ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 11, Issue 11, November 2024

Experimental Study of Heat Exchange Processes in a Multi-Stage Solar Desalination

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ABSTRACT: Solar desalination are an environmentally friendly and cheap energy device that works on solar energy. Currently, there is a large amount of research work on improving the efficiency of solar water desalination devices for fresh water. In this research paper, experimental values of multi-stage solar still heat exchange processes, fresh water efficiency, energy conversion, exergetic losses and energetic and exergetic efficiency are presented. The results presented in the research work can be fully used in the design and modeling of multi-stage solar water purifiers.

I. INTRODUCTION

The rapid development of industry and the sharp increase in the population in the world are increasing the demand for fresh and drinking water every day. According to recent data, the demand for fresh water in the world will increase from 130 to 400%, at which time only 0.01% of the available water will be available [1]. Environmentally friendly and easy-to-use solar desalination (SD) devices are a good alternative to meet this high demand for fresh water. however, the low productivity of these devices for fresh water (2 to 5 l/m^2/day) is the main problem, which limits their large-scale use [2]. A large number of research works have been carried out to solve the problem of increasing the performance of SD devices. It is known that the amount of fresh water output in SD devices is significantly dependent on the difference between the temperatures of the brine and the clear coat and the absolute temperature of the water in the basin. Therefore, if the distillation process is carried out at a relatively high temperature, high productivity of fresh water can be achieved. The process of desalination of salt water at high temperature can be solved based on the transfer of preheated salt water to the evaporation chamber, the use of external condensers and solar collectors.

Rohit and others [3] conducted an experimental study of the operation of the step SD device in open and laboratory conditions. According to the results, with the help of their proposed design, the daily productivity of fresh water was 3.7 l/m^2/day, and the maximum theoretical productivity was 6.4 l/m^2/day. Gawande and Bhuyars [4] conducted an experimental study of the efficiency of a simple step SD device. According to the results, the maximum daily productivity was 1.2 l/m^2/day when the wind speed was 1.45 m/s. Jagannath and others [5] studied the effectiveness of a simple step SD device when the height of the salt water layer is 5, 7.5 and 10 mm. According to the results, the daily productivity of fresh water was 1.44, 0.91 and 0.75 l/m^2/day, respectively, when the height of the water layer was 5, 7.5 and 10 mm.

II. MATERIALS AND METHODS

As can be seen from the above literature review, no experimental studies have been conducted to determine the temperature change, heat and mass transfer processes, and fresh water performance in combined multistage SD devices with external condenser and solar water collector. Taking this into account, a pilot sample of simple and combined MSSD devices was built and tested at the base of the educational and scientific laboratory of the "Heat Energy" department of the Karshi Institute of Engineering and Economics. The general view of the experimental device is shown in Fig. 1. The experimental device measures the temperatures of the transparent coating, absorber plate and salt water in simple and combined MSSD devices, heat exchange processes in each unit that make up the device, and various parameters (solar radiation intensity, wind speed, outdoor air temperature, transparent coating thickness, sho It is intended to carry out pilot studies to determine the productivity of fresh water, taking into account the effect of inlet water temperature. Heat exchange processes in a typical MSSD device were carried out according to the measurement-control scheme shown in Fig. 2.

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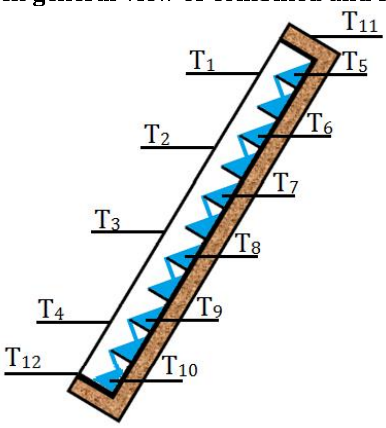
Thermocouples that allow to measure the temperature at 12 points in total on the MSSD device, that is, T_1, T_2, T_3 and T_4 thermocouples for measuring the temperatures on the outer surface of the transparent coating; thermocouples T_5, T_6, T_7, T_8, T_9 and T_{10} are installed to measure the temperatures of the water in the steps, thermocouples T_{11} and T_{12} are installed to measure the temperatures of the salt water at the inlet and outlet. Brine to be evaporated is passed from the top of the evaporation chamber and filling is continued until all the steps are filled. After all the steps in the chamber are filled with water, the water transfer is stopped, and after the water evaporates and begins to condense, a constant consumption of salt water (0.07 kg/min) is ensured. The temperature of the water in the evaporation chamber rises to 70-80℃. In the experimental study, the measured temperatures at all points are recorded.

Fig. 1. Front and back general view of combined and simple MSSD device



T_1-T_4-temperatures on the surface of the transparent coating; T_5-T_{10}-temperatures of salt water in the step of the SD device; T_{11} and T_{12} - inlet and outlet water temperatures

Fig. 2. Measurement and control diagram of the evaporation chamber of a typical MSSD device

Calculation of the heat exchange process and energy efficiency in a simple MSSD device was carried out according to the following methodology. Total solar radiation incident on the SD device:

$$Q_s = IA_c\tau_c\alpha_c\tau_w \quad (1)$$

where I-solar radiation intensity, W/m^2; A_c-the area of the transparent coating surface, m^2; τ_c-permeability of transparent coating; α_c-absorbency of transparent coating; τ_w-water permeability.

The convective (Q_{con}), radiative (Q_r) and evaporative (Q_e) heat quantities transferred from the surface of salt water to the transparent coating in the SD device are as follows:

$$Q_{con} = h_{con}(t_w - t_c)A_c \quad (2)$$

$$Q_r = h_r(t_w - t_c)A_c \quad (3)$$

$$Q_e = h_e(t_w - t_c)A_c \quad (4)$$

The amount of convective heat transferred from the transparent coating to the external environment:

$$Q_{con} = h_{con}(t_c - t_{amb})A_c \quad (5)$$

where h_{con}-convective heat transfer coefficients, $W/(m^2\cdot℃)$; t_c-average temperature of transparent coating, ℃; t_{amb}-outdoor temperature, ℃.

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The amount of radiant heat transferred from the transparent coating to the external environment:

$$Q_r = h_r(t_c - t_{sky}) \quad (6)$$

where h_r-coefficient of radiative heat transfer from the transparent coating to the sky, $W/(m^2 \cdot$°C):

$$h_r = \varepsilon_c \sigma \left[\frac{(t_c+273)^4-(t_{sky}+273)^4}{t_c-t_{sky}}\right] \quad (7)$$

where t_{sky}-sky temperature, °C:

$$t_{sky} = 0{,}0552 t_{amb}^{1,5} \quad (8)$$

where $\varepsilon_c = 0{,}88$-dimensionless blackness coefficient of transparent coating; σ-Stefan-Bolsmann constant.

The coefficient of thermal efficiency of the MSSD device is determined as follows:

$$\eta_{th} = \frac{Q_e}{Q_s} = \frac{h_e A_c (t_w - t_c)}{I A_c \tau_w \tau_c \alpha_c} \quad (9)$$

III. RESULTS AND DISCUSSION

Experimental studies of heat exchange processes in a typical MSSD device were conducted on August 22 and 23, 2024. Changes of solar radiation intensity and outdoor air temperatures on August 22 and 23, 2024 are shown in Fig. 3 and 4.

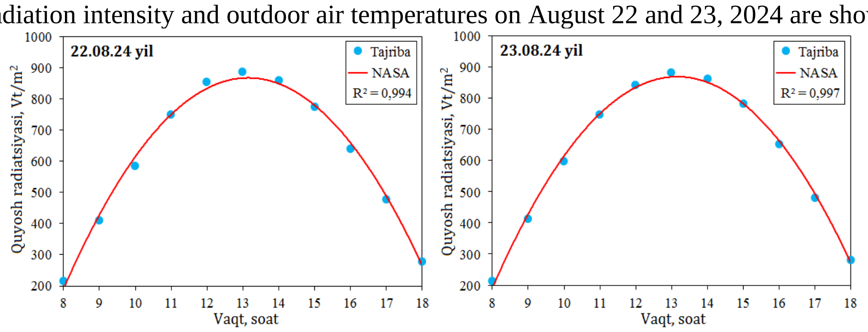

Fig. 3. Results of changes in solar radiation intensity over time

As can be seen from the results presented in Fig. 3 above, the results of the pilot studies are very little different from the results in the source. In the experimental studies, the total solar radiation energy received between 8^{00} and 18^{00} on August 22 and 23 was 6.72 and 6.73 kWh/m^2, respectively, and the validation of the results was checked with the approximation reliability respectively, R^2=0.994 and R^2=0.997.

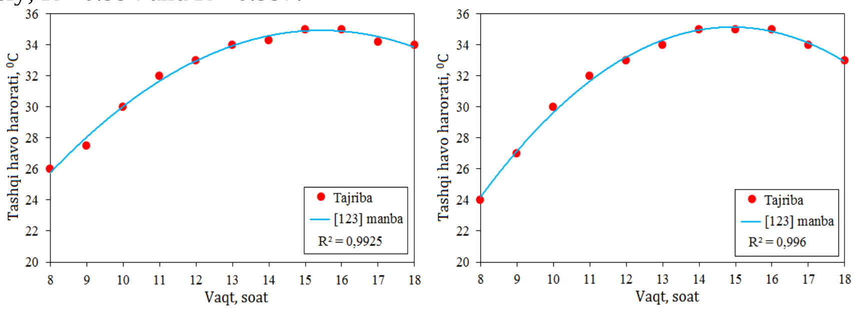

Fig. 4. Results of changes in outdoor air temperature over time

As can be seen from the results presented in Fig. 4 above, [6] differs little from the values of outdoor air temperature given in the source. In experimental studies, on August 22 and 23, between 8^{00} and 18^{00} hours, the outdoor temperature varied between 26.7...35.4°C and 23.6...35.7°C, respectively, validation was R^2=0.9925 and R^2=0.996, respectively, when examined by approximation reliability. Fig. 5 shows the results of brine water, cover and absorber plate temperatures over time when the flow rate of brine to the MSSD is constant at 0.07 kg/min.

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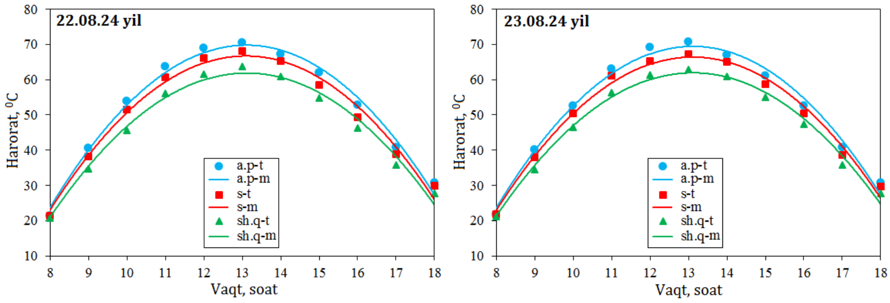

a.p-absorber plate; w-water; t.c-transparent coating; e-experiment; m-model

Fig. 5. Results of temperature variation in a typical MSSD device:

As can be seen from the results in Fig. 5 above, on August 22, the temperature of the absorber plate was 21.4...70.5℃, the temperature of the brine was 21.3...68℃, and the temperature of the transparent coating was 20.8...63.7℃ varied in the range. The reliability of approaching the experimental values of the temperatures of the absorber plate, salt water and transparent coating to the theoretical values was R^2=0.9866, R^2=0.9829 and R^2=0.9838, respectively. On August 23, the temperature of the absorber plate was 21.8...70.8℃, the temperature of the salt water was 21.7...67.3℃, and the temperature of the transparent coating was in the range of 21.2...62.9℃ has changed. The reliability of approaching the experimental values of the temperatures of the absorber plate, salt water and transparent coating to the theoretical values was R^2=0.9871, R^2=0.9873 and R^2=0.9877, respectively. As can be seen from the results of the analysis, the maximum error of the theoretical and experimental results does not exceed 5%, which means that the developed mathematical model can be fully used to calculate the temperatures of the absorber plate, salt water and transparent coating.

Based on the values of the convective, radiative and evaporative heat transfer coefficients determined by the temperature values determined in the experimental study, the change in the value of the total amount of heat transferred in the evaporation chamber of the SD device over time was experimentally determined and compared with the results of the theoretical study. The obtained results are shown in Fig. 6.

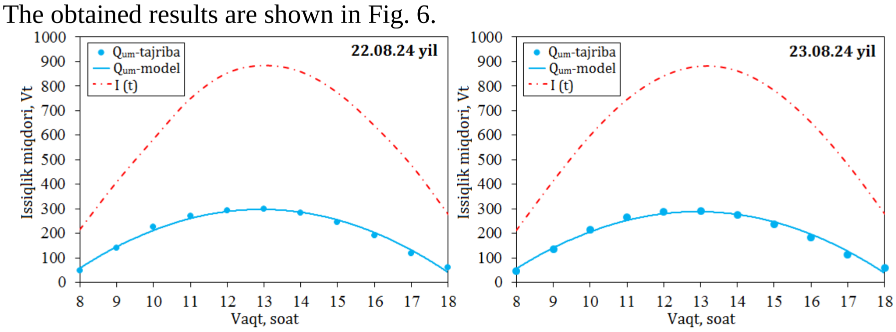

Fig. 6. Results of variation of heat content with time in a typical MSSD device

As can be seen from the results in Fig. 6 above, on August 22, solar radiation energy in the amount of 6.73 kWh/m^2 was transferred to the evaporation chamber of the SD device. The amount of heat received in the evaporation chamber varied between 46.2...299.4 W and a total of 2.17 kWh/m^2 of energy was received. The convergence reliability of the model and experimental results was R^2=0.9851. On August 23, solar radiation energy in the amount of 6.75 kWh/m^2 was transferred to the evaporation chamber of the SD device. The amount of heat received in the evaporation chamber varied between 45.7...291.5 W and a total of 2.1 kWh/m^2 of energy was received. The convergence reliability of the model and experimental results was R^2=0.9841. Based on the experimental results of the amount of heat received in the evaporation chamber of the SD device, the variation of the coefficient of thermal efficiency of a simple SD device over time was determined (Fig. 7).

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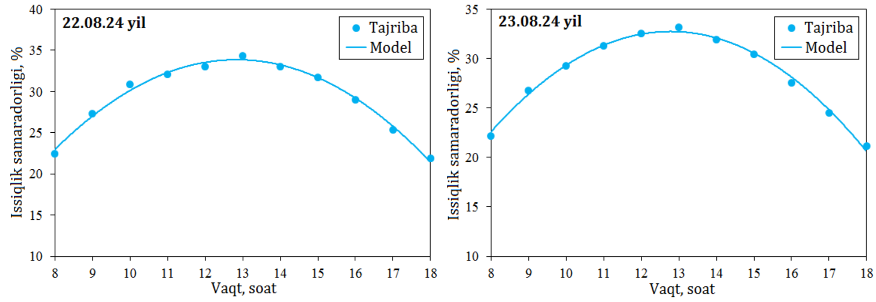

Fig. 7. Results of variation of thermal efficiency coefficient of a typical SD device over time

From the results in Fig. 7 above, it can be seen that on August 22, the thermal efficiency of the evaporation chamber of the SD device varied between 21.87...34.31%, with a daily average efficiency of 29.2% reached, in which the reliability of approximation of the model and experimental results was R^2=0.9902. On August 23, the thermal efficiency of the evaporation chamber of the SD device varied from 21.13 to 33.20%, and the daily average efficiency reached 28.26%, with the convergence reliability of the model and experimental results R^2=0.9928.

The useful exergy values of a simple SD device were determined based on the experimental values of the temperatures of the external air, salt water, transparent coating and absorber plate. The results of time variation of exergy values in a typical SD device are shown in Fig. 8.

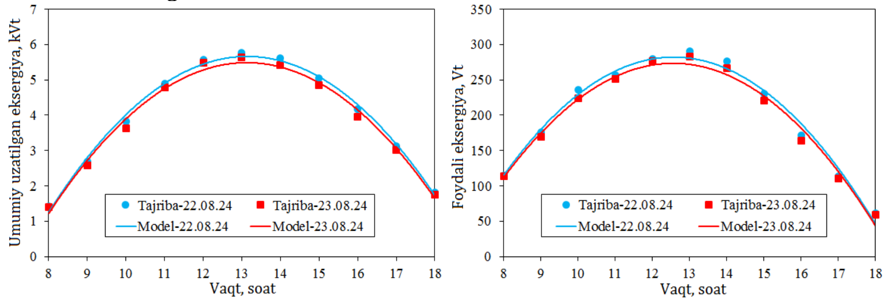

Fig. 8. Results of time variation of exergy values in a typical SD device

As can be seen from the results in Fig. 8 above, the total amount of exergy transferred to the SD device on August 22 and 23 was between 1.41...5.78 kW and 1.40...5.62 kW, respectively, changed, reaching a maximum of 5.78 and 5.62 kW at 13^{00} hours, where the approximation reliability of the model and experimental results, respectively R^2=0.994 and R^2=0.989. On August 22 and 23, the amount of useful exergy in the SD device varied between 60.8...295.0 W and 58.7...282.4 W, respectively, with a maximum of 295.0 at 13^{00} and reached 282.4 W, where the approximation reliability of the model and experimental results is R^2=0.9853 and R^2=0.9832, respectively established. Based on the theoretical and experimental results of the amount of useful exergy, the exergetic efficiency of a simple SD device was determined (Fig. 9).

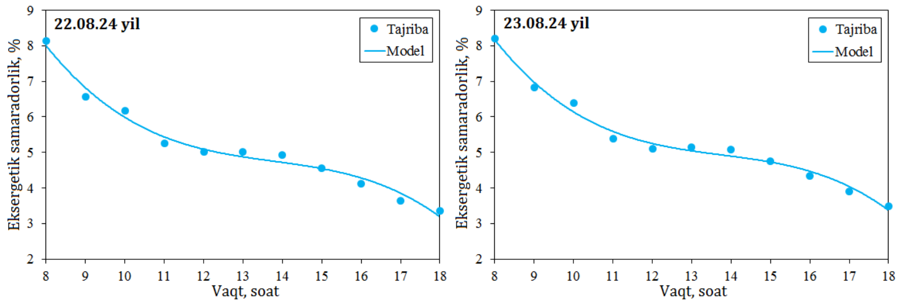

Fig. 9. Results of time-varying exergetic efficiency of a typical SD device

As can be seen from the results in Fig. 9 above, on August 22, the exergetic efficiency of the SD device changed in the range of 3.4...8.1%, where the convergence reliability of the model and experimental results is R^2=0,9836. On August 23, the exergetic efficiency of the SD device changed in the range of 3.5...8.2%, and the reliability of approximation of the model and experimental results was R^2=0.9861. Hence, the exergetic efficiency decreased with time, indicating that the exergetic loss varied over time. According to the results of theoretical and experimental studies conducted on a simple SD device, the proposed energetic and exergetic models can be used to design an MSSD device.

IV. CONCLUSION

The thermal technical parameters of the CMSSD device were based, an experimental sample was built, and it was put into operation and tested.

An experimental study of heat exchange processes in a typical MSSD device was carried out, according to the results, the average thermal efficiency when receiving 2.17 and 2.1 kWh/m^2 of solar radiation energy in the evaporation chamber on August 22 and 23, respectively It was 29.2% and 28.26%.

An experimental study of exergetic efficiency in a typical MSDS device was conducted, according to the results, the useful exergy in the evaporation chamber on August 22 and 23 was in the range of 60.8...295 W and 58.7...282.4 W, respectively, exergetic efficiency was 3.4...8.1% and 3.5...8.2%, respectively.

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