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Assessment of the exergy efficiency of a combined multi-stage solar water desalination device

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Abstract

This article presents the results of evaluating the exergy efficiency of a combined multi-stage solar water desalination unit and a conventional multi-stage solar water desalination unit. It includes the findings on average daily exergy efficiency at varying inlet flow rates of saline water, along with their analysis. These data are recommended for use in assessing the exergy efficiency of multi-stage solar water desalination units.

Keywords: Solar Energy; Solar Water Desalinator; Exergy; Exergy Efficiency; Saline Water; Fresh Water

1. Introduction

In recent years, the use of the exergy principle in evaluating and optimizing energy systems has generated significant interest [1]. Exergy analysis characterizes the quality of energy and enables obtaining information that is not available through conventional energy analysis [2]. Numerous studies have been conducted on the assessment of solar water desalination (SWD) systems based on exergy analysis [3-9].

Sharshir et al. [10] conducted research on the theoretical comparison between a modified SWD device using various nanoparticles and a traditional SWD device. Energy and exergy efficiency, as well as exergy destruction in the components of the SWD device, were calculated and evaluated for both systems. According to the results, when using graphite nanoparticles, energy and exergy efficiency improved by 41% and 64%, respectively, compared to the traditional SWD device. Additionally, the improvement in energy and exergy efficiency when using CuO nanoparticles was 32% and 44%, respectively. Bait [9] developed an active SWD device, in which the passive SWD device is combined with a tubular solar water collector. According to the experimental results, the annual productivity of the conventional and modified SWD devices was 405.04 and 549.77 kg/m², respectively. The exergy efficiency for passive and active SWDs was 30% and 41%, respectively.

Yousef et al. [11, 12] evaluated the energy and exergy efficiency of a single SWD device using various water sources, a wire mesh, and a ribbed absorber. According to the results, when a ribbed absorber and a wire mesh made of porous material were installed in the evaporation chamber, the daily exergy efficiency reached 14% and 23%, respectively. Khanmohammadi [13] evaluated the performance of a stepped SWD device with phase-change material and various insulation types from energy, exergy, economic, and environmental perspectives. A three-criteria optimization was carried out based on three objectives: exergy efficiency, total annual costs, and CO₂ emission reduction, using exergy-based functions. According to the results of multi-criteria optimization, all three selected objectives for all considered cases showed significant improvement compared to the unoptimized SWD system.

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2. Material and methods

The exergy efficiency of the SWD system is generally determined by the ratio of the outgoing exergy of evaporated water (Ex_{out}) to the incoming exergy of solar radiation (Ex_{in}) [14-16]:

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} = \frac{Ex_{dest}}{Ex_{sun}} \dots \dots \dots (1)$$

Hourly exergy produced by the SWD device [17]:

$$Ex_{out} = Ex_{dest} = \frac{m_{vap}L}{3600} \left[1 - \left(\frac{t_{am} + 273}{t_w + 273} \right) \right] \dots \dots \dots (2)$$

where Ex_{dest} -the exergy of evaporating water; t_w and t_{am} -temperatures of saline water and outside air, °C; m_{vap} -quantity of vaporized water, kg/s.

Exergy input to the SWD device [18, 19]:

$$Ex_{in} = Ex_{sun} = A_p I \left[1 - \frac{4}{3} \left(\frac{t_{am} + 273}{t_{sun}} \right) + \frac{1}{3} \left(\frac{t_{am} + 273}{t_{sun}} \right)^4 \right] \dots \dots \dots (3)$$

where t_{am} -ambient temperature, °C; $t_{sun} = 5327^\circ\text{C}$ -sun temperature.

Thus, exergy is considered a practical approach to effectively evaluating the energy transformation process in a system, meaning that the efficiency of an energy system is not assessed solely by energy efficiency. The exergy approach examines the irreversibility of the systemic process. Consequently, through exergy analysis, the system's irreversibility can be reduced and its efficiency increased.

3. Results and discussion

The results of changes in the exergy efficiency of the ordinary and CMSSWD devices at varying inlet flow rates of saline water are shown in Figure 1.

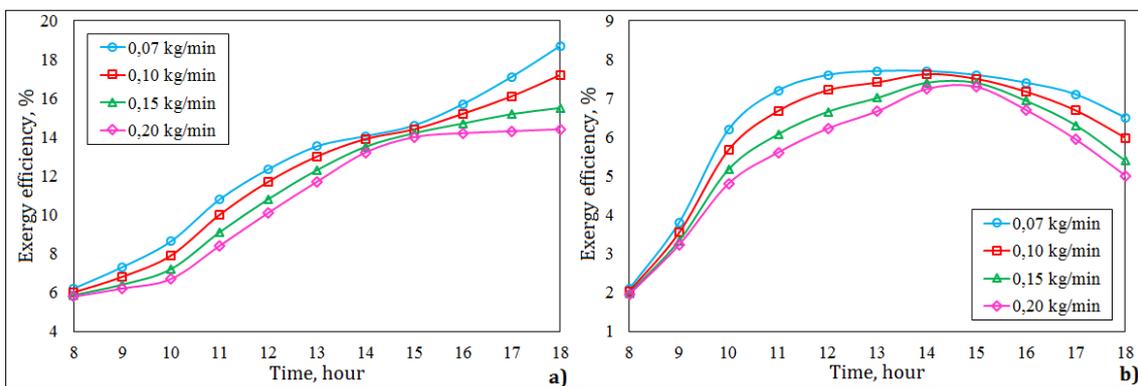


Figure 1 Results of changes in exergy efficiency in the combined (a) and simple (b) MSSWD devices

As evident from the results presented in Figure 1 above, the exergy efficiency value increased as the intake flow rate of saline water decreased. In the CMSSWD device, the value of exergy efficiency continued to increase until the end of the day, and according to the results at 18:00, the difference in exergy efficiency values became clearly noticeable. The maximum exergy efficiency values were 18.7%, 17.2%, 15.5%, and 14.4% for saline water intake flow rates of 0.07, 0.1, 0.15, and 0.2 kg/min, respectively. In a standard MSSWD device, the exergy efficiency value continued to increase until 11:00 and remained almost unchanged until 16:00, after which it slightly decreased. The maximum exergy efficiency values were 7.7%, 7.6%, 7.4%, and 7.3%, respectively, when the inlet salt water flow rates were 0.07, 0.1, 0.15, and 0.2 kg/min. As can be seen, the KKPQSch device had higher exergy efficiency due to its higher freshwater productivity and evaporation exergy. This is related to the following: in the CMSSWD device, exergy efficiency increased with an increase

in freshwater productivity and salt water temperature, while it decreased with an increase in ambient temperature and solar radiation intensity. When comparing the results of exergy and energy efficiency, we observe that the nature of their changes is almost identical. However, although they exhibit the same growth trend, the value of exergy efficiency is lower than that of energy efficiency. This is because the exergy method takes into account not only the quantitative characteristics of energy transfer but also additional qualitative characteristics. Furthermore, exergy analysis considers the irreversibility of energy within the system.

Figure 2 illustrates the variation in average exergy efficiency of the simple and CMSSWD devices under different inlet flow rates of saline water.

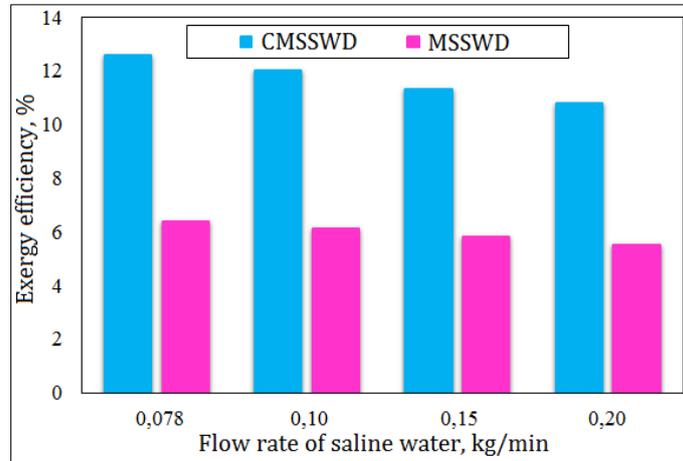


Figure 2 Average daily exergy efficiency values in the combined (a) and simple (b) MSSWD device

As evident from the results presented in Figure 2 above, the average exergy efficiency is also higher in the CMSSWD device. The maximum average exergy efficiency reached 12.6% in the CMSSWD device, while it was 6.4% in the conventional MSSWD device. When the inlet salt water flow rate was 0.07, 0.10, 0.15, and 0.20 kg/min, the average exergy efficiency in the CMSSWD device was 12.6%, 12.0%, 11.3%, and 10.8%, respectively. In comparison, for the same flow rates, the conventional MSSWD device achieved average exergy efficiencies of 6.4%, 6.1%, 5.8%, and 5.5%, respectively. The effect of increasing the inlet flow rate and temperature of salt water on exergy efficiency is shown in Figure 3.

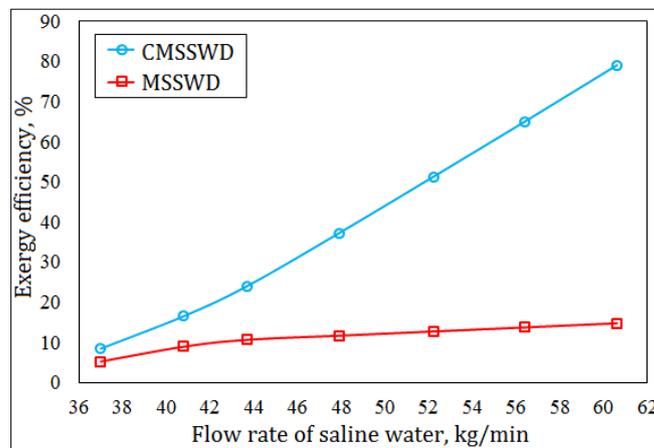


Figure 3 Effect of inlet salt water flow rate and temperature on exergy efficiency

As can be seen from the results presented in Figure 3, with a decrease in the inlet flow rate and an increase in the temperature of saline water, the exergy efficiency increased significantly. However, at high saline water flow rates, the interaction time and heat transfer rate decrease, resulting in a decrease in the evaporation rate and evaporation exergy, which leads to a decrease in exergy efficiency. Increasing the inlet temperature of saline water is the main factor in

enhancing freshwater productivity. This is because higher temperatures accelerate water evaporation, resulting in increased evaporation exergy and freshwater productivity.

4. Conclusion

When the inlet temperature of salt water varies between 37...61°C, the exergy efficiency value ranges from 8.4...79.0% in the CMSSWD device, while in the conventional MSSWD device, it ranges from 5.2...14.7%. Thus, the energy and exergy efficiencies of the CMSSWD device are significantly higher than those of the ordinary MSSWD device. Although the energy and exergy efficiencies of the CMSSWD device have been fully evaluated, it is also necessary to assess the environmental and economic efficiencies of this device.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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