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CFD Simulation of Solar Dish Concentrator with Different Cavity Receivers

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ABSTRACT

The use of solar dish concentrators for harnessing solar energy is an established technology in the Realm of renewable energy solutions. This study presents a comprehensive Computational Fluid Dynamics (CFD) simulation to analyze the performance of a solar dish concentrator equipped with different cavity receivers. The aim is to optimize the thermal efficiency and energy absorption capabilities of the system. Various geometries of cavity receivers, including cylindrical, cubical, and hemispherical shapes, are evaluated under identical operational conditions. The simulations consider factors such as incident solar radiation, heat losses, temperature distribution, and fluid flow dynamics within the cavity. Results indicate significant variations in thermal performance based on the cavity design, with certain geometries exhibiting superior heat retention and minimal thermal losses. This research provides critical insights into the design and optimization of cavity receivers, contributing to the advancement of high-efficiency solar dish concentrator systems. The findings are expected to aid in the development of more efficient solar energy harvesting technologies, promoting sustainable energy solutions.

1. Introduction

The increasing demand for renewable energy sources has intensified the focus on optimizing solar energy systems. Among various solar technologies, solar dish concentrators are highly efficient in converting solar energy into thermal energy. However, their performance can be significantly influenced by the type of working fluid and the design of the cavity receiver. Innovative cavity designs can play a crucial minimizing heat loss and maximizing the absorption of solar radiation. The design of the cavity receiver, where the concentrated solar radiation is absorbed and converted into thermal energy, is critical for the overall efficiency of the system. Factors such as cavity shape, size, and material can influence the thermal performance and optical efficiency of the concentrator. Diverse

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cavity designs, including conical, cylindrical, and spherical shapes, offer varying degrees of thermal insulation and radiation trapping, impacting the efficiency of solar energy conversion. Some studies numerically have considered the nanofluid application in the solar collectors [1-3]. Edalatpour and Solano [4] numerically investigated a flat plate collector using Al_2O_3/water nanofluid as the solar working fluid. The results indicated that the working fluid outlet temperature decrease with increasing Reynolds number at fix nanoparticle volume fraction. Mahian *et al.,* [5] 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. Kaloudis *et al.,* [6] numerically investigated the application of the nanofluid as the solar working fluid in a parabolic trough collector. Bellos *et al.,* [7] 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.,* [8] numerically investigated a volumetric absorber in a concentrating direct absorption solar collector using the nanofluid application as the solar working fluid. Their simulated results show a good agreement with the experimental results. Application of nanofluid in the solar collector was experimentally investigated by many researches as [9-17]. The thermal performance of a vacuum tube solar collector using two nanofluids including water/TiO2 and water/carbon nanotube, under sunny and cloudy weather conditions has been evaluated by [17]. They concluded that the water/carbon nanofluid shows higher performance compare to water/TiO_2. Taylor *et al.,* [18] considered the influence of the nanofluid application in the concentrating solar thermal system. The results indicate the thermal efficiency of the based concentrating solar thermal system could be increased by 10% in the application of nanofluid as the working fluid. Mahian *et al.,* [5] studied the effect of the alumina/water-ethylene glycol nanofluid application as the solar working fluid in a flat plate minichannel-based solar collector. The influence of the different shape of nanoparticles on the energy and exergy analysis was evaluated. They concluded that the outlet temperature increased by application of the nanofluids independent of nanoparticle shape. Meibodi *et al.,* [19] experimentally considered a flat-plate solar collector using SiO_2/ ethylene glycol–water nanofluids as the solar working fluid. The influence of the different parameters such as nanoparticle volume fractions, mass flow rate, and solar radiation was evaluated in their study. The results show the exergy efficiency is higher at higher nanoparticle volume fraction. Yousefi *et al.,* [14-16] experimentally evaluated the application of Al_2O_3/water nanofluid as the solar working fluid in a flat-plate solar collector. Mwesigye *et al.,* [20] numerically research the application of the Al_2O_3/synthetic oil nanofluid as a solar working fluid of a parabolic trough collector. The results reveal that the thermal efficiency of the investigated collector can be increased by up to 7.6% using nanofluids as the solar working fluid.

This study aims to perform a detailed CFD simulation of a solar dish concentrator equipped with various cavity receiver geometries. The primary objective is to evaluate and compare the thermal performance of cylindrical, cubical and hemispherical cavity receivers under identical operational conditions.

2. Methodology

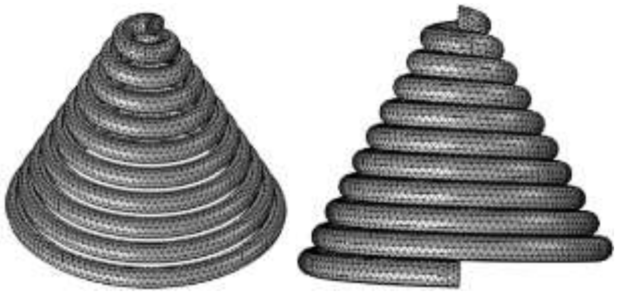
2.1 Validation

Numerical results of this study were validated based on some experimental results. 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. A view of the investigated experimental setup is presented in Figure 1.

Fig. 1. A view of the solar dish concentrator and the wounded cavity receivers with copper tube including a) cylindrical, b) cubical, and c) hemispherical cavity receiver

2.2 CFD Simulation

The analysis of the temperature gradient in the solar dish concentrator system was conducted using COMSOL Multiphysics software to visually display the distribution of temperature contours. Figure 2 illustrates the detailed gridded model of the solar concentrator system, incorporating fine grids to enhance calculation accuracy. The number of elements required in different cases is depicted in Figure 2. The selection of elements has been done meticulously to ensure grid independence, allowing for precise calculations while also minimizing computation time and cost. Triangular grids were utilized in this study, offering a higher number of elements compared to other grid types.

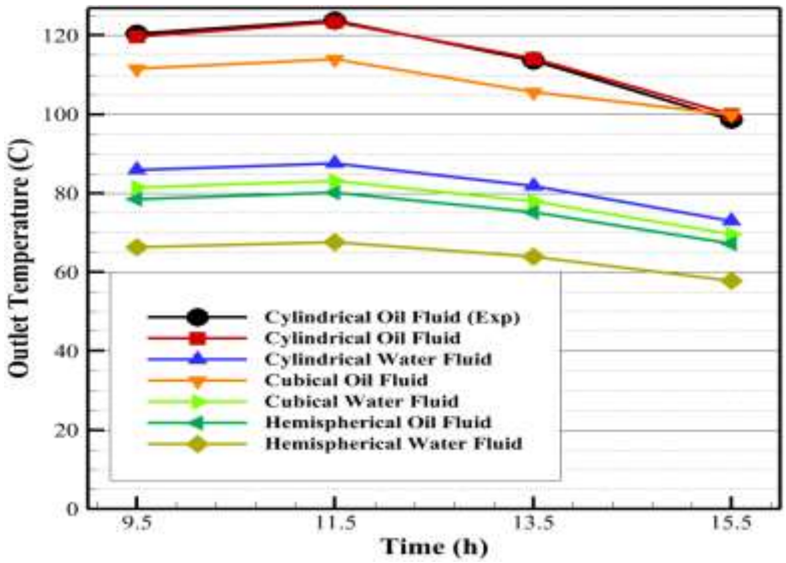


(c)

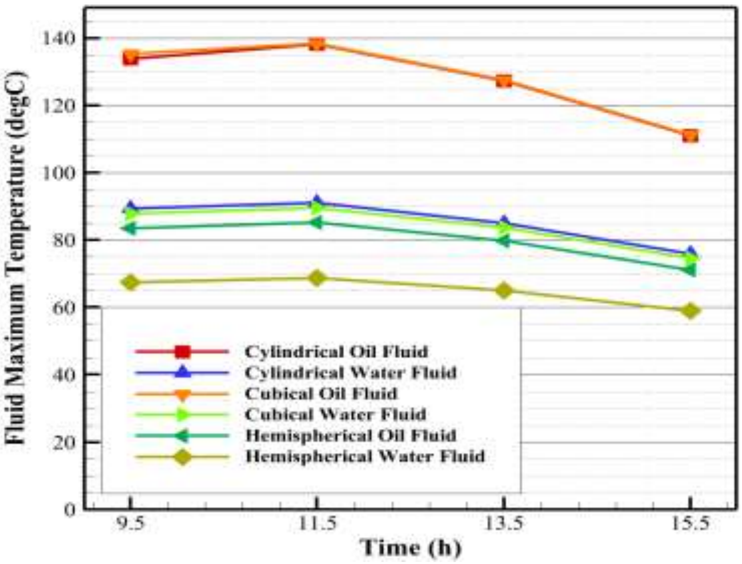
Fig. 2. Domain elements, boundary elements and edge elements of different solar cavities. (a) Cylindrical, (b) Cubical and (c) Hemispherical

3. Results

As can be seen in Figure 3, the maximum and average temperature of the fluid first decreases, then increases, and finally decreases, because the amount of solar radiation hitting the collector reaches its maximum in the middle of the day and at 11:30 AM. Also, the maximum and average temperature of the oil in all three geometries is higher than the water fluid because the specific heat capacity of the oil is lower. Also, the cylindrical and cubical cavities have shown a higher maximum temperature because they have a larger cavity coil length, as a result, they have a higher contact surface for heat transfer and receiving heat flux [12-18]. Figure 3 shows the maximum fluid temperature and fluid outlet temperature in different cavities and in the case of water and oil at a volumetric flow rate of 10 ml/s.



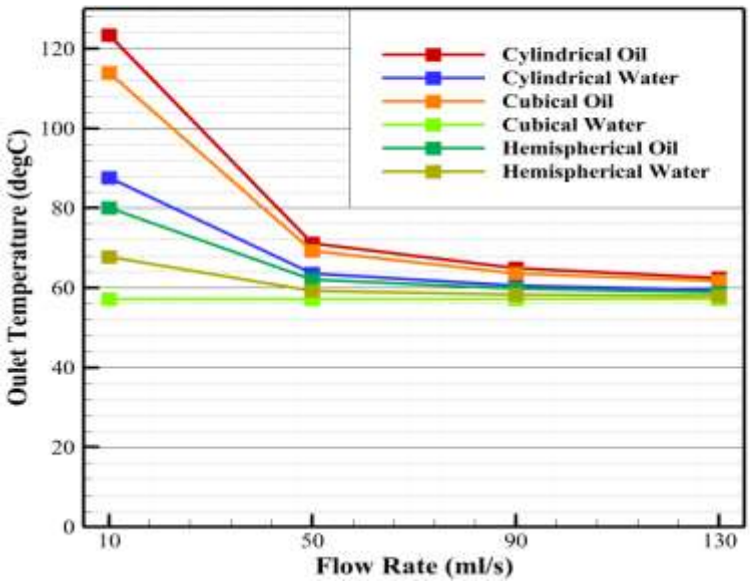
(a)



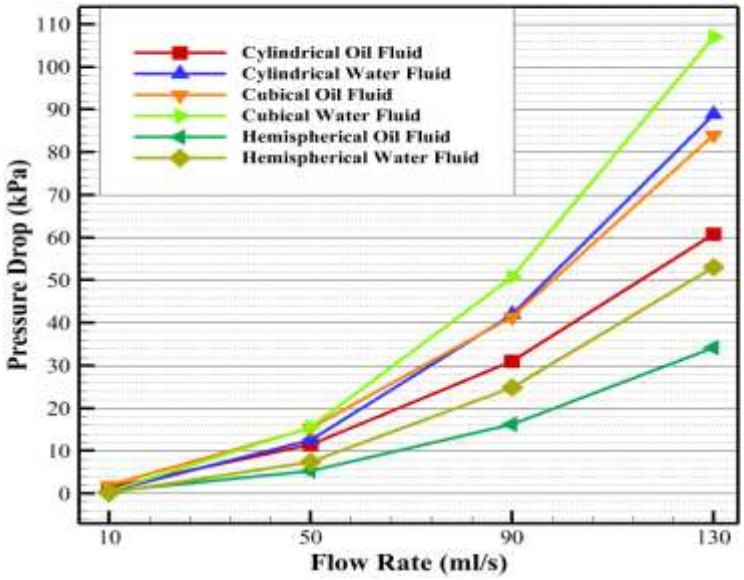
(b)

Fig. 3. (a) Outlet temperature and (b) Fluid maximum and average temperature for three geometries of cavities at volume flow rate of 10 ml/s in two modes of oil and water

Figure 4 shows the pressure drop and outlet temperature of water and oil working fluid at 11.30 am in the state of maximum solar radiation in different volumetric flow rates. With the increase in volumetric flow rate, the output temperature of the working fluid has decreased in all three geometric states, i.e., cylindrical, cubical, and hemispherical, because the retention time and the opportunity for heat exchange between the fluid and the thermal coil have decreased. Also, with the increase in volumetric flow rate, the pressure drop has increased because the friction of the fluid layers with the wall and also with the internal layers of the fluid increases, which leads to an increase in flow turbulence and a decrease in the thickness of the boundary layer, as a result, the amount of pressure drop increases [19-24].



(a)



(b)

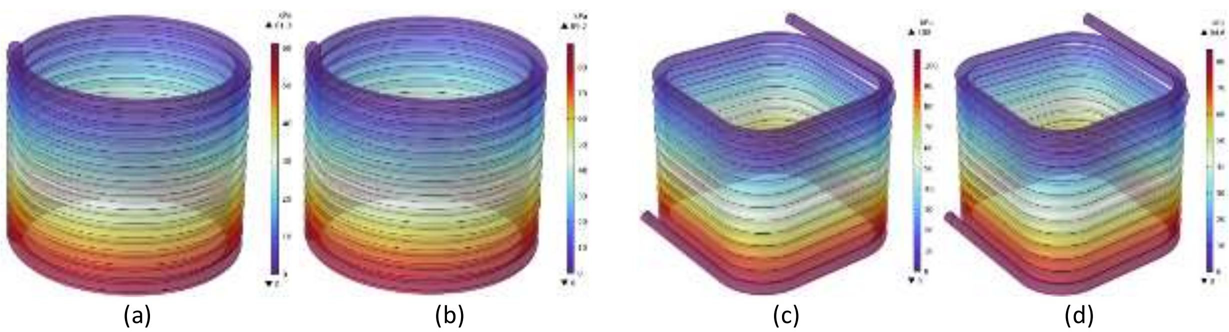
Fig. 4. (a) Outlet temperature and (b) Pressure drop of working fluid at 11.30 am

Figure 5 shows the pressure drop of the water and oil working fluid at 11:30 am in the state of maximum sunlight at a volumetric flow rate of 130 ml/s and also the pressure drop of the working fluid in a cylindrical state at different volumetric flow rates.

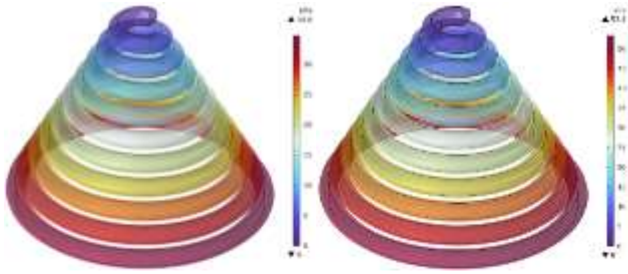
With the increase in volumetric flow rate, the pressure drop has increased because the friction of the fluid layers with the wall wall and also with the internal layers of the fluid increases, which leads to an increase in flow turbulence and a decrease in the thickness of the boundary layer, as a result, the amount of pressure drop increases [25-28].

The maximum pressure in the working fluid in the cylindrical state at a volumetric flow rate of 130 ml/s reaches about 60 kPa, while at a volumetric flow rate of 10 ml/s, this amount is approximately 1.5 kPa.

Figure 6 shows the working fluid temperature of water and oil in volumetric flow rate of 10 ml/s and cylindrical, cubical and hemispherical states at 11.30 am. In all simulation cases, the temperature of the fluid in the oil state has increased more than in the water state because the specific heat capacity of the oil is lower than that of the water. As a result, the oil temperature increases due to the increase in the heat flux and the temperature received by the coil. Also, the temperature of the fluid in the cylindrical and cubical state has increased more than in the hemispherical state because they have longer thermal coils. Of course, if higher heat fluxes hit the hemispherical coil, this coil will also experience a higher temperature increase [29-31].

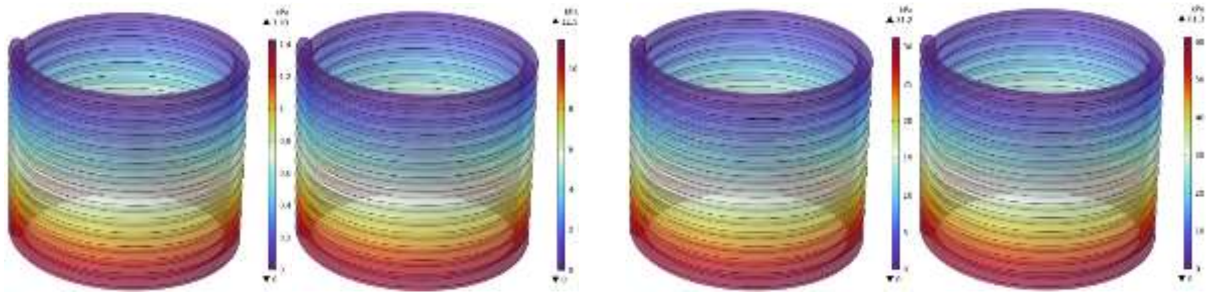


(a) (b) (c) (d)



(e) (f)

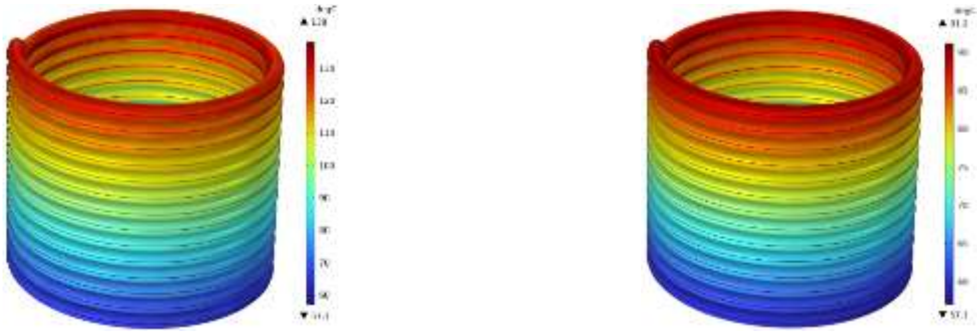
(i)



(a) (b) (c) (d)

(ii)

Fig. 5. Pressure drop for three different cavity geometries at different volumetric flow rates **(i)** Pressure at 11:30 AM for Cylindrical a) Oil, b) Water, Cubical c) Oil, d) Water and Hemispherical e) Oil, f) Water 130 ml/s and **(ii)** Pressure of Cylindrical cavity a) 10 ml/s, b) 50 ml/s, c) 90 ml/s and d) 130 ml/s oil Fluid



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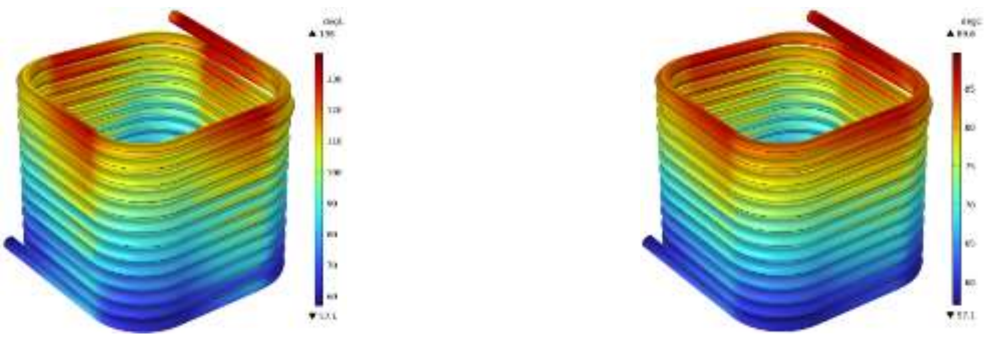

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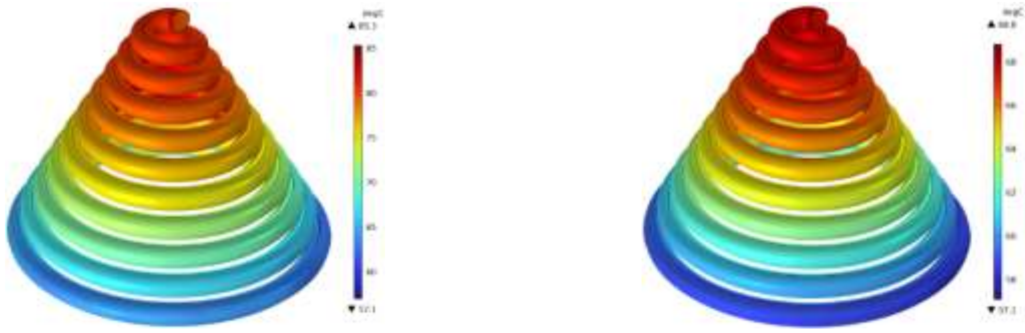
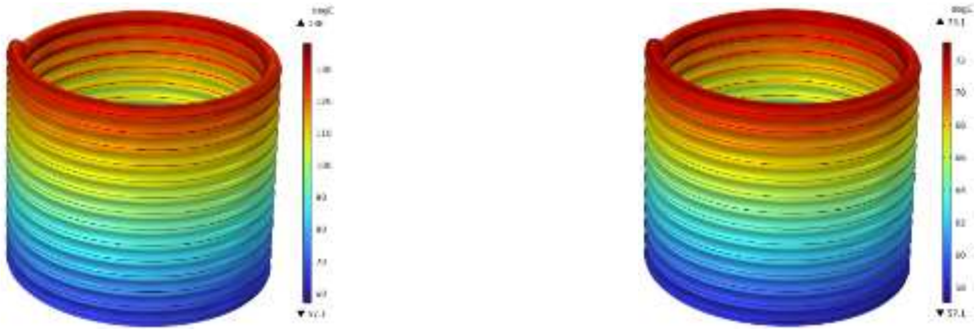


(e) (f)

Fig. 6. Working fluid temperature of different cavities in two states of water and oil, at 11:30 AM for Cylindrical a) Oil, b) Water, Cubical c) Oil, d) Water and Hemispherical e) Oil, f) Water 10 ml/s

Also, Figure 7 evaluates the temperature of the water and oil working fluid in a cylindrical state at different volumetric flow rates. The results show that in the cylindrical state, the temperature of the working fluid has increased more than in other states, and the temperature of the working fluid in the oil state has a significant increase compared to the water state, which is due to the thermal properties of the oil that has been mentioned [32-40].

Also, at a higher volumetric flow rate, the temperature of the working fluid at the end of the coil length decreases in both water and oil states, because the increase in the speed of the working fluid reduces the heat exchange time between the fluid and the wall, and the conduction and convection heat transfer process takes less time. It does not work well [41-50].



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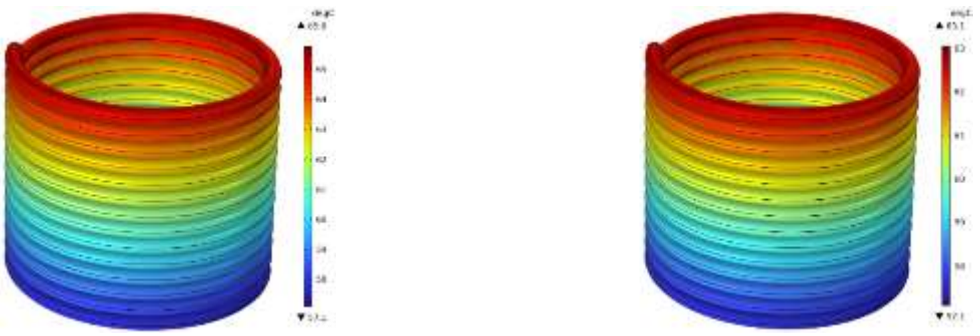

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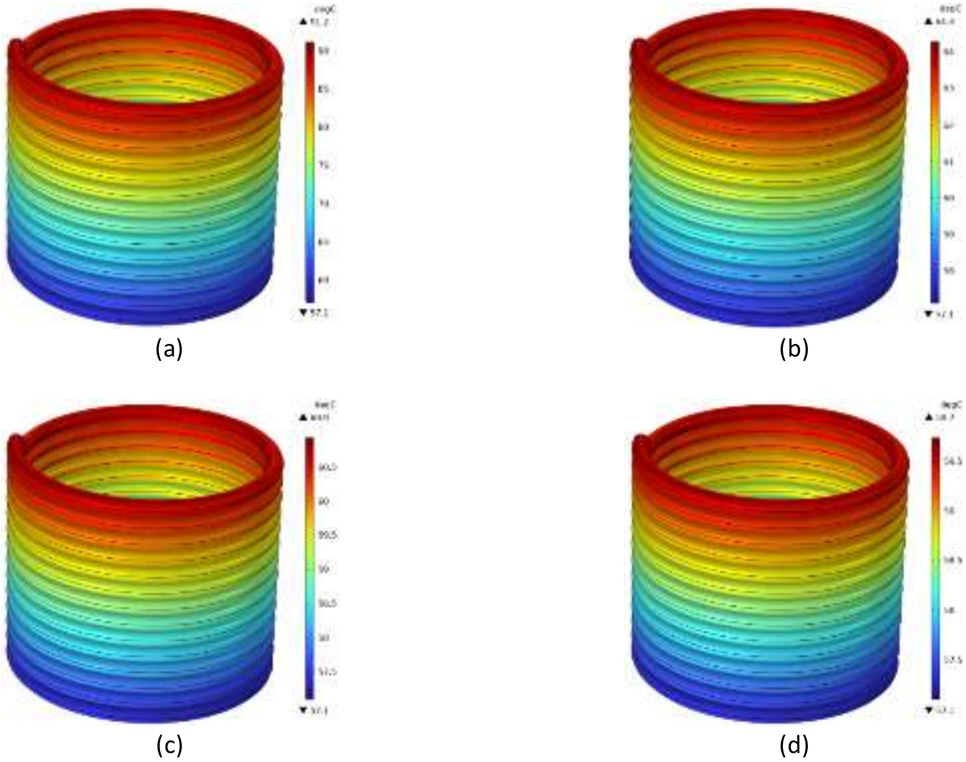

(ii)

Fig. 7. Temperature distribution contour for cylindrical cavity at two modes of **(i)** oil and **(ii)** water when a) 10 ml/s, b) 50 ml/s, c) 90 ml/s and d) 130 ml/s at 11:30

4. Conclusions

This study conducted a comprehensive CFD simulation to analyze the performance of solar dish concentrators equipped with different cavity receiver geometries, including cylindirical, cubical, and hemispherical shapes. The primary focus was to evaluate the thermal efficiency, and fluid flow dynamics of each receiver design under identical operational conditions. The simulation results revealed significant variation in thermal performance based on the geometry of the cavity receiver:

i) Cylindrical Receiver: Demonstrated a balanced performance with moderate heat absorption and retention. The cylindrical shape provided a relatively uniform temperature distribution but experienced higher thermal losses compare to the cubical and hemispherical designs.
ii) Cubical Receiver: Exhibited superior thermal efficiency with enhanced heat retention and minimal thermal losses. The cubical geometry facilitated effective heat transfer to the working fluid, resulting in higher overall efficiency. This design proved to be particularly effective in reducing convective and radiative losses.
iii) Hemispherical Receiver: Showed the highest heat absorption capability due to its large surface area exposed to concentrated solar radiation. However, it also experienced significant thermal losses, primarily due to its extensive surface area, which increased the potential for radiative losses.

The analysis underscores the critical role of cavity receiver design in optimizing the performance of solar dish concentrator systems. These findings provide valuable insights for the design and optimization of cavity receivers in solar dish concentrators, highlighting the potential for enhanced thermal performance through careful geometric considerations. Overall, this research contributes to the advancement of high-efficiency solar energy harvesting technologies, supporting the broader goal of sustainable energy solutions. The optimized designs and insights gained from this study can aid in the development of more effective solar dish concentrator systems, promoting the transition to cleaner a more sustainable energy sources.

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