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# Performance Evaluation of a Double-Slope Solar Distiller Integrated with Air Heater and Air-Cooled Condenser

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**ABSTRACT:** In this study, the covers of the conventional double slope solar distiller (CDSSD) were replaced with a glass air heater and a glass air-cooled condenser. Ambient air was circulated through the air heater and air-cooled condenser to recover unavoidable heat losses in air heating as an auxiliary product. The thermal performance of the double slope solar distiller integrated with an air heater and an air-cooled condenser (DSSD-AH-ACC) was mathematically evaluated under real weather conditions and varying air flows. The results showed that increasing air flow through the air heater and air-cooled condenser improved the efficiency of the DSSD-AH-ACC by nearly 40%. Additionally, the DSSD-AH-ACC, under air flows of 0.01–0.1 kg/s, was 14%–60% more efficient than CDSSD, despite an 18% reduction in distillate production. Furthermore, the thermal performance of the DSSD-AH-ACC responded directly to hot weather with calm wind.

**KEYWORDS:** Distiller; double-slope; air heater; condenser; efficiency

## 1 Introduction

Fresh water crisis has been an urgent global challenge, especially in arid and semi-arid areas where fresh water sources are limited. In addition, these resources are rapidly depleting due to many factors such as rapid population growth, urbanization, pollution, and increasing agricultural and industrial development. Moreover, widespread water contamination continues to make the problem even worse [1]. Solar distillation of saline or brackish water stands out as a decentralized, sustainable alternative to address the crisis, especially where solar energy is abundant and the climate is favorable for solar applications. Solar distillers are generally characterized by their simple and cost-effective designs with little operational and maintenance efforts, despite their limited distillate production and low thermal efficiency.

A great amount of work has been dedicated to improving the distillate production and thermal efficiency of various configurations of solar distillers, including single slope distillers [2], double slope distillers [3], pyramidal distillers [4], hemispherical distillers [5], stepped distillers [6], tubular distillers [7], wick distillers [8], and diffusion distillers [9]. Among various solar distiller configurations, double-slope solar distillers (DSSD) have demonstrated notable advantages in distillate production under hot weather conditions, especially compared with single-slope distillers [10]. Additionally, the ability to independently vary the tilt angles of the north- and south-facing covers guarantees design flexibility across different orientations and seasonal conditions [11].



In this context, Gnanaraj and Velmurugan [12] enhanced the distillate yield of a DSSD by nearly 62.97% through the incorporation of an external reflector. Patel et al. [13] incorporated transparent acrylic side walls into a DSSD to enhance capturing both diffuse and direct solar irradiation. However, replacing the glass cover with translucent PVC sheets adversely affected the distillate production of the distiller [14].

Jeyaraj et al. [15] improved the performance of DSSD by preheating saline water using integrated channels, and Hedayati-Mehdiabadi et al. [16] preheated saline water through a PV/T collector. Boudhief et al. [17] demonstrated that replacing the conventional rectangular basin in a DSSD with a concave basin improved distillate production by approximately 65%. Zayed et al. [18] improved the distillate output of a DSSD by nearly 50% through the use of a prismatic absorber basin covered with linen wicks.

Various approaches have been reported in the literature to enhance saline water evaporation within DSSDs. For example, Sharshir et al. [19] employed a metal-organic framework that increased distillate productivity by approximately 35%–92%. Elsheikh et al. [20] achieved an 18% increase in water production of a DSSD through the integration of a wicked prismatic basin equipped with feed-spray nozzles. Sharshir et al. [21] employed carbon black nanoparticles and linen wicks to enhance the evaporation within a stepped DSSD, which increased distillate production by about 81%. Modi and Jani [22] evaluated the impact of incorporating circular hollow fins in the basin of DSSD. Ghriss et al. [23] incorporated twelve square fins in the basin of DSSD, increasing its distillate production by about 55%.

Moreover, Hussen et al. [24] increased the distillate yield of a DSSD by 40% through the use of an elevated basin containing phase change material (PCM) enhanced with nanoparticles. Sibagariang et al. [25] utilized palm kernel as a sensible heat storage material within the basin of a DSSD, resulting in a 30% increase in distillate production. Agrawal and Singh [26] compared the performance of conventional DSSDs with modified ones incorporating eutectic PCM and steel wool fiber.

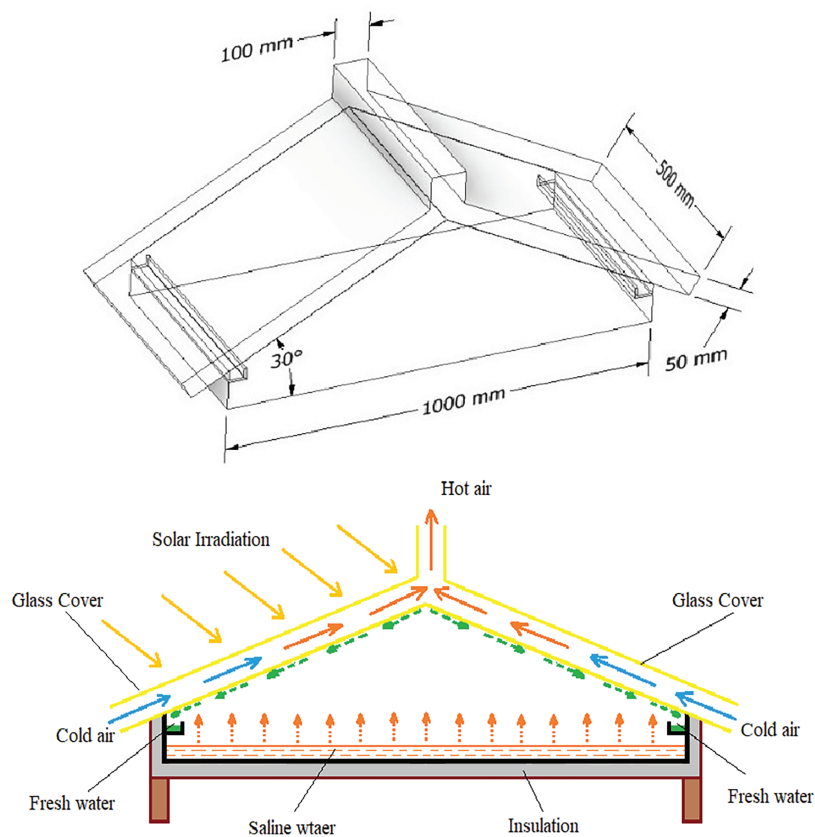
Thermal losses from the covers of DSSDs to the ambient surroundings are unavoidable in distillate production. However, recovering these losses through an auxiliary process, such as air or water heating, can significantly enhance the thermal performance of DSSDs and increase the effective utilization of incident solar energy per unit of collecting area. In this context, Ghazy [27] enhanced the thermal performance of a DSSD to 67%–76% by recovering condensation losses from the north-facing cover in air heating. Additionally, utilizing those losses for water heating raised the performance of the DSSD to about 59%–63% [28]. Moreover, recovering condensation losses from the south-facing cover in air heating increased the thermal performance to around 58%–67% [29]. Nevertheless, replacing the south-facing cover with an air heater [29] and the north-facing cover with an air-heater condenser [27] alters the cover temperatures, the temperature gradient between the saline water and the covers, and consequently the distillate production. Moreover, installing an air heater on the south-facing side [29] reduces the solar irradiance reaching the basin water, which contributes to the observed decline in system performance compared with the configuration that employs an air-heater condenser on the north-facing cover [27].

This study aims to evaluate the performance enhancement of a conventional double-slope solar distiller (DSSD) by recovering unavoidable condensation losses from its south- and north-facing covers through auxiliary air heating. In the proposed configuration, the south-facing cover is replaced with an air heater (AH), while the north-facing cover is substituted with an air-cooled condenser (ACC), forming the hybrid DSSD-AH-ACC. The system's performance metrics will be assessed under actual weather conditions in Saudi Arabia. Additionally, the influence of relevant climate and operational parameters on the DSSD-AH-ACC's performance will be investigated.

## 2 Mathematical Analysis

### 2.1 System Configuration

Fig. 1 illustrates the schematic configurations of the DSSD-AH-ACC. The distiller consists of a  $1\text{ m} \times 0.5\text{ m}$  basin fabricated from galvanized steel sheet and coated with matte black paint to enhance solar energy absorption. The basin is insulated with 50 mm of polyurethane foam to minimize thermal losses. Transparent glass channels, positioned at a  $30^\circ$  tilt from the horizontal on both sides of the distiller, serve as the air heater (AH) and air-cooled condenser (ACC). Distillate collection channels are installed along the lower edges of these glass covers. The air-cooled condenser is located on the northern side, while the air heater is placed on the southern side. Each unit comprises a  $0.5\text{ m} \times 0.05\text{ m}$  glass channel. Ambient air is circulated through them either by natural thermosyphon action or by a DC fan, recovering the unavoidable thermal losses from the distiller covers.



**Figure 1:** Schematic diagram of the DSSD-AH-ACC

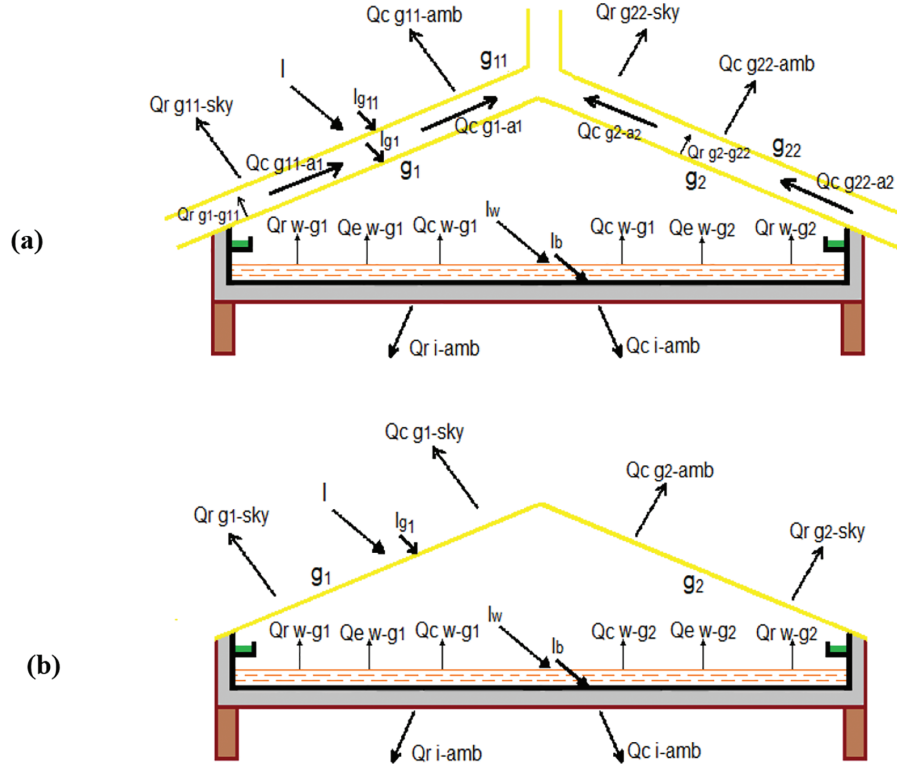
### 2.2 System Energy Analysis

Fig. 2 compares the energy analysis of the DSSD-AH-ACC with that of the CDSSD. Adding the air heater (AH) and the air-cooled condenser (ACC) interact with the solar irradiance, lowering solar transmittance to the distiller while simultaneously reducing convective and radiative losses to the ambient.

The following assumptions were adopted in the analysis:

- Constant thermophysical properties.

- No water leakage occurs from the DSSD, and no air leakage occurs from the air heater (AH) or the air-cooled condenser (ACC).
- Water vapor losses from the distiller are negligible.
- Heat distribution within all distiller components is uniform.
- The interaction between incident solar radiation and the humid air inside the distiller is considered negligible.
- Temperature and vapor concentration gradients within the humid air domain are assumed to be negligible.



**Figure 2:** Energy analysis of (a) DSSD-AH-ACC, (b) CDSSD

### 2.2.1 Energy Analysis of Glass Covers

The energy analysis of the cover ( $g_{11}$ ) of the DSSD-AH-ACC is

$$m_{g11} C_{g11} \frac{dT_{g11}}{dt} = S_{g11} + Q_{R,g1-g11} - Q_{C,g11-a1} - Q_{R,g11-sky} - Q_{C,g11-amb} \quad (1)$$

where,  $S_{g11}$  is the absorbed portion of solar energy by ( $g_{11}$ ),  $Q_{R,g1-g11}$  is the radiative heat exchange between ( $g_1$ ) and ( $g_{11}$ ),  $Q_{C,g11-a1}$  is the convection heat transfer between ( $g_{11}$ ) and the air flowing through the AH,  $Q_{R,g11-sky}$  is the radiative losses from ( $g_{11}$ ) to the sky, and  $Q_{C,g11-amb}$  is the convective losses from ( $g_{11}$ ) to the ambient, which are defined as follows

$$S_{g11} = \alpha_g I A_g$$

$$Q_{R,g1-g11} = \frac{\sigma A_g (T_{g1}^4 - T_{g11}^4)}{\frac{2}{\epsilon_g} - 1}$$

$$\begin{aligned}
Q_{C,g11-a1} &= h_{g11-a} A_g (T_{g11} - T_{a1}) \\
h_{g11-a1} &= 0.664 \left( \frac{k_a}{L_g} \right)^{0.333} \text{Pr} \text{Re}^{0.5} \\
Q_{R,g11-sky} &= \sigma \varepsilon_g A_g (T_{g11}^4 - T_{sky}^4) \\
T_{sky} &= \left[ 0.0522 (T_{amb} + 273)^{1.5} \right] - 273 \\
Q_{C,g11-amb} &= h_{g11-amb} A_g (T_{g11} - T_{amb}) \\
h_{g11-amb} &= 5.7 + 3.8 \times V_{wind}
\end{aligned}$$

The energy analysis of the cover ( $g_1$ ) of the DSSD-AH-ACC is

$$m_{g1} C_{g1} \frac{dT_{g1}}{dt} = S_{g1} + Q_{R,sw-g1} + Q_{C,sw-g1} + Q_{e,sw-g1} - Q_{R,g1-g11} - Q_{C,g1-a1} \quad (2)$$

where,  $S_{g1}$  is the absorbed portion of solar energy by ( $g_1$ ),  $Q_{R,sw-g1}$  is the radiative heat exchange between the saline water and ( $g_1$ ),  $Q_{C,sw-g1}$  and  $Q_{e,sw-g1}$  are the convection heat and mass transfer from the saline water to ( $g_1$ ),  $Q_{R,g1-g11}$  is the radiative heat exchange between ( $g_1$ ) and ( $g_{11}$ ), and  $Q_{C,g1-a1}$  is the convection heat transfer from ( $g_1$ ) to the air flowing through the SAH, which are written as

$$\begin{aligned}
S_{g1} &= I A_g \tau_g \alpha_g \\
Q_{R,sw-g1} &= \sigma \varepsilon_{sw} F_{g1} A_b (T_{sw}^4 - T_{g1}^4) \\
Q_{C,sw-g1} &= h_{sw-g1} A_b (T_{sw} - T_{g1}) \\
h_{sw-g1} &= 0.884 \left[ (T_{sw} - T_{g1}) + (P_{sw} - P_{g1}) (T_{sw} + 273) / (268900 - P_{sw}) \right]^{0.33} \\
P_{sw} &= 1000 \times \left[ (0.14862 \times T_{sw}) - (0.0036526 \times T_{sw}^2) + (0.0001124 \times T_{sw}^3) \right] \\
P_{g1} &= 1000 \times \left[ (0.14862 \times T_{g1}) - (0.0036526 \times T_{g1}^2) + (0.0001124 \times T_{g1}^3) \right] \\
Q_{e,sw-g1} &= h_e A_b (P_{sw} - P_{g1}) \\
h_e &= 0.016 h_{sw-g1} \\
Q_{R,g1-g11} &= \frac{\sigma A_g (T_{g1}^4 - T_{g11}^4)}{\frac{2}{\varepsilon_g} - 1} \\
Q_{C,g1-a1} &= h_{g1-a} A_g (T_{g1} - T_{a1}) \\
h_{g1-a} &= 0.466 \left( \frac{k_a}{L_g} \right)^{0.333} \text{Pr} \text{Re}^{0.5}
\end{aligned}$$

Similarly, the energy analysis of the cover ( $g_{22}$ ) of the DSSD-AH-ACC is

$$m_{g22} C_{g22} \frac{dT_{g22}}{dt} = S_{g22} + Q_{R,g2-g22} - Q_{C,g22-a2} - Q_{R,g22-sky} - Q_{C,g22-amb} \quad (3)$$

where,

$$\begin{aligned}
S_{g22} &= \alpha_g I A_g \\
Q_{R,g2-g22} &= \frac{\sigma A_g (T_{g2}^4 - T_{g22}^4)}{\frac{2}{\varepsilon_g} - 1}
\end{aligned}$$

$$\begin{aligned}
Q_{C,g22-a2} &= h_{g22-a} A_g (T_{g22} - T_{a2}) \\
Q_{R,g22-sky} &= \sigma \varepsilon_g A_g (T_{g22}^4 - T_{sky}^4) \\
Q_{C,g22-amb} &= h_{g22-amb} A_g (T_{g22} - T_{amb})
\end{aligned}$$

and the energy analysis of the cover ( $g_2$ ) of the DSSD-AH-ACC is

$$m_{g2} C_{g2} \frac{dT_{g2}}{dt} = Q_{R,sw-g2} + Q_{C,sw-g2} + Q_{e,sw-g2} - Q_{R,g2-g22} - Q_{C,g2-a2} \quad (4)$$

where,

$$\begin{aligned}
Q_{R,sw-g2} &= \sigma \varepsilon_{sw} F_{g2} A_b (T_{sw}^4 - T_{g2}^4) \\
Q_{C,sw-g2} &= h_{sw-g2} A_b (T_{sw} - T_{g2}) \\
Q_{e,sw-g2} &= h_e A_b (P_{sw} - P_{g2}) \\
Q_{R,g2-g22} &= \frac{\sigma A_g (T_{g2}^4 - T_{g22}^4)}{\frac{2}{\varepsilon_g} - 1} \\
Q_{C,g2-a2} &= h_{g2-a} A_g (T_{g2} - T_{a2})
\end{aligned}$$

While the energy analysis of the cover ( $g_1$ ) of the CDSSD is

$$m_{g1} C_{g1} \frac{dT_{g1}}{dt} = S_{g1} + Q_{R,sw-g1} + Q_{C,sw-g1} + Q_{e,sw-g1} - Q_{R,g1-sky} - Q_{C,g1-amb} \quad (5)$$

where,

$$\begin{aligned}
S_{g1} &= \alpha_g I A_g \\
Q_{R,sw-g1} &= \sigma \varepsilon_{sw} F_{g1} A_b (T_{sw}^4 - T_{g1}^4) \\
Q_{C,sw-g1} &= h_{sw-g1} A_b (T_{sw} - T_{g1}) \\
Q_{e,sw-g1} &= h_e A_b (P_{sw} - P_{g1}) \\
Q_{R,g1-sky} &= \sigma \varepsilon_g A_g (T_{g1}^4 - T_{sky}^4) \\
Q_{C,g1-amb} &= h_{g1-amb} A_g (T_{g1} - T_{amb})
\end{aligned}$$

and the energy equation of the glass cover ( $g_2$ ) in the CDSSD is

$$m_{g2} C_{g2} \frac{dT_{g2}}{dt} = Q_{R,sw-g2} + Q_{C,sw-g2} + Q_{e,sw-g2} - Q_{R,g2-sky} - Q_{C,g2-amb} \quad (6)$$

where,

$$\begin{aligned}
Q_{R,sw-g2} &= \sigma \varepsilon_{sw} F_{g2} A_b (T_{sw}^4 - T_{g2}^4) \\
Q_{C,sw-g2} &= h_{sw-g2} A_b (T_{sw} - T_{g2}) \\
Q_{e,sw-g2} &= h_e A_b (P_{sw} - P_{g2}) \\
Q_{R,g2-sky} &= \sigma \varepsilon_g A_g (T_{g2}^4 - T_{sky}^4) \\
Q_{C,g2-amb} &= h_{g2-amb} A_g (T_{g2} - T_{amb})
\end{aligned}$$

The energy analysis of the air through the AH and ACC of the DSSD-AH-ACC are

$$m_{a1} C_a \frac{dT_{a1}}{dt} = Q_{C,g1-a1} + Q_{C,g11-a1} \quad (7)$$

$$m_{a2} C_a \frac{dT_{a2}}{dt} = Q_{C,g2-a2} + Q_{C,g22-a2} \quad (8)$$

### 2.2.2 Energy Analysis of Basins

The energy analysis of the saline water in both DSSD-AH-ACC and CDSSD is as follows

$$m_{sw} C_{sw} \frac{dT_{sw}}{dt} = S_{sw} + Q_{C,b-sw} - Q_{C,sw-g1} - Q_{C,sw-g2} - Q_{e,sw-g1} - Q_{e,sw-g2} - Q_{R,sw-g1} - Q_{R,sw-g2} \quad (9)$$

where  $S_{sw}$  is the absorbed portion of solar energy by the saline water, and  $Q_{C,b-sw}$  is the convection heat transfer from the basin to saline water, which are defined as follows

$S_{sw} = \tau_g \tau_g \alpha_{sw} I A_g$  for the DSSD-AH-ACC and  $S_{sw} = \tau_g \alpha_{sw} I A_g$  for the CDSSD.

$$Q_{C,b-sw} = h_{b-sw} A_b (T_b - T_{sw})$$

$$h_{b-sw} = 0.54(k_{sw}/L_b) (GrPr)^{1/4} \quad GrPr < 8 \times 10^6$$

$$h_{b-sw} = 0.15(k_{sw}/L_b) (GrPr)^{1/3} \quad GrPr > 8 \times 10^6$$

while the temporal variation in the saline water mass in the basins of both the DSSD-AH-ACC and CDSSD due to evaporation is expressed as

$$m_{sw} = m_{sw,o} - m_{yield} \quad (10)$$

The energy analysis of the basin bodies in both the DSSD-AH-ACC and CDSSD is written as

$$m_b C_b \frac{dT_b}{dt} = S_b - Q_{C,b-sw} - Q_{Cd,b-i} \quad (11)$$

where  $S_b$  is the absorbed portion of solar energy by the basin, and  $Q_{Cd,b-i}$  is the thermal losses by conduction heat transfer from the basin's body to its outer insulation, which are defined as

$S_b = \tau_g \tau_g \tau_{sw} \alpha_b I A_g$  for the DSSD-AH-ACC and  $S_b = \tau_g \tau_{sw} \alpha_b I A_g$  for the CDSSD.

$$Q_{Cd,b-i} = \frac{2 \frac{k_b \times k_i}{k_b + k_i} A_b (T_b - T_i)}{\frac{L_b + L_i}{2}}$$

The thermal losses from the basin's insulation to the ambient surroundings can be expressed as

$$m_i C_i \frac{dT_i}{dt} = Q_{Cd,b-i} - Q_{R,i-sky} - Q_{C,i-amb} \quad (12)$$

where,  $Q_{R,i-sky}$  is thermal losses by radiation heat transfer from the insulation to the sky, and  $Q_{C,i-amb}$  is thermal losses by convection heat transfer from the insulation to the ambient surroundings, which are defined as

$$Q_{R,i-sky} = \sigma \epsilon_i A_i (T_i^4 - T_{sky}^4)$$

$$Q_{C,i-amb} = h_{i-amb} A_i (T_i - T_{amb})$$

### 2.2.3 Overall Thermal Efficiency

The overall thermal efficiency of the DSSD-AH-ACC can be written as the summation of the efficiencies of the distillation and air heating through both the AH and ACC, as

$$\eta = \eta_{dist} + \eta_{AH} + \eta_{ACC} = \frac{\sum_{t=0}^{t=t_{op}} ((m_{yield} \times H) + (m_{a1} \times C_a \times \Delta T_{a1}) + (m_{a2} \times C_a \times \Delta T_{a2}))}{\sum_{t=0}^{t=t_{sun}} IA} \quad (13)$$

However, the overall thermal efficiency of the CDSSD is expressed as

$$\eta_{dist} = \frac{\sum_{t=0}^{t=t_{op}} (m_{yield} \times H)}{\sum_{t=0}^{t=t_{sun}} IA} \quad (14)$$

where the latent heat of evaporation is calculated as

$$H = 2503.3 - 2.398 \times T_{sw}$$

## 3 Results and Discussion

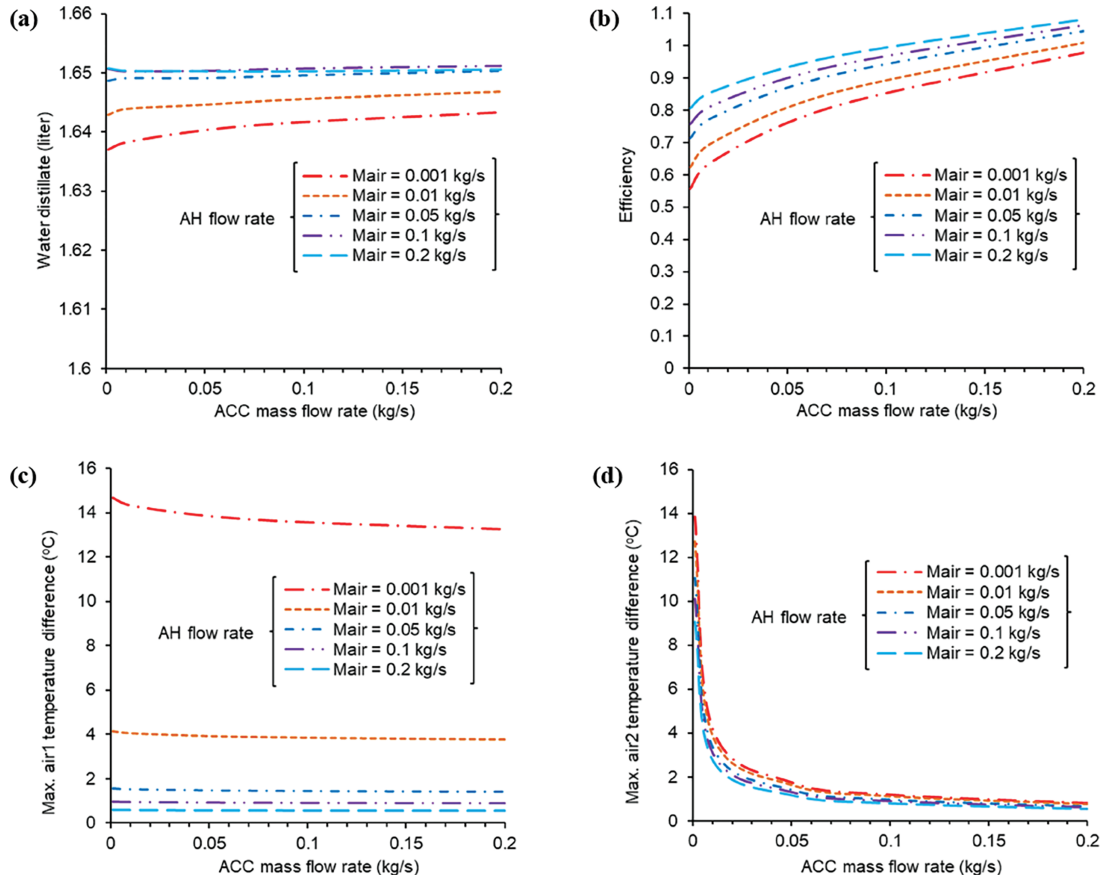
Two numerical models were developed to evaluate the transient thermal performance of the DSSD-AH-ACC and CDSSD components by solving the energy balance equation for each system component. The codes progressed temporally from sunrise to nightfall, with component temperatures at each time step computed using values from the preceding step. Additionally, the models calculated both current and cumulative distillate yield on the glass covers, along with instantaneous and average thermal efficiencies throughout the day. The model validation against the experimental data measured by Jeyaraj et al. [15] was documented in Ghazy [29].

The simulations were conducted across a range of air flows within the AH and the ACC, spanning from 0.001 to 0.2 kg/s, to encompass both natural and forced air circulation scenarios. The models incorporated the meteorological data recorded on September 20th in Al-Jouf (29.9°N, 39.3°E), KSA, including solar irradiance, dry-bulb air temperature, and local wind speed. On that day, solar exposure lasted approximately 12 h, with peak irradiance reaching around 1050 W/m<sup>2</sup> at midday. The maximum ambient temperature observed was approximately 40°C, while wind speed fluctuated near 2 m/s. These climate conditions are characteristic of KSA's location within the global "sun belt," making it well-suited for solar distillation applications.

### 3.1 Air flows through the Air Heater and Air-Cooled Condenser

Air flows through the air heater (AH) and air-cooled condenser (ACC) of the DSSD-AH-ACC play a pivotal role in governing distillate condensation on the distiller covers, condensation losses recovery, minimizing thermal losses to the ambient surroundings, and, ultimately, determining the overall thermal efficiency of the DSSD-AH-ACC. Fig. 3 illustrates the impact of varying air flow rates through the AH and ACC, from 0.001 to 0.2 kg/s, on key performance metrics of the DSSD-AH-ACC. Notably, increasing air flow through the AH had a minimal impact on enhancing distillate production (Fig. 3a), with this effect vanishing gradually at higher flows. Conversely, increasing air flow through the ACC had an insignificant impact on distillate production. Overall, the higher the air flow rates through the AH and ACC, the higher the distillate production, and *vice versa*. The thermal efficiency (Fig. 3b) was significantly affected by increasing

both air flows. Maximum efficiency was achieved at the highest air flows through the AH and ACC, while minimum efficiency corresponded to the lowest air flows. This highlights the contribution of recovering the distiller thermal losses on the overall performance of the DSSD-AH-ACC. The temperature difference of the exiting air from the AH (Fig. 3c) was primarily affected by AH flow. It significantly decreased with increasing AH flow and remained unaffected by ACC flow, particularly at higher AH flows. In contrast, the temperature difference of the exiting air from the ACC (Fig. 3d) declined sharply with increasing ACC flow, while increasing the AH flow slightly contributed to decreasing it.



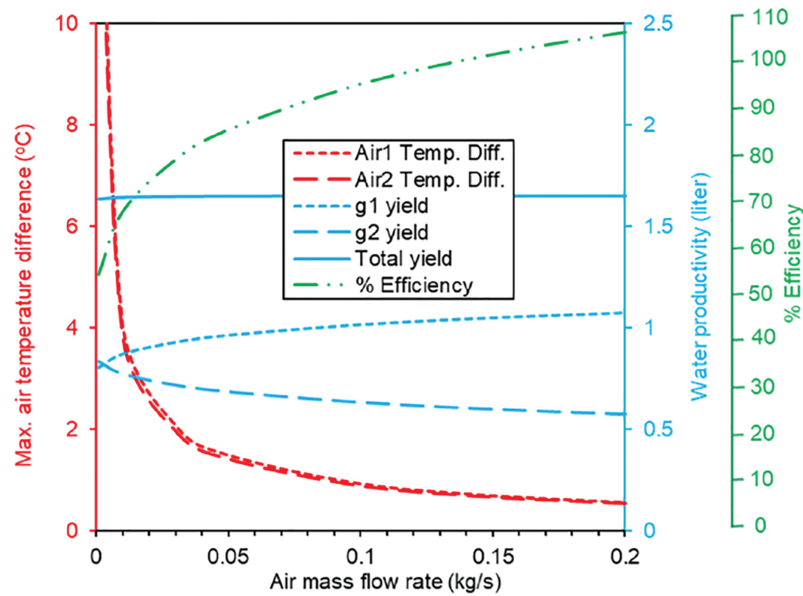
**Figure 3:** Influence of air flows through the AH and ACC on the DSSD-AH-ACC performance: (a) distillate production, (b) thermal efficiency, (c) AH air exit temperature, (d) ACC air exit temperature

Fig. 4 further explores the effect of uniform air flows through both the AH and ACC on the performance of the DSSD-AH-ACC. Increasing both flows equally, from 0.001 to 0.2 kg/s, had a minimal effect on improving distillate production. However, the  $g_1$  cover distillate yield increased by nearly 34% while the  $g_2$  cover distillate yield decreased by nearly 31%. This shows only a redistribution of the distillate across the distiller covers. The temperature difference of the exiting air from the AH and ACC declined by approximately 96%. Nevertheless, the thermal efficiency rose by about 94%. These findings are discussed in greater detail later in this section.

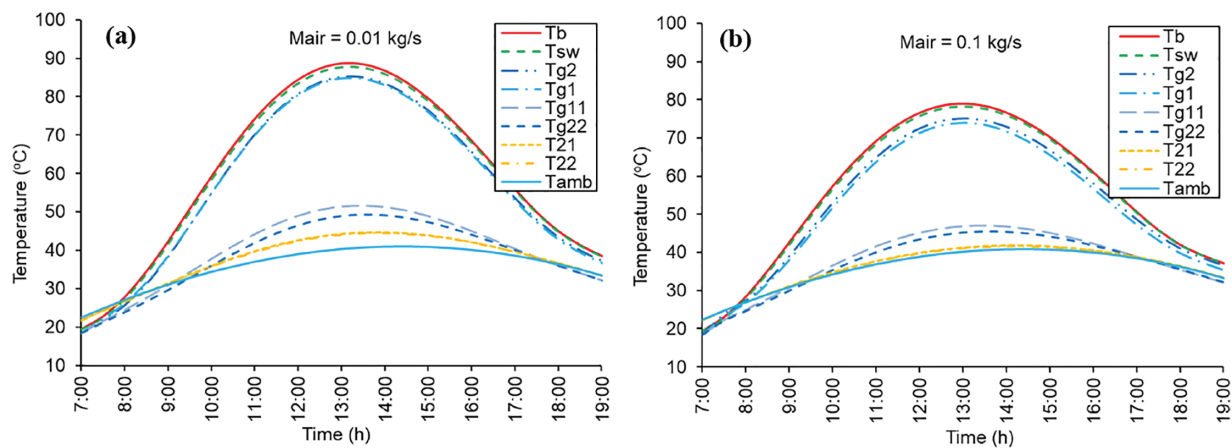
### 3.2 Temperature Distributions under Varying Air Flows

Fig. 5 illustrates the temporal temperature profiles within the DSSD-AH-ACC and CDSSD with the ambient temperature ( $T_{amb}$ ) serving as a baseline across the three parts of the figure. Fig. 5a,b correspond

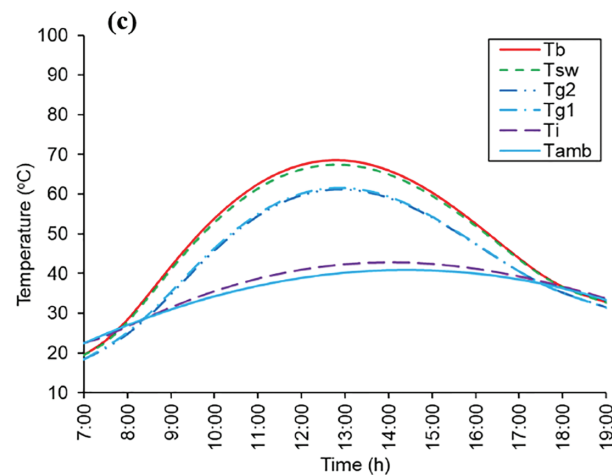
to air flows of 0.01 and 0.1 kg/s, respectively, while Fig. 5c represents the temperature distribution within the CDSSD. At low air flows of 0.01 kg/s (Fig. 5a), the DSSD-AH-ACC exhibits temperature profiles with higher peaks compared to those at high air flows of 0.1 kg/s (Fig. 5b). The reduced convective heat transfer inside both the AH and ACC at low air flows limited thermal dissipation from the components of the DSSD-AH-ACC, resulting in elevated internal temperatures. Conversely, high air flows of 0.1 kg/s (Fig. 5b) noticeably reduced the air exit temperatures from the AH and ACC as a result of the increased heat capacity of the flowing air through them. On the other hand, the CDSSD (Fig. 5c) showed lower overall temperatures compared to the DSSD-AH-ACC. The absence of the auxiliary AH and ACC allowed for greater thermal dissipation to the ambient environment, leading to lower internal temperatures.



**Figure 4:** Influence of uniform air flows through the AH and ACC on the DSSD-AH-ACC performance



**Figure 5:** (Continued)

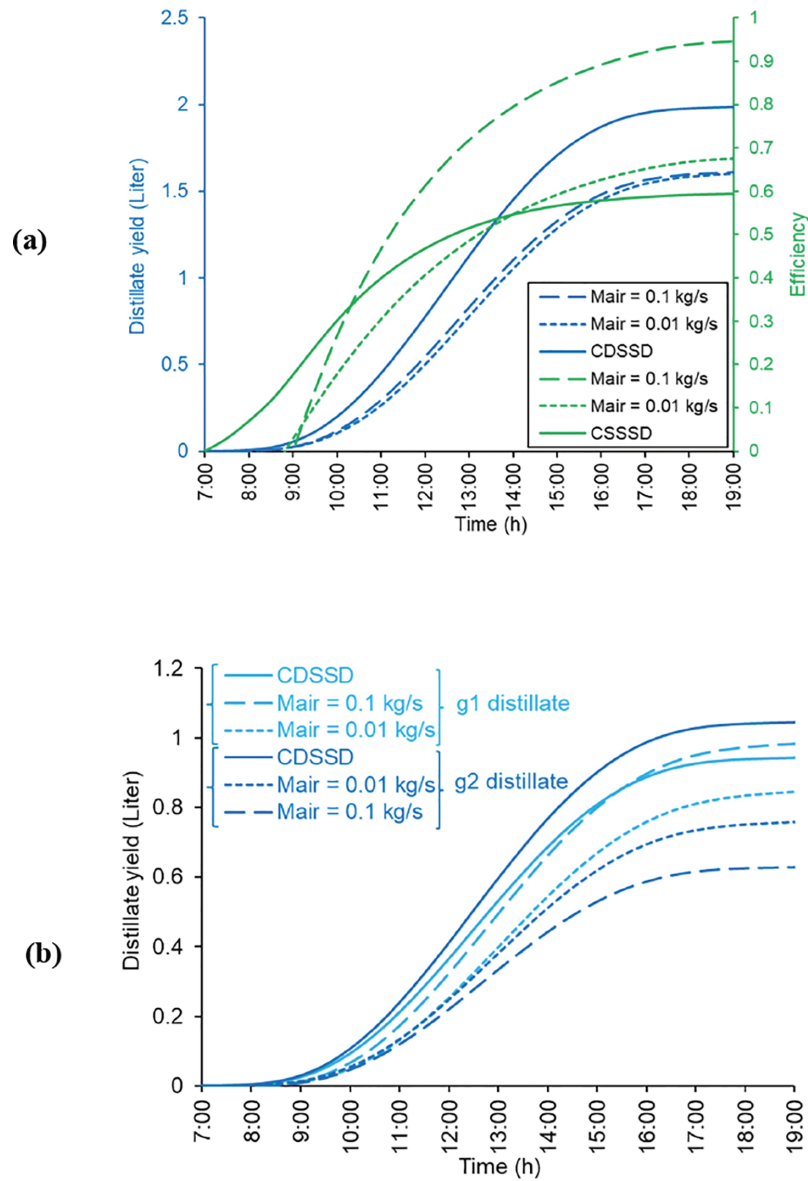


**Figure 5:** Temperature distributions within the DSSD-AH-ACC (a) for 0.01 kg/s air flow, (b) for 0.1 kg/s air flow, and (c) inside the CDSSD

### 3.3 Comparative Thermal Performance and Distillate Yield

Fig. 6 illustrates the temporal evolution of distillate yield and thermal efficiency for the DSSD-AH-ACC under air flow rates of 0.01 and 0.1 kg/s, in comparison with the CDSSD. As shown in Fig. 6a, the DSSD-AH-ACC achieved thermal efficiency improvements of about 14% and 60% at air flows of 0.01 and 0.1 kg/s, respectively, relative to the CDSSD. These gains are primarily attributed to enhanced recovery of thermal losses within the AH and ACC, facilitated by increased air flow and improved convective heat transfer. Despite the higher thermal efficiency, the distillate yield of the DSSD-AH-ACC showed a reduction of about 19% under both air flows when compared to the CDSSD. This decline is attributed to elevated glass cover temperatures ( $g_1$  and  $g_2$ ) in the DSSD-AH-ACC, which surpassed condensation rates on these surfaces relative to the cooler covers of the CDSSD.

Fig. 6b offers detailed insight into the distillate contributions from the  $g_1$  and  $g_2$  covers. In the CDSSD, the  $g_2$  cover is typically cooler than the  $g_1$  cover because of its position on the shaded side of the distiller, while  $g_1$  is directly exposed to solar radiation. This temperature differential favors greater condensation on the  $g_2$  cover compared to  $g_1$ . In contrast, in the DSSD-AH-ACC system, the presence of the AH significantly reduces the solar irradiation reaching the  $g_1$  cover, resulting in a lower temperature than  $g_2$ . Consequently, distillate condensation on  $g_1$  exceeds that on  $g_2$  under all air flows. The greater the airflow through the AH, the greater the distillate condensation on the  $g_1$  cover. Additionally, the rise in distillate yield from  $g_1$  is associated with a corresponding reduction from  $g_2$ , since the total distillate output is primarily governed by the thermal content of the saline water. Nevertheless, the presence of the AH and ACC elevated the temperatures of both  $g_1$  and  $g_2$  covers relative to those of the CDSSD. This temperature increase, in turn, led to lower total distillate yields on both covers of the DSSD-AH-ACC system compared to the CDSSD.

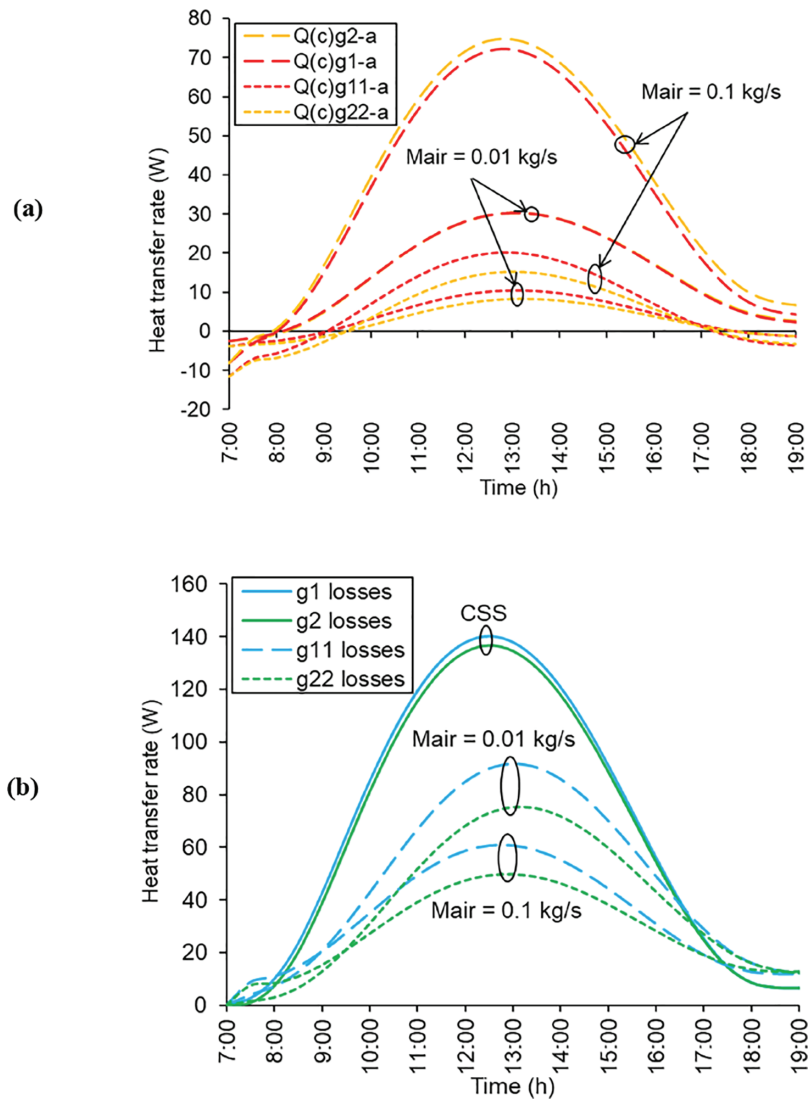


**Figure 6:** DSSD-AH-ACC Overall thermal performance vs. CDSSD: (a) total distillate production, (b) glass covers distillate contributions

### 3.4 Energy Analysis of the Air Heater and Air-Cooled Condenser

Fig. 7a presents a comprehensive energy analysis of the convective heat transfer from the glass covers to the circulating air within the AH and the ACC under varying air flow rates. In general, the heat transfer from the  $g_1$  and  $g_2$  covers to the air, under various air flows, is greater than that from the  $g_{11}$  and  $g_{22}$  covers, primarily due to their higher surface temperatures. In addition, the heat transfer from the  $g_2$  and  $g_{11}$  covers is greater than that from the  $g_1$  and  $g_{22}$ , respectively, under various air flows, again because of their temperatures. Notably, the convective heat transfer from all covers at 0.1 kg/s air flow is approximately twice that at 0.01 kg/s air flow. This enhancement is attributed to the increased thermal capacity and velocity of the circulating air with increased air flow.

Fig. 7b illustrates the combined convective and radiative thermal losses from the  $g_{11}$  and  $g_{22}$  covers in the DSSD-AH-ACC in comparison to those from the  $g_1$  and  $g_2$  covers in the CDSSD. The losses from the  $g_{11}$  and  $g_{22}$  covers, at various air flows, are notably less than those from the  $g_1$  and  $g_2$  covers. This contributes to the superior thermal efficiency of the DSSD-AH-ACC relative to the CDSSD. Additionally, the losses from the  $g_{11}$  and  $g_{22}$  covers decreased with increasing air flow rates as a result of enhanced energy recovery by the circulating air, as stated earlier. Lastly, the losses from the  $g_1$  and  $g_2$  covers are consistently greater than those from the  $g_2$  and  $g_{22}$  covers owing to their higher surface temperatures.



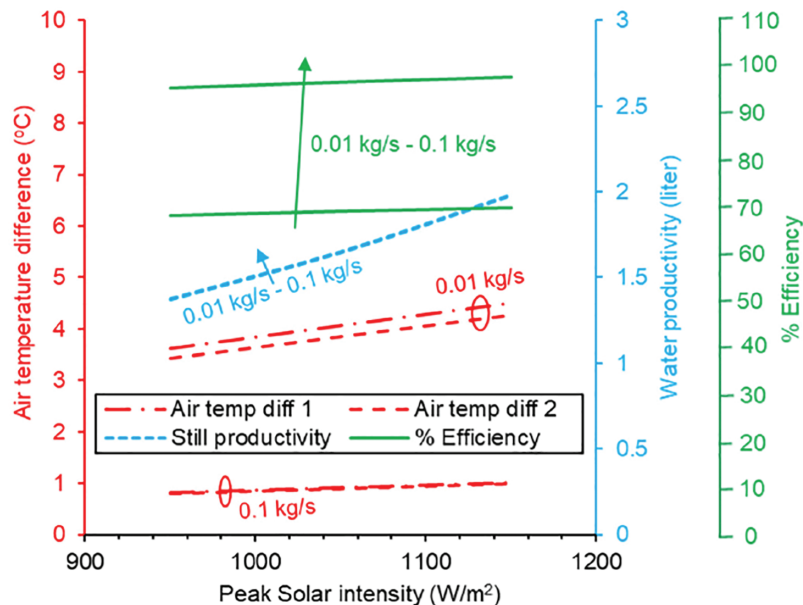
**Figure 7:** Energy analysis of the DSSD-AH-ACC covers (a) heat gain by the air, and (b) heat losses from the covers

### 3.5 Influence of Climate Conditions on System Performance

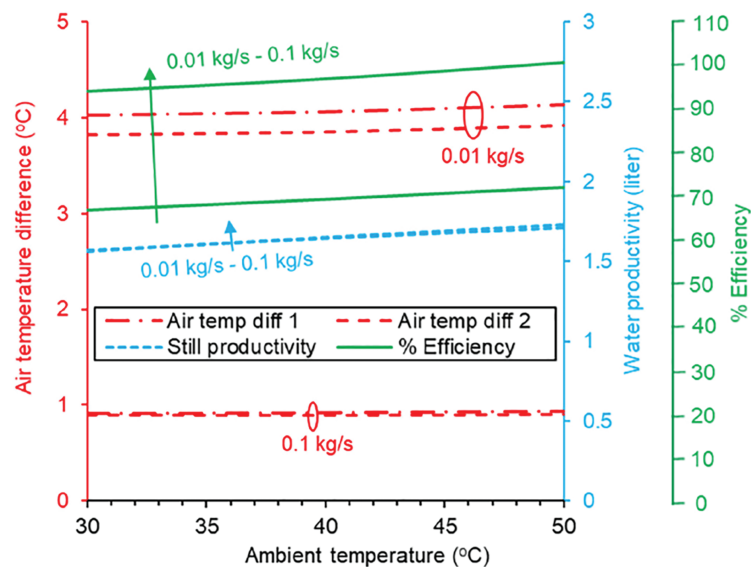
This section examines the influence of climate conditions, including received solar intensity, ambient air temperature, and ambient wind speed, on key performance metrics of the DSSD-AH-ACC, namely water productivity, thermal efficiency, and the temperature difference of air exiting the AH and ACC, under varying air flow rates.

Fig. 8 illustrates the influence of incident solar intensity on key performance metrics of the DSSD-AH-ACC under air flows ranging from 0.01 to 0.1 kg/s. As expected, the increase in the incident solar intensity led to an enhancement in the evaporation within the DSSD-AH-ACC. This, in turn, improved the distillate production and elevated the temperature difference of the air exiting the AH and ACC, and consequently increased the overall thermal efficiency of the DSSD-AH-ACC. Specifically, the increase in solar intensity from 950 to 1150 W/m<sup>2</sup> boosted distillate production by approximately 40%, raised the air temperature difference by about 23%–25%, and thereby improved thermal efficiency by nearly 2.5%. Furthermore, increasing the air flow from 0.01 to 0.1 kg/s enhanced the thermal efficiency by about 40%, even though the air exiting temperature differences dropped to nearly one-quarter and the distillate production remained unchanged. This improvement is attributed to the enhanced convective heat transfer and greater energy recovery by the circulating air, whose thermal capacity increased tenfold as the flow rate increased from 0.01 to 0.1 kg/s.

Ambient air temperature governs thermal losses from the DSSD-AH-ACC to the surrounding environment, thereby determining its overall performance. As the ambient temperature increases, the temperature difference between the DSSD-AH-ACC components and their surroundings decreases, resulting in reduced heat losses and, consequently, improved thermal performance of the DSSD-AH-ACC. Fig. 9 illustrates the impact of ambient air temperature on key performance metrics of the DSSD-AH-ACC across air flows ranging from 0.01 to 0.1 kg/s. Under all air flow conditions, distillate production, thermal efficiency, and the temperature difference of air exiting from the AH and ACC increased with an increase in ambient temperature. Specifically, the efficiency increased by about 7%–8%, the air temperature difference elevated by about 0.5%–3%, and distillate production rose by nearly 9%–10%. These findings reveal that the DSSD-AH-ACC performs more efficiently in hot climates than in cold climates. In addition, the increase in the ambient temperature preserved the 40% enhancement in thermal efficiency and the 75% reduction in air temperature differences as air flow increased from 0.01 to 0.1 kg/s, while the distillate production remained unchanged.

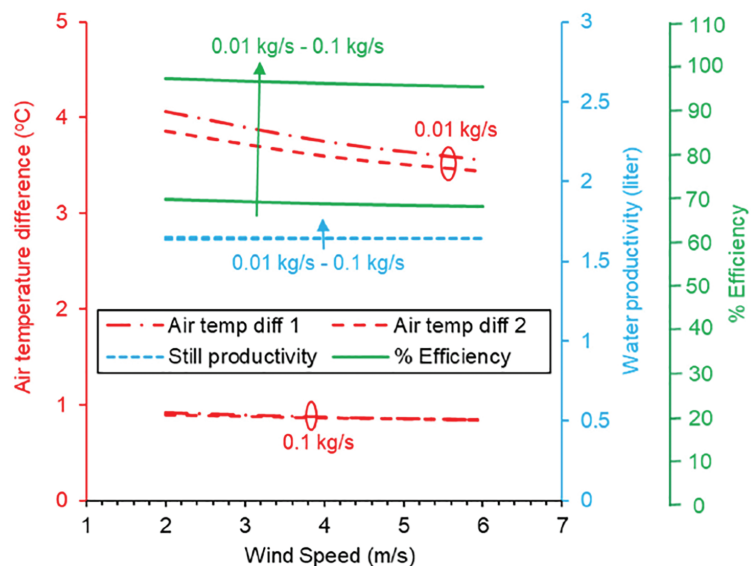


**Figure 8:** Influence of peak solar intensity on the performance of the DSSD-AH-ACC



**Figure 9:** Influence of ambient air temperature on the performance of the DSSD-AH-ACC

Ambient wind speed has a direct impact on convective thermal losses from the DSSD-AH-ACC to the surrounding environment. As wind speed increases, losses from both the AH and ACC rise, reducing thermal losses recoveries by the circulating air through them and thereby worsening the overall thermal performance of the DSSD-AH-ACC. Fig. 10 illustrates this effect across air flows ranging from 0.01 to 0.1 kg/s. When wind velocity increased from 2 to 6 m/s, the temperature difference of the air exiting from the AH and ACC decreased by about 11%–12% under 0.01 kg/s air flow and by about 6%–8% under 0.1 kg/s air flow. Consequently, thermal efficiency declined by nearly 2% although distillate production remained unaffected. Remarkably, the rise in wind velocity maintained the 40% improvement in thermal efficiency and the 75% reduction in air temperature differences achieved by increasing air flow from 0.01 to 0.1 kg/s, while the distillate production remained unchanged.

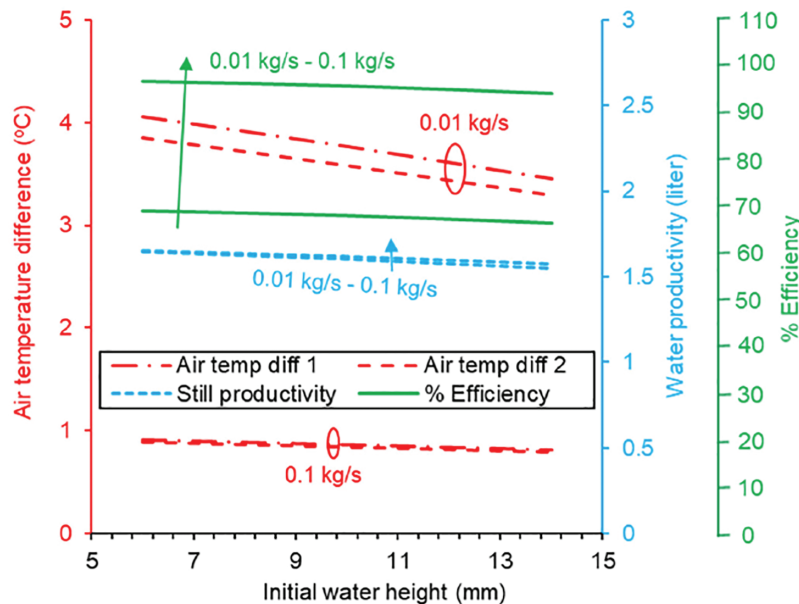


**Figure 10:** Influence of ambient wind speed on the performance of the DSSD-AH-ACC

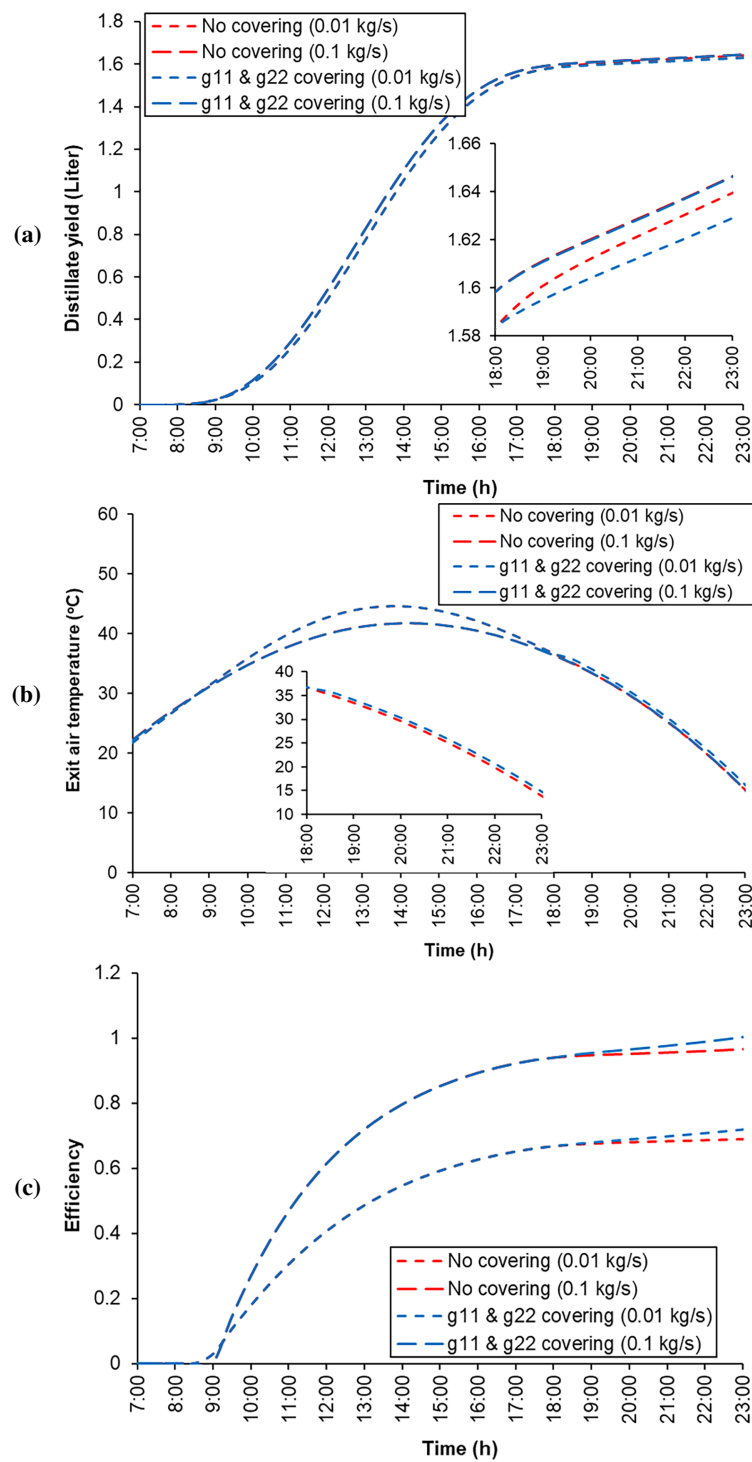
### 3.6 Influence of Operational Conditions on System Performance

The initial saline water mass directly regulates the temperature difference between the saline water and the distiller covers by governing the saline water temperature, and thereby influencing distillate production. Fig. 11 shows the impact of varying the initial saline water height, from 6 to 14 mm, on the performance metrics of the DSSD-AH-ACC under air flows ranging from 0.01 to 0.1 kg/s. Increasing the initial saline water height in the distiller basin reduced distillate production by about 4.5%–6%, the air temperature difference at the exit from the AH and ACC by about 11%–15%, and thermal efficiency by about 3%–4%. Consistent with earlier findings, increasing air flow from 0.01 to 0.1 kg/s sustained the 40% improvement in thermal efficiency and the 75% reduction in air temperature differences, for various water heights, while the distillate production remained unaffected.

Minimizing thermal losses from the DSSD-AH-ACC glass covers to the ambient surroundings during off-sun hours can improve the DSSD-AH-ACC performance. This can be achieved by covering the  $g_{11}$  and  $g_{22}$  glass covers with insulation boards after sunset to preserve residual heat. Fig. 12 compares the performance of the DSSD-AH-ACC with and without insulation covering during off-sun hours under air flows of 0.01 and 0.1 kg/s. With insulation covering, distillate production (Fig. 12a) decreased by nearly 1% under 0.01 kg/s air flow, while it remained unchanged at 0.1 kg/s. The average temperature of the air exiting the AH and ACC (Fig. 12b) increased by about 9% under 0.01 kg/s and 1% under 0.1 kg/s air flow. As a result, thermal efficiency (Fig. 12c) improved by approximately 5% under 0.01 kg/s and 4% under 0.1 kg/s air flow.



**Figure 11:** Effect of saline water initial height on the performance of the DSSD-AH-ACC



**Figure 12:** Influence of glass covering during off-sun hours on the performance of the DSSD-AH-ACC: (a) distillate production, (b) hot air temperature difference, and (c) thermal efficiency

### 3.7 Comparison with Passive DSSDs Reported in the Literature

Table 1 compares the distillate production and thermal efficiency of the DSSD-AH-ACC with those of the most recent passive DSSDs reported in the literature. The distillate production of the DSSD-AH-ACC lies within the range documented for other DSSDs, despite its relatively simple design compared to most DSSDs included in the table. Notably, the DSSD-AH-ACC demonstrated the highest thermal efficiency among all listed DSSDs, as well as among related DSSDs [27–29] that employed the concept of recovering the inevitable heat losses from the distiller in auxiliary air or water heating.

**Table 1:** A comparison between the DSSD-AH-ACC and various passive DSSDs

| DSSD configuration                                             | Distillate yield<br>(Liter/m <sup>2</sup> .day) | Efficiency<br>(%) |
|----------------------------------------------------------------|-------------------------------------------------|-------------------|
| DSSD + PCM + steel wool fibre [26]                             | 3.4                                             | 38%               |
| DSSD + fin + wick + PCM + external condenser [30]              | 3                                               | 40%               |
| DSSD + raised basin [24]                                       | 4.3                                             | 40%               |
| Stepped DSSD + linen wicks [21]                                | 3.3                                             | 41%               |
| DSSD + nano-enhanced PCM [31]                                  | 4.2                                             | 49%               |
| Prismatic basin DSSD + linen wicks + glass cooling [18]        | 8.2                                             | 49%               |
| DSSD + parabolic finned basin [32]                             | 1.7                                             | 53%               |
| DSSD + black wick + gravel + carbon black + glass cooling [10] | 4.9                                             | 60%               |
| DSSD + water heater condenser [28]                             | 4                                               | 59%–63%           |
| DSSD + solar air heater [29]                                   | 3.5                                             | 58%–67%           |
| DSSD + air heater condenser [27]                               | 4                                               | 67%–76%           |
| DSSD-AH-ACC (This study)                                       | 3.3                                             | 69%–97%           |

## 4 Conclusions

A novel DSSD-AH-ACC was designed by replacing the north- and south-facing covers of a conventional DSSD with glass AH and ACC to recover thermal losses to the ambient surroundings. The thermal performance of the DSSD-AH-ACC was mathematically evaluated under varying air flow rates and real weather conditions in Al-Jouf, KSA. Simulation results revealed that the DSSD-AH-ACC performance responded directly to increases in air flow through both the AH and ACC. The DSSD-AH-ACC, under air flows of 0.01–0.1 kg/s, was 14%–60% more efficient than a CDSSD of the same size, despite an 18% reduction in distillate production. In addition, increasing air flow from 0.01 to 0.1 kg/s improved the efficiency of the DSSD-AH-ACC by about 40%. Hot climate conditions with high solar irradiance and elevated ambient temperature significantly enhanced the performance of the DSSD-AH-ACC, while windy weather conditions negatively impacted its performance. Increasing the initial saline water mass in the basin of the DSSD-AH-ACC worsened its performance, whereas insulating the glass covers during off-sun hours improved the thermal efficiency by about 4%–5%.

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**Availability of Data and Materials:** The data that support the findings of this study are available from the corresponding author, [AG], upon reasonable request.

**Ethics Approval:** Not applicable.

**Conflicts of Interest:** The author declares no conflicts of interest to report regarding the present study.

## Nomenclature

|     |                                |
|-----|--------------------------------|
| $A$ | Area                           |
| $C$ | Specific heat                  |
| $F$ | Radiation view factor          |
| $h$ | Heat/mass transfer coefficient |
| $H$ | Latent heat of evaporation     |
| $I$ | Solar Irradiance intensity     |
| $k$ | Thermal conductivity           |
| $L$ | Thickness                      |
| $m$ | Mass                           |
| $P$ | Partial pressure               |
| $Q$ | heat transfer rate             |
| $S$ | Absorbed solar radiation       |
| $T$ | Temperature                    |
| $t$ | Time                           |

## Greek Letters

|               |                           |
|---------------|---------------------------|
| $\alpha$      | Surface absorptivity      |
| $\varepsilon$ | Surface emissivity        |
| $\eta$        | Efficiency                |
| $\sigma$      | Stefan-Boltzmann constant |
| $\tau$        | Surface transmissivity    |

## Subscripts

|                       |                          |
|-----------------------|--------------------------|
| $a$                   | Air                      |
| $amb$                 | Ambient environment      |
| $b$                   | Basin                    |
| $C$                   | Convection heat transfer |
| $Cd$                  | Conduction heat transfer |
| $e$                   | Evaporation              |
| $g, g1, g11, g2, g22$ | Glass cover              |
| $AH$                  | Air heater               |
| $i$                   | Basin insulation         |
| $o$                   | Initial state            |
| $op$                  | Operation duration       |
| $R$                   | Radiation heat transfer  |
| $sky$                 | Sky temperature          |
| $dist$                | Solar distiller          |
| $sun$                 | day time                 |
| $sw$                  | Saline water             |
| $yield$               | Water distillate         |

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