ORIGINAL RESEARCH ARTICLE   **Open Access**

Study of wastewater treatment for freshwater production in a solar desalination unit

Alireza Baghizade[1], Farshad Farahbod[2]* and Omid Alizadeh[1]

Abstract

While desalination of water is energy intensive, traditional use of fossil fuels makes it not only costly, but also unsustainable and environmentally unfriendly; utilization of solar energy for desalination is therefore highly encouraged. This paper presents a study on the technical performance of a solar desalination unit located in Tehran city. The process is modeled using standard energy equations and performance indices are defined. The model simulation results are compared with experimental data from laboratory tests. This study observed that there is good agreement between the experimental data and the model simulation results. It is observed that the maximum solar radiation intensity is found in June and the highest evaporation rate in this month is about 5×10^{-3} m^3. It is found that the treatment efficacy of the plant decreases with increasing depth of wastewater. Performance of the desalination unit is found to be satisfactory.

Keywords Fresh water, Maximum radiation, Density, Average temperature, Theoretical model, Laboratory data

Introduction

Due to growing population in the world, the need for fresh water and energy is increased (Dong et al., 2022). On the one hand, human societies are highly dependent on wastewater for fresh water supply in the domestic, agricultural and industrial sectors. On the other, humans have polluted environmental resources such as surface and underground water. Eventually, this has led to the unequal distribution of water in different parts of the Earth. In addition, drinking water is very insufficient in dry areas. Therefore, people have serious issues regarding access to water (Ines et al., 2019). Water occupies about three quarters of the Earth's surface. More than

97% of the planet's water is deep sea saline water. That means, only 3% of the total water resources is fresh water. About 2.1% of the fresh water is inaccessible. The problem of water shortage can be solved a little by desalination of brackish water. However, process of removing salt from brackish water requires a lot of energy. If the needed energy to desalinate brackish water is provided using fossil fuels, the emissions are harmful. The use of solar energy to extract fresh water from brackish water is environmentally friendly (Taherizadeh et al., 2019). In recent years, desalination technologies for fresh water production from wastewater have grown, rapidly. The desalination process of seawater with a salt content between 1 and 10 g per liter can be useful. The efficiency of desalination processes is different and one of the factors affecting the efficiency of desalination is the amount of salt in the water (Shah et al., 2022). Naturally, saline water needs less energy to desalinate than seawater. The main function of desalination technologies is to reduce concentration of salt in water to convert it to drinking water. There are many technologies for desalination that

*Correspondence:
Farshad Farahbod
mf_fche@yahoo.com
[1] Department of Chemistry and Chemical Engineering, Rasht Branch, Islamic Azad University, Rasht, Iran
[2] Department of Chemical Engineering, Firoozabad Branch, Islamic Azad University, Firoozabad, Iran

Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 2 of 8

can be divided into two main types: thermal separation processes and membrane separation processes (Farahbod, 2020a). The choice of technology is based on operational and maintenance considerations, location, energy, cost and water characteristics. Conventional desalination technologies produce more than 90% of the world's fresh water. The basis of thermal processes is distillation and evaporation (Siefan et al., 2022). In membrane processes, reverse osmosis method and semi-permeable membranes can be used to desalinate seawater. This technology requires pressure differences across the membrane (Khan et al., 2020). The solar pond as a new technology uses solar energy for wastewater treatment. Solar pond uses free and clean energy and work throughout the year, continuously (Shalaby et al., 2022). A solar desalination pond uses a significant amount of salt water to conserve thermal energy from solar radiation, indirectly. The solar desalination pond consists of three dissimilar layers. The upper convection zone (surface zone), the lower convection zone (reserve zone), and the middle zone between the upper and lower regions, called the gradient zone. Figure 1 shows the different layers of wastewater in the solar desalination unit. The upper convection zone, which is shallow and has a low salt concentration, absorbs some sunlight, and the rest is transferred to the underlying layer (Farahbod, 2020b). This layer has about 2 to 3% salinity. The temperature range in this layer is equal to the average ambient temperature. The middle layer is gradient layer, which is identified as non-convective zone. This zone is created by the salt gradient in the top layer and bottom layer. In principle, the salt concentration increases with increasing depth. The bottom layer has saline water that absorbs the sun's heat energy, highly. This area is a place of heat accumulation and has a high density (Xie et al., 2022).

Some researchers have investigated performance of stationary passive solar ponds in terms of increasing efficiency by using heat absorbent materials (Farahbod

et al., 2012). In other researches, different types of solar ponds equipped with plastic cover with different types of heat storage materials have been studied and their performance has been investigated, experimentally (Tamimi & Rawajfeh, 2007). In another study, a trapezoidal solar pond was investigated. Sponge compounds were placed on the bottom of this solar pond to absorb heat. In yet another study, the thermal efficiency of two simple solar ponds equipped with porous compounds was investigated and compared. Performance of a triangular stainless steel solar still covered with glass is presented in Jadidoleslami and Farahbod (2016). Another study was on the performance of two triangular and trapezoidal solar ponds equipped with glass cover and circular hollow balls as heat absorbers (Ganguly et al., 2019). Cost analysis of produced fresh water is found in Ganguly et al. (2019). Performance of a solar pond that uses cotton fabrics and black clay pieces as heat absorbers is presented in Farahbod and Omidvar (2018). Solar pond painted with different colors was investigated and the performance is evaluated in Farahbod and Omidvar (2018).

This research examines performance of a solar desalination pond located in Tehran city. The wastewater entering the solar pond is collected from a disinfection unit. The studied pond is modeled with energy equations. Model simulation results are compared with experimental data.

Materials and methods

Figure 2 shows a flowchart of the wastewater treatment process. The outlet wastewater from a petrochemical industry enters the primary treatment unit and then the secondary treatment unit, as seen in the diagram. The outlet of this unit flows to the disinfection unit and then enters the solar desalination pond.

Description of solar desalination pond

The studied solar pond consists of a metal floor and glass covers. The length and width of the floor are 1.5 m and 1 m, respectively. The thickness of the floor is 1 cm and that of the cover is 4 mm. The floor of this unit is made of stainless steel to have resistance against corrosion and pressure. Angle of the glass roof is 36° to match the geographical location of Tehran city. The solar pond is facing south. So, it can be exposed to the maximum solar energy. Two metal blades divide the floor into three parts. Wastewater stream enters the middle part. The pond absorbs solar energy during the day and evaporates wastewater. The vapors turn into liquid during the night and leave by the sides of this unit. Figure 3 shows this unit.

The outlet wastewater from the disinfection unit enters the solar unit and gets converted into two
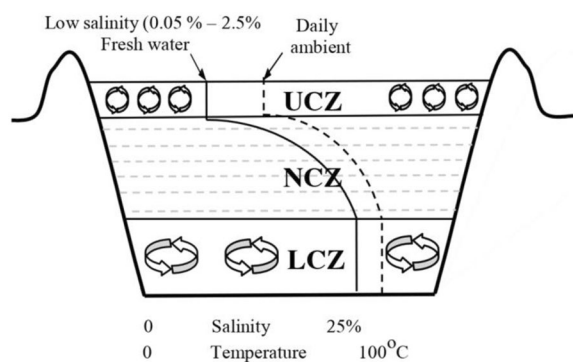
Fig. 1 Schematic of different layers of wastewater in solar pond

Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 3 of 8
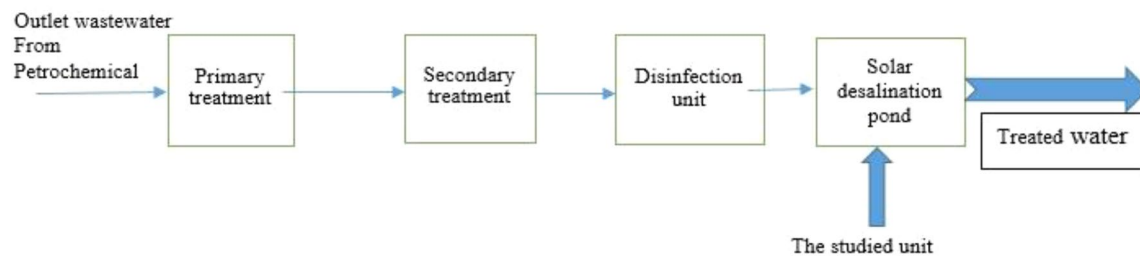
Fig. 2 Schematic of wastewater treatment process

streams of pure water and brine. Operational parameters, such as intensity of solar radiation, average air temperature and other meteorological data are provided by Tehran Meteorological Organization. Wastewater temperature in different layers, production rate of fresh water, physical properties of wastewater and treatment yield are studied. The characteristics of the wastewater entering the solar unit are presented in Table 1.

Method of measuring BOD, COD, phosphate, nitrate and TDS

In this research, indicators such as BOD, COD, phosphate, nitrate and TDS of wastewater have been moni-
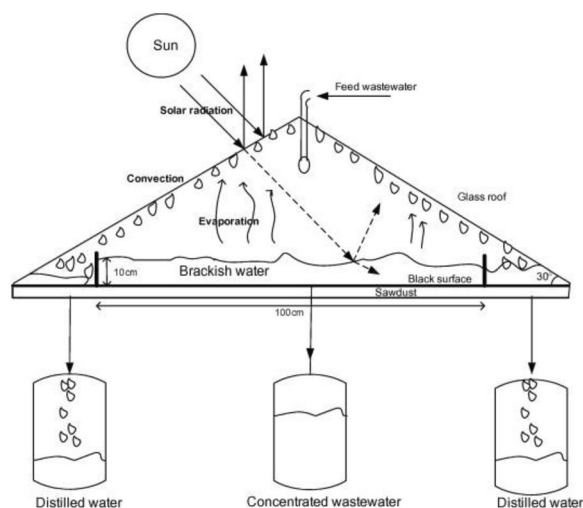
tored. The amount of phosphate is measured by Aztec AW636, with accuracy ± 3% and nitrate is measured using a nitrate meter, model LAQUA Twin, with accuracy ± 2%, China. Also, chemical oxygen and biological oxygen are measured by oxygen meter, model RBR*coda*[3]

Fig. 3 Schematic of the solar desalination unit under study

with accuracy ± 5%, China. The TDS is measured using an EC meter, model PAL-EC 4331, with accuracy ± 20 ppm, Japan. All of the measuring devices have metal probes. The amounts of pollutants are measured once before the wastewater enters the solar pond and again after the wastewater exits the solar pond. The average reduction of phosphate, nitrate, COD, BOD and TDS parameters is defined as "treatment efficiency". Equation (1) provides a relation of reduction of emission index:

$$\text{Reduction of pollution index} = \frac{\text{Initial value} - \text{Final value}}{\text{Initial value}}. \tag{1}$$

In addition, Eq. (2) shows the calculation of treatment efficiency:

$$\text{Treatment efficiency} = \frac{\text{Sum of reduction in BOD, COD, TDS, phosphate, nitrate}}{5} \times 100. \tag{2}$$

Model-based study of solar desalination unit

The energy conservation equations are used to model solar pond floor, wastewater and glass cover (Farahbod, 2020b). The energy absorption by solar pond floor follows convective mechanism. Equation (3) shows this energy balance. Also, released energy by convective mechanism between wastewater and glass, evaporative heat transfer between wastewater and glass, and radiant heat transfer between wastewater and glass occur. Therefore, obtained energy by the wastewater is written

Table 1 Characteristics of the wastewater entering to the solar desalination pond

Physical characteristic's	Amount
Viscosity	1091 cP
Density	$1120 \frac{kg}{m^3}$
Specific heat	3.11 kJ/kg °C
Salinity	7.2%
TDS	207.6 ppm
Turbidity	1.13 NTU

Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 4 of 8

as Eq. (4) (Farahbod et al., 2012). Obtained energy by the glass from the sun follows convective mechanism, radiant heat and evaporation of wastewater. The lost energy is found through the radiant mechanism between glass and sky (Farahbod, 2020b). Therefore, the equation of energy conservation of glass is written as Eq. (5). In addition, the intensity of solar radiation is defined as Eq. (6) (Farahbod et al., 2012):

$$R\alpha_{ba}S_{ba} - H_{c,b-ba} - H_{loss} = m_{ba}c_{ba}(dT_{ba}/dt), \quad (3)$$

$$R\alpha_b S_b + H_{c,b-ba} - H_{c,b-g} - H_{r,b-g} - H_{e,b-g} = m_b c_b(dT_b/dt), \quad (4)$$

$$R\alpha_g S_g + H_{c,b-g} - H_{r,g-s} - H_{c,g-a} + H_{r,b-g} + H_{e,b-g} = m_g c_g(dT_g/dt), \quad (5)$$

$$R = R_0\left[(1 - 0.14z)\exp(-0.357(\sec\theta_i)^{0.678}) + 0.14z\right]. \quad (6)$$

R is direct radiation in the region. Also, R_0 is $1353\frac{W}{m^2}$. In addition, θ_i is zenith angle. In addition, the heat capacity is written in terms of salinity as Eq. (7) (Farahbod, 2020b):

$$c_b = 4180 + 4.396\zeta + 0.0048\zeta^2. \quad (7)$$

The viscosity, conductive heat transfer coefficient, specific heat at constant pressure and density of salty wastewater are listed as Eqs. (8) to (11) (Farahbod et al., 2012):

$$\mu_b = -0.002d^2 + 0.057d + 0.725, \quad (8)$$

$$k_b = 5.553 \times 10^{-1} - 8.13 \times 10^{-5}\zeta + 8 \times 10^{-4}(T_{ave} - 20), \quad (9)$$

$$Cp_b = 1E - 4d^2 - 0.0041d + 3.181, \quad (10)$$

$$\rho_b = 998 + 0.65\zeta - 0.4(T_{ave} - 20). \quad (11)$$

The latent heat of wastewater is expressed by Eqs. (12) and (13). Equation (12) is used when evaporation temperature is higher than 70 °C. And, Eq. (13) is used when evaporation temperature is less than 70 °C:

$$H_{fg} = \left\{3.1615 \times 10^{-6}\left[1 - (7.616 \times 10^{-4}T_v)\right]\text{ For }T_v \geq 70\,^{\circ}\text{C}\right\}, \quad (12)$$

$$H_{fg} = \left\{2.5 \times 10^6\left(1 - 9.5 \times 10^{-4}T_v + 1.3 \times 10^{-7}T_v^2 - 4.8 \times 10^{-9}T_v^3\right)\text{ For }T_v \langle 70^{\circ}\text{C}\right\}. \quad (13)$$

In addition, the pressure of brackish water and that of inner side of glass cover are represented by Eqs. (14) and (15) (Farahbod et al., 2012):

$$P_b = \exp\left[25.317 - \frac{5144}{(T_b + 273.15)}\right], \quad (14)$$

$$P_g = \exp\left[25.317 - \frac{5144}{(T_g + 273.15)}\right]. \quad (15)$$

Equation (16) shows the flow rate of fresh water output from the solar pond in terms of the average temperature and effluent temperature (Farahbod, 2020b):

$$dm_{cond.}/dt = h_{e,b-g}(T_b - T_{ave})/h_{lv}. \quad (16)$$

The correlation between theoretical model and experimental data is greater if the mean temperature is expressed as Eq. (17) (Farahbod et al., 2012):

$$T_{ave} = 0.77T_g + 0.23T_{ba}. \quad (17)$$

Results and discussion

Study of radiation intensity and wastewater treatment

The intensity of the sun's radiation was measured by the pyranometer of Tehran Meteorological Organization. The relationship between intensity of solar radiation and wastewater treatment is investigated in this section. Figure 4 shows that contaminants removal increases with increasing solar radiation intensity.

Figure 4 shows that the maximum rates of removal of BOD, COD, phosphate, nitrate and TDS are 28.1%, 25%, 39.9%, 39.2% and 24.4%, respectively. It means that solar desalination pond has an acceptable performance in treatment process. Table 2 shows the percentage of pollutants reduction in the solar desalination pond.

Study of wastewater depth and wastewater treatment

Figure 5 shows the relationship between treatment efficiency and wastewater depth. Treatment efficacy is the average reduction of BOD, COD, phosphate, nitrate and TDS. Figure 5 shows that treatment efficiency decreases with increasing wastewater depth.

At increased depth of the wastewater, the amount of salt deposition also has increased and this factor has a significant effect on reducing treatment efficiency. Figure 5 shows that difference of the treatment efficiency at top and bottom of the solar pond is 74.6%. It is reasonable to expect a reduction in the overall treatment efficiency. Because considerable heat is trapped in the lower areas.

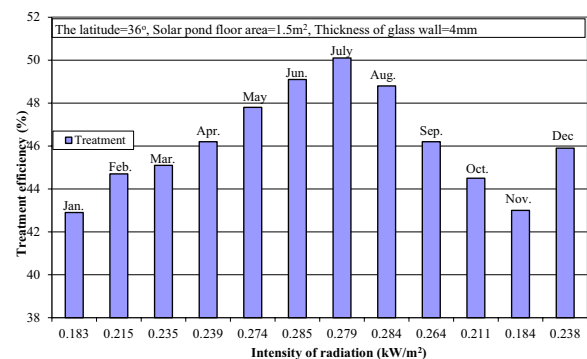Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 5 of 8
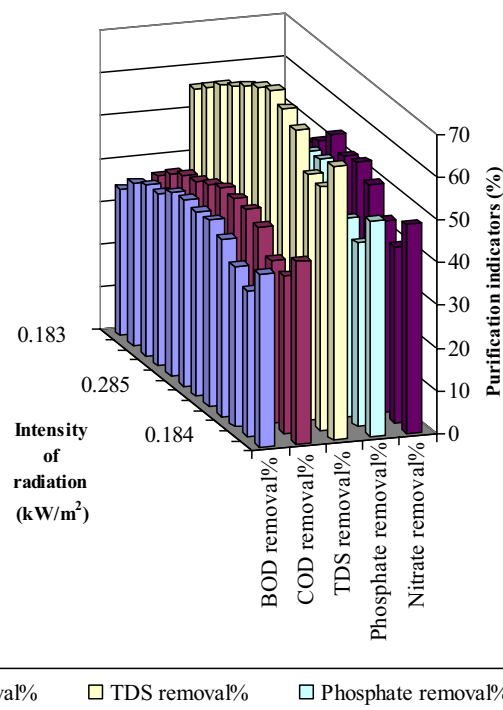
Fig. 4 Relationship between solar radiation intensity and contaminants removal

Table 2 Reduction of pollutants in outlet stream compared to the inlet stream

Pollution index	Percentage reduction, %
BOD	28.1
COD	25
Phosphate	39.9
Nitrate	39.2
TDS	24.4
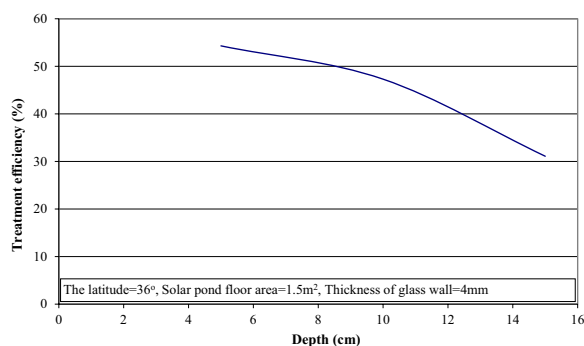
Fig. 6 Monthly average treatment efficiency in 12 months

Fig. 5 Relationship between treatment efficiency and wastewater depth

Study of radiation intensity and wastewater treatment

Figure 6 shows average treatment efficiency achieved in every month of the year; average solar radiation intensity of the respective month is given alongside. Results show that the treatment efficacy increases with increasing intensity of solar radiation in general. In fact, the intensity of radiation has a significant effect on pollutants reduction. However, the maximum efficacy is seen in July, whereas the intensity of radiation is higher in June and August. This anomaly is understood to be due to change in the velocity and direction of wind and changes in the physical properties of the effluent, consequently.

Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 6 of 8
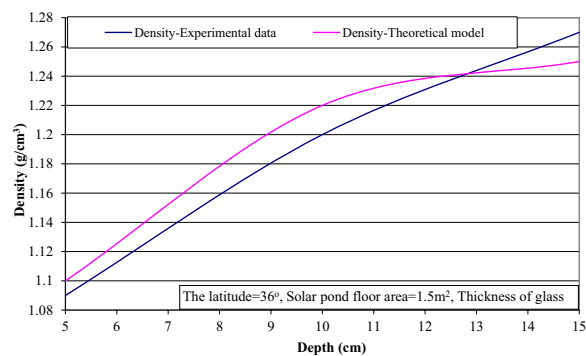
Fig. 7 Investigation of wastewater density versus wastewater depth

Fig. 9 Plot of wastewater heat capacity versus wastewater depth

Fig. 8 Variation of wastewater viscosity with respect to wastewater depth
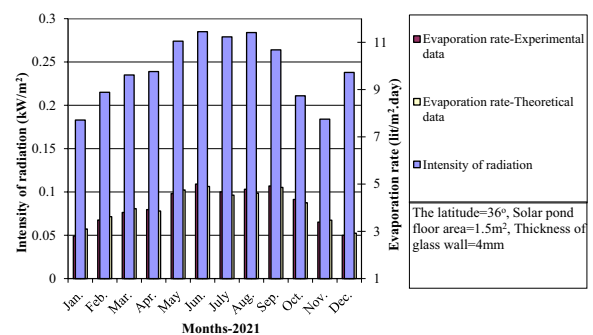
Fig. 10 Theoretical and experimental water production rates versus radiation intensity

Study of wastewater physical properties versus depth

The physical properties of wastewater play a significant role in fresh water production. The physical properties such as density, viscosity and heat capacity of the wastewater are investigated in this research.

Investigation on density in terms of effluent depth

Figure 7 shows wastewater density plotted against wastewater depth. The wastewater density changes from 1090 to $1270 \frac{kg}{m^3}$. The deposited salt in the floor of the pond is considerably high and it increased the density of the effluent at a depth 0.15 m.

Study of viscosity versus wastewater depth

Figure 8 shows the viscosity at different depths. Results show that viscosity of wastewater at the floor is about 19% higher than that near the surface. This is due to salt accumulation in the pond floor.

Study of the heat capacity of wastewater at different depths

The heat capacity of wastewater at different depths is shown in Fig. 9. As seen, the heat capacity of the wastewater decreases by 0.67% from surface to floor as the salinity increases.

Study of water production versus radiation intensity

The theoretical and experimental evaporation rates of the wastewater at different level of intensity of solar radiation is investigated in this section. Figure 10 shows that intensity of radiation as well as evaporation rate from to September is higher than that of other months. Several factors like solar radiation intensity, wind speed and wind direction influence wastewater evaporation. Figure 9 confirms that energy equations are well able to predict evaporation rate.
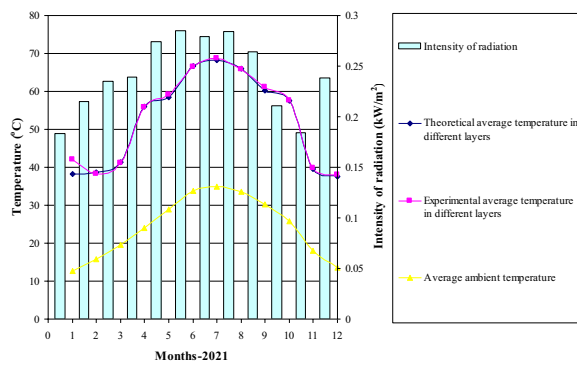
Study of wastewater temperature in different months

Figure 11 shows theoretical and experimental values of average temperature in different months. The result again confirmed that there is a good agreement between the mathematical model and the experimental data. The maximum average temperature of brine occurs in July and the minimum in December.
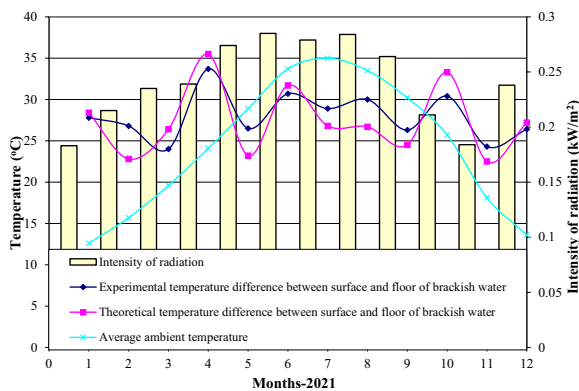
Study of wastewater temperature difference in different months

Figure 12 shows that the difference between the surface and the floor temperature is sinusoidal over a period of 1 year. This may be due to the trapped energy in lower

Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 7 of 8

Fig. 11 Theoretical and experimental average temperature in different months

Fig. 12 Difference between surface and floor temperatures in different months

convective zone. Actually, accumulated heat in the bottom of wastewater has caused difference between surface and floor temperatures in consecutive months. Laboratory data and model results indicate that maximum difference between surface temperature and floor temperature occurs in April. Results show that minimum temperature difference occurs in November. Undoubtedly, wind direction and sun angle can be the causes of this event.

Conclusion

Wastewater from a petrochemical industry is treated in the solar desalination unit and clean water is produced by evaporation. The significance of solar desalination is that it saves fossil fuels and avoids the corresponding emissions. The present study targeted performance analysis of the plant through model-based computation and verification of the results by physical measurements in laboratory. While a

satisfactory performance of the plant is established on one side, validation of the mathematical model has been achieved on the other hand, having confirmed good agreement between the experimental data and model simulation results. That the model has been developed using energy equations available in literature is worth noticing.

List of symbols

Variables

A_b	Surface of solar pond base (m^2)
A_{ba}	Surface of brackish water (m^2)
A_g	Surface of glass covers (m^2)
c	Specific heat (J/kg K)
R	Solar flux (W/m^2)
h	Heat transfer coefficient (W/m^2K)
h_{lv}	Latent heat of vaporization (J/kg)
ζ	Salinity (g/kg)
m_c	Condensate mass
H	Heat flux (W/m^2)
T	Temperature (C)
t	Time
dt	Time interval (s)
T_s	Sky temperature (C)

Subscripts

A	Ambient
Ba	Base (of solar pond)
B	Brackish water
E	Evaporative
Eff	Effective
G	Glass
R	Radiative
S	Sky
C	Convective
T	Time

Greek

ε	Emissivity factor
α	Absorptivity
δ	Stefan–Boltzmann constant (W/m^2K^4)

Declarations

Ethics approval and consent to participate
Not applicable.

Baghizade *et al. Sustainable Energy Research*   (2023) 10:4

Page 8 of 8

References
Dong, S., Zhao, Y., Yang, J., Li, W., Luo, W., Li, S., Liu, X., Guo, H., Yu, C., Sun, J., Feng, J., & Zhu, Y. (2022). Solar water recycling of carbonaceous aerogel in open and closed systems for seawater desalination and wastewater purification. *Chemical Engineering Journal, 431*(1), 133824.

Farahbod, F. (2020a). Simultaneous use of mass transfer and thermodynamics equations to estimate the amount of removed greenhouse gas from the environment by a stream of water. *Environmental Modeling & Assessment*. https://doi.org/10.1007/s10666-020-09740-8

Farahbod, F. (2020b). Practical investigation of usage of nano bottom in the production of fresh water from brackish wastewater in a closed shallow solar basin. *Environmental Progress & Sustainable Energy*. https://doi.org/10.1002/ep.13496

Farahbod, F. (2022). Experimental evaluation of nano-zinc oxide coating applying on inner surface of a rotary dryer to produce NaCl. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-022-03943-0

Farahbod, F., & Farahmand, S. (2013). Experimental study of solar pond coupled with forced circulation crystallizer as major stages of proposed zero discharge desalination process. *Journal of Thermal Science and Engineering Applications, 6*(2), 021002. https://doi.org/10.1115/1.4025420

Farahbod, F., Mowla, D., Jafari Nasr, M. R., & Soltanieh, M. (2012). Investigation of solar desalination pond performance experimentally and mathematically. *Journal of Energy Resources Technology, 134*(4), 041201.

Farahbod, F., & Omidvar, M. (2018). Experimental evaluation of collection, thermal, and conductivity efficiency of a solar distiller pond as a free concentration unit in wastewater treatment process. *Energy Science & Engineering, 6*(5), 584–594.

Ganguly, S., Date, A., & Akbarzadeh, A. (2019). On increasing the thermal mass of a salinity gradient solar pond with external heat addition: a transient study. *Energy, 168*, 43–56.

Ines, M., Paolo, P., Roberto, F., & Mohamed, S. (2019). Experimental studies on the effect of using phase change material in a salinity-gradient solar pond under a solar simulator. *Solar Energy, 186*, 335–346.

Ismail, M. S., Mohamed, A. M., Poggio, D., Walker, M., & Pourkashanian, M. (2022). Modelling mass transport within the membrane of direct contact membrane distillation modules used for desalination and wastewater treatment: Scrutinising assumptions. *Journal of Water Process Engineering, 45*, 102460.

Jadidoleslami, M., & Farahbod, F. (2016). Experimental and mathematical evaluation of solar powered still equipped by nano plate as the principle stage of zero discharge desalination process. *Advance Energy Research, 4*(2), 147–161.

Khan, N. A., Khan, S. U., Ahmed, S., Farooqi, I. H., Yousef, M., Mohammadi, A. A., & Changani, F. (2020). Recent trends in disposal and treatment technologies of emerging pollutants-a critical review. *TrAC Trends in Analytical Chemistry, 122*, 115744.

Shah, K. M., Billinge, I. H., Chen, X., Fan, H., Huang, Y., Winton, R. K., & Yip, N. Y. (2022). Drivers, challenges, and emerging technologies for desalination of high-salinity brines: A critical review. *Desalination, 538*, 115827.

Shalaby, S. M., Kabeel, A. E., Abosheiasha, H. F., Elfakharany, M. K., El-Bialy, E., Shama, A., & Vidic, R. D. (2022). Membrane distillation driven by solar energy: A review. *Journal of Cleaner Production, 366*, 132949.

Siefan, A., Rachid, E., Elashwah, N., AlMarzooqi, F., Banat, F., & van der Merwe, R. (2022). Desalination via solar membrane distillation and conventional membrane distillation: Life cycle assessment case study in Jordan. *Desalination, 522*, 115383.

Taherizadeh, M., Farahbod, F., & Ilkhani, A. (2019). Experimental evaluation of solar still efficiencies as a basic step in treatment of wastewater. *Heat Transfer-Asian Research, 49*(Part 1), 236–248.

Tamimi, A., & Rawajfeh, K. (2007). Lumped modeling of solar-evaporative ponds charged from the water of the Dead Sea. *Desalination, 216*, 356–366.

Xie, W., Tang, P., Wu, Q., Chen, C., Song, Z., Li, T., Bai, Y., Lin, S., Tiraferri, A., & Liu, B. (2022). Solar-driven desalination and resource recovery of shale gas wastewater by on-site interfacial evaporation. *Chemical Engineering Journal, 428*, 132624.