Rotating-drum solar still with enhanced evaporation and condensation techniques: Comprehensive study


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ABSTRACT

In this study, the thermal performance of the solar still was aimed to be improved in successive stages. This improvement was achieved via using a rotating drum inside the basin still to be nominated as drum distiller. The drum helps to increase the evaporative surface area and decrease the thickness of the saline water film. In the next stage of experimentations, a solar water heater was integrated into the drum distiller. After that, an external condenser was incorporated with drum still. Then, in the last stage of experiments, the effect of copper oxide nanoparticles on the performance of drum distiller was investigated. Different rotational speeds such as 0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 rpm were investigated. A theoretical model was built to predict the performance of the distillers under different conditions. An acceptable agreement was noticed between the experimental and theoretical values (7–13%). Results revealed that the maximum productivity was obtained at 0.1 rpm and using the condenser, heater, and nanofluid. Under these conditions, the freshwater productivity was 9220 L/m² for the drum still compared to 2050 L/m² for the conventional still with an enhancement percentage of 350%. Additionally, the estimated cost of 1 L of distillate for traditional and drum stills are about 0.05 and 0.039 $, respectively.

1. Introduction

The era of green energy is promising for the most problems such as drinkable water shortage and environmental pollution which face the developed and developing countries [1]. The distillation methods, based-green energy, are used to overcome the lack of drinkable water. Traditional solar still is the simplest water purifying method among distillation technologies. Despite of the numerous merits of the solar still, such as the simplicity of construction and fabrication, cheap, sustainability of freshwater production, eco-friendly, and non-complex technology, it suffers from the lack of freshwater productivity [2]. As a result, during the last decades, the researchers paid their attention to increase the output of freshwater production of the solar stills [3,4]. They concluded that the output acquires from the solar still depends on several parameters. These parameters are: surrounding environmental conditions [5], the design and construction shape of the solar still [6], the temperature and salinity of the feed water [7], the depth of the saline water inside the solar still [8], the existence of the absorbing materials inside the basin still [9], and the temperature difference between the saline water and the glass cover of the still [3,4].

Due to the increase in absorptivity of the basin water, the distilled water of the solar still can be increased. Therefore, several materials were used by scientists in solar still, like the dyes, charcoal, rubber material, glass balls, soot powder, sponge cubes, granite gravel, and potassium dichromate [10]. In addition, nanomaterials [11–13], volcanic rocks [14], floating aluminum sheet [15], desiccant [16], and wick materials [17] were used. Furthermore, the design modifications incorporated the solar still with reflectors [18], solar dishes [5], condensers [19,20], multiple-effect basins [21], sun-tracking devices [22], energy-storing materials [23], and vacuum technologies [24] were presented. In addition, several other designs of solar stills such as multi-stage stills [25], tubular still [26], PV/T active solar still [27], pyramid still [28], hemi-spherical still [29], stepped solar stills [23,30], and vertical stills [31] were proposed.

The free surface area for the evaporation process inside the basin still affects the distilled freshwater [14]. Only attachment of external

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Some of the researchers studied the effect of movement inside the solar still. Zeinab and Ashraf [38] introduced a rotating shaft inside the solar still. Haddad et al. [36] and Gad et al. [37] investigated the performance of a solar still incorporated with a rotating drum inside the basin still. Gad et al. [37] investigated the performance of a solar still incorporated with a rotating drum inside the basin still, as shown in Fig. 1. The projected area of both the test-rig consisted of one feed water reservoir, a drum still, two distillers as well as a traditional solar still. Fig. 1 and Fig. 3 illustrate a photograph and schematic diagrams of the experimental test-rig, respectively. The test-rig was used as a reference to compare the productivity and enhanced distiller was used as a reference to compare the productivity of the traditional distiller. The feed water tank, which is 0.5 m diameter and 1.0 m in height, was used to feed saline water in the solar distillers. The traditional distiller was tested, evaluated, and compared with the drum distiller. The drum distiller was tested, evaluated, and compared with the solar distiller under different rotational speeds for the drum, starting from 0.02 to 4.0 rpm (0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 rpm). Finally, the drum still was fed by the water-copper oxide nanofluid. 2.1. Test-rig description

The test-rig consists of one feed water reservoir, a drum still, two distillers as well as a traditional solar still. Fig. 1 and Fig. 3 illustrate a photograph and schematic diagrams of the experimental test-rig, respectively. The test-rig was used as a reference to compare the productivity and efficiency of the traditional distiller. The feed water tank, which is 0.5 m diameter and 1.0 m in height, was used to feed saline water in the solar distillers. The traditional distiller was tested, evaluated, and compared with the drum distiller. The drum distiller was tested, evaluated, and compared with the solar distiller under different rotational speeds for the drum, starting from 0.02 to 4.0 rpm (0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 rpm). Finally, the drum still was fed by the water-copper oxide nanofluid.
solar distillers was chosen to be constant at 0.5 m² for a fair comparison. The higher and lower wall heights of the conventional solar still are 0.39 m and 0.16 m, respectively, as shown in Fig. 3. In addition, both the solar stills were made of 1.5 mm thick galvanized sheet painted by black spray to increase the absorbed quantity of solar rays. Then, the glass wool (5 cm thickness) was used to fill the space between the wooden box and the outer surface of the basin still. It worked as an insulator to prevent the heat transfer from the still to the surroundings. A glass sheet of 3 mm thickness was used to cover the distiller, as illustrated in Fig. 1a. A tilted trough was fixed at the lower edge of the glass to accumulate the distilled water through a plastic pipe into an external calibrated bottle. Also, a feed water pipe was connected at 1 cm above the distiller base in the middle of the solar still liner. Additionally, the brine waste pipe was provided at the bottom of the distiller.

Moreover, the drum still had a rotating light-weight hollow drum, which was closed from both ends and fixed on a rotating shaft using a bearing bracket. The drum was made of aluminum sheet with 0.5 mm thickness. The drum dimensions are 0.48 m in diameter and 0.98 m in length. The rotating shaft was made of low carbon-steel with 20 mm in diameter and 1.6 m in height. A DC motor of 3 W, rotated the drum, which was fixed with the shaft, and the capacity of the condenser fan was 2 W. The motor and the fan were operated by a photovoltaic solar panel (10 Watt) fixed with a battery and a converter to decrease the use of the traditional sources of energy as much as possible. A speed control device was integrated with the motor to adjust conveniently the rotational speed of the drum. To increase the absorption rate of solar rays, the outer surface of the drum was painted in mat black color. Besides,
the distiller was placed into a wooden box (3 cm thickness). Due to the rotation of the drum, a thin water film was formed on the outer surface of the drum. This helped to enlarge the evaporation surface area. As a result, the water film was evaporated quickly due to the high temperature of the drum. Here, the glass cover (0.5 m in diameter and 1.0 m in length) had the same shape of the drum (half circle facing down) rotating inside the distiller as illustrated in Fig. 1. Four aluminum troughs with the outlet pipes were fixed at the ends of the glass cover to collect the distillate outside the distiller into external calibrated bottles. Additionally, the excess drain was controlled by the pipe fixed at the bottom of the distiller. Silicone rubber was used as sealing to prevent the vapor leakage outside the solar stills.

In the next stages, the experiments were continued to investigate the performance of the drum still with a solar water heater and an external condenser, as shown in Fig. 2 and Fig. 3. The external condensing unit comprised of an air fan and a copper tube with 2 cm diameter and 3 m long. This tube was encased in the tank filled with cold water. While the air fan (axial-flow type) was connected to the drum distiller and used to suck water vapor from the inside of the still to the condensing unit. The fan speed was about 800 rpm with a 10-cm blade diameter. The end of the copper tube was connected with a graded container to collect the condensate water coming out from the condensing unit. As shown in Fig. 2, the spiral solar water heater consisted of a galvanized steel box (40 × 40 × 5 cm and 1.5 mm thickness) with single glazing that worked as a receiver of solar energy and a copper spiral coil through which water flows. This spiral coil was placed inside the galvanized steel box and acted as a collector. The copper coil had a cylinder-shaped spiral tube. It was fabricated by bending an 8.00 mm inner diameter straight copper tube with 15.5 m length, into a spiral-coil of 21 turns. The coil was painted black to maximize the absorption of radiation. It served as a collector to the solar energy which was incident on a heater. The whole internal surfaces of the box were black painted to increase their absorptivity. As well known, to avoid the heat loss to the surroundings, the bottom wall of the heater was well insulated by fiberglass. The glazing was 3 mm-glass cover on the top of the heater. The heater was inclined at 24° (which is the latitude of Al Kharj City, KSA) from the horizontal and was oriented to south direction to collect maximum solar radiation.

One of the main parameters affecting the performance of the drum distiller is the drum rotational speed. For that purpose, a speed control device was integrated to the motor, which operates the drum. The rotational speed was varied systematically from 0.02 rpm to 4 rpm (0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 3, and 4 rpm) using the inverter, shown in Fig. 4. The components of this inverter are a voltage regulator LM317, a LED, diode, a transistor, two capacitors, a variable resistor, and a potentiometer.

2.2. Experimental procedures

Experimental tests were performed in the outdoor environment. They were conducted from May to August 2018 in University of Prince Sattam bin Abdulaziz, Al Kharj, KSA (24° N Latitude and 47° Longitude). The solar distillers were directed to the north-south direction during the tests to receive as much solar radiation as possible during the daytime. The setup was equipped with measuring devices for all variables that affect the performance of the solar distiller. Incident solar radiation, wind speed, and temperatures of the ambient, glass cover, saline water, and basin liner were measured simultaneously from the morning (08:00 am) until evening (06:00 pm). Also, the sunrise starts at 05:15 am, and the sunset is at 06:45 pm. So, the total sunshine hours are 13 h and a half. As a result, the tests were extended for ten hours through the sunshine time of the day. Also, the amount of the output freshwater productivity was measured hourly. The drum and conventional solar stills were fed by the saline water from the feed water tank. The depth of the saline water inside the distillers was kept constant at 1 cm during all experiments. While the lower side of the drum was designed to be placed over the basin liner by 0.5 cm. Therefore, the lower side of the rotating drum was submerged by the saline water from the outer surface. The temperature of basin water and evaporation process were increased due to the increase of solar radiation. Besides, the temperature of the water inside the solar water heater was increased. Because of the density difference, the water of the heater was moved naturally to heat the water inside the drum still through the coil fitted inside the distiller. At the beginning of the day, the drum is not moving, and its body from the bottom is in direct contact with the basin water. When operating the system, the drum begins to run at the target low speed. And after around four minutes (for the speed of 0.1 rpm), the bottom side of the drum becomes the upper side with the continuous rotation of the drum. Besides, the thin water film formed on the drum outer surface starts to be evaporated directly because the drum body is heated through this time of operation. Moreover, rotating the drum creates a thin water layer film on the black-drum surface. As the drum rotates at low speeds, the thin water layer film evaporates rapidly. As a result, a large amount of vapor content was created. But the glass cover did not condensate this amount of vapor. So, the fan withdrew some of the generated vapor to be condensed into the external condensation unit (external condenser). Additionally, total productivity was accumulated and measured every 24 h. As illustrated in Fig. 5, and in the first stage of experimentations, the drum distiller was tested, evaluated, and compared with the traditional still under different rotational speeds of the drum, starting from 0.02 to 4.0 rpm (0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 rpm). While, in the second stage of tests, a solar water heater was integrated into the drum distiller to be tested at the best rotational speed from the first testing stage. In addition to the solar water heater, the performance of the drum still was studied when incorporating an external condenser to the distiller during the third stage of the experimentations. Finally, the drum still was fed by water-copper oxide nanofluid and tested the complete system in the presence of the solar water heater and the external condenser. The properties of the copper oxide nanoparticles are tabulated in Table 1.

Several devices were used to measure the parameters that affect the performance of the solar distiller. Datalogging solar power meter (0–5000 W/m²) was used to measure the total solar intensity at the same level as the glass cover of the distillers. Furthermore, the various temperatures of the basin liner, glass cover, and saline water were measured with the help of calibrated copper constantan type thermocouples. Theses thermocouples were connected to G4L-CUEA modular programmable logic control (MPLC) to be able to read the digital values of the different temperatures. While a van type anemometer (0.4–30 m/s) was used to measure the digital values of the wind speed at the ambient. Finally, a calibrated graded flask (1.5 L capacity and 5 mL accuracy) was used to measure the amount of the distilled freshwater.
In the morning, the DC motor is switched on, and the shaft begins to rotate at the target rotational speed. As aforementioned, the lower side of the drum is immersed in the saline water inside the distiller, and it is closed from both the ends. The drum rotates slowly and changes the direction of the upper side to be lower and the lower side to be upper. As a result, a water layer film is formed on the drum surface. This arrangement accelerates the evaporation rate inside the solar distiller due to the increase in the evaporating surface area. Herein, the lower side rewets the drum with water and rotates to evaporate this water. As usual, the glass cover with lower temperature is used to condensate the generated vapor inside the solar still. There are four troughs fixed at the glass edges. Finally, the condensed droplets are guided by the troughs and pipes and collected into the graded flasks.

Table 1
Specifications of the copper oxide nanoparticles.

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity (W/m K)</th>
<th>Average particle size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuO</td>
<td>6320</td>
<td>76.5</td>
<td>10–14</td>
</tr>
</tbody>
</table>

In the morning, the DC motor is switched on, and the shaft begins to rotate at the target rotational speed. As aforementioned, the lower side of the drum is immersed in the saline water inside the distiller, and it is closed from both the ends. The drum rotates slowly and changes the direction of the upper side to be lower and the lower side to be upper. As a result, a water layer film is formed on the drum surface. This arrangement accelerates the evaporation rate inside the solar distiller due to the increase in the evaporating surface area. Herein, the lower side rewets the drum with water and rotates to evaporate this water. As usual, the glass cover with lower temperature is used to condensate the generated vapor inside the solar still. There are four troughs fixed at the glass edges. Finally, the condensed droplets are guided by the troughs and pipes and collected into the graded flasks.

Fig. 3. Schematic of the drum distiller integrated with the solar water heater and the external condenser.

Fig. 4. Photo of inverter circuit.

Testing the drum under different rotational speeds (0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 rpm).

A solar water heater was integrated to the drum distiller to be tested at the best rotational speed from the first testing stage.

The performance of the drum still was studied when incorporating an external condenser to the distiller.

The drum still was fed by water-copper oxide nanofluid and tested in the existence of the solar water heater and the external condenser.

Fig. 5. Methodology of the present study.
3. Governing equations of the theoretical system

The distribution of heat transfer rates for both solar stills is shown in Fig. 6. The energy balance equations for the drum, water, plate, and glass cover were used to predict the performance of the investigated conventional and drum solar stills. The theoretical analyses were investigated and verified through the experimental results. The differential equations were solved using Engineering Equation Solver (EES). The analytical results were obtained by solving the energy balance equations for saline water, glass cover, and basin plate (absorber). Water and glass temperatures can be evaluated at every instant, respectively.

3.1. The reference distiller

The energy equation for the basin plate is calculated from [39,40];

\[ I(t) A_b \alpha_b \tau_g \tau_d \tau_d = m_b C_{pb} \frac{dT_b}{dt} + Q_{c,b-w} + Q_{loss} \]  

(1)

The energy equation for the saline water is calculated from [39,40];

\[ I(t) A_w \alpha_w \tau_g + Q_{c,b-w} = m_w C_{pw} \frac{dT_w}{dt} + Q_{c,w-g} + Q_{c,w-g} + Q_{pw} \]  

(2)

The energy equation for the glass cover is found from [39];

\[ I(t) A_g \alpha_g + Q_{c,w-g} + Q_{e,w-g} = m_g C_{pg} \frac{dT_g}{dt} + Q_{c,g-s} + Q_{c,g-u} \]  

(3)

The hourly distillate is calculated from the equation [33],

\[ m_{ew} = 0.01623 \left( \frac{h_{c,b-w}}{h_{gb}} \right) \left( P_w - P_g \right) \]  

(4)

where \( h_{gb} \) is the water latent heat.

The basin-water convective heat transfer coefficient [20],

\[ Q_{c,b-w} = h_{c,b-w} A_b (T_b - T_w) \]  

(5)

where \( h_{c,b-w} \) is the basin-water convective heat transfer coefficient, and \( A_b \) is the basin liner surface area.

The basin-water convective heat transfer coefficient, \( h_{c,b-w} \), is given by [33];

\[ h_{c,b-w} = 0.2 \left( \frac{K_w}{\delta} \right) R a^{0.26} \]  

(6)

where \( K_w \) is the water thermal conductivity, and \( \delta \) is the characteristic length.

Besides, the modified Rayleigh number, \( Ra \), is calculated from [33];

\[ Ra = \left( \frac{g \beta (P_w - P_g)}{\rho_w D} \right) (\Delta T) \]  

(7)

where the coefficient of thermal expansion is given by [33]: \( \beta = \frac{2}{T_b + T_w} \)

\[ \Delta T = T_w - T_b + \frac{(P_w - P_g) T_w}{268900 - P_w} \]  

(8)

The convective heat losses through the liner and sides are given as [20];

\[ Q_{loss} = U_b (A_b + A_{slides}) (T_b - T_w) \]  

(9)

where \( U_b = \frac{K_b}{L_i} \) and \( K_b \) and \( L_i \) are the thermal conductivity and thickness of the insulation, respectively.

The water-glass convective heat transfer is calculated from [20];

\[ Q_{c,w-g} = h_{c,w-g} A_w (T_w - T_g) \]  

(10)

where the water-glass convective heat transfer coefficient, \( h_{c,w-g} \), is given by [20];

\[ h_{c,w-g} = 0.884 \left( T_w - T_g + \frac{(P_w - P_g) T_w}{268900 - P_g} \right)^{\frac{1}{3}} \]  

(11)

where \( P_w \) and \( P_g \) is the partial pressure of the water and glass, respectively.

The values of \( P_w \) and \( P_g \) (for the range of temperature 100–900°C) can be obtained from the expression;

\[ P(T) = \exp \left[ 25.317 - \frac{5144}{T + 273} \right] \]  

(12)

where \( P(T) \) is the saturated vapor pressure.

The basin-glass radiative heat transfer is predicted from [20];
where $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon_{\text{eff}}$ is the glass-water effective emissivity, and $A_w$ is the water surface area.

$$
\varepsilon_{\text{eff}} = \left[ \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1 \right]^{-1}
$$

(14)

The water-glass evaporative heat transfer is found by [20];

$$
Q_{w-g} = h_{w-g} A_w (T_w - T_g)
$$

(15)

where the water-glass evaporative heat transfer coefficient, $h_{w-g}$, is found by [20];

$$
h_{w-g} = 0.016237 \times \frac{h_{c,g}}{(T_w - T_g)}
$$

(16)

The heat taken by the feed water is estimated from the equation [39];

$$
Q_w = m_w C_{pw} (T_w - T_b)
$$

(17)

where $C_{pw}$ is the water specific heat at constant pressure.

The glass-sky radiative heat transfer is calculated by [20];

$$
Q_{r-g} = h_{r-g} A_g (T_r - T_g)
$$

(18)

where the glass-sky radiative heat transfer coefficient, $h_{r-g}$, is found by [20];

$$
h_{r-g} = \varepsilon_g \sigma \left( T_r^4 - (T_g)^4 \right) / (T_r - T_g)
$$

(19)

The sky temperature is given as [40];

$$
T_r = T_b - 6.0
$$

(20)

The glass-ambient convective heat transfer, $Q_{g-a}$, is calculated by [20];

$$
Q_{g-a} = h_{g-a} A_g (T_g - T_a)
$$

(21)

In addition, the glass-ambient convective heat transfer coefficient, $h_{g-a}$, is given as [41];

$$
h_{g-a} = 5.7 + 2.8 V \text{ for } V > 5 \text{ m/s}
$$

(22)

$$
h_{g-a} = 2.8 + 3 V \text{ for } V \leq 5 \text{ m/s}
$$

(22)

3.2. The drum distiller

The transient energy equation for the drum can be written as [33]:

$$
I(t) A_d q_d = \frac{d}{dt} \left( m_{nf} C_{nf} \cdot \Delta T_d \right) + m_{w} - C_{pw} \cdot \Delta T_d + Q_{c,d-g}
$$

(23)

The transient energy equation for the glass cover of the drum distiller can be written as [33]:

$$
I(t) A_d q_d A_t = \frac{d}{dt} \left( m_{nf} C_{nf} \cdot \Delta T_d \right) + Q_{d,g-a}
$$

(24)

The transient energy balance for the saline water can be written as [33]:

$$
\frac{d}{dt} \left( m_{sf} C_{pw} \cdot \Delta T_w \right) + Q_{c.w-g} + Q_{r.w-g} + Q_{c.d-g} = m_{w} C_{pw} \cdot \Delta T_w
$$

(25)

The transient energy equation for the basin liner of the drum distiller can be written as [33]:

$$
\frac{d}{dt} \left( m_{sf} C_{pw} \cdot \Delta T_b \right) + Q_{c.b-w} + Q_{loss}
$$

(26)

Finally, the daily efficiency, $\eta_d$, can be calculated for both distillers based on;

$$
\eta_d = \frac{\sum m \times h_{nf}}{A \times I(t) + \text{Fan Power} + \text{Motor Power}}
$$

(27)

The heat transfer $Q_{c.d-g}$ between the cover and the drum of width $X_d$ and length $L_d$ is given by [33];

$$
Q_{c.d-g} = X_d = h_{d,g'} (T_d - T_g)
$$

(28)

where for a time increment $t$ [s], the length of the incremental distance $X_d$ [m] is calculated from [33];

$$
X_d = \pi D_d t \times 60 N
$$

(29)

where $D_d$ is the diameter of the drum [m] and $N$ is the rotational speed of the drum [rpm].

When using nanofluid, the thermo physical properties of nanofluid for a volume concentration ($\phi_v$) are calculated as follows.

The nanofluid density ($\rho_{nf}$) is calculated with the help of Pak and Cho’s equation [42],

$$
\rho_{nf} = (1 - \phi_v)\rho_{sf} + \phi_v\rho_{pw}
$$

(30)

The nanofluid viscosity ($\mu_{nf}$) is determined by the correlation introduced by Einstein [45];

$$
\mu_{nf} = \phi_v\mu_{sf} + (1 - \phi_v)\mu_{pw}
$$

(31)

The nanofluid specific heat ($C_{nf}$) is obtained by Xuan and Roetzel’s equation [44],

$$
\frac{\rho C P_n}{\rho_{sf}} = (1 - \phi_v)(\rho C P_{sf}) + \phi_v(\rho C P_{pw})
$$

(32)

The nanofluid viscosity ($\mu_{nf}$) is determined by the correlation introduced by Einstein [45];

$$
\frac{1 - \phi_v}{\phi_v} = \left( \frac{1 - \phi_v}{\phi_v} \right) \frac{\rho_{pw}}{\rho_{sf}}
$$

(33)

On the second hand, when integrating the external condenser to the solar still, the heat transfer coefficient due to convection, between water and glass cover, becomes zero [47]. Since there is no vapor diffusion through the air. Then, the evaporative heat transfer coefficient is obtained using the thermal balance equation at the glass cover.

Steady state heat transfer through the glass is assumed at the glass cover without any appreciable error. So, $h_{w-g}$ is calculated by [47];

$$
h_{w-g} = \frac{(h_{c,g} + h_{g,a}) (T_g - T_b)}{(T_w - T_g)} - h_{c,g}
$$

(35)

4. Model validation

The model is validated by comparing the theoretical results with the corresponding experimental results obtained from the present work. During the current simulation, the experimentally determined operational and metrological parameters are used. Fig. 7 shows the comparison between experimental and theoretical water productivity for the drum and conventional solar stills at 0.1 rpm. It is observed that there is an acceptable agreement between the experimental and theoretical data. The deviations between experimental and theoretical results were about 7% and reached up to 13% for conventional and drum solar stills, respectively. These deviations may be because the ambient conditions were considered hourly constant in theoretical solving.
while they varied during the hour in the case of experimental work.

5. Results and discussion

The effect of different rotational speeds of the drum, integrating solar water heater and condenser, and using copper oxide nanoparticles on the thermal performance of the still is investigated. The thermal performance of the introduced distiller is evaluated by analyzing the parameters of solar radiation, temperature, and daily productivity. Thermal performance (i.e., productivity and thermal efficiency) of the conventional still is also investigated to compare with the thermal performance of the present modified still (rotating drum still).

5.1. Thermal performance of the distillers with rotating drum

The authors interested in presenting the thermal performance (solar radiation, temperatures, and productivity) at one rotational speed (0.1 rpm) to prevent the repetition and also because this speed gives the best distillate production. Fig. 8 indicates the hourly solar radiation and temperatures of the solar stills at the drum rotational speed of 0.1 rpm. As observed from the figure, the water inside the drum distiller has a temperature lower than that of the conventional still by around 0–11 °C. This is because the transmitted solar rays are directly incident on the water inside the conventional distiller, while in the modified drum still, the basin water is warmed and heated by the drum heat. The temperature of the saline water inside the traditional distiller is higher than that of the drum solar still. In addition, it was observed that the water temperatures have almost the same values at 06:00 pm for both solar stills. Additionally, although the water temperature of the drum distiller is mostly lower than that of the conventional still, the glass temperature of the drum distiller is higher than that of the conventional distiller. This is due to the high amount of the evaporation resulted from the drum still. In short, it is found that the glass temperature of the modified distiller is about 0–2 °C higher than that of the traditional distiller.

Depending upon the weather conditions, the wind speed varies from 0.35 to 5.1 m/s at different days, and solar intensity changes from 30 to 1050 W/m². The hourly variation of wind speed during the 6th and 10th of May 2018 is shown in Fig. 9. From Fig. 8 and Fig. 9, it can be noticed that the behavior of distillation is more similar to the solar intensity curve than the wind speed curve. Consequently, the dependency of productivity on solar radiation is more than wind velocity.

The hourly change in the output yield of the solar distillers at the rotational speed of 0.1 rpm is shown in Fig. 7. Observations reveal that the distillate is minimum during the morning because the drum and the saline water is not heated up yet, and the feeding cold water needs time to warm up. Then, the distillate in both stills begins to increase with the solar radiation to record the maximum values of 950 and 450 L around 01:00 pm for the drum still and reference still, respectively. Here, it is found that the distillate has dramatically increased in case of drum still. Later, the amount of distilled water starts to decrease to follow solar intensity behavior, as illustrated in Fig. 8. Quantitatively, the hourly freshwater distillate of the solar still with the rotating drum is higher than that of the conventional basin still as shown in the figure. This
increase is due to three main reasons. First, the water layer film over the drum surface is thin; hence, the evaporation rate is high compared to that of the conventional basin still. Second, the high surface area exposed to solar radiation for the solar still with rotating drum increases the evaporation rate inside the modified distiller. For instance, the surface area of the conventional basin still is 0.5 m², while the drum still is of 3.45 m² (0.5 m² for the projected area, 1.50 m² for the outer side of the drum, and 1.45 m² for both sides of the drum). Additionally, the surface area of the drum body exposed to the solar radiation is around 0.8 m² (0.7 m² for the side exposed surface area + 0.1 m² for the base exposed surface area) compared to only 0.5 m² for the conventional solar still. As a result, the evaporation rate inside the modified solar still is greater than that of the traditional basin still due to the high evaporation area. The third reason is the turbulence occurred inside the modified still due to the rotating drum, which increases the evaporation rate. The drum creates turbulence in the content of the water vapor and the air above the basin water. This leads to the formation of water vapor away from the surface of the saline water to be condensed on the inner surface of the glass cover. As aforementioned, the speed of 0.1 rpm is enough to continually formulate the thin water layer film and evaporate it on the surface of the drum. This avoids the existence of the dry spots on the drum surface. As a result, the drum distiller introduced higher distillate than that of the reference still as obtained from Fig. 7.

The hourly accumulative output yield of the rotating drum and conventional distillers at 0.1 rpm for the drum is shown in Fig. 10. As illustrated from the figure, the drum solar still has a higher freshwater production than that of the conventional distiller. The daily accumulated freshwater production is recorded as 2025 L/m² for the conventional distiller compared to 6420 L/m² for the modified distiller with an enhancement percentage of 217%. This is because the thin film of the saline water reduces the water mass heat capacity. Moreover, the evaporating surface area and the heat transfer coefficients are increased due to the rotating drum. Furthermore, using the drum raises the response to the transmitted solar intensity compared to the normal distiller, and hence, the evaporation rates of the saline water are increased [48]. Besides, the heat transfer rate between the drum and the thin water layer film in the drum still is higher, than between the water and the basin liner of the conventional distiller, hence the distillate is augmented.

5.2. Rotating drum still integrated to solar water heater, external condenser, and using the copper oxide nanoparticles

From the previous experiments, it was concluded that the water inside the drum distiller has a temperature lower than that of the conventional still. As a result, the authors tried to solve this problem by integrating the drum distiller with a spiral solar water heater. Fig. 11 illustrates the hourly solar radiation and temperatures of the drum solar still with water heater at 0.1 rpm. Using the solar water heater leads to raise the water temperature inside the drum distiller by about 0–3°C over that of the conventional distiller. However, the temperatures of the saline water have almost the same values at 06:00 pm for both solar stills. On the other hand, the glass temperature of the drum distiller is increased by about 0–7°C as compared to that of the conventional distiller. This is due to the high amount of the evaporation resulted from the drum still. Therefore, the glass temperature of the modified distiller is higher than that of the traditional distiller.

The hourly change in the output yield of the tested conventional solar distiller and the drum solar still with water heater at 0.1 rpm for the rotating drum is shown in Fig. 12. In this part, the productivity has the same behavior shown in Fig. 7 with different values. The maximum hourly distillate of the modified drum still and conventional basin still is around 1100 and 360 L, respectively, and this value is taken at 01:00 pm. It is concluded that the distillate of the drum distiller integrated with the water solar heater is higher than that of the same basin still without the water heater. This means that the drum distiller has more additional heat capacity to be used in the evaporation of the saline water inside the basin.

The hourly accumulative output yield of the conventional solar still and the drum still with heater, at the drum speed of 0.1 rpm is shown in Fig. 13. The figure illustrates that the drum solar still with water heater has higher distillate than that of the conventional distiller. The daily accumulated yields of the drum and conventional distillers are 8330 L/m² and 2140 L/m² respectively with a substantial increase in percentage of 289.25%. In addition, the distilled freshwater of the modified drum still with a solar water heater at 0.1 rpm is higher than that of the same basin still without a solar water heater at the same speed.

As aforementioned, the conclusion of the presence of a large amount
of vapor content in the space between the saline water and the glass cover was revealed. This led to raise the temperatures of the glass cover and the saline water inside the drum distiller. Therefore, the drum still integrated with the water heater still has parameters to be optimized. As a result, the authors integrated an external condenser through a small fan to the drum distiller with the solar water heater. This new arrangement led to decrease the temperature of glass cover by about 1 – 1.5 °C, comparing the drum still integrated with the condenser and water heater, over the drum still without a condenser. Indeed, presence of external condenser also led to decline the water temperature inside the drum still by around 0 – 2 °C, mainly due to the withdrawn vapor from the basin still to the condensation unit. These temperature differences led to increase the total accumulated distilled water of the drum distiller by 335% greater than that of the conventional one. This improvement in productivity is explained by the existence of the fan connecting the drum still to the external condenser. That fan develops the vapor above the saline water in turbulence. This enhanced turbulence helped to increase the evaporation inside the solar still. Besides, the bad effect of the non-condensable gases was avoided because the fan took them away from the drum still into the external condenser. Moreover, this led to increase the amount of condensation of the drum distiller. To prevent repetition and duplication in the paper, the authors did not prefer to present the figures of this subtitle because it looks like the previous ones.

Herein, in the final stage of experimentations, the authors tried to maximize the output distillate productivity of the drum still via feeding the distiller by copper oxide–water nanofluid. As expected, the hourly distillate of the drum still is higher than that of the traditional one. Also, the total productivity is enhanced by around 350% for the drum still in the existence of the external condenser, solar water heater, and nanofluids over the conventional type. This enhancement is considered because the heat transfer properties of the nanofluid are better than that of both the pure and saline water. Moreover, the thermal conductivity, as well as the convective heat transfer coefficients, of the copper oxide–water nanofluid is better than that of the saline water only [20]. Furthermore, the nanoparticles-water mixture has better heat storing properties than that of the saline water only. It is evaluated that the solar still working with nanofluids provides higher distillate than the conventional still in the late-night times [49]. This means that the nanoparticles can store latent heat in the daytimes and release it in the absence of sun. In addition, the existence of nanoparticles increases the surface area of the drum and acts as thermal storage material. Then, the addition of nanoparticles helps to absorb more heat than that without nanoparticles. Consequently, the evaporation and production rates are better in when using nanoparticles due to increasing the heat transfer rate and water temperature. As a result, the evaporation and condensation rates are improved in the drum basin still when using the copper oxide nanoparticles, external condenser, and solar water heater.

5.3. Effect of the drum rotational speed on the thermal performance of the drum distiller

Fig. 14 illustrates the hourly change in the productivity of the tested conventional solar distiller and the drum solar still under different
The daily distillate rise of the drum still under different drum rotational speeds.

drum speeds (0.02, 0.05, 0.1 rpm). The days of tests have almost the same solar intensity. As observed from Fig. 14, the curves of the conventional still and the drum still at 0.1 rpm have the same behavior of the solar radiation and temperatures of water and glass. But the curves of the drum still at 0.02 and 0.05 rpm have a semi constant line from 10:00 am to 04:00 pm and from 11:00 am to 03:00 pm respectively and do not follow the same trend of the previous curves. This may be due to that the drum evaporates all the carried water content around the drum body due to the slow motion (one complete loop for 0.02 and 0.05 rpm takes 50 and 20 min, respectively). This leads to make the drum body as dry. As a result, the productivity curve is constant under this period, and there is no effect for the solar radiation (loss of solar radiation). After 05:00 pm, the productivity decreases due to the decline of the solar radiation and temperatures. As illustrated from Fig. 14, the distillate of the drum still working under 0.1 rpm is higher than that of the same distiller working under different drum speeds.

Fig. 15 and Table 2 present a summary of the effect of different rotational drum speeds on the daily improvement in productivity of the drum distiller with the different modifications over the conventional still. It is observed from the figure that the rise in productivity of the drum still is always higher than that of the reference still. In addition, the rise in productivity when using nanofluid, solar water heater, and external condenser has the greatest improvement compared to that obtained when using either one or two modifications. This conclusion is generalized through all the rotational speeds implemented in this study. In addition, for the drum distiller, the drum rotational speed provided the highest productivity is 0.1 rpm. The rise in the percentage of the daily freshwater distillate decreases when increasing the rotational speed of the drum. The values of such improvements in the distillers are tabulated in Table 2. Also, the values tabulated in Table 2 and shown in Fig. 15 obtain that the modifications conducted on the drum still have a small effect on the productivity of the distiller. For instance, the effect of using nanofluid provides an increase in the productivity by 1% only.

The daily efficiency, $\eta_d$, of the solar distiller is calculated by summing up the hourly condensate production $n_t$, multiplied by the latent heat of vaporization $h_{fg}$, hence, the result is divided by the daily average solar radiation $I(t)$ over the whole area $A$ of the device [34]:

$$\eta_d = \frac{\sum n_t \times h_{fg}}{\sum A \times I(t) + \text{Fan Power} + \text{Motor Power}}$$

To present the evaluated performance of the modified distiller, the thermal efficiency of the distillers is displayed in Fig. 16, and tabulated in Table 3. As illustrated from the figure, the efficiency has a similar behavior and trend as the daily distillate rise of the basin stills. The conventional basin still has an average thermal efficiency of 34–35% while the thermal efficiency of the rotating drum distiller has different values based on the drum rotational speed, as shown in Fig. 16 and Table 3. As observed, the highest efficiency (85.5%) is obtained at the tested drum rotational speed of 0.1 rpm for the drum distiller integrated with the solar water heater, external condenser, and using copper oxide-water nanofluid. In addition, the thermal efficiency of the drum still at 0.02 rpm is lower than that of the conventional still due to the decrease of productivity of the drum still at this speed. Finally, there is a point at which the thermal efficiencies of the conventional still and drum still at different speeds are equal as illustrated in Fig. 15. Furthermore, the speeds below 0.03 rpm obtained an adverse effect on the performance of the drum still either
with modifications or not. In addition, rotating the drum at speeds above 3.5 rpm had a negative effect on the thermal performance of the drum solar still without any modifications as observed from Fig. 15 and Fig. 16.

5.4. Evaluation cost of distillers

The evaluation costs of the solar stills and the costs of one liter of distilled water are conducted as obtained in details in Appendix (A). The cost estimation for the components depends upon the distiller type and its components. The costs of the different components are calculated for both fixed and variable costs. Based on the average daily productivity and the life time for both solar stills, the cost of 1 L from the solar still can be calculated. As a result, the cost of 1 L from a reference distiller equals to 0.05 $. Moreover, the cost of 1 L from a drum distiller with condenser and heater only equals 0.034 $. In addition, the cost of 1 L from a drum distiller with condenser, heater, and nanoparticles equals 0.039 $. The details of the calculation can be found in Appendix (A).

6. Concluding remarks and future work

Based on the discussion in the previous section about the results obtained in this study, it is revealed that:

1- The rotating drum still had higher performance than the conventional solar still.
2- Integrating a solar water heater and an external condenser, as well as using the copper oxide nanoparticles, enhanced the thermal performance significantly.
3- The performance of the drum still was superior at the drum speed of 0.1 rpm.
4- At the drum speed of 0.1 rpm, using the external condenser, solar water heater, and nanofluids improved the productivity of the drum still by 350% compared to that of the conventional solar still.
5- At the drum speed of 0.1 rpm, using the external condenser, solar water heater, and nanofluids raised the efficiency of the drum still to 85.5%.
6- Rotating the drum at speeds below 0.03 rpm and above 3.5 rpm had a negative effect on the thermal performance of the drum solar still.
7- Estimated cost of 1 L of distillate for conventional and rotating drum solar stills with the condenser, heater, and nanoparticles were about 0.05 and 0.039 $, respectively.

Further studies are proposed as following:

1- Different designs for rotating drum as a corrugated drum to increase the absorption and evaporation area.
2- Using hollow cylinder as a rotating drum.
3- Adding external and internal reflectors to improve the rotating drum efficiency.
4- Using a rotating drum with tubular solar still.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Evaluation cost of distillers

The estimation of cost for different components (practical units) utilized in the present solar distillers depends upon the distiller type and its components, as shown in Table 4.

For the reference still

The fixed cost of reference distiller is F = 102 $ per 1 m². To acquire the average cost of the production, it is assumed that;

\[ C = F + V \]  

where the variable cost is V and the annual total cost is C. According to [38], let the annual variable cost V equals 0.3 F per year, and the variable cost includes the cost of maintenance. Let the expected distiller life time is 10 years, then C = 102 + (0.3 × 102 × 10) = 408 $. Average daily productivity is about at 2.45 L/m² day, and that the distiller operates 340 days in a year, where the sun rises along the year in Saudi Arab with the distiller life at 10 years. The production during the life of distiller is 2.45 × 340 × 10 = 8160 L. The cost of 1 L from a reference distiller = 408/8160 = 0.05 $.

For the drum still

The fixed cost of rotating drum distiller per 1 m² with condenser, heater, and without nanoparticles is about F = 312 $. Then,
C = 312 + (0.3 × 312 × 10) = 1248 $. Average daily productivity is about 10.7 L/m² day. The production during the distiller life is 10.7 × 340 × 10 = 36380 L. The cost of 1 L from a rotating drum distiller = 1248/36380 = 0.034 $. The fixed cost of rotating drum distiller per 1 m² with condenser, heater, and nanoparticles is about F = 372 $. Then, C = 372 + (0.3 × 372 × 10) = 1488 $. Average daily productivity is about 11 L/m² day. The production during the distiller life is 11 × 340 × 10 = 37400 L. The cost of 1 L from a rotating drum distiller = 1488/37400 = 0.039 $.

References

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