

Enhancing Solar Still Efficiency with Film Cooling and Flat Plate Collector: A Numerical Study

Reda Aftiss¹ , **Monssif Najim^{1,2}** , **Taoufik Tbatou¹** .

¹ Laboratory of engineering Sciences and Biosciences (LSIB), Faculty of science and technology, Hassan II University of Casablanca, Mohammedia, Morocco.

² GEMS Laboratory, ENSA, Ibn Zohr University, Agadir, Morocco.

E-mail: reda.aftiss-etu@etu.univh2c.ma

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ABSTRACT

This study presents a numerical investigation of a solar desalination system enhanced with water film cooling and a flat plate collector. Solar still systems are increasingly recognized as effective solutions for reducing reliance on conventional energy sources in water treatment and for addressing the growing challenge of water scarcity. To this end, three system configurations are analyzed and compared: a conventional solar still (CSS), a solar still with film cooling (SSC), and a solar still incorporating both film cooling and a flat plate collector (SSP). Simulations are carried out under the climatic conditions of Errachidia, Morocco (latitude: 31.91°, longitude: -4.42°). The results demonstrate notable performance enhancements, with daily freshwater yields of 3.48, 4.51, and 8.45 kg/m²·day for CSS, SSC, and SSP, respectively.

*Corresponding author.



تعزير كفاءة المقطر الشمسي باستخدام تقنية تبريد الزجاج والمجمع الشمسي المسطح: دراسة عدديّة

رضا أفتيس، منصف ناجيم، توفيق أتباتو

ملخص: تقدم هذه الورقة البحثية دراسة عددية لتحسين أداء المقطر الشمسي التقليدي عن طريق تبريد الغطاء الخاص به، إضافة إلى استعمال مجمع الطاقة الشمسية المسطح. حيث تعتبر المقطرات الشمسية واحدة من أهم الحلول للتقليل من ارتباطنا بالأنظمة التي تعتمد على الطاقات غير متجددة. بالإضافة إلى ذلك فهي تلعب دوراً محورياً في معالجة مشكل ندرة المياه. لهذا الغرض، تمت مقارنة ثلاثة أنظمة وهي كالتالي: المقطر الشمسي التقليدي، المقطر الشمي التقليدي مع تبريد الزجاج، والمقطر الشمسي مع التبريد والربط بمجمع الطاقة الشمسية المسطح. تمت إجراء الدراسة تحت الظروف المناخية لمدينة الراشيدية، بالمغرب (خط العرض: 31.91 درجة، خط الطول: -4.42). النتائج أظهرت تحسن ملحوظ في أداء المقطر الشمسي التقليدي، حيث سجلت الإنتاجية القيم التالية: 3.48، 4.51 و 8.45 كغ/متر مربع، بخصوص المقطر العادي، المقطر مع التبريد، المقطر مع المجمع والتبريد، على التوالي.

الكلمات المفتاحية: - جهاز التقطير الشمسي، المجمع الشمسي، سائل التبريد، المياه العذبة.

1. INTRODUCTION

The integration of renewable energy into clean water production is considered a promising solution. In particular, the use of solar energy for freshwater production has emerged in recent years as a widely adopted alternative to conventional fossil fuel-based sources. Various desalination technologies exist, including membrane techniques, chemical methods, and thermal processes. The integration of solar energy as a primary energy source for these technologies is becoming increasingly viable. In this regard, Mundu et al. [1] present a detailed review of various solar-powered water purification techniques. Furthermore, Davies et al. [2] concluded that small-scale desalination systems, such as reverse osmosis units powered by solar energy, provide a valuable solution, particularly in areas affected by conflict and instability where electricity supply is often interrupted or damaged. In addition, the solar still (Fig. 1), as one of the solar thermal desalination methods, offers a practical and cost-effective approach. Its low investment cost makes it suitable for meeting drinking water needs in an environmentally sustainable manner. However, the output of a conventional solar distillation system is relatively low. Therefore, combining it with an external renewable energy source to supply additional thermal energy is highly recommended. In this context, Badran et al. [3] improved the efficiency of a solar still by integrating it with a flat plate collector (FPC). The results revealed a notable improvement in the productivity of the conventional system, with a substantial increase of 231% when tap water was used as the feed water. Dwivedi and Tiwari [4] conducted a numerical validation of a dual-slope solar still connected to a vacuum tube collector (ETC). The thermal modeling demonstrated strong agreement with the experimental findings, and an enhancement in the total yield from 1838 to 2790 g/m² was observed. Additionally, Singh et al. [5] examined the efficiency of a solar still combined with a vacuum tube collector (ETC). Their study primarily aimed to optimize the saline water depth and the number of collector tubes. The findings showed that the most productive daily output was achieved at a water depth of 0.03 m with 10 vacuum tubes. Furthermore, Mevada et al. [6] experimentally improved the efficiency of a solar still by incorporating an innovative air-

evacuated system with a zigzag configuration and coupling it with an ETC device. A significant enhancement was achieved, increasing the daily freshwater yield of the basic system by 73.45%. Similarly, Shoeibi et al. [7] conducted an experimental analysis of a solar still combined with an evacuated heat pipe and an external condenser. The findings indicated that the upgraded solar still, incorporating the proposed enhancements, increased output by a factor of 2.13 compared to the benchmark model. Moghadam et al. [8] suggested using an evacuated tube as an absorber, with a cube-shaped glass condenser installed to collect the distilled water. In addition, parametric optimization was performed using the response surface methodology (RSM). The results revealed that a combination of a 2940 cm³ cube volume, a 3360 cm² condenser surface area, and a 4 mm cover thickness achieved the highest productivity of 7.231 kg/m². Moreover, Panchal et al. [9] investigated the effectiveness of calcium stones as a sensible heat storage medium in combination with an evacuated tube collector. The daily yield of the modified solar still was 5.31 L, representing an improvement of approximately 113.52% over the conventional type. A parabolic-trough collector (PTC) equipped with an ETC filled with PCM was also incorporated to improve the performance of the solar still [10]. Furthermore, the effect of the heat transfer fluid type (water, oil, or nanofluid) and water depth was investigated. The modified solar still demonstrated a significant enhancement in freshwater yield, achieving a 250% increase over the conventional system. Bhargava et al. [11] studied the effect of shading (with cotton), cooling the glass cover, and coupling the system with an ETC. The results revealed that partially shading the glass cover (up to half its surface), combined with cooling and an ETC, enhanced the efficiency of the conventional still by approximately 3.8%. Additionally, Shehata et al. [12] performed an experimental investigation on the effect of implementing ultrasonic humidifiers, phase change materials (PCM), and coupling the system with an ETC. The findings showed that the conventional type, including all modifications, achieved the highest productivity of 5.24 kg. Moreover, Ayoobi and Ramezanizadeh [13] presented a review of recent advancements in solar stills integrated with flat plate collectors. In addition to using an external energy source, cooling the glazing surface is regarded as a promising approach for improving the con-densation rate of water vapor. Zeroual et al. [14] experimentally investigated the effect of the glass cooling technique affects the efficiency of a dual-slope solar still. Their findings revealed an improvement in daily fresh-water yield of approximately 11.82% compared to the traditional system. Morad et al. [15] enhanced the performance of CSS by implementing two modifications: cooling the glass cover and integrating a flat plate collector as an external heat source. The obtained findings demonstrated a significant improvement in the system's productivity, from 6.38 to 10.06 l/m². Abu-Arabi et al. [16] conducted a comprehensive investigation on a solar distiller improved by cooling the glass cover, using phase change material, and integrating of FPC as an external energy source. The outcomes of the theoretical study demonstrated that implementing these improvements increased the total yield by approximately 2.3 times compared to a solar still utilizing only film cooling. Shoeibi and colleagues [17] performed an experimental investigation on a dual-slope distiller that integrates glass cooling and water heating using a thermoelectric resistance. Their results indicated that the efficiency of the system was enhanced by approximately 1.67 times. Given that graphite is distinguished by its high thermal conductivity and ability to store energy in sensible form [18]. Kabeel and Abdelgaied [18] performed an experimental investigation on

a pyramid solar distiller equipped by a cooling cover and a graphite absorber. The total daily yield of the traditional pyramid distiller and the upgraded one was 4.43 and 9.19 L/m², respectively. Khan et al. [19] applied a cooling technique to a hemispherical solar still, producing an improvement in energy efficiency from 34% to 42%. Similarly, Attia et al. [20] improved the efficiency of a hemispherical solar distiller by utilizing a thin film over the transparent cover. In addition, they incorporated a wick absorber material to further improve the system's productivity. They concluded that the modified solar distiller improved the fresh water production by approximately 69.23%. Furthermore, Omara et al. [21] and Elsheikh et al. [22] presented in their review paper the advancements and the various technologies for cooling the glass cover. The literature review demonstrates that the integration of external energy sources such as FPC, PV/T, etc., with solar still extensively contribute in the enhancement of the system's performance. Furthermore, various economic, environmental, enviroeconomic, and exergoeconomic analyses of solar stills have been conducted to evaluate their impact on CO₂ mitigation and cost per liter compared to other technologies. Thus, An energy, exergy, economic, and environmental analysis of a solar still integrated with a cooling cover was thoroughly investigated by Shatar et al. [23]. In this study, the integration of a partially coated glass cover and a thermoelectric cooler (TEC) was examined. The results indicate that the yield of the conventional system could be increased by approximately 129%. Additionally, the modified solar still achieved a lifetime CO₂ emission reduction of 2.97 tonnes, and the cost per liter of distilled water was USD 0.036, the lowest among the compared systems, including the reference system and the solar still with a TEC of 12 W. Furthermore, Kaviti et al. [24] conducted a comprehensive analysis of the energy, exergy, economic, and environmental performance of solar stills integrated with magnets and finned absorbers. Two configurations were examined experimentally: a solar still equipped with magnets and parabolic-shaped fins, and another with magnets and truncated fins. The results revealed that the system with parabolic-shaped fins achieved a 20.9% lower cost per liter compared to the truncated fin configuration, demonstrating superior cost-effectiveness. Furthermore, Aftiss et al. [25] investigated the effect of integrating a dynamic phase change material (PCM) layer to enhance thermal performance. Three solar still configurations were studied and compared: a conventional solar still, a solar still with fixed PCM, and a solar still with mobile PCM. The results revealed that CO₂ mitigation was highest with the solar still using mobile PCM, reaching 27.4 tones. Dhivagar et al. [26] enhanced solar still productivity by using magnetic powder as an energy storage medium. They also conducted an exergy and environmental analysis. The findings revealed that CO₂ reduction increased by approximately 43% compared to conventional systems.

This research paper presents a numerical analysis of a conventional solar still enhanced by cooling the glass cover and integrating a flat plate collector. Three cases are examined and compared numerically: a conventional solar still (CSS), a solar still with film cooling (SSC), and a solar still combining glass cooling and a flat plate collector (SSP).

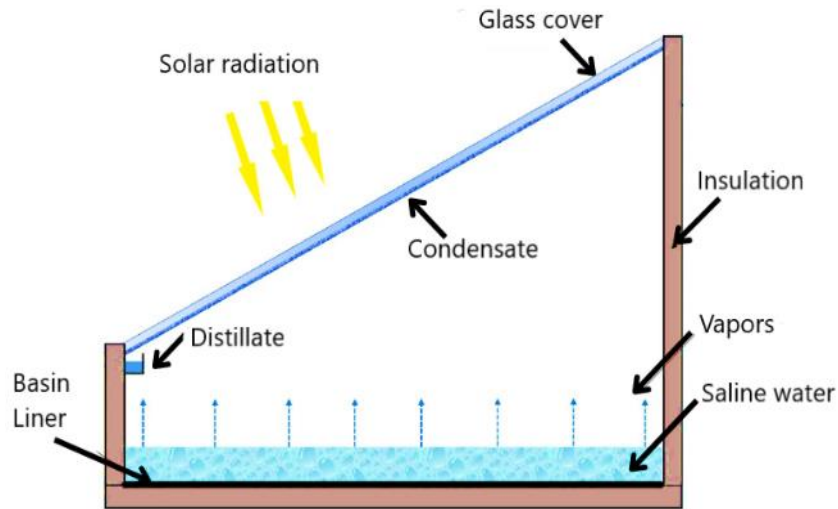


Figure 1. Conventional solar still

2. SYSTEM DESCRIPTION

The working principle of a solar still relies on the key concepts of evaporation and condensation. As illustrated in Figure 1, solar energy is absorbed by the absorber plate, which raises the temperature of the brackish water and generates water vapor. This vapor condenses on the inner layer of the glass cover, and the resulting droplets move downward under gravity to be collected in a storage tank. Figure 2 provides a comprehensive schematic of the present study. The conventional setup is integrated with a flat-plate collector via a pump, supplying heated water to the solar still. Additionally, a cooling system is installed above the transparent cover to enhance condensation yield.

The three solar stills are numerically studied under the same conditions. It is important to note that the solar stills have identical geometries. Table 1 presents the main parameters of the solar stills used in this investigation.

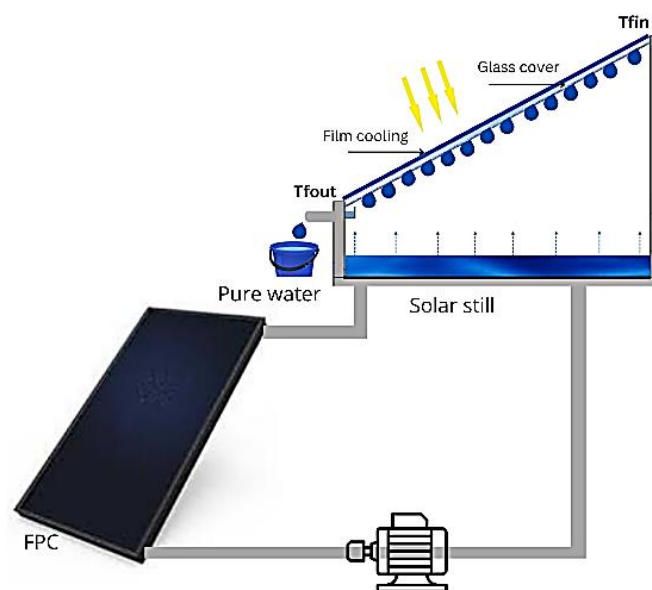


Figure 2. Solar still with flat plate collector and cooling glass cover.

Table 1. Physical properties of solar still

Parameter	Value
A_w	1.0 m ²
A_b	1.0 m ²
C_w	4190 J/kg K
C_g	800 J/kg K
C_b	896 J/kg K
α_w	0.05
α_p	0.95
α_b	0.4
e_g	0.88
e_w	0.96
t_g	0.95
S	$5.669 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$
m_w	20 kg
U_b	14 W/m ² .K

3. MATHEMATICAL MODEL

This numerical simulation compares three configurations of solar stills (CSS, SSC, SSP) to investigate the effects of glass cover cooling and integration of a flat plate collector. The study determines the productivity of each system by formulating and solving thermal balance equations for each component of the solar still, including the glass cover, brackish water, absorber plate, and water film cooling system. The equations were solved considering these assumptions:

- The thickness for the cooling fluid was considered thin; therefore, the solar energy absorbed through the film is negligible.
- The solar distiller still is well-sealed; thus, it is impermeable to vapor leakage.
- The brackish water thickness is considered constant.

3.1. Conventional solar still

- Energy balance for the absorber [25]:

$$\frac{m_b C_b}{A_b} \frac{dT_b}{dt} = q_{ib} - q_{cwb} - q_{pb} \quad (1)$$

- Energy balance for brackish water [25]:

$$\frac{m_w C_w}{A_w} \frac{dT_w}{dt} = q_{iw} + q_{cwb} - q_{rwg} - q_{ewg} - q_{cwg} \quad (2)$$

- Energy balance for the glass cover [27]:

$$\frac{m_g C_g}{A_g} \frac{dT_g}{dt} = q_{ig} + q_{cwg} + q_{rwg} + q_{ewg} - q_{cga} - q_{rga} \quad (3)$$

3.2. Solar still with film cooling

For the SSC case, the governing equations for the water and absorber plate are similar to those for the CSS case. Therefore, only the equations for the glass cover and water are presented.

- Energy balance for film cooling [28]:

$$\frac{m_f C_f}{A_f} \frac{dT_f}{dt} = m_{rf}(T_{f1} - T_{f2}) + q_{cwf} - q_{rf} - q_{cfa} \quad (5)$$

- Energy balance for the glass cover [28]:

$$\frac{m_g C_g}{A_g} \frac{dT_g}{dt} = q_{ig} + q_{cwg} + q_{rwg} + q_{ewg} - q_{cwf} \quad (4)$$

3.3. Solar still with film cooling and FPC

In this section, the energy balance equations are similar to those of the SSC system, except for the saline water equation, which includes additional energy input from the flat plate collector (FPC). By incorporating the term representing the thermal energy received from the FPC, the energy balance equation for brackish water is expressed as follows [31].

$$\frac{m_w C_w}{A_w} \frac{dT_w}{dt} = q_{iw} + q_u + q_{cwb} - q_{rwg} - q_{ewg} - q_{cwg} \quad (6)$$

3.4. Productivity and energy efficiency

The hourly productivity and average energy efficiency of SSP and CSS are determined using the following expressions [29]:

$$\dot{m} = \frac{h_{ewg} \times (T_w - T_g) \times 3600}{L_{ev}} \quad (7)$$

$$\eta = \frac{\sum m \times L_{ev}}{3600 \times A_b \times \sum I(t)} \quad (8)$$

For a solar distiller coupled to a flat-plate collector, both the energy supplied by the pump and the useful energy from the FPC are considered. Consequently, the thermal efficiency is expressed by the following equation [16]:

$$\eta = \frac{\sum m \times L_{ev}}{3600 \times (A_b \times \sum I(t) + Q_u + P_{pum})} \quad (9)$$

4. NUMERICAL SIMULATION

4.1. Numerical method

The energy balance equations (1–6) describing the heat transfer of solar stills are solved numerically using the 4th-order Runge-Kutta method. A code developed in Fortran 90 is used in this study. At each one-second time step, the energy equations are solved, and parameters such as temperatures and heat transfer rates are estimated and used in the subsequent time step. The calculations continue until the desired simulation time is reached. The flow chart in Figure 3 presents the various steps followed during the computation.

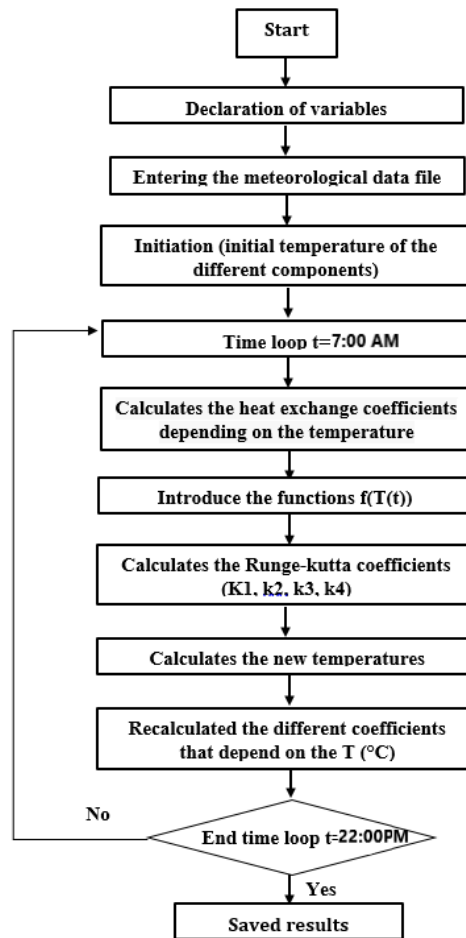


Figure 3. Flowchart illustrating the steps involved in the numerical modelling process.

4.2. Numerical method

To ensure the reliability and accuracy of the results, the present study is validated against the theoretical and experimental results reported in previous studies [29, 30]. The results show good agreement with the published data. Figure 4 compares the absorber temperature and hourly productivity with the experimental results of Agrawal et al. [29]. Figure 5 shows the validation against the theoretical results of El-Sebaili et al. [30].

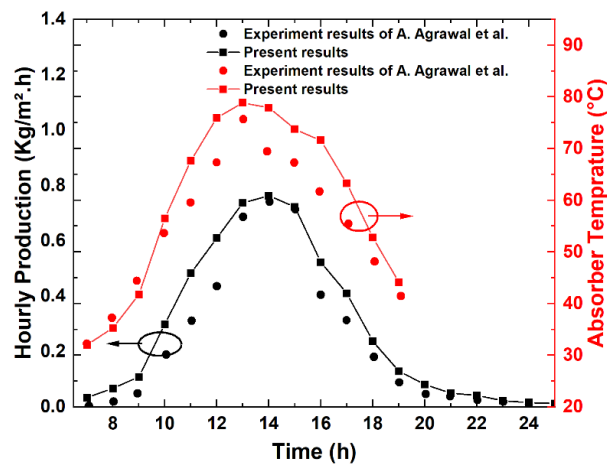


Figure 4. Validation of the numerical model against experimental data [29].

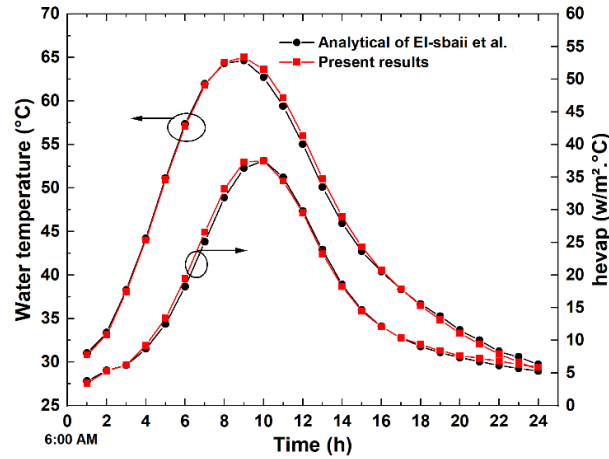


Figure 5. Validation of the numerical simulation with analytical data [30].

5. RESULTS AND DISCUSSION

This study provides a detailed comparison of three distinct solar still systems: CSS, SSC, and SSP. It focuses on improving the performance of the conventional system by increasing the temperature of saline water while reducing the glass temperature, thereby enhancing the temperature gradient and boosting the evaporation process. Specifically, the study examines the effects of glass cover cooling and the integration of a flat plate collector on the solar still systems. Table 2. Meteorological data of a typical summer day in Errachidia city, Morocco.

Table 2. Meteorological data of a typical summer day in Errachidia city, Morocco.

Time (h)	Ta (°C)	I (t)	Vw (m/s)
7 :00	30	19.7	2
8:00	31.41	105.04	1.93
9:00	36.45	300.23	1.79
10:00	38.14	516.69	1.24
11:00	38.84	613.28	1.31
12:00	39.36	831.46	2.14
13:00	40.11	936.79	2.97
14:00	40.65	971.22	3.52
15:00	41.65	881.23	3.72
16:00	42.28	751.07	3.79
17 :00	41.86	570.4	3.86
18 :00	39.62	340.53	3.45
19 :00	35.99	158.48	2.9
20 :00	33.68	32.23	2.34
21 :00	30.95	0	1.45
22 :00	26.09	0	0.76

5.1. Water temperature

Figure 6 depicts the hourly variation in water temperature for the cases under investigation. The temperature rises gradually over time, reaching peak values around noon, after which the water temperature begins to decline. The graph demonstrates that the temperature variations closely follow the solar radiation profile. In the initial hours of operation, the water temperature of the SSP is higher, highlighting the effect of the energy supplied by the FPC. Afterward, the

conventional system surpasses the SSP and remains higher until the end of the day. This is attributed to the cooling film effect, which reduces the water temperature through convective heat transfer between the glass and the water. The maximum temperatures recorded are approximately 64.46°C for CSS, 51.61°C for SSC, and 61.07°C for SSP.

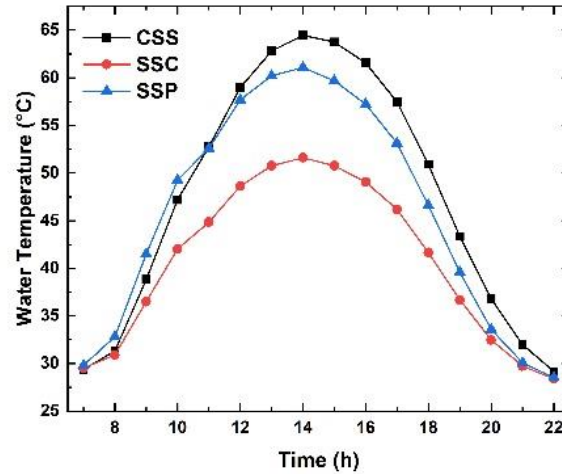


Figure 6. Hourly variation of glass temperature.

5.2. Cumulative productivity

The freshwater productivity of solar distillation systems is an important indicator for **evaluating the system's performance**. The implemented modifications to the traditional solar distiller significantly enhanced its daily productivity. The integration of water film cooling considerably increased the temperature difference between the glass cover and the water basin, consequently improving the system's output. Moreover, integrating the system with a flat plate collector raised the water temperature, which in turn enhanced the evaporation rate. The daily productivity of CSS, SSC, and SSP is 3.48, 4.48, and 8.45 kg/m²·day, respectively.

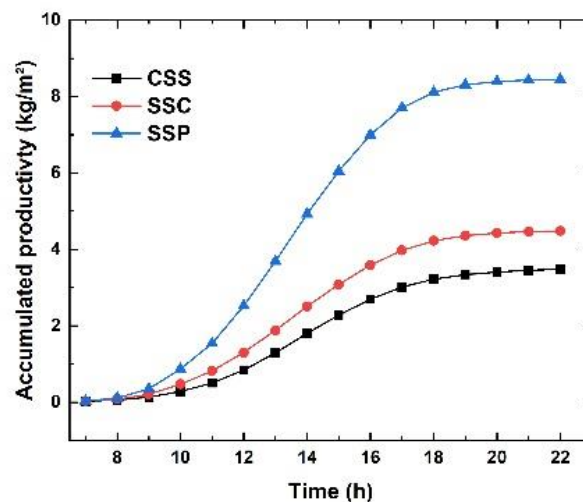


Figure 7. Accumulated productivity of solar stills.

5.3. Energy efficiency

The energy efficiency of the solar desalination system was calculated based on its daily productivity and the total energy received. Figure 8 illustrates the average thermal performance

of the three distillation systems. The findings indicate that SSP exhibits the highest efficiency at 47.57%, followed by SSC at 43.56%, and CSS at 35.2%.

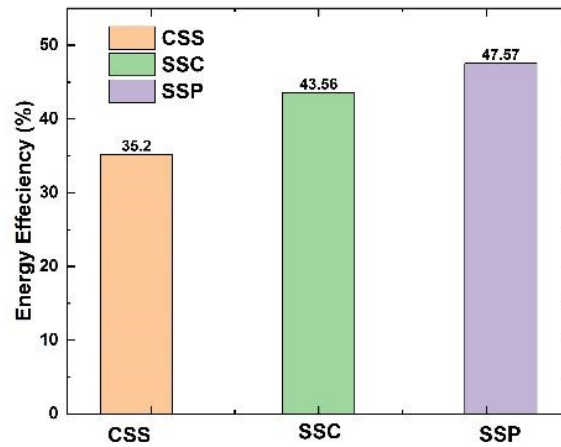


Figure 8. Energy efficiency of solar stills.

6. CONCLUSION

The present investigation aimed to enhance the productivity of a conventional solar still (CSS) by implementing a water film cooling technique and coupling the system with a flat plate collector (FPC). Based on numerical analysis, the following conclusions can be drawn:

- The daily productivity of CSS, SSC (solar still with cooling), and SSP (solar still with cooling and FPC) was found to be 3.48, 4.48, and 8.45 kg/m²-day, respectively.
- A productivity enhancement of 28% was achieved using film cooling alone, while a remarkable 142% increase was observed when combining film cooling with the FPC.
- The average energy efficiency for CSS, SSC, and SSP was found to be 35.2%, 43.56%, and 47.74%, respectively, confirming the benefits of external energy integration.

These results demonstrate that integrating of the passive and active techniques can substantially enhance both the efficiency and freshwater yield of solar distillation systems.

APPENDIX E:

It should describe the meaning of the results, especially in the framework of the subject. It should include general and specific conclusions but not the summary of the article.

- The heat flux delivered by the flat plate collector is can write as follows [31]:

$$q_u = A_c Fr (\alpha_p \tau_G G - U_{collector} (T_w - T_a))$$

- The heat flux expressions in solar still [27]

$$q_{ig} = (1 - R_g) \times \alpha_g \times I(t)$$

$$q_{c,wg} = h_{c,w-g} (T_w - T_g)$$

$$q_{r,wg} = h_{r,w-g} (T_w - T_g)$$

$$\begin{aligned}
q_{e,wg} &= h_{e,w-g}(T_w - T_g) \\
q_{c,ga} &= h_{c,g-a}(T_g - T_a) \\
q_{r,ga} &= h_{r,g-a}(T_g - T_{sky}) \\
q_{iw} &= (1 - \alpha_g)(1 - R_g)(1 - R_w) \times \alpha_w \times I(t) \\
q_{c,wb} &= h_{c,w-b}(T_b - T_w) \\
q_{ib} &= (1 - \alpha_g)(1 - R_g)(1 - R_w)(1 - \alpha_w) \times \alpha_b \times I(t) \\
q_{p,b} &= U_b(T_b - T_a)
\end{aligned}$$

Nomenclature

\dot{m}_h	Mass flow rate of the hot fluid coming from the solar collector.	(kg/s)
A	Area.	(m^2)
D_c	Diameter of solar collector tubes.	(m)
F_r	Heat removal factor for the solar collector.	(dimensionless)
K_w	Thermal conductivity of brackish water.	($W \cdot m^{-1} \cdot ^\circ C^{-1}$)
L_{ev}	Latent heat of vaporization of water.	($J \cdot kg^{-1}$)
P_g	Partial saturated vapour pressure at glass cover temperature.	($N \cdot m^{-1}$)
P_w	Partial saturated vapour pressure at a basin water temperature.	($N \cdot m^{-1}$)
m_w	Weight of water.	(Kg)
$U_{collecto}$	Overall heat loss coefficient of the solar collector.	(W/m ² K)
$h_{c,ga}$	Convective heat transfer coefficient from glass cover to ambient.	($W \cdot m^{-2} \cdot ^\circ C^{-1}$)
$h_{c,wb}$	Convective heat transfer coefficient from basin liner to water.	($W \cdot m^{-2} \cdot ^\circ C^{-1}$)
$h_{c,wg}$	Convective heat transfer coefficient from basin water to glass cover.	($W \cdot m^{-2} \cdot ^\circ C^{-1}$)
$h_{e,wg}$	Evaporative heat transfer coefficient from basin water to glass cover.	($W \cdot m^{-2} \cdot ^\circ C^{-1}$)
$h_{r,ga}$	Radiative heat transfer coefficient from glass cover to ambient.	($W \cdot m^{-2} \cdot ^\circ C^{-1}$)
$h_{r,wg}$	Radiative heat transfer coefficient from basin water to glass cover.	($W \cdot m^{-2} \cdot ^\circ C^{-1}$)
h_{wt}	Heat transfer coefficient for water inside the collector tubes.	(W/m ² K)
F	Fin efficiency.	(dimensionless)
F'	Fin efficiency factor for the solar collector.	(dimensionless)
w	Spacing between solar collector tubes.	(m)
v_w	Wind velocity.	($m \cdot s^{-1}$)

Authors contribution: Conceptualization: Reda Aftiss; Methodology: Reda Aftiss; Project administration: Monssif Najim; Supervision: Monssif Najim, Taoufik Tbatou; Writing-original draft: Reda Aftiss; Writing-review & editing: Monssif Najim, Taoufik Tbatou.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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