EXPERIMENTAL AND NUMERICAL STUDY ON TEMPERATURE DISTRIBUTIONS OF A SALT GRADIENT SOLAR POND

[1]NI NI AUNG, [2]MYAT MYAT SOE, [3]MON MON AYE

[1,2,3]Mechanical Engineering Department, Mandalay Technology University, Patheingyi Township, Mandalay, Myanmar
Email: [1]angelkalay123@gmail.com, [2]myatmyatsoe.mtu@gmail.com, [3]monmonaye.mech@gmail.com

Abstract: The aim of this research is to perform the experimental setup on a salt gradient solar pond (SGSP) to be used for desalination. The objectives are to provide experimental data on the performance of a SGSP and to investigate the temperature distribution in a SGSP by using ANSYS-CFX software for the CFD numerical simulation. An experimental study is performed on a SGSP made of cylindrical shape polyethylene tank of 1000 L volume, 1.04 m diameter, 1.29 m height and 10 mm thick.The bottom and side walls of the pond are plated with the iron sheets. The tank's wall is insulated with polystyrene foam of 14 cm thickness. The bottom of SGSP is supported by an iron stand insulated with polystyrene foam sheets of 30 cm thickness to prevent heat loss to the ground. The inner surface is painted with matt-black and covered with black plastic to increase the absorption of incident solar radiation.Pure sodium chloride salt (NaCl ≥ 98.5 %) is used to make the salt gradient. During a period of two months of experimentation, the maximum storage temperature is reached to 32.2ºC at 5 pm during daytimes and 32.4ºC at 10 pm during night time. According to the numerical result, the maximum storage temperature is reached to 36.2ºC. The numerical temperature distributions also show a good agreement with experimental results.

Keywords: heat storage, numerical simulation, performance analysis, salt-gradient solar pond, temperature distribution

I. INTRODUCTION

Energy is an important factor for every country all over the world. Solar energy is one of the effective solution to environment pollution, the largest source, and abundantly available in all parts of the earth. It can be used as thermal energy during sunshine hours but it is not available all the time. Therefore, heat storage has been considered for using at night and cloudy day. Heat storage save energy during sunshine hour and then it can be used off-shine hour. Conservation of solar energy into thermal energy is the easiest and the most widely method. Compared with other solar technologies, solar ponds which combined solar collector and thermal energy storage system provide the most convenient and least expensive option for heat storage for daily and seasonal cycles. Due to this nature, solar pond can play an important role in the solar energy systems [1]. The solar pond works on a very simple principle. Most people know in natural pond, when the sun's rays heat up the water, this heated water from within the pond, being lighter, rises up to the surface and losses its heat to the atmosphere. The net result is that the pond water remains at the atmospheric temperature [7, 11]. The solar pond restricts this tendency by dissolving salt in the bottom layer of the pond making it too heavy to rise. Solar radiation entering the pond penetrates through the lower layer, which contains concentrated salt solution. The temperature in this layer rises since the heat it absorbs from the sunlight is unable to move upwards to the surface by convection [7]. A salt-gradient solar pond is an inexpensive solar energy collection and storage system for low-temperature heat-sources. It is an artificially constructed water pond with three main zones as shown in Fig. 1. The top zone is the Upper Convection Zone (UCZ) or surface zone that acts as solar collector/receiver. This is a homogeneous layer of the lowestsalt concentration. The thickness of thiszone should be kept as shallow as possible. The middle zone is the Non-Convection Zone (NCZ) or gradient zone that acts as transparent insulator layer permitting sunlight to reach the bottom zone but also entrapping it there. This layer is not homogeneous because it consists of multi sub-layers in which each sub-layer is heavier and hotter than the ones above it. This density gradient prevents the heat loss from the lower zone to the upper zone.The thickness of thiszone is much thicker and occupies more than half the depth of the pond.The bottom zone is theLower Convection Zone (LCZ) that acts as the heat storage zone. This is a homogenous layer of highestsalt concentration (20% to 30%).Thiszone is almost as thick as the middle zone.Thermal energy stored in this zone can be used for desalination, electricity generation, heating, cooling and drying processes [5, 7].

Solar ponds have been studied by many researchers in the US, Israel, Australia and several other countries because of their excellent heat collection and storage performances. Experimental works basically concentrate on design, application and experimental thermal measurements in solar ponds to investigate the thermal behaviour of various types of solar ponds in different dimensions [2, 3, 4, 8, and 9]. The mathematical formulation of the behaviour of solar ponds was first given by Weinberger. Theoretical studies are particularly focused on modelling of solar ponds for their performance analysis and predicting temperature variations in the ponds. Solar energy is absorbed by a solar pond from its surrounding during the day and stored in the form of heat energy in it.

During the nights, due to non-existence of solar energy, no contribution is made to the pond's thermal energy [10]. The use of numerical methods for studying the solar pond was first suggested by Tabor; however Hull first used the finite difference method to investigate solar pond performance [1, 3, and 11].

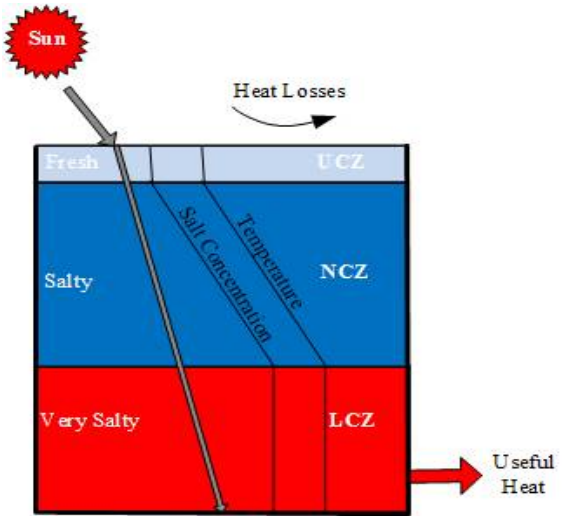


Fig.1. Schematic Diagram of Salt Gradient Solar Pond (SGSP)

Myanmar is enriched in solar energy. However, the performance of a solar pond in this region has not been evaluated and constructed yet. In this study, experimental setup was performed on a salt gradient solar pond to be used for desalination.The project aims were to obtain experience with operating solar pond, to study the design, construction, filling, operation and maintenance and the temperature distribution of salt gradient solar pond. The CFD commercial software considered to be utilized is ANSYS CFX and the challenge is to visualize the transient effect of temperature distribution.

II. EXPERIMENTAL SETUP

The experimental salt gradient solar pond set-up is located at Mechanical Engineering Department in Mandalay Technological University where maximum sun exposure and water supplies are easily available. The main solar pond body is made up of cylindrical shape polyethylene water tank of 1000 L volume, 1.04 m diameter, 1.29 m height and 10 mm thick. The inner and outer surfaces of it are painted with matt black color to increase the absorption of incident solar radiation. It is enclosed in an iron box which is made of 1.2 mm iron sheet at a height of 1.65 m and size of 1.32 m × 1.32 m. The inner and outer surfaces of box are painted with red oxide to avoid corrosion. The tank's wall was insulated with polystyrene foam sheets of 0.14 m thickness. The bottom of solar pond was supported by an iron stand insulated with polystyrene foam sheets of 0.3 m thickness. Plywood is used to cover the insulation, drilled to fill the foam liquid which cannot trap the air for the spaces between insulation and pond, and then painted with black color. All these system are covered with black plastic. The copper tube of 16 mm diameter, 0.71 mm thick and 18 m length is used as a straight and coil heat exchanger and stainless steel solid rod of 14 mm diameter and 3 m length is used to stand the heat exchanger in the middle of pond. To measure the temperature distributions in each layer, the ten digital thermometers are used. The wires are connected for the short sensors to be sufficient. The PVC pipes and lips of 12 mm diameter are used to insert the temperature sensors for each layer. The PVC pipe of 76 mm diameter is used to make the salt charger. The solution from the pond is piped to measure the salt concentration of each layer. If the salt lost from the bottom zone, the require amount of salt can add to the salt charger without destroying the various layers. All temperature sensors, salt charger and pipes are fixed to the inside wall of the pond. The secondary plastic tank of 200 L capacity is used to supply the fresh/ salt water to the main solar pond. The four legged iron stands are appropriate to construct the main solar pond (height 1.52 m and size 1.32 m × 1.32 m) and secondary tank (height 3.66 m and size 0.61m × 0.61 m) stands. The eight concrete stands are used to make the strong based frames of main solar pond and secondary tank and placed under the ground and then installed with iron stands.



Fig.2. Photographic View of Experimental Set up of SGSP

The top of solar pond is covered by 8 mm thick transparent glass with aluminium frame. The iron ladder is used to observe the temperature distribution of solar pond. A diffuser can be made of plastic pipe in circular form and several holes along them led the higher density brine out. The foam sheet and circular plastic pipe are tied for coming to light. It is an essential role for filling process. The flow of water from plastic tank to pond can be controlled by flexible hose and valve. Single-phase submersible pump of 0.55 kW power, 35 m head, 6 m3/h flow and 2860 rpm speed is used to mix the salt and water, and to supply the solution to the secondary tank. The experimental apparatus of solar pond is shown in Fig.2.

2.1.Salt Gradient Establishment

Experiments in small laboratory tanks were also carried out to try out and verify procedures for pond filling and gradient establishment. The salinity gradient was achieved using the salinity redistribution method. Pure sodium chloride salt (NaCl≥ 98.5 %) is used to establish the salt gradient layer. Salt and water is mixed to prepare the brine solution and this process is done externally using the other fiberglass tank. This solution is sent to the secondary plastic storage tank. There are three steps in Zangrando or redistribution method. Firstly, saturated brine solution can be poured to fill the depth of the LCZ without any difficulty. The bottom zone has 0.48 m depth and 24 % concentration. Secondly, a diffuser is placed horizontally at the middle of the pond and the top of LCZ surface. Diluted concentrated brine solution is injected very gradually at the top of it. It is raised to the next higher position and injected again for the next period. It is moved upward continuously at a rate twice that of the increase in the pond water level until it reaches the water surface at the predetermined ending level.The middle zone has 0.6 m depth and split into five equal size layers, 0.12 m each and 20, 16, 12, 8, and 4 % concentration respectively. Finally, fresh water is added to make the surface zone. The top zone has 0.12 m depth and 0 % concentration. Time of maturation depends upon the quantity of total capacity of solar pond. During the maturation period, it may lose about two weeks to create three independent zones and care should be taken so that no disturbance occurs. Never try to remove the solar pond when experimentation is carried out.

2.2.Instrumentation Measurement

A measurement system had been installed for recording the experimental data. Ten digital thermometers with stainless steel sensor prose of -50ºC to +300ºC temperature range and ±0.1ºC accuracy were used to measure temperature distribution in solar pond. Temperature at different depths of the pondwas measured at distances of 6, 12, 18, 24, 30, 36, 42, 48, 54, and 60 cm from the bottom. The 250 ml measuring cylinder, salt meter and hydrometer are used manually to measure the salt concentration of solution samples. Solar power meter was used to determine the solar radiation intensity of pond's surface. Ambient temperature from the surrounding was taken using thermometer. Anemometer is used to measure the air velocity from the surrounding. Infrared Thermometer is used to measure the glass outside temperature.Measurements are taken for every one hour between 8:00 am and 5:00 pm.

III. NUMERICAL SIMULATION APPROACH

Computational Fluid Dynamics (CFD) is a branch within fluid dynamics where numerical methods and algorithms, are used to solve heat transfer problems that are far too complex to solve analytically. A key benefit of CFD is that a great amount of time and money can be saved concerning experiments. The commercial software ANSYS was used for the CFD numerical simulation. ANSYS CFD solvers are based on the Finite Volume Method (FVM). ANSYS can also be used transient thermal and steady state thermal field, fluid flow, explicit dynamic, vibration and static structural. ANSYS Workbench combines access to ANSYS applications with utilities that manage the product workflow. CFD numerical simulation is performed for temperature distribution in a solar pond by using ANSYS CFX software. ANSYS CFX is a state-of-the-art computer program for modeling heat transfer and chemical reactions in complex geometries. ANSYS CFX software can be coupled with the ANSYS Multiphysics solver to perform fluid structure interaction simulation with conjugate heat transfer (CHT) which is one example of multi-domain simulation. In CFX, only the coupled solver is implemented and the vertex based FVM approach is used for discretisation. Two main multiphase model are available; a homogeneous and an inhomogeneous model. The homogeneous corresponds to a VOF model. The inhomogeneous model is based on the Euler-Euler approach and can be used together with several subsidiary models to model dispersed flow, mixtures of continuous fluids etcetera. A first order scheme, a blending scheme and a higher resolution scheme are available. Depending on the types of phases, for example continuous or dispersed fluid, different interphase transfer models are made available. This CFD numerical simulation has five steps. They are creating geometry, meshing to geometry, CFX-Pre, CFX-Solver and CFD-Post.

3.1. Geometry

Firstly, three dimensional geometry models for solar pond are drawn in ANSYS ICEM CFD software which allows for the use of CAD geometries or to build the geometry using a number of geometry tools. The cylindrical domain of consideration is that of the existing pond dimensions with 1.04 m diameter and 1.2 m height. The pond has been divided in three zones. The bottom zone (LCZ) has 0.48 m depth. The middle zone (NCZ) has 0.6 m depth and five equally divided sub-layers, each 0.12 m depth. The top zone (UCZ) has 0.12 m depth. Therefore, the physical domain consists of seven layers.

3.2. Mesh

The mesh structure and properties play an essential role in the overall accuracy of the simulation. The shape of the mesh elements can be triangular, quadrilateral, tetrahedral, hexahedral or prism. The shape and size of the mesh elements can be varied and are kept according to the dimension of the geometry, accuracy required, computational power of the system and memory. After drawing 3D geometry, meshing is done in the ANSYS ICEM CFD which

employs a block-structured meshing approach. In this meshing, the geometries are used tetrahedron method. The number of mesh nodes is 207500 and elements1086200. The meshing of model has been shown in Fig. 3.

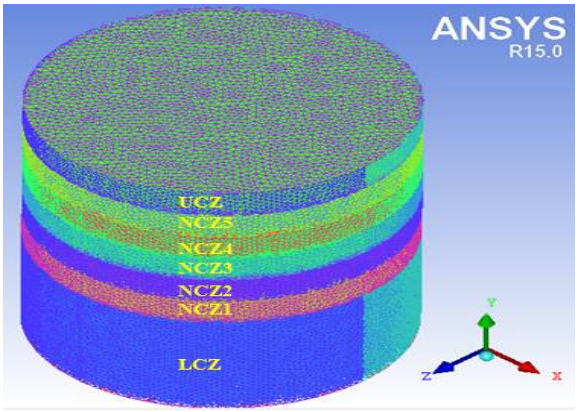


Fig. 3.Mesh Generation of SGSP

3.3. CFX-Pre

The mesh is imported to ANSYS CFX-15 software. In ANSYS CFX-Pre, the properties of the domains are defined along with their interface properties. The gravitational acceleration was set as 9.81 m/s², and absolute pressure 1 atm. The fluid motion was considered as laminar flow, since water velocity didn't achieved greater magnitudes. Bottom and vertical walls of the pond are set to be impermeable and thermally insulated. Also the top surface is taken to be at ambient temperature according to local meteorological data. Modelling of the physics included creating interfaces for flow zones, assigning boundary conditions, assigning initial conditions, applying governing equations with appropriate models and choosing the flow materials. After setting physics definition CFX-Pre, the overall approach for solving this problem is to set up a transient simulation.The solution control and declaration of variables were also done in the ANSYS CFX-Pre.

3.4. CFX-Solver

The governing equations used to model fluid flow, heat transfer in ANSYS CFX are described. The problem presented in this simulation consists in solving the combined equations of Navier-Stokes and energy equation for compressible fluid and subjected to density and concentration variation with temperature. For this case, ANSYS CFX uses the finite volume method for modelling the constitutive equations of the system in their conservation form.

Natural convection occurs when temperature differences in the fluid result in density variations. This is one type of buoyancy driven flow. For buoyancy calculations, a source term is added to the momentum equations as follows:

$$S_{M,buoy} = (\rho - \rho_{ref})g \qquad (1)$$

For buoyancy flows where the density variation is driven by small temperature variations, the Boussinesq model is used. The density difference is evaluated using this model as follows:

$$\rho - \rho_{ref} = -\rho_{ref}\ \beta\ (T - T_{ref}) \qquad (2)$$

The instantaneous equations of mass, momentum and energy conservation can be written as follows in a stationary frame:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \qquad (3)$$

Momentum equation

$$\frac{\partial (\rho U)}{\partial t} + \nabla.(\rho U \otimes U) = -\nabla \rho + \nabla.\tau + S_M \qquad (4)$$

Energy equation

$$\frac{\partial (\rho h_{tot})}{\partial t} - \frac{\partial \rho}{\partial t} + \nabla.(\rho U h_{tot}) = \nabla.(\lambda \nabla T) + \nabla.(U\tau) + U.S_M + S_E \qquad (5)$$

where, $\tau = \mu\left(\nabla U + (\nabla U)^T - \frac{2}{3}\delta \nabla.U\right)$

$$h_{tot} = h + \frac{1}{2}U^2$$

When the solver has finished, a completion massage appears in dialog box.

3.5. CFD-Post

After solving the governing equations in solver, the results of CFD simulation are showed in CFD-Post. It includes all expected plotting objects like planes, volumes, contours, isosurfaces, vectors, streamlines, animations, etc. CFD-Post includes automatic reports, charts and tables.

IV. RESULTS AND DISCUSSION

After performing the filling process, the temperature distribution inside the pond was measured manually with ten digital thermometer distributed vertically with a gap around 6 cm. Daily data was observed once an hour from 8 am until 5 pm. According to the experimental result, SGSP has been able to operate properly by the increase of temperature at 5 pm on every day, although there is still a decreasing in temperatures that occurs in the next morning due to heat loss from the sides and bottom of the tank at night. Therefore, the data for average temperature at the bottom (LCZ) layer of SGSP at 5 pm is shown in Fig. 4.

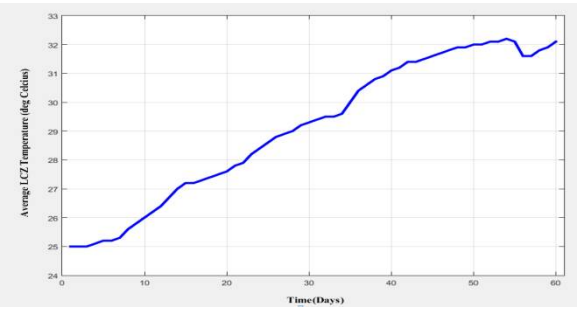


Fig. 4. Average Heat Storage Temperature Rise of SGSP During Daytimes after Two Months of Filling Process

There are variances in the figure, the stored temperature started at the time due to pond filling preparations, and salt concentration arrangements, which last several days, collecting and storing solar energy as heating energy mode, which increased storage region temperatures. The temperature differences increased with time to reach its maximum value. Solar pond heats up slowly but store heat in a longer period of time. It can be seen that the maximum storage temperature reaches 32.2°C after two monthsof the filling process.It can be expected to achieve higher temperature degrees.

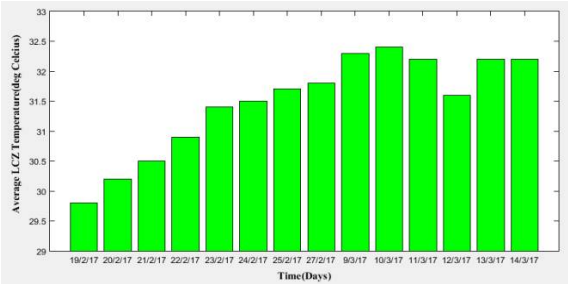
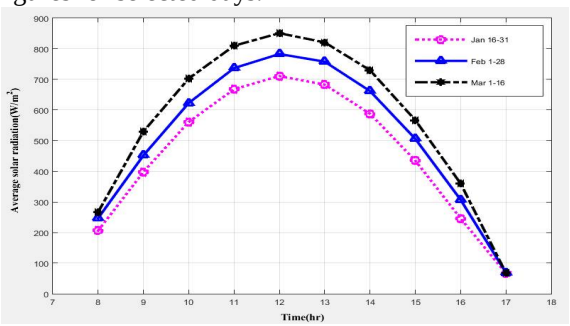


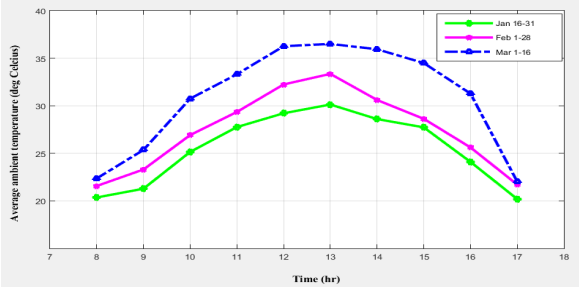
Fig. 5. Average Heat Storage Temperature Rise of SGSP During Night Time for Selected Days

The experimental temperatures were measured from 6 pm until 10 pm during nighttime of the selected days. Although at nighttime there are larger heat losses referring to discharging process due to the inexistence of the solar irradiation, at 10 pm the storage temperature still increased. The maximum storage temperature reaches 32.4°C. During the cloudy and raining days, heat storage temperature still maintains, 31.6°C occurs at 10 pm of raining day (12/3/2017).

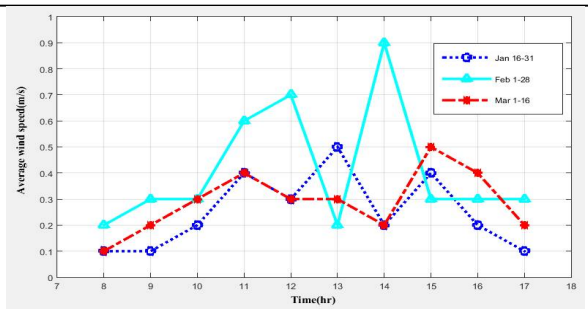
The temperature variations depend on the solar energy that reaches on the pond's surface, the climate conditions of the place and time. All these data was measured manually and shown in the following figures for selected days.



(a)



(b)



(c)

Fig 6.(a) Average Solar Radiation on the Pond's Surface, (b) Average Ambient Temperature, (c) Average Wind Speed

It can be seen that the maximum solar radiation occurs at 12:00 and the minimum at 17:00. The maximum ambient temperature occurs 13.00. The maximum wind speed is 0.9 m/s and minimum 0.1 m/s.

Three-dimensional (3D) CFD simulation is performed for heat transfer in a solar pond by using ANSYS CFX software. A complete workflow for CFD simulation is presented in this section. For geometry and mesh generation, the ANSYS software ICEM CFD was used. Meshing of model was inputted into CFX which consists of pre-processing, solver and post-processing. The resulting CFD case in ANSYS Workbench is depicted in Fig. 7.

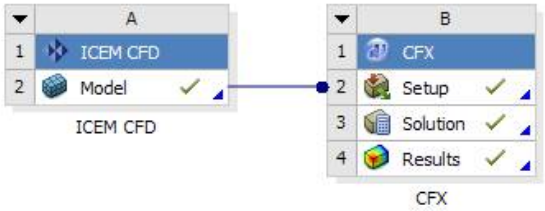


Fig. 7. CFD Numerical Simulation Procedure

After the post-processing of simulation results, the temperaturedistribution of SGSP is obtained and presented in the Fig. 8.

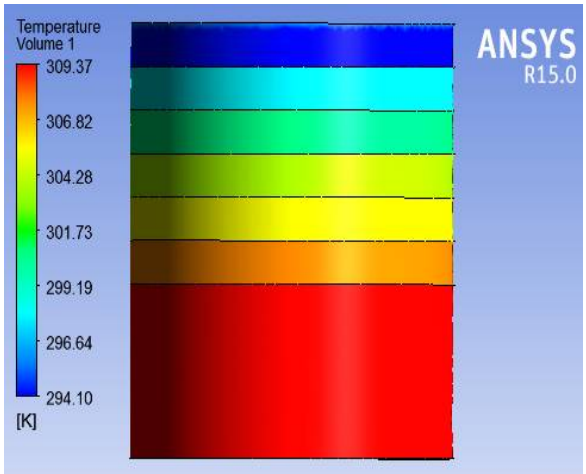


Fig. 8. Temperature Distribution of SGSP

The temperature distribution of SGSP is shown in Fig. 8. In three dimensional simulation, the total

depth of solar pond is analyzed. It is already possible to visualize the thermal stratification in a solar pond. The different colours defined the value of temperature in each zone of solar pond.As can be see that the temperature distributes to bottom and this heat can store in the bottom of SGSP.

CONCLUSIONS

This paper deals with an experimental and numerical study of temperature distributions in an insulated solar pond, particularly during daytimes and night time. The experimental setup was performed on a SGSP to be used for desalination. The great advantage of SGSP is their unique ability to store thermal energy in the bottom layers of the saturated brine. The data for daily temperature distributions, solar radiation and ambient temperature is collected from 16th of January until 16th of March 2017. The maximum storage temperature reaches 305.55 K after two months of the filling process. It can be expected to achieve higher temperature degrees. The maximum storage temperature of 309.37 K occurs according to the results of ANSYS CFX software. Heat extraction started after 120 days of operating the pond according to the literature review. Therefore, SGSP should be placed about four months to get the required temperature distribution to extract heat energy from the pond. The results are reasonable compared to other studies.

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