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Factorial design of experiment for modeling solar still parameters

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ABSTRACT

The design of experiments method is used to evaluate the performance of the solar still's input factors influencing the responses. Nine factors (solar radiation, basin area, saline water depth, insulation material, insulation thickness, absorptivity, ambient temperature the thickness of glass cover, and wind speed) that have an impact on the performance of the solar still were studied to show their effects on the responses. Three system's responses (distilled water, water temperature and glass cover temperature) were evaluated. An accurate theoretical model of the thermal behavior of the solar still was developed. The highly complex behavior of the solar still was accurately described by the developed mathematical model. A numerical technique (Runge–Kutta method) is used to solve the non-linear system of differential equations. The statistical analysis to show the effect of solar still's factors on solar still performance was evaluated using Minitab software. The statistical results demonstrate that the most important factors that have high effect on the solar still productivity are basin area, saline water depth, and solar radiation respectively. While the insulation thermal conductivity, ambient temperature, and glass thickness have no effect on the performance of still. On the other hand, water depth, solar radiation and wind speed have major impact on the water and glass temperature.

Keywords: Solar still; Design of experiments; Factorial design; Fins; Thickness; Productivity; Water depth; Insulation

1. Introduction

About 1.1 billion persons, globally, are deprived of clean freshwater [1]. Along with expensive fossil fuel, the deficiency of drinkable water becomes aggravated for these people [2]. Solar still technology came as one of the optimal suitable solutions for this problem, especially in areas where solar energy is abundant which coincides with the pretense of the deprived water communities [3].

Solar stills can be placed at each house for producing at least potable water. They are economical and inexpensive, simple in design, and pollution-free. Yet, there is a serious challenge associated with solar still. The small amount of produced water is one of the most challenges. Solar still is affected by a set of factors that increase the temperature difference between saline water and glass cover inside solar still such as the amount of solar radiation, saline water depth, basin area, insulation thickness, and many other parameters.

Khalifa and Ahmad [4] studied the effect of insulation thickness on the productivity of solar still. Three insulation thicknesses have been examined (30, 60, and 100 mm). The results found that the insulation thickness has a significant impact on the productivity of the still up to a thickness of

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60 mm. Al-Karaghouli and Alnaser [5] fabricated two solar-stills; one with still-sides insulation and the other without. The results showed that the influence of side insulation has a significant impact on water production reached to about 43.8%. Muthu Manokar et al. [6] investigated the effect of water depth and insulation on the productivity of acrylic pyramid solar still, the results showed that the maximum productivity without insulation at 2, 3, and 3.5 cm of water depth were 2.8, 2.26, and 1.67 kg/m^2, respectively. While, the effect of adding insulation increased the productivity to 3.38, 2.94, and 2.06 kg/m^2 respectively. Velmurugan et al. [7] increased the exposure area of the basin liner of solar still in different ways (still with sponges, still with wick type, and still with fins at the basin plate). The results inferred that the productivity increased about 29.6%, 15.3% and 45.5% when wick type, sponges and fins have been added respectively. El-Sebaii et al. [8] examined the effect of fin arrangement on the solar still productivity. The results inferred that the fin height was direct proportional to the productivity while the fin thickness and fin number were inversely proportional to the performance. Essa et al. [9] compared the performance of single and double-staged vertical solar distillation systems that have two rotating discs with conventional tilted and vertical solar still. They applied different rotational speeds (from 0.125 to 2.5 rpm) to identify the most effective disc speed. The experimental results showed that the modified single staged vertical solar still and double staged vertical solar still improved the performance of still by 350% and 617.4%, respectively at rotational speed of 1.5 rpm over that of conventional tilted solar still.

Nisrin and Taamneh [10] conducted an experiment to study the effect of using absorber plates made of carbon fiber/nanomaterials-modified epoxy composites at different concentrations on pyramid solar still. Their experimental results showed that the productivity of still increased about 109% and 65% by adding 5% and 2.5% nano weight concentrations respectively. Ghoneyem and Ileri [11] used software to solve some of the Empirical equations to statement the dependency of the water output on the ambient temperature and solar radiation fallen on solar still cover. The results concluded that the average daily output has been improved by increasing the amount of solar radiation.

Badran and Abu-Khader [12] performed theoretical and experimental analysis on single inclination solar still based on a change of solar radiation intensity. The results concluded that as the solar intensity increases, the productivity of water output increases due to the increasing in the latent heat of basin water. Almuhanna [13] revealed that the efficiency of solar stills increases as solar radiation intensity increases. Sahoo et al. [14] showed that the efficiency of solar still increases 11%, by increasing the capacity of water in the solar basin from 10 to 20 kg. Suneja and Tiwari [15] used numerical calculations on double basin solar still to analyses the effect of water depth on the water productivity. The results described that as increasing the depth of water, the efficiency of the solar still decreases. Rajamanickam and Ragupathy [16] studied the effect of water depth on water productivity of the double slope (DS) solar still. Four depths have been used at the same condition (0.01, 0.025, 0.05 and 0.075 m). The results found that the maximum purified water has been achieved at minimum water depth. Abd Elaziz et al. [17] introduced an ensemble random vector functional link networks (EnsRVFL) to anticipate the productivity of active solar stills (integrated with suction fan and external condensation system) with Cu_2O and Al_2O_3 nanoparticles. The performance of the active solar still was improved by about 140% and 100% when using Cu_2O and Al_2O_3 respectively compared with that of conventional solar still. Moreover, adding the fan enhanced the efficiency of the active solar still with Cu_2O and Al_2O_3 to 36.02% and 32.82%, respectively. Sebaii [18] used numerical calculations on typical summer and winter days to analyze the effect of wind speed on water yield. It has been found that the productivity of still increases as increasing wind speed up to a critical value beyond which, the increasing in wind speed becomes inefficient. Rahmani and Boutriaa [19] carried out numerical and experimental study to find the effect of wind velocity on condensation surface area of solar still in summer and winter conditions. The results showed that the wind speed was more effective on small condensation area. El-Sebaii [20] studied the effect of wind velocity on the daily water output for passive and active solar distillation. The results revealed that the daily productivity increases as wind speed reaches to a typical velocity (10 m/s in summer and 8 m/s in winter) beyond which, the increase in wind speed becomes inefficient. Essa et al. [21] investigated two designs of rotating wick solar stills. They integrated a wick belt of black jute cloth in the first design to be rotated inside the solar still in a 'L shaped path' and they called it L-RWSS. The second design is called LC-RWSS, where the wick belt is designed to be rotated in a path of an "L" character with a chamfer at the bottom end. The rotational belt is under on time of 5 min and different off times (zero, 10, 20, 30, 40, 50, and 60 min). Moreover, they studied the influence of using quantum dots nanofluid on the productivity of LC-RWSS. Results indicated that the optimum thermal performance of LC-RWSS is achieved at 30 min off time either with or without adding nanofluid. In addition, the total accumulated daily yield of LC-RWSS is higher than that of L-RWSS by 19% and 17% with and without adding nanofluid, respectively. The daily productivity of L-RWSS and LC-RWSS reached 8,200 and 9,600 mL/m^2 d, respectively. The thermal efficiency of LC-RWSS is 88% and 86% with and without adding nanofluid respectively compared to 82% for L-RWSS. Edeoja et al. [22] studied the effect of using five glass cover thickness on solar still performance. Still 1 has one glass cover, still 2 has two glass covers, still 3 has two glass covers with airspace layer between each other, still 4 has three glass covers without airspace, and still 5 has three glass covers with airspace between each one. The results showed that still 1 has the highest water productivity and efficiency reached to about 306 cm^3 and 24% respectively. Panchal and Shah [23] conducted three experiments to investigate the effect of different glass cover thicknesses on single slope solar still. The three thicknesses of glass cover were 0.004, 0.008, and 0.012 m. The experiment results showed that as increase glass cover thickness, the distillate water and the efficiency decrease. Abu Abbas and Al-Abed Allah [24] investigated the effect of condenser materials type and condenser slope on the performance of the solar still numerically. Five types of condenser materials have been examined: poly(methyl methacrylate), polyethylene terephthalate, polycarbonate plastic, glass, and polyvinyl chloride. Moreover, four slope angels for condenser have been tested at different seasons: 5°, 20°, 35°, and 45°. The results revealed that the daily solar still productivity increases as transmissivity value of condenser material increase. Besides, it was noted that the maximum productivity in summer (May) was at the lowest condenser slope angle (5°) and it decreased as the condenser slope angle increased. While, the maximum productivity of solar still in the winter season (January) was at (20°) and then decreased as the condenser slope angle increased.

The performance of solar still and its productivity depend mainly on increasing the temperature difference between saline water and glass cover. Many parameters have been studied by different researchers to improve the temperature difference. These parameters are solar radiation intensity, ambient temperature, depth of saline water, bottom and side insulation material and thickness, basin area, and wind speed. The parameters like solar insolation intensity and wind speed are uncontrolled because they depend on environmental conditions. While other parameters such as basin water depth, basin area, insulation, etc. are controllable parameters and could be improved effectively to increase the productivity of still. It might be observed that all the researches have explored the influence of employing one parameter at a time while maintaining the other parameters unchanged. This technique will not aid understanding the relationship between elements. In this research design of experiments (DOE) is employed by gathering all the parameters that could affect the solar still system to show which parameters have the most significant effect and which of them does not has any influence when they are being together at the same time. Moreover, DOE is used to explain the interaction between parameters that affect three responses: distilled water, saline water temperature, and glass cover temperature. Furthermore, regression equations for all responses have been illustrated.

2. Methodology

2.1. Mathematical model

The key components of the solar distillation system have been modelled in a non-linear differential equations framework. There are equations that can be used to determine how much distilled water and how hot the condenser cover is at any given time and in various system setups. Basin plate, saline water, glass cover of solar distillation system key energy balance equations were solved for the theoretical results. Solar distillation system productivity was measured every 5 h by comparing the saline water, the basin plate, and the condenser cover temperatures. MATLAB software was used to solve the numerical model. The following are the energy balance equations for the primary solar still components [7]:

As shown in Eq. (1), fraction of the solar radiation connected with the solar distillation system is transmitted to the basin plate as heat and then it is transferred to saline water by convection. Other amount of energy is lost to the ambient through bottom insulation material by conduction.

$$I_t A_b = m_b C p_b \frac{dT_b}{dt} + Q_{\text{cb}-w} + Q_{\text{loss}-\text{ba}} \tag{1}$$

The transient energy balance equation for the saline water is given as Eq. (2), fraction of heat is transmitted to saline water by convection. All heat gained is lost in two approaches; specific quantity of energy is stored in saline water due to its specific heat property. The rest of energy is released to the condenser cover by evaporation, convection and radiation.

$$Q_{\text{cb}-w} = m_w C p_w \frac{dT_w}{dt} + Q_{\text{cw}-c} + Q_{\text{ew}-c} + Q_{\text{rw}-c} + Q_{\text{mw}} \tag{2}$$

Energy balance equation for the glass cover is presented as Eq. (3). The heat energy arrived from saline water surface is absorbed by the condenser cover and then released by conduction through thickness of the cover.

$$Q_{\text{cw}-c} + Q_{\text{ew}-c} + Q_{\text{rw}-c} = m_c C p_c \frac{dT_c}{dt} + Q_{\text{cc}-a} + Q_{\text{rc}-\text{sk}} \tag{3}$$

2.2. Design of experiment

DOE is a tool for designers and experts that use for product design and development. This tool can reduce time effort and cost. Moreover, it has high reliability than other approaches. The main objective of the experiment is to determine which variables are most influential on the responses. The influential factors that affect the system performance can be set near the desired values and neglect the effects of fewer influence factors. Eq. (1) represents the statistical regression analysis using DOE analysis [25].

$$f(x) = a_o + \sum_{i=1}^{k} a_i x_i + \sum a_{i,i} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} a_{i,j} x_i x_j + \varepsilon \tag{4}$$

Here, $f(x)$ is the predicted response variable, and a_o, a_i, $a_{i,i}$ and $a_{i,j}$ are the regression coefficients of the intercept, linear, quadratic and interaction effects, respectively, while x_i and x_j are independent input variables, and ε is a random error.

A reduced factorial design has been used to investigate the significance of nine factors that are mostly concerned with solar desalination systems. Three responses have been studied (distilled water, water temperature and glass cover temperature). A $2^{(9-2)}$ reduced factorial has been used to specify the most significant factors affecting on the system, determine their interactions and investigate the regression equations for all responses. Table 1 shows the main parameters of this study. While, Fig. 1 represent a schematic view of the proposed solar still and detailed side view. The thermal resistance network of solar still system is shown in Fig. 2.

Reduced factors have been chosen very carefully by checking the alias structure, resolution, balancing and orthogonally. In this study a $2^{(9-2)}$ reduced factorial has performed with IV resolution, which means no main effects are aliased with any other main effect or 2-factor interactions, but some 2-factor interactions are aliased with other 2-factor

Table 1
Description of factor levels

Symbol	Factor name	Low level	High level	Unit
A	Insulation thickness	0	5	mm
B	Insulation thermal conductivity	0.025	0.12	W/m·°C
C	Basin area	0.5	2	m
D	Solar radiation	600	1,200	W/m^2
E	Absorptivity	0.88	0.95	Unitless
F	Wind speed	1	20	m/s
G	Ambient temperature	10	40	°C
H	Glass thickness	2	6	mm
J	Water depth	1	10	cm

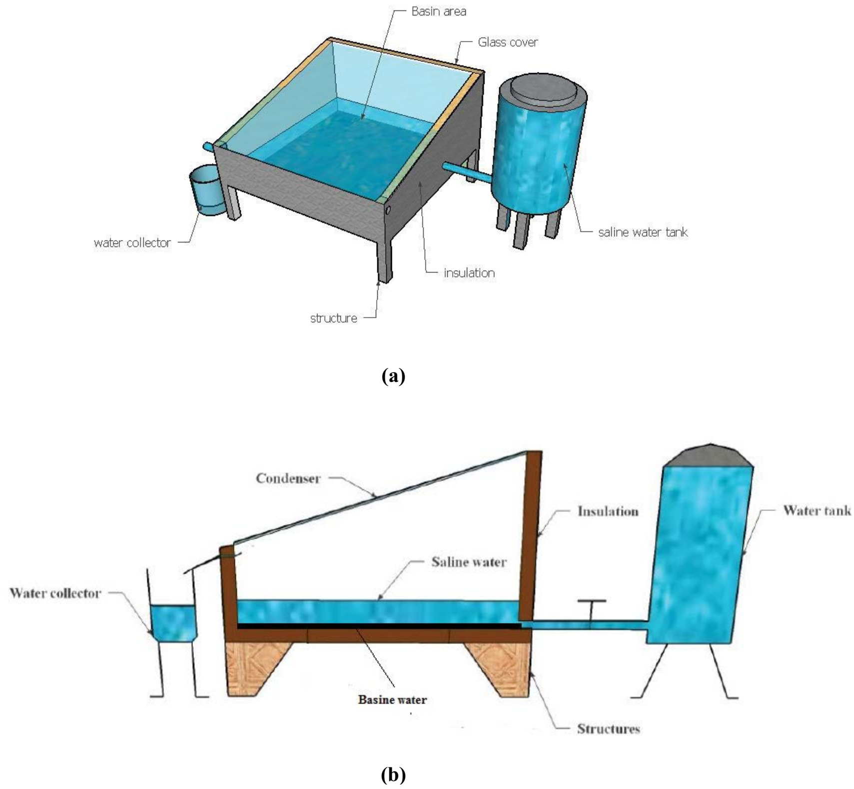


Fig. 1. (a) A schematic view of the proposed single slope solar still and (b) a side view of solar still.

interactions and main effects are aliased with 3-factor interactions. In this step we concerned with the significance of the main effects which mentioned above. Matlab program has been used to simulate the three responses and Minitab software for DOE.

2.3. Simulation assessment

The flowchart corresponding to the applied method in this study is shown in Fig. 3. The simulation starts with a select type of analysis, the number of factors and nature of runs (randomity or non-randomity) using Minitab. The unknown temperatures such as glass temperature (T_g), water temperature (T_w), and basin liner temperature (T_b) in addition to distilled water are obtained by solving the differential equations [26]. The best method for solving the system of equations is Runge–Kutta fourth-order method using MATLAB software. The values of T_g, T_w, T_b, and distilled water are calculated for 1 h.

3. Results and discussion

The chosen mathematical formula [26] and numerical procedure determine the amount of freshwater, water temperature, and glass cover temperature for a given conditions. Hence, solar radiation intensity, basin area, water depth, insulation material, thickness of insulation, thickness glass cover, wind velocity, and ambient temperature

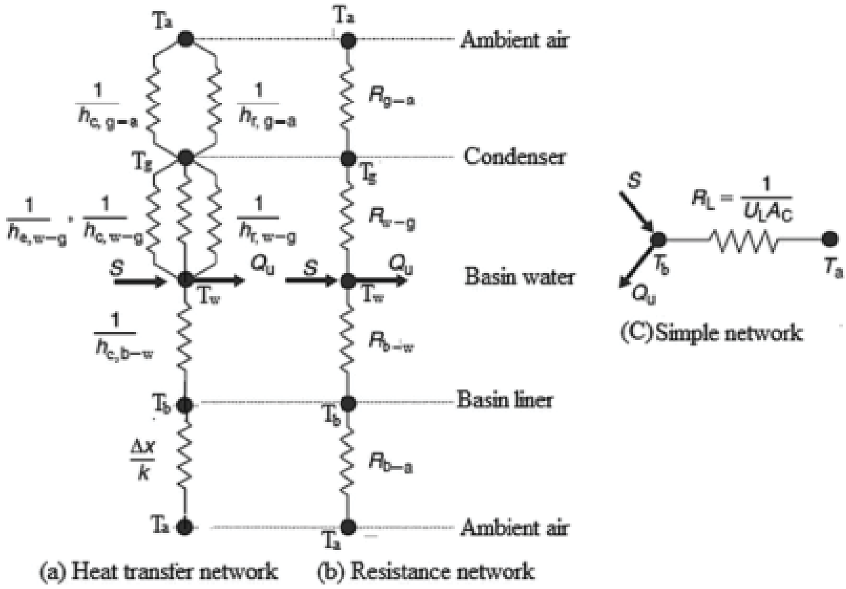


Fig. 2. Thermal resistance network of solar still system.

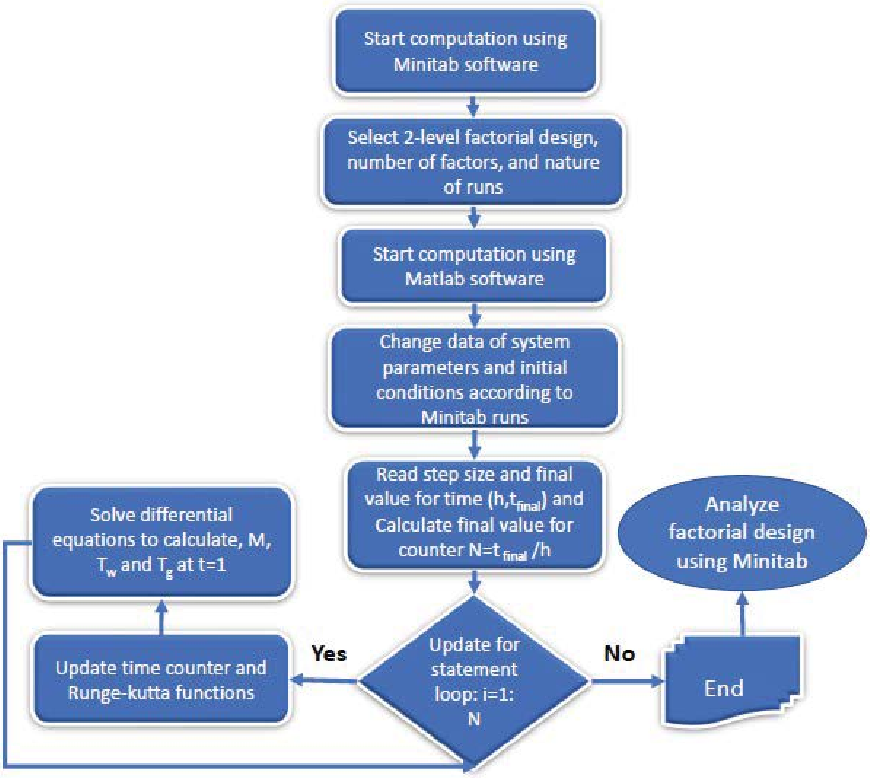


Fig. 3. Simulation steps using Minitab and MATLAB softwares.

are considered as variables to understand their effects on the freshwater production. To be more efficient, test conditions are designed based on the methodology of DOE performed on 2^k at two levels. Therefore, understanding the parameters effect and interactions on the desired responses.

3.1. Main effect plots results

Fig. 4a–c illustrate the main factors affecting on the responses of the solar desalination system. It has been observed that there is a proportional relationship between

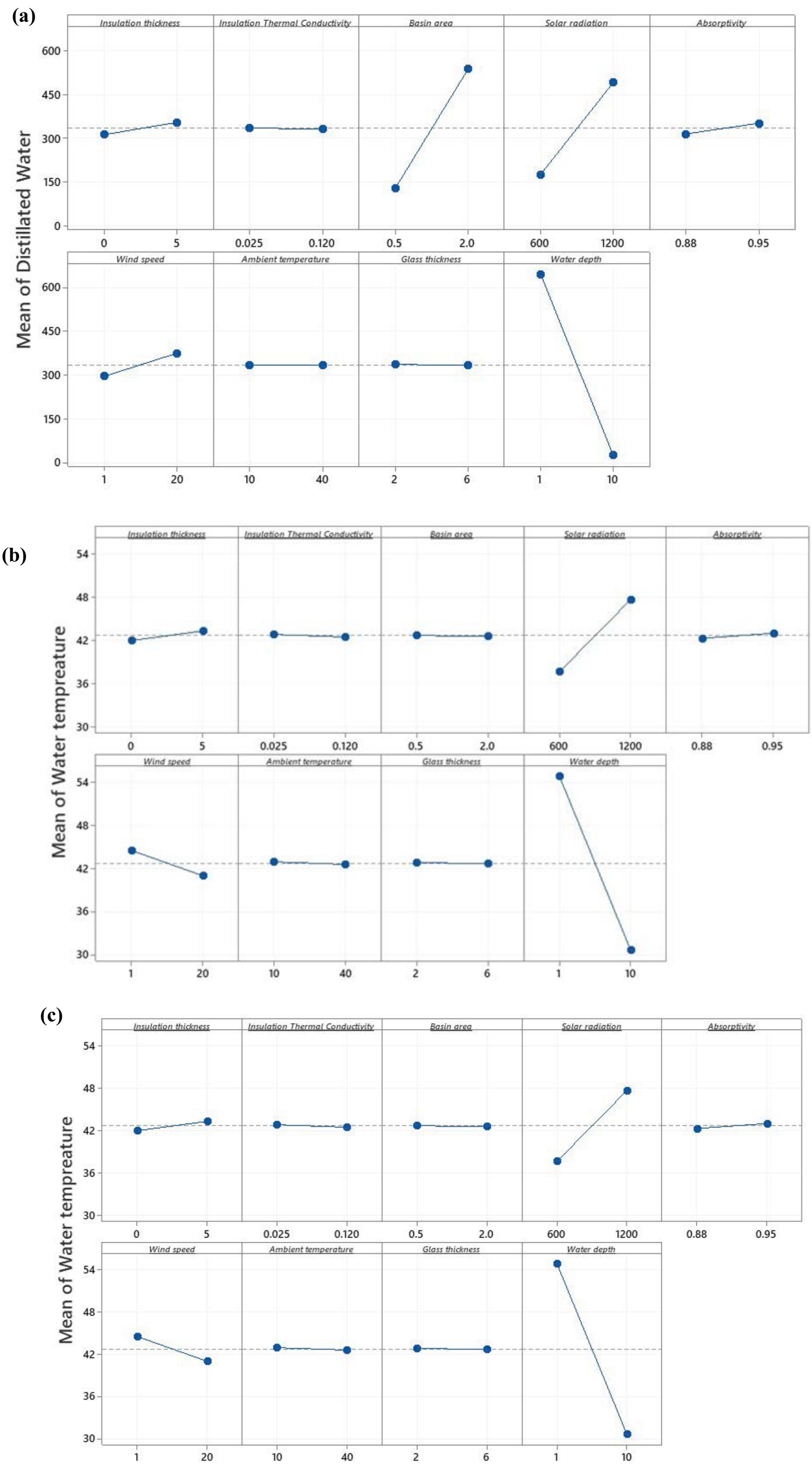
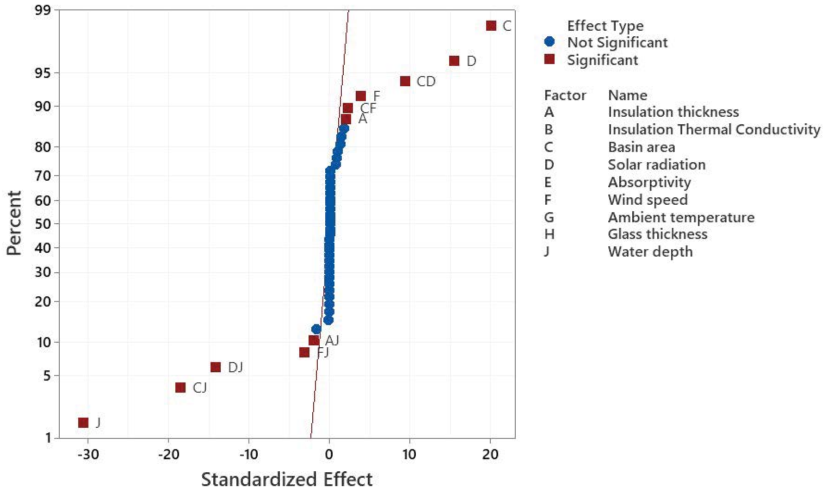
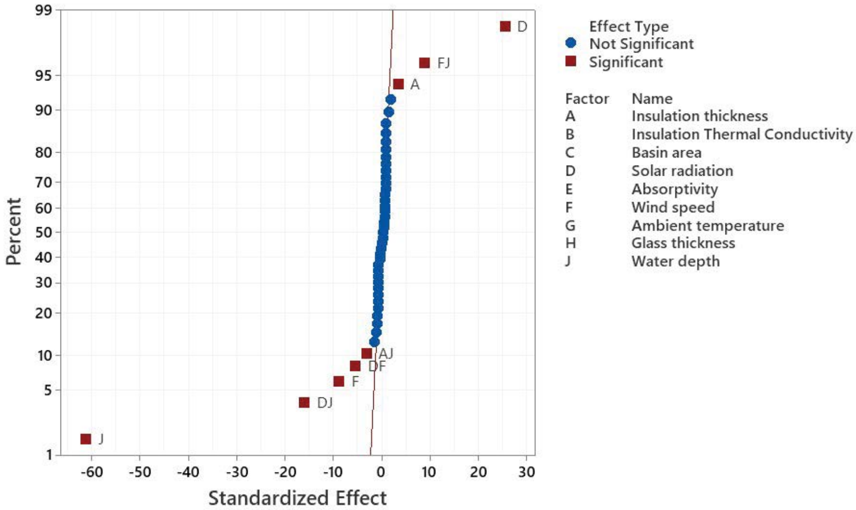


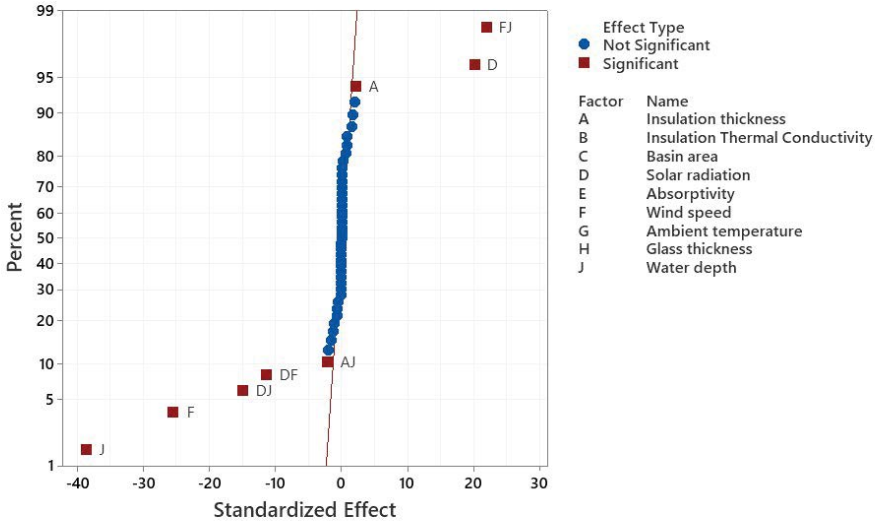
Fig. 4. Main effect plots for (a) distilled water, (b) water temperature and (c) glass cover temperature.



(a)



(b)



(c)

Fig. 5. Normal plots of the standardized effects for (a) distilled water (b) water temperature and (c) glass cover temperature.

the slope of line and the effect of the parameters on the responses. As inclination of the lines increases, the effect of the factors on the responses will be significant, Fig. 4a demonstrates that the most significant factors that increase the amount of distilled water are water depth, basin area, and solar radiation respectively. In contrast, glass thickness, ambient temperature, and insulation material have no effect on the system. Fig. 4b shows that water depth and solar radiation are the main factors affecting the water temperature of the solar desalination system. While the other factors have a neglectable impact on the water temperature. Furthermore, the simulation concludes that the main factors affecting on the glass cover temperature are water depth, solar radiation, and wind speed respectively as shown in Fig. 4c. The reason behind that can be explained in terms of the evaporation rate. As decreasing the basin water depth, the basin water temperature increases faster. Hence, the evaporation rate is improved. Therefore, water productivity will be enhanced [27].

Moreover, as increasing basin water area, the amount of distilled water increases due to fact that the evaporation rate of basin water is directly proportional to the exposure area [28]. Furthermore, as increasing the amount of solar radiation, the basin water temperature increases. Therefore, the evaporation rate will be improved. Consequently, distilled water is boosted [29]. Also, as increasing the air speed on the upper condenser layer, the convection heat transfer increases. Thus the condenser temperature will be declined [20]. The designers should select high-level values for factors that increase water temperature and low-level values for factors that decrease glass cover temperature to get the maximum level of distillation.

3.2. Normal plots of the standardized effects' results

The obtained results from the simulation illustrates all the influencing and non-influencing factors on the responses. Fig. 5a–c show normal plots of the standardized effect for distilled water, water temperature, and glass temperature respectively. Furthermore, it illustrates the interactions between factors for each response. Where the independent variables (factors) might interact with each other. It happens when the influence of one factor depends on the value of another factor. Moreover, the interaction effects show that a third variable affecting the relationship between an independent and dependent (responses) factor. In Fig. 5a it is clearly observed that the highly weighted factors which play a key role in producing highly distilled water are basin area, solar radiation, and interaction between them respectively. For example, the interaction between basin area and solar radiation explains that mass output level is high when the solar radiation and the basin area values are high. On the other hand, at low-level values, the major factors that improve the distilled water productivity are water depth, the interaction between water depth and basin area in addition to the interaction between water depth and solar radiation, respectively. As shown in Fig. 5b the main parameters affecting the water temperature at high-level values are solar radiation, the interaction between wind speed and water depth, and insulation thickness. While at the low-level values, the most significant factors that increase water temperature are water depth and interaction of solar radiation with water depth respectively. Additionally, Fig. 5c indicates that the most influential factors at high-level values are the interaction of wind speed with water depth, solar radiation, and insulation thickness respectively. While at low-level values the most significant factors are water depth and wind speed respectively.

3.3. Regression equations

Regression has been performed on the obtained data, results, of factorial in order to reveal the effects of these parameters on the freshwater production. Eqs. (5)–(7) are the regression functions estimated from DOE analysis of 2^k factorial model to predict three responses: distilled water, water temperature and glass cover temperature respectively. The constants refer to the affecting coefficient of each factor while the plus and minus signals refer to the high or low level of the factors.

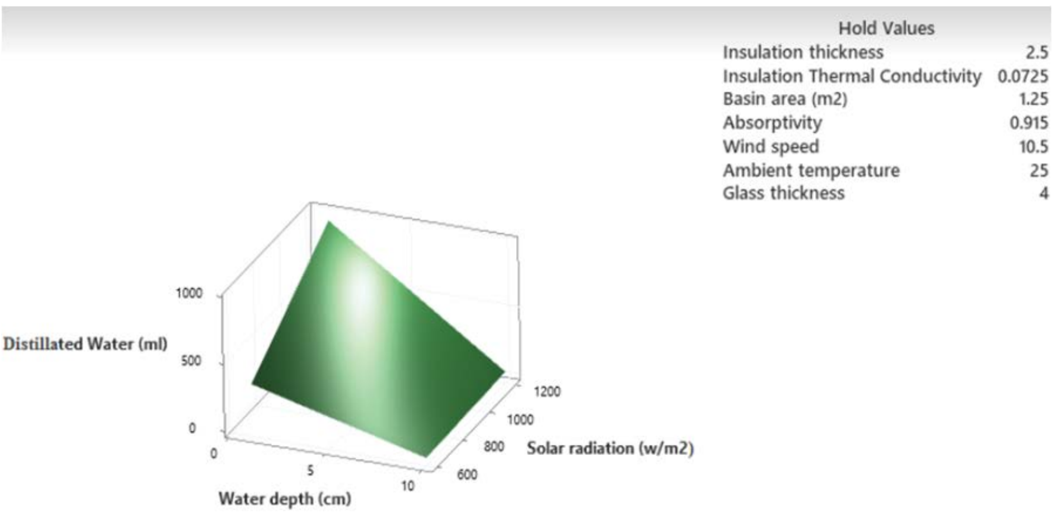


Fig. 6. Surface plot curve of solar radiation and water depth on distilled water.

$$\text{Distillated Water} = -489 - 14\,A - 232\,B - 225\,C - 0.140\,D - 40\,E - 3.5\,F + 1.6\,G + 14\,H + 202.6\,J - 0.8\,AB + 7.10\,AC + 0.0126\,AD + 12\,AE + 0.013\,AF + 0.033\,AG + 0.13\,AH - 1.832\,AJ - 4\,BC + 0.006\,BD + 158\,BE + 0.2\,BF + 0.6\,BG + 7\,BH + 4.4\,BJ \quad (5)$$

$$\text{Water temperature} = 33.5 - 1.03\,A + 68\,B + 4.96\,C + 0.0088\,D + 0.1\,E - 0.309\,F + 0.227G - 1.83\,H - 0.12\,J + 1.43\,AB + 0.097\,AC - 0.000082\,AD + 1.76\,AE - 0.01264\,AF + 0.00455\,AG - 0.0325\,AH - 0.0567\,AJ - 4.01\,BC + 0.0101\,BD - 98\,B \times E + 0.318\,BF - 0.197\,BG + 1.79\,BH + 0.800\,BJ \quad (6)$$

$$\text{Glass temperature} = 12.9 + 0.18\,A - 1.7\,B + 0.46\,C + 0.0181\,D + 15.2\,E + 0.150\,F + 0.007G - 0.11\,H + 0.93\,J + 0.06\,AB + 0.0096\,AC + 0.000181\,AD + 0.08\,AE - 0.00954\,AF + 0.00020\,AG - 0.0038\,AH - 0.0323\,AJ + 0.20\,B \times C - 0.0004\,BD + 1\,BE - 0.012\,B \times F + 0.012\,BG + 0.03\,BH + 0.043\,BJ + 0.000111\,CD \quad (7)$$

3.4. Surface plot curves

Surface plots are master tools to describe the effect of each parameter simultaneously rather than calculating one by one via the simulation code. Fig. 6 represents the effect of water depth and solar radiation on the freshwater

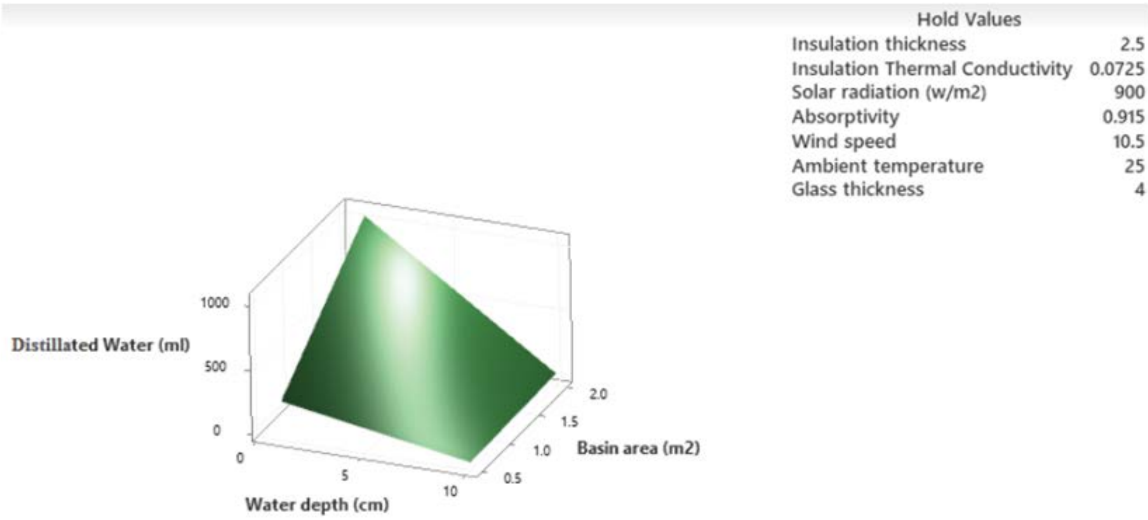


Fig. 7. Surface plot curves of basin area and water depth on distilled water.

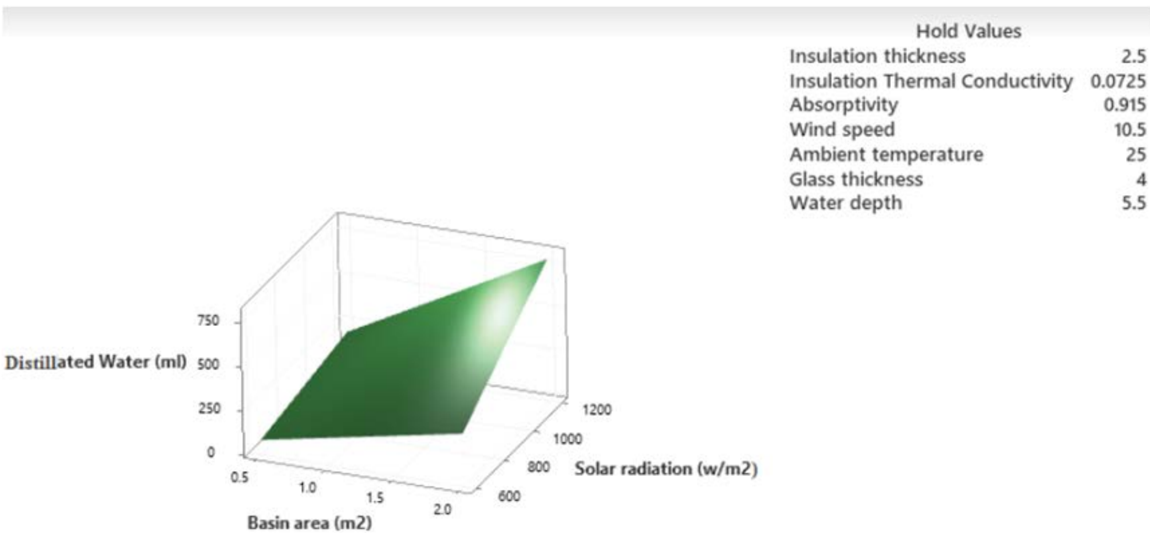


Fig. 8. Surface plot curves of solar radiation and basin area on distilled water.

production for a given conditions (A–J). It is shown that the distilled water production is improved when water depth is decreased, and solar radiation is increased. Fig. 7 represents another surface plot that illustrates the effect of water depth and basin area on the freshwater production. As seen, for a given aforementioned parameters (A–J), decreasing the water depth and increasing basin area could play a role in increasing the amount of distilled water. Interesting information is found in Fig. 8 that shows the effects of basin area and solar radiation on the distilled water production. As seen, for given conditions (A–J), as increasing basin area and solar radiation, the productivity of distilled water increases. These kinds of surface plots could be drawn for different considered parameters in order to find suitable conditions for the system.

4. Conclusion

Design of experiment was used to investigate the effect of a large number of parameters influencing the solar desalination system. Therefore, reaching the optimal design that achieves the highest purified water productivity. The results of statistical and theoretical analyses of solar desalination system can be summarized as follows: The most significant factors that have a high impact on the water productivity were basin area, saline water depth, and solar radiation respectively. The insulation thermal conductivity, ambient temperature, and glass thickness have no influence on the performance of still. Water depth and solar radiation are the most important factors affecting the water temperature comparing to other factors that have a little impact on the water temperature. The statistical results reveal that the main factors influencing the glass cover temperature are water depth, solar radiation, and wind speed respectively.

Conflict of interest

The authors declare that they have no conflict of interest.

Symbols

A_p — Basin area, m^2
cp_b — Basin Specific heat, J/kg k
cp_w — Water Specific heat, J/kg k
cp_c — Condenser Specific heat, J/kg k
I_t — Solar radiation, W/m^2
Q_{cb-w} — Convection heat transfer from basin plate to saline water, W
Q_{cw-c} — Convection heat transfer from saline water to condenser, W
Q_{rw-c} — Radiation heat transfer from saline water to condenser, W
Q_{ew-c} — Evaporation heat transfer from saline water to condenser, W
Q_{cw-c} — Convection heat transfer from saline water to condenser, W
Q_{cc-a} — Convection heat transfer from condenser cover to ambient, W
Q_{rc-sk} — Convection heat transfer from condenser cover to sky, W
$Q_{loss-ba}$ — Conduction heat transfer from basin plate to ambient, W
Q_{mw} — Make-up saline water, W
T_b — Basin temperature, °C
T_c — Condenser temperature, °C
T_w — Water temperature, °C
m_b — basin mass, kg
m_w — Inlet water mass, kg
m_c — Condenser mass, kg

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