Thermal Performance Improvement of Hemispherical Cavity Receiver using MWCNT/ Oil Nanofluid

[1]Ph.D. graduated student, University of Mohaghegh Ardabili, Department of Biosystems Engineering,
rloni@uma.ac.ir
[2]Facularity member, University of Tarbiat Modares, Department of Biosystems Engineering,
ghobadib@modares.ac.ir
[3]Facularity member, University of Mohaghegh Ardabili, Department of Biosystems Engineering,
ezzataskari@uma.ac.ir

ABSTRACT

Dish collector using cavity receivers are accounted as an efficiently technology for converting the solar energy to thermal or electricity power. In the current study, the dish concentrator using a cylindrical cavity is thermally investigated. Multi Wall Carbon Nano Tube (MWCNT)/thermal oil nanofluid is used as the solar heat transfer fluid. The effect of the nanofluid concentration in the range of 0%VF to 5%VF, and volume flow rate in the range of 10ml/s to 150ml/s, are examined. The developed thermal modeling is conducted by writing code in the Maple software. Also, the optical modeling is conducted in the SolTrace software. The results reveal that the cavity heat gain, thermal efficiency improve by increasing the volume fraction of the investigated nanofluid. So, the application of the MWCNT/oil nanofluid is suggested as a way for improving the thermal performance of the dish collector using the cavity receiver. It is concluded that the thermal performance of the investigated solar system increased with increasing the volume flow rate of the working fluid. The results show that the pressure drop increase with increasing the volume fraction of the nanoparticle and volume flow rate of the solar working fluid. Finally, the volume flow rate of 70 ml/s can be defined as the optimum volume flow rate for the investigated hemispherical cavity receiver.

Keywords: Thermal performance; MWCNT/thermal oil nanofluid; hemispherical cavity receiver.

1- Introduction

Recently, the energy production and source are important problems with environmental changes such as the fossil fuel depletion, emissions of CO, CO_2, global warming, and ozone depletion. So, the human need for renewable and alternative energy resources, increase. Solar energy application as a favorable and clean renewable energy can be investigated as a reliable source for global energy demand. Parabolic dish collector is accounted as an efficient solar system for converting solar energy radiation to the thermal energy or power producing.

There are different types of the receiver for dish concentrator that includes the volumetric, particle, tubular cavity and spiral absorber receivers (Ho & Iverson, 2014; Pavlovic et al., 2017). The tubular cavity receivers because of especial structure have a higher efficiency compared to external receivers (Günther, Shahbazfar, Fend, & Hamdan). There are some researches about modeling and optimizing study on the cavity receivers [4-12]. Different shapes of cavity receiver for a dish concentrator were studied by Harris and Lenz (Harris & Lenz, 1985). Kaushika and Reddy (Kaushika & Reddy, 2000) optimized the different parameters of a dish collector using a modified cavity receiver. They designed and developed a dish concentrator with the modified cavity receiver. Reddy and Kumar (Kumar & Reddy, 2008) a modeling study conducted on the natural convection heat losses of three types of cavity receiver. They investigated the influence of different parameters such as the cavity inclination angle, cavity geometry and area ration of the cavity. The results reveal that the modified cavity receiver shows the best thermal performance for the investigated dish collector. Uzair et al. (Uzair, Anderson, & Nates) numerically evaluated the convection heat losses from a cavity receiver. The investigated the effects of the wind direction, dish-receiver orientations. The results reveal that the dish-receiver orientation has an effective influence on the thermal performance of the investigated cavity receiver.

Reddy and Kumar (Reddy & Kumar, 2009) evaluated the natural convection heat loss of a modified cavity receiver numerically. There was a good agreement between their predicted results of the investigated model and other well-known models results. Chang et al. (Chang et al., 2015) numerically considered the thermal performance of a modified cavity receiver. Their investigated system constructed from a cavity receiver using a glass cover and a secondary reflection. They concluded that the glass cover application at the cavity aperture and the application of the secondary reflection surface can improve the thermal performance of the investigated solar dish collector. Le Roux et al. (Le Roux, Bello-Ochende, & Meyer, 2014) simulated a dish collector using a rectangular cavity receiver that the air was applied as the solar working fluid. Their results reveal that the higher thermal efficiency has an inverse relation with the tube diameter of the cavity inner tube. Loni et al. (Loni, Kasaeian, Asli-Ardeh, Ghobadian, & Le Roux, 2016) numerically evaluated a dish collector using a rectangular cavity receiver and the thermal oil as the solar working fluid. They predicted the optimum structural and operational condition of the investigated cavity receiver for obtaining highest thermal efficiency. In another work, Loni et al. (Loni, Kasaeian, Asli-Ardeh, & Ghobadian, 2016) numerically considered the optimum structure of a cylindrical cavity receiver as the heat source of the ORC system. The thermal oil was applied as the solar heat transfer fluid. They investigated different parameters such as cavity depth, aperture diameter, inner tube diameter, mass flow rate, inlet temperature. Finally, the results reveal the optimum structure and operational parameters of the investigated cavity receiver.

On the other hand, some researches were conducted on the evaluation of nanofluids as the solar working fluid [13-17]. Khullar et al. (Khullar et al., 2012) numerically investigated a nanofluid-based concentrating parabolic solar collector (NCPSC). The Al_2O_3/ Therminol VP-1 was used as the solar working fluid. The results show thermal performance enhancement about 5–10% for the investigate NCPSC compare with the conventional parabolic solar collector. Mahian et al. (Mahian, Kianifar, Sahin, & Wongwises, 2014) numerically evaluated the first and second thermodynamic laws on the different water-based nanofluids (Cu/water, Al_2O_3/water, TiO_2/water, and SiO_2/water) in a minichannel-based solar collector. The results show the Cu/water nanofluid is the appropriate nanofluid for application in the investigated solar collector due to the highest outlet temperature and the lowest entropy generation. Mohammad Zadeh et al. (Zadeh, Sokhansefat, Kasaeian, Kowsary, & Akbarzadeh, 2015) numerically investigated the influence of the Al_2O_3/synthetic oil nanofluid as the solar working fluid of a parabolic trough collector. A hybrid optimization method was used as the optimization method for the investigated system. The results show that the higher nanoparticles concentration and lower operational temperature caused the higher heat transfer manner of the investigated solar system. Bellos et al. (Bellos, Tzivanidis, Antonopoulos, & Gkinis, 2016) theoretically considered a parabolic trough collector using a nanofluid as the solar working fluid. They concluded that the thermal performance of the investigated collector can be improved by 4.25% using the nanofluid as the solar heat transfer fluid. Dugaria et al. (Dugaria, Bortolato, & Del Col, 2017) numerically investigated a volumetric absorber in a concentrating direct absorption solar collector using nanofluid application as the solar working fluid. Their simulated results show a good agreement with the experimental results.

It could be seen from the mentioned literature review that there isn’t any report of the MWCNT/oil nanofluid application in the solar cavity receivers. So, the thermal performance investigation of the MWCNT/oil nanofluid as the working fluid of the cylindrical cavity receiver is a new idea. In the current study, the effect of the nanofluid concentration in the range of 0%VF to 5%VF, and volume flow rate in the range of 10ml/s to 150ml/s, are examined. Some thermal performance parameters are considered such as thermal efficiency and cavity heat gain. Also the effect of the nanofluid concentration and volume flow rate, are examined on the pressure drop of the investigated system.

2- Modelling and Methodology

A schematic of the investigated hemispherical cavity receiver is depicted in **Figure 1**. According to (Le Roux et al., 2014; Loni, Kasaeian, Asli-Ardeh, & Ghobadian, 2016; Loni, Kasaeian, Asli-Ardeh, Ghobadian, et al., 2016), the factors contributing the temperature profile and net heat transfer rate on the receiver wall can be divided into two components as the geometry-dependent and temperature-dependent factors. The researches have shown that the effects of the geometry-dependent factors can be found with the software “SolTrace” (Loni, Kasaeian, Asli-Ardeh, & Ghobadian, 2016; Loni, Kasaeian, Asli-Ardeh, Ghobadian, et al., 2016). The temperature-dependent factors including the radiation heat loss to the environment, the re-radiation from the inner-cavity walls, the convection heat loss, and the conduction heat loss can be calculated from the heat loss equations. In this study, these methods were applied to calculate the temperature profile and the net heat transfer rate on the receiver wall.

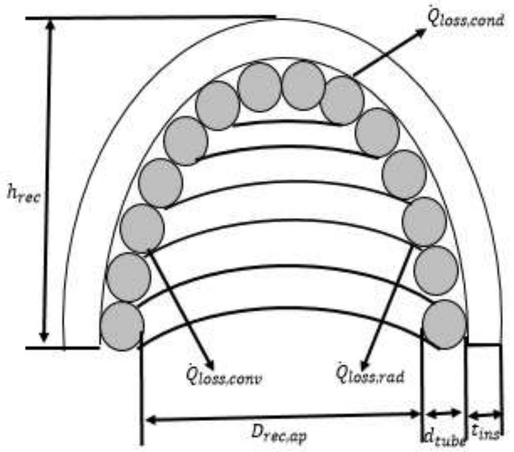

Figure 1: The investigated hemispherical cavity receiver.

The net heat transfer rate at the receiver tube is (Yunus & AFSHIN, 2007):

$$\dot{Q}_{net} = \dot{Q}^{*} - \dot{Q}_{loss} \tag{1}$$

$$\dot{Q}_{loss} = \dot{Q}_{loss,cond} - \dot{Q}_{loss,rad} - \dot{Q}_{loss,conv} \tag{2}$$

$$\dot{Q}^{*} = \eta_{optical}\eta_{refl}\,\dot{Q}_{solar} \tag{3}$$

$$\dot{Q}_{solar} = I_{sun}\pi D_{conc}^{2}/4 \tag{4}$$

The surface temperature ($T_{s,n}$) and the net heat transfer rate ($\dot{Q}_{net,n}$) at different elements of the tube are determined by solving Eqs. (5) and (6) using the Newton–Raphson Method (Le Roux et al., 2014):

$$\dot{Q}_{net,n} = \frac{\left(T_{s,n} - \sum_{i=1}^{n-1}\left(\frac{\dot{Q}_{net,i}}{\dot{m}_{f}c_{p0,nf}}\right) - T_{in,0}\right)}{\left(\frac{1}{hA_n} + \frac{1}{2\,\dot{m}_{f}c_{p,nf}}\right)} \tag{5}$$

and

$$\dot{Q}_{net,n} = \dot{Q}^{*}_{n} - A_n\varepsilon_n\sigma\left({T_{s,n}}^{4}\right) + A_n\sum_{j=1}^{N}F_{n-j}\varepsilon_j\sigma\left({T_{s,n}}^{4}\right) - A_n\varepsilon_n\sigma F_{n-\infty}T_{\infty}^{4} - A_n\left(m_2T_{s,n} + c_2\right) - \frac{A_n}{R_{cond}}\left(T_{s,n} - T_{\infty}\right) \tag{6}$$

The receiver surface temperature at different elements of the tube and the net heat transfer rate depend on the receiver aperture size, the cavity receiver depth, the mass flow rate of the solar working fluid, the receiver tube diameter, the working fluid inlet temperature and the dish reflectivity. Finally, the outlet temperature of the fluid can be obtained as followings:

$$T_{out} = T_{in} + \frac{\dot{Q}_{net}}{\dot{m}\,C_p} \tag{7}$$

For more details, please refer to ref. (Loni, Kasaeian, Asli-Ardeh, Ghobadian, et al., 2016). Another important parameter for the thermal analysis is the thermal efficiency. The thermal efficiency of the cavity receivers is defined as the receiver energy gained to the rate of the total incoming solar energy, which is expressed as:

$$\eta_{th} = \dot{Q}_{net} / \dot{Q}_{solar} \tag{8}$$

$$\dot{Q}_{net} = \dot{m} c_{p,nf} (T_{out} - T_{in}) \tag{9}$$

The total pressure drop of the absorber can be estimated using Equations **(10)** and **(11)** [23, 44-45]:

$$\Delta P = \frac{\rho\left(V^2{}_{Avg}\right)}{2} \left(f_r \frac{L}{d} + \sum_y K_y\right) \qquad \textbf{(10)}$$

$$\Delta P = \frac{8\,\dot{m}^2}{\rho \pi^2 d^4} \left(f_r \frac{L}{d} + \sum_y K_y\right) \qquad \textbf{(11)}$$

It could be mentioned that the analysis is performed based on real meteorological data for three investigated cavity receivers for 12:00 PM in a typical day in Tehran, Iran (**Table 1**).

Table 1: Values of solar irradiance on the collector, ambient temperature, and wind velocity for 12:00 PM in a typical day (19 October 2016) in Tehran, Iran.

Wind speed (m/s)	2.1
Solar irradiation (W/m^2)	632.97
Ambient temperature (°C)	20.2

In this paper, the operation with nanofluids is investigated. The MWCNT/thermal oil nanofluid is tested and its thermal properties are calculated according to the equations of this section. **Table 2** includes the thermal properties of the examined nanoparticle. It is obvious, that the nanoparticle present high density, high thermal conductivity and low specific heat capacity.

Table 2: Properties of nanoparticle.

Property	MWCNT
Thermal conductivity (W/m K)	2000
Heat capacity (J/kg K)	733
Density (kg/m^3)	2100

Equations **(12)-(15)** present the thermal properties of the nanofluids. The base fluid is symbolized with (bf), the nanoparticle with (np) and the nanofluid with (nf). The thermal conductivity of the nanofluid is calculated according to the suggested equation by Yu and Choi (Yu & Choi, 2003):

$$k_{nf} = k_{bf} \cdot \frac{k_{np} + 2 \cdot k_{bf} + 2 \cdot \left(k_{np} - k_{bf}\right) \cdot (1+\beta)^3 \cdot \phi}{k_{np} + 2 \cdot k_{bf} - \left(k_{np} - k_{bf}\right) \cdot (1+\beta)^3 \cdot \phi} \qquad \textbf{(12)}$$

The parameter β in this equation is the ratio of nano-layer thickness to the nanoparticles diameter which is considered to be 0.1 in of this study (Duangthongsuk & Wongwises, 2010). The density of the mixture is given by equation **(13)** (Kasaeian, 2012) and the specific heat capacity according to equation **(14)** (Khanafer & Vafai, 2011):

$$\rho_{nf} = \rho_{bf} \cdot (1-\phi) + \rho_{np} \cdot \phi \qquad \textbf{(13)}$$

$$c_{p,nf} = \frac{\rho_{bf} \cdot (1-\phi)}{\rho_{nf}} \cdot c_{p,bf} + \frac{\rho_{np} \cdot \phi}{\rho_{nf}} \cdot c_{p,np} \qquad \textbf{(14)}$$

The dynamic viscosity is calculated according to the Batchelor model (Batchelor, 1977):

$$\mu_{nf} = \mu_{bf} \cdot \left(1 + 2.5 \cdot \phi + 6.5 \cdot \phi^2\right) \qquad \textbf{(15)}$$

3- Results and Discussion

Variation of the cavity heat gain and thermal efficiency of the hemispherical cavity receiver versus different nanoparticle volume fraction, is presented in **Figure 2**. It could be seen from **Figure 2**, the thermal efficiency and cavity heat gain have improved by increasing the concentration of the nanofluid. Consequently, it would be resulted that the application of the MWCNT/thermal oil nanofluid is an efficiently way for improving the hemispherical cavity receiver compare to the application of pure oil (φ = 0%VF). On the other side, variation of the pressure drop versus different nanoparticle volume fraction is shown in **Figure 3**. As seen from **Figure 3**, the pressure drop of the investigated hemispherical cavity receiver is increased with application of the nanofluid at the higher concentration. Consequently, the appropriate nanofluid concentration could be selected based on the requiring the pump power and achieving the highest thermal performance.

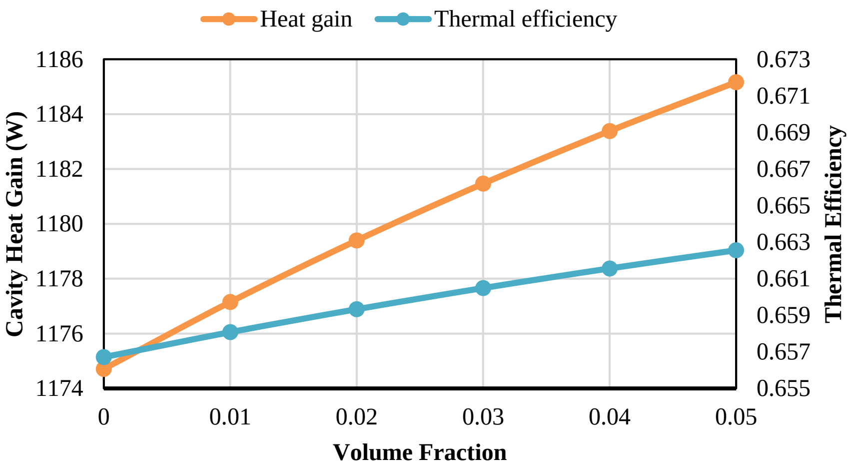

Figure 2: Variation of the cavity heat gain and thermal efficiency of the hemispherical cavity receiver versus different nanoparticle volume fraction.

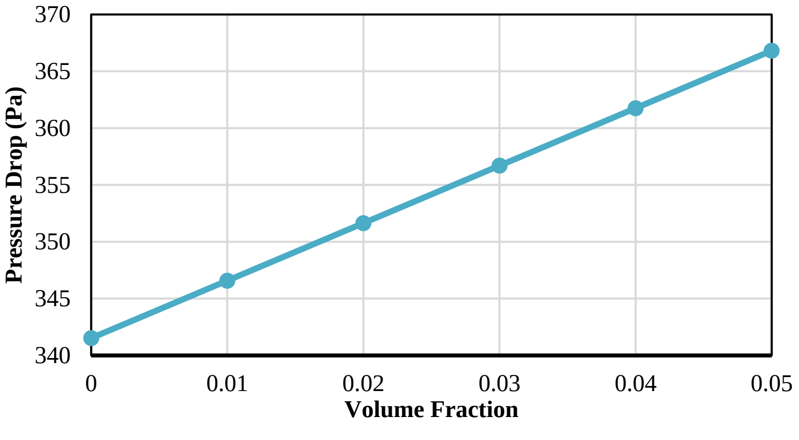

Figure 3: Variation of the Pressure drop of the hemispherical cavity receiver versus different nanoparticle volume fraction.

Figure 4 shows variation of the cavity heat gain and thermal efficiency of the hemispherical cavity receiver versus volume flow rate for nanofluid at concentration of 3%VF. It could be concluded that the thermal efficiency and cavity heat gain increase by increasing the volume flow rate of the nanofluid. As seen, the thermal performance of the cavity receiver shapely increase at volume flow rate of 30 ml/s, then the increasing rate continues until volume flow rate of 70 ml/s. After volume flow rate of 70 ml/s, the thermal performance of the investigated cavity receiver remain almost constant at the higher volume flow rate. Consequently, it could be resulted that the volume flow rate of 70 ml/s can be defined as the efficiently volume flow rate for the investigated hemispherical cavity receiver.

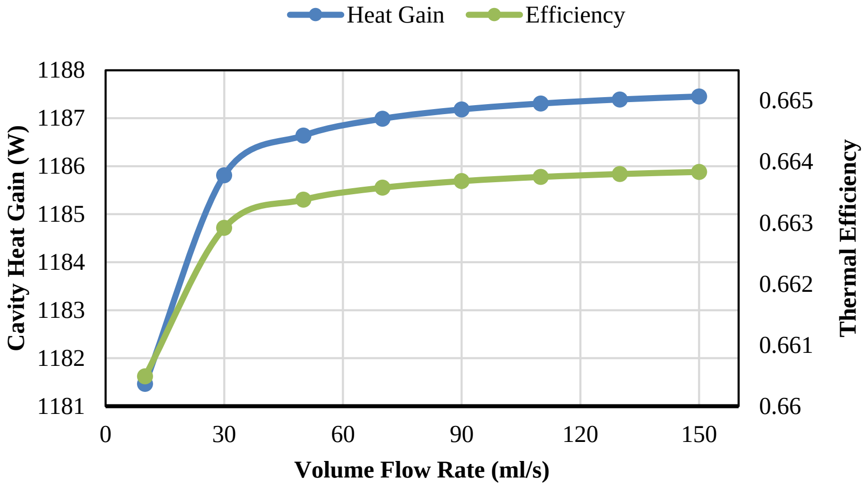

Figure 4: Variation of the cavity heat gain and thermal efficiency of the hemispherical cavity receiver versus volume flow rate of nanofluid at 3%VF.

Finally, **Figure 5** displays the variation of pressure drop versus volume flow rate for nanofluid at concentration of 3%VF. It could be resulted from **Figure 5**, the pressure drop of the investigated cavity receiver increase by increasing the volume flow rate of the nanofluid. So, based on the previous paragraph, it would be concluded the volume flow rate of 70 ml/s is the optimum flow rate for the investigated hemispherical cavity receiver.

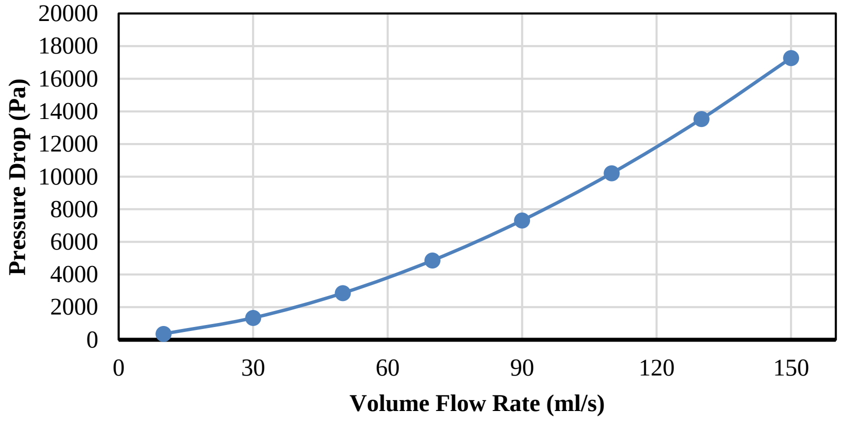

Figure 5: Variation of pressure drop of the hemispherical cavity receiver versus volume flow rate of nanofluid at 3%VF.

4- Conclusion

In this study, a dish concentrator using a hemispherical cavity receiver is investigated using MWCNT/thermal oil nanofluid. The main aim of this research is study the effect of nanofluid application for improving the thermal performance of the investigated hemispherical cavity receiver. The effect of the nanofluid concentration in the range of 0%VF to 5%VF, and volume flow rate in the range of 10ml/s to 150ml/s, are examined. The main results could be summarized as following:

- The thermal efficiency and cavity heat gain have improved by increasing the concentration of the nanofluid. It would be resulted that the application of the MWCNT/thermal oil nanofluid is an efficiently way for improving the hemispherical cavity receiver compare to the application of pure oil (φ = 0%VF).

- Also, the pressure drop of the investigated hemispherical cavity receiver is increased with application of the nanofluid at the higher concentration and higher volume flow rate of the investigated solar working fluid.
- The thermal efficiency and cavity heat gain increase by increasing the volume flow rate of the nanofluid. Also, the volume flow rate of 70 ml/s can be defined as the optimum volume flow rate for the investigated hemispherical cavity receiver.

References

Batchelor, G. (1977). The effect of Brownian motion on the bulk stress in a suspension of spherical particles. *Journal of fluid mechanics, 83*(1), 97-117.

Bellos, E., Tzivanidis, C., Antonopoulos, K., & Gkinis, G. (2016). Thermal enhancement of solar parabolic trough collectors by using nanofluids and converging-diverging absorber tube. *Renewable Energy, 94*, 213-222.

Chang, H., Duan, C., Wen, K., Liu, Y., Xiang, C., Wan, Z., . . . Shu, S. (2015). Modeling study on the thermal performance of a modified cavity receiver with glass window and secondary reflector. *Energy Conversion and Management, 106*, 1362-1369.

Duangthongsuk, W., & Wongwises, S. (2010). An experimental study on the heat transfer performance and pressure drop of TiO 2-water nanofluids flowing under a turbulent flow regime. *International Journal of Heat and Mass Transfer, 53*(1), 334-344.

Dugaria, S., Bortolato, M., & Del Col, D. (2017). Modelling of a direct absorption solar receiver using carbon based nanofluids under concentrated solar radiation. *Renewable Energy*.

Günther, M., Shahbazfar, R., Fend, T., & Hamdan, M. Solar Dish Technology.

Harris, J. A., & Lenz, T. G. (1985). Thermal performance of solar concentrator/cavity receiver systems. *Solar energy, 34*(2), 135-142.

Ho, C. K., & Iverson, B. D. (2014). Review of high-temperature central receiver designs for concentrating solar power. *Renewable and Sustainable Energy Reviews, 29*, 835-846.

Kasaeian, A. B. (2012). Convection heat transfer modeling of Ag nanofluid using different viscosity theories. *IIUM Engineering Journal, 13*(1).

Kaushika, N., & Reddy, K. (2000). Performance of a low cost solar paraboloidal dish steam generating system. *Energy Conversion and Management, 41*(7), 713-726.

Khanafer, K., & Vafai, K. (2011). A critical synthesis of thermophysical characteristics of nanofluids. *International Journal of Heat and Mass Transfer, 54*(19), 4410-4428.

Khullar, V., Tyagi, H., Phelan, P. E., Otanicar, T. P., Singh, H., & Taylor, R. A. (2012). Solar energy harvesting using nanofluids-based concentrating solar collector. *Journal of Nanotechnology in Engineering and Medicine, 3*(3), 031003.

Kumar, N. S., & Reddy, K. (2008). Comparison of receivers for solar dish collector system. *Energy Conversion and Management, 49*(4), 812-819.

Le Roux, W. G., Bello-Ochende, T., & Meyer, J. P. (2014). The efficiency of an open-cavity tubular solar receiver for a small-scale solar thermal Brayton cycle. *Energy Conversion and Management, 84*, 457-470.

Loni, R., Kasaeian, A., Asli-Ardeh, E. A., & Ghobadian, B. (2016). Optimizing the efficiency of a solar receiver with tubular cylindrical cavity for a solar-powered organic Rankine cycle. *Energy, 112*, 1259-1272.

Loni, R., Kasaeian, A., Asli-Ardeh, E. A., Ghobadian, B., & Le Roux, W. (2016). Performance study of a solar-assisted organic Rankine cycle using a dish-mounted rectangular-cavity tubular solar receiver. *Applied thermal engineering, 108*, 1298-1309.

Mahian, O., Kianifar, A., Sahin, A. Z., & Wongwises, S. (2014). Performance analysis of a minichannel-based solar collector using different nanofluids. *Energy Conversion and Management, 88*, 129-138.

Pavlovic, S., Daabo, A. M., Bellos, E., Stefanovic, V., Mahmoud, S., & Al-Dadah, R. K. (2017). Experimental and numerical investigation on the optical and thermal performance of solar parabolic dish and corrugated spiral cavity receiver. *Journal of Cleaner Production, 150*, 75-92.

Reddy, K., & Kumar, N. S. (2009). An improved model for natural convection heat loss from modified cavity receiver of solar dish concentrator. *Solar energy, 83*(10), 1884-1892.

Uzair, M., Anderson, T., & Nates, R. Impact of dish structure on the convective heat loss from a parabolic dish solar cavity receiver.

Yu, W., & Choi, S. (2003). The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model. *Journal of Nanoparticle Research, 5*(1-2), 167-171.

Yunus, A. Ç., & AFSHIN, J. G. (2007). Heat and mass transfer. *McGrawHill, New York*.

Zadeh, P. M., Sokhansefat, T., Kasaeian, A., Kowsary, F., & Akbarzadeh, A. (2015). Hybrid optimization algorithm for thermal analysis in a solar parabolic trough collector based on nanofluid. *Energy, 82*, 857-864.