Chapter 39
Thermal Performance of Improved Inverted Trickle Solar Still

Fadi A. Ghaith and Ahmed Bilal

Abstract In this paper, the inverted trickle solar still was integrated with a flat plate collector and a basin still in order to improve the overall productivity. The flat-plate collector was used to pre-heat the saline water entering the inverted trickle solar still. Saline water flows at the backside of the inclined absorber plate on wire screen so that the water remains attached to the plate. Water evaporates from the plate and condenses in the lower compartment. The remaining non evaporated water and the condensed water on the back plate which has high temperature was collected and fed to the basin solar still. A comprehensive mathematical thermal model was developed to predict the productivity and to investigate the effects of several operating conditions on the overall productivity of the integrated system. Based on the performed parametric studies, the maximum mass flow rate of 0.002 kg/s was found to be optimum as it maximized both the efficiency and the productivity of the integrated solar still system. On the other hand, the obtained results at the optimum flow rate showed that the maximum overall productivity on a typical summer day (i.e. 1st of July) and a typical winter day (i.e. 1st of February) were 11.25 kg/day and 5.227 kg/day, respectively for Dubai weather conditions. This study revealed that the productivity of the proposed integrated inverted trickle solar still is almost doubled due to the incorporation of flat plate collector in comparison of the previous work posted in the literature.

Keywords Integrated inverted trickle solar still · Basin solar still · Productivity

List of symbols

A_c	Area of Flat plate collector, m^2
U_L	Total loss coefficient, W/m^2K
$\dot{m}$	Mass flow rate of water, kg/s

F. A. Ghaith (✉) · A. Bilal
Department of Mechanical Engineering, Heriot-Watt University,
P.O. Box 294345, Dubai, The United Arab Emirates
e-mail: f.ghaith@hw.ac.uk

M. O. Hamdan et al. (eds.), *ICREGA'14 - Renewable Energy: Generation and Applications*, Springer Proceedings in Energy, DOI: 10.1007/978-3-319-05708-8_39,
© Springer International Publishing Switzerland 2014

G_t	Absorbed solar radiation, W/m^2
$(\tau\alpha)_e$	Effective transmittance absorptance
T_{fi}	Inlet temperature of fluid, K
T_{fo}	Outlet temperature of fluid, K
T_{pm}	Mean absorber plate temperature still, K
T_a	Ambient temperature, K
Q_u	Useful energy gain, W
η_f	Efficiency of flat plate collector
q_b	Heat loss from lower condenser plate, W/m^2
q_{p-c}	Heat loss from plate to cover, W/m^2
q_{c-a}	Heat loss from cover to ambient, W/m^2
q_s	Heat loss from sides per unit still area, W/m^2
A_{ic}	Area of collector for Inverted trickle Solar still, m^2
T_{io}	Outlet temperature of water from Inverted trickle, K
T_{ii}	Inlet temperature of water of inverted trickle solar still, K
T_w	Condenser wall temperature, K
h_0	Heat transfer coefficient between condenser and ambient, W/m^{2}K
U_2	Overall heat loss coefficient from plate to cover, W/m^{2}K
U_e	Heat transfer coefficient from the sides of the still, W/m^{2}K
M	Productivity of distillate water, kg/s
h_{fg}	Heat of vaporization of water, KJ/Kg
η_i	Efficiency of the Inverted Trickle Solar still
q_{be}	Heat transfer by evaporation-condensation, W/m^2
q_r	Heat loss by radiation, W/m^2
q_c	Heat loss by convection, W/m^2
q_k	Heat loss by conduction, W/m^2
T_b	Basin temperature, K
T_g	Glass temperature, K
A_b	Area of basin solar still, m^2
η_{bi}	Efficiency of basin solar still
M_b	Productivity of basin solar still, kg/s

39.1 Introduction

Water sustains health, food production, and economic progress of nations. Therefore; fresh and clean water is an urgent need for survival of mankind. Around 97 % of the world's water is either saline or contaminated with harmful bacteria, 2 % is frozen in polar ice caps and glaciers whereas only 1 % of the world's water is available for drinking and for domestic purposes readily [1]. In many countries there is a vital need for immediate supply of quality drinking water. Apart from the saline water even brackish water available from ponds, lakes and rivers is usually contaminated with dissolved salts and bacteria therefore not suitable for drinking. Approximately about 67 % of the global population has access to clean water, with only 46 % of the people in Africa able to access clean water [2]. Water shortage problem is generally observed in dry and warm countries of Middle East and Africa [3]. According to the predictions of The United Nations, 30 countries will be facing shortage of water, out of which 18 will be in the Middle East and Africa [4]. Desalination is an important and efficient technology in the world, as of 1986 more than 90 % of the world's clean water was a product of fuel fired distillation process [5] but it is the most expensive way to produce water due to its high energy consumption. Furthermore, desalination is not only expensive but also causes severe environmental impacts contributing to global warming. However, a simpler method is solar water distillation that relies on the process of evaporation and condensation of water with the aid of a solar still. With excessive availability of solar radiance, solar distillation becomes an attractive mode of water purification technique. The water distillation process is a simple method for converting salt water into potable water. In understanding current barriers in solar distillation, researchers are coming up with new and innovative designs of solar stills and constantly striving to provide cheap and clean water in abundance, using solar energy.

Solar stills have been widely researched and studied for the improvement of producing clean water using solar energy. Many researchers have evaluated the performance of solar stills by different factors affecting the still which includes solar input, ambient temperature, and depth of water, wind speed and heat losses [6]. The single basin solar still has been the most popular solar still for producing clean water. Salah et al. [7] tested the single basin solar still in Jordan and found the maximum production of distillate to be 0.8 $l/m^2/hr$. and with an overall production of around 4.1 liters/day. In another research by Muhammad Ali et al. [8] in Pakistan the distillate production for the single basin was around 3.15 $liters/day/m^2$ and the efficiency of the system was about 31 %. Badran et al. [9] coupled flat plate collector with a single basin solar still and found higher production of 3.51 liters/day as compared to 2.24 liters/day of single basin without the flat plate collector under those conditions. Abdullah et al. [10] combined sun tracking technology with single basin solar still and found that the productivity increased by 22 % as compared to a fixed system. Tanaka et al. [11] modified the tilted wick solar still with an external flat plate reflector and found that it increased the production of water by 9 %. Furthermore, Ahsan et al. [12] customized the previous models and researched an improved tubular solar still, in which a basin like structure which contains water is surrounded by a circular glass cover, the water evaporates and then condenses on the glass cover. The water flows around the cover and is collected beneath the basin the results showed a production of 5 $kg/m^2/day$. Ali [13] have well researched a distinct design of inverted trickle solar still. It consists of an inclined absorber plate, with water flowing on the back of it with the aid of a wire screen. The water absorbs solar radiation and evaporates. The vapor moves to another compartment where it condenses and with the help of a heat exchanger the heat lost due to condensation is used to preheat the water coming into the still. Based on the conducted study at a fixed flow rate of 0.5 g/s, the condensate productivity was about 2.5 l/day without recovery and 2.8 l/day with recovery, which was a 12 % increase. The intermediate productivity (i.e. the water that drops into the back plate from the wire screen, it is partly clean water) was 5.67 l/day with and 5.75 without recovery. This work has been extended by Badran et al. [14] in 2004, in which experimental studies along with simulation were performed. It was found that the productivity and efficiency increases when the flow rate decreases and also concluded that lower salinity of water led to higher productivity. Moreover, the results from the simulation predicted 35–40 % more than the actual value due to the use of clear sky model. Therefore; the available literature was found useful to develop and extend the concept of inverted trickle solar still in order to enhance the productivity and the efficiency of the solar still. The primary objective of this paper is to investigate the thermal performance and the productivity of the integrated inverted trickle solar still in UAE. This system involves integrating a flat plate collector, inverted solar trickle still and basin type still. This study includes developing a comprehensive thermal model which is utilized to generate wide range of parametric studies in order to predict the overall productivity at different operating conditions and to be compared with available conventional systems in the literature.

39.2 Description of the Integrated Inverted Solar Still

The proposed system consists of integrating the inverted trickle solar still with a single basin solar still and a flat plate collector as shown schematically in Fig. 39.1. Water flows from the main tank into the flat plate collector of an area of 1 m^2 in which it is heated and then flows into the inverted trickle solar still as illustrated by Fig. 39.2. The inverted trickle solar still is a device in which the raw water flows as a thin layer attached to the backside of an inclined metallic absorber. Water is kept attached to the plate by means of a wire screen welded to it, and a piece of porous material made of jute, covers the absorber plate backside area. Raw water flows by gravity and capillary effects; a process that produces a uniform distribution of water on the absorber backside. The fact that raw water flows in a thin layer and a low flow rate on the backside of the absorber has given the chance for water temperature to be near to that of the absorber plate. The temperature difference between the water and the plate is almost eliminated. This technique enhances the transmitted radiation through the glass cover to reach the raw water without being forced to penetrate the distilled product, as in the conventional basin-type still.

The evaporated vapor moves into the compartment of the inverted trickle solar still where it condenses and then collected in a small water tank. The remaining non evaporated water and the condensed water on the back plate which has high temperature is collected and fed to the basin solar still where again evaporation

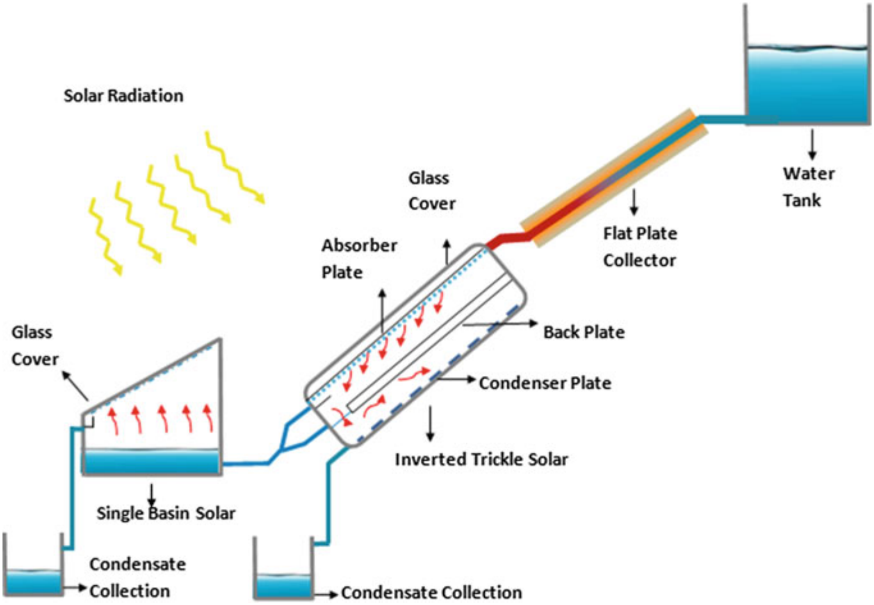

Fig. 39.1 Schematic diagram of the integrated trickle solar still

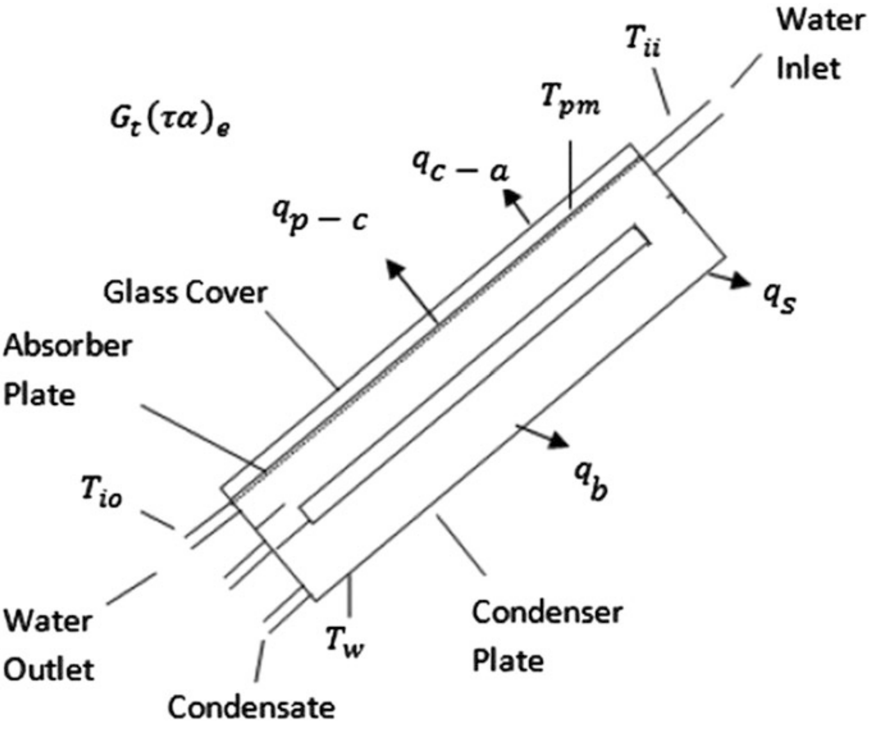

Fig. 39.2 Schematic diagram of the inverted trickle solar still

takes place and distillate is collected. The area of the inverted trickle solar still was chosen to be 1.26 m^2 similar to Badran et al. [14] for the purpose of conducting comparative studies while the area of the basin still is 2 m^2. The advantage of adding a flat plate collector is to pre-heat the water in order to increase the inlet temperature going into the inverted trickle solar still which will enhance the thermal performance and hence the productivity of the still. Moreover, the integration of single basin solar still is a useful addition for producing distillate from partially heated water.

39.3 Mathematical Model

This section describes the basic energy balance equations that govern the thermal performance and the productivity of the proposed integrated still system. The following are the main assumptions underlying this formulation: (i) The system is assumed to be under steady state conditions; (ii) All phases are in thermal and mechanical equilibrium; (iii) The sky can be considered as black body for long-wavelength radiation; (iv) Shading of collector absorber plate is negligible.

39.3.1 Solar Collector

By referring to Fig. 39.3, the useful energy, Q_u collected by the thermal collectors can be related to the incident solar radiation, G and other thermal and optical losses by the following equation [15]:

$$Q_u = A_c F_R \left(G_t (\tau\alpha)_e - U_L \left(T_{fi} - T_a\right)\right) \tag{39.1}$$

The thermal collector efficiency, $\eta_{t,c}$ is defined as a ratio between the output useful energy to the incident radiation on the solar collector and can be expressed mathematically as

$$\eta_f = \frac{Q_u}{A_c G_t}. \tag{39.2}$$

39.3.2 Inverted Trickle Solar Still

By referring to Fig. 39.4, energy balance on the inverted trickle solar still absorber plate can be written as

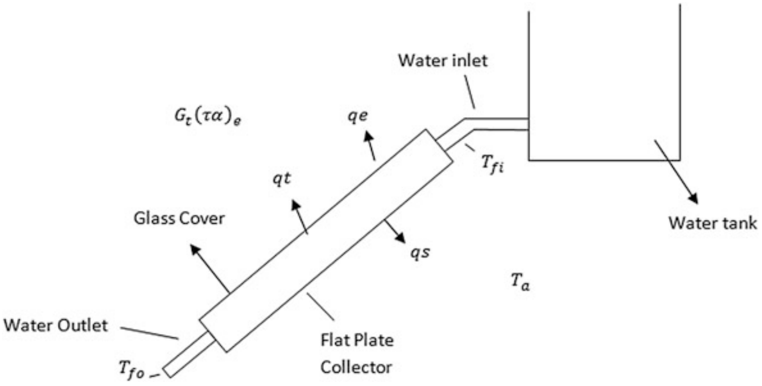

Fig. 39.3 Schematic diagram of the flat plate collector

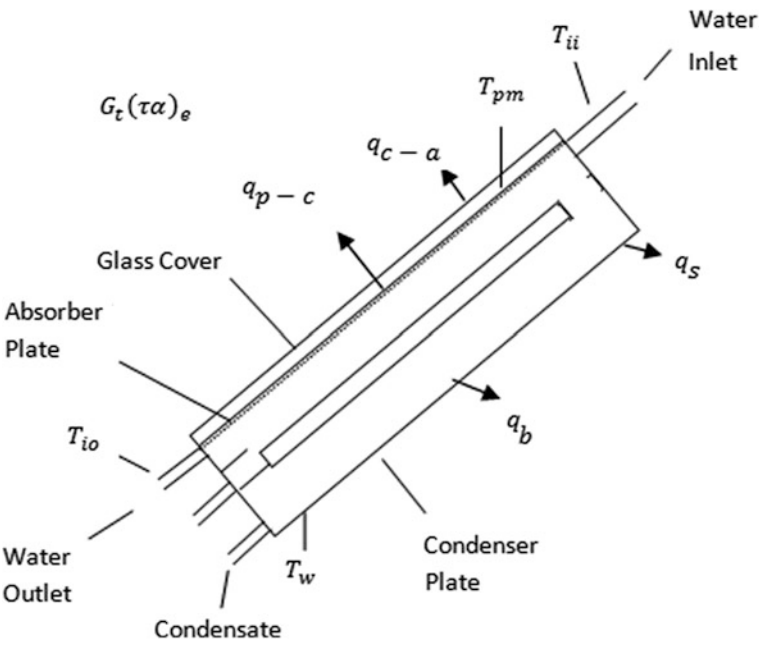

Fig. 39.4 Schematic of the inverted trickle solar still

$$(\tau\alpha)_e G_t = q_b + q_{p-c} + q_s + \left(\frac{\dot{m} - M}{A_{ic}}\right) C_p (T_{io} - T_{ii}) \qquad (39.3)$$

where M is the productivity of the still and q_b is the heat lost from lower condenser plate which can be related to the still productivity by

$$q_b = \frac{M \times hfg}{A} \tag{39.4}$$

Substituting Eq. (39.4) into (39.3) and rearranging terms, the productivity can be written as

$$M = \frac{(\tau\alpha)_e G_t - q_{p-c} - q_s - \left(\frac{\dot{m}}{A_c}\right) C_{pw}(T_{io} - T_{ii})}{\frac{hfg}{A} - \left(\frac{C_p}{A_{ic}}\right)(T_{io} - T_{ii})} \tag{39.5}$$

The heat lost from the lower condenser plate can be also represented as

$$q_b = h_0(T_w - T_a) \tag{39.6}$$

By considering the energy balance on the glass cover, we may write

$$q_{p-c} = q_{c-a} \tag{39.7}$$

The heat lost from the plate to cover can be expressed as

$$q_{p-c} = U_2\left(T_{pm} - T_a\right) \tag{39.8}$$

where U_2 is the top loss coefficient which can be calculated following the steps of Duffie and Beckman [15]. The heat lost from the sides of the still to the ambient can be estimated

$$q_s = U_e\left(T_{pm} - T_a\right) \tag{39.9}$$

where U_e is the edge losses coefficient which can be calculated as

$$U_e = \frac{\frac{Insulation\,Conductivity}{Insulation\,Thickness} \times Perimeter \times Collector\,thickness}{Area\,of\,collector} \tag{39.10}$$

Once all the heat transfer losses are determined using the heat transfer coefficients, they can be substituted into Eq. (39.5) to predict the productivity of the still. Also the efficiency of the still maybe expressed as:

$$\eta_i = \frac{q_b}{G}. \tag{39.11}$$

39.3.3 Basin Type Solar Still

By referring to Fig. 39.5, the energy balance of double slope Basin solar still is given by

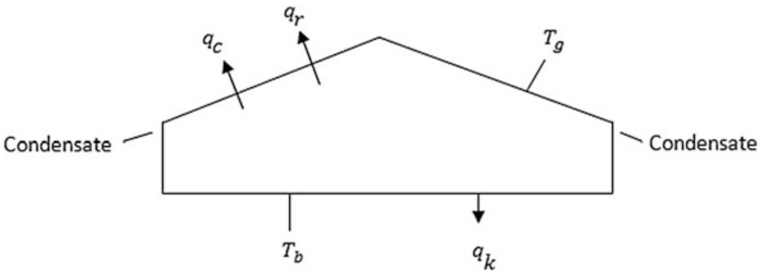

Fig. 39.5 Schematic of the Basin type solar still

$$(\tau\alpha)_e G_t = q_e + q_{r,b-g} + q_{c,b-g} + q_k + \left(\frac{\dot{m}}{A_b}\right) C_p (T_{bo} - T_{bi}) \tag{39.12}$$

The productivity of the basin still can be expressed as

$$M_b = \frac{q_{be} A_b}{h_{fg}} \tag{39.13}$$

where q_{be} is the heat transfer by evaporation-condensation process.

Finally, the efficiency of the basin solar still can be expressed by

$$\eta_{bi} = \frac{q_{be}}{G_t}. \tag{39.14}$$

39.4 Results

Numerical customized algorithm is developed based on the obtained mathematical model described in Sect. 39.3. This algorithm involves energy analyses of integrated inverted solar trickle system. A general-purpose computer simulation program, INSEL was used to predict the radiation levels for Dubai. The software uses the stored metrological data for calculating the radiation on tilted surface. The angle of the slope $\boldsymbol{\beta}$ is taken to be 25° which matches the latitude of Dubai. Figure 39.6 shows the radiation levels for typical day in summer (i.e. 1st of July) and winter (i.e. 1st of February) against the time of the day, as generated from INSEL. It was found that the average radiation for 10 h of sunshine on the 1st of July is 712 W/m^2, while it was found to be about 463 W/m^2 on the 1st of February. The radiations for these two days are considered the basis for the current analysis in order to predict the output productivity from the system and to provide a comparison between the productivity of summer and winter. In order to investigate the effects of water flow rates on the performance of the system, different flow rates were plotted versus the outlet flat plate temperatures as shown in Fig. 39.7. The productivity of the inverted

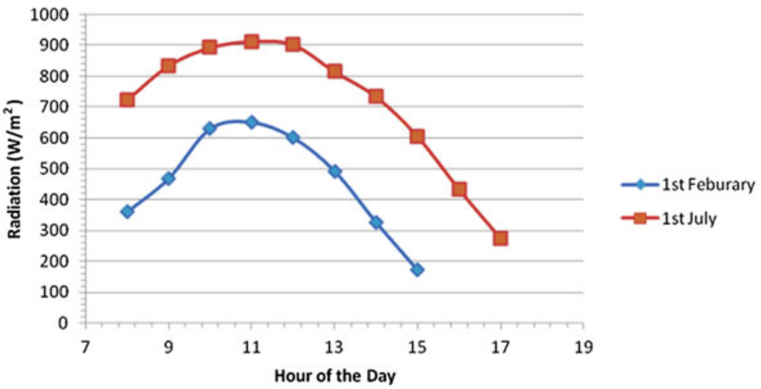

Fig. 39.6 Solar radiation levels at different day hours for typical summer and winter seasons

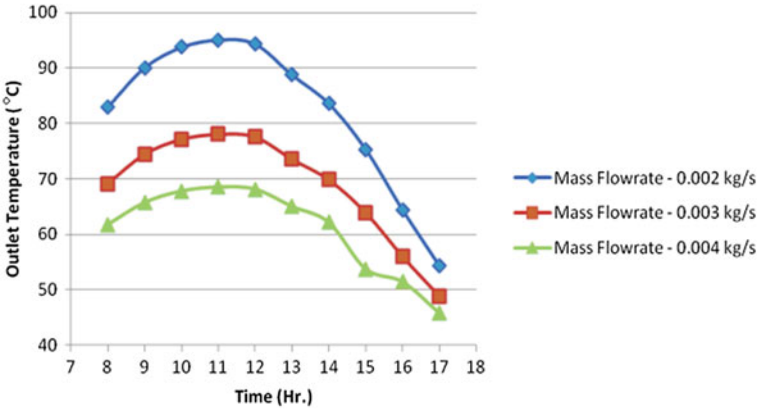

Fig. 39.7 Estimated inverted trickle outlet temperatures versus day hours at different mass flow rates

trickle solar still was determined as shown in Fig. 39.8. Figure 39.7 indicates that at a lower mass flow rate the outlet temperature is generally higher throughout the day, whereas when the flow rate increases, the temperatures decrease as expected. A minimum mass flow rate of 0.002 kg/s was selected since at a lower flow rate than 0.002 kg/s, the water tends to evaporate at the peak solar hours of the day which would damage the system and reduce the productivity significantly. Figure 39.8 shows that at a lower flow rate of 0.002 kg/s, the productivity of the inverted trickle solar still is higher and it reaches about 5.9 l/day. Also it was noted as the flow rate increases, the productivity tends to be less because the flow requires higher energy to reach the temperature for evaporation.

As the inverted trickle solar still in operation, some of the water drips back in the back plate and some of the water that doesn't evaporate flows into the single basin solar still. The water from the inverted trickle solar still is allowed to flow into the

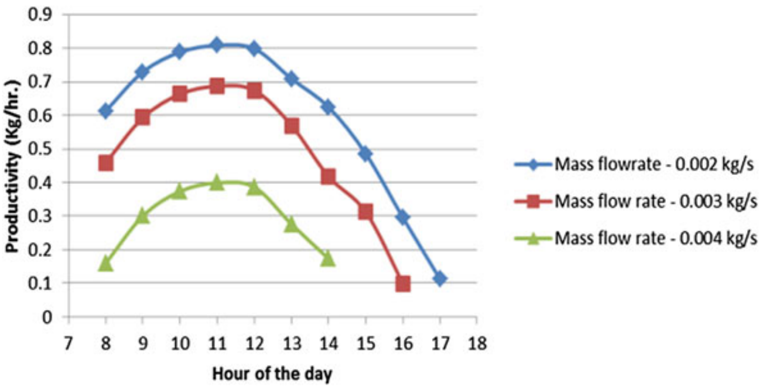

Fig. 39.8 Estimated inverted trickle productivity versus day hours at different mass flow rates in typical summer day

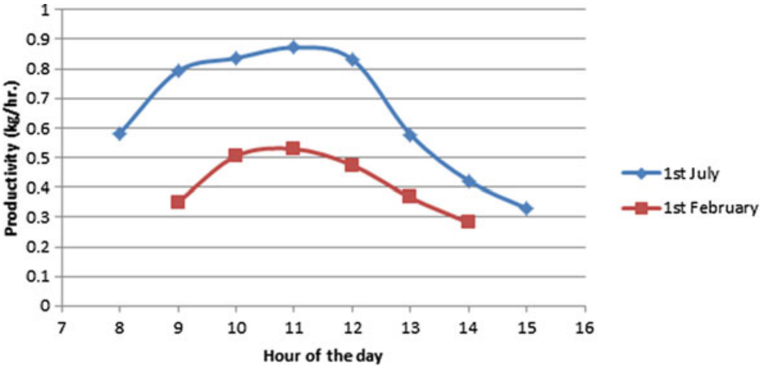

Fig. 39.9 Estimated productivity of the basin solar still versus day hours for selected summer and winter days

basin still during the peak 4 h of radiation when the temperature of the water is expected to be maximum. At a flow rate of 0.002 kg/s approximately 28 kg of water flows into the basin still. To sustain this amount of water an area of 2 m^2 is selected, which would also give an optimum depth of water in the still. Figure 39.9 shows the productivity of the basin solar still as a function of a day operating hours. It is shown that the basin solar still operates for 8 h during the summer and for 6 h during the winter, set according to the amount of sunshine available. Based on Fig. 39.9, one can find that the total productivity of the basin solar still is 5.24 kg/day in the summer (i.e. 1st of July) and around 2.51 kg/day in winter (i.e. 1st of February). Figure 39.10 shows the overall productivity of the integrated solar still system against the day hours. It was found that the total productivity of the complete system is 11.21 kg/day on the 1st of July and 5.23 kg/day on the 1st of February. In order to

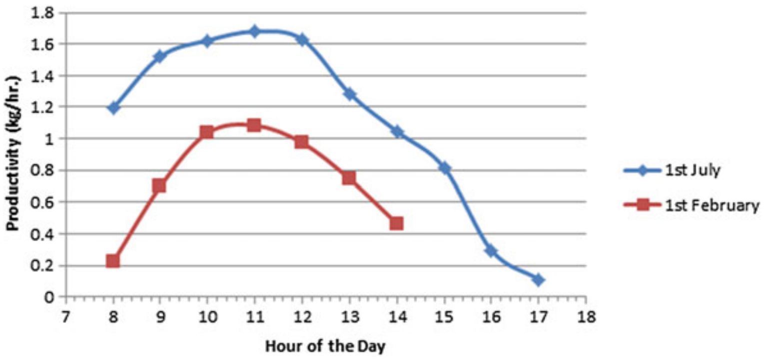

Fig. 39.10 Estimated productivity of the overall integrated solar still system versus day hours for selected summer and winter days

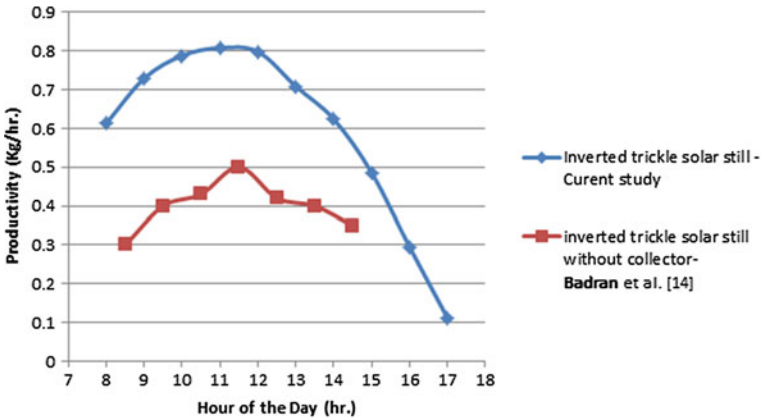

Fig. 39.11 Comparison between the proposed integrated solar still and simple inverted tickle in terms of the productivity

validate the feasibility and efficiency of the proposed integrated solar still system with the solar stills reported in the literature, a comparative study was established between the proposed integrated system in this work and the inverted trickle solar still tested by Badran et al. [14]. The test was performed on the 1st of July in Jordan with operating period of 7 h and the radiation was comparable to that of Dubai. The productivity was around 2.8 l/day with a maximum efficiency of around 20 % at a flow rate of 0.0007 kg/s. It should be noted that the previous design consisted of a heat exchanger in the condenser compartment. The inlet water would flow through the heat exchanger and absorb heat from the vapor and in this process; it would speed up condensation and pre-heat the water as well. However, the improved design consists of a flat-plate collector to pre-heat the water entering the inverted trickle solar still and accordingly there is no need for heat recovery. Figure 39.11

showed that the inverted trickle solar still within study was sufficient to produce around 5.068 l/day when operating for 7 h while it was only 2.8 l/day in the absence of the pre-heating collector.

39.5 Conclusions

In this work, an integrated inverted trickle solar still was investigated. The proposed system consists of flat plate collector to pre-heat the water which was fed to the inverted trickle solar still. The remaining water which either drips back in the back plate and/or doesn't evaporate inside the inverted trickle solar still was utilized in the basin solar still. A comprehensive mathematical model was developed in order to study the heat transfer mechanisms and energy balances associated with steady state operation. The obtained mathematical model was found to be efficient and reliable to predict the collector and inverted trickle solar still outlet temperatures and to estimate the overall productivity. Based on several numerical runs, it was found that a flow rate of 0.002 kg/s is optimum for achieving the maximum productivity. It was observed that lowering the flow rate below this value, leads to evaporate water in the flat-plate collector. Upon carrying the simulation for typical summer day (i.e. 1st of July) for Dubai weather conditions, it was found that the overall productivity of this system is 11.21 kg/day which is about 4 times higher than the productivity of the conventional single inverted trickle solar still and also about 4 times higher than the productivity of a single Basin still.

References

1. V. Velmurugan, M. Gopalakrishnan, R. Raghu, K. Srithar, Single basin solar still with fin for enhancing productivity. Energy Convers. Manag. **49**, 2602–2608 (2008)
2. Y. Taamneha, M.M. Taamneh, Performance of pyramid-shaped solar still: experimental study. Desalination **291**, 65–68 (2012)
3. F.F. Tabrizia, M. Dashtbana, H. Moghaddam, K. Razzaghib, Effect of water flow rate on internal heat and mass transfer and daily productivity of a weir-type cascade solar still. Desalination **260**, 239–247 (2010)
4. Paula Koch, Water Scarcity in the Middle East. in *Your Middle East*, http://www.yourmiddleeast.com/features/water-scarcity-in-the-middle-east_5865. Accessed 29 April 2013
5. H.P. Garg, *Advances in Solar Energy Technology* (Riedel Publishing, Amsterdam, 1987)
6. A.E. Kabeel, S.A. El-Agouz, Review of researches and developments on solar stills. Desalination **276**, 1–12 (2011)
7. S. Abdallah, O.O. Badran, M.A.K Mazen, Evaluating thermal performance of a single slope solar still. Desalination **219**, 222–230 (2008)
8. S. Muhammad Ali, K.M. Umar, M Tariq, A Nasir, Design and performance of a simple single basin solar still. Renew. Sustain. Energy Rev. **11**(3), 543–549 (2007)

9. O.O. Badran, H.A. Al-Tahaineh, The effect of coupling a flat-plate collector on the solar still productivity. Desalination **183**, 137–142 (2005)
10. S. Abdullah, O.O. Badran, Sun tracking for productivity enhancement of solar still. Desalination **220**, 669–676 (2008)
11. Hiroshi Tanaka and Yasuhito Nakatake, Improvement of the tilted wick solar still using a flat plate reflector. Desalination **216**, 139–146 (2007)
12. A. Ahsan, M. Imteaz, A. Rahman, B. Yusuf, T. Fukuhara, Design, fabrication and performance analysis of an improved solar still. Desalination **292**, 105–112 (2012)
13. A.A. Badran, Inverted trickle solar still: effect of heat recovery, Desalination **133**, 167–173 (2001)
14. A.A. Badran, L.M. Assaf, K.S. Kayed, F.A. Ghaith, M.I. Hammash, Simulation and experimental study for an inverted trickle solar still. Desalination **164**, 77–85 (2004)
15. J.A. Duffie, W.A. Beckham, *Solar Engineering of Thermal Processes*, 4th edn. (Wiley, New York, 2013)