Penerbit Akademia Baru

Journal of Advanced Research in Numerical Heat Transfer

Journal homepage: http://www.akademiabaru.com/submit/index.php/arnht/index
ISSN: 2735-0142

Nusselt Number Prediction for Oil and Water in Solar Tubular Cavity Receivers

Reyhaneh Loni[1], Gholamhassan Najafi[1,*], Rizalman Mamat[2], Mohamed Mazlan[3], Nor Azwadi Che Sidik[4]

1 Department of Biosystems Engineering, Tarbiat Modares University (T.M.U.), Tehran, Iran
2 Faculty of Mechanical Engineering, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
3 Faculty of Bio Engineering and Technology, Advanced Material Cluster, Universiti Malaysia Kelantan, Jeli, Kelantan, Malaysia
4 Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia

ABSTRACT

In this study, a numerical model was developed for prediction of Nusselt number in solar cavity receivers. Thermal oil and water were used as the working fluid. A dish concentrator with different shapes of the cavity receiver, including hemispherical, cylindrical, and cubical, was investigated. The different shapes of cavity receiver were studied under the same operating conditions for prediction of the internal heat transfer coefficient correlation for each cavity receiver. The system is investigated under the variation of solar radiation, flow rate, and inlet temperature of solar working fluids. The developed thermal model is validated based on the experimental data for the cylindrical cavity receiver using thermal oil. The results reveal that the hemispherical cavity receiver had the highest cavity heat gain, heat transfer coefficient, and Nusselt number values compared to two other cavity receivers. It could be concluded that the cavity heat gain, and heat transfer coefficient, and Nusselt number amounts had improved with increasing solar radiation, increasing flow rate, and decreasing inlet temperature of the working fluid. Some equations were suggested for prediction of Nusselt number with the variation of solar radiation, flow rate of the working fluid, and inlet temperature of working. It was concluded that application of thermal oil had resulted in higher Nusselt numbers than the use of water as the solar working fluid. Consequently, the application of oil is suggested for high-temperature systems.

Keywords:
Nusselt number prediction; solar cavity receivers; thermal oil; water

Received: 2 January 2022 **Revised: 14 January 2022** **Accepted: 15 January 2022** **Published: 12 February 2022**

1. Introduction

Nowadays, the application of solar energy due to the negative impact of fossil fuel application such as global warming, environmental pollution, ozone layer depletion, and acid rains, is increased. Solar collector manners as a heat exchanger for converting solar radiation energy to thermal energy [1]. The solar dish concentrator is accounted as an impact and high-temperature technology for producing power and heat [2]. There are different shapes of receiver for the dish concentrator, including external, cavity, spiral, and volume receivers [3]. Generally, cavity receivers due to low heat losses are accounted as the efficient receiver for the dish collectors systems [4]. On the other side,

* *Corresponding author.*
E-mail address: g.najafi@modares.ac.ir

investigation of convection heat transfer, and prediction of Nusselt number in the solar system are accounted as important parameters for estimating thermal performance of solar systems.

Some researchers investigated thermal modelling of solar dish concentrators with cavity receivers [5]. Bellos et al. [6] numerically optimized different shapes of cavity receiver as dish absorber under the aspect of thermal and optical analyses. They found the highest optical and thermal performance for the dish concentrator with a cylindrical-conical cavity design. Venkatachalam and Cheralathan [7] experimentally considered a solar dish concentrator with different aspect ratios of a conical cavity receiver under energy and exergy aspects. They evaluated overall thermal heat losses from the solar dish system. They found the aspect ratio of the solar system as an effective parameter for estimating the thermal performance of the dish collector. Loni et al. [8] presented a research review paper related to the application of nanofluids as a solar working of dish concentrators based on experimental tests. Different shapes of cavity receiver were used as dish absorbers. They reported the highest thermal performance improvement for hemispherical cavity receiver with the application of nanofluid. Pavlovic et al. [9] studied a dish concentrator with spiral and conical cavity receivers under optical, energy, and exergy aspects. They reported conical cavity receiver had resulted in higher optical and energy performance compared to the spiral cavity receiver.

Yan et al. [10] investigated and optimized a new structure of a dish concentrator. They presented equations for designing the novel dish structure with the highest performance. Loni et al. [11] showed a comparison study related to energy and exergy performance of a dish concentrator with different shapes of cavity receiver. Thermal oil and water were used as solar working fluid. They found the highest exergy performance of the dish concentrator with the application of a hemispherical cavity receiver. Also, thermal oil and water were introduced as the best selection for high-temperature, and low-temperature use, respectively. Yang et al. [12] suggested a new structure of a solar dish concentrator with a cavity receiver. They found increasing the thermal and optical performance of the proposed system compared to a conventional dish-cavity structure. In another work, researchers [12] considered numerically and experimentally the performance of a dish concentrator with a cubical and cylindrical cavity receivers. They concluded the highest thermal performance of the dish collector using the cubical cavity receiver compared to the cylindrical one. Soltani et al. [13] investigated an optical and thermal performance of a dish collector with a helically baffled cylindrical cavity receiver. They investigated different parameters for the optimization performance of the solar system. They found selective optical properties of the system can be accounted for as an effective parameter for increasing performance of the system.

On the other hand, some researchers were investigated convection heat transfer of the working fluid in solar systems. El-Genk and Pourghasemi [14] studied convection heat transfer in microchannel based on laminar flows. Water and air were used as the working fluid. They presented some Nusselt number equations for the investigated system. Hu et al. [15] developed a numerical model for the simulation of silica/molten nanofluid in a solar system. They predicted an average Nusselt number that shows a good agreement with the experimental tests. Zhang and Yang [16] considered a numerical model for prediction of heat transfer of air in vertical channels. Ghritlahre and Prasad [17] developed heat transfer modelling of roughened solar air heaters using the ANN method. Kumar et al. [18] developed a numerical method for prediction of Nusselt number in a multiple V-pattern dimpled obstacles solar air passage based on experimental tests. Du et al. [19] predicted Nusselt number of a porous volumetric solar receiver based on numerical models.

It could be seen from the literature review, there is no reported research related to the prediction of the Nusselt number for different shapes of cavity receivers. Consequently, prediction of Nusselt number of a dish collector using different shapes of the cavity receiver is a novelty subject for research. In the current study, the influence of various parameters such as solar irradiation, inlet temperature, and volume flow rate of the working fluid, is investigated. Three types of cavity receiver, including hemispherical, cubical, and cylindrical cavity receivers, are numerically simulated. Thermal oil and water are examined as solar working fluid. The Nusselt numbers of different investigated shapes of the cavity using various investigated working fluids are predicted based on the developed numerical model. The mathematical model is validated according to some experimental tests with a cylindrical cavity receiver using thermal oil. The results of this work predict the internal heat transfer of different cavity receivers (cubical, cylindrical, and hemispherical) under variation of solar irradiation, inlet temperature and volume flow rate of the various working fluids (water and thermal oil).

2. Methodology and Description

2.1 Optical and Thermal Modeling

In this research, internal heat transfer of three shapes of cavity receiver was investigated based on the numerical method. Internal heat transfer and Nusselt number of working fluids are assumed as important parameters for prediction of thermal performance of solar thermal systems. A solar one point concentrator with different tubular cavity receivers was evaluated based on optical and thermal analyses. Three shapes of cavity receiver, including cubical, cylindrical, and hemispherical cavities, were considered. Also, thermal oil and water were used as the solar heat transfer fluid. It should be mentioned that real optical, and structural parameters of a dish concentrator with tubular cavity receivers were used as solar dish reflectivity of 0.84, tracking error of 1º, optical error of 10 mrad, dish aperture diameter of 1.9 m, focal dish distance of 0.693 m, cubical aperture wide and height of 14 cm, cylindrical aperture diameter and height of 12.5 cm, aperture hemispherical diameter of 12. cm, and cavity tube diameter of 10 mm [20].

It should be noted, the cavity receiver dimensions were selected based on optimization analyses that were conducted by previous papers of Loni et al. [2], [3], and [21] for the cubical, cylindrical, and hemispherical cavity receivers, respectively. Also, it is good to know, the optimized cavity receivers as mentioned above were built and tested using oil, and different oil-based nanofluids such as alumina/oil, silica/oil, and CNT/oil nanofluids based on experimental tests by authors [5, 22-24]. A schematic of the investigated solar system with different cavity receivers is presented in Fig. 1.

Analyses of the current study were conducted in two steps. At the first step, the optical performance of the solar system was investigated by SolTrace software. Based on the developed optical analyses in the SolTrace, heat flux distribution along the cavity tubes, and absorbed solar heat flux by the cavity walls were estimated. A view of the optical analyses of the dish concentrator with three investigated tubular cavity receivers is presented in Fig. 2. At the second step, thermal performance of the solar systems and prediction of the Nusselt number were numerically developed in Maple software. Energy balance equations and thermal resistance method were used for thermal modelling. The internal heat transfer of the solar working fluids, including oil and water, was numerically developed and investigated in the tubular cavity receivers for prediction of Nusselt number and cavity performances.

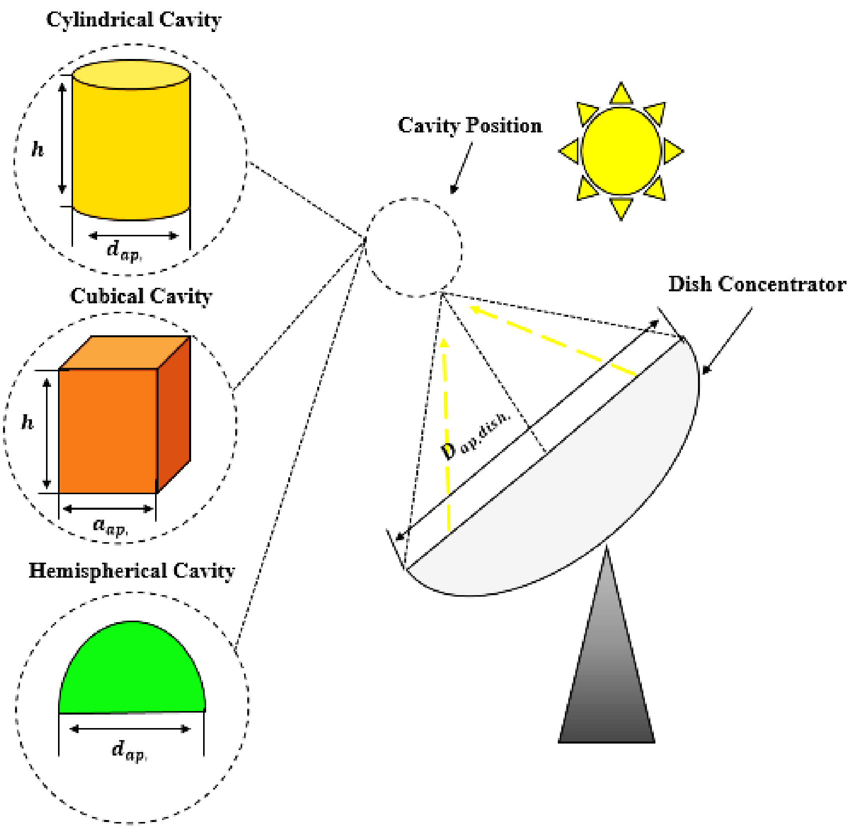


Fig. 1. A schematic of the investigated solar system with different cavity receivers

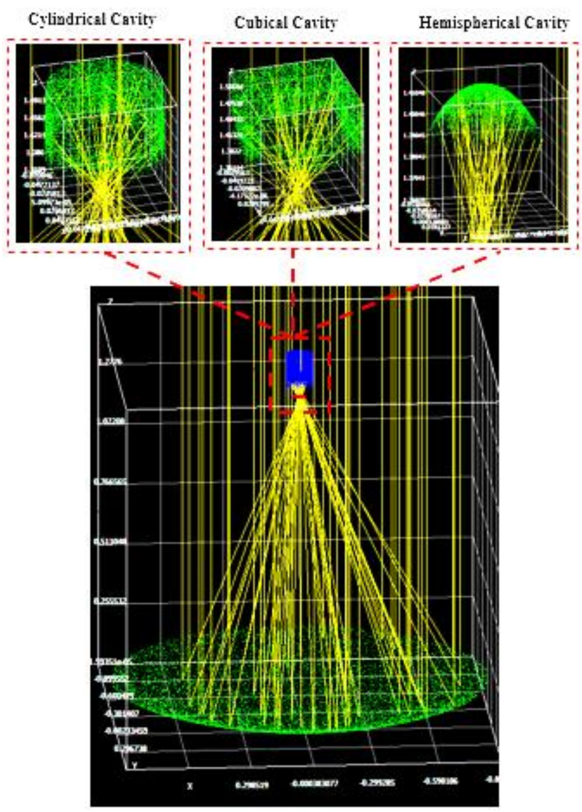


Fig. 2. A view of the optical analyses of the dish concentrator with three investigated tubular cavity receivers

In this section, developed thermal modelling for the solar focal point concentrator will be presented. As mentioned energy balance equation was used for thermal modelling of the solar system. Generally, thermal heat losses from the cavity receivers include convection, conduction, and radiation heat losses. It should be mentioned that the cavity receivers were insulated with mineral wool for reducing heat losses. The conduction heat losses accrue from the insulation layer in a thickness of 5 cm. The convection heat losses occurred from the inside of the cavity receivers, and outside of the wall cavity receivers. Finally, radiation heat losses from the inner space of the cavity receivers are accented during thermal modelling.

Absorbed heat by the solar working fluid ($\dot{Q}_{net}$) can be calculated as follows [25]:

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

Where $\dot{Q}^{*}$(W) is received solar heat flux by the cavity walls that can be calculated using the SolTrace, and $\dot{Q}_{loss}$(W) is heat losses from the cavity receiver that can be estimated by the below equation [25]:

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

Where $\dot{Q}_{loss,cond}$(W) is conduction heat losses, $\dot{Q}_{loss,rad}$(W) is radiation heat losses, and $\dot{Q}_{loss,conv}$(W) is convection heat losses. More detail about the heat loss calculation form the cubical, cylindrical, and hemispherical cavity receivers are presented in refs. [2], [3], and [21], respectively. It should be mentioned that the thermal efficiency of the solar system is calculated as follows [25]:

$$\eta_{th} = \dot{Q}_{net} / \dot{Q}_{solar} \tag{3}$$

Where $\dot{Q}_{solar}$(W) is received solar energy by the dish concentrator that can be calculated as below [25]:

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

In this equation, I_{sun} (W/m^2) is solar beam radiation, and $D_{ap,dish}$ (m) is aperture dish diameter. For calculation more accuracy results, the cavity tube was divided to smaller elements along the receiver tube of three cavity receivers. Then the receiver surface temperature ($T_{s,n}$) and the useful heat flow ($\dot{Q}_{net,n}$) at the different elements of the tube are calculated by solving the equations of this subsection with the Newton–Raphson Method [25]:

$$\dot{Q}_{net,n} = \frac{\left(T_{s,n} - \sum_{i=1}^{n-1}\left(\frac{\dot{Q}_{net,i}}{\dot{m}\, c_{p0}}\right) - T_{inlet,0}\right)}{\left(\frac{1}{h_{inner} A_n} + \frac{1}{2\, \dot{m} c_{p0}}\right)} \tag{5}$$

The Nusselt number of the internal working fluid flow is estimated as [26]:

$$Nu_{inner} = \frac{\left(\frac{f_r}{8}\right). Re. Pr}{1 + 12.8. \sqrt{\frac{f_r}{8}}. \left(Pr^{0.68} - 1\right)} \tag{6}$$

The friction factor (f_r) is calculated as [26]:

$$f_r = (0.79 \ln Re - 1.64)^{-2} \tag{7}$$

Moreover, the inner heat transfer coefficient is calculated as [27]:

$$h_{inner} = \frac{Nu_{inner} K_{fluid}}{d_{tube}} \tag{8}$$

The net heat transfer rate can be calculated using the below equations [25]:

$$\dot{Q}_{net,n} = \dot{Q}^*{}_n - \dot{Q}_{loss,rad,n} - \dot{Q}_{loss,internal\ conv,n} - \dot{Q}_{loss,external\ conv,n} \tag{9}$$

$$\begin{aligned}\dot{Q}_{net,n} = \dot{Q}^*{}_n - A_n \varepsilon_n \sigma\left({T_{s,n}}^4\right) + A_n \sum_{j=1}^{N} F_{n-j} \varepsilon_j \sigma\left({T_{s,n}}^4\right) - A_n \varepsilon_n \sigma F_{n-\infty} T_\infty^4 \\ - A_n\left(m_2 T_{s,n} + c_2\right) - \frac{A_n}{R_{cond}}(T_{s,n} - T_\infty)\end{aligned} \tag{10}$$

Finally, the heat transfer of each element of the cavity receiver can be defined as [27]:

$$h_n = \dot{Q}_{net,n} \Big/ \left(A_n(T_{s,n} - ({T_{in,n} + T_{out,n}}/{2}))\right) \tag{11}$$

Then the Nusselt number for each element of cavity revivers can be defined as [27]:

$$Nu_n = \frac{h_n . d_{tube}}{k_{wf}} \tag{12}$$

Consequently, the overall Nusselt number of the investigated cavity receiver can be calculated as [27]:

$$Nu_{overall} = \frac{\sum_1^N Nu_n}{N} \tag{13}$$

Where N is the total element number of the investigated cavity receiver.

It should be mentioned that the thermal properties of the thermal oil are calculated based on the bellow relationships [28]:

$$k_f = 0.1882 - 8.304 \times 10^{-5}(T_f) \qquad \left(\frac{W}{mK}\right) \tag{14}$$

$$c_{p,f} = 0.8132 + 3.706 \times 10^{-3}(T_f) \qquad \left(\frac{kJ}{kgK}\right) \tag{15}$$

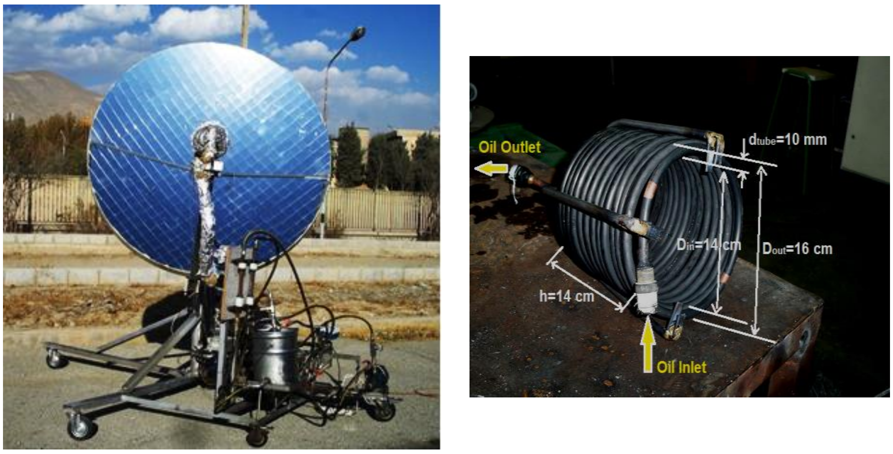
$$\rho_f = 1071.76 - 0.72(T_f) \qquad \left(\frac{kg}{m^3}\right) \tag{16}$$

$$Pr = 6.73899 \times 10^{21}(T_f)^{-7.7127} \tag{17}$$

Whereas, the thermal properties of water were estimated by [27].

2.2 Validation

Numerical results of this study were validated based on some experimental results that were carried out in the Renewable Energy Research of the Tarbiat Modares University, Tehran, Iran (located at 35.68° N latitude and 51.42° longitude). The experimental setup consisted of a dish concentrator, cylindrical cavity receiver, and hydraulic cycle. Thermal oil was used as the solar working fluid. Inlet and outlet temperature of the solar working fluid at inlet and outlet of the cavity receiver, and working fluid volume flow rate were measured during the experimental tests. Whereas, ambient parameters, including solar radiation, ambient temperature, and wind speed, were measured, too. More detail related to the experimental tests was reported by ref. [29]. A view of the investigated experimental setup is presented in Fig. 3.



(a) **(b)**

Fig. 3. A view of the investigated experimental setup, including a) dish concentrator, and b) cylindrical cavity receiver [29]

A comparison between the experimentally measured data by ref. [29], and calculated numerical data in the current study was presented in Table 1. It should be mentioned that all of the operational and ambient measured parameters, as reported in Table 1 were used as input of the numerical modelling. It can be seen from Table 1, there is a good agreement between the measured experimental data, and calculated data at noon when the system is at the steady-state condition. The average amount of the deviation was calculated to equal to 1.89% that shows acceptable accuracy of the calculated numerical results.

Table 1
A comparison between the experimentally measured data for the cylindrical cavity by ref. [29], and calculated numerical data in the current study

	Measured Parameters				Experimental		Numerical		Derivation	
Time	T_{in} (°C)	I_{total} (W/m^2)	T_{amb} (°C)	V_{wind} (m/s)	T_{out} (°C)	η_{th}	T_{out} (°C)	η_{th}	T_{out} (°C)	η_{th}
9:10	47.00	850.00	25.40	0.20	105.44	0.56	106.62	0.61	1.11%	10.35%
9:30	56.00	879.50	27.50	0.20	120.36	0.56	119.78	0.60	0.48%	7.06%
10:00	63.00	911.80	25.60	1.10	126.32	0.57	124.12	0.59	1.74%	4.33%
10:30	57.00	941.80	24.10	0.00	121.84	0.60	117.65	0.60	3.44%	0.96%
11:00	61.50	942.30	24.00	1.00	127.53	0.61	121.60	0.60	4.65%	1.75%
11:30	57.10	926.00	27.70	0.70	123.82	0.58	121.06	0.60	2.23%	3.40%
12:15	58.00	926.00	28.30	0.00	121.08	0.59	117.78	0.60	2.73%	2.38%
12:30	52.10	924.00	26.90	0.20	119.72	0.59	116.84	0.61	2.40%	3.17%

13:00	53.00	902.00	28.40	0.10	113.26	0.57	112.27	0.61	0.87%	6.33%
13:30	54.50	913.00	25.70	0.90	113.56	0.56	113.39	0.60	0.15%	7.86%
14:00	55.10	877.30	26.20	0.10	118.10	0.58	115.47	0.60	2.23%	3.49%
14:30	55.20	840.00	26.70	1.10	120.00	0.59	116.17	0.60	3.19%	1.54%
15:00	49.90	824.00	26.20	0.00	110.00	0.58	108.96	0.61	0.95%	6.19%
15:30	49.90	726.00	27.20	0.30	98.60	0.57	98.91	0.62	0.31%	9.28%
15:50	62.60	670.00	26	0.00	107.60	0.53	109.64	0.60	1.90%	13.84%

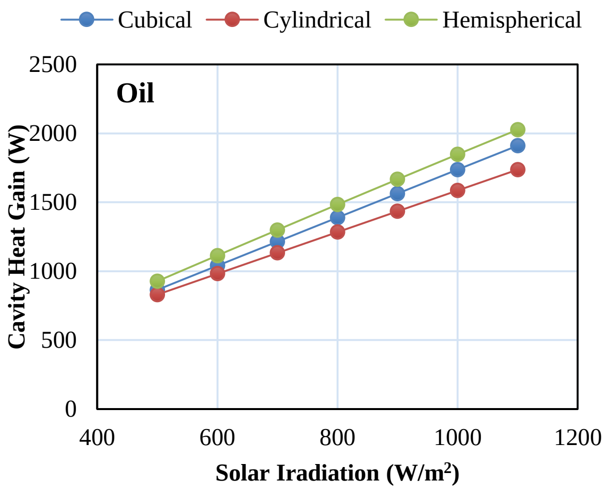
3. Results and Discussion

In this section, calculated results will be presented in two subsections as follows:

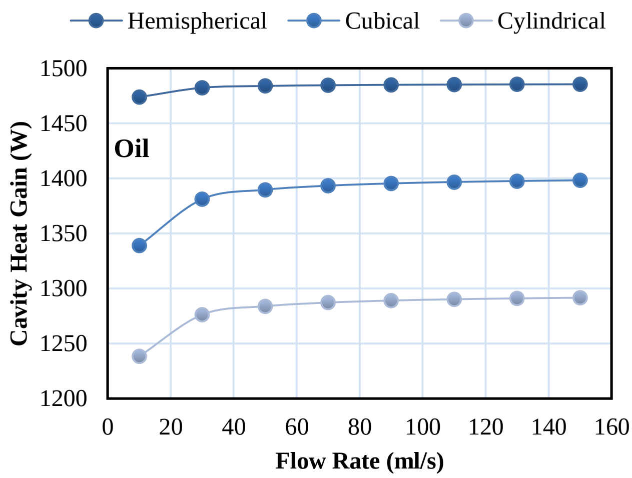
- In the first subsection, the influence of three shapes of cavity receiver on convection heat transfer and Nusselt number of oil as the working fluid will be presented.
- In the second subsection, convection heat transfer and Nusselt number of hemispherical cavity receiver with water and oil will be compared.

3.1 Comparison of Three Cavity Receivers

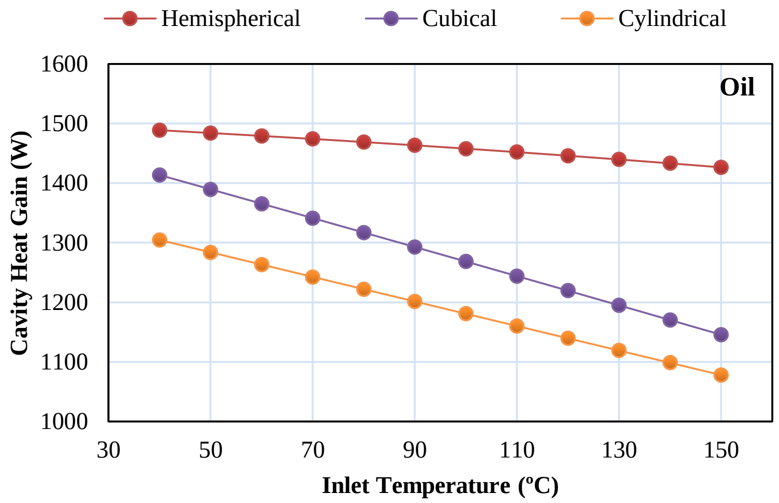
In this section, a variation of cavity heat gain versus change of solar radiation, flow rate of working fluid, and inlet temperature of working fluid for three investigated cavity receivers using oil was depicted in Fig. 4a, 8b, and 8c, respectively. Hemispherical, cylindrical, and cubical cavity receivers were studied. It should be mentioned that default values of solar radiation, flow rate of the solar working fluid, and inlet temperature of the solar working fluid are assumed equal to 800 W/m^2, 50 ml/s, and 50ºC, respectively. On the other side, variation of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid are investigated in the range of 500 W/m^2 to 1100 W/m^2, 10 ml/s to 150 ml/s, and 40ºC to 90ºC for water and 40ºC to 150ºC for oil, respectively. As seen in Fig. 4, the hemispherical cavity receiver had resulted in the highest cavity heat gain compared to other cavity receivers for all of the investigated conditions. It could be concluded that the cavity heat gain had increased with increasing solar radiation, increasing flow rate, and decreasing inlet temperature of the working fluid. Also, there is an optimum value for the flow rate of the working fluid nearly 30 ml/s for three investigated cavity receiver that can be saved requested energy for pumping oil with achieving the highest thermal performance.



(a)



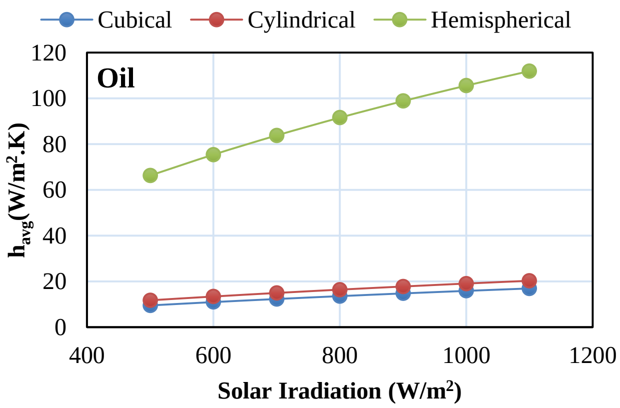
(b)



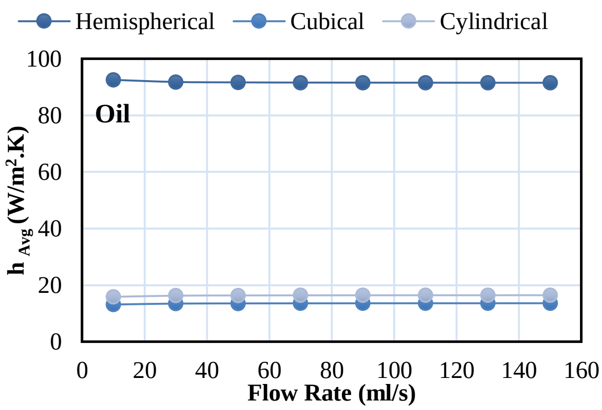
(c)

Fig. 4. Variation of cavity heat gain versus variation of a) solar radiation, b) flow rate of working fluid, and c) inlet temperature of working fluid for three investigated cavity receivers using oil

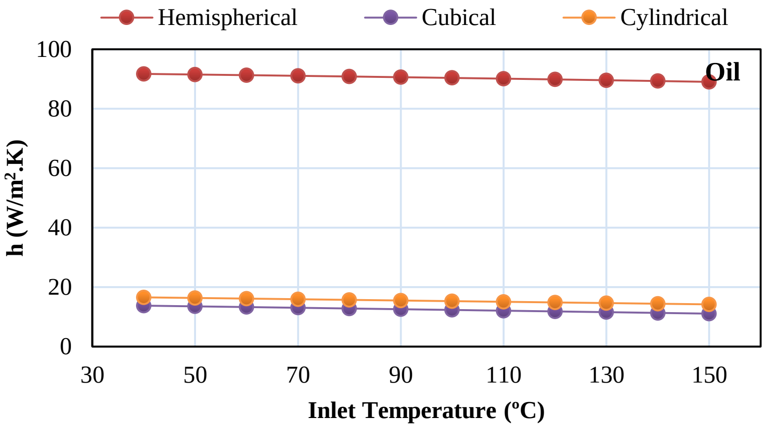
Fig. 5a, 9b, and 9c present variation of heat transfer coefficient of the working fluid versus variation of solar radiation, flow rate of working fluid, and inlet temperature of working fluid for three investigated cavity receivers, respectively. Thermal oil was used as the solar working fluid. Different shapes of cavity receiver were studied as the dish absorber, including hemispherical, cylindrical, and cubical cavity receiver. Default values of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were assumed equal to 800 W/m^2, 50 ml/s, and 50ºC, respectively. Whereas, a variation of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were investigated between 500 W/m^2 to 1100 W/m^2, 10 ml/s to 150 ml/s, and 40ºC to 90ºC for water and 40ºC to 150ºC for oil, respectively. As understood from Fig. 5, the highest heat transfer coefficient was calculated for the hemispherical cavity receiver for all of the investigated conditions. Also, it could result that increasing solar radiation, increasing heat transfer coefficient in a meaningful manner. On the other side, a variation of flow rate and inlet temperature of the solar working fluid has not shown a significant difference in values of the heat transfer coefficient.



(a)



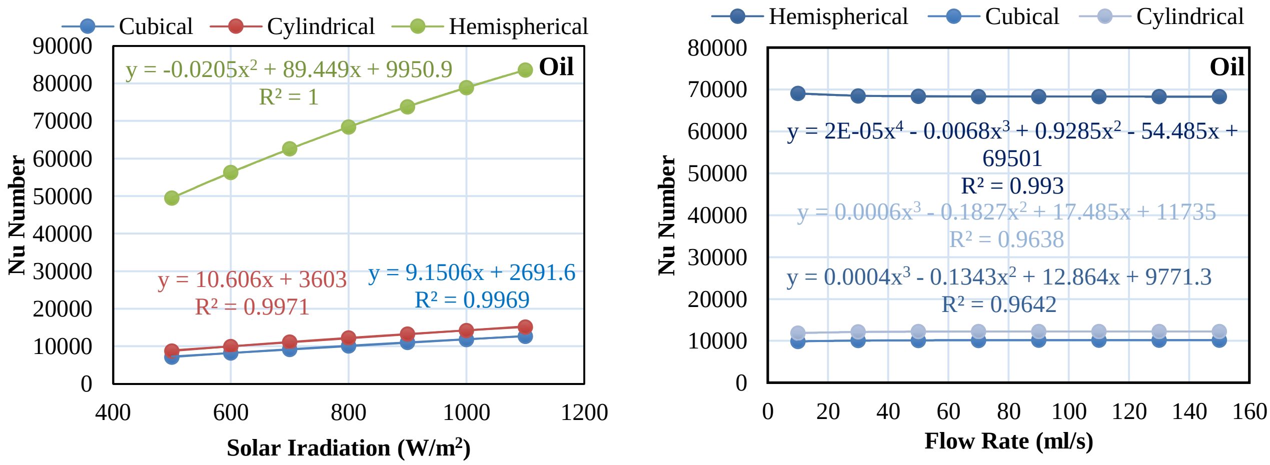
(b)



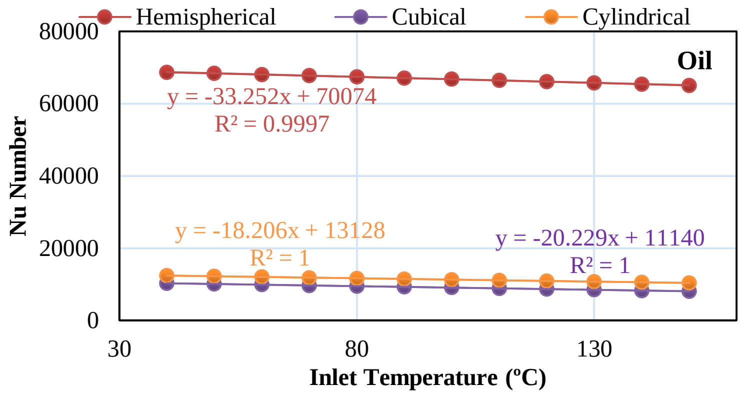
(c)

Fig. 5. Variation of convection heat transfer coefficient versus variation of a) solar radiation, b) flow rate of working fluid, and c) inlet temperature of working fluid for three investigated cavity receivers using oil

Variation of Nusselt number prediction of thermal oil as the solar working fluid versus change of solar radiation, flow rate of working fluid, and inlet temperature of working fluid for three investigated cavity receivers have been presented in Fig. 6a, 10b, and 10c, respectively. Different shapes of cavity receiver including hemispherical, cylindrical, and cubical were investigated. Default amounts of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were assumed equal to 800 W/m^2, 50 ml/s, and 50ºC, respectively. On the other side, variation of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were studied in the range of 500 W/m^2 to 1100 W/m^2, 10 ml/s to 150 ml/s, and 40ºC to 90ºC for water and 40ºC to 150ºC for oil, respectively. As seen in Fig. 6, the hemispherical cavity receiver had resulted in the highest Nusselt number amounts compared to two other cavity receivers that followed with the cylindrical cavity, and finally the cubical cavity receiver for all of the investigated conditions. It could result that the Nusselt number had improved with increasing solar radiation, increasing flow rate, and decreasing inlet temperature of the working fluid. Also, some prediction equations of Nusselt number with variation solar radiation, flow rate of the working fluid, and inlet temperature of working fluid for three cavity receivers with thermal oil as the solar working fluid are presented in Table 2, **Error! Reference source not found.**, and **Error! Reference source not found.**, respectively.



(a) (b)



(c)

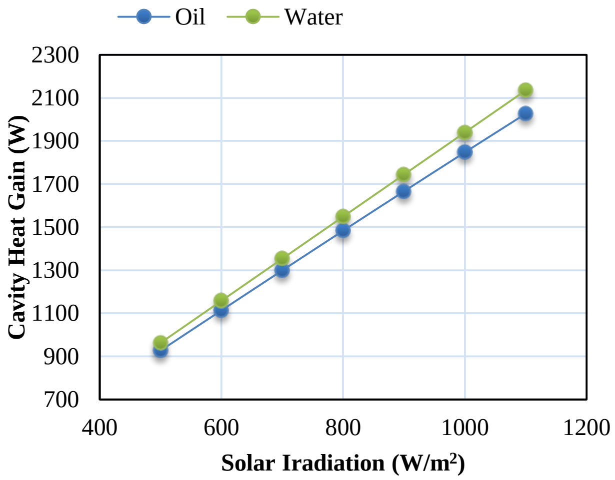
Fig. 6. Variation of Nusselt number versus variation of a) solar radiation, b) flow rate of working fluid, and c) inlet temperature of working fluid for three investigated cavity receivers using oil

Table 2
Nusselt number prediction with the variation of solar radiation, flow rate, and inlet temperature

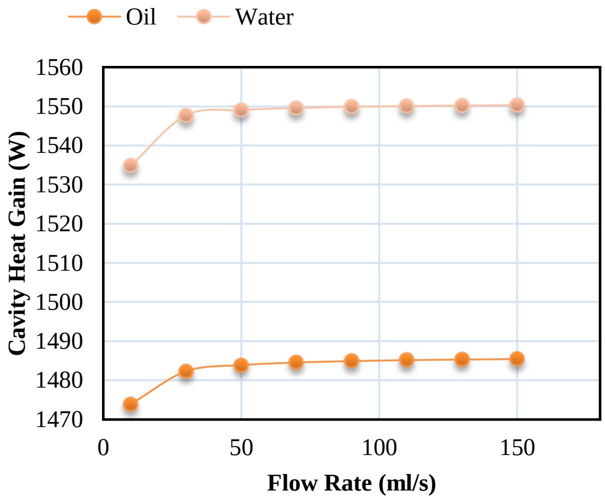
Cavity Shape	Nusselt number prediction	R^2
	Variation of solar radiation (I_{beam})	
Hemispherical	Nu = $-0.0362 I_{beam}^2 + 115.19 I_{beam}$	0.9976
Cylindrical	Nu = $10.606 I_{beam} + 3603$	0.9971
Cubical	Nu = $9.1506 I_{beam} + 2691.6$	0.9969
	Variation of flow rate ($\dot{m}_{oil}$)	
Hemispherical	Nu = $2E\text{-}05 \dot{m}_{oil}^4 - 0.0068 \dot{m}_{oil}^3 + 0.9285 \dot{m}_{oil}^2 - 54.485 \dot{m}_{oil} + 69501$	0.993
Cylindrical	Nu = $0.0006 \dot{m}_{oil}^3 - 0.1827 \dot{m}_{oil}^2 + 17.485 \dot{m}_{oil} + 11735$	0.9638
Cubical	Nu = $0.0004 \dot{m}_{oil}^3 - 0.1343 \dot{m}_{oil}^2 + 12.864 \dot{m}_{oil} + 9771.3$	0.9642
	Variation of inlet temperature ($T_{in,oil}$)	
Hemispherical	Nu = $-33.252\ T_{in,oil} + 70074$	0.9997
Cylindrical	Nu = $-18.206\ T_{in,oil} + 13128$	1
Cubical	Nu = $-20.229\ T_{in,oil} + 11140$	1

3.2 Comparison of Two Working Fluids

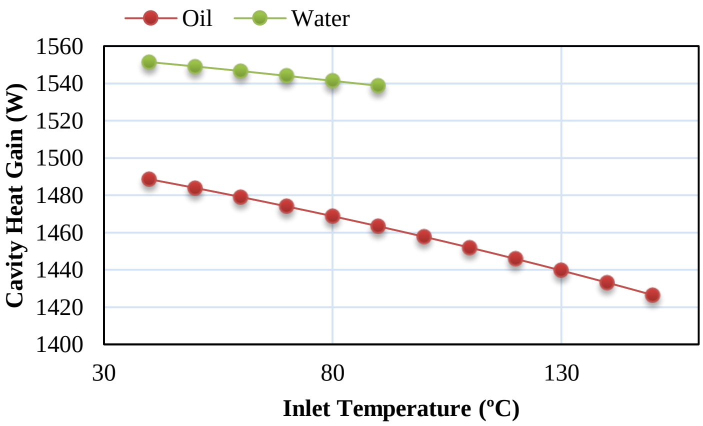
In this part, a variation of cavity heat gain versus change of solar radiation, flow rate of working fluid, and inlet temperature of working fluid for the hemispherical cavity receiver using water and oil have been displayed in Fig. 7a, 11b, and 11c, respectively. It should be noted that default values of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were assumed as 800 W/m^2, 50 ml/s, and 50ºC, respectively. Also, as seen in Fig. 7a, 11b, and 11c variation of solar radiation in the range of 500 W/m^2 to 1100 W/m^2, flow rate of the solar working fluid between 10 ml/s to 150 ml/s, and inlet temperature of solar working fluid in the range of 40ºC to 90ºC for water and 40ºC to 150ºC. As understood from Fig. 7, water as the solar working fluid had absorbed higher thermal energy compared to thermal oil at all investigated conditions. Also, it was concluded that the cavity heat gain improved with increasing solar radiation, increasing flow rate, and decreasing inlet temperature of the working fluid.



(a)



(b)



(c)

Fig. 7. Variation of cavity heat gain versus variation of a) solar radiation, b) flow rate of the working fluid and c) inlet temperature of working fluid for hemispherical cavity receiver using water and oil

Fig. 8a, 12b, and 12c depict a variation of cavity surface temperature versus a change of solar radiation, the flow rate of working fluid, and inlet temperature of working fluid using water and oil, respectively. The hemispherical cavity receiver was investigated as the dish absorber. The default values of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were 800 W/m^2, 50 ml/s, and 50ºC, respectively. On the other side, variation of solar radiation in the range of 500 W/m^2 to 1100 W/m^2, flow rate of the solar working fluid between 10 ml/s to 150 ml/s, and inlet temperature of solar working fluid in the range of 40ºC to 90ºC for water and 40ºC to 150ºC for oil were investigated in Fig. 8a, 12b, and 12c, respectively. As seen in Fig. 8, the highest cavity surface temperature was estimated for application of oil with the highest solar radiation, lowest flow rate, and the highest inlet temperature of the working fluid.

Also, a variation of heat transfer convection coefficient using water and oil versus a change of solar radiation, the flow rate of working fluid, and inlet temperature of the working fluid are presented in Fig. 9a, 13b, and 13c, respectively. As mentioned, default values of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were assumed as 800 W/m^2, 50 ml/s, and 50ºC, respectively. On the other side, solar radiation was varied in the range of 500 W/m^2 to

1100 W/m^2, flow rate of the solar working fluid was changed between 10 ml/s to 150 ml/s, and inlet temperature of solar working fluid was investigated in the range of 40ºC to 90ºC for water and 40ºC to 150ºC. As shown in Fig. 9, the application of water as the solar working fluid had resulted in higher values of the heat transfer coefficient compared to water one. Also, the heat transfer coefficient improved with increasing solar radiation, increasing flow rate, and decreasing inlet temperature of the solar working fluids.

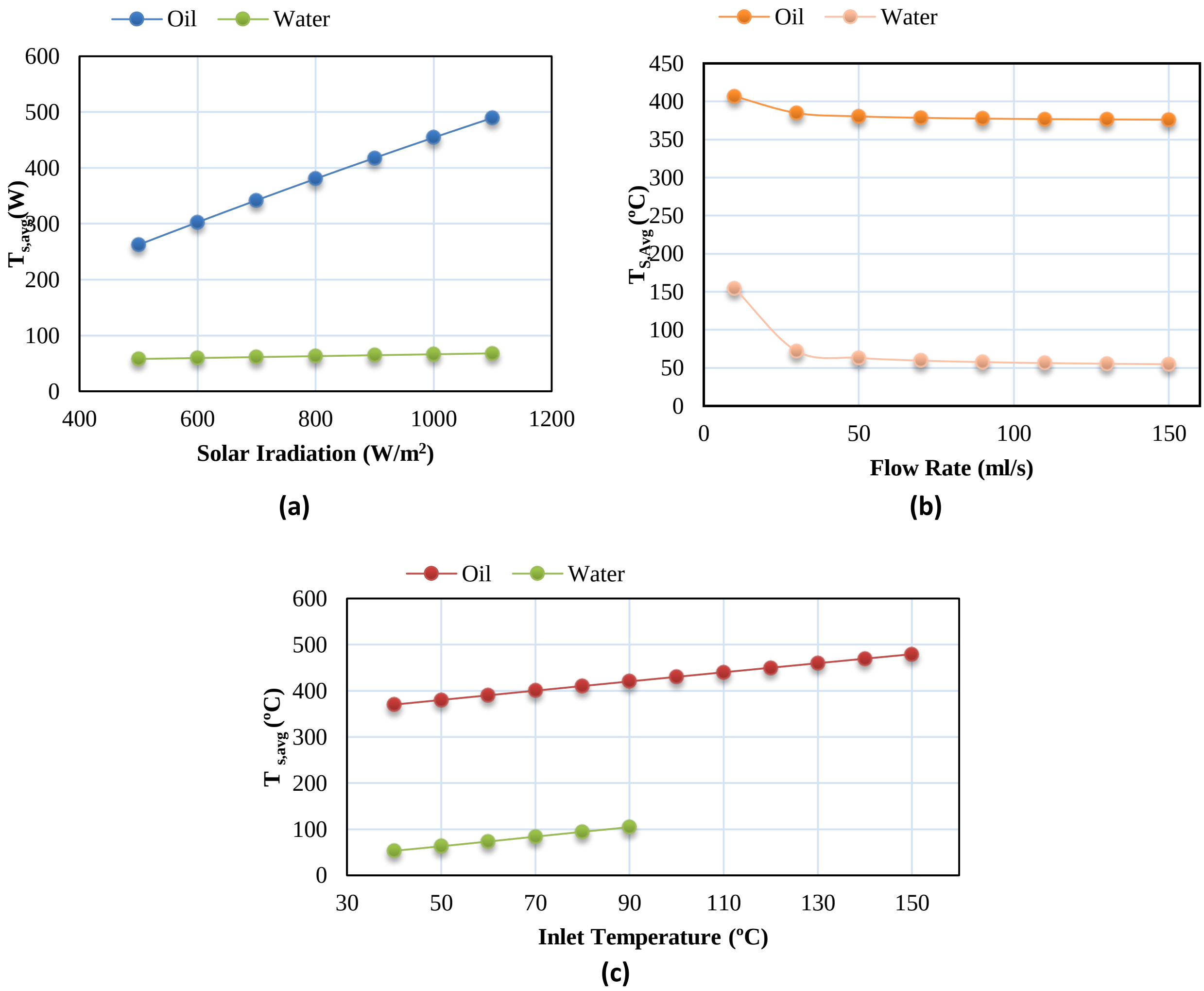


Fig. 8. Variation of cavity surface temperature versus variation of a) solar radiation, b) flow rate of the working fluid and c) inlet temperature of working fluid for hemispherical cavity receiver using water and oil

Finally, Fig. 10a, 14b, and 14c depict a variation of Nusselt number values for water and oil in the hemispherical cavity receiver versus a change of solar radiation, the flow rate of working fluid, and inlet temperature of working fluids, respectively. Default values of solar radiation, flow rate of the solar working fluid, and inlet temperature of solar working fluid were assumed equal to 800 W/m^2, 50 ml/s, and 50ºC in this analysis, respectively. Whereas variation of solar radiation was studied between 500 W/m^2 to 1100 W/m^2, flow rate of the solar working fluid was investigated between 10 ml/s to 150 ml/s, and inlet temperature of solar working fluid was evaluated in the range of 40ºC to 90ºC for water and 40ºC to 150ºC. As revealed in Fig. 10, oil had resulted in higher amounts of Nusselt number compared to water as the solar working fluid. Consequently, the application of oil is suggested for high-temperature systems.

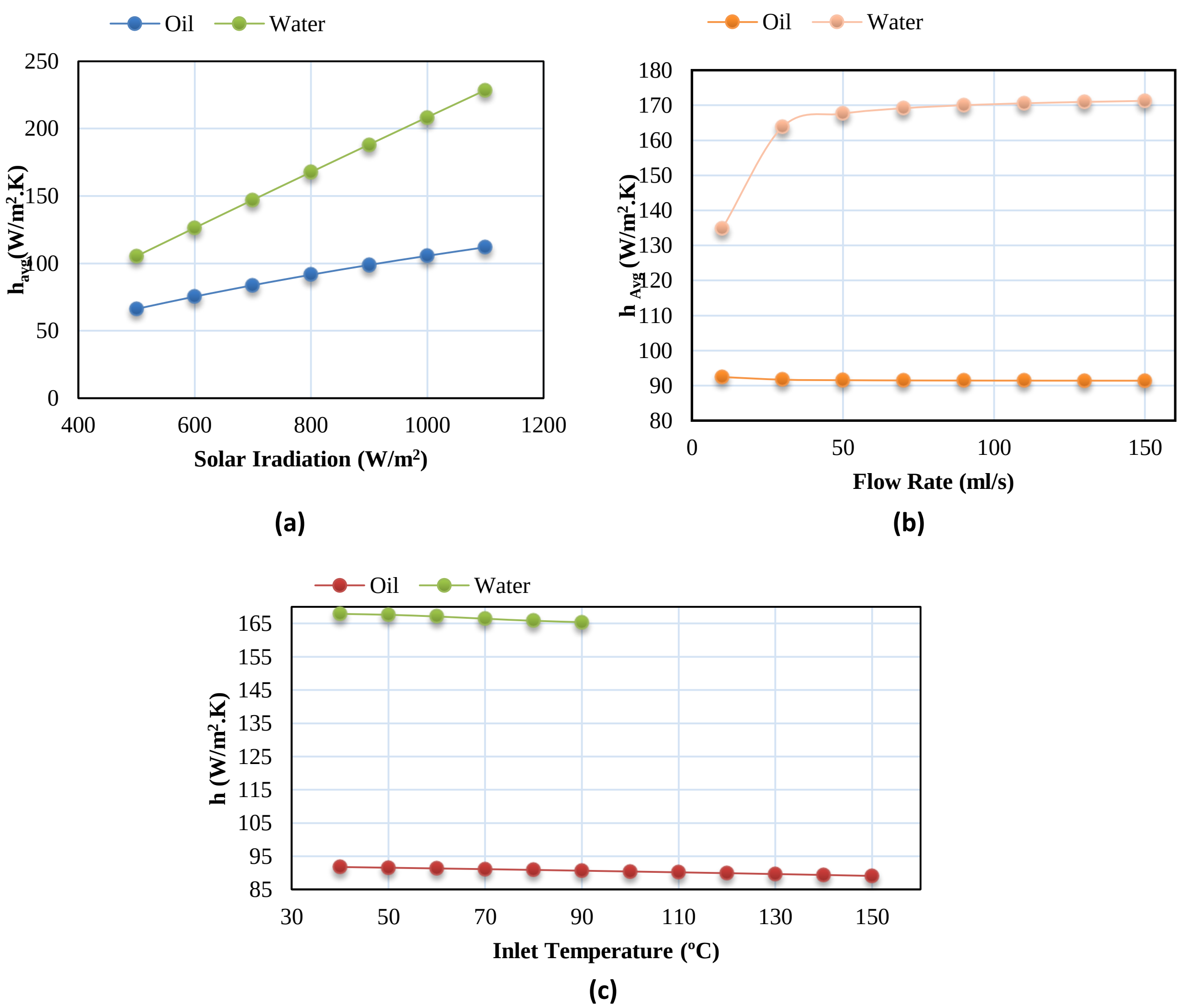
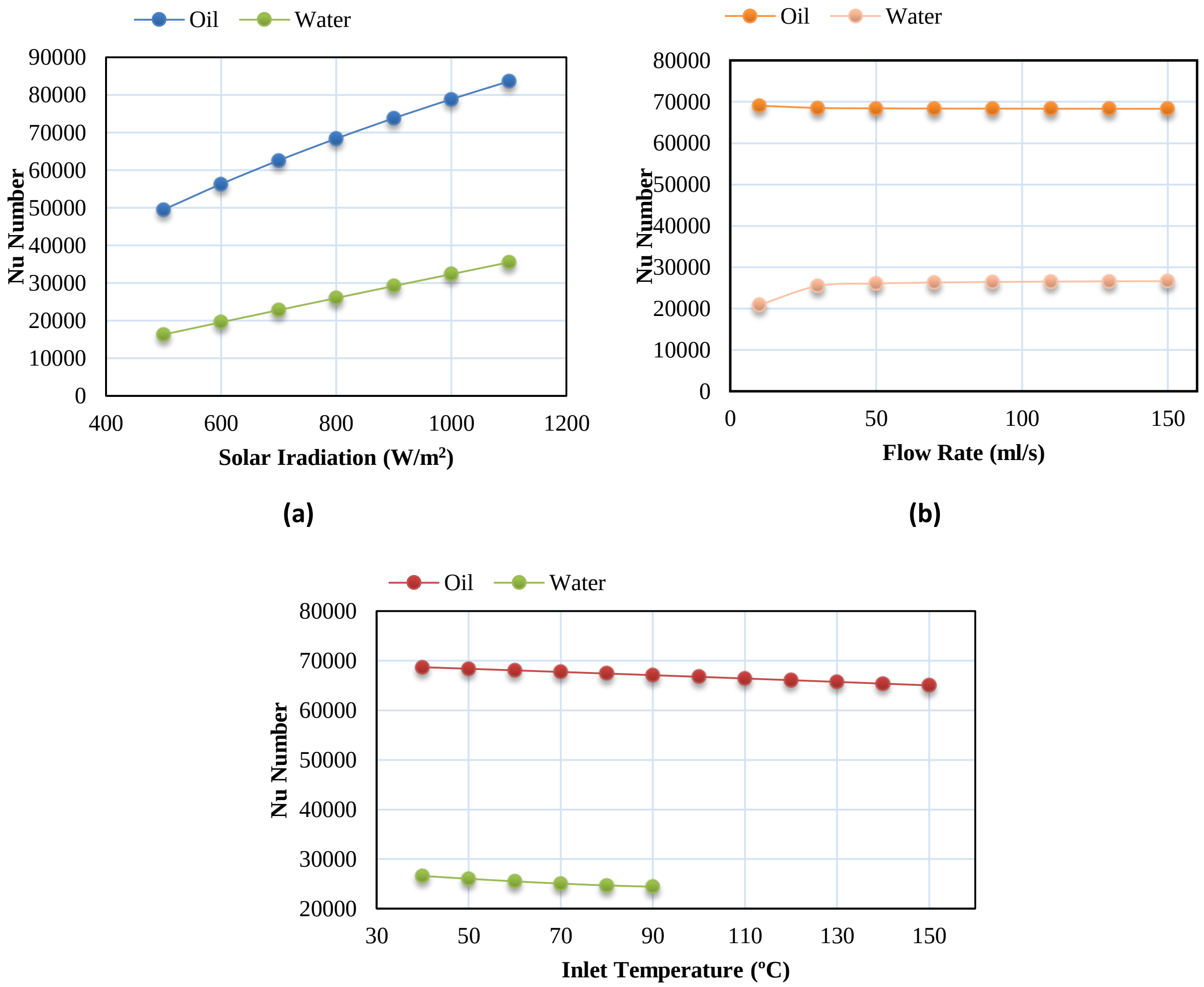


Fig. 9. Variation of convection heat transfer coefficient versus variation of a) solar radiation, b) flow rate of working fluid, and c) inlet temperature of working fluid for hemispherical cavity receiver using water and oil



(c)

Fig. 10. Variation of Nusselt number versus variation of a) solar radiation, b) flow rate of the working fluid and c) inlet temperature of working fluid for hemispherical cavity receiver using water and oil

4. Conclusions

In this research, the internal heat transfer coefficient of water and oil as the solar working fluid in cavity tube was investigated. A dish concentrator with three shapes of cavity receiver including hemispherical, cylindrical, and cubical cavity was investigated. Influence of some operational and environmental parameters including solar radiation, flow rate, and inlet temperature was investigated on the thermal performance of the solar system. The main achievement could be summarized as below:

- It was found that the hemispherical cavity receiver had resulted in the highest cavity heat gain, heat transfer coefficient, and Nusselt number values compared to two other cavity receivers for all of the investigated conditions.
- It could be concluded that the cavity heat gain, and heat transfer coefficient, and Nusselt number amounts had increased with increasing solar radiation, increasing flow rate, and decreasing inlet temperature of the working fluid. Also, there is an optimum value for the flow rate of the working fluid nearly 30 ml/s for three

investigated cavity receiver that can be saved requested energy for pumping oil with achieving the highest thermal performance.

- Some equations were suggested for prediction of Nusselt number with variation solar radiation, the flow rate of the working fluid, an inlet temperature of working fluid for three cavity receivers with thermal oil were presented.
- It was found, water as the solar working fluid had absorbed higher thermal energy compared to thermal oil at all investigated conditions.
- The highest cavity surface temperature was estimated for application of oil with the highest solar radiation, lowest flow rate, and the highest inlet temperature of the working fluid.
- It was resulted, application of water as the solar working fluid had resulted in higher values of the heat transfer coefficient compared to oil.
- It was concluded that application of thermal oil had resulted in higher amounts of Nusselt number compared to water as the solar working fluid. Consequently, use of oil is suggested for high-temperature systems.

Acknowledgement
Authors are grateful to the Tarbiat Modares University (http://www.modares.ac.ir) for financial supports given under IG/39705 grant for renewable Energies of Modares research group.

References
[1] Abdulhamed, Ali Jaber, Nor Mariah Adam, Mohd Zainal Abidin Ab-Kadir, and Abdul Aziz Hairuddin. "Review of solar parabolic-trough collector geometrical and thermal analyses, performance, and applications." *Renewable and Sustainable Energy Reviews* 91 (2018): 822-831.
[2] Loni, R., A. B. Kasaeian, E. Askari Asli-Ardeh, B. Ghobadian, and W. G. Le Roux. "Performance study of a solar-assisted organic Rankine cycle using a dish-mounted rectangular-cavity tubular solar receiver." *Applied Thermal Engineering* 108 (2016): 1298-1309.
[3] Loni, R., A. B. Kasaeian, E. Askari Asli-Ardeh, and B. Ghobadian. "Optimizing the efficiency of a solar receiver with tubular cylindrical cavity for a solar-powered organic Rankine cycle." *Energy* 112 (2016): 1259-1272.
[4] Günther, Matthias, Reza Shahbazfar, Thomas Fend, and Mohammad Hamdan. "Solar dish technology." *Advanced CSP teaching materials* 1 (2011): 1-63.
[5] Loni, R., E. Askari Asli-Ardeh, B. Ghobadian, A. B. Kasaeian, and Evangelos Bellos. "Thermal performance comparison between Al2O3/oil and SiO2/oil nanofluids in cylindrical cavity receiver based on experimental study." *Renewable energy* 129 (2018): 652-665.
[6] Bellos, Evangelos, Erion Bousi, Christos Tzivanidis, and Sasa Pavlovic. "Optical and thermal analysis of different cavity receiver designs for solar dish concentrators." *Energy Conversion and Management: X* 2 (2019): 100013.
[7] Venkatachalam, Thirunavukkarasu, and M. Cheralathan. "Effect of aspect ratio on thermal performance of cavity receiver for solar parabolic dish concentrator: An experimental study." *Renewable energy* 139 (2019): 573-581.
[8] Loni, Reyhaneh, E. Askari Asli-Areh, B. Ghobadian, A. B. Kasaeian, Sh Gorjian, G. Najafi, and Evangelos Bellos. "Research and review study of solar dish concentrators with different nanofluids and different shapes of cavity receiver: Experimental tests." *Renewable Energy* 145 (2020): 783-804.
[9] Pavlovic, Sasa, Reyhaneh Loni, Evangelos Bellos, Darko Vasiljević, Gholamhassan Najafi, and Alibakhsh Kasaeian. "Comparative study of spiral and conical cavity receivers for a solar dish collector." *Energy Conversion and Management* 178 (2018): 111-122.
[10] Yan, Jian, You-duo Peng, and Zi-ran Cheng. "Optimization of a discrete dish concentrator for uniform flux distribution on the cavity receiver of solar concentrator system." *Renewable energy* 129 (2018): 431-445.
[11] Loni, Reyhaneh, E. Askari Asli-Ardeh, B. Ghobadian, Evangelos Bellos, and Willem Gabriel Le Roux. "Numerical comparison of a solar dish concentrator with different cavity receivers and working fluids." *Journal of Cleaner Production* 198 (2018): 1013-1030.
[12] Yang, Song, Jun Wang, Peter D. Lund, Chuan Jiang, and Bingkun Huang. "Design and performance evaluation of a high-temperature cavity receiver for a 2-stage dish concentrator." *Solar Energy* 174 (2018): 1126-1132.

[13] Soltani, Sara, Mohammad Bonyadi, and Vahid Madadi Avargani. "A novel optical-thermal modeling of a parabolic dish collector with a helically baffled cylindrical cavity receiver." *Energy* 168 (2019): 88-98.
[14] El-Genk, Mohamed S., and Mahyar Pourghasemi. "Nusselt number and development length correlations for laminar flows of water and air in microchannels." *International Journal of Heat and Mass Transfer* 133 (2019): 277-294.
[15] Hu, Yanwei, Yurong He, Hongda Gao, and Zhenduo Zhang. "Forced convective heat transfer characteristics of solar salt-based SiO2 nanofluids in solar energy applications." *Applied Thermal Engineering* 155 (2019): 650-659.
[16] Zhang, Tiantian, and Hongxing Yang. "Flow and heat transfer characteristics of natural convection in vertical air channels of double-skin solar façades." *Applied Energy* 242 (2019): 107-120.
[17] Ghritlahre, Harish Kumar, and Radha Krishna Prasad. "Prediction of heat transfer of two different types of roughened solar air heater using Artificial Neural Network technique." *Thermal science and engineering progress* 8 (2018): 145-153.
[18] Kumar, Anil, Raj Kumar, Rajesh Maithani, Ranchan Chauhan, Muneesh Sethi, Anita Kumari, Sushil Kumar, and Sunil Kumar. "Correlation development for Nusselt number and friction factor of a multiple type V-pattern dimpled obstacles solar air passage." *Renewable Energy* 109 (2017): 461-479..
[19] Du, Shen, Zi-Xiang Tong, Hong-Hu Zhang, and Ya-Ling He. "Tomography-based determination of Nusselt number correlation for the porous volumetric solar receiver with different geometrical parameters." *Renewable Energy* 135 (2019): 711-718.
[20] Loni, R., E. Askari Asli-Ardeh, B. Ghobadian, and A. Kasaeian. "Experimental study of carbon nano tube/oil nanofluid in dish concentrator using a cylindrical cavity receiver: Outdoor tests." *Energy Conversion and Management* 165 (2018): 593-601.
[21] Loni, R., E. Askari Asli-Ardeh, B. Ghobadian, A. B. Kasaeian, and Sh Gorjian. "Numerical and experimental investigation of wind effect on a hemispherical cavity receiver." *Applied Thermal Engineering* 126 (2017): 179-193.
[22] Loni, Reyhaneh, E. Askari Asli-Ardeh, B. Ghobadian, M. H. Ahmadi, and Evangelos Bellos. "GMDH modeling and experimental investigation of thermal performance enhancement of hemispherical cavity receiver using MWCNT/oil nanofluid." *Solar Energy* 171 (2018): 790-803.
[23] Loni, Reyhaneh, E. Askari Asli-Ardeh, B. Ghobadian, A. B. Kasaeian, and Evangelos Bellos. "Energy and exergy investigation of alumina/oil and silica/oil nanofluids in hemispherical cavity receiver: Experimental Study." *Energy* 164 (2018): 275-287.
[24] Loni, R., A. B. Kasaeian, E. Askari Asli-Ardeh, B. Ghobadian, and Sh Gorjian. "Experimental and numerical study on dish concentrator with cubical and cylindrical cavity receivers using thermal oil." *Energy* 154 (2018): 168-181.
[25] Le Roux, Willem Gabriel, Tunde Bello-Ochende, and Josua P. Meyer. "The efficiency of an open-cavity tubular solar receiver for a small-scale solar thermal Brayton cycle." *Energy Conversion and Management* 84 (2014): 457-470.
[26] Pavlovic, Sasa, Evangelos Bellos, and Reyhaneh Loni. "Exergetic investigation of a solar dish collector with smooth and corrugated spiral absorber operating with various nanofluids." *Journal of cleaner production* 174 (2018): 1147-1160.
[27] Ya, Cengel, A. Ghajar, and H. Ma. "Heat and Mass Transfer Fundamentals & Applications." *McGraw-Hill* (2015).
[28] Baghernejad, A., and M. Yaghoubi. "Thermoeconomic methodology for analysis and optimization of a hybrid solar thermal power plant." *International journal of green energy* 10, no. 6 (2013): 588-609.
[29] Loni, R., A. B. Kasaeian, E. Askari Asli-Ardeh, B. Ghobadian, and Sh Gorjian. "Experimental and numerical study on dish concentrator with cubical and cylindrical cavity receivers using thermal oil." *Energy* 154 (2018): 168-181.