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Design optimization of desalination system using design of experiment method

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ABSTRACT

The Design of Experiments method is used to evaluate the performance of the desalination system's input factors influencing the responses. Eleven variables (basin area, depth of saline water, external power, air blowing system, condenser material, condenser thickness, condenser area, insulation thickness, insulation material, ambient air temperature, and make-up water system) were studied to show their effects on three responses (mass output, saline water temperature and condenser cover temperature). An accurate theoretical model of the thermal behavior of the desalination system was developed. The highly complex behavior of the desalination system 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 results show that the most significant factors affecting distilled water are the external power, the depth of the saline water, and the basin area of the active still, Where the effect of adding external power on the mass output at high and low levels were 3.02 and 1.24 L respectively while the effect of water depth on the mass output at high and low levels were 1.3 and 2.8 L respectively. Furthermore, the effect of the basin area on the mass output at high and low levels were 2.8 and 1.4 L. respectively, Furthermore, the most influential factors affecting the temperature of saline water and the glass cover are the depth of saline water, external power, and air blowing system, respectively. These factors increased the saline temperature to 70.3°C, 70°C, and 65.9°C respectively and raised the condenser temperature to 57.9°C, 57.1°C and 56.7°C, respectively.

Keywords: Desalination system; Design of experiments; Factorial design; Thickness; Productivity; Water depth; Insulation

1. Introduction

The solar still is a green energy product that utilizes the natural energy of the sun to purify water. Solar stills are able to provide distilled water for cooking and drinking purposes, even in areas where there are no other sources of energy. Solar stills are broadly classified into two types namely, passive and active solar stills. Active solar stills use external power to fast the evaporation process, while passive solar stills use solar radiation to produce distilled water. Design modifications of active solar stills include a solar still integrated with solar concentrators, a solar still with solar heater, and a solar still with heat exchanger while passive solar stills include spherical solar still and wick type stills.

The daily production and efficiency of the conventional solar still are relatively low, in best optimized operating conditions; daily production and efficiency are about 3–5 L/m^2·d and 30%–45% respectively. Many attempts have been made to enhance its efficiency and productivity [1–4].

The daily production of the solar still depends on several factors such as climatic conditions (solar radiation intensity, ambient temperature and wind speed) [5,6], condensation

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surface inclination [7], insulation type and thickness [8], a solar still geometry [9], the orientation of still and the depth of salty water [10]. Enhancing the productivity of the solar still has received high attention from many researchers [8,11–14].

Bataineh and Abu Abbas [11] studied numerically the effect of the solar still productivity by adding vertical fins, external reflectors and fins with reflectors together at different seasons. The theoretical results showed that the productivity has not been affected considerably by adding fins. However, as a result of adding external reflectors, the efficiency of still increased by 13%, 20%, 28%, 33%, 37% and 46% in June, April, September, October, January, and December respectively. Taamneh and Al-Abed Allah [15], Bataineh and Abu Abbas [16] investigated theoretically and experimentally the performance of the single sloped solar still when adding Al_2O_3 and SiO_2 nanoparticles. The results showed that the productivity of the still was boosted by 10% and 8.5% for Al_2O_3 and SiO_2 respectively, at a water depth of 0.005 m saline water, and nanoparticles concentrations of 0.2%. Manokar et al. [8] analyzed the performance of the pyramid solar still at different saline water thickness, the solar still with insulation material and the solar still without insulation material. The experimental results inferred that the performance of the still increased as saline water depth decreased. Furthermore, the productivity of the still was improved by 113% by adding the insulation material to the still's wall. Khalifa et al. [12] verified the effect of insulation thickness on the efficiency of the solar still. The experimental results described that the productivity of the still increased as insulation thickness rose up to a certain value beyond which the effect of increasing thickness became unimportant. Abu Abbas and Al-Abed Allah [17] examined numerically the impact of condenser materials and condenser incline on the productivity of the solar still. The results revealed that the daily solar still productivity increased as the transmissivity of the condenser material increased. Moreover, it was noted that the maximum productivity of the still in summer and winter seasons was recorded at condenser slope of 5° and 20°, respectively. Dubey and Mishra [18] studied the influence of three glass cover angles (15°, 30°, and 45°) on the solar still productivity. They found that the maximum productivity was obtained at tilt angle of 15°. Madhlopa et al. [14] figured out that utilizing multi evaporators and condensers boosted the solar still performance by 62%. Hansen et al. [19] enhanced the solar still productivity by using fin shaped absorber. Their results showed that the solar still efficiency increased by 25.75%. Kabeel et al. [20] investigated the influence of using a different type of phase change materials (PCM) to enhance the solar still performance. The theoretical results showed that the A48 type of PCM had the highest efficiency (92%). Zurigat et al. [13] studied the effect of a regenerative condenser on the solar still performance. The results illustrated that the performance of the still was higher by 20% than the conventional solar still. Nisrin Abdelal et al. [21] conducted an experiment to study the effect of using absorber plates made of carbon fiber/nanomaterials-modified epoxy composites at different concentrations. Their results showed that the productivity of the still increased by 109% and 65% when adding 5% and 2.5% Nano weight concentrations respectively. Agrawal et al. [22] conducted a practical and theoretical study to investigate the effect of saline water depths (2, 4, 6, 8 and 10 cm) on the performance of the solar distillation system. Their results revealed that the distilled water of the solar distillation system increased as decreasing water depth. Hitesh et al. [23] analyzed the effect of floating plates (such as galvanized iron and aluminum) on the solar still productivity. It was observed that the aluminum plate enhanced the productivity of still more than galvanized iron plate. Poblete et al. [24] investigated experimentally the effect of several factors (heating of basin liner, condenser cover material, reflectors (mirrors) and air extractor) on the efficiency of the solar still. The results showed that the factors of mirror and heating of basin liner were the most influencing factors on the productivity.

Design of experiment is an efficient tool to reduce the data required to identify the most significant factors affecting on the desalination system performance. It was noted that all the researchers studied the influence of utilizing one parameter on the system at a time while keeping the other parameters fixed [25]. This approach will not lead to understand the interaction between factors. In this research, the parameters of basin area, depth of saline water, external power, air blowing system, condenser material, condenser thickness, condenser area, insulation thickness, insulation material, ambient air temperature, and make-up water system were considered to show their effects on three responses (mass output, saline water temperature and condenser cover temperature). The main goal of this study is to show which of these parameters have the most effect and which of them have the least influence on the system. Moreover, illustrating the interaction between the factors and their regression equations, as well as, highlighting the most important factors that can form the optimal design for the desalination system.

2. Methodology

2.1. Description

The main components of the distillation system are shown in Fig. 1. The water tank was used as a make-up water system to compensate purified water. The external power device was used to heat the basin plate. A large proportion of the heat was transferred by convection to the saline water, while the rest of it was lost outside by conduction through the bottom of the still. The heat was then conveyed from the high temperature of saline water to the internal surface of the condensation cover by evaporation, convection and radiation. Then a part of the heat was transferred by conduction from the inner to the outer surface of the condenser, and by radiation and convection from the outer surface of the condenser to the surrounding air. An inclined condensation cover was used to move evaporated water to the water collector. The bottom and all sides of distillation system was made of a specific insulation material with a proper thickness to minimize heat loss from the heated saline water to the surrounding. Moreover, Fig. 2a and b show the desalination system when increasing the area of the condensation cover, and adding a fan, respectively, to enhance the convection heat transfer

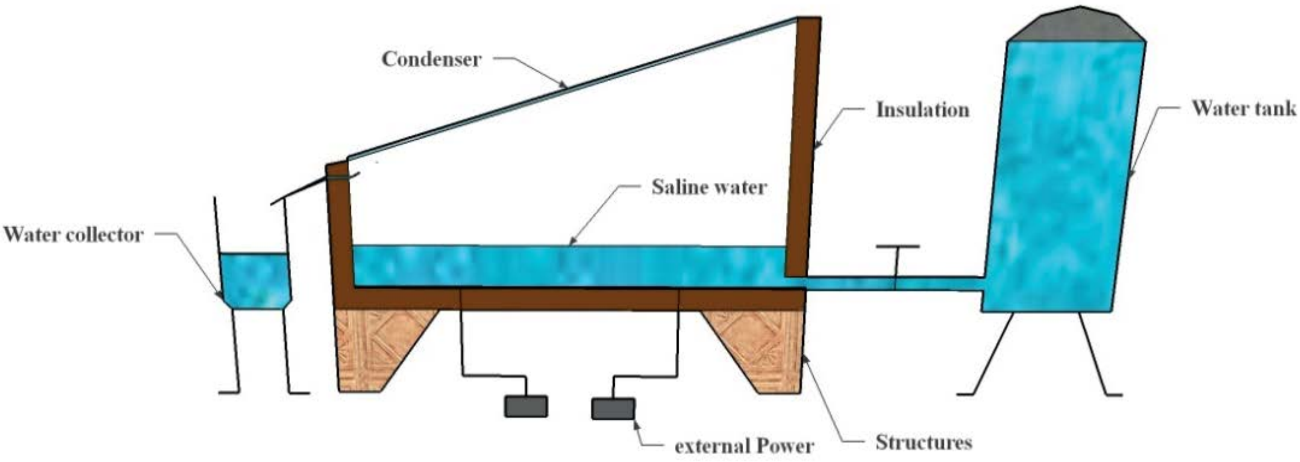

Fig. 1. Solar distillation system.

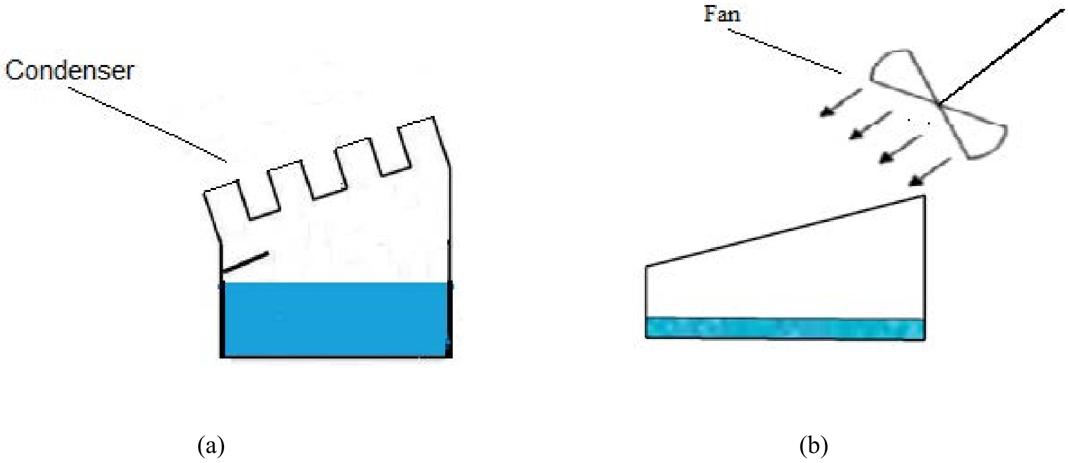

Fig. 2. (a) Increasing condensation cover area and (b) adding fan to solar still.

from the outer surface of the inclined surface to the ambient air. As a result, the condensation rate increased. Fig. 3 shows the distilled water cycle for the distillation system.

2.2. Mathematical model

A complete model of non-liner differential equations that shows the heat transfer and energy processes in the main components of the active distillation system was written [16]. These equations help to calculate the quantity of the distilled water, saline water temperature and the condenser cover temperature at any time with different configurations. The theoretical results were founded by solving the main energy balance equations for the basin plate, saline water and the inner and the outer condenser covers of the distillation system. The temperature of saline water, the basin plate, the inner and the outer condenser cover were evaluated every 5 h to show the effect of different parameters on the productivity of the distillation system.

The numerical model was solved by Matlab software. Energy balance equations for the main desalination system components are presented below [26]:

As shown in Eq. (1), a fraction of the heat that resulted from the external power is transmitted to the basin plate, and then it is transferred to saline water by convection. Energy is lost to the ambient through the bottom insulation material by conduction.

$$P_t A_b = m_b \mathrm{cp}_b \frac{\mathrm{dT}_b}{\mathrm{dt}} + Q_{\mathrm{cb-}w} + Q_{\mathrm{loss-ba}} \quad (1)$$

The transient energy balance equation for the saline water is given in Eq. (2). The heat transmitted to saline water by convection is lost in two ways; a specific quantity of energy is stored in saline water, while the rest is released to the inner cover of the condenser by evaporation, convection, and radiation.

$$Q_{\mathrm{cb}\text{-}w} = m_w \mathrm{cp}_w \frac{\mathrm{dT}_w}{\mathrm{dt}} + Q_{\mathrm{cw-}c1} + Q_{\mathrm{ew-}c1} + Q_{\mathrm{rw-}c1} + Q_{\mathrm{mw}} \quad (2)$$

The energy balance equation for the inner condenser cover is illustrated in Eq. (3). The heat transferred from the

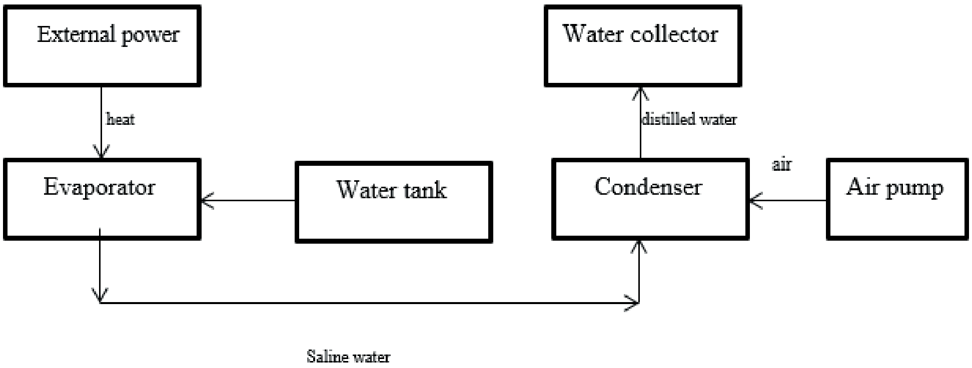

Fig. 3. Distilled water cycle system.

Table 1
Effect of the system factors on mass output at high and low levels (L)

Factor	A	B	C	D	E	F	G	H	J	K	L
High value	2.23	2.14	2.86	1.38	2.21	2.22	2.06	3.02	2.2	2.15	2.04
Low value	2.03	2.11	1.4	2.88	2.05	2.04	2.2	1.2	2.06	2.11	2.21

saline water is absorbed by the inner condenser cover and then released by conduction through the cover's material.

$$Q_{\text{cw}-c1} + Q_{\text{ew}-c1} + Q_{\text{rw}-c1} = m_c cp_{c1} \frac{dT_{c1}}{dt} + Q_{\text{cnc}1-c2} \quad (3)$$

As for outer condenser cover, the energy balance equation is shown in Eq. (4).

The heat lost by conduction from the inner to the outer condenser cover is transferred to the air and sky through convection and radiation, respectively.

$$Q_{\text{cnc}1-c2} = m_c cp_c \frac{dT_{c2}}{dt} + Q_{\text{rc}2-\text{sk}} + Q_{\text{cc}2-a} \quad (4)$$

2.3. Design of experiment

Design of experiment is a valuable tool for researchers and designers to develop a design of any system. This tool can save design's time and cost with higher reliability than other approaches [27]. The main purpose of conducting an experiment is to find which system's parameters have the most and least affecting factors on the response (output of the system).

In this study, the factorial design was used to determine the highest or the lowest influence of 11 factors, interaction between them and regression equations of a distillation system. Three responses were evaluated: the amount of distilled water, the saline water temperature and the inner condenser temperature.

2.3.1. Factorial design

The most valuable advantages of the factorial design are to find the regression equations and identify the interactions between the factors that can't be identified using the other analysis approaches. In order to achieve these advantages, the factorial design method sets two levels for each factor. Therefore, the researcher has to create many trials using Minitab software according to probability counting rule (2^k). Where k is the number of factors, since each one has two levels (+1 value for a high level and –1 value for a low level). Table 1 gives information about the main factors of interest.

2.3.2. Reduced Factorial $2^{(11-4)}$

The main purpose of reduced factorial design is to reduce the number of trials by sacrificing interactions for more than three factors. The selected reduced factorial type is $2^{(k-r)}$. Where r refers to the number of reduced factors. Moreover, the reduced factors were carefully chosen by checking the alias structure, resolution, balancing and orthogonally. A $2^{(11-4)}$ reduced factorial type was used with V resolution, which means that 2-factor interactions were only aliased with 3-factor interactions and main effects were aliased with 4-factor interactions. Matlab was used to solve the required simulation of the system, while Minitab was used to investigate the main influencing factors and interactions with high accuracy.

2.4. Numerical simulation assessment

Fig. 4 shows the flowchart used to evaluate the most significant factors that have impacts on the distillation system. The simulation starts with the Minitab program to find the number of the system trials (runs), and to determine the type of the analysis (reduced or full factorial), the number of factors and the nature of runs (randomized or non-randomized). Furthermore, the resulted system's trials from the Minitab program were entered to Matlab, to analyze

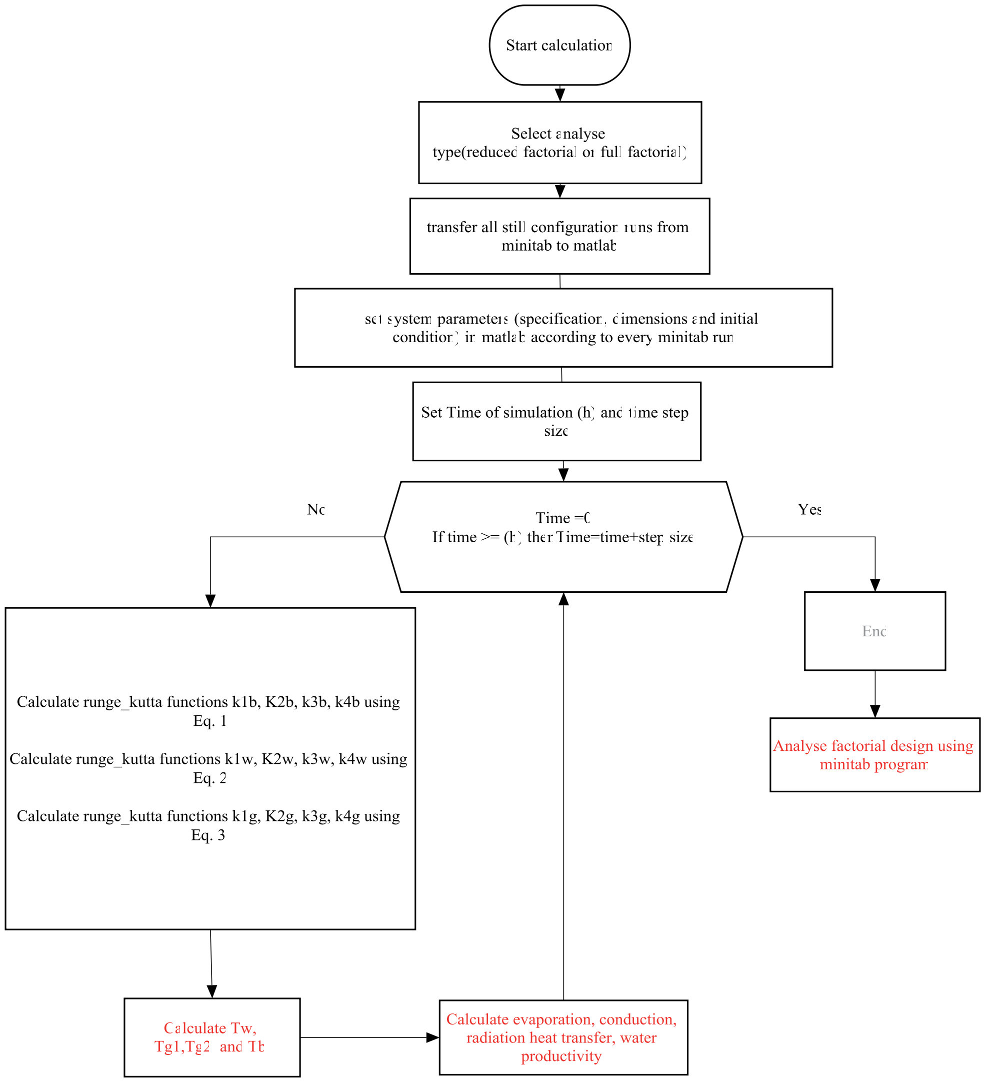

Fig. 4. System flow chart.

the effect of each trial on the responses. The amount of distilled water, and the temperature of the saline water and the condensation cover was found by solving the numerical model using Runge–Kutta method every 5 h. The initial temperature of the saline water and the condensation cover were equal to the ambient temperature. By using these initial temperatures, the quantity of the distilled water, the saline water temperature and the condensation cover's temperature were calculated. The procedures were repeated for every trial. Finally, the results of every trial were analyzed using Minitab to show their effects on the system.

3. Results

The results of the mathematical model and the statistical analysis show the effect of different factors on the active desalination system responses. Three responses were studied: the amount of distilled water (mass output), saline water temperature, and the condenser cover temperature. The external power, the basin area, the water depth, the insulation's material and thickness, the condenser material (according to the thermal conductivity of the material), the condenser area, the thickness of the condenser, air blowing system according to air speed (with and without air blowing system, since air speed were 0 and 20 m/s, respectively), make-up water system, and ambient temperature were considered as variables. The design of the experiment approach was used to reveal the effect of 11 factors on the system, the interaction between factors and optimal design for the system to achieve maximum productivity.

3.1. Effect of the system factors on the responses

Fig. 5a–c show the main factors influencing the responses of the desalination system. It was clearly noted that, as the difference between high and low levels values increased, the effect of the factors on the responses was large. The results show that the most important factors that enhance mass output were the amount of external power, the water depth, and basin area, respectively. Where the

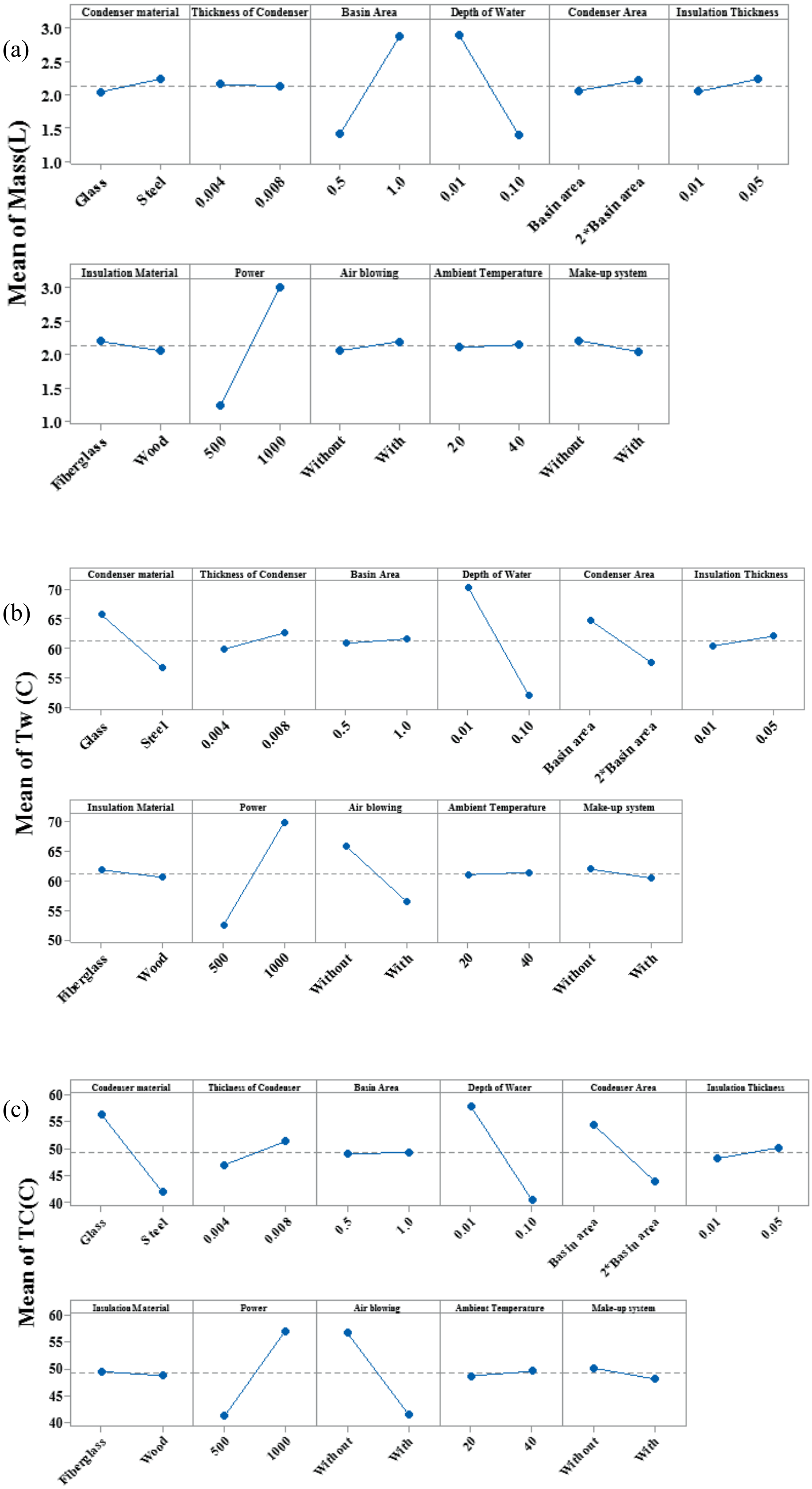

Fig. 5. Main effect factors on (a) mass output, (b) water temperature and (c) condenser cover temperature.

effect of adding external power on the mass output at high and low levels were 3.02 and 1.24 L, respectively. Moreover, the effect of water depth on the mass output at high and low levels were 1.3 and 2.8 L respectively. Furthermore, the effect of the basin area on the mass output at high and low levels were 2.8 and 1.4 L, respectively. The reason behind that can be explained in terms of the evaporation rate. When increasing the amount of external power, the temperature of saline water increased. Therefore, the evaporation rate rose. Consequently, distilled water was boosted [28]. Moreover, when decreasing the depth of saline water, the temperature of saline water increased faster. Hence, the purified water was enhanced as a result of improving the evaporation rate [22]. Furthermore, when increasing basin water area, the amount of distilled water increased. Owing to the fact that the evaporation rate of the saline water was directly proportional to the exposure area [29]. According to the simulation results the primary factors that have the major impact on the temperature of the saline water and the condenser cover were the water depth, the amount of external power, the air blowing system, and the condenser material, respectively.

3.2. Interaction effect plots

The interaction between factors happens when the influence of one factor was dependent on the value of another factor. Moreover, the Interaction effects show that a third variable affects the relationship between an independent (factor) and dependent (response). This kind of interaction plot represents the fit values of the dependent factor on the y-axis, while the x-axis displays the values of the first independent factor. Besides, the different lines describe the values of the second independent factor. About the interaction schemes, parallel lines show that there was no interaction between the two factors while the crossed lines and the lines that could be crossed infer that there was an interaction effect between the factors. Fig. 6a shows the interaction effect on the mass output. It was clearly noted that basin area external power, basin area depth of water, depth of water external power, depth of water air blowing system, and condenser material depth of water respectively had the greatest interaction effect. The interaction of basin area external power interaction explains that the mass output level was high when the external power and the basin area values were high. Conversely, the maximum mass output was achieved when the external power and the basin area values were low. Fig. 6b shows the effect of the interaction on the saline water temperature of the desalination system. The maximum saline water temperature was associated with the highest interactions between depth of water air blowing system, condenser material depth of water, depth of water condenser area, external power air blowing system, and depth of water external power respectively. For instance, the interactions of the depth of water condenser area and depth of water air blowing system indicate that at the low level of the water depth, the condenser material, and the air blowing system the saline water temperature was high. Also, the interaction plots affecting the temperature of the condenser cover are described in Fig. 6c. The most important interactions were depth of water air blowing system, condenser material depth of water, power air blowing system, depth of water condenser area, and depth of water external power, respectively.

3.3. Pareto charts of the standardized effects

Fig. 7 represents the Pareto charts of the standardized effects for various responses. These charts determine the order of the most influencing factors including main and interaction factors that affect the responses' values. It was clearly observed that the most influential factors on mass output were external power, depth of water, basin area, the interaction between the basin area and external power, and the interaction between basin area and depth of water, respectively. Moreover, the high factors affecting the saline water temperature and condenser cover temperature were the depth of water, the external power, the air blowing system, and the condenser material, respectively. The results agree with the findings of Agrawal et al. [22] who reported that the distilled water of the distillation system increases as decreasing the depth of saline water. The importance of the heated basin was underlined by Hamadou and Abdelatif [30] who reported that productivity can be increased by providing an extra supply of heat to the seawater through an exchange with a heat transfer fluid heated previously in a solar collector system. Moreover, using an additional exposure area augments the evaporation rate according to [14,31].

3.4. Regression equations

Eqs. (5)–(7) represent the regression equations predicted from the reduced factorial method to illustrate the highest and the lowest influential factors on the three responses: distilled water, saline water temperature and condenser cover temperature, respectively.

$$\begin{aligned}\text{Mass} = &-1.026 - 0.0349A - 8.1B + 0.480C + 17.52D \\ &+ 0.0809E + 4.67F - 0.0715G + 0.000990H \\ &- 0.1068J + 0.00196K - 0.1711L + 2.406AD \\ &- 23.92CD + 0.005022CH - 0.02169DH \\ &+ 3.194DJ + 1.554DL \end{aligned} \tag{5}$$

$$\begin{aligned}T_w = &16.72 + 4.36A + 3386B + 17.19C - 10.7D - 3.52E \\ &+ 41.5F - 0.627G + 0.04329H - 4.11J + 0.0179K \\ &- 0.761L - 759AB + 1.166AE - 0.00571AH \\ &- 2617BC - 13448BD + 58.2DE - 0.1492DH \\ &+ 80.9DJ - 0.00433EH + 1.545EJ - 0.00675HJ \end{aligned} \tag{6}$$

$$\begin{aligned}T_c = &10.21 + 3.61 + 2095B + 0.70C + 97.3D - 3.20E \\ &+ 50.4F - 0.397G + 0.04501H - 3.61J + 0.0436K \\ &- 1.013L - 1203AB + 77.4AD - 0.01053AH \\ &- 1.815AJ - 18424BD + 60.7DE - 0.2414DH \\ &+ 92.2DJ - 0.00717EH + 1.633EJ - 0.01207HJ \end{aligned} \tag{7}$$

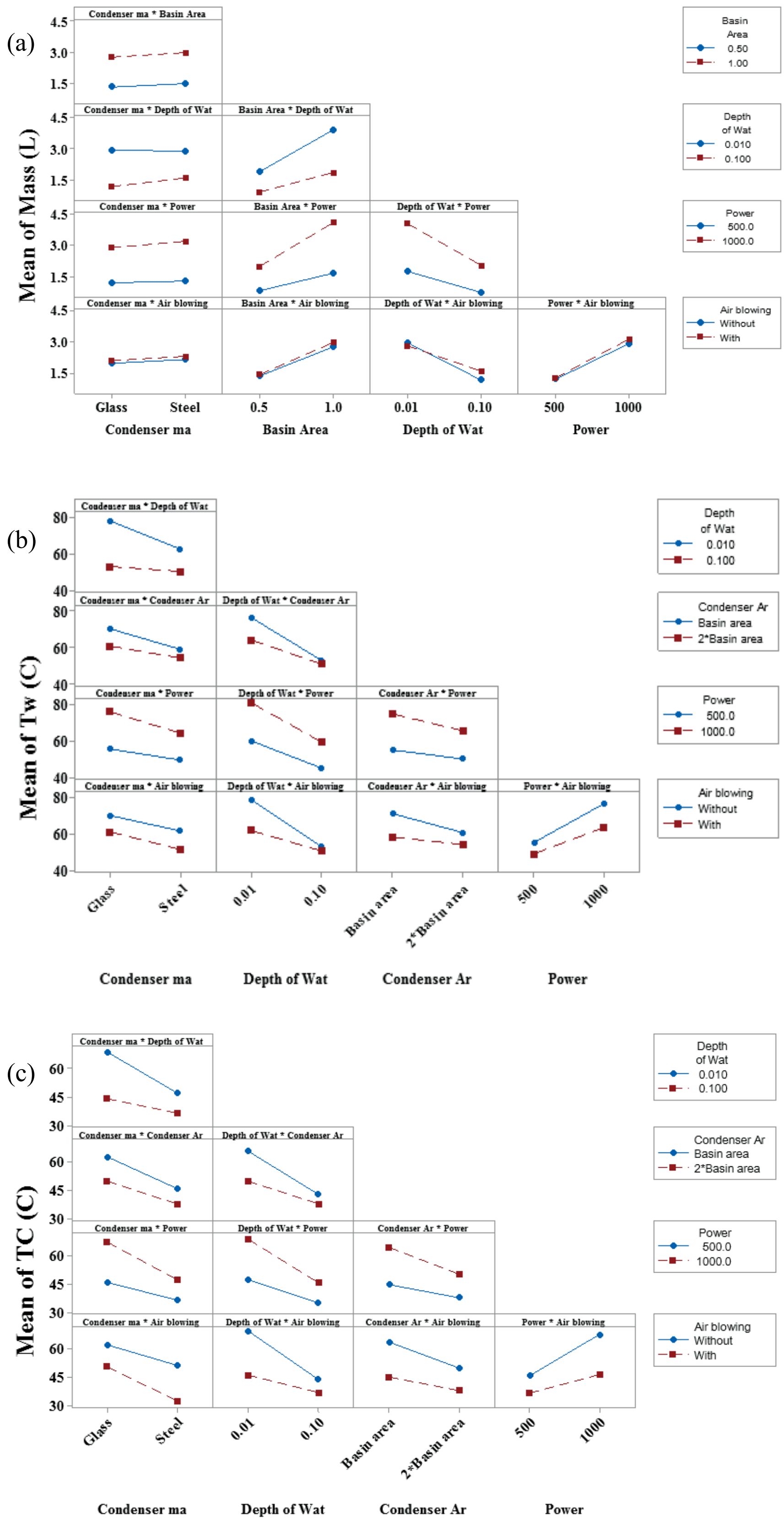

Fig. 6. Interaction effect plot on (a) mass output, (b) water temperature and (c) condenser cover temperature.

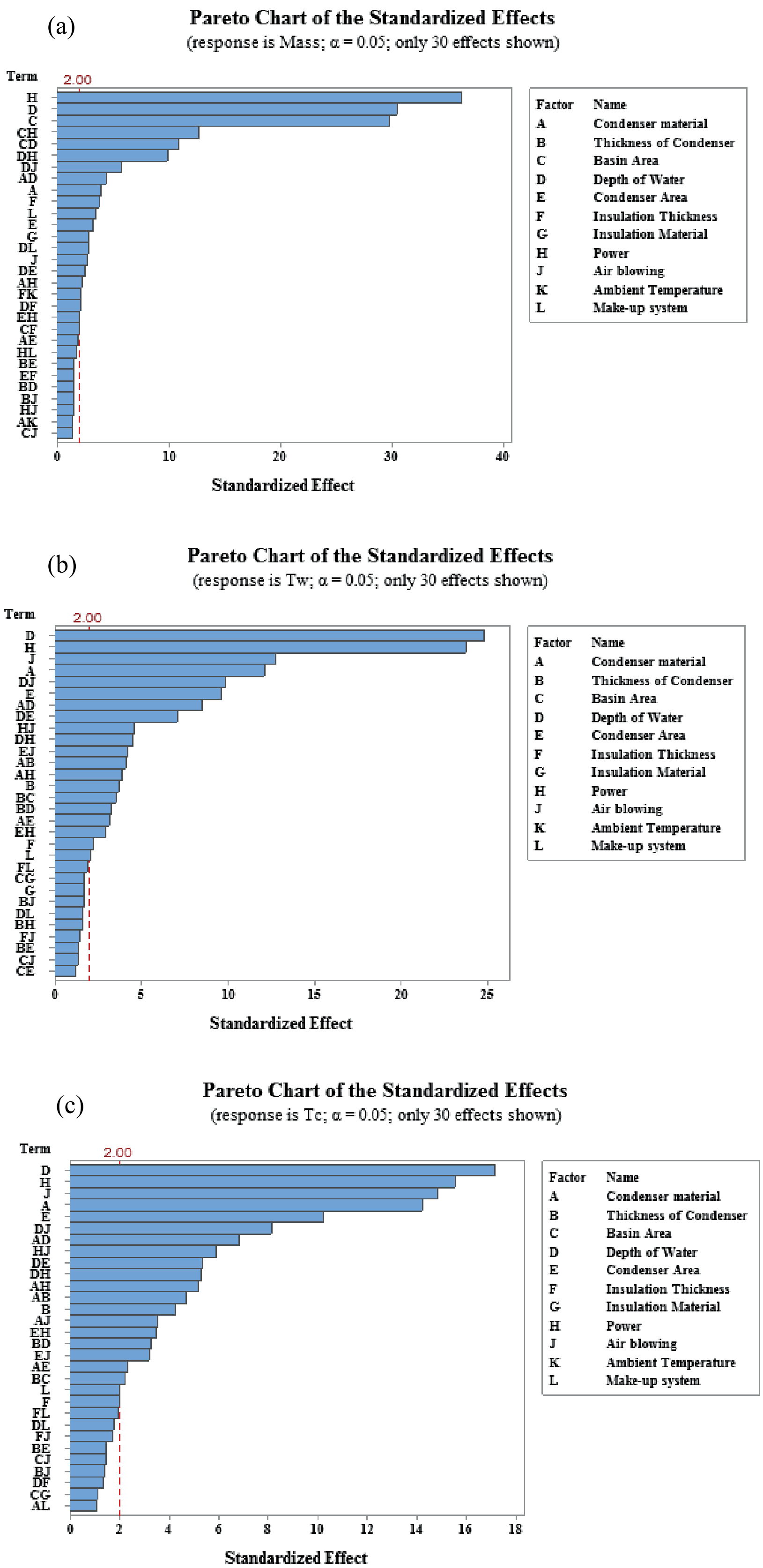

Fig. 7. Pareto charts of the standardized effects for (a) mass output, (b) water temperature and (c) condenser cover temperature.

Table 2
Effect of the system factors on the water temperature at high and low levels (°C)

Factor	A	B	C	D	E	F	G	H	J	K	L
High value	56.7	62.5	61.6	52	57.6	62	60.6	70	56.4	61.4	61.2
Low value	65.7	59.8	60.8	70.3	64.7	60.3	61.8	52.4	65.9	61	61.9

Table 3
Effect of the system factors on the condenser cover temperature at high and low levels (°C)

Factor	A	B	C	D	E	F	G	H	J	K	L
High value	41.9	51.3	49.3	40.4	43.9	50.2	48.8	57.1	41.6	49.6	48.1
Low value	56.4	47	49	57.9	54.4	48.1	49.6	41.2	56.7	48.7	50.2

3.5. Optimization design

The designers should create the system by selecting the value of the optimal factors that could enhance mass output. As mentioned above, the maximum water output produced from desalination system could be achieved through increasing the saline water temperature and decreasing the condenser cover temperature. Tables 2 and 3 list the fit values and optimal design selected respectively, to achieve the optimal value for the mass output, saline water temperature and condenser cover temperature.

- The optimal design of the system can be attained by:
- Selecting the highest values of the external power, the basin area, the condenser thickness, the ambient temperature, and the insulation thickness.
- Choosing the lowest values of the condenser area and the depth of water.
- Using steel condenser material and the fiberglass insulation rather than any other materials.
- Adding the air blowing system and removing the make-up system.

4. Conclusion

Design of experiment was selected in order to investigate the sensitivity of different parameters influencing the desalination system in terms of achieving maximum productivity. The results of theoretical and statistical analyses of desalination system can be summarized as follows:

- The most important factors that have a high effect on the mass output were the amount of external power, the water depth and the basin area, respectively. Where the effect of adding external power on the mass output at high and low levels were 3.02 and 1.24 L respectively while the effect of water depth on the mass output at high and low levels were 1.3 and 2.8 L respectively. Furthermore, the effect of the basin area on the mass output at high and low levels were 2.8 L and 1.4 L, respectively.
- The water depth (at low level), the amount of external power (at high level), the air blowing system (at high level), and the condenser material (at low level), respectively, were the main factors that had the most influence on the saline water temperature of the system. These factors increased the saline temperature to 70.3, 70, 65.9 and 65.6 respectively.
- Basin area power, basin area depth of water, depth of water power, depth of water air blowing system and condenser material depth of water, respectively, had the greatest interaction that influence the mass output.
- The large interaction affecting the temperature of the saline water and the condenser were depth of water air blowing system, condenser material depth of water, power air blowing system, depth of water condenser area and depth of water power, respectively.

Symbols

A_b	—	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
P_t	—	External power, W/m^2
Q_{cb-w}	—	Convection heat transfer from basin plate to saline water, W
Q_{cw-c1}	—	Convection heat transfer from saline water to the condenser, W
Q_{rw-c1}	—	Radiation heat transfer from saline water to the inner condenser, W
Q_{ew-c1}	—	Evaporation heat transfer from saline water to the inner condenser, W
Q_{cw-c1}	—	Convection heat transfer from saline water to the inner condenser, W
Q_{cc2-a}	—	Convection heat transfer from outer condenser cover to ambient, W
Q_{rc2-sk}	—	Convection heat transfer from outer condenser cover to the sky, W
$Q_{cnc1-c2}$	—	Conduction heat transfer from inner condenser cover to the outer condenser, 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

Conflict of interest

The authors declare that they have no conflict of interest.

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