Experimental Investigation and Comparison of Desalination using Conventional Solar Still, Stepped-Cup Solar Still with and without Biomass

A.Senthilrajan[a,*], C.Ramji[b],

[a c] Department of Mechanical Engineering, Mohamed Sathak Polytechnic, Killakarai, Tamilnadu 623806, India

[b] Department of Mechanical Engineering, University College of Engineering, Ramanathapuram, Tamilnadu 623501, India.

* Corresponding author senthilrajan.73@gmail.com

Abstract

Desalination of water has become one of the vital areas of research because of the increasing demand for fresh water. The usage of solar stills is one of the conventional methods for the process of desalination. In this paper, a novel design variation is given to the conventional solar still to increase the productivity of desalination. The plain basin plate of the conventional still is replaced with steps with cup shaped trays. Experiment has been done to measure the hourly desalinate productivity of both conventional solar still and the stepped-cup solar still in the month of May in Tamilnadu, India. Further, a biomass boiler is connected to the stepped-cup solar still to increase the heat inside the still. Productivity of the stepped-cup solar still with the biomass boiler setup has been measured and compared with the productivity of conventional solar still. Results have shown that the proposed stepped-cup solar still design has increased the productivity by 12% compared to the conventional still. Also, the productivity of the stepped-cup solar still has shown an enormous 70% increase on the addition of the biomass when compared to the conventional solar still.

Key words- cup type still,biomass,solar,productivity

1. Introduction

Earth is the only human living planet having water in our solar system, out of which 97% of water is salty and only 2.6% is fresh water. The fresh water sources like ponds, lake, and river are getting polluted due to environmental pollution and hence there is an increasing scarcity of and demand for fresh water. Desalination of sea water could bring the complete solution for the fresh water problem.

In the early decades of the new millennium, various methods have been developed to desalinate the sea water such as Reverse Osmosis (RO), Multi-Stage Flash (MSF), Multi-Effect distillation (MEF) and electro dialysis. Of these, the reverse osmosis and the electro dialysis are cost-effective conventional methods. Though there are various methods to distill fresh water from sea water the simplest method is the conventional solar still. Solar energy which plays an important role in the process of desalination is obtained from the sun. Earth's surface receives 70% of the total solar energy radiation which is about 174000 terawatts (TW).

Solar stills are used in the process of desalination by using solar energy radiation as an energy source. The best desalination technique is the one which has high efficiency at low cost, and solar stills are low in cost, simple in construction and easy to operate. Since the efficiency of the solar still is comparatively low this paper advocates a modification in design.

Various design modifications to a basic solar still are advocated in the literature to increase the efficiency of desalination. Moustafa et al.[1] investigated and compared basin type stepped solar still with wick-type still. The wick-type evaporator collector system showed an increase in overall efficiency when compared to the basintype system. A flat plate collector added to a single basin solar still was designed by Tiris et al.[2] and was found that there was a 52% increase in the productivity. Zurigat and Abu-Arabi [3] constructed a regenerative solar desalination unit using double glass cover which increased the productivity by 20%.Asymmetrical and symmetrical greenhouse type solar stills were studied by El-Hayek and Badran [4]. Suleiman [5] investigated on different water depths in the still and found that productivity increased bydecreasing the water depth on the basin absorbing plate.A triple basinsolar still was constructed by El-Sebaii [6] for enhancing the productivity.A.Senthil Rajan et al. [3], Velmurugan et al. [7], [8] incorporated a mini solar pond for improving the productivityof solar still and also discussedabout several applications ofsolar pond[9].A stepped solar still was designed by Velmurugan et al. [10] and its performance was analysed.An altered stepped solar stll with aflashing chamber was constructed and examined by El-Zahaby et al. [11].

Researchers have improved the performance of the solar still by incorporating various thermal storage materials into the still. A multi basin solar still was developed by Senthil Rajan et al. [12] enhance the productivity. To further increase the performance of the still sensible heat materials like sand, cement block, glass and latent heat storage materials such as wax were added. A 73% increase in productivity was obtained by using sensible heat storage material when compared to the conventional solar still. Kalidasa Murugavel et al. [13]incorporated sensible heat storage materials such as cement concrete pieces, quartzite rock, washed stones, iron scraps and red brick pieces into the still and found that an inch quartzite rock showed increased productivity than the other materials. Similarly in a double slope solar still Kalidasa Murugaveland Srithar [14] used various wick materials like waste cotton pieces light cotton, sponge cloth, and coir mate among which black cotton cloth showed higher productivity. Velmurugan et al. [15] integrated fins, sponges and pebbles into a stepped solar still and analysed its performance. Omara et al. [16] constructed a modified stepped solar still with and without reflector and found that there was a 20% increase in the daily efficiency of modified solar still than a conventional solar still.

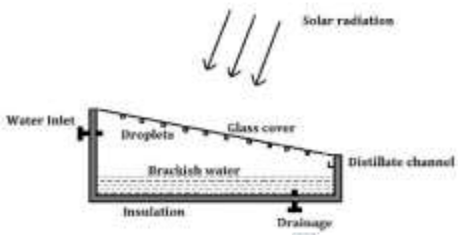
In this paper, a new design variation is given to the stepped cup still. The steps of the solar still are replaced with a cup shaped tray. An experimental investigation is carried out on the stepped-cup solar still in the climatic condition of Tamilnadu, India.

2. Experimentation

The conventional solar still is constructed using galvanized steel of 1.6 mm thickness in which the base of the solar still is made of a steel box of 600mm length and 600mm breadth. The solar still basin plate is mounted at the height of 550mm at the top and 200mm at the bottom. The glass is mounted over the still at an angle of 30^0 as mentioned in Fig. 1. A transparent tempered glass cover is used in this experiment which acts as a condensing cover and also allows the solar radiation to reach the basin plate. The thickness of the glass is 4mm, height of the glass is 700mm and the breadth is 600mm. The solar still is completely sealed with silicon to prevent the vapor escaping out. Water temperature and glass temperatures are measured using thermocouples. On account of solar radiation the temperature of the water inside the still increases and condensation process takes place. The water vapor gets condensed on the glass cover. A stopper is provided at the bottom of the glass to collect the condensed water in the collection tank.

The stepped-cup solar still is constructed with the same dimensions as of the conventional solar still. The plain basin plate of the conventional solar still is replaced with steps at an angle of 30^0. The steps of the still are trays that are curved cup like structures as illustrated in Fig. 2. This stepped-cup tray structure can provide more volume of sea water to flow inside the still thereby increasing the amount of condensation. The stepped cups are made up of galvanized steel. The diameter of the cup is 80mm and height of the cup is 40mm. A channel is provided at the top for the sea water to enter the still. The entered water flows down and fills the cup in each step due to gravity. Water temperature and glass temperatures are measured.

The amount of solar radiation obtained may vary from time to time throughout the day. This may cause variation in temperature inside the still and thus varying the efficiency of desalination. To maintain a constant temperature Biomass setup is connected to the still as given in Fig. 3. The term biomass refers to the renewable energy produced from burning or decaying of the organic materials like plant and animal waste and in this experiment the organic waste burnt is the coconut husk. The calorific value of coconut husk is 4,300 K Cal/kg. The dimensions of the biomass boiler are 133 mm outer diameter and 550 mm height. The lower portion of the boiler is called the furnace. The biomass material viz., coconut husk is burnt in the furnace to supply heat to the boiler. The ashes are removed and the coconut husk is added so as to maintain the boiler temperature at 80^0C.Hot water from the biomass boiler enters and flows continuously through the still. Each cup of the still contains two heat exchanger tubes arranged in parallel. Hot water flowing through the tube delivers heat to the sea water present inside the still. This arrangement further increases the temperature of the sea water and thus increases the efficiency of desalination. The inlet and outlet temperatures of heat exchanger are measured using digital temperature indicator. Inlet temperature of heat exchanger is maintained at 80^0C. Valves and pressure gauge are equipped to ensure safety. Hot water is circulated continuously throughout the experiment and the circulation is done by motor pump in the water circuit. The fresh water is collected and the quantity is measured. Fig. 3 gives the experimental setup of stepped-cup solar still with biomass



.

Fig. 1. Construction of conventional solar still

Fig. 2. Construction of stepped-cup solar still

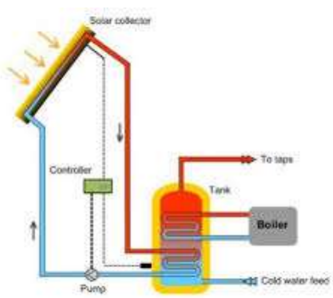


Fig. 3. Construction of stepped-cup solar still with biomass

3. Theoretical Simulation

The hourly yield is calculated theoretically using the energy balance equations associated with the solar still. The energy balance equations have been formulated based on the thermodynamics involved viz., convection, radiation and conduction. The heat loss in the still is mainly due to these three processes.

Energy balance for the basin plate is given by [17],

$$I(t)A_b\alpha_b = m_b c_{pb}(dT_b / dt) + Q_{c,b-w} + Q_{loss} \quad (1)$$

Energy balance for the sea water is given by [17], [18],

Energy balance for

$$I(t)A_w\alpha_w + Q_{c,b-w} = m_w c_{pw}(dT_w / dt) + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} + Q_{fw} \quad (2)$$

the glass cover is given by [17],

$$I(t)A_g\alpha_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} = m_g c_{pg}(dT_g/dt) + Q_{r,g-sky} + Q_{c,g-sky} \quad (3)$$

The hourly distillate yield from the still is given by the following equation,

$$m_{ew}^{\cdot} = h_{e,w-g}(T_w - T_g) * 3600/(h_{fg}) \quad (4)$$

The convective heat transfer between the basin plate and water $Q_{c,b-w}$ is given by [19], [20],

$$Q_{c,b-w} = h_{c,b-w}A_b(T_b - T_w) \quad (5)$$

where $h_{c,b-w}$ is the convective heat transferco-efficient between basin and water and its value is taken as 135 W/m^2 K [19], [20].

Thermal loss due to convection to the ground and surrounding through the sides and base of the basin is given by [21],

$$Q_{loss} = U_b(A_b + A_s) \times (T_b - T_a) \quad (6)$$

Here U_b is the ratio of thermal conductivity to the thickness of the insulation, $U_b = K_i/L_i$

The convective heat transfer from water to the glass is given as follows [19], [20],

$$Q_{c,w-g} = h_{c,w-g}A_w(T_w - T_g) \quad (7)$$

where $h_{c,w-g}$ is the convective heat transferco-efficient between water and glass and is given by [22],

$$h_{c,w-g} = 0.884\left\{(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273.15)}{(268900 - p_w)}\right\}^{1/3} \quad (8)$$

The radiation heat transfer from the basin to glass cover is given by [23],

$$Q_{r,w-g} = \sigma\varepsilon_{wg}A_w[(T_w + 273.15)^4 - (T_g + 273.15)^4] \quad (9)$$

where

$$\varepsilon_{wg} = (1/\varepsilon_w + 1/\varepsilon_g - 1)^{-1} \quad (10)$$

The evaporative heat transfer from the water to the glass is given by [19], [20],

$$Q_{e,w-g} = h_{e,w-g}A_w(T_w - T_g) \quad (11)$$

where $h_{c,b-w}$ is the evaporative heat transferco-efficient between water and glass is given by,

$$h_{e,w-g} = (16.237 \times 10^{-3})h_{c,w-g}(p_w - p_g)/(T_w - T_g) \quad (12)$$

The convective heat transfer between glass and sky, $Q_{c,g-sky}$ is given by [24],

$$Q_{c,g-sky} = h_{c,g-sky}A_g(T_g - T_{sky}) \quad (13)$$

where $h_{c,g-sky}$ is given by [24],

$$h_{c,g-sky} = 2.8 + 3.0V \tag{14}$$

The amount of radiative heat transferred from the glass to the sky is given by [19], [20],

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \tag{15}$$

where $h_{r,g\text{-}sky}$ is the radiative heat transferco-efficient between glass and sky is given by [19], [20],

$$h_{r,g-sky} = \varepsilon\sigma[(T_g + 273)^4 - (T_{sky} + 273)^4]/(T_g - T_{sky}) \tag{16}$$

where T_{sky} is the sky temperature and is given by [24],

$$T_{sky} = T_a - 6 \tag{17}$$

4. Error Analysis

Digital temperature indicator, Kipp–Zonan solarimeter,vane type digital anemometers, andbeakerare used to measure temperature, solar intensity, wind velocity and the amount of distillate collected.

5. Result and discussion

A solar still was constructed with aforementioned dimensions. Experiment was done for the desalination of sea water using this set up under the climatic condition of Tamilnadu, India and the results have been analyzed.

5.1. Conventional solar still

Sea water was passed into the conventional solar still via inlet. The water gets condensed and was collected at the outlet placed at the bottom of the still. The water temperature and glass temperature of the conventional solar still was measured periodically at every hour using thermocouples. The variation of the water temperature throughout the day is plotted in Fig. 4. It is seen that the temperature is low at morning, high around noon and decreases in the evening. Hourly productivity is plotted against time and is shown in Fig. 5. It is apparent that the productivity of the desalinated water increases with increase in temperature.

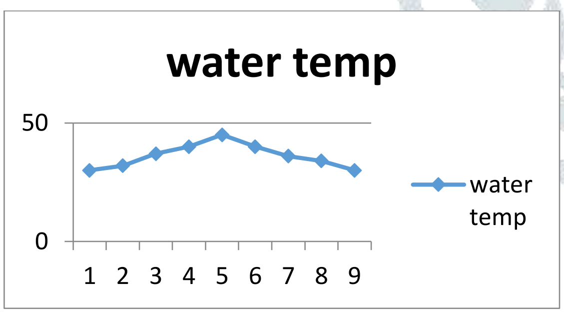


Fig.4 Effect of temperature

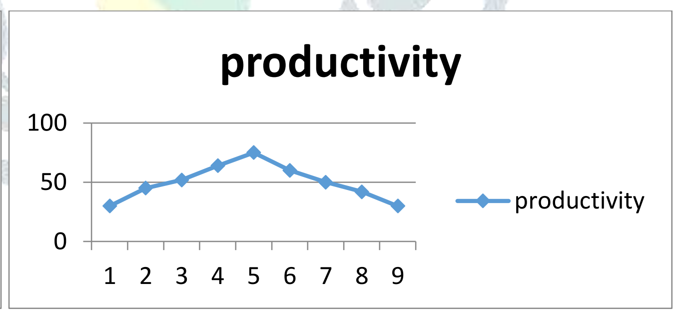


Fig.5 Effect of productivity

5.2. Stepped-cup solar still

Desalinated sea water from the stepped-cup set up was collected every hour. The water temperature, glass temperature and productivity of the collected desalinated water were measured. The variation of the water temperature throughout the day is plotted in Fig.5. It is seen that the temperature is low at morning, high around noon and decreases in the evening. In Fig.6, the productivity of desalinated water is plotted against time. The productivity increases at higher temperatures. It has been observed that the efficiency of desalination process increases due to the stepped-cup design proposed in this paper.Productivity reaches peak value around 14.00 to 15.00 hours and decreases slightly after 15.00 hours. There is no drastic decrease in the productivity after 15.00 hours due to the stepped-cup design. The stepped-cup design retains the temperature inside the still and produces output almost at a constant rate. This construction provides 12% increase in the efficiency compared to the conventional solar still.

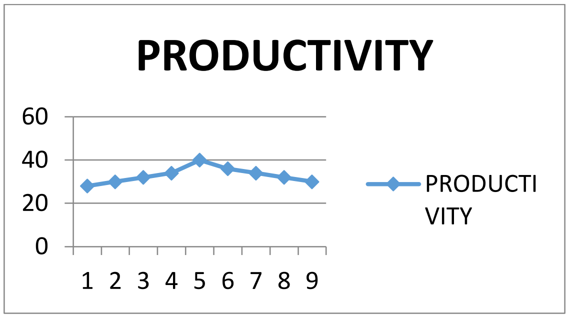


Fig.6 stepped cup production

5.3. Stepped-cup solar still with biomass

Desalinated water was collected every hour after connecting the biomass boiler setup to the stepped-cup solar still. The water temperature, glass temperature, inlet and outlet temperatures of the heat exchanger and productivity of the collected desalinated water were measured. Water temperature variation throughout the day is plotted in Fig.7. It is observed that after the addition of biomass boiler higher temperature is maintained throughout the day.

Productivity of desalinated water using stepped-cup solar still with and without biomass is compared with the productivity of a conventional solar still and is plotted in Fig.6. It is evident that the efficiency of desalination of sea water has increased by 12% using the stepped-cup design. Also there is an abundant 70% increase in the productivity after the addition of biomass boiler to the stepped-cup solar still when compared to the conventional solar still. Water has to be sprinkled over the glass at regular interval to avoid over heating of glass.

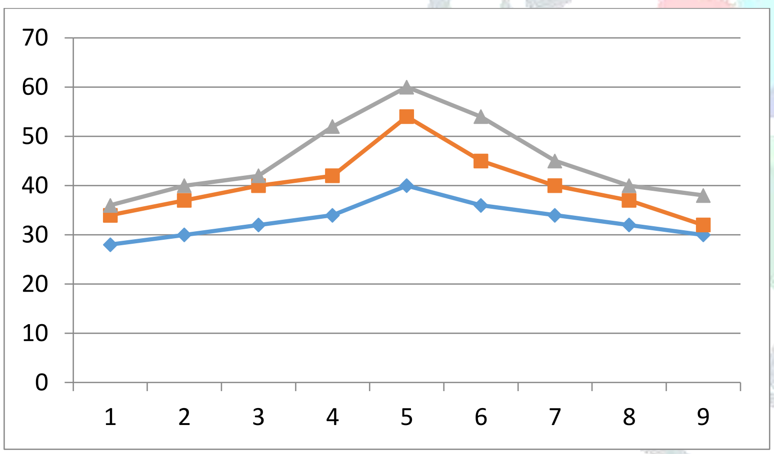


Fig. 7. Comparison of productivity vs time in conventional, stepped-cup and stepped-cup with biomass stills

5.4. Effect of output in solar mode and biomass modes

Productivity of conventional solar still is compared with the productivity of stepped-cup solar still and is plotted in Fig. 8. Increasing time tends to increase the water temperature of the still and hence increases the productivity. Stepped-cup solar still produces output at higher rate compared to the conventional still. In conventional solar still Productivity is highest during 12.00 to 13.00 hours. Whereas in stepped-cup solar still water temperature increases during peak hours and it is maintained even after the peak hours. The productivity is highest during 14.00 to 15.00 hours because of the stepped-cup design proposed in this paper. Stepped-cup still maintains the water temperature till 15.00 hours. Stepped-cup still shows 12% increase in productivity compared to the conventional solar still.

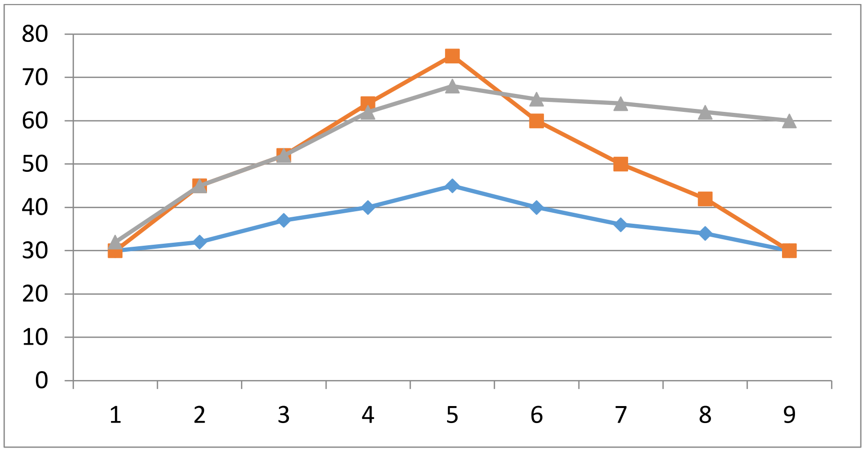


Fig. 8. Productivity of conventional still vs stepped-cup still (solar mode)

6. Conclusion

This paper proposes a novel stepped-cup design for desalination of sea water using solar still. There is 12% increase in the productivity of desalinated water on using this design when compared to the existing conventional solar still. The efficiency of desalination process is further increased by the introduction of biomass to the stepped-cup solar still. On the addition of the biomass boiler setup, a significant 70% increase in the productivity compared to conventional solar still is observed on experimental investigation and comparison of results.

References

1. Moustafa, S.M.A., Brusewitz, G.H., Farmer, D.M., 1979. Direct use of solar energy for water desalination. Solar Energy 22, 141–148.
2. Tiris C, Tiris M, Erdalli Y, Sohmen. Experimental studies on a solar still coupled with a flat-plate collector and a single basin still. Energy Conversion and Management 1998;39:853–6.
3. Zurigat, Y.H., Abu-Arabi, M.K., 2004. Modeling and performance analysis of a regenerative solar desalination unit. Applied Thermal Engineering 24, 1061–1072.
4. Al-Hayek Imad, Badran Omar O. The effect of using different designs of solar stills on water distillation. Desalination 2004;169:121–7.
5. Suleiman, M., Tarawneh, K., 2007. Effect of water depth on the performance evaluation of solar still. Jordan Journal of Mechanicaland Industrial Engineering 1, 23–29.
6. El-Sebaii AA. Thermal performance of a triple-basin solar still. Desalination 2005;174:23–37.
7. Velmurugan V, Mugundhan K, Srithar K. Experimental studies on solar stills integrated with a mini solar pond. Third BSME–ASME international conference on thermal engineering, Dhaka, Bangladesh; 2006.
8. Velmurugan V, Srithar K. Solar stills integrated with a mini solar pond – analytical simulation and experimental validation. Desalination 2007;216:232–41.
9. Velmurugan V, Srithar K. Prospects and scopes of solar pond – a detailedreview. Renewable and Sustainable Energy Review 2008;12:2253–63.
10. Velmurugan V, Senthil Kumaran S, Niranjan Prabhu V, Srithar K. Productivityenhancement of stepped solar still – performance analysis. Thermal Science2008;12:153–63.
11. El-Zahaby, A.M., Kabeel, A.E., Bakry, A.I., El-agouz, S.A., Hawam,O.M., 2010. Augmentation of solar still performance using flashevaporation. Desalination 257, 58–65.
12. A.Senthil Rajan , K.Raja, Multi basin desalination using biomass heat source and using analytical validation using RSM, Energy Conversion and Management 87(2014) 359-366.
13. Kalidasa Murugavel, K., Srithar, K., 2011. Performance study on basin type double slope solar still with different wick materials and minimum mass of water. Renewable Energy 36, 612–620.
14. Kalidasa Murugavel, K., Sivakumar, S., Ahamed Riaz, J., Chockalingam, Kn.K.S.K., Srithar, K., 2010. Single slope still with minimum basin depth and energy storing materials. Applied Energy 87, 514–523.

15. Velmurugan V, Senthil Kumaran S, Niranjan Prabhu V, Srithar K. Productivity enhancement of stepped solar still – performance analysis. Thermal Science2008;12:153–63.
16. Omara, Z.M., Kabeel, A.E., Younes, M.M., 2013. Enhancing thestepped solar still performance using internal reflectors. Desalination314, 67–72.
17. Velmurugan, V., S. Pandiarajan, P. Guruparan, H. Subramanian, D. Prabaharan andK. Srithar,*Integrated performance of stepped and single basin solar stills with mini solar pond*, Desalination 249 (2009) 902–909.
18. Tabrizi, F.F.,M. Dashtban and H. Moghaddam, *Experimental investigation of a weir-type cascade solar still with built-in latent heat thermal energy storage system*, Desalination 260 (2010) 248–253.
19. Velmurugan, V., S.S. Kumaran, N. Prabhu and K. Srithar, *Productivity enhancement of stepped solar still – performance analysis*. Thermal Science 12 (2008) 153–163.
20. Velmurugan, V., K.J.N. Kumar, T.N. Haq and K. Srithar, *Performance analysis in stepped solar still for effluent desalination*, Energy 34 (2009) 1179–1186.
21. Rahul D. and G.N. Tiwari, *Characteristic equation of a passive solar still*, Desalination 245 (2009) 246–265.
22. Velmurugan, V., S. Pandiarajan, P. Guruparan, H. Subramanian, D. Prabaharan and K. Srithar, *Integrated performance of stepped and single basin solar stills with mini solar pond*, Desalination 249 (2009) 902–909.
23. Murugavel, K.K., S. Sivakumar, J. Riaz Ahamed, Kn.K.S.K. Chockalingam and K. Srithar, *Single basin double slope solar still with minimum basin depth and energy storing materials*,Applied Energy 87 (2010) 514–523
24. Yousef, Z.H. and K.A. Mousa, *Modeling and performance analysis of a regenerative solar desalination unit*, Applied Thermal Engineering 24 (2004) 1061–1072.