Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1035541

57 (2016) 9602–9608
May

Taylor & Francis
Taylor & Francis Group

Improving the productivity of a falling film solar desalination unit

Hasan Mousa[a,c,*], Ala'a H. Al-Muhtaseb[a], Mousa Abu-Arabi[b,c]

[a]*Faculty of Engineering, Petroleum and Chemical Engineering Department, Sultan Qaboos University, Muscat, Oman, email: hasana@squ.edu.om (H. Mousa)*
[b]*Department of Chemical Engineering, College of Engineering & Petroleum, Kuwait University, Safat, Kuwait*
[c]*Department of Chemical Engineering, Jordan University of Science and Technology, Irbid 22110, Jordan*

Received 20 August 2014; Accepted 19 March 2015

ABSTRACT

This study aimed at improving the productivity of a falling film solar desalination unit by cooling the glass cover and by improving the hot surface wettability. The glass cover was made of double layers through which cooling water passes. The advantage of this design is that the latent heat of evaporation is absorbed by the cooling water and returned to the system. The effect of the various parameters such as feed water flow rate, cooling water flow rate, weather conditions, solar irradiation intensity, and collector's surface area was investigated. The results showed that increasing the cooling water flow rate enhanced fresh water production. The productivity of the unit decreased with increasing feed water flow rate. Recycling the hot water to the feed water tank improved the productivity of the unit from 0.13 to 0.18 L/h (~34%). Fog formation on the double glass cover was found to reduce the productivity of the unit. Modifying the surface of the black plate with cotton cloth or with plastic strips improved the productivity by 50% (0.13–0.19 L/h).

Keywords: Solar desalination; Falling film; Evaporation/condensation; Brackish water; Double glass cover

1. Introduction

Jordan is one of the world's scarcest countries in water resources. With unpredictable rainfall and an increasing population, the demand for water in the country exceeds the available resources and the gap between the water supply and demand is continuously increasing. This has led to deterioration of the groundwater quality and an increase in its salinity levels. Therefore, it is very important to consider non-conventional water resources, such as sea and brackish water desalination [1]. Another problem is that Jordan is a non-oil producing country in which the energy sector is almost very dependent on imported natural gas and crude oil, which overloaded the national economy and retarded the social and industrial development of the country [2]. These aspects motivated the government and the researchers to pay more attention for the utilization of solar energy resource. Use of renewable energy sources to drive desalination processes can be a sustainable and affordable approach to reclaim potable water from seawater and brackish waters [3].

Solar energy for desalination via solar still presents a sustainable method for providing potable water. However, the main drawback of solar still is its low productivity compared to conventional desalination

*Corresponding author.

processes [4]. Therefore, various modifications and methods have been attempted in order to enhance the productivity of solar stills [5,6]. Aybar et al. [7] designed an inclined solar water distillation system. The system generated 3.5–5.4 kg distilled water/m absorber plate area day. The temperature of the produced hot water reached as high as 60℃, and the average water temperature was about 40℃. Hongfei et al. [8] experimentally and theoretically investigated desalination from three effects falling film coupled with flash evaporation unit. The unit has the characteristics of low operation steady state temperature and high production efficiency reaching 135 kg/h. Abu-Arabi et al. [9] and Mousa and Abu-Arabi [10] investigated experimentally and theoretically water desalination from an inclined solar water distillation unit with falling film. The effects of various parameters such as feed water flow rate, ambient temperature, cooling glass cover, and water salinity were also investigated. The results showed that water productivity could be increased by decreasing the temperature of the glass surface and reducing the feed water flow rate. Alaudeen et al. [11] constructed a stepped tray type basin along with an inclined flat plate collector and a conventional basin. Maximum productivity of 1.47 kg/m^2 was obtained for 2 cm water depth. Suneesh et al. [12] designed a "V" type solar still with a Cotton Gauze Top Cover Cooling. The water production rate was increased by 34%. The productivity was further improved by blowing air through the system. Omara et al. [13] enhanced the stepped solar still performance by using internal and external reflectors. The productivity of the modified stepped solar still was higher than that for conventional still by approximately 125%.

In a previous research conducted by the authors, a falling film desalination unit was built and tested [9,10]. The effect of various parameters such as feed water temperature and glass surface cooling was evaluated. The objective of the current research is to modify the existing unit to study the effect of cooling the glass cover and changing feed water temperature and distribution on the solar collector on the productivity of the unit. The rate of cooling will be achieved by changing the rate of cooling water flow rate and varying feed water temperature will be achieved by recycling the hot water to the feed tank. The study will also cover the effect of weather conditions and solar insolation on the unit performance.

2. Experimental setup

The solar desalination unit consists of the following main components: an inclined black painted surface (1 m × 1 m) acting as a solar collector, a double glass cover, feed water and a hot water collecting tanks of 20 L capacity each, a fresh water collecting flask of 2 L capacity, and a pump to circulate produced hot water back to the feed water tank. Fig. 1 is a schematic representation of the apparatus. The solar collector is made of two square aluminum plates (1 m × 1 m) each having 4 mm thickness connected in parallel arrangement (lower and upper plates, as shown in Fig. 2) with a gap of 1 cm between them. This arrangement provides a channel for the feed water to pass through. The upper plate is painted black to absorb solar irradiation. The lower plate is insulated from the bottom using polystyrene (5 cm thickness) to minimize heat losses. As shown in Fig. 2, the feed water enters channel at the bottom side of the inclined surface, rising through the channel reaching the top where it flows through a slit then downward as a film on the upper plate. Hence, the water gets heated in the way up through the channel from the heat passing the upper plate and as it falls downward on the upper plate by absorbing the heat stored in the plate. Part of this water evaporates and the rest is withdrawn as hot water which is collected in a hot water tank. The generated vapor condenses on the glass cover located 8 cm above the solar collector. To enhance the condensation process, the glass cover is also made of two parallel glass plates spaced 1 cm apart. Cold water enters between the glass plates at the top and is used to cool the lower glass surface (Fig. 2). The cooling rate of the glass cover is controlled by controlling the cold water flow rate. The solar unit is mounted facing the south at an angle of 45˚. A photograph of the unit is depicted in Fig. 3. It is worth noting that the design of the double glass cover allows hot water production at higher temperature by reducing the cooling water flow rate. Moreover, the double glass acts as an insulator and prevents heat losses to the surrounding.

3. Results and discussion

3.1. Double glass cover

The effect of cooling water flow rate (M_c) on the productivity of the unit is shown in Fig. 4. Fresh water production increases as the cooling water flow rate. This result is in accordance with the results obtained by Mousa and Abu-Arabi [14] from a solar basin enhanced by a solar collector. Increasing the cooling water flow rate reduces the glass surface temperature which increases the driving force for evaporation. This in turn enhances water vapor condensation rate and hence fresh water production. Fig. 5 shows the effect

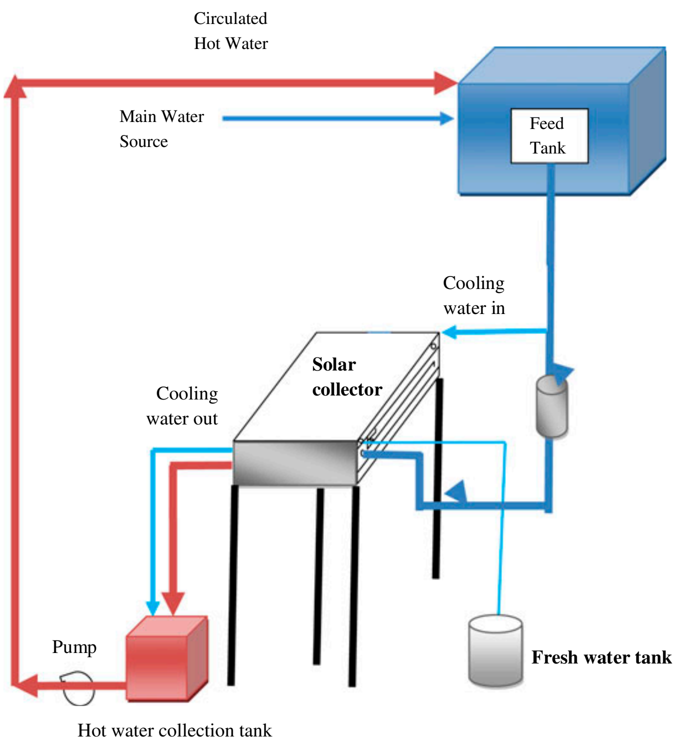

Fig. 1. A schematic diagram of the experimental setup.

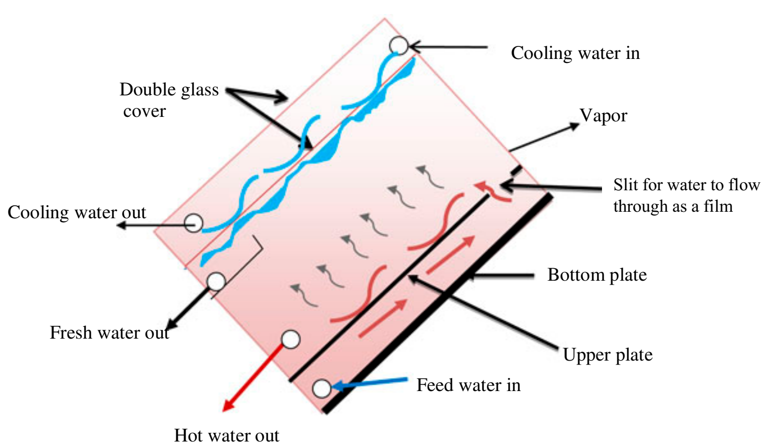

Fig. 2. A detailed sketch of the solar collector and the glass cover.

of feed water flow rate (M_F) on the productivity of the unit where it can be seen that as the feed water flow rate decreases the productivity increases. Lower flow rate means that less amount of water need to be heated by the collector's surface and higher water residence time inside the channel. Both reasons lead to increase in the unit productivity.

To study the effect of the temperature of the feed water on the productivity of the unit, the hot water produced was recycled to the feed water tank. This effect is shown in Fig. 6 where it can be seen that the productivity of the unit is improved from 0.13 to 0.18 L/h (~34%) upon heating the feed (or recycling the hot water to the feed water tank). These experiments were performed at a feed water flow rate of 12.5 L/h and a cooling water flow rate of 180 L/h.

Weather conditions have a strong effect on the productivity of the unit. Fig. 7 shows the amount of fresh

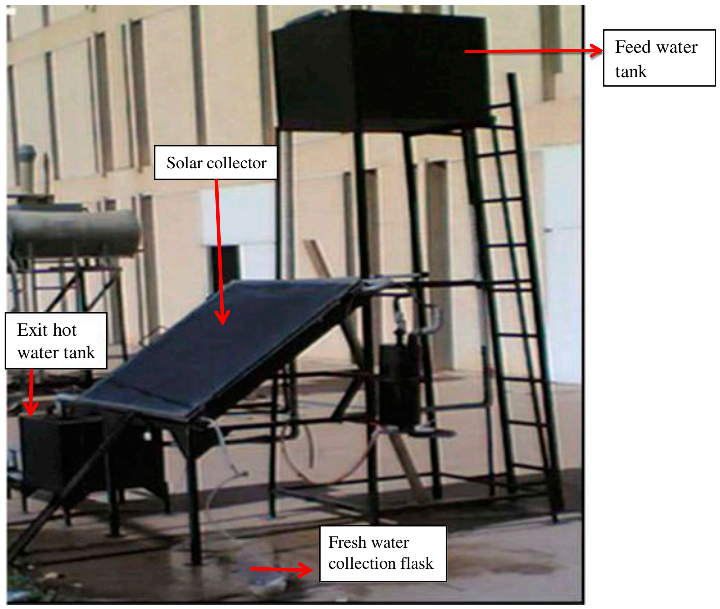

Fig. 3. A photograph of the experimental setup.

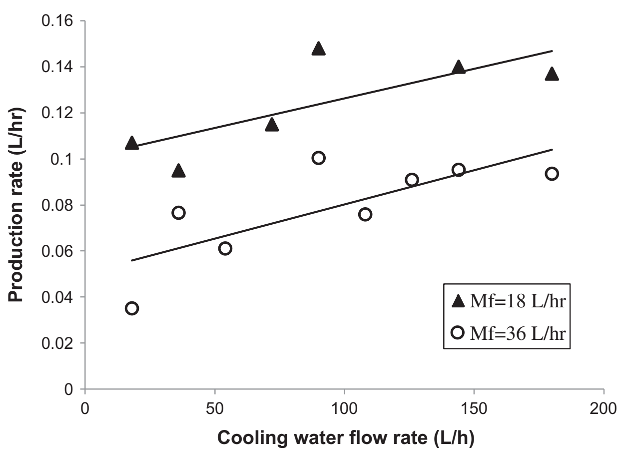

Fig. 4. Fresh water production rate vs. the cooling water flow rate for feed water flow rates of 18 L/h ($T_F = 27 \pm 5$°C) and 36 L/h ($T_F = 25 \pm 4$°C). The experiments were performed during the months of May ($T_a = 28 \pm 3$°C, $Q_s = 776$ W/m^2) and June ($T_a = 33 \pm 3$°C, $Q_s = 751$ W/m^2). The experiments were performed between 8:00 am and 4:00 pm.

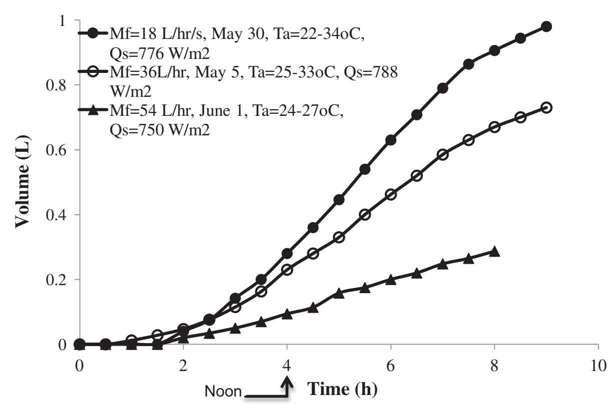

Fig. 5. Fresh water produced vs. time for different feed flow rates at a constant water-cooling rate of 90 L/h.

water obtained during a sunny day, a cloudy day, and a cloudy rainy day. Such results are important and should be taken into account when designing similar unit.

3.2. System modifications

With the double glass cover, two problems were encountered. The first, it was not possible to fill the space between the two glass plates comprising the double glass cover. Trying to fill the space caused the spacing to expand due to the water weight. Thus, a water film was introduced from the top allowing water to partially accumulate in the spacing. However, this resulted in the second problem, which is fog formation in the space between the glass plates. The fog particles scatter sunlight and attenuate the solar intensity received by the black plate (solar collector) hence reducing the productivity. Therefore, the upper surface of the glass cover was removed and continued cooling the glass cover with the water film. In other words, the cooling water was allowed to flow as a film on the outer surface of the glass cover and was

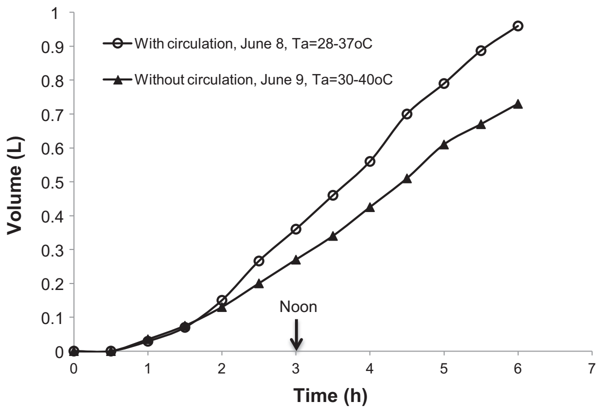

Fig. 6. Fresh water produced vs. time for the case where the hot water is recycled to the feed tank at a cooling water rate of 180 L/h and feed water flow rate of 12.5 L/h. $Q_s = 826\ W/m^2$, and the experiments were conducted from 9:00 am to 3:00 pm.

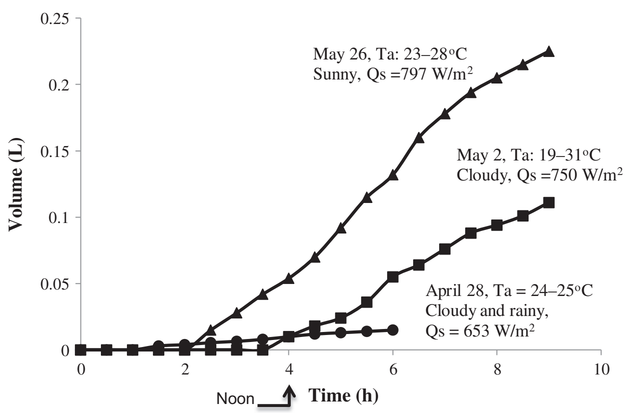

Fig. 7. The effect of weather condition on the productivity of the unit (feed flow rate = 36 L/h, cooling water flow rate = 18 L/h).

collected in the hot water collection tank at the bottom. The results are presented in Fig. 8, and the productivity of the unit is greatly improved where 0.15–0.33 L/h of fresh water was produced. Comparing this value to the double glass case where 0.02–0.15 L/h shows that a 100% increase in the productivity is achieved.

Another modification on the system was made to have better distribution of the feed water on the solar collector surface and to avoid channeling. Channeling occurred at low feed flow rate, which reduced the surface covered by water film and lowered evaporation rate. Distribution of the water film on the black surface is an important factor to have high productivity. To improve water distribution, the surface was modified by one of the following ways:

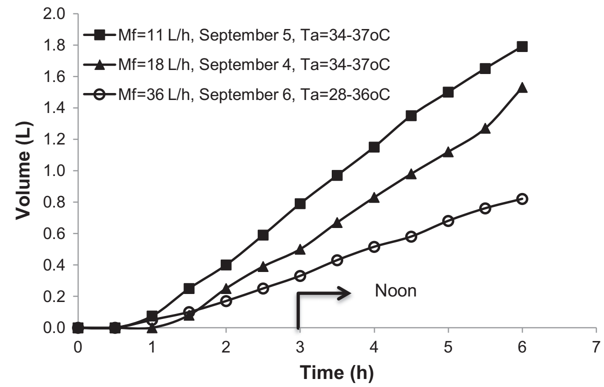

Fig. 8. The effect of feed flow rate on the productivity of the unit for single layer glass cover. Cooling water flow rate = 72 L/h, $Q_s = 570\ W/m^2$.

(1) Laying black cotton cloth on the whole surface, or
(2) Attaching strips of black plastic mesh spaced 10 cm apart, each strip has a 1 cm width and a length equals to that of the black plate surface or
(3) Attaching strips of black cloth in a fashion similar to that of the plastic strips.

Fig. 9 shows the results obtained with the surface modifications. The productivity is improved by 50% (0.13 L/h productivity when no surface modification was made vs. 0.19 L/h with the modification). It is worth mentioning that the experiments without surface modification were performed in August

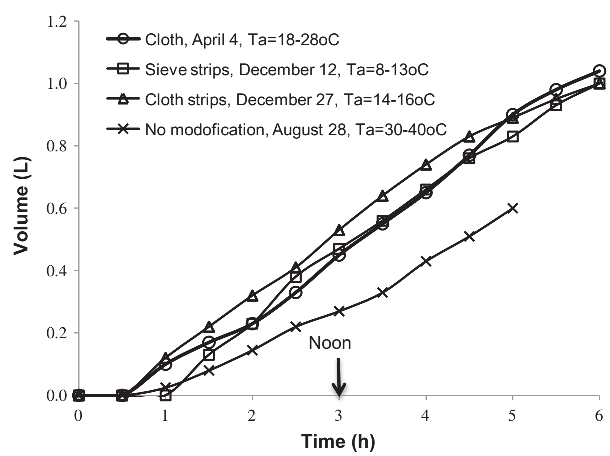

Fig. 9. A comparison between the amounts of fresh water produced with and without surface modification. The average solar insolation, Q_s, in April, August, and December is 713, 740, and 380 W/m^2, respectively, between 9:00 am and 3:00 pm, respectively.

Table 1
Variation of the inlet feed and the exit water (hot water source) temperature with time. M_F = 36 L/h

	M_c = 18 L/h[a]		M_c = 36 L/h[b]		M_c = 54 L/h[c]		M_c = 90 L/h[d]		M_c = 108 L/h[e]	
Time (h)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)
0	22	24	18	20	16	19	25	27	23	25
1	27	30	21	23	17	19	27	30	25	29
2	31	33	25	30	21	25	29	35	28	32
3	32	34	26	33	26	32	32	39	30	35
4 (noon)	33	39	28	36	28	36	34	42	32	38
5	35	40	30	37	29	36	36	43	33	38
6	35	39	32	41	30	36	37	43	34	39
7	34	38	33	40	31	36	36	43	33	37
8	34	36	34	39	30	35	36	41	32	35
9	34	35	33	38	30	33	35	41	–	–

The above experiments were conducted during 2011 on:
[a]May 26, T_a = 23–31℃.
[b]April 27, T_a = 21–31℃.
[c]May 15, T_a = 18–29℃.
[d]May 5, T_a = 25–34℃.
[e]May 17, T_a = 22–34℃.

where the ambient temperature ranged between 30 and 40℃ (hot period). However, the other experiments were performed during cooler periods of the year (December and April). In spite of this effect, the productivity of the unit was improved indicating surface modifications (to have better distribution of the water film) is necessary.

3.3. Temperature of the cooling water and the hot water

The temperature of the hot water as a function of time for various dates is summarized in Table 1. As shown in Table 1, the temperature of the hot water can reach 41℃. It should be noted that these experiments were performed during the month of April and May

Table 2
Variation of the inlet and the exit cooling water temperature with time. M_F = 36 L/h

	M_c = 18 L/h[a]		M_c = 36 L/h[b]		M_c = 54 L/h[c]		M_c = 90 L/h[d]		M_c = 108 L/h[e]	
Time (h)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)	Inlet T (℃)	Exit T (℃)
0	22	24	18	21	16	18	25	27	23	25
1	27	30	21	22	17	19	27	29	25	28
2	31	35	25	28	21	24	29	33	28	31
3	32	34	26	31	26	30	32	35	30	34
4 (noon)	33	38	28	35	28	34	34	39	32	36
5	35	41	30	37	29	35	36	41	33	37
6	35	39	32	39	30	35	37	41	34	38
7	34	38	33	39	31	34	36	40	33	35
8	34	35	34	37	30	34	36	39	32	34
9	34	34	33	37	30	32	35	39	–	–

The above experiments were conducted during 2011 on:
[a]May 26, T_a = 23–31℃.
[b]April 27, T_a = 21–31℃.
[c]May 15, T_a = 18–29℃.
[d]May 5, T_a = 25–34℃.
[e]May 17, T_a = 22–34℃.

where the weather is still relatively cool, windy and dusty and largely affected by the "Khamaseen winds" that strikes Jordan at this time of the year. These temperatures get higher during the hot summer months reaching up to 75°C. The temperature of the cooling water as it enters and leaves the unit was also measured (Table 2). A comparison between the data in Tables 1 and 2 show that the cooling water could be used as a source of hot water and also can be used as a feed water to the unit which can improve its productivity.

In all the experiments, the quality of the produced fresh water was tested by measuring its conductivity. It was found that it ranges between 9 and 18 μS/cm.

4. Conclusions

This research investigated production of fresh and hot water from brackish water using falling film solar desalination unit. The unit can produce both hot water for domestic applications and fresh water. The production rate of fresh water is affected by the cooling water flow rate, feed temperature and its flow rate, film distribution over the collector plate, solar insolation, and ambient weather conditions. The amount of fresh water production can be increased by increasing the cooling water flow rate, recycling the hot water to the unit, and uniformly distributing the water film over the collector's surface. The fresh water production is reduced when the feed water flow rate increases. Fog formation and accumulation on the glass cover also reduces fresh water production. Recycling hot water to the feed water tank improved the productivity of the unit by ~34%. Preventing fog formation increased the production of fresh water by 100%. Uniform distribution of the water film on the collector surface enhanced the productivity by 50%.

Acknowledgments

The authors gratefully acknowledge the financial support of this work by Abdul Hamid Shoman Foundation. The authors also wish to thank the workshop unit of the Jordan University of Science & Technology for building and maintaining the experimental setup.

References

[1] M.S. Mohsen, Water strategies and potential of desalination in Jordan, Desalination 203 (2007) 27–46.
[2] Z. Al-Hamamre, A. Al-Mater, F. Sweis, K. Rawajfeh, Assessment of the status and outlook of biomass energy in Jordan, Energy Convers. Manage. 77 (2014) 183–192.
[3] V.G. Guide, N. Nirmalakhandan, Sustainable desalination using solar energy, Energy Convers. Manage. 51 (2010) 2245–2251.
[4] Y.A.F. El-Samadony, A.E. Kabeel, Theoretical estimation of the optimum glass cover water film cooling parameters combinations of a stepped solar still, Energy 68 (2014) 744–750.
[5] V. Sivakumar, E. Ganapathy Sundaram, Improvement techniques of solar still efficiency: A review, Renew. Sust. Energy Rev. 28 (2013) 246–264.
[6] A. Muftah, M.A. Alghoul, A. Fudholi, M.M. Abdul-Majeed, K. Sopian, Factors affecting basin type solar still productivity: A detailed review, Renewable and Sustainable Energy Rev. 32 (2014) 430–447.
[7] H.S. Aybar, F. Egelioğlu, U. Atikol, An experimental study on an inclined solar water distillation system, Desalination 180 (2005) 285–289.
[8] Z. Hongfei, H. Kaiyan, Y. Yinjun, C. Ziqian, L. Hui, Study on a multi-effects regeneration and integral type solar desalination unit with falling film evaporation and condensation cycle, Sol. Energy 80 (2006) 1189–1198.
[9] M. Abu-Arabi, H. Mousa, R. Abdelrahman, Solar desalination unit with falling film, Desalin. Water Treat. 3 (2009) 58–63.
[10] H. Mousa, M. Abu-Arabi, Theoretical study of water desalination by a falling film solar unit, Desalin. Water Treat. 12 (2009) 331–336.
[11] A. Alaudeen, K. Johnson, P. Ganasundar, A. Syed Abuthahir, K. Srithar, Study on stepped type basin in a solar still, J. King Saud Univ.—Eng. Sci. 26 (2014) 176–183.
[12] P.U. Suneesh, R. Jayaprakash, T. Arunkumar, D. Denkenberger, Effect of air flow on "V" type solar still with cotton gauze cooling, Desalination 337 (2014) 1–5.
[13] Z.M. Omara, A.E. Kabeel, M.M. Younes, Enhancing the stepped solar still performance using internal and external reflectors, Energy Convers. Manage. 78 (2014) 876–881.
[14] H. Mousa, M. Abu-Arabi, Desalination and hot water production using solar still enhanced by external solar collector, Desalin. Water Treat. 51 (2013) 1296–1301.