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Experimental and mathematical evaluation of solar powered still equipped by nano plate as the principle stage of zero discharge desalination process

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Abstract. To start with, finding a sustainable method to produce sweet water and electricity by using renewable energies is one of the most important issues at this time. So, experimental and theoretical analysis of the performance of a closed solar powered still, which is jointed to photovoltaic cells and vacuum pump and equipped by nano plate, as the principle stage of zero discharge desalination process is investigated in this project. Major goal of this work is to reuse the concentrated brine of the Mobin petrochemical complex in order to produce potable, sweet water from effluent saline wastewater and generating electricity in the same time by using solar energy instead of discharging them to the environment. It is observed the increase in brackish water temperature increases the average daily production of solar desalination still considerably. Therefore, the nano plate and vacuum pump are added to augment the evaporation rate. The insolation rate, evaporation rate, the average brackish temperature, ambient temperature, density are investigated during a year 2013. In addition to obtain the capacity of solar powered still, the highest and lowest amount of water and electricity generation are reported during a twelvemonth (2013). Results indicate the average daily production is increased 16%, which represents 7.78 kW.h energy saving comparing with traditional solar still.

Keywords: solar powered desalination still; wastewater; nano plate; zero discharge desalination

1. Introduction

Water is extremely important and necessary to the life, and access to sufficient quantities of safe water for drinking and domestic uses is one of the fundamental human neediness. The problem of shortage of sweet and potable water is increasingly felt in all parts of the world especially in Middle East. This problem every day becomes bigger due to the world natural resources of fresh water are constant but the world population continues to grow rapidly (Velmurugan *et al*. 2001). Additionally most of the water on the earth is seawater or brackish water, non-saline water is just from lack, rivers and aquifers, which is highly contaminated by

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human activities (Fronk *et al*. 2010, Karellas *et al*. 2011). The transformation of seawater, polluted and wastewater to sweet and fresh water can be a good option to solve this problem. In recent years the progress of new technologies such as Multi Stage Flash has given hope for solving the problem of shortage of drinking water. However by using these technologies the problem of lack of sweet water might be solved but it will face the problem of unlimited amount of nonrenewable energy sources and also global warming of climate changing. In this distillation process, source water is heated and vaporized; and then condensed, whereas concentrated brine is produced as a residual and also consume a big amount of fossil fuel. In addition according to statists the oil and gas reserves even with the same oil extraction rate as in 1995 of 3.32 billion tons per day and gas extraction of 2.3 trillion m^3 the recourses will be finished by about 2040 and 2050 respectively. However the highest worldwide amount of extraction is predicted to be reached during 2010 and 2020. In other hand the environment and the climate are being dramatically changed and damaged to an ever-greater extent by the burning of fossil fuels (Klausner *et al*. 2004). The cause of this is the emission of hazardous substances such as sulphur dioxide; oxides of nitrogen and carbon dioxide connected with the incineration processes. Moreover generating electricity by using coal, gas and oil generate large amounts of pollution or carbon dioxide emissions, therefore, increasing health risks. So using of solar energy may also guarantee water production when nonrenewable energy sources are finished. Thus the use of solar energy for the production of fresh water seems to be an excellent choice due to many significant advantages. It is the most environmentally friendly, pollution-free, self-contained, reliable, quiet, long-term, maintenance-free, year-round continuous and unlimited operation at moderate costs form of all energies that can be used for desalination. Therefore to achieve the goal of providing a sustainable source of inexpensive potable fresh water and also generating electricity using solar energy, the solar closed powered desalination still is introduced. Solar closed desalination power still is one the promising technology to produce drinking water from effluent saline wastewater and generate electricity by solar cells instead of discharging them to the sea or desert, which causes major environmental problems. So polluting and damaging the environment specially the sea will be prevented relevantly by using this technique. Solar desalination systems have been classified in many ways, i.e., direct and indirect systems or in other definition the solar distillation systems are also classified as passive and active solar stills. Direct systems use solar energy to produce distillate directly in the solar still or collector, whereas in indirect systems, two sub-systems are employed: one for solar energy collection and one for desalination (Kalogirou *et al*. 2005). The solar still integrated with a heater or solar concentrator panel is generally referred to as an active solar still while others are referred to as passive stills. Water reservoir commonly called solar still is one passive type, which can be used to convert saline, brackish water into drinking water. In this case, some techniques like applying single slope in cold climate versus double slope in hot climate, cover cooling, using an additional condenser and injecting black dye in the wastewater can have operating performance augmented. Scholars mostly, have fulfilled their investigation of the technical feasibility of solar stills during 1986 to 199 5 (Ortiz *et al*. 2008, Al-Hussaini *et al*. 1995). After that till to 2000, the focus has gone on the development of solar still. Since 2000, economics and thermodynamic efficiency factors have been investigated in order to make it more economically and competitive with other desalination techniques such as RO, multistage flash (MSF), multi effect distillation (MED), ED, etc., which some of them (i.e., MED and MSF) employ with direct use of fuel energies (Mink *et al*. 1998, Zhao *et al*. 2009). Farshad Farahbod (2013) investigated experimental study of a solar desalination pond, as second stage in proposed zero discharge desalination process. He also worked on experimental study of solar pond coupled with forced circulation crystallizer, as major stages of proposed zero discharge desalination process in the same year. Generally solar stills represent one of the simplest methods for directly collecting solar irradiation and converting it to thermal energy. Moreover, it is a solar power collector and a thermal storage unit at the same time. The principle of the salinity gradient solar still, on the other hand, is to prevent vertical convection and/or evaporation (according to the type of solar still). Based on the convection behavior of the saline solution in solar stills, they may be classified into two main categories: non-convecting and convecting solar stills. Totally, solar stills are becoming more popular each day due to many significant reasons such as; combined collection and storage of solar energy, ease of construction and on-demand extraction of heat. Today, the effluent concentrated brine is discharged into the sea. So usage of solar still, in the proposed ZDD unit, prevents salt shocking and thermal shocking, therefore this technique is really helpful to prevent the environment and ecosystem to become more polluted (Farahbod *et al*. 2012, Wong *et al*. 2013). In this experimental work a closed solar powered desalination still as the desalination unit is introduced. In this experimental work, several effective parameters of closed solar powered-still, which is applied to desalination unit, are surveyed. Evaluation of insolation rate in during the day (hourly), annual ambient temperature, and daily insolation rate are studied.

In addition, temperature gradient, evaporation rate, amounts of highest and lowest production, electricity generation and density are investigated in this closed solar powered-still during a year. Additionally, the effect of nano plate, which is directly influenced on efficiency, is surveyed.

2. Materials and methods

2.1 Experimental set up

The closed solar desalination still has a simple geometry. The solar still is formed of a rectangular box, which is equipped with a sloped glass cover. The base of the box is made from stainless steel to prevent corrosion. The floor of solar-powered still is made from zinc oxide Nano plate in order to augment evaporation rate. The top cover of the box is made of transparent glass to allow for the passage of solar energy. The thickness of glass roofs and walls is chosen 4 mm to obtain the most transmissivity coefficient. According to the literature adjustment of the glass cover inclination can increase the production rate by up to 50%. The maximum amount of insolation rate is received when the inclination of the glass roof equals to the latitude of area. Therefore the net evaporation rate area of solar desalination still is $1m^2$, facing south with an inclination of 35.7^oC (the latitude of Tehran city) to achieve the most solar radiation. Insolation rate is the amount of radiant energy from the Sun which impacts upon a unit surface area. This depends upon the angle of the Sun with respect to the vertical over the surface. Also, the surface of solar still bottom is dyed black. The solar still area consists of 3 parts, which are separated by means of 2 long rectangles. The middle part is filled with the concentrated brine wastewater and its level is 100 cm. So, the maximum amount of solar insolation rate is absorbed in these conditions. The feed is conveyed into the still through a 2 cm diameter hole, the distillate is collected into a vessel and concentrated brine wastewater is drained through another 2 cm diameter hole. The photograph of used closed solar powered still is shown in Fig. 1. The floor of used solar still is situated a nano plate. This floor is black and is made from nano particles of zinc oxide. This choice is helped to enhance the trapped thermal energy.

Fig. 1 The photograph of used closed solar powered still

3. Methods

The function of solar still is very simple; basically. The glass covers enclose a still of saline wastewater. Gradually concentrated brine traps solar energy within the enclosure (Leblanc *et al*. 2011, Mahdi *et al*. 2011).

This heats up the water causing evaporation and condensation on the inner face of the sloping glass covers. Distillate is accumulated in side parts of the solar still and is drained into collector vessels ultimately. The produced water is generally potable; the quality of the distillate is very high because all the salts, inorganic and organic components are left behind in the still. Generally, the evaporation rate is defined as the amount of liquid evaporates per square meter per day. The properties of air such as moisture content and temperature, insolation rate and wind velocity affect on this rate. The specific gravity and temperature are evaluated in each part of the solar still. Also, evaporation rate, average ambient temperature, density, viscosity, average temperature of different layers, insolation rate, maximum and minimum values of production rate is measured in this work. The specific gravity of the layers is calculated by weight-volume method.

Initial volume and initial salinity percentage of feed of solar still are 1000 Liters and 5.45%, respectively. The height of brine wastewater in solar still is 100 cm and it is divided to 5 parts therefore the height of each part is 20 cm. Distillate exit from two sides of still continuously, so the system remains under non-equilibrium condition. Concentrated wastewater is drained when the concentration reaches 20% and solar desalination still is recharged with wastewater that contains 5.45% of salinity. In the proposed next stage, saline water will be saturated in forced circulation crystallizer. The maintenance cost of the used solar-powered still is not significant comparing with the other technologies and other systems. The quality of produced water is very high because the

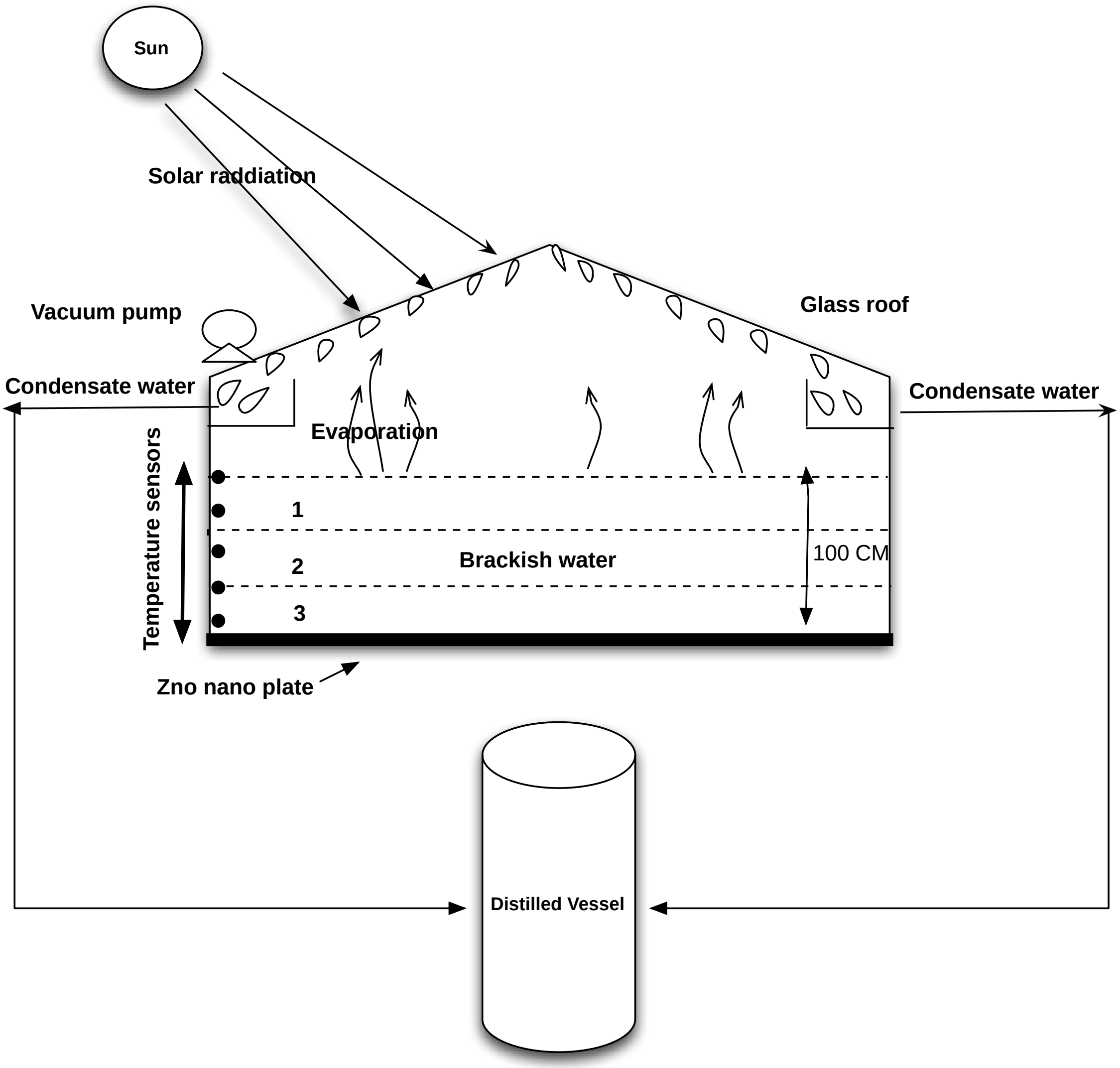

Fig. 2 The schematic of the used solar powered desalination still

evaporation method is utilized in the closed system. The schematic of the used solar powered desalination still is shown in Fig. 2.

4. Results and discussion

The main goal of this experimental project is to produce fresh and sweet water from brackish wastewater. Clearly the increase in brackish water temperature increases the average daily production of solar desalination still considerably. So the nano plate and vacuum pump are added to augment the evaporation rate. Therefore experiments are held to find the effect of nano plate and vacuum pump on solar energy adsorption. The vacuum pump pulls out the water vapor slightly

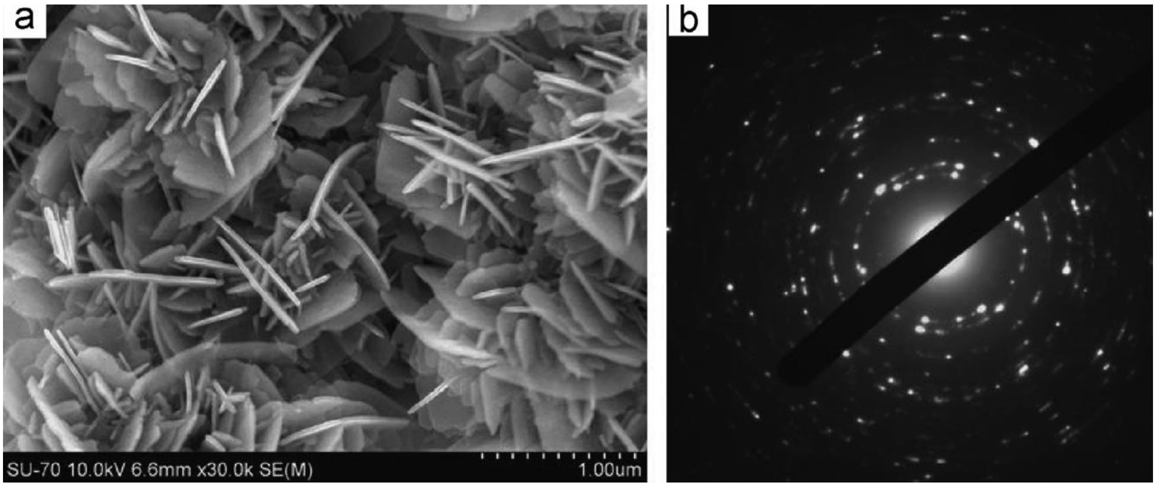

Fig. 3 Photos of zinc oxide nano particles

from the solar box and improves the vaporization. So, the effect of weather moisture and wind velocity on the vaporization may be minor comparing with the effect of insolation rate.

4.1 Nano plate

To increase the closed solar powered still efficiency, the nano plate is situated under the proposed solar still as the floor. The used material for making this plate is zinc oxide nano particles (Farahbod *et al*. 2013).

4.1.1 Synthesis method of ZnO nano-sized

Zinc metal is used to make a solution containing one molar Zn^{2+} ion. At first, this solution is purified, and then a type of surface-active reagent (zinc acetate dehydrate) 0.05 M is added. At the next step, approximately, 10% of ethanol is added under the ultrasonic conditions.

The produced solution is agitated for 25 to 30 minutes. The obtained solution will be homogenized after this time interval. Same reagents are added to Na_2CO_3, 1M solution under the same conditions. Then another surface-active reagent (folic acid) is added. The solution is agitated for 30 min again. In the nest step, filtering and washing of the solution is done several times by ethanol and distilled water alternately under the ultrasonic action. The produced substance is prepared to dry for fifty minutes at 80℃. Then it roasted at 450℃ for forty fifty minutes to obtain zinc oxide nano particles. The obtained produced substance has a light yellow colour, and can be characterized by XRD and TEM. Produced spherical particles with the average diameter of 35 -55 nm in size are observed approximately and finally the crystal is pure zinc oxide with hexahedral structure (Farahbod *et al*. 2013). Fig. 3 shows the photos of nano particles in two different visions. The nano plate, which is situated as the floor of solar still is made of zinc oxide nano particles.

The insolation rate, evaporation rate, the average brackish temperature, ambient temperature, density are investigated during a year (2013). The amount of insolation rate during a year is shown in Fig. 4 (2013).

Insolation rate is defined as the amount of sun irritation. In this experimental work insolation rate is considered as the most important independent parameter on solar powered still efficiency.

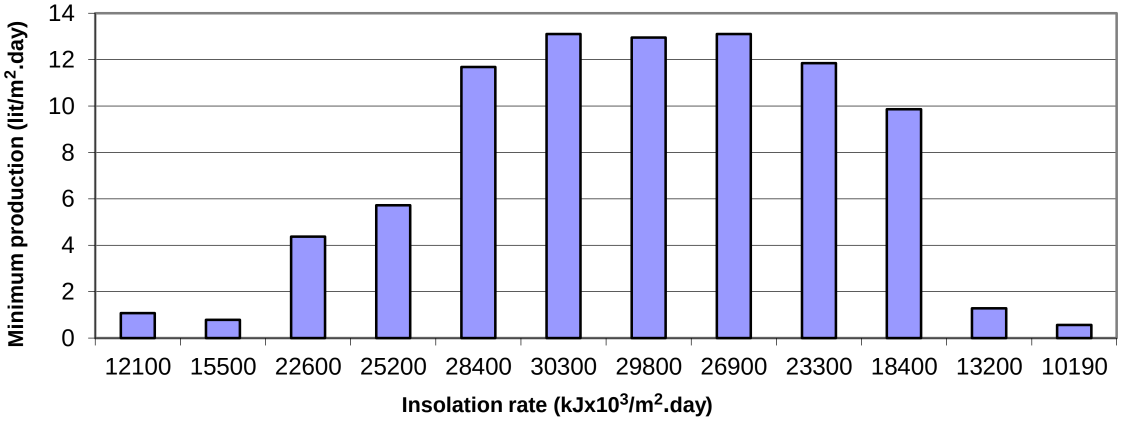

Fig. 4 The insolation rate in different months of year (2013)

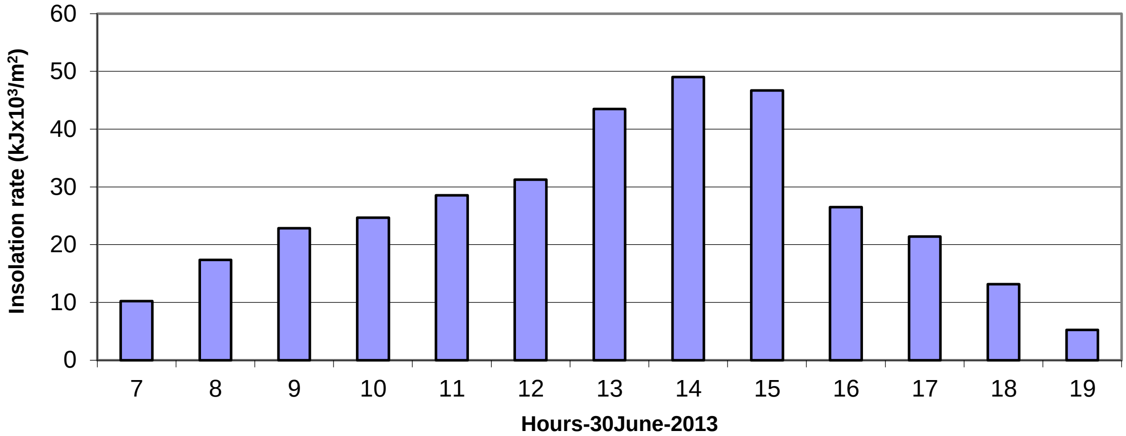

Fig. 5 Variation of insolation rate with time (7 a.m. till 7 p.m.) in Jun. 30, 2013

The highest insolation rate is obtained in June 30300 kJ×10^3/m^2.day and the lowest insolation rate is obtained in December 10190 kJ×10^3/m^2.day. The increase in insolation rate increases the temperature of wastewater inside the solar powered still thereby the solar powered still efficiency is increased. The highest average temperature of wastewater is taken in July 68.96℃. However, the highest insolation rate is obtained in June, higher average temperature value is obtained in July this inconsistency may be related to moisture content in the air due to raining in June, which moderates the ambient temperature. Mathematically the variation in solar radiation during 365 days of a year can be calculated by following expression. This equation is presented by (Aizaz *et al*. 2013).

$$I_0 = I_{sc}[1 + 0.034\cos(2\pi \frac{n}{365.25})] \quad (1)$$

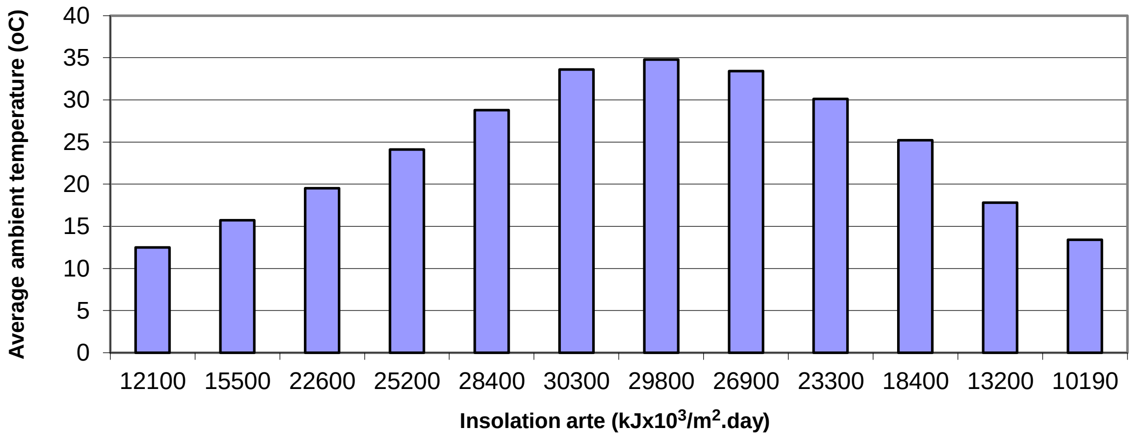

Fig. 6 The variation of average temperature and insolation rate versus different months of 2013

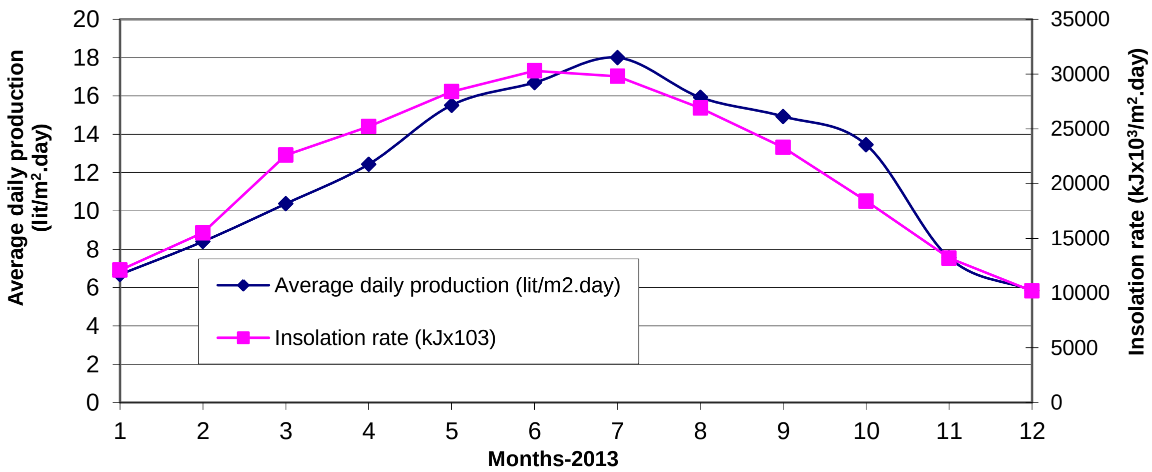

Fig. 7 The variation of average daily production versus insolation rate

Due to the maximum value of insolation rate is obtained in June; June 30 is selected for the investigation of variation of insolation rate, hourly, for 12 h. This variation is shown in Fig. 5. According to Fig. 5, the maximum value of insolation rate is 49.015 kJ×10^3/m^2.day and it occurred at 2 p.m. on Jun. 30, 2013. However the lowest insolation rate is occurred at 7 pm.

Fig. 6 shows the amount of insolation rate and the average temperature of wastewater during a year. Three zones can be considered in wastewater with different mechanisms of heat transfer. Temperature sensors are located each 20 cm in wastewater and Fig. 7 shows the average temperature of five layers of wastewater.

Highest and lowest amount of insolation rate is obtained on June and December, respectively with at least 20000 kJ/m^2.day differences. The increase in wastewater average temperature with the increase in insolation rate is predictable. However, with the same amount of insolation rate on November and March, higher average temperature value is obtained on March and this might be

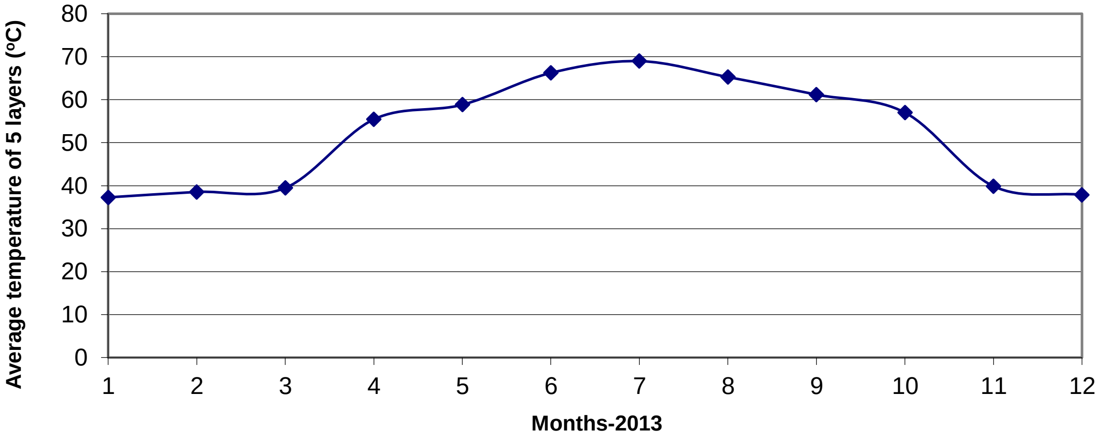

Fig. 8 Average tempreture of layers of wastewater versus months

related to regular windy days on the last month of fall.

The variation of average daily production versus insolation rate is shown in Fig. 7. Evaporation rate indicates the performance efficiency of solar desalination still. Experimental results show maximum and minimum rate of water production is reported in July, 18 lit/m^2.day and on December, 5.8 lit/m^2 day, respectively. Although the amount of insolation rate in January and November is the same approximately but the value of water production on January is less than what is measured on November. This may be related to higher relative humidity and lower temperature difference between ambient and layer 1 on January, which affect the amount of evaporation rate.

Eq. (2), (3) is represented to predict the amount of evaporation rate, the difference between wastewater average temperature, T_w, and one average temperature, T_{ave}, is considered as driving force. Eq. (4) shows a definition for the average temperature. Evaporative heat transfer coefficient is also dependent on this difference. These equations are defined by (Medugu *et al*. 2009).

$$dM_e \, / \, dt = h_{e,w-g}(T_{w-} \; T_g \;) \;/\; h_{lv} \tag{2}$$

$$dM_e \, / \, dt = h_{e,w-g}(T_{w-} \; T_{ave} \;) \;/\; h_{lv} \tag{3}$$

$$T_{ave} \;=\; 0.8 \; T_g \; + 0.2 \, T_s \tag{4}$$

Experimental values of glass temperature, T_g, and basin surface temperature, T_s, are used in this equation. The average temperature of layers of wastewater versus months is illustrated in Fig. 8. As it is predictable the highest average temperature is obtained in summer 68.96℃.

Theoretically, the brine temperature depends on the insolation rate according to unsteady state energy balance, which is shown in

$$E_{ph.cell} + I\alpha_w A_w + H_{c,w-s} \; - H_{c,w-g} - H_{r,w-g} - H_{e,w-g} - \; Q_{loss.ph.cell} \; = M_w C_w (dt_w / d_t) \tag{5}$$

Temperature difference is the major driving force for heat transferring, Eqs. (6)-(9) show this

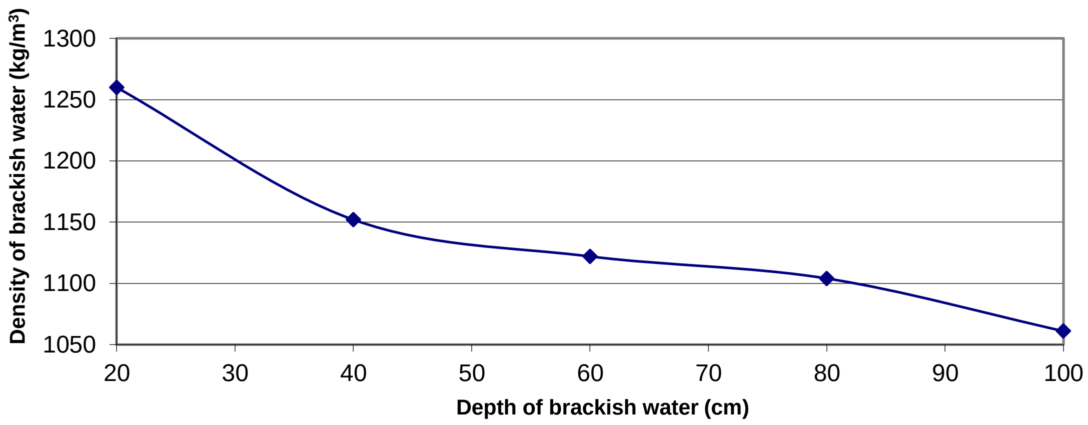

Fig. 9 Density of wastewater through the depth

where the surface of wastewater is A_w, the specific heat capacity coefficient of wastewater is C_w, and M_w and T_w is the weight and the average temperature of the wastewater, respectively.
Glass roof temperature is dependent on the ambient temperature and wind velocity, V. Eq. (10) shows that convective heat transfer coefficient, $H_{c,g-a}$, between glass and ambient, relates to wind velocity and ambient temperature

$$H_{c,w-g} = h_{c,w-g} A_w (T_w - T_g) \quad (6)$$

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

Insolation rate, I, and convective heat transfer between wastewater and black basin surface, H_{c,w_s}, increase the wastewater energy. The brine loses energy by means of radiation heat transfer, $H_{r,w-g}$, and convective heat transfer, $H_{c,w-g}$, between wastewater and glass roof and by evaporation, $H_{e,w-g}$ (Farahbod *et al*. 2012, cooper *et al*. 1973, Gnanadason *et al*. 2011).

$$H_{e,w-g} = H_{e,w-g} A_w \left(T_w - T_g\right) \quad (8)$$

$$H_{c,w\_s} = H_{c,w-s} A_s (T_w - T_g) \quad (9)$$

$$H_{c,g-a} = 2.8 + 3V \quad 10)$$

Fig. 9 shows the density of wastewater through the depth of solar still. The density of concentrated brine wastewater at the bottom of solar desalination still reaches to 1260 Kg/m^3. The higher concentration decreases the thermal conductivity of wastewater and increases the thermal resistance of lower layers. Nano plate adsorbs irradiation and increases temperature of the adjacent layer of wastewater but higher thermal resistance of the layer decreases the rate of heat transfer to the upper layers. So, the highest thermal energy is saved in this region of the solar desalination still. Experiments show the density of wastewater reduces sharply to 40 cm depth and then has slight reduction to 20 cm. The density reaches 1061 Kg/m^3 at the surface of concentrated wastewater.

Srithar and Mani have calculated the specific heat coefficient of brackish water, c_w. These

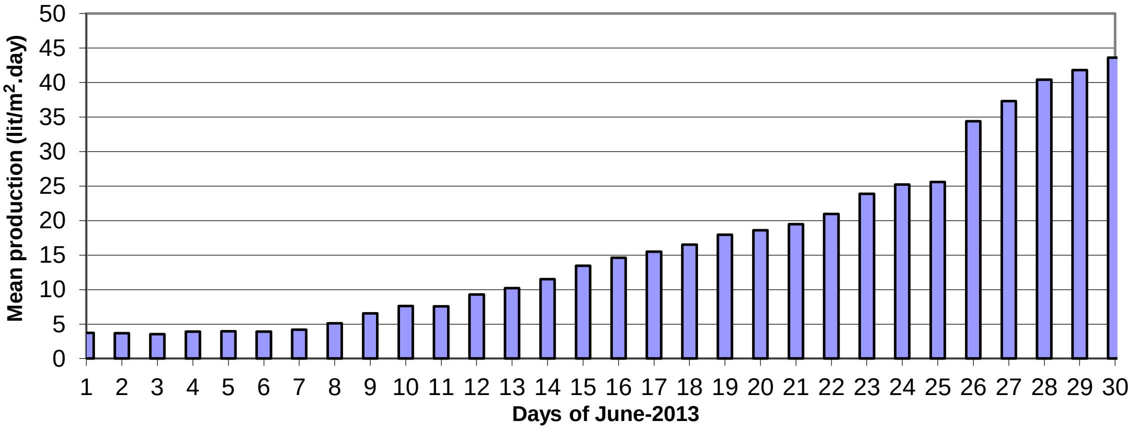

Fig. 10 Amount of produced potable water during June 2013

equations show the dependency of c_w on the salinity percentage (Srithar *et al*. 2004).

$$c_w = A + BT_W + CT^2w + DT^3w \tag{11}$$

$$A = 4206.8 - 6.6197\xi + 1.2288\times 10^{-2}\xi^2 \tag{12}$$

$$B = -1.1262 + 5.4178\times 10^{-2}\xi - 2.2719 \times 10^{-4}\xi^2 \tag{13}$$

$$C = -1.2026\times 10^{-2} - 5.5366\times 10^{4}\xi + 1.8906\times 10^{-6}\xi^2 \tag{14}$$

$$D = 6.8774\times 10^{-7} + 1.517 \times 10^{-6}\xi - 4.4268 \times 10^{-9}\xi^2 \tag{15}$$

The ξ parameter indicates the salinity percentage of brackish water. Obviously, the specific heat value can increase with the increasing of *A*, *B*, *C*, or *D* constants.

On the other hand, the heat is inclined to accumulate in layer 1 when compared with the other layers. Undoubtedly, this logic causes to utilize these ecofriendly solar energy systems for electricity generation, desalination, hot water applications in agriculture, greenhouse heating, domestic hot water production and space heating and cooling of buildings. Both, insolation rate and ambient temperature near the still are recorded as two significant parameters in heat transfer phenomenon occurred in the still. Obviously, the ambient temperature is a function of insolation rate and varies in seasons, but local data are recorded to consider the effects of other parameters, wind velocity, and humidity, experimentally.

Fig. 10 shows the amount of produced potable water during June 2013. It can say the most important parameter, which directly influences the performance of solar powered still efficiency is insolation rate. The highest insolation rate is obtained in June so June is selected to be analyzed monthly for 30 days. According to the Fig. 10, the amount of produced potable water is increased daily. Moist weather due to rainy days in the last days of spring may cause the lower amount of produced water at the begin of June. The increase in insolation rate, ambient temperature the increase in amount of produced potable water is obtained in dry last days on June. According to Fig. 10, the maximum amount of water production is 43.6 Lit/m^2 and it occurred on 30 June 2013.

The Investigation of electricity generation and energy saving is illustrated in Fig. 11. Insolation

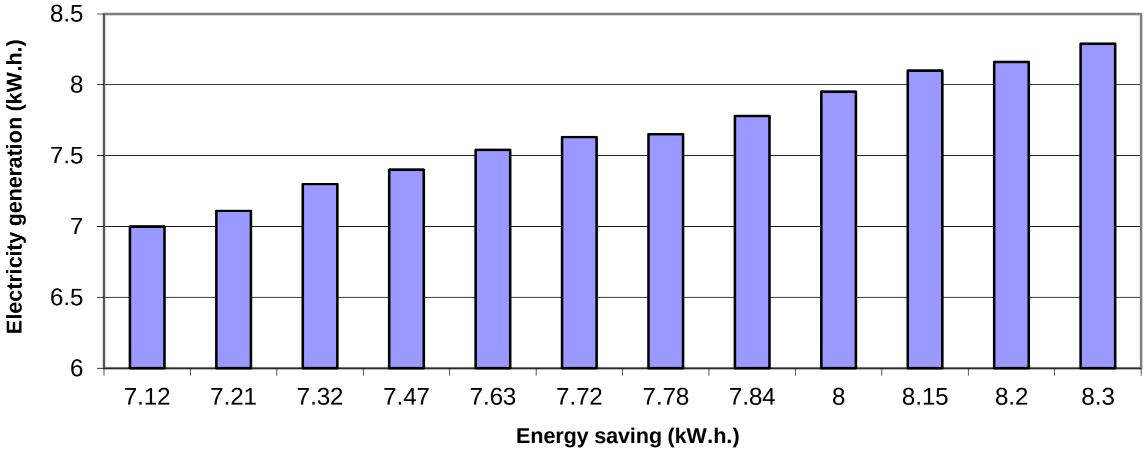

Fig. 11 Investigation of electricity generation and energy saving

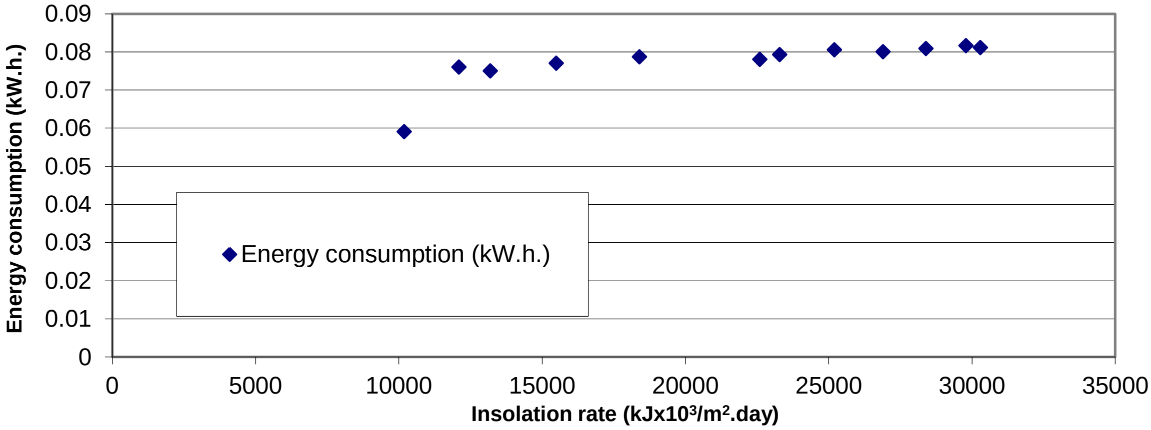

Fig. 12 The values of energy consumption which vacuum pump used versus insolation rate

rate is an important factor in energy production by solar cell in the proposed solar powered desalination still. Maximum and minimum amounts of electricity generation are 7.3 and 8.3 kW/m^3.day respectively. Vacuum pump consumes electricity, which is produced by solar cells and helps vaporization by decreasing water vapor pressure on the wastewater. Remained electrical energy is called saved energy. Fig. 12, shows the increase in the amount of generated electricity increases the amount of energy saving. This shows the low amount of electricity required by pump when nano plate is used as the bottom of the solar desalination still.

The comparison between the amount of water production in the proposed solar powered still equipped by nano plate and usual solar still in different months are given in Fig. 13. According to the results, using ZnO nano plate improves the performance efficiency of solar still about 16%. Experimental data prove that efficiency by using this novel solar still is 17% higher than traditional solar power still.

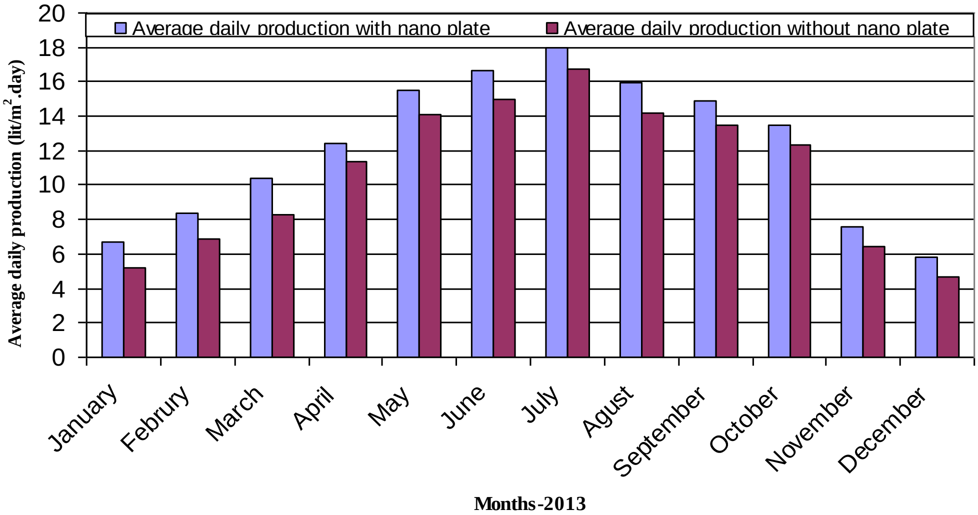

Fig. 13 Comparison between equipped solar powered still and usual solar powered still

5. Conclusions

The energy demand has always been the first and an important driving force in the progress of industrial capability. On the other hand, a solar energy source provides pollution-free, self-contained, reliable, quiet, long-term, maintenance-free, year-round continuous and unlimited operation at moderate costs. In addition the problem of shortage of sweet water is going to be a huge disaster in many parts of the world. Therefore the performance of a closed solar desalination power still is investigated in this work. This solar system reuse concentrated brine to produce distillated water and electricity at the same time. Insolation rate, ambient temperature, average temperature of wastewater, density of wastewater in still, amount of produced water, electrical energy are obtained experimentally. Experiments show the highest average amount of produced water is 18 lit/m^2.day on July which represents 7.78 kW.h energy saving. The effect of ZnO nano plate on solar power still efficiency is reported. Therefore the water production rate in solar powered still equipped with nano plate increased more about 16% comparing with usual solar still. Experimental data prove that efficiency by using this novel solar still is 17% higher than traditional solar powered still. The mentioned solar desalination powered still is totally an environmental friendly and cost saving process competitive with other desalination techniques.

References

Aizaz, A. and Yousaf, R. (2013), “Construction and analysis of a salt gradient solar still for hot water supply”, *Euro. Sci. J.*, **9**, 517-529

Al-Hussaini, H. and Smith, I.K. (1995), “Enhancing of solar still productivity using vacuum technology”, *Energ. Convers. Manage*., **36**, 1047-1051

Cooper, P. I. (1973), “Maximum efficiency of a single effect of solar still”, *Sol. Energy*, **15**, 205-212.

Farahbod, F., Farahmand, S., Fard, M.J.S. and Nikkhahi, M. (2013), “Finding of optimum effective parameters on sweetening of methane gas by zinc oxide nanoparticles”, *J. Nanotech. Eng. Medic.*, **4**(2),

021003.
Farahbod, F., Mowla, D., Jafari Nasr, M.R. and Soltanieh, M. (2012), "Investigation of solar desalination still performance experimentally and mathematically", *J. Energy Resour. Technol*., **134**, 041201.
Farshad, F., Narges B. and Fereshteh. M. (2013), "Effect of solution content ZnO nanoparticles on thermal stability of poly vinyl chloride", *J. Nanotech. Eng. Medic.*, **4**(2), 021001.
Fronk, B.M., Neal. R. and Garimella, S. (2010), "Evolution of the transition to a world driven by renewable energy", *ASME J. Energy Resour. Technol*., **132**(2), 021009.
Gnanadason, M.K., Kumar, P.S., Sivaraman, G. and Samuel Daniel, J.E. (2011), "Design and performance analysis of a modified vacuum single basin solar still", *Smart Grid Renew. Energy,* **2**, 388-395.
Karellas, S., Terzis, K. and Manolakos, D. (2011), "Investigation of an autonomous hybrid solar thermal ORC-PV RO desalination system", *Renew. Energy*, **36**, 583-590.
Klausner, J.F., Li, Y., Darwish, M. and Mei, R. (2004), "Innovative diffusion driven desalination process", *ASME J. Energy Resour. Technol*., **126**(3), 219-225.
Leblanc, J., Akbarzadeh, A., Andrews, J., Lu, H. and Golding, P. (2011), "Heat extraction methods from salinity-gradient solar stills and introduction of a novel system of heat extraction for improved efficiency", *Sol. Energy*, **85**, 3103-3142.
Mahdi, J.T., Smith, B.E. and Sharif, A.O. (2011), "An experimental wick-type solar still system: Design and construction", *Desalination*, **267**, 233-238.
Medugu, D.W. and Ndatuwong, L.G. (2009), "Theoretical analysis of water distillation using solar still", *Int. J. Phys. Sci.*, **4**, 705-712.
Mink, G., Horvath, L., Evseev, E.G. and Kudish, A.I. (1998), "Design parameters, performance testing and analysis of a double-glazed, air-blown solar still with thermal energy recycle", *Sol. Energy*, **64**, 265-277.
Ortiz, J.M., Expósito, E., Gallud F., García-García V., Montiel, V. and Aldhaz, A. (2008), "Desalination of underground brackish water using an electrodialysis system powerd directly by photovoltaic energy", *Sol. Energy*, **92**, 1677-1688.
Srithar, K. and Mani, A. (2004), "Analysis of a single cover FRP flat plate collector for treating tannery effluent", *Appl. Therm. Eng*., **24**, 442 873-883.
Tamimi, A. and Rawajfeh, K. (2007), "Lumped modeling of solar-evaporative stills charged from the water of the dead sea", *Desalination*, **216**, 356-366.
UNICEF and World Health Organization, Progress on Drinking Water and Sanitation (2012), Update, New York.
Velmurugan, V. and Srithar, K. (2011), "Performance analysis of solar stills based on various factors affecting the productivity-A review", *Renew. Sust. Energ. Rev*., **15**, 1294-1304.
Velmurugana, V. and Srithar, K. (2007), "Solar stills integrated with a mini solar still-analytical simulation and experimental validation", *Desalination*, **216**, 232-224.
Wong, K.V. and Chan, R. (2013), "Smart glass and its potential in energy savings", *ASME J. Energy Resour. Technol*., **136**(1), 012002.
Zhao, Y., Akbarzadeh, A. and Andrews, J. (2009), "Simultaneous desalination and power generation using solar energy", *Renew. Energy*, **34**, 401-408.

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Nomenclature

Symbols		Subscripts	
A	Heat transfer surface area, (m^2)	a	Ambient
A, B, C, D	Constant of equation	ave	Average

C_w	Specific heat coefficient
h	Heat transfer coefficient, (W/m^2 K)
H	Heat flux, (W/m^2)
I	Solar flux, (W/m^2)
I_0	The extraterrestrial irradiance
I_{sc}	The solar constant for the earth, (1367 W/m^2)
M_e	Evaporated mass
n	The day of the year
V	Wind velocity, (m/s)
T	Temperature, (C)
α	Absorption factor
h_{lv}	Latent heat of vaporization, (J/Kg)
ξ	Salinity, (gr/Kg)

c	Convection
e	Evaporation rate
g	Glass roof
r	Radiation
s	Surface of still
w	Wastewater