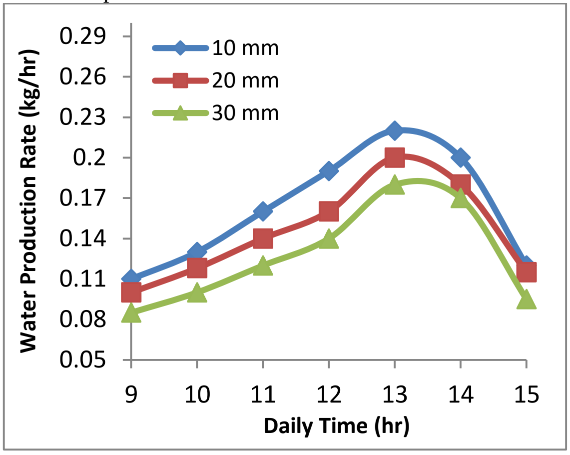


Figure 13. Water productions with local time for flat absorber plate at different water height

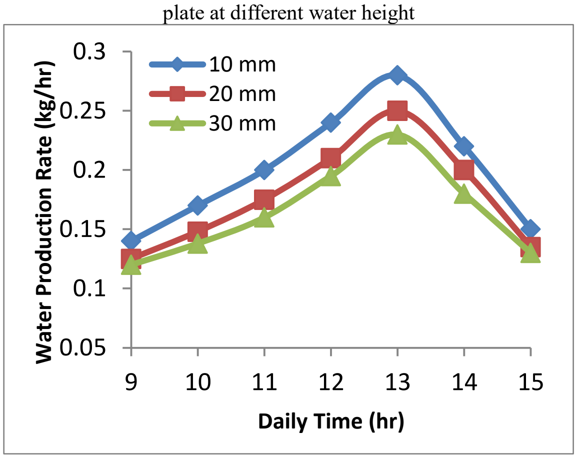


Figure 14. Water productions with local time for coal rocks absorber plate at different water height

The evaporative heat transfer coefficient with the hours daily for crushed porous coal rocks and flat absorber plates at a water height of 10 mm can be seen in Figure 15. In general, the evaporative heat transfer is increased to reach a

maximum value at 1:00 PM and then decreased gradually depending on the solar radiation intensity. Also, it is seen that

the evaporative heat transfer is an enhancement of about 56.3% by using crushed porous coal rocks compared to traditional flat plate.

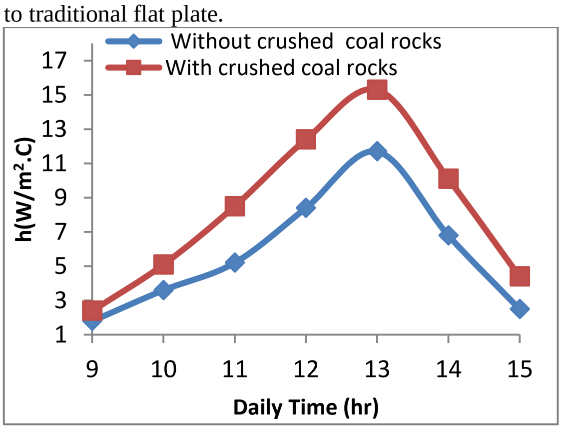


Figure 15. Evaporative heat transfer coefficient for coal rocks and flat absorber plates at 10 mm water height

4.1. Numerical and experimental results comparison

The rate of outlet water distilled with the daily time shows in Figure 16 for the numerical and experimental data. In general, it is noted that the water production begins to increase with the time to reach maximum value at 1:00 PM and then it is decreased gradually depending on the solar radiation intensity. Also, it is seen that the water height level is an important factor affecting water production as shown in the figure.

The liquid water and water vapor temperatures can be shown in Figures 17 and 18 for numerical simulation and experimental data with a water level of 10 mm. The behavior of the numerical and experimental results is shown the convergence between them. The vapor and water temperatures in the figures begin to increase to reach the maximum values at 1:00 pm and then they are decreased gradually depending on the intensity of the solar radiation.

4.2. Comparison with previous literature

Figures 19 and 20 show the experimental comparison with previous research [13] and [16] to show the extent of convergence in the behavior and accuracy of the results obtained in the experimental aspect.

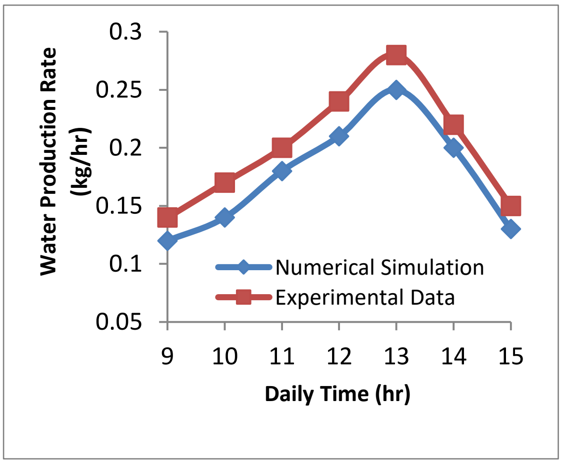


Figure 16. Daily water production rates to compare experimental and numerical results

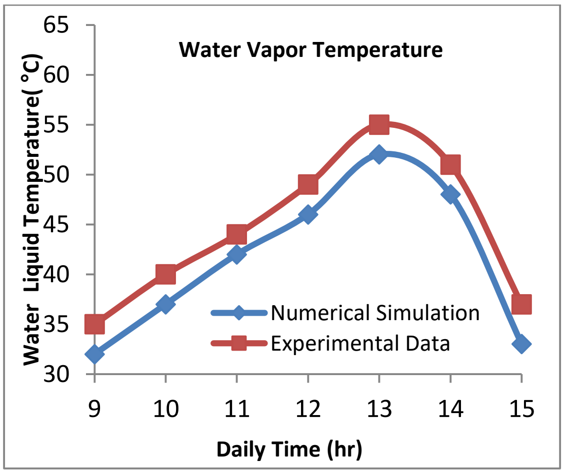


Figure 17. Daily water liquid temperatures to compare experimental and numerical results

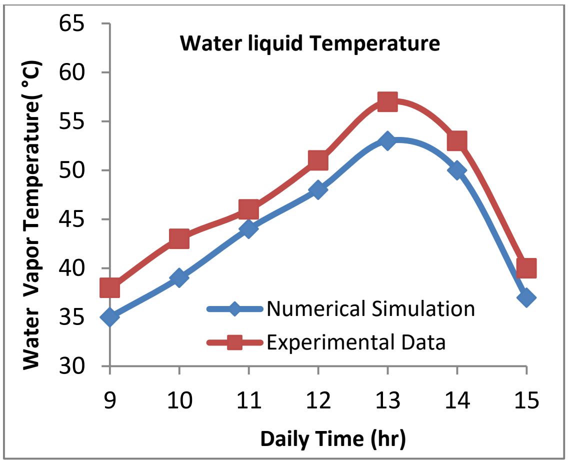


Figure 18. Daily water vapor temperatures to compare experimental and numerical results

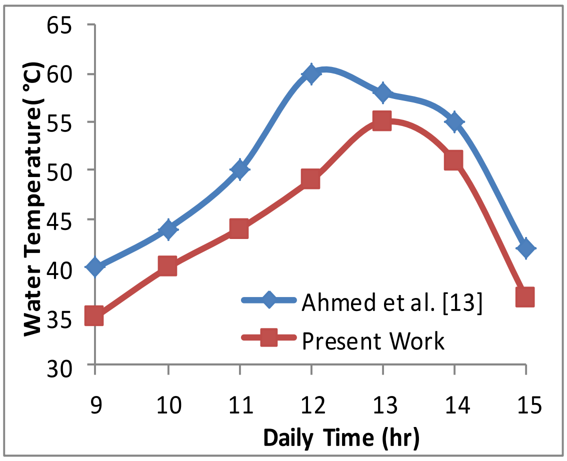


Figure 19. Daily water temperatures to compare present work and previous research Ahmed et al. [13]

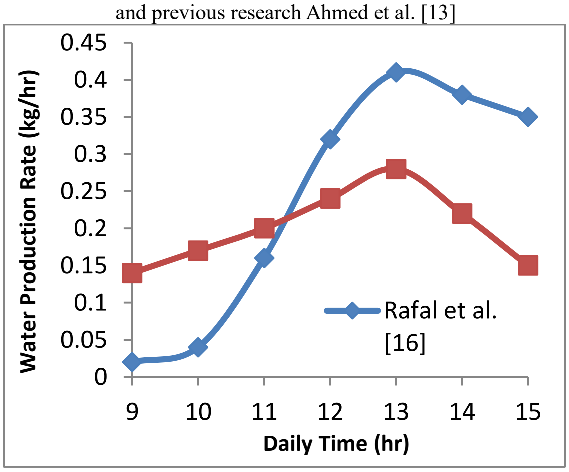


Figure 20. Water productions with local time between present work and previous research Rafal et al. [16]

5. Conclusions

Present work investigated numerically and experimentally the impact of using crushed porous coal rocks as an endothermic surface with varying water heights of (10, 20, and 30) mm on the water production rate of a solar distillation system. The study proved that using crushed porous coal rocks as an endothermic surface caused to increase in the water production rate by about 52.3% numerically and 56.3% experimentally as an increase in coefficient of evaporative heat transfer if it is compared to the traditional absorber plate. The change in water height level is an important factor that can affect on water production rate. The maximum value of water production was produced at a water height of 10 mm for absorption plates of flat and crushed coal rocks because of an increase in the condensation and evaporation of a solar distillation system.

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