Experimental evaluation of collection, thermal, and conductivity efficiency of a solar distiller pond as a free concentration unit in wastewater treatment process

Farshad Farahbod | Mohammadnabi Omidvar

1Department of Chemical Engineering, Firoozabad Branch, Islamic Azad University, Firoozabad, Iran
2Department of Computer Engineering, Firoozabad Branch, Islamic Azad University, Firoozabad, Iran

Correspondence
Farshad Farahbod, Department of Chemical Engineering, Firoozabad branch, Islamic Azad University, Firoozabad, Iran. Email: farahbod.f@srbiau.ac.ir

Abstract
The performance of one solar pond as a passive step in distilled and potable water production from desalination effluent is surveyed in this research. This solar pond is proposed in a zero discharge desalination process to prevent the salinity shocking which is made by a brackish water stream that exists from desalination units. The solar pond performance is evaluated by measuring three types of efficiency, experimentally, and mathematically. The efficiencies which are defined and calculated from experimental data are conductivity efficiency, thermal efficiency, and water recovery efficiency. The mathematical results are verified by experimental data which has been obtained during a year. The theoretical modelings show very good agreement with experimental data, especially for water collection and conductivity efficiency evaluation. The relative error of theoretical and experimental results for thermal efficiency evaluation through the day and night is obtained 7.2% and 4.9%, respectively.

Keywords
conductivity efficiency, recovery ratio, solar pond performance, thermal efficiency

1 INTRODUCTION

Undoubtedly, water resources have been focused to support both human lives and the environment, for years. Earth’s fresh water is distributed unevenly, depends on the seasons and also, geographical region. The Middle East countries are one of the regions which face water scarcity due to the population growth and also a natural cycle of renewable fresh water. The brackish water with high salinity amount is one of the effluent streams which treat the sea and dry ecosystems. In other word, the disposal of this concentrated stream makes new concerns for environmental engineers. In fact, frequent discharges of rejecting streams which contain salt, heavy metals, and free ions into the sea or on the ground disturb the natural culture of the ecosystem. The salinity and temperature of effluent wastewater from desalination units such as MSF, MED, or other thermal technologies is so high. So, the drain of this stream can threat the ecosystem via salinity and thermal shocks. In fact, the zero discharge desalination (ZDD) process is a feasible solution to decrease or also, remove the biological problems which are resultant of concentrated brine wastewater drainage into sea or land ecosystem. Processes which focus on waste problems and reduce the risks of these disposal streams are introduced.
as zero discharge desalination processes. This solution includes a series of processes lead to beneficial products as water and purified element, such as salt and other ions. These technical requirements. A passive process which applies solar energy is one of this type of zero desalination processes and high-quality distilled water is produced through this passive method. Recently, some commercial packages of membranes are proposed as zero discharge desalination, which eliminates specific components related to the customer needs. These new membrane technology is fast, accurate and also needs some technical requirements. High volume drainage of concentrated from desalination plants needs large packages of new zero discharge desalination (ZDD) membrane processes which lead to high process cost. So, the traditional integral type of zero discharge desalination is more convenient and also applicable. Especially, countries which have vast sea boundaries beside the huge amount of solar can use the potential of integral type of zero discharge desalination process to produce potable water and salt from sea water. The mentioned type is an environmentally friendly and cost saving process, competitive with other desalination techniques. Solar pond feasibility was illustrated before 2000 and later researches have been focused on the development and improvement of solar pond performance in commercial applications.

1.1 Solar desalination ponds

The solar ponds are passive methods to collect and store solar energy, with simple construction and on-demand extraction of heat. The natural cycle of water is occurring in one solar pond. The solar pond is an enclosed space with transparent roof which usually made up of transparent plates such as glass. The solar irradiation absorbed by water in the pond, water evaporates and condenses through the glass roof, finally. The slope of the roof, geographical position, volume of water and solar pond, water surface area influence the performance of a solar pond. The solar ponds usually construct on the upper level from the ground and if the bottom edge of the solar pond is insulated from nonthermal conductive materials such as sawdust, the thermal loss to the ground or the outside environment can be neglected. The various types of solar ponds have been made, although all obey the simple rules of heat conservation. Spherical solar pond, pyramid solar pond, hemispherical solar pond, double basin, glass solar pond, concentrator-coupled single slope solar pond, tubular solar pond, and tubular solar pond are some kinds of solar pond which have been constructed and examined. In addition, the solar ponds are obeying the same mechanism as in a solar pond, however, located usually in the ground and are roofless. Vast and deep natural lakes and artificial basins can be considered as solar ponds. The other application of solar ponds and solar ponds is introduced as a storage place of solar energy. Basically, salty water basins or salty lakes are good samples of solar storage ponds. A nonconvective layer should be built as a thermal insulation and reduce the convection from the lower layer to the upper surface. Middle East countries have good potential as area since of vast rural places and also as sufficient emerged solar power. The solar pond has been considered as a feasible and efficient process due to nonexpensive material for solar pond construction, simple manufacturing method, and consumption of renewable energy. Undoubtedly, there are some restrictions in their operation with streams contain high amount of salt concentration. For example, the fouling is the build-up of particulates such as mineral salts, colloids, heavy metals, microorganisms, and suspended solids totally on the membrane. So, the membrane technologies are not suitable for sweetening of brackish waste streams. In addition, the fouling, deformation, high pressure drop, and high electrical power requirements are some of the mentioned limitations using membrane technologies. Furthermore, the factories need huge source of thermal energies to change brine wastewater to distilled stream and this item is not cost beneficial, chiefly. Although, membrane technologies are common in commercial methods in sea water desalination plants to provide soft water for drinking and also for industrial and agricultural usages. But, the lifetime of membranes is a function of salinity and suspended solids in sea water, severely.

1.2 Zero discharge desalination as promised solution

The presenting integral type of zero discharge desalination to eliminate the concentrated discharges into the seawater, seeks a feasible and cost effective desalination method which works with high salt concentration. Also, providing high-quality water which can be used in different ways and desired salt crystals is expected from this type of zero discharge desalination. Especially, an integrated arrangement which insists on usage of cost effective, low restricted operating problems will be suggested when clean solar energy is as one of the power source of the process. This technology will be used for streams with high concentration of salt.

The introduced process is cost beneficial as water production or brine concentration for use in salinity control and environmental cleanup applications is remarkable. Therefore, several effective factors such as insolation rate and the average ambient temperature in the efficiency of a solar desalination pond are surveyed, in this research. Also, temperature gradient and specific gravity are evaluated in this solar desalination pond during a year.

As shown a schematic of the used solar desalination pond is in the Figure 1. The method of this solar pond is follows from the evaporation process.
The aim of this study was an evaluation of thermal, conductivity, and collection efficiency. In fact, the performance of a solar desalination pond is investigated experimentally and theoretically in this research.

2 | MATERIALS AND METHOD

In this present research, a pyramid solar desalination pond as a second stage of one integer type of zero desalination process is considered, experimentally and theoretically. This zero desalination process is proposed for the production of salt and distilled water from the effluent stream of a Mobin petrochemical desalination unit. This process will be feasible due to the huge volume of salty wastewater and also the geographical position of the factory which provides required solar energy make. Besides, this integral type of process is a solution to prevent discharging the salty wastewater into the sea producing salt and distilled water. The concentrated stream is led into the evaporator-crystallizer as 3rd step and then centrifugal equipment as 4th step. Passing through a dryer, salt crystals are produced. The rotary dryer is considered as a 5th step in the ZDD process.

2.1 | Experimental set up

Solar desalination pond consists of an airtight basin to trap the solar energy and enhance the transmissivity coefficient. The solar pond is located according to the latitude of Shiraz city in Iran and is imposed the most solar radiation. The construction of solar pond is set on a table and the space between the base of a solar desalination pond and the table is filled with sawdust for insulation purpose. So, these conditions provide maximum solar absorption for brackish wastewater.

The solar pond which is used in this study is composed by a metallic basin with a dimension of 100 cm × 170 cm × 46.5 cm. The floor of a solar desalination pond is made from stainless steel-316 to prevent corrosion which may happen due to high temperature and also high amount of salt concentration in concentrated brine wastewater. The experimental setup is located on a table about 70 cm higher than the ground.

In addition, the thickness of the table is about 4 cm and acts as an insulating layer to store solar energy in wastewater. The space between the table and base of solar desalination pond consists of an airtight basin to trap the solar energy and enhance the transmissivity coefficient. The solar pond is located according to the latitude of Shiraz city in Iran and is imposed the most solar radiation. The construction of solar pond is set on a table and the space between the base of a solar desalination pond and the table is filled with sawdust for insulation purpose. So, these conditions provide maximum solar absorption for brackish wastewater.

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pond is filled with sawdust for insulation purpose. So, the maximum amount of solar insolation rate is absorbed and energy losses approaches to zero in these conditions, finally.

The roof of solar pond is made from glass. The thickness of roof and walls is 4 mm to enhance photo transmissivity. The solar pond is made from stainless steel to prevent corrosion which may happen due to high temperature and concentration of salt in brackish wastewater. The net evaporation area of solar distiller pond is one square meter, facing south with an inclination of 29°. The latitude of Shiraz city to absorb the maximum amount of solar radiations is 29°. Also, the surface of solar distiller pond bottom is dyed black. The solar distiller pond area consists of three sections which are separated by means of 2 long rectangles with 15 cm height. The middle section is filled with the concentrated brine wastewater and its level is 15 cm, approximately. This bench scale is located on a table about seventy cm upper than the ground. As mentioned, the thickness of table is about 4 cm and acts as an insulate layer of storage solar energy in wastewater. The space between the table and base of solar distiller pond is filled with sawdust for insulation purpose. The maximum amount of solar insolation is absorbed in these conditions. The feed is conveyed into the pond through a hole with 2 cm as diameter. The distilled water is collected into a vessel and concentrated brine wastewater is drained through another 2 cm diameter hole. The used solar distiller pond is shown in Figure 1, schematically. The evaporation technique separates distilled water from the wastewater in the solar pond. Vapors condense on the glass roof and slip to the corners of the pond. Distillates exit from two sides of solar desalination pond continuously so non equilibrium condition between liquid and vapor remains in the system. Table 1 shows the physical characteristics of solar pond.

In addition, the Table 2 shows the chemical analysis of entrance wastewater to solar desalination pond.

The depth of brackish wastewater which is fed into the solar pond is 15 cm. Three regions are assumed for the changes in thermophysical properties and thermal qualification of brackish wastewater. Three sample valves are located at the sides and bottom of the solar pond to enable the operator gathering the wastewater samples. Measuring the values of air temperature, water temperature, wind velocity, and solar irradiation is possible by digital apparatus. The used gauges have a smart mode that provides accurate measurements by factoring in the angle the unit is being held. The resolution of thermometer is 0.1°C. The temperature of different layers of wastewater is measured by thermometer sensors. The sensor is connected to a monitor for reading temperature profile. In addition, the salinity of wastewater is measured in different layers of solar pond by salt meter. The probe of salt meter sense the salt content of waste water and can be reported. The salt meter is suitable for measuring salt contents in aqueous solutions and also viscous media. It is important to know that a salt meter usually emits electric conductivity as a measurement value in μS/cm.

### Table 1: The characteristics of solar distiller

| Physical characteristics                        |
|-----------------------------------------------|
| Material                                      | Galvanized iron (zinc coated iron to prevent corrosion) |
| Dimensions                                    | 100 cm × 170 cm × 46.5 cm |
| Glass roof thickness                          | 4 mm |
| Inclination                                   | 29° facing south |
| Height from the ground                        | 70 cm |
| Drainage diameter                             | 2 cm |
| Initial Volume of feed                        | 100 lit |

### Table 2: The chemical analysis of inlet wastewater to solar pond

| Chemical analysis | Unit | Brine outlet line |
|-------------------|------|-------------------|
| Ca++ ppm as CaCO₃| 14 616.3 |
| Mg++ ppm as CaCO₃| 36080 |
| Fe++ ppm          | Trace   |
| Ba++ ppm          | Trace   |
| SO₄²⁻ kg/m³       | 5.25    |
| HCO₃⁻ kg/m³       | 0.185   |
| Total hardness ppm as CaCO₃ | 453 |
| Salinity percent  | 5.45    |
| Conductivity s/m  | 58 666× 10⁻⁴ |
| Silica ppm        | 0.1     |
| Specific gravity at 15 c | 1.06 |
| pH                | 10.43   |
| Viscosity (Kinematic) m²/s | 0.75× 10⁻⁶ |
| TSS kg/m³         | Trace   |

#### 2.2 Theoretical analysis

Consequently, theoretical analysis is being made to achieve the temperature variations of brine wastewater in solar desalination pond, glass covers and base of solar pond at every instant and the condensation rate equation is formulated. Amount of condensation rate represents the performance of a solar pond. Finally, the operating efficiency of a solar pond is introduced as thermal efficiency, conductance efficiency, collection efficiency, and recovery ratio.

#### 2.2.1 Solar distiller pond

The thermal performance of the solar pond requires temperature variations of the basin, salty water, and glass roof, simultaneously. These parameters are effective on...
evaluation of thermal efficiency. So, solving mass conservation equation and three interconnected energy conservations of the basin, salty water, and glass roof obtains the required results.

\[ Ia_{b,a}A_{ba} - \dot{E}_{c,b-ha} - \dot{E}_{loss} = m_{ba}c_{ba} \left( \frac{dT_{ba}}{dt} \right) \]  (1)

\[ Ia_{b,a} + \dot{E}_{c,b-ha} - \dot{E}_{t,b-ha} - \dot{E}_{c,b-g} = m_{ba}c_{b} \left( \frac{dT_{b}}{dt} \right) \]  (2)

\[ Ia_{g,a} + \dot{E}_{c,b-ha} - \dot{E}_{t,g-s} - \dot{E}_{c,b-g} + \dot{E}_{c,b-g} = m_{g}c_{g} \left( \frac{dT_{g}}{dt} \right) \]  (3)

\[ I = I_0(1 - 0.14z) \exp (-0.357(\sec \theta)^{0.678}) + 0.14z, \]  (4)

where \( I \) is the direct radiation in a region of altitude \( z \), km, above the mean sea level which is given by Leblanc et al. (2011). The value of \( I_0 \) is 1353 W/m\(^2\). In addition, \( \theta_i \) is the zenith angle, \( \lambda \) is the angle of declination in degree, \( \phi \) is the angle of latitude, and \( \omega \) is the hour angle which are presented in Equations (5-7).

In fact, declination is the angle made between the plane of the equator and the line connecting the two centers of the earth and the sun and this parameter is shown by the \( \lambda \) symbol in related equations.

\[ \cos \theta_i = \cos \lambda \cos \phi \cos \omega + \sin \lambda \sin \phi \]  (5)

In addition, the Zenith Angle, \( \theta_i \), is the incidence angle of sunbeam on a horizontal surface and this item can be calculated by Equation (5).

\[ \lambda = 23.45 \sin \left( \frac{360(284 + n)}{365.25} \right) \]  (6)

The \( \theta_i \) as Zenith angle is between 0\(^\circ\) to 90\(^\circ\). Also, \( \omega \) is hour angle and its depend on the sight angle of sun to earth. Undoubtedly, it is a function of time in a day. So, it is clear the Zenith angle is a function of radiant rays of the sun as an energy source to earth as a receiving center.

\[ \omega = \frac{2\pi(z - 12)}{24} \]  (7)

Each terms of heat transfer in energy conservation equations between basin-brackish water, glass-brackish water, glass-atmosphere, evaporation, and heat loss is introduced as follows:

\[ \dot{E}_{c,b-ha} = h_{c,b-ha}A_{ba} (T_{ba} - T_b) \]  (8)

\[ \dot{E}_{loss} = U_{ba}A_{ba} (T_{ba} - T_a) \]  (9)

\[ \dot{E}_{c,b-g} = h_{c,b-g}A_{ba} (T_{ba} - T_b) \]  (10)

\[ \dot{E}_{r,b-g} = h_{r,b-g}A_{ba} (T_{ba} - T_g) \]  (11)

\[ \dot{E}_{c,b-g} = h_{c,b-g}A_{ba} (T_{ba} - T_b) \]  (12)

\[ \dot{E}_{r,g-s} = h_{r,g-s}A_{g} (T_s - T_b) \]  (13)

\[ \dot{E}_{c,g-s} = h_{c,g-s}A_{g} (T_s - T_b) \]  (14)

According to Farahbod et al. (2013), Velmurugan et al. (2007), Al-harashsheh et al. (2018), and Farahbod et al. (2012), the related coefficients are: \( h_{c,b-ha} = 135 \) W/m\(^2\)K, \( c_{ba} = 473 \) J/KgK, \( a_{ba} = 0.93 \), \( a_b = 0.05 \), \( c_g = 800 \) J/KgK, \( \epsilon_g = 0.88 \), \( \epsilon_b = 0.97 \) and \( \alpha_s = 0.048 \), \( U_{ba} = 14 \) W/m\(^2\)K, \( m_g = 6.2 \) Kg, \( m_b = 100 \) kg, \( m_{ba} = 7.6 \) Kg.

The specific heat coefficient of brackish water, \( c_b \), is calculated related to the salt concentration, \( \zeta \), in kg/m\(^3\), and temperature, \( T_b \).

\[ c_b = 4180 + 4.396\zeta + 0.0048\zeta^2 \]  (15)

Heat-transfer coefficients are defined as below, according to Farahbod et al. (2013), Tamimi et al. (2007), Velmurugana et al. (2007), and Farahbod et al. (2014).

\[ h_{c,b-g} = 0.884 \left( \frac{(T_b - T_g) + \frac{[P_b - P_g]T_b + 273.15]}{(268.9 \times 10^3 - P_b)} \right)^{1/3} \]  (16)

\[ h_{g,b-ha} = \alpha_{eff} \sigma (T_g^2 + T_b^2) (T_g + T_b) \]  (17)

\[ \alpha_{eff} = \left( \frac{1 - \alpha_s}{\epsilon_s - 1} \right)^{-1} \]  (18)

\[ h_{c,b-g} = 16.273 \times 10^{-3} h_{c,b-g} \frac{(P_b - P_g)}{(T_b - T_g)} \]  (19)

\[ h_{g,b-ha} = \alpha_{eff} \sigma (T_g^2 + T_b^2) (T_g + T_s) \]  (20)

\[ \alpha_{eff} = \left( \frac{1 - \alpha_s}{\epsilon_s - 1} \right)^{-1} \]  (21)

The wind velocity is important in absorbing irradiation energy. This item affects the convective heat transfer between sky and glass according to Velmurugana et al. (2007). This relation is presented in Equation (22).
\[ h_{c,g,a} = 2.8 + 3V_w \]  

(22)

Obviously, the effect of convective heat transfer between glass covers and ambient is not considerable in the evaporation rate in the closed solar pond. The average value of the convective heat-transfer coefficient is and its depend on the normal geographical conditions. So, this item is a function of wind velocity. The weather stations use anemometers for measuring of wind velocity. So, the wind velocity average value is caught from the meteorology office of Shiraz city.

\[ \text{Where, } 22 \text{ is adjusted as an average value of } h_{c,g,a} \text{ according to Farahbod et al. (2014).} \]

Finally, the thermal performance of solar pond and productivity of solar pond in other term is introduced in evaporation rate as Equation (23) according to Farahbod et al. (2012).

\[ \frac{dm_{\text{cond.}}}{dt} = h_{c,b-g}(T_b - T_{\text{ave}})/h_v \]  

(23)

\[ T_{\text{ave}} = 0.8T_g + 0.2T_{ba} \]  

(24)

Amount of condensation rate shows the productivity of solar desalination still as a performance index of solar desalination pond. The average temperature is calculated with Equation (24). This formula shows the effect of glass temperature is 80% and the effect of solar pond basis is 20%. In fact, this relation is modified for getting the accurate data.

The evaporation rate, which is calculated using \( T_{\text{ave}} \), shows better agreement with experiments.

The thermal efficiency and conductivity efficiency is defined as Equations (26) and (27), respectively, during a defined felly. The conductivity and density of brackish water are modified according to the extracted experimental data and defined as 28-a and 29-a, respectively. Three types of efficiency is calculated in this research. The thermal efficiency is defined as total heat which is removed from solar pond to total of trapped solar radiation.

\[ \eta_{th} = \frac{\frac{dm}{dt}h_v}{1/T_{ba}A_{ba}} \]  

(25)

\[ \eta_{th} = \frac{h_{c,b-g}(T_b - T_{\text{ave}})}{1/T_{ba}A_{ba}} \]  

(26)

\[ \eta_{th} = \frac{\text{total heat removed from the solar pond}}{\text{total amount of solar radiation which has fallen on the surface of the solar pond}} \]

Also, the conductivity efficiency can be calculated by conductive heat transfer per energy storage.

\[ \eta_{\text{cond.}} = \text{conducted thermal energy/stored thermal energy.} \]

\[ \eta_{\text{cond.}} = \frac{k_b}{\rho_bV_b\epsilon_b}\Delta t \]  

(27)

\[ k_b = 5.553 \times 10^{-1} - 8.13 \times 10^{-5} \zeta + 8 \times 10^{-4}(T - 20) \]  

(28)

\[ k_b = 5.553 \times 10^{-1} - 8.13 \times 10^{-5} \zeta + 8 \times 10^{-4}(T_{ave} - 20) \]  

(28a)

The salinity percentage as a concentration of salt in the brackish water is so effective in the thermal storage. So, this variable is defined in the Equations (28) and (28a).

\[ \rho_b = 998 + 0.65\zeta - 0.4(T - 20) \]  

(29)

\[ \rho_b = 998 + 0.65\zeta - 0.4(T_{ave} - 20) \]  

(29a)

\[ \text{R.R.} = \frac{V_{\text{cond}}}{V_b} \times 100 \]  

(30)

The three sections are supposed for solar desalination ponds. The first region is an upper convective zone, and the middle is gradient zone and the lower zone is named as storage zone. The density of this layer which is situated at the bottom of solar pond is so high. So, sun rays accumulate in this layer.

The recovery ratio, R.R., is defined as producing fresh water volume per feed volume. This relation is introduced in the Equation (30).

Another efficiency is called as collection efficiency. This type of efficiency can be calculated from stored sensible energy in a storage layer per absorbed total energy by storage water layer.

\[ \eta_c = \frac{10^4c_b\Delta T}{I\bar{A}_{ba}} \]  

(31)

where, \( \bar{I} \) is the average amount of solar irradiation during the month. In addition, \( t \) is an operational time interval of solar pond during a month and \( \Delta T \) is temperature changes of storage layer. In addition, \( A_{ba} \) is the surface area of the storage water layer and this is important in receiving of solar irradiations.

3 | RESULTS AND DISCUSSION

Focusing on the thermal properties of wastewater, the effect of depth of wastewater, and the insolation rate at each month is investigated on the operational efficiency of a solar pond.
3.1 | Thermophysical properties

Density is a main parameter in heat storage. This factor can increase the capacity of stored heat in the lower zone of solar pond. The density values of brackish water versus depth are shown in the Figure 2. The density in each layer of wastewater is recorded using probes related to vibration-type liquid density meter DM8.

The deeper layer contains more amount of salt and higher density value is expected. At each 0.05 cm the density value is measured. At the surface, the density is 1060 kg/m³, in the middle of the first layer (0.05 cm) the density value is 1 and after that the density of layer two and three is 1120 and 1270, respectively.

The variation in wastewater heat capacity is shown in the Figure 3. The increase in the depth of the solar pond decreases the amount of heat capacity of salty water. The amount of heat capacity is presented for four points in salty wastewater. The deeper level contains more salt than the other upper levels. Whereas, heat capacity of water is higher than the heat capacity of salt. The specific heat of water is \((4200 J/kg \times °C)\) and for salt is \((864 J/kg \times °C)\). So, the decrease in the amount of total specific heat of capacity of salty wastewater through the depth is predictable.

The Figure 4 shows the different values of viscosity versus depth of wastewater. The salinity and temperature are two effective parameters on the amount of viscosity. The decrease in value of viscosity is obtained through the depth. The increase in salt content increases the value of viscosity, however; the increase in temperature decreases the value of viscosity. In this case, this is obtained that the value of high temperature in a storage layer (third layer) has much more effect than amount of salt content.

The other heat property of wastewater, such as thermal conductivity is measured in different layers of wastewater. The Figure 5 shows the values of thermal conductivity through the depth of wastewater. The decrease trend of thermal conductivity due to the increase in salt concentration is obtained through the depth. The increase in wastewater temperature enhances the thermal conductivity, slightly.

3.2 | Investigation of thermal and conductivity efficiency

The thermal efficiency as defined as the ratio of total heat removed from the solar pond to the total amount of solar radiation is calculated from derived theoretical equations and is shown in the Figure 6. In addition, the obtained experimental data for thermal efficiency is compared with the theoretical one. The calculations are done during day and night, separately to cover night and day hours. The relative error for thermal efficiency in day and night is 7.2% and 4.9%, respectively. In addition, Rapaka et al. (2013), investigated on the solar pond with polymer gels. Literatures prove the effect of transmittance on the temperature profile in different layers of wastewater. The stored heat will increase in the bottom of solar pond and the production rate will increase, finally.34
Sideways, the insolation rate and also, temperature profile is variable in the daytime. Whereas, these items are effective on the yield percentage of solar desalination pond. So, evaluation of yield is considered, capitally.

The conductivity efficiency is calculated for more investigation. The conductivity ratio is evaluated on the day and night for 2017 months and is shown in the Figure 7. The relative error for conductivity efficiency in day and night is calculated as 7% and 5.6%, respectively.

Farahbod et al. (2013), evaluated the nonconvective salt gradient layer in a solar desalination pond. They stated that the salt content has directed relation with conductivity factor. It means, the conductive heat-transfer coefficient will increase with increasing of salinity percentage in the different layers of wastewater.20

3.3 | Evaluation of recovery ratio

The recovery ratio, which is defined as producing potable water per unit volume of inlet brackish water to solar pond is calculated, theoretically and experimentally. The Figure 8 shows the amount of recovery ratio, and insolation rate versus different months of 2017. The Figure 8 states the calculated relative error of the recovery ratio in a day is 6.1% and 7.3% for the night. Jadidoleslami et al. (2016), Farahbod et al. (2012), investigated on the production rate of distilled water from solar desalination pond. They stated the radiation in different months is variable and so affect on the salt content in brackish water and increase/decrease the amount of producing distilled water.16,35

The Figure 9 shows the relation between the amounts of insolation rate and amount of collection efficiency during the year of 2017. There is good agreement between experimental and theoretical data of collection efficiency. This difference may be related to the temperature prediction by the mathematical equations. According to the Figure 9 the insolation rate is not the only effective parameter on the collection efficiency.

3.4 | Sensitivity analysis and economic aspect

The average convective heat-transfer coefficient is considered according to the regular wind velocity reported in the literature to calculate external convection. Also, the
sensitivity of the ambient temperature of the dust and tiny particles is ignored and a fixed transmisivity factor for the ambient is used. The lower operating costs in the form of alternative energy source have been found to be key factors in the economic viability of solar desalination ponds. The construction cost of this desalination method is not considerable compared with other desalination method. Solar desalination plants have a mean lifetime of about 20 years while the cost of fresh water produced by solar plants ranges from 0.62 to 3.5 US$/m³, depending on the plant and the cost analysis method. It is important to realize that the maximum production rate free of energy charge and lower operating costs are main indexes of the performance evaluation of solar pond.

4 | CONCLUSIONS

The performance of solar desalination pond is investigated as basic concepts of efficiency. The thermal efficiency, conductivity efficiency, and collection efficiency are investigated in this paper, experimentally and mathematically. Some thermophysical properties such as specific heat of capacity and density of saline water are reported to evaluate the mentioned efficiency for solar pond. These efficiency definitions had not been presented before any literatures. So, the authors are claiming that the calculations of these yields are presented for the first time. Undoubtedly, this is the outstanding novelty of presenting papers. Results state the relative error for thermal efficiency at day and night is 7.2% and 4.9%, respectively. In addition, the relative error for conductivity efficiency at day and night is calculated as 7% and 5.6%, respectively. The relative error for collection efficiency of the storage layer during month at each day is about 3.5%. Sideways, this solar desalination pond is closed and uses an evaporation method without fuel energy and electrical energy charges and also is environmentally friendly. Whereas, the produced distilled water is not keeping in touch the surrounding. So, the quality of producing water is very high due to evaporation method is utilized. So, the produced water can be consumed for drinking, pharmaceutical purposes, laboratories, factories,
and microirrigation. This solar desalination pond can be used in parallel for obtaining more potable water production. In addition, maintenance cost of this solar pond is not significant compared with the other technologies.

**NOMENCLATURES**

**Symbols**

- \( A_b \) Surface of solar pond base, (m²)
- \( A_{ba} \) Surface of brackish water, (m²)
- \( A_g \) Surface of glass covers, (m²)
- \( c \) Specific heat, (J/kg.K)
- \( I \) Solar flux, (W/m²)
- \( h \) Heat-transfer coefficient, (W/m²K)
- \( \bar{c} \) Heat capacity at average temperature, (J/kg.K)
- \( h_{lv} \) Latent heat of vaporization, (J/kg)
- \( \zeta \) Salinity, (gr/kg)
- \( \dot{E} \) Heat rate, (W)
- \( T \) Temperature, (C)
- \( t \) Time
- \( dt \) Time interval, (s)
- \( T_s \) Sky temperature, (C)
- \( \rho \) Density, (kg/m³)
- \( k \) Conductivity factor, (W/m.K)
- \( l \) Height of brackish water, (m)
- \( V \) Volume, (m³)
- R.R. Recovery Ratio
- \( z \) Altitude, above the mean sea level, (m)

**Subscripts**

- A Ambient
- ba Base (of solar pond)
- b Brackish water
- c convective
- cond. condensate
- con. conducted
- e Evaporative
- eff. Effective
- g Glass
- r Radiative
- s Sky
- t Time
- th. thermal

**Greek**

- \( \varepsilon \) Emissivity factor
- \( \alpha \) Absorptivity
- \( \delta \) Stefan-Boltzman constant, (W/m²K⁴)
- \( \zeta \) Salt concentration (kg/m³)
- \( \theta_i \) the zenith angle
- \( \lambda \) angle of declination in degree
- \( \phi \) angle of latitude
- \( \omega \) the hour angle
- \( \eta \) Efficiency

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**ORCID**

Farshad Farahbod [http://orcid.org/0000-0003-2341-3329]
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