*JOURNAL OF NANO- AND ELECTRONIC PHYSICS*
Vol. **12** No 1, 01016(5pp) (2020)
*ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ*
Том **12** № 1, 01016(5cc) (2020)

# Thermal Performance Enhancement of a Shallow Solar Pond Based on Nanofluids

A. Terfai, Y. Chiba, M.N. Bouaziz

*Biomaterials and Transport Phenomena Laboratory, Mechanical Engineering Department, University of Medea, 26000, Algeria*

(Received 25 November 2019; revised manuscript received 15 February 2020; published online 25 February 2020)

In this work, the thermal performance enhancement of a shallow solar pond (SSP) was verified theoretically. The SSP operates under the open cycle to extract heat in order to increase own efficiency. SSP was provided with two transparent glass covers to reduce heat loss and increase global warming. It was also coated with a heat insulation material; the bottom of the SSP is painted in black to improve the absorption of solar radiation. In order to enhance heat extraction, five types of nanofluids with different physical properties were passed through a heat exchanger in the form of a serpentine welded to the bottom of the SSP. Five types of metal nanoparticles such as $Al_2O_3$, CuO, $TiO_2$, $SiO_2$, and Cu were mixed with pure water under various concentrations ranging from 0 to 5 % to obtain the nanofluids. A numerical model was developed based on the solution of thermal balance equations after discretization by using real meteorological conditions of the Medea city located in Algeria. The simulation was conducted on June 8 from 5 am to 6 am hours for the next day. The obtained results, including thermophysical properties, temperature of the pond and exergy performance, were presented and discussed.

**Keywords:** Nanoparticles, Nanofluids, Shallow solar pond, Numerical simulation, Performance.

DOI: 10.21272/jnep.12(1).01016 PACS numbers: 85.30.Fg, 73.40.Kp, 73.40. – c

## 1. INTRODUCTION

Solar energy is one of the most important renewable energies. Its importance is due to the fact that it is available throughout the world and during the year. In addition, it is a clean energy that has no negative impact on the environment and is considered a good substitute for fossil fuels [1]. Among the methods of collecting and storing solar energy is the shallow solar pond (SSP), which has been touched by many scientific researches during the last century. Tiwari et al. have proposed a mathematical model to predict the performance of a SSP fitted with a single cover and a heat exchanger, which was simulated through a change in insulation thickness, flow rate, and water mass [2]. This mathematical model was proposed to predict the performance of a SSP with a single cover and a baffle plate. Digital simulation was performed on a cold day on December 18, 1984 in New Delhi. It was concluded that the performance of the SSP using a baffle plate was better than a pond without a baffle plate (Tiwari et al. [3]). A mathematical model was proposed to predict the performance of a SSP combined with a baffle plate. The energy balance equations for different parts of the pond are solved analytically using the removal technique. The theoretical results were compared with the experimental results based on the prevailing weather conditions in Tanta, Egypt (El-Sebaii et al. [4]). The thermal performance of a SSP was tested theoretically and experimentally under the climatic conditions of the city of Tanta in Egypt. During summer 2001, the pond was operating under the open cycle for heat extraction. The study showed that the use of a second glass cover significantly reduces thermal loss (Ramadan et al. [5]). The thermal performance of a SSP operating under the open cycle to extract heat has been verified. Heat is extracted by a heat exchanger once immersed in the pond water and once welded with the absorbent plate. A mathematical model was proposed and dissolved, and a computer program was developed to simulate the pond (El-Sebaii et al. [6]). El-Sebaii et al. [7] undertook a theoretical study to find out the effect of linking a shallow solar pond on the performance of a single-basin solar still. It was found that the performance of a solar still associated with the pond is 52.36 %, and without the pond is 43.80 %. Janarthanan [8] compared the thermal performance of two solar ponds experimentally and theoretically: one with a depth of 0.06 m and the other with a depth of 0.15 m. He concluded by his study that the pond with a depth of 0.06 m with a maximum temperature of 57 °C provides a better performance than the pond with a depth of 0.15 m with a maximum temperature of 42 °C. Mohammad A. et al. [9] tested the effect of nanoparticles on the performance of a SSP by comparing the performance of two solar ponds working side by side: one filled with water, and the second – with aluminum oxide. The results obtained showed that the best performance of the pond is the addition of aluminum oxide by 0.2 %. It is able to store as much heat energy as possible compared to the pond filled with water.

There are three ways to extract heat from the SSP, either by emptying the pond of water, which is the direct method, or open cycle mode and finally the closed cycle mode. The methods of open and closed cycle to extract heat depend on the heat exchanger and heat transfer fluid. Common heat transfer fluids, such as water, ethylene glycol and oil, have low heat conductivity, which adversely affects heat transfer. To overcome this problem, scientific research has attempted to improve the thermal conductivity of fluids by suspending small solid particles in an order of 1-100 nm in liquid. These types of liquids have been used for nearly two decades. The method of preparation of nanofluid and nanofluid hybrid synthesis was examined and the different characteristics and applications of these liquids were also mentioned [10]. The research papers dealing with nanofluid applications in heat exchangers were reviewed including shell and tube heat exchangers, compact heat exchangers and double pipe heat exchangers (Huminic et al. [11]). An experimental study was conducted on the effectiveness of nanofluids (Cu-water) use in a serpentine heat exchanger with variable straight-section lengths and its effect on thermal transfer (Khoshvaght et al. [12]). Yousfi et al. [13] conducted an experimental study to see the effect of using nanofluids ($Al_2O_3 + H_20$) as heat transfer fluid on the efficiency of flat plate solar collector, and they found that the best performance of the collector was 28.3 % at a nanoparticle concentration of 0.2 %. Nanofluids are used in many thermal applications, including solar pond, solar still, thermal energy storage, solar cells, solar thermoelectric cells, photovoltaic/thermal systems, and many other applications [14].

The aim of this work is to study the effect of using different types of nanofluids at varying concentrations on the thermal performance of a shallow solar pond.

## 2. MATERIAL AND METHOD

### 2.1 Schematic Diagram of the Pond

As shown in Fig. 1, the system studied is a shallow solar pond working under the open cycle and continuous heat extraction. The pond area is 1 m$^2$ and its depth is 0.06 m. The SSP is equipped with two glass covers to increase the greenhouse effect, the distance between the two covers is 0.06 m. The bottom of the pond was painted black in order to increase the absorption of solar radiation. In order to reduce heat loss, the SSP is coated with polyester material from the sides and from the bottom. The SSP is connected to a cold reservoir by serpentine welded to the bottom of the SSP. In order to extract the collected heat from the SSP, five types of different physical properties of nanofluids were used. These nanofluids are used in different concentrations ranging from 0 to 5 %.

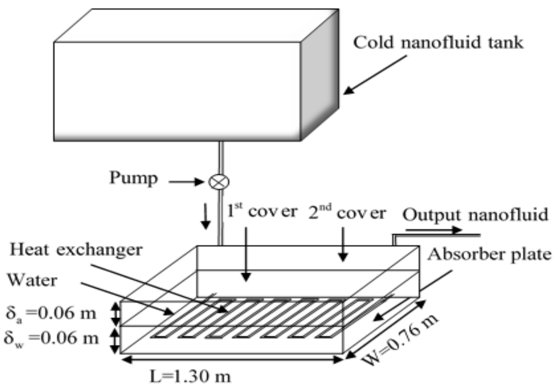


**Fig. 1** – Schematic diagram showing the dimensions of the SSP with two glass covers

These nanofluids are pumped with a flow of 0.003 kg/s, the heat exchanger length is 8 m and the diameter is 0.01 m. Based on the solutions of differential equations resulting from the thermal equations of the SSP, a computer program was developed using the Matlab program in order to simulate the thermal performance of the SSP. The simulation was performed on 08/08/2019 from 5 am to 6 am the next day. The Bird and Hulstrom model [15] was also used to calculate solar radiation using climatic conditions for the city of Medea in Algeria. Latitude is 36.28° and longitude is 2.73°.

### 2.2 Thermophysical Properties of Nanofluids

In order to extract heat from the SSP, we propose five types of heat transfer fluids consisting of water ($H_2O$) as a basic fluid, and five types of solid materials with different physical properties, namely copper (Cu), titanium dioxide ($TiO_2$), silicon dioxide ($SiO_2$), copper oxide (CuO) and finally aluminum oxide ($Al_2O_3$). These particles are immersed in water at different concentrations to raise the properties of the basic fluid.

The different physical properties of these nanoparticles and the basic fluid are shown in Table 1.

**Table 1** – Thermophysical properties of base fluid and nanoparticles

| Thermophysical properties | Basic fluid | Nanoparticles | | | | |
|---|---|---|---|---|---|---|
| | $H_2O$ | $Al_2O_3$ | $TiO_2$ | CuO | Cu | $SiO_2$ |
| $\rho$ (kg/m$^3$) | 998.2 | 3960.14 | 4157 | 6450 | 8954 | 2220 |
| $C_p$ (J/kg·K) | 4182 | 761.55 | 710 | 561 | 385 | 745 |
| $K$ (W/m·K) | 0.597 | 37.17 | 8.4 | 20 | 401 | 1.38 |
| $\beta$ (K$^{-1}$)·10$^{-6}$ | 210 | 7.5 | 8.4 | 18 | 16.7 | 0.55 |
| $\mu$ (Kg/m·s)·10$^{-6}$ | 993 | | | | | |

Thermal conductivity of nanofluids was calculated using the Maxwell model [11]:

$$K_{nf} = \left[\frac{K_p + 2K_{bf} + 2\varphi\left(K_p - K_{bf}\right)}{K_p + 2K_{bf} - \varphi\left(K_p - K_{bf}\right)}\right]K_{bf}\,, \qquad (2.1)$$

where $K_p$ and $K_{bf}$ are the thermal conductivities of the particles and basic fluid, respectively, $\varphi$ is the volume fraction (%).

Viscosity of nanofluids was calculated using the Wang et al. model [11]:

$$\mu_{nf} = \left(1 + 7.3 + 123\varphi^2\right)\mu_{bf}\,, \qquad (2.2)$$

where $\mu_{bf}$ is the absolute viscosity of basic fluid (N·s/m$^2$).

Density of nanofluids was calculated using the model [11]:

$$\rho_{nf} = \left(1 - \varphi\right)\rho_{bf} + \varphi\rho_p\,, \qquad (2.3)$$

$\rho_{bf}$ and $\rho_p$ are the mass densities (kg/m$^3$) of the basic fluid and particles respectively.

Specific heat capacity of nanofluids was calculated using the Pak and Cho model [11]:

$$C_{p_{nf}} = \frac{\left(1-\varphi\right)\left(\rho C_p\right)_{bf} + \varphi\left(\rho C_p\right)_p}{\rho_{nf}}. \qquad (2.4)$$

### 2.3 Mathematical Model

We take into account the schematic diagram of SSP shown in Fig. 1. We will assume that the solar pond is thermally insulated and that the lower glass cover touches the surface of the pond water and there is no thermostat for the pond water. We also note that the mathematical model detailed was mentioned in a previous work [1].

Energy balance equation for heat exchanger tube:

$$\left(\frac{P}{2}\right) I\tau_c^2\tau_w^{'}\alpha_{he}dx + h_{c,p\to nf}\left(\frac{P}{2}\right)\left(T_p - T_{nf}\right)dx$$
$$+h_{c,w\to nf}\left(\frac{P}{2}\right)\left(T_w - T_{nf}\right)dx = \dot{m}_{nf}C_{pnf}\left(\frac{\partial T_{nf}}{\partial x}\right)dx \quad (2.5)$$
$$+A_t\rho_{nf}C_{p_{nf}}\left(\frac{\partial T_{nf}}{\partial t}\right)dx.$$

Here $P$ is the perimeter of the heat exchanger (m), $I$ is the solar radiation (W/m$^2$), $\tau_c^2$ is the transmissivity of the glass cover, $\tau_w'$ is the transmissivity of the pond water in the presence of the pond heat exchanger tube, $\alpha_{he}$ is the absorptivity of the heat exchanger tube, $h_{c,w\to nf}$ and $h_{c,p\to nf}$ are the convective heat transfer coefficient from the pond water to the nanofluid and from the absorber plate to the nanofluid (w/m$^2$ K) respectively, where

$$h_{c,p\to nf} = h_{c,w\to nf} = \frac{Nu_{nf}\times K_{nf}}{D_{he}}, \quad (2.6)$$

$D_{he}$ is the diameter of the heat exchanger tube (m).

To calculate the Nusselt number, Maiga correlation is used that is valid for $\phi < 10\,\%$, $\mathrm{Re} \le 1000$, and $6 < \mathrm{Pr} < 753$. This correlation is expressed [11] by:

$$Nu_{nf} = 0.086\,\mathrm{Re}_{nf}^{0.55}\,\mathrm{Pr}_{nf}^{0.5}, \quad (2.7)$$

$T_p$ and $T_w$ are the temperatures of the absorber plate and pond water (K) respectively, $A_t$ is the cross-sectional area of the $h_e$ tube (m$^2$) and $\dot{m}_{nf}$ is the mass flow rate of the nanofluid (kg/s).

Temperature of the heat exchanger fluid:

$$T_{nfo} = T_{nf}\left(x,t\right)_{x=L_{he}} = T_{nfi}\,\exp\left[-\left(\frac{b_1}{2}\right)\left(L_{he}+\frac{t}{a_1}\right)\right]+$$
$$\left(\frac{f_1(t)}{b_1}\right)\left\{1-\exp\left[-\left(\frac{b_1}{2}\right)\left(L_{he}+\frac{t}{a_1}\right)\right]\right\}, \quad (2.8)$$

where $T_{nfi}$ is the initial temperature of the nanofluid (K),

$$a_1 = \left(\frac{A_t\rho_{nf}}{\dot{m}_{nf}}\right) \quad (2.9)$$

and $L_{he}$ is the length of the heat exchanger tube (m), $t$ is the time (s),

$$b_1 = \frac{\left(\frac{P}{2}\right)\left(h_{c,p\to nf}+h_{c,w\to nf}\right)}{\dot{m}_{nf}C_{pnf}} \quad (2.10)$$

and

$$\eta_d(\%) = \frac{\sum\dot{Q}}{A_c\times\sum I}\times 100. \quad (2.11)$$

Daily efficiencies of the SSP are obtained as:

$$\eta_d(\%) = \frac{\sum\dot{Q}}{A_c\times\sum I}\times 100,$$

$$f_1(t) = \frac{\left(\frac{P}{2}\right)\left(I\tau_C^2\tau_W^{'}\alpha_{he}+h_{c,p\to nf}T_p+h_{c,w\to nf}T_w\right)}{\dot{m}_{nf}C_{Pnf}}, \quad (2.12)$$

where $\dot{Q}$ is the rate of thermal energy (W),

$$\dot{Q} = \dot{m}_{nf}Cp_{nf}\left(T_{nfo}-T_{nfi}\right), \quad (2.13)$$

Finally, the exergy can be calculated as:

$$\dot{E}_X = \dot{Q}\left(1-\frac{T_a}{T_w}\right). \quad (2.14)$$

## 3. RESULTS AND DISCUSSION

Fig. 2 illustrates hourly variations of solar radiation $I$, ambient temperature $T_a$, the initial temperature $T_{fi}$, the outlet temperature $T_{fo}$, the calculated temperature for water $T_w$, the temperature of the SSP $T_p$, the temperature of the upper and lower glass cover $T_{C1}$ and $T_{C2}$, respectively. The value of solar radiation calculated by the Bird and Hulstrom model on June 8 increases with time until its maximum value is 957 W/m$^2$ at 12 pm. Note that the temperature of the various elements of the SSP, including the temperature of the absorber plate $T_P$, the temperature of the pond water $T_w$, and the temperature of the lower glass cover $T_{C1}$, simulates the behavior of solar radiation in its develoment where the maximum temperature is respectively equal to 50.12 °C, 50.08 °C at 3 pm and 49.27 °C at 4 pm. On the other hand, ambient air temperature $T_a$ is limited by a minimum value of 24 °C and a maximum value of 30 °C in the afternoon. The temperature of the upper glass cover $T_{C2}$ in its evolution simulates the ambient air temperature $T_a$ and peaked at 33.54 °C at 4 pm. Finally, the temperature of the primary heat transfer fluid $T_{fi}$ is equal throughout the day to 27 °C and 50.02 °C.

The thermal performance of the SSP operating under the open cycle mode for heat extraction was theoretically investigated under different configurations of the heat transfer and two different mass flow rates. In order to extract heat from the SSP, we propose five types of heat transfer fluids consisting of water ($H_2O$)

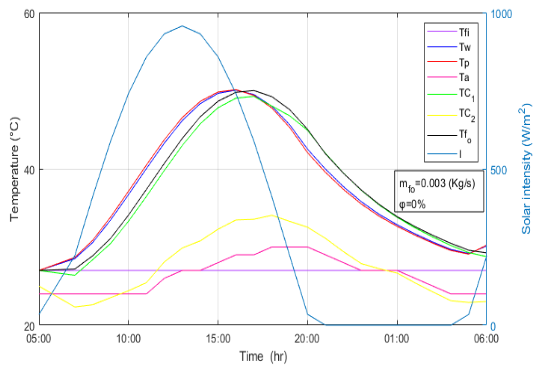


**Fig. 2** – Hourly variations of solar intensity $I$, ambient temperature $T_a$ and calculated temperatures for the pond elements with a double glass-cover

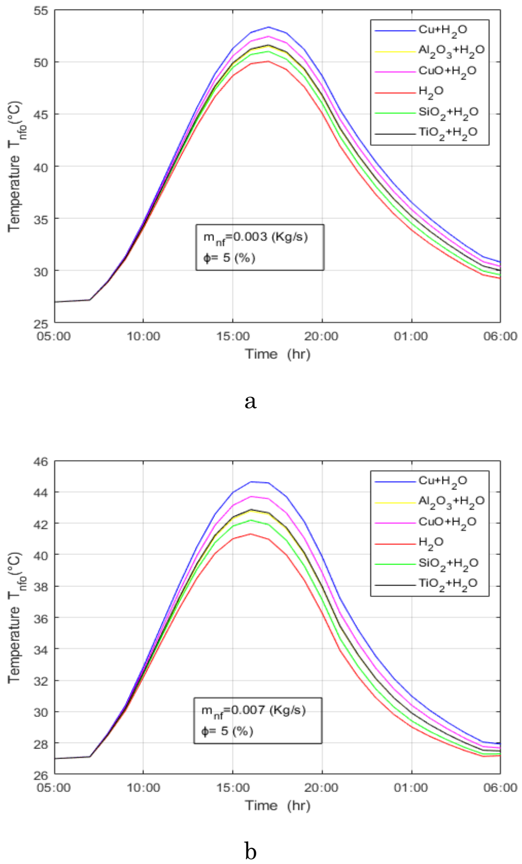


**Fig. 3** – Calculated outlet temperature of the nanofluids $T_{nfo}$ vs time with nanoparticle volume fraction $\varphi = 5$ % for different types of nanofluids: $\dot{m}_{nf} = 0.003$ kg/s (a) and $\dot{m}_{nf} = 0.007$ kg/s (b)

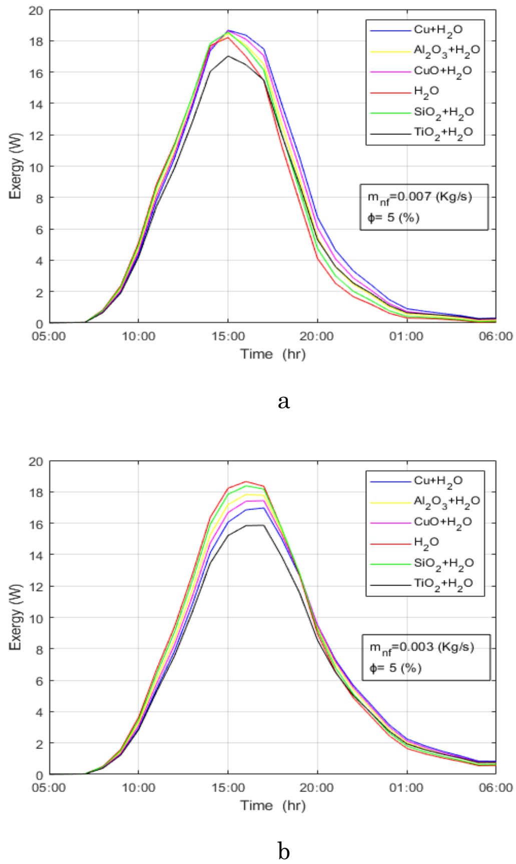


**Fig. 4** – Calculated energy vs time with nanoparticle volume fraction $\varphi = 5$ % for different types of nanofluids: $\dot{m}_{nf} = 0.003$ kg/s (a) and $\dot{m}_{nf} = 0.007$ kg/s (b)

as a basic fluid, and five types of solid nanomaterials with different physical properties, namely copper (Cu), titanium dioxide ($TiO_2$), silicon dioxide ($SiO_2$), copper oxide (CuO) and finally aluminum oxide ($Al_2O_3$). Fig. 3 shows the initial temperature of the nanofluids of 27 °C. For a period ranging from 5 am to 5 pm, the nanoparticles temperature increases and peaks for all types of nanoparticles, indicating the positive effect of nanofluids on intensifying heat exchange. The effect of the mass flow rate on the temperature of the nanofluids is negative with a mass flow rate $\dot{m}_{nf} = 0.003$ kg/s; the maximum values of the nanofluids temperature at 5 pm are obtained around: 53.31, 52.41, 51.59, 51.46, 50.97 and 50.02 °C for the nanofluids based on Cu, CuO, $TiO_2$, $Al_2O_3$, $SiO_2$ and $H_2O$, respectively. However, as the mass flow rate increases, $\dot{m}_{nf} = 0.007$ kg/s, the temperature drops significantly, the maximum values at 4 pm are found to be 44.56, 43.70, 42.86, 42.76, 42.19 and 41.31 °C for Cu, CuO, $TiO_2$, $Al_2O_3$, $SiO_2$ and $H_2O$, respectively.

The performance of the SSP is studied through the exergy under the open cycle to extract heat. Fig. 4 illustrates the evolution of the exergy efficiency as a function of time for two values of mass flow rate for nanofluids Cu, $SiO_2$, $TiO_2$, CuO and $Al_2O_3$. In contrast to the temperature, the flow rate had a positive effect on exergy with a flow rate $\dot{m}_{nf} = 0.003$ kg/s. Here we mention the maximum values of exergy for $H_2O$, $SiO_2$, $Al_2O_3$, CuO, Cu and $TiO_2$, which are estimated at 18.65, 18.18, 17.77, 17.43, 16.96, and 15.86 W, respectively.

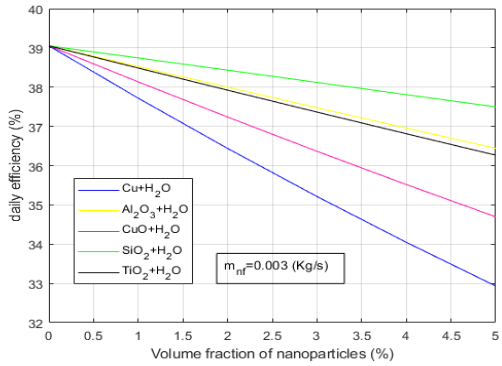


**Fig. 5** –Daily efficiency with nanoparticle volume fraction $\varphi = 5$ % for different types of nanofluids: $\dot{m}_{nf} = 0.003$ kg/s (a) and $\dot{m}_{nf} = 0.007$ kg/s (b)

When the value of the flow rate increases, we notice that the exergy has a maximum value at 3 pm for all types of nanofluids used. For these values, we mention a descending order for the following nanofluids: Cu, CuO, $SiO_2$, $Al_2O_3$, $TiO_2$ and $H_2O$, which is 18.66, 18.63, 18.55, 18.46, 18.20 and 17.02 W, respectively.

As shown in Fig. 5, the daily efficiency in its development exhibits a behavior contrary to temperature, where the results obtained showed that $SiO_2$ nanofluid achieved the highest value for daily efficiency, while the smallest value of the daily efficiency was achieved for Cu nanofluid.

## 4. CONCLUSIONS

The numerical investigation of the SSP operating under the open cycle to extract heat is studied under the different operational parameters.

The results obtained by numerical modeling are analyzed for the SSP operating under the open cycle to extract heat, as well as five different types of nanofluids with a concentration up to 5 % are used for enhancing the heat transfer performance. The carried nanofluids flow into the serpentine welded to the absorption plate. The following conclusions are summarized:

- Temperature of Cu nanofluid is recorded at the highest value, followed by CuO, $TiO_2$, $Al_2O_3$, $SiO_2$ and $H_2O$ nanofluids, respectively.
- The increase in the mass flow rate has a negative effect on the temperature of nanofluids.
- Exergy of $SiO_2$ nanofluid is recorded at the highest value, followed by $Al_2O_3$, CuO, Cu, and $TiO_2$ nanofluids, respectively.
- The increase in the mass flow rate has a positive effect on daily efficiency and exergy.
- The daily efficiency decreases with the increase in the volume fraction.

## REFERENCES


1. A. Terfai, Y. Chiba, M.N. Bouaziz, *Int. Conf. Artif. Intellig. Renew Energ. Systs.* (Springer: Cham: 2018).
2. G.N. Tiwari, H.P. Garg, U. Singh, *Energy Convers. Manag.* **24**, 223 (1984).
3. G.N. Tiwari, *Energy Convers. Manag.* **26**, 217 (1986).
4. A.A. El-Sebaii, *Appl. Energy* **81**, 33 (2005).
5. M.R.I. Ramadan, A.A. El-Sebaii, S. Aboul-Enein, A.M. Khallaf, *Energy Build.* **36**, 955 (2004).
6. A.A. El-Sebaii, S. Aboul-Enein, M.R.I. Ramadan, A.M. Khallaf, *Energy Convers. Manag.* **47**, 1014 (2006).
7. A.A. El-Sebaii, *Energy Convers. Manag.* **49**, 2839 (2008).
8. K.S.B. Janarthanan, *Mapana-J. Sci.* **13**, 13 (2014).
9. M.A. Hamdan, L.A. Al-Qudah, *Int J Therm. Environ. Eng.* **11**, 0 (2016).
10. D.K. Devendiran, V.A. Amirtham, *Renew. Sust. Energy Rev.* **60**, 21 (2016).
11. G. Huminic, A. Huminic, *Renew. Sust. Energy Rev.* **16**, 5625 (2012).
12. M. Khoshvaght-Aliabadi, A. Alizadeh, *Exp. Thermal Fluid Sci.* **61**, 1 (2015).
13. T. Yousefi, F. Veysi, E. Shojaeizadeh, S. Zinadini, *Renew. Energy* **39**, 293-298 (2012).
14. A.N. Moh'dA, A.M.A. Al-Dafaie, *Energy* **68**, 318 (2014).
15. R.E. Bird, R.L. Hulstrom, *Simplified clear sky model for direct and diffuse insolation on horizontal surfaces* (Energy Research Inst.: Golden: CO: USA: 1981).


## Підвищення теплової продуктивності SSP, заповненого нанорідиною

A. Terfai, Y. Chiba, M.N. Bouaziz

*Biomaterials and Transport Phenomena Laboratory, Mechanical Engineering Department, University of Medea, 26000, Algeria*

У роботі теоретично підтверджено підвищення теплової продуктивності SSP, який працює за відкритим циклом для вилучення тепла з метою підвищення власної ефективності. SSP було забезпечено двома прозорими скляними кришками для зменшення тепловтрат та збільшення загальної тепловіддачі. Він також був покритий теплоізоляційним матеріалом; дно SSP було пофарбоване у чорний колір для поліпшення поглинання сонячної радіації. Щоб посилити відведення тепла п'ять типів нанорідин з різними фізичними властивостями пропускали через теплообмінник у вигляді змійовика, привареного до дна SSP. П'ять типів металевих нано-частинок, таких як $Al_2O_3$, CuO, $TiO_2$, $SiO_2$ і Cu, змішували з чистою водою в різних концентраціях, що варіювалися у межах від 0 до 5 % для отримання нанорідин. Числову модель було розроблено на основі розв’язку рівнянь теплового балансу після дискретизації з використанням реальних метеорологічних умов міста Медея, розташованого в Алжирі. Отримані результати, включаючи теплофізичні властивості, температуру SSP та експлуатаційні характеристики, були представлені та обговорені.

**Ключові слова:** Наночастинки, Нанорідини, SSP, Чисельне моделювання, Продуктивність.