REVIEW ARTICLE

Solar parabolic dish collector for concentrated solar thermal systems: a review and recommendations

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Abstract

Energy demand in the present scenario is rising to meet the increasing demands of energy usage. On the other hand, the use for renewable energy sources now becomes essential to mitigate the climate change as well as to reduce gradual depletion of fossil fuels. Among these renewable energy sources, solar energy particularly solar thermal systems have phenomenal scope in present and future research. In solar thermal systems, concentrators are used to extract the energy from solar irradiation and convert it into useful form. Among different types of solar concentrators, the parabolic dish solar concentrator is preferred as it has high efficiency, high power density, low maintenance, and potential for long durability. In this paper, a detailed review has been carried out on the design parameters like focal length, concentration ratio, and rim angle of the parabolic dish solar concentrator system for achieving higher overall efficiency. The effects of different geometrical shapes of receivers on the overall heat transfer rates are discussed in this paper. Conical shaped receiver is having high overall optical and thermal efficiency comparing with other shapes of receivers. This study also shows that how the thermal performance of the receiver gets enhanced by 10–13% using nanofluids in place of general heat transfer fluids. The paper highlights different models using ray-tracing method for estimation and evaluation of the solar irradiation distribution on the receiver surface. The empirical relations for the design of parabolic dish solar concentrator system are derived for estimating overall concentrator efficiency and heat available at the receiver are given in this review. From the literature, the thermal performance of the receiver affecting the overall performance of the system is observed. Thermal losses due to geometrical properties and ordination of the receiver are explained in the observation section.

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Highlights
Illustrious review has been carried out on the parabolic dish solar concentrator (PDSC) system for achieving higher overall efficiency. The following points are discussed in details
1. Optimization criteria of geometrical and optical parameters for PDSC to enhance the efficiency.
2. Effects of different geometrical shapes of receiver on thermal performance of the receiver.
3. This study also includes that how the outlet temperatures at receiver get enhanced by use of nanofluids to maximize the overall efficiency.
4. The paper also highlights different models using ray-tracing method for estimation and evaluation of the solar irradiation distribution on the receiver surface.
5. The empirical relations are also derived for estimating overall concentrator efficiency and heat available at the receiver considering heat losses through conduction, convection, and radiation modes.

Extended author information available on the last page of the article

Introduction

Solar energy resource is one of the best alternatives to non-renewable energy resources. There are many ways to extract solar energy in which solar concentrated thermal energy is one way. Concentrated solar energy is an alternative source for thermal applications with high temperatures like solar cooling, solar cooking, desalination and power generation. To collect solar thermal energy solar concentrators are used namely parabolic trough collector, parabolic dish collector, linear Fresnel collector, and heliostat field–central receiver collector (Manuel Blanco n.d.), see Fig. 1. This review discuss about parabolic dish solar collector (PDSC). PDSC uses concentrating solar irradiation at a focal point technology, where the output of PDSC is coupled with a number of useful applications. PDSC has higher concentration ratios (1000–3000) when comparing with other concentrating technologies (A. Kalogirou. 2018). Considering
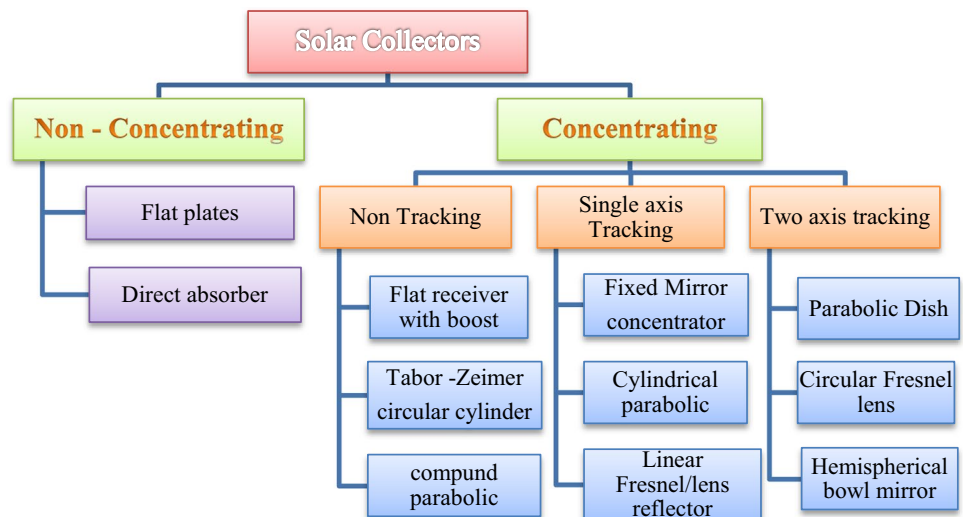
the design of the PDSC system, we can see from Fig. 2a, b that this system has three main components which are concentrator, receiver, and tracking system. Concentrator is used to extract the solar irradiation and concentrate it at a focal point. This concentrator is in parboiled shape and it is made with a reflected material on its front face of the body. Receiver is used to convert the concentrated solar energy into desired form of energy like electrical energy or mechanical energy. Currently active research is being done in different designs of receivers. Solar tracking system tracks the position of sun and improves the efficiency of the collector system by extracting more solar irradiation. This tracking system is used for tracking the sun by day wise and season wise. There are two types of tracking system available in the present market: one is single axis tracking system and the second one is dual axis tracking system.

Poulliklas et al. (2010) reviewed installation of solar dish technologies in Mediterranean regions for power generation. Loni et al. (2020) reviewed solar dish concentrator performance with different shapes of cavity receivers and nanofluids experimentally. Hafez et al. (2017) made a fundamental study of the solar parabolic dish systems to investigate the working principles and descript worldwide. Poullikkas et al. (2010) carried out a study which helps to install solar dish plant in the Mediterranean region. This work gives a feasible result for installation based on the availability of solar potential in the Mediterranean region.

In this paper, our review is presented in the following ways:

Experimental and numerical analysis studies of PDSC.
Mathematical modelling for PDSC.
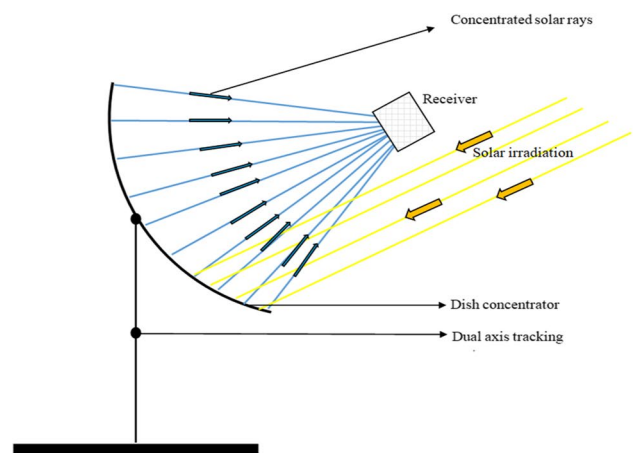
(a)

(b)

Fig. 2 **a** Parabolic dish solar concentrator model. **b** Euro dish stirling parabolic dish collector (Hafez et al. 2017)

Literature review

This review aims to give an overall view on PDSC design, as well as the behavior of different shapes of receivers and an overview of research being done on new research in heat transfer fluids used in the receiver to retrieve thermal energy and its impact on the performance of dish solar concentration system.

This review will stand out from other reviews which are focused on concentrating solar energy because it only aims on experimental and numerical works done on parabolic dish solar collector. (a) Various geometrical shapes of receivers used in PDSC and their efficiency with respect to the design and shape of the receiver has been discussed. (b) To find out the heat flux distributed on the receiver inner surface is analyzed using ray-tracing methods. Various ray-tracing methods followed in the previous research are reviewed. (c) Mathematical formulation has been done to find out the optimum design of PDSC and also to find the maximum efficiency of the receiver and heat flux generated at focal point of PDSC. The main highlight of this review is that it has covered maximum number of works in the literature that have been done on PDSC system. It also focused on the applications that are using PDSC as a heat source for their applications. This review can help in designing PDSC system with maximum efficiency of its kind.

Numerical and experimental studies of PDSC

Numerical works done on PDSC design from the researches are huge in number; some of the works related to numerical and experimental studies are discussed in this literature. Castellanos et al. (2017) proposed a methodology to characterize the control system of solar tracking and suggested the appropriate dish angle which proceeds to improvement in heat flow over the receiver cavity. They also developed an algorithm for the sizing and to determine Opto—geometric parameters which affect the overall efficiency. Hafez et al. (2016) used Matlab software to model and simulate different parabolic dish Stirling engine designs and to give theoretical guidance. They also studied about the features affecting dish design like reflector material, reflector shape, and receiver diameter. Some other factors like aperture area and focal length of the concentrator, concentration ratio, and rim angle and sizing of the receiver's aperture area. Ruelas et al. (2013) developed a new mathematical model and applied it for estimating intercept factor for Scheffler type solar concentrator (STSC) based on optical behavior and geometry of the concentrator in Cartesian coordinates. Comparing the results, they concluded that concentration is the same for STSC and PDSC at 45° rim angle. Azzouzi et al. (2015) used heat equation to develop a model and predict the heat

flux and temperature distribution at the focal zone. Using Soltrace code, they noted that the predicted and experimental results are in good agreement. Pavlović et al. (2016) had done optical and thermal analysis to find out the ideal position of the receiver from the concentrator to maximize optical efficiency and to improve the flux distribution on the receiver. They observed that temperature achieved in the receiver depends on the heat flux distribution on the receiver. Beltrán-Chacon et al. (2015) simulated a power generation system with a dish concentrator and cavity receiver; by using variable dead volume, they proposed a control system which influences the mechanical performance.

Alarcon et al. (2013) developed a PDSC prototype for rural areas having high solar resources in Columbia. They have done theoretical analysis, structural design, and manufacturing of PDSC. Kaushika and Reddy (2000) et al. presented the design and development of a low-cost solar stem generation system and analyzed performance characteristics of the system. They have done a cost analysis and preliminary field measurement. Li and Dubowsky (2011) developed a new concept to design and fabricate a large parabolic dish concentrator. They used thin optimal-shape flat metal plates of high reflective surface, to optimize shape and thickness of these metal plates based on analytical model. Shanmugam et al. (2011) modelled PDSC-driven thermoelectric power generator through a set of mathematical equations derived from the first law of thermodynamics. This model helps to solve the set of design and operating parameters. Gholamalizadeh and Chung (2017) mathematically modelled a dish Stirling system to improve its performance by taking design factors into account. They developed a thermodynamic model to predict the thermal efficiency of the system, and also analyzed the performance of the system. Results show in the middle of the June month with improved concentration ratio of 2499.88 the system performance is increased by 1.66 times comparing with original Kerman pilot. Wu et al. (2010a) proposed a parabolic dish/AMTEC (alkali metal thermal to electric converter) solar thermal power system and evaluated its performance of overall thermo-electrical conversion. On the other hand, a theoretical analysis is undertaken by varying the relative parameters like average operating temperature and performance parameters. Mohammed (2013) designed and developed a domestic parabolic dish heater for water applications. Sun tracking system is developed for effective performance and an automatic electric control system is also developed to eliminate the monitoring of humans. Thakkar (2015) have used mathematical model to develop a performance analysis methodology for PDSC system used for heating heat transfer fluid for process heating application. Using the results they suggested using glass cover over the receiver decreases the convection heat transfer losses. Affandi et al. (2014) modelled and designed

a concentrator with a 1 kW parabolic dish system in the Malaysia environment using Matlab Simulink. A methodology is proposed for development of higher efficiency concentrator.

Palavras and Bakos (2006) used an old satellite dish to develop a dish concentrator and polymer film used as a reflecting surface. They analyzed performance characteristics, used for zeolite desorption as an application of this dish concentrator. Ngo (2013) evaluated actual exergy available from PDSC by carrying out an exergetic and optimization analysis. For this analysis, they took incident solar irradiation into consideration and concluded that exergy efficiency increases with an increase in receiver temperature to an optimum and then efficiency starts decreasing. Zanganeh et al. (2012) proposed the design of PDSC with polyester mirror membrane facets. Using Monte Carlo ray-tracing technique, focal point and flux distribution of PDSC are found. Through maximum solar flux distribution at focal point optimization of the membrane deflection is concluded. Yosra et al. (2013) developed a model to design a PDSC system as per the environmental conditions of Tunisia. Mathematical and thermal models of the receiver are numerically validated based on the experimental measurements. Sup et al. (2015) had done a numerical study on geometry and flux distribution and the focal region of a PDSC. In this study, they concluded that to find out the imaging and non-imaging diameter of the flux distribution rim angle of dish concentrator is an important parameter. To find flux distribution by they used ray-tracing simulation and 2D designing method. Beltran et al. (2012) proposed a procedure to develop a graphical method for designing a dish concentration system. To describe the optical behavior, thermal behavior due to climatic variables, and parametric study of the main geometry of PDSC, a mathematical model is also presented. Pavlovic et al. (2014) explained a procedure to design square facet concentrator on a small laboratory scale which is useful to the thermal process for medium temperature applications. A system performance model is generated using ray-tracing method. The optical performance of the concentrator is analyzed using the Monte Carlo ray-tracing method.

The summary of these theoretical and experimental studies in designs is given in Tables 1 and 2.

Numerical and experimental studies of receiver

In PDSC system receiver is the main component where the total heat flux is concentrated and converted into a useful energy form. Enormous works have been done on receiver design and analysis; Loni et al. (2019b) used cavity receivers with three different shapes as seen in Fig. 3 to run the organic Rankine cycle (ORC), also used three different nanofluids to increase the efficiency of ORC. Using experimental data a numerical model is validated. They concluded that by

the evaluation of the results cubical shaped receiver can be the option for ORCs heat source. Daabo et al. (2020, 2017a, b, 2018, n.d.) studied and examined open cavity receivers with different arrangements using ray-tracing methods, 3D simulation is carried out to evaluate the performance of three different cavity receivers circuited with Brayton cycle for domestic applications. Azzouzi et al. (2017) has done an experimental study on cylindrical cavity receiver and analytical study on parameters affecting thermal efficiency and total heat loss of cavity for a given angle. Daabo et al. (2016a, 2016b) further studied about the behavior of heat flux distribution and optical efficiency of three different shapes of receivers using ray-tracing and computational fluid dynamics software as seen in Fig. 4. From the results, they concluded that conical shaped receiver reached maximum efficiency and good flux distribution for all the focal lengths compared with other shaped receivers. Idlimam et al. (2019) used Comsol Multi physics simulation software to examine the thermal behavior of PDSC with different shapes of the receiver. This software uses a finite element method to analyze heat flux distribution and temperatures on the internal surface of the receiver. They observed that receiver with conical geometry has high internal energy and temperature than other geometries.

Kumar and Reddy (2010) have done a numerical study on the modified cavity receiver heat losses considering for radiation and natural convection process using computational fluid dynamics. Karimi et al. (2018) proposed and developed a comprehensive mathematical model for a cylindrical cavity receiver. This model main approach is towards the non-isothermal internal walls of a cavity receiver. Considering the results author suggested that receiver should be designed as per the concentrating capacity of the dish collector. Madad et al. (2015) have done experimental and theoretical work on cylindrical cavity receiver to investigate heat losses. Different parameters affecting receiver's efficiency is analyzed. From the results they observed that heat loss due to radiation is low compared to heat loss due convective which is less than 10%. Loni et al. (2018e; Loni et al. 2018f) used nanofluids as heat transfer medium in a hemispherical cavity receiver to examine the behavior of the nanofluids on improving the thermal performance of the cavity receiver. They observed that using nanofluids increased thermal performance by 13%. Loni et al. (2018d) used a mathematical model to validate the experimental results obtained from cavity receiver with hemispherical shape. They also compared hemispherical, cubical, and cylindrical receivers under the same experimental working conditions like volumetric flow rate and solar irradiation. From the results, cubical cavity receiver experiences high pressure drop compared to other receivers. In another research, Loni et al. (2018a, b, d, e, f) tested experimentally wounded cylindrical cavity receivers with MWCNT

Table 1 Theoretical studies in design and development of PDSC

Authors	Study	Investigation system	Research goals	Results
Castellanos et al. (2017)	Theoretical	Dish/Stirling	Suitable design to obtain desired heat at the receiver	Maximum thermal efficiency of 68% and maximum surface temperature of 1596 K is obtained at receiver for 10.5[m] diameter of concentrator
Hafez et al. (2016)	Theoretical	Dish/Stirling	Design for optimum power output of dish/Stirling system	Selecting the optimal concentrator diameter based on the material used for the concentrator, for Polished stainless is 6.06[m], Polymeric film is 8.48[m]
Pavlović et al. (2016)	Numerical	Spiral coil/absorber	Optical and thermal analysis of PDSC	Ideal position of the receiver for uniform flux distribution is analyzed, which is 2.1 [m] slightly lower than focal point
Beltrán-Chacon et al. (2015)	Theoretical	Dish/Stirling	Analysis of parameters influencing mechanical properties of the system	Designed a PDSC system with increase of 23.38% in net effective solar conversion to electric
Shanmugam et al. (2011)	Theoretical	Thermo electric generator	Design of thermo electric generator driven by PDSC	Maximum thermal efficiency obtained by the system is 48–60% at irradiation of 1200 W/m^2
Wu et al. (2010a)	Theoretical	Dish/AMTEC	Evaluation of thermal power	At an operating temperature of 1280 K systems conversion efficiency attained up to 20.6%
Thakkar (2015)	Theoretical	Dish collector	Performance analysis of PDSC	Designed a performance analysis methodology for thermal fluids used in process application
Affandi et al. (2014)	Theoretical	Dish concentrator	Methodology for designing concentrator	Aluminum is one of appropriate concentrator material which is effective and low cost
Ngo (2013)	Theoretical	Dish concentrator	Finding actual exergy available at dish concentrator	Used expression of exergy efficiency to investigate optimum design and operating conditions for exergy distraction and losses in the receiver
Yosra et al. (2013)	Theoretical	Dish concentrator	Designing a dish concentrator for a given environmental conditions	With a rim angle of 45° maximum concentration at focal point is achieved
Sup et al. (2015)	Theoretical	Dish concentrator	Flux distribution at the focal radius	Imaging diameter is ranging from 17 to 286 mm and nonimaging diameter is ranging from 23 to 345 mm
Beltran et al. (2012)	Theoretical	Dish/Stirling	Optical behavior of parabolic dish	Errors observed by comparing theoretical and experimental results. Error in radiation loss is 14% and remaining thermal losses is 3%

**Table 2** Experimental studies in design and development of PDSC

Authors	Study	Investigation system	Research goals	Results
Azzouzi et al. (2015)	Experimental	Dish/Stirling	Optimization study	Theoretical and experimental value of focal length is close to each other with a value of 52.75[cm] and max temperature attained 1118 °C
Alarcón et al. (2013)	Experimental	Solar cooker	Developing a prototype of PDSC	Suggested AISI 430 material for construction of concentrator also recommended using laser cutting or water cutting for this material
Kaushika and Reddy (2000)	Experimental	Solar steam generator	Design and development of low-cost solar steam generator	Developed a system with a cost of Rs 8000–9000/m² with a conversion efficiency of 70–80%
Mohammed (2013)	Experimental	Dish/water heater	Design and development of a solar water heater	Overall performance solar water heater is satisfied with thermal efficiency of 52–56%
Palavras and Bakos (2006)	Experimental	Dish concentrator	Developing low cost dish concentrator	Design of low cost is achieved with a cost of 86 €/m² compared with same model used in previous literature

nanofluids to observe the performance of the receiver cavity. Experimental results show that thermal efficiency during day time varies from 54 to 64%. Pavlovic et al. (2017b) examined the spiral absorber receiver of the parabolic dish concentrator experimentally. They developed a model using Engineering Equation Solver to investigate numerically and also used OptisWorks software to explain the solar ray distribution on the helical coil and also inside the heat transfer fluid. Pavlovic et al. (2018a, b) used a thermal model to investigate spiral and conical cavity receivers. They used different operating temperatures and flow rates to analyze the optical, thermal, and exergetic performance of both the receivers. They also developed a thermal model to validate spiral absorber with experimental results. Pavlovic et al. (2017a, b) examined a simple low-cost PDSC with spiral absorber; three different working fluids are validated using Engineering Equation Solver for various operating conditions like solar irradiation, volumetric flow rate, and ambient temperature. According to the results obtained from the experiment thermal efficiency of collector is observed as 35%. Kumar and Reddy (2008) Reddy and Sendhil Kumar (2008) numerically investigated the performance of cavity receiver, semicavity receiver, and modified cavity receiver for natural convection heat losses. They varied the inclination angle from 0° to 90° and natural convection heat loss from the receiver is estimated.

Soltani et al. (2019) studied helically baffled cylindrical receiver experimentally and numerically; they used Soltrace software to find out the flux distribution on the receiver and ANSYS tool for CFD analysis. Results shows that the thermal performance is increased up to 65% with the optimal selection of parameters for the experimental setup. Stefanovic et al. (2018) investigated parametrically to find out the optimum operating conditions of spiral-coil absorber

Fig. 3 Wounded cavity receivers with cylindrical, cubical, and hemispherical shapes (Loni et al. 2020)
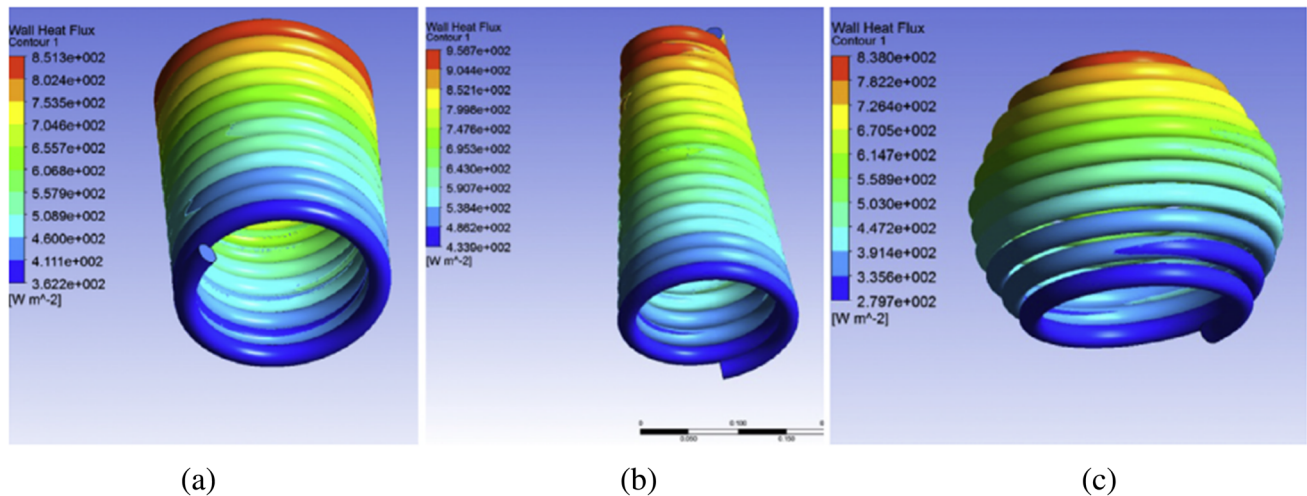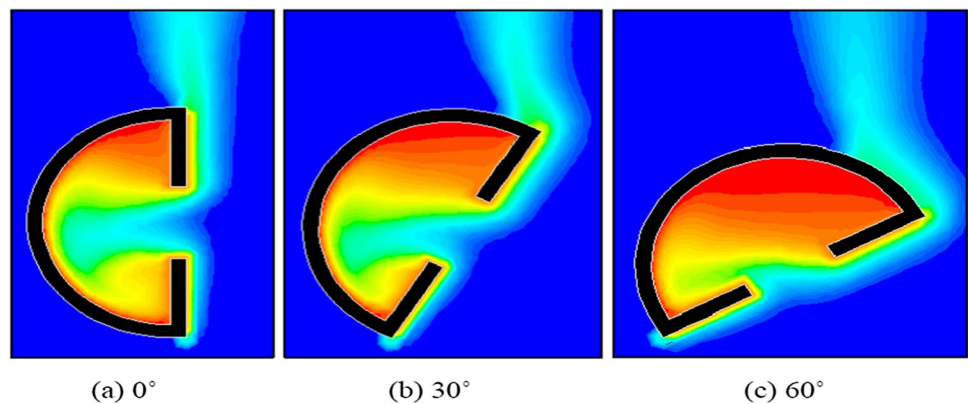

(a)　　　　　(b)　　　　　(c)
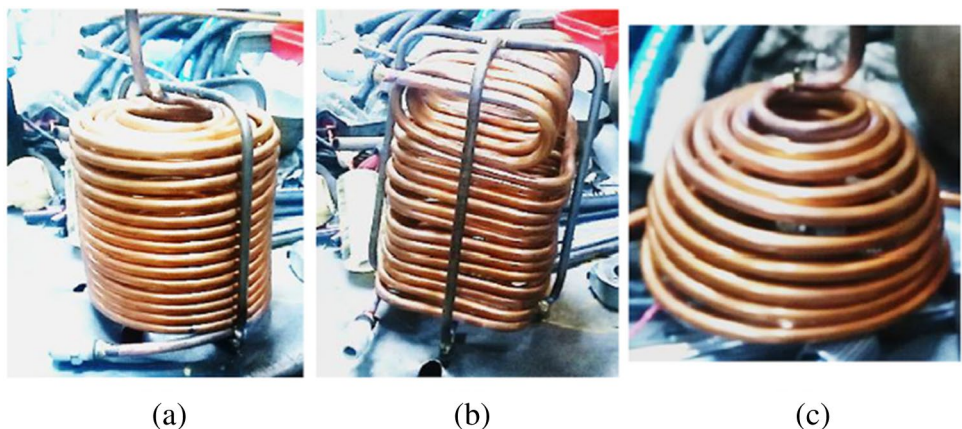
Fig. 4 Analysis of flux distribution on the cavity receivers using ANSYS/Fluent (Daabo et al. 2016b)

Fig. 5 Temperature distribution for different inclinations in modified cavity receiver (Kumar and Reddy 2006)

using Engineering Equation Solver. Optimum temperature and optimum flow rate for the fluid are 212 ℃ and 314.6 L/h. Uzair et al. (2018) worked on the dish cavity receiver to find out conditions of forced convection on the dish cavity receiver. They estimated the convective heat losses from the cavity receiver by performing numerical simulation using ANSYS CFX at various wind direction and orientation of the cavity receiver. They observed that the orientation and position of the receiver will affect the performance of the cavity receiver. Zou et al. (2017) used a finite element method in ANSYS to find out the effect of aperture diameter and cavity length numerically. They considered convection and radiation losses to this process. From the results, they observed that increase in aperture diameter of the receiver will increase in combined heat loss from the cavity receiver. Loni et al. (2018g) developed a numerical thermal model to validate experimental results of the spiral cavity receiver used nanofluids in the receiver as heat transfer fluid. From the results we can estimate proper water based nanofluid with thermal and exergetic criteria. Kumar and Reddy

(2006) used CFD and Fluent software as seen in Fig. 5 for numerical study of combined laminar natural convection and surface radiation of a 2D modified cavity receiver used in PDSC. Correlation with Nusselt number for natural convection and radiation is developed for practical interest.

Loni et al. (2018c) investigated the cubical and cylindrical shaped cavity receiver and developed a numerical model to predict the receiver performance and also observed experimental data is complementing the numerical results. Jilte et al. (2014) investigated convective heat loss from the cavity receiver of different shapes using a normal 3D model under different wind conditions. From the results they observed that for head-on wind condition convection heat loss are high. Prakash et al. (2010) have done numerical and experimental studies to point out the stagnation and convective zone of the receiver with different orientations of the receiver. They observed that convection zone is high at 0° inclination and least at 90° inclination. Shuai et al. (2008) introduced a model effect of the sun shape on the distribution of radiation flux on the receiver using the Monte

Table 3 Theoretical studies on receivers used in PDSC

Authors	Study	Investigation system	Research goals	Results
Daabo et al. (2017a)	Theoretical	Different shapes of cavity receivers	Flux distribution and optical losses for different cavity receiver	Pitch value for the cavity tubes to be 0.5D for better optical and thermal performance
Dabbo et al. (2016a)	Theoretical	Different cavity receivers	Optical efficiency and flux distribution in receiver with different geometries	Optical efficiency of conical receiver is high compared to other receiver at 85% absorptivity
Dabbo et al. (2016b)	Theoretical	Different cavity receivers	Optical efficiency and flux distribution in receiver with different geometries	Conical shaped receiver absorbed more amount of het flux about 91% compared to other shaped receivers
Idlimam et al. (2019)	Theoretical	Different cavity receivers	Flux distribution, temperature on the surface of the receiver with different shapes	Conical shape gives better thermal performance with a maximum surface temperature of 250 °C
Kumar and Reddy (2010)	Theoretical	Modified cavity receivers	Convection and radiation heat loss from receiver	Convection and radiation heat loss are affecting by the parameters like Grashof number, angle of inclination, temperature ratio and diameter ratio
Pavlovic et al. (2018a, b)	Theoretical	Different cavity receivers	Comparing conical and spherical cavity receiver	Maximum thermal efficiency of conical receiver is 85.21% and spiral receiver with 84.06%
Reddy and Sendhil Kumar (2008)	Theoretical	Modified cavity receiver	Surface radiation and laminar natural convection behavior in modified cavity receiver	Convection heat loss significantly influencing by inclination of the receiver and radiation loss affected by surface properties
Sendhil Kumar and Reddy (2008)	Theoretical	Different cavity receivers	Convection heat loss in different type of cavities	For modified cavity receiver convection heat loss at 0° and 90° are respectively 26.03% and 25.42%
Stefanovic et al. (2018)	Theoretical	Cylindrical cavity	Optical and thermal behavior of cylindrical cavity	Geometrical, optical, and structural parameters of the system are influencing thermal performance of the system
Uzair et al. (2018)	Theoretical	Cavity receiver	Convective heat loss from the cavity receiver in different modes	Orientation of the dish concentrator effects convective heat loss from the cavity receiver
Zou et al. (2017)	Numerical	Cylindrical receiver	Thermal performance effect with respect to geometrical parameters of the receiver	With increase in the diameter of the receiver thermal loss from the receiver is increasing
Kumar and Reddy (2006)	Theoretical	Modified cavity receiver	Heat transfer in receiver by convection and radiation	Convective heat loss in the receiver depends on the orientation of the cavity receiver and radiation heat loss is independent of cavity receiver's orientation
Jilte et al. (2014)	Theoretical	Different cavity receiver	Heat loss in cavity receiver with different wind condition	With the help of cavity inclination in wind and no-wind conditions we can reduce effect of convective heat loss

Carlo ray-tracing method. Wang et al. (2013) tried to solve the problem of dead space in the receiver by designing two new cavity-type receivers and analyzed to investigate the flux distribution on that cavity receiver using Monte-Carlo ray-tracing method. Zheng et al. (2017) introduced a new method to put different porous medium in the receiver tube to enhance convective heat transfer and also numerically investigated heat flux distribution. From the results, they observed that due to better heat transfer enhancement property, enhanced receiver tubes (ERTs) with porous inserts are used to avoid the hotspots in the receiver caused by non-uniform flux distribution.

A summary describing the design and analysis of the receiver cavity used in PDCS based on numerical and experimental work is given in Tables 3 and 4.

Nanofluids used as working fluids

To increase the thermal efficiency of PDSC, nanofluids are generally introduced in spite of heat transfer fluids like water and oil. Researchers are concentrating on this area to estimate the increase in thermal efficiency by numerical and experimental works. Loni et al. (2018a, b, d, e, f) used MWCNT/oil nanofluid as seen in Fig. 6 in PDSC with hemispherical, cylindrical cavity receivers and observed the efficiency increased using nanofluids. Results show that efficiency increase to 12.9% using MWCNT/oil nanofluid. Pavlovic et al. (2018a) have done experimental work using thermal oil and water dispersed with nanoparticles like Al_2O_3, Cu, CuO, and TiO_2 up to 5% concentration ratio. Evaluation of thermal losses and pressure losses are evaluated exergically. With the observed results, they concluded that oil-based nanofluids have high thermal performance. Loni et al. (2017, 2018b; 2019a) used nanofluids as a working fluid in the cavity receiver of a dish concentrator. They used four different types of nanofluids with 0 to 5% of nanoparticle concentration and showed explained that thermal efficiency decreases with an increase in nanoparticle volume concentration. In another research, they investigated experimentally two oil-based nanofluids namely alumina/oil and silica/oil in cylindrical receiver of dish concentrator system as seen in Fig. 7. They examined the performance of these two nanofluids exegetically and energetically at steady-state conditions. As per the results, the performance of alumina/oil nanofluid is better than silica/oil nanofluid. They also investigated to select the appropriate cavity receiver shape to solar dish concentrator with nanofluids as heat transfer fluids.

Three different cavity receivers are tested by them with alumina/oil nanofluid, and thermal analysis is done using first law and second law of thermodynamics. Results showed that efficiency and outlet temperature increases with a decrease in Al_2O_3 particle size and an increase in the concentration ratio.

In other papers, Chandrashekara and Yadav (2017) used exfoliated graphite coating on the receiver in place of nanofluids for Sheffuler dish concentrator to increase the performance of the concentrator. From the results, they concluded that system performance was enhanced up to 40% by using exfoliated graphite coating on absorber plate. Pakhare et al. (2018) investigated the experimental performance of PDSC using nanofluids under various operating conditions. The results showed that the temperature increase in water storage tank was raised by about 5ºC when Al_2O_3 nanoparticle is used in the receiver. Loni et al. (2019b) investigated experimentally to find out the increase in efficiency using nanofluids in PDSC as a heating source to the organic Rankine cycle. Three different nanofluids Al_2O_3/oil, CuO/oil, SiO_2/oil are used and three shapes of receivers are compared with different inlet temperatures and fixed fluid flow rates. From results, a little increase in thermal efficiency and also increase in pressure drops are noticed marginally. Khan et al. (2019) and Bashir et al. (2020) investigated the energy and exergy performance of PDSC with cavity receiver and nanofluids as working fluid in the receiver. Three different thermal oil-based nanofluids are investigated for various operating conditions like solar irradiation intensity, wind speed, ambient and inlet temperatures, flow rate, and nanoparticle concentration. Results show that Al_2O_3-based nanofluid has high thermal and exergy efficiency. Alnaqi et al. (2021) used three different nanofluids where the base fluid is thermal oil and MWCNT-Mgo as nanoparticles in the fluid. It is observed that using nanofluid in place of base fluid increases the energy efficiency by reduction in the pressure drop penalty. Aslfattahi et al. (2021) examined soybean oil-based MXene nanofluid in PDSC with different geometrical shaped receivers. They considered these nanofluids based on the thermal properties like high thermal conductivity and heat capacity. Results show that receiver with hemispherical shape gives best thermal efficiency with respect to the nanofluid used as working fluid. Ouyang et al. (2021) investigated performance of PDSC and flat plate solar system using MWCNT nanoparticles with different working fluids. In the same way, Zayed et al. (2021) used thermal oil-based MWCNT in their research work where they developed three types of algorithm fuzzy information systems to predict the temperature difference of the working in the cavity receiver. Abid et al. (2016) used nanofluids in two different solar collectors for the exergy and energy analysis. Parabolic dish and parabolic trough contractors are compared for different operating conditions with alumina oxide and ferric oxide-based nanofluids. As the results revealed, the parabolic dish collector has high overall performance using nanofluids.

Table 4 Experimental studies on receivers used in PDSC

Authors	Study	Investigation system	Research goals	Results
Loni et al. (2019)	Experimental	Different shapes of cavity receivers	Cavity receiver shape affecting the efficiency of PDSC	Cubical cavity receiver has more out let temperature and thermal efficiency compared to other shaped receivers so cubical receiver is good choice as a receiver for PDSC
Azzouzi et al. (2017)	Experimental	Cylindrical cavity receiver	Convection and radiation heat losses at receiver	Predicted heat loss from the receiver and thermal efficiency of the receiver is found as 12%
Madadi et al. (2015)	Experimental	Cylindrical cavity receiver	Heat loss from the cylindrical cavity	Radiative heat loss in the cylindrical cylinder is less than 10%
Loni et al. (2018d)	Experimental/numerical	Different cavity receivers	Suitable receiver cavity for specific solar dish concentrator	For high temperature thermal applications hemispherical receiver with thermal oil is best suitable
Loni et al. (2018a, b,d, e, f)	Experimental	Cylindrical cavity receiver	Thermal efficiency prediction for cavity receiver	Using thermal oil with nanofluids thermal efficiency of cavity receiver is increased by 13.12%
Pavlovic et al. (2017b)	Experimental/numerical	Spiral cavity receiver	Solar irradiation distribution on the receiver geometry	Helical conical receiver with aperture an area of 0.01606 m^2 absorbed heat flux with a value of 2.6×10^5 W/m^2
Karimi et al. (2018)	Experimental/numerical	Cylindrical cavity receiver	Investigation of thermal performance	Maximum thermal efficiency observed for the receiver with aperture area 0.2 m is 90%
Pavlovic et al. (2017a)	Experimental	Spiral cavity receiver	Finding suitable working fluid for heat transfer	For low-temperature application water is suitable as a working fluid
Loni et al. (2018a, b, c, d, e, f, g)	Experimental	Cubical and cylindrical receiver	Optimization of cubical and cylindrical receiver shapes	Cubical cavity receiver is having high heat gain and thermal performance comparing with cylindrical cavity receiver
Prakash et al. (2010)	Experimental/numerical	Cavity receiver	Identifying focal zone in the cavity receiver	Convection zone in receiver will appear least with 90° inclination and high at 0° inclination

Fig. 6 **a** Microscopic view of MWCNT. **b** Prepared MWCNT nanofluid for testing (Loni et al. 2018a, b, d, e, f)
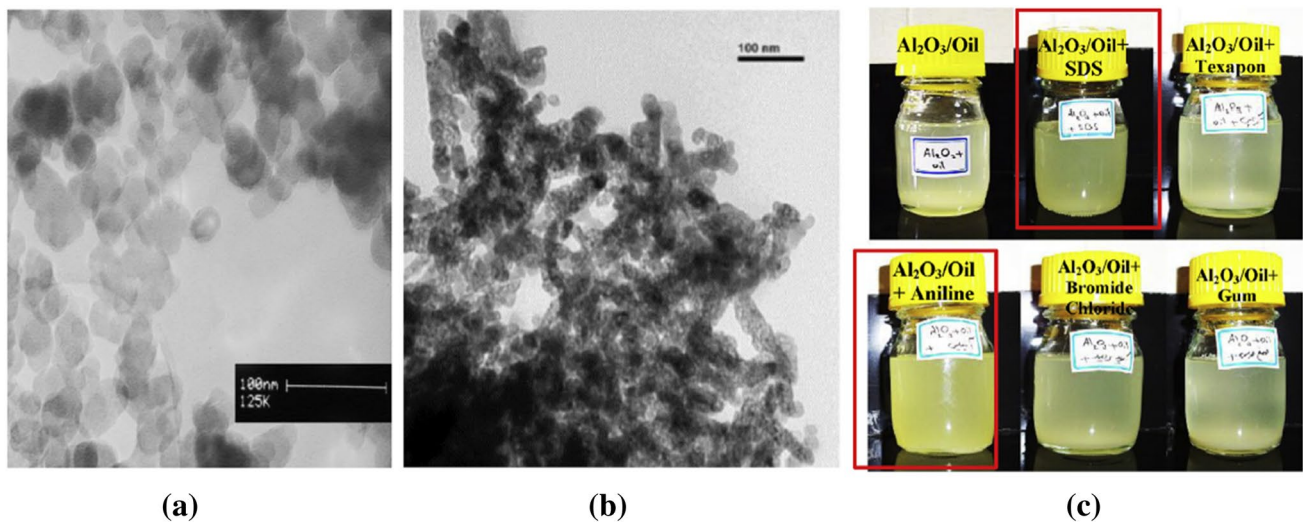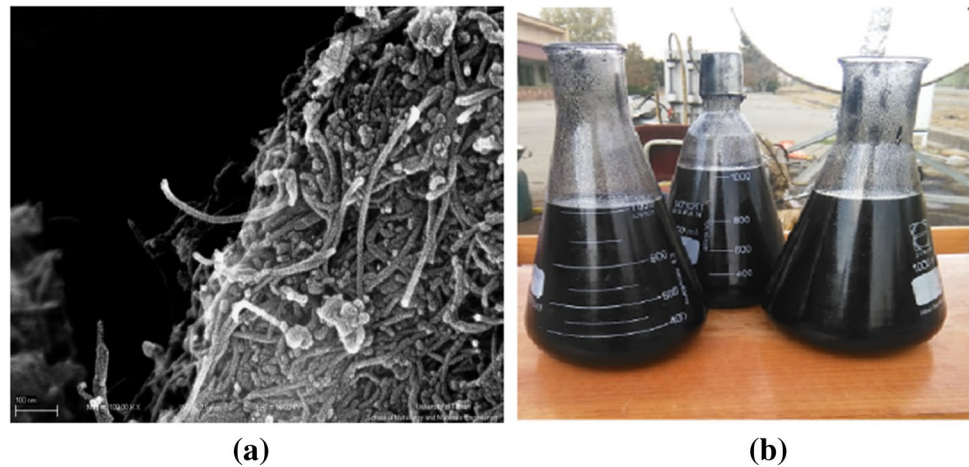

(a)

(b)

(a)

(b)

(c)

Fig. 7 TME view of nanoparticles. **a** Alumina. **b** Silica. **c** Al_2O_3/oil nanofluid with different surfactants (Reyhaneh Loni, Askari Asli-Ardeh, et al. 2019)

A summary of nanofluids used in theoretical and experimental studies of PDSC is shown in Tables 5 and 6.

Use of ray-tracing methodology in PDSC

To predict the optical behavior of the PDSC, there are some alternatives to the experimental work to cut the cost and make it more economical. Here, computational models play a key role to predict a wide range of alternatives. These computational models use the Monte Carlo method for ray tracing to estimate the flux distribution, mapping of radiance function at the input of receiver aperture. The summary of ray tracing methods used in PDSC is given in Table 7. In a ray-tracing model, bundle of photons are incident on the concentrating system, and thus, the surface absorbs the photons. By this flux distributed on the surface, the number of photon bundles absorbed per unit surface area of the concentrating system can be easily computed. Some of the works done by researchers on the ray-tracing model are described here. Azzouzi et al. (2017) developed an analytical model using a variable separable method based on heat equation to predict the temperature and heat flux distribution at the focal zone or solar image. The analytical and experimental models are computed using the Soltrace code, and the results are in good argument with each other. Sup et al. (2015) used Tonatiuh software as shown in Fig. 8a to study flux distribution at the focal region of the parabolic dish concentrator. They took the rim angle as a parameter to determine the imaging and non-imaging of the flux radiation. Daabo et al. (2017a) examined the open cavity receiver at different positions of the focal point for flux distribution on the internal walls of the cavity receiver. For this work, they used OptisWorks software based on Monte Carlo ray-tracing technique.

Table 5 Nanofluids used in theoretical studies of PDSC

Authors	Study	Heat transfer fluid used	Research goals	Results
Loni et al. (2017)	Theoretical	Al_2O_3, Cu, SiO_2, TiO_2 based thermal oil	Thermal performance of PDSC system	SiO_2/oil-based nanofluid has high thermal efficiency compared with other nanofluids
Loni et al. (2019)	Theoretical	Alumina/oil	Thermal performance of cavity receiver	By decreasing Al_2O_3 nanoparticle size and increasing concentration ratio thermal efficiency of the receiver is increasing
Loni et al. (2018a, b, d, e, f)	Theoretical	Al_2O_3, Cu, SiO_2/oil	Improving efficiency of dish collector	Thermal efficiency increased 2–3% using Al_2O_3/oil or CuO/oil nanofluids in ORC
Khan et al. (2019)	Theoretical	Al_2O_3, Cu, TiO_2/oil	Thermal analysis with nanofluids	Al_2O_3/oil nanofluid has high energy and exergy efficiency compared with other nanofluids
Alnaqi et al. (2021)	Theoretical	MWCNT-Mgo/thermal oil	Thermal analysis with nanofluids	Observed reduction in pressure drop and increase in the efficiency with the use of nanofluids

Table 6 Nanofluids used in experimental studies of PDSC

Authors	Study	Heat transfer fluid used	Research goals	Results
Loni et al. (2018d)	Experimental	MWCNT/oil	Effect of nanofluid on solar thermal performance	Using MWCNT/oil nanofluid thermal performance is increased up to 13%
Loni et al. (2018a, b, c, d, e, f)	Experimental	MWCNT/oil	Performance evolution of cavity receiver with nanofluid	Thermal performance of cavity receiver is increased by 13.12% after using nanofluinds in the receiver
Pavlovic et al. (2018a)	Experimental	Al_2O_3, Cu, CuO, TiO_2-based thermal oil/water	Effect of nanofluid as working fluid in PDSC	Water based nanofluids enhanced exergetic efficacy of the PDSC up to 14%
Loni et al. (2018f)	Experimental	Alumina, silica/oil	Thermal performance of cavity receiver	Compared with silica/oil nanofluid alumina/oil nanofluid has high cavity thermal efficiency
Pakhare et al. (2018)	Experimental	Al/water	Nanofluid effect on the performance of PDSC	Temperature output increased to 90 °C and thermal efficiency of the collector increased by 10%
Aslfattahi et al. (2021)	Experimental	MXene/soybean oil	Observation of nanofluids effect with respect to receiver shape	Hemispherical shaped receiver gives best efficiency with the use of nanofluids

Daabo et al. (2018, 2020) used OptisWorks software to determine the optical efficiency and flux distribution for three different geometries (cylindrical, conical, and spherical) of cavity receiver. They employed a 3D CFD model with the help of ray-tracing software to explain the optical and thermal behavior of the three shapes of receivers and also their flux distribution. Idlimam et al. (2019) examined how the receiver shapes are affecting the thermal behavior of parabolic solar collector for three different shapes of the receiver (cubical, conical, and cylindrical) using COMSOL Multiphysics simulation software works based on the finite element method. They analyzed flux distribution and temperature on the receiver with this software. Pavlovic et al.

(2017b) performed numerical simulation using OptisWorks ray tracing software as seen in Fig. 9 to analyze solar ray distribution inside the receiver geometry and also on the helical coils used inside the receiver. Soltani et al. (2019) used Soltrace to analyze real flux distribution on the surface of the helically baffled cylindrical receiver; to increase the accuracy of the results, ANSYS Fluent is used.

Shuai et al. (2008) introduced models that show the effects of sun shape and surface slope errors. The Monte Carlo ray-tracing method is applied for the dish solar concentrator/cavity receiver system to predict radiation performance. In other works, Sandoval et al. (2019) evaluated parabolic dish using Tonatiuh software applying Monte Carlo

Table 7 Ray-tracing models used in PDSC to find heat flux distribution

Authors	Study	PDSC diameter (m)	Solar irradiation (W/m^2)	Concentration ratio	Ray-tracing model	Rim angle (°)
Azzouzi et al. (2015)	Theoretical	0.14	965	4920	Soltrace	69.5
Daabo et al. (2016a)	Theoretical	1–3	500–1000	—-	OptisWorks	45
Daabo et al. (2016b)	Theoretical	1	514	—-	OptisWorks	15–90
Idlimam et al. (2019)	Theoretical	2	800	80	Meteonorm 7	45
Pavlovic et al. (2018a, b)	Theoretical	3.08	900	23.6	OptisWorks	45.6
Soltani et al. (2019)	Theoretical	2.88	500–1000	100–200	Soltrace	–-
Sandoval et al. (2019)	Theoretical	7.5	25–5000	—-	Tonatiuh	–-
Roux et al. (2014)	Theoretical	4.5	1000	—-	Soltrace	45
Loni et al. (2016)	Theoretical	1.6	650	—-	Soltrace	45
Roux and Meyer (2015)	Theoretical	2.4	747	—-	CFD	45
Li et al. (2016)	Theoretical	12.7	—-	—-	Monte Carlo	45.9
Yan et al (2018)	Theoretical	2.3	650–1000	270–1000	Tracepro	60

ray-tracing method to know solar irradiation distribution on the dish surface. Roux et al. (2014) determined the net heat transfer rate and temperature profile along the surface of the cavity shaped receiver tube using Soltrace software. Using this software, they found an optimum receiver to concentrator area ratio. Barreto et al. (2018) had done three-dimensional modelling and analysis of a porous volumetric receiver of PDSC using the Monte Carlo ray-tracing method. From the results, we can understand absorption distribution of energy on the receivers used in solar concentrator system. Qiu et al. (2015) used the Monte Carlo ray-tracing method on the air tube cavity solar receiver to simulate and evaluate flux distribution on each turn in helical coil tube and concentrated receiver energy distribution on the walls of the receiver. Loni et al. (2016) modelled and optimized a cylindrical cavity receiver in Organic Rankine Cycle using Soltrace software as shown in Fig. 8b and receiver modelling

technique. Optimum aspect ratio for receiver and concentrator is found using these modelling techniques.

Roux and Meyer (2015) had done analysis on a parabolic dish tubular cavity receiver using computational fluid dynamics. They solved the radiative transfer equation using the finite volume method and direct ordinate method to evaluate the optical performance and radiation absorbed by the receiver. Li et al. (2016) used the Monte Carlo ray-tracing method to analyze the optical performance of PDSC with a cavity receiver. This analysis is done to investigate geometrical and surface properties of cavity receiver and optical performance with various parameters. Daabo et al. (2017a, b) introduced various configurations of open cavity receivers of PDSC with three different shapes of the receiver (conical, cylindrical, and spherical). OptisWorks ray-tracing method and computational fluid dynamics simulation method are made for minimizing optical and thermal

Fig. 8 **a** Ray-tracing model using Tonatiuh (Sup et al. 2015). **b** Ray-tracing model using SolTrace (Qiu et al. 2015)
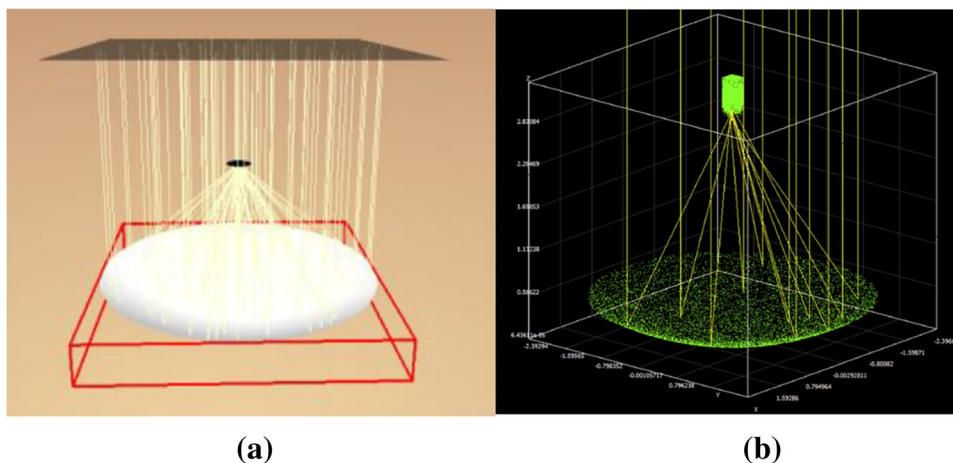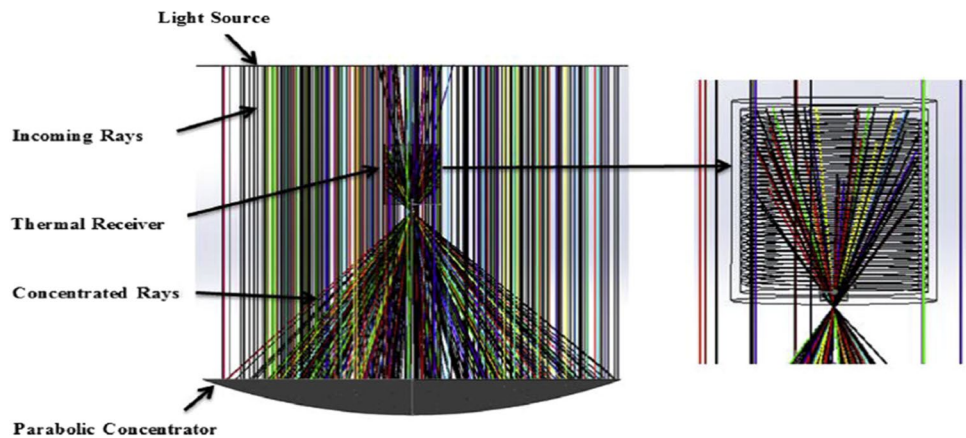
(a)　　　　　　　**(b)**

Fig. 9 Ray-tracing simulation using OptisWorks (Daabo et al. 2016a, 2016b)

losses and maximize output temperature of working fluid. Yang et al. (2018) Simulated cylindrical cavity receivers behavior with respect to influence of geometrical and optical parameters using MCRT and CFD to determine optical and thermal characteristics of the receiver. From the results, it is observed that with increase in the tube diameter optical and thermal efficiencies and conversion efficiencies are reduced. In mass flow rate above 0.03 kg/s, no significant effect can be observed in efficiency. Yan et al. (2018) developed a generic C^{++} program to optimize discrete solar dish concentrator with the help of ray tracing to homogenize the distribution of flux on the absorber surface.

Applications of PDSC

Application of PDSC in the present world has been enormous and a lot of work is being done by the researchers using this technology; Amin et al. (2016) used a solar dish concentrator designed with a cavity receiver as an energy receiving source to produce hydrogen by solid oxide electrolyzed cell. They concluded that the dish diameter of the concentrator affecting the cost of hydrogen production. Onokwai et al. (2019) designed and fabricated a parabolic dish solar cooker with cheap material available in Nigeria. The design of the cooker is validated at pressure 0.05 Pa for energy and exergy efficiency. Energy and Exergy efficiency of the cooker is noted as 39% and 44%. Bellos et al. (2019b) developed a trigeneration system driven with a dish collector. The system includes an organic Rankine cycle operating with toluene this is operated with medium temperature levels served by the dish collector. Sagade (2013) used the PDSC system for water heating for domestic applications. They conducted experimental analysis to compare the effect in variation in natural and convective heat loss of PDSC with receiver coated and non-coated. They achieved 63% instantaneous efficiency for coated receiver and 48% for non-coated receiver. Gavagnin et al. (2018) find an optimum design of solar micro turbine sourced with PDSC. The mean annual

conversion efficiency for base model is from 11 to 16%, and for advanced model, it is increasing by 14–19%. Javidmehr et al. (2018) analyzed economically and thermodynamically to optimize a multi-generation system using a solar dish collector, where the collector is used to increase compressed air temperature. Results reveal that the increase in diameter of the collector's aperture decreases exergy efficiency, fuel consumption, and a little increase in round trip efficiency of the whole system.

Roux and Meyer (2016) developed a solar thermal Brayton cycle mounted on a solar dish concentrator with a cavity receiver. Exergy analysis is done by them to determine power output from the system using an analytical model in Matlab software. Power output of the system is compared with Flownex, CFD software. From the results, they observed that there is 12% of efficiency increase in solar to mechanical conversion. Mohammadi and Mehrpooya (2018) had done analysis and optimization of an integrated system with a solar dish collector as energy input source, compressed air energy storage system, and a microgas turbine to observe energy output from the system. Reddy et al. (2013) modelled a parabolic dish Stirling engine solar power plant of 50 MW$_e$ and done analysis on this system to know the energetic and exergetic behaviour of different components in the system. Sandoval et al. (2019) developed a methodology used for evaluating the performance of a system composed with a Stirling engine and a solar dish concentration system. To evaluate the dish concentrator Tonathiuh software is used based on the Monte Carlo ray-tracing method.

Gholamalizadeh and Chung (2018) analyzed the thermal performance of receiver in the solar dish–Stirling engine system. Model is developed to estimate thermal losses, input energy, and thermal efficiency of the receiver, and validation of the receiver model is done with experimental results of the Euro Dish project. Barreto and Canhoto (2017) had done modelling and simulation of the Stirling engine system powered by a parabolic dish collector to determine the power generation and efficiency of the system. The model evaluated

Table 8 A summary of theoretical studies on PDSC applications

Authors	Study	PDSC diameter (m)	Solar irradiation (W/m²)	Application
Mohammadi and Mehrpooya (2016)	Theoretical	20	800	Hydrogen generations
Bellos et al. (2019a)	Theoretical	7.3	1000	Trigeneration system
Sagade (2013)	Theoretical	1.4	1000	Water heater
Gavagnin et al. (2018)	Theoretical	8	800	Micro turbine
Javidmehr et al. (2018)	Theoretical	10	900	Multigeneration system
Roux et al. (2016)	Theoretical	4.8	1000	Solar thermal Brayton cycle
Mohammadi and Mehrpooya (2018)	Theoretical	9	800	Microgas turbine
Reddy et al. (2013)	Theoretical	10.57	1000	Dish Stirling engine
Sandoval et al. (2019)	Theoretical	7.3	20–1500	Dish Stirling engine
Gholamalizadeh and Chung (2018)	Theoretical	3	—–	Dish Stirling engine
Dähler et al. (2018)	Theoretical	4.4	—–	Thermo-chemical redox cycles

the heat transfer rate of thermal receive, the concentration of solar radiation and the conversion of thermal, mechanical, and electrical energies. Karabulut et al. (2009) constructed a system having a parabolic dish concentrator and Stirling engine and developed an equation for appropriate design of the concentrator to show the reflective behavior of solar rays on the hot zone of the displacer cylinder in the engine. Temperature at the hot zone is measures as 165 ℃. Nepveu et al. (2009) presented a thermal model of the Euro dish/Stirling unit for energy conversion. Optical measurements are made to calculate losses by the parabolic reflector and also a nodal method proposed for calculating losses in the cavity by conduction, convection, and radiation. The differential equation developed by the model is solved using Matlab software. Results show that at 900 W/m² DNI conversion efficiency of solar to electricity is about 21%. Wang et al. (2015) introduced the design of a hybrid gas turbine–receiver unit with PDSC as a power source to generate 25 kW. To predict the radiative flux boundaries of the receiver, the design of the parabolic dish and the focal plane ray-tracing method is developed. Semprini et al. (2016) presented a thermodynamic model for microgas turbine comparing with PDSC simulate on-design and off-design performance of the system, thermal aspects of concentrator, turbine and receiver are validated.

In other literature, Aichmayer et al. (2015a, b) designed a 150-kW solar power plant combined with PDSC as a power source. The designed concept is compared with conventional combined cycle power plant and hybrid solar tower combined cycle solar power plant. From the observations, they concluded that power plant with solar dish power plant is gaining high solar irradiation compared with solar tower power plant. Aichmayer et al. (2015a, b) designed a 10-KW$_e$ small-scale hybrid solar microgas turbine system powered with a parabolic dish collector. Detailed analysis of the operating conditions is done based on the initial design

results, using CFD/FEM coupled simulation. Results show that microgas turbine solar dish system with volumetric solar receivers as a heat source is best solution with some limitation of material parameters below permissible limits. Roux et al. (2011) optimized the PDSC based solar thermal Brayton cycle to overcome the disadvantages like pressure loss in the receiver and recuperator for producing maximum output. Ragnolo et al. (2015) proposed an approach to design hybrid solar microgas turbine combined with PDSC as a heat source. The conversion efficiency of the microgas turbine is shown as 29.6% from the results. Dähler et al. (2018) explained the theoretical and experimental characteristics for the production of fuel using the thermochemical redox cycle using PDSC as a heating source.

The summary of the overall applications of PDSC is given in Tables 8 and 9.

PDSC as a heat source for desalination

One of the major applications of concentrating solar energy is desalination. Using parabolic dish concentrator as a heat source, researchers constructed solar desalination systems in which Jabari et al. (2020) proposed a zero energy building which uses solar dish Stirling engine as a heat source which generates energy from solar irradiation. Dish Stirling engine is linked with combined humidification and dehumidification desalination unit to produce cool and clean water. To check the performance and feasibility of the proposed system they simulated a nonlinear algebraic mathematical modelling system. Bahrami et al. (2019) investigated a desalination system in which a solar still is mounted at the focal point of parabolic dish collector system experimentally and theoretically. To describe the overall system, they developed a mathematical model. From the results observation carried out like optical properties and geometrical properties of the solar still have a significant effect on production of

Table 9 A summary of experimental studies on PDSC applications

Authors	Study	PDSC diameter (m)	Solar irradiation (W/m^2)	Application
Karabulut et al. (2009)	Experimental	1.7	820	Dish Stirling engine
Onokwai et al. (2019)	Experimental	0.86	800	Solar cooking

desalinated water. Modi et al. (2020) developed and investigated the performance of spherical basin solar still which is combined with parabolic dish reflector. From the results, it has been observed that with increase in the mass of the water in basin, desalinated water output is increased.

Abubakkar et al. (2020) designed a small-scale solar still desalination system and a parabolic dish concentrator is working as a heat source to the solar still. They conducted experiment to observe the PH, hardness, chloride, and TDS values of the water before and after desalination. From the results, they observed that there is 98% drop in TDS content after desalination. Chaouchi et al. (2007) built a small solar desalination unit with combination of parabolic dish concentrator. They also developed a theoretical model to determine the average absorbed temperature and flow rates as a function of solar heat flux. Results show a small difference in the average absorber temperature between theoretical and experimental values. Kabeel et al. (2019) developed a desalination system using two identical parabolic dish solar collectors. The system went into vagaries testing for 3 months in various conditions at Ismalila, Egypt. Results showed that use of two identical dish concentrator increases the amount of desalination water compared with single dish concentrator operation. Omara and Eltawil (2013) also worked on desalination systems to develop and install modified brackish water desalination system with the help of solar parabolic dish. This developed desalination system is compared and evaluated with conventional solar still. From the results, they observed that desalination system developed by the authors has more efficiency compared with conventional solar still.

To optimize the desalination system and increase the efficiency, some authors concentrated on computational simulation in which Prado et al. (2016) proposed a study to design and construct a solar dish concentrator for desalination unit; analysis is also been done to determine the performance of the system. Potential energy and dynamic heating of the system are analyzed using computational simulation, and they are validated with experimental values. Rafiei et al. (2019, 2020) used hybrid solar desalination system to investigate the performance of three different geometries of the receiver used in parabolic dish concentrator. They observed that receiver with hemispherical geometry results with highest freshwater production. In the other research, they used nanofluids as working fluids in the receiver to collect the heat. Results shown that Cu/oil nanofluids with high concentration has achieved high fresh water production at low output ratio. Research done on solar thermal desalination system has wide opportunities in present world due to lack of pure drinking water. Above researches can help to reach next step in construction of desalination system using parabolic dish concentrator.

Mathematical modelling of PDSC

Mathematical modelling in this paper is explained in two parts, the first part gives the geometrical modelling for PDSC and the second part is based on thermal modelling for PDSC system.

Geometrical modelling of concentrator and receiver system

This modelling will help to maximize the efficiency of the concentrator and receiver's solar energy reach. Good modelling will result in better interaction with sunlight. To design a parabolic dish shaped solar collector following steps shown in Fig. 10 are taken into consideration like choosing size and type of parabolic dish used; material for the reflector; dish diameter calculation; parabolic dish size calculation; focal
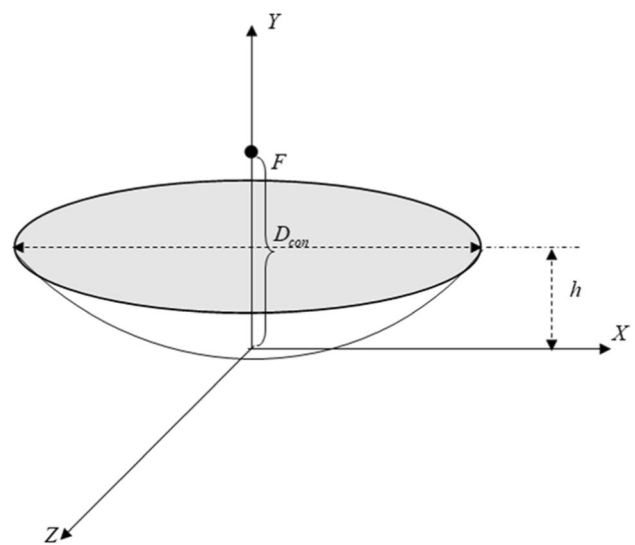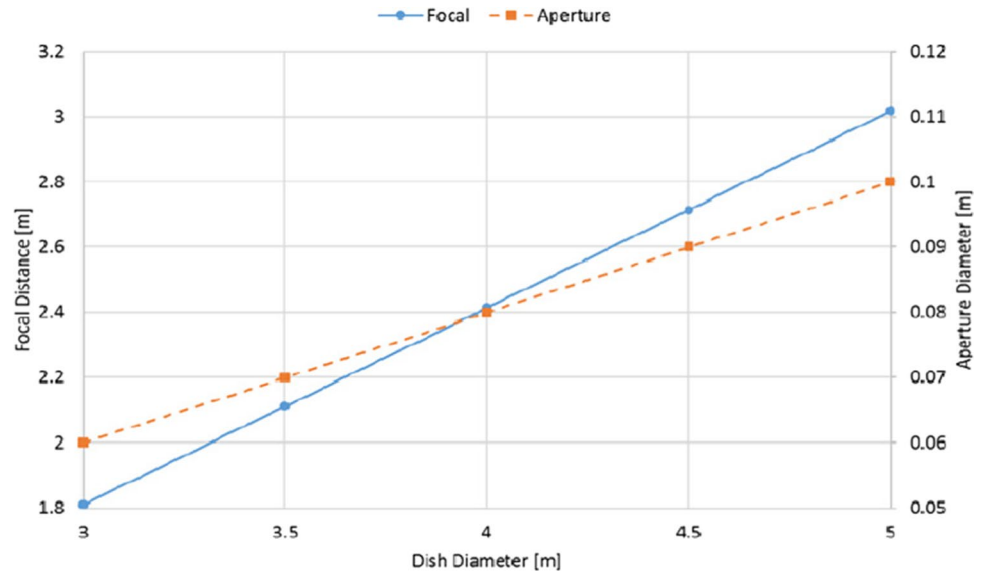

Fig. 10 Geometrical representation of the parabolic dish

Fig. 11 Aperture diameter and focal length with respect to dish diameter (Gholamalizadeh and Chung [2017])

length calculation for parabolic dish; focal point diameter calculation; rim angle calculation; finding concentration ratio; selecting receiver size, shape, and material; and designing the geometry and structure of the dish collector.

Important geometrical parameters like focal length, the height of the dish, edge radius, focal point diameter, and height of the receiver are modelled in this section by considering the geometry of the dish reflector as a paraboloid. Considering the parabolic equation with algebraic representation with a coordinate $\left(\frac{D_{con}}{2}, h_{rim}\right)$.

$$x^2 = 4fy \tag{1}$$

The diameter of the parabolic dish

The main parameter where the overall output energy of the PDSC is depends on. To design a dish concentrator, diameter (D_{con}) is the main parameter to be considered. Total efficiency of the system is dependent on the diameter of the dish concentrator. As we can observe from Fig. [11], there would not be any change in the total efficiency of the system in midday but if we observe it in the early morning cases total efficiency improves with increase in the dish diameter. Also, as observed in Fig. [12], focal length and aperture diameter are also dependent on the diameter of the dish concentrator.

Height of the parabolic dish concentrator

Taking Eq. [1] into consideration and the coordinate points $\left(\frac{D_{con}}{2}, h_{rim}\right)$, height of the dish is calculated using Eq. [2] (Fig. [13]).

$$h_{rim} = \frac{1}{4f}\left(\frac{D_{con}}{2}\right)^2 \tag{2}$$

Rim angle

The effect of the incoming solar irradiation depends on the rim angle (φ_{rim}) of the parabolic dish (Hafez et al. [2016]). Rim angle is defined as the angle which is measured at the focal point to the axis of the rim in the parabolic dish. The parameter which affects the efficiency of the receiver in the system is the solar geometric concentration. To calculate this parameter, rim angle of the concentrator is taken into consideration. From Fig. [14], we can observe the variation in geometric concentration with respect to the rim angle of the concentrator for different geometrical properties.

Focal length of the parabolic dish concentrator

A parabolic dish concentrator will focus solar irradiation at a point where the receiver has positioned this point is called focal point. Considering diameter (D_{con}) and the rim angle (φ_{rim}) to calculate focal point and from Fig. [13], we can observe that distance from the vertex of the dish to the focal point is called focal length. Equation of focal length is given in Eq. [3]. Focal length with respect to the rim angle and solar concentration can be observed in Fig. [15].

$$f = \frac{D_{con}}{4tan\left(\frac{\varphi_{rim}}{2}\right)} \tag{3}$$

Fig. 12 Change in total efficiency with respect to change in dish diameter (Gholamalizadeh and Chung 2017)
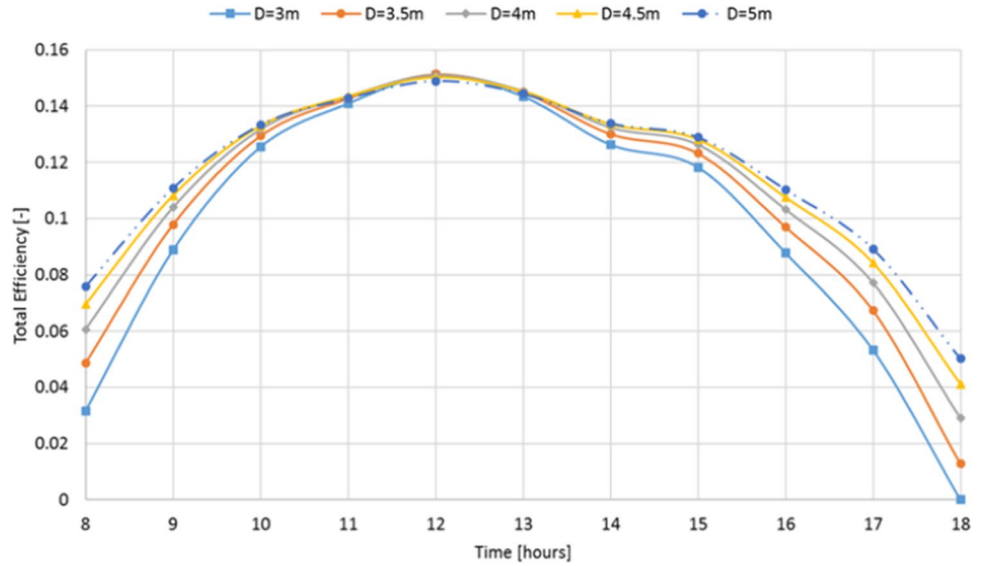
Edge radius of the parabolic dish

It is another important parameter which is also called maximum distance value between the focal point and extreme end of the dish which is given in Eq. 4.

$$r_r = \frac{2f}{1 + cos(\varphi_{rim})} \tag{4}$$

Focal point diameter

The diameter of the focal point for the dish concentrator is given in Eq. 5 (Thakkar 2015).

$$D_{rec} = \frac{f \times \theta}{cos\varphi_{rim}(1 + cos\varphi_{rim})} \tag{5}$$

As shown in Fig. 16, focal point diameter will affects the size of the receiver. The acceptance angle (θ) is the angle of the reflected solar radiation at the focal point in a small time of sun tracking. Focal point diameter is also called as solar image width, and from Fig. 15, we can observe the change in solar image with respect to the solar concentration and rim angle.

Height of the receiver

With the reference of Fig. 11 height of the receiver (d_f) is computed to estimate the distribution of solar irradiation on the receiver surface uniformly (Castellanos et al. 2017). The height of the receiver is calculated using Eq. 6. Change in thermal and optical efficiency with respect to the height of the receiver can be seen in Fig. 17.

$$d_f = \left(f - \frac{1}{4f}\frac{D_{con}^2}{4}\right)\frac{D_{rec}}{D_{con}} \tag{6}$$

Aperture area of the dish concentrator

Aperture area is termed as the total surface area of the dish concentrator where the solar irradiation is concentrating (Hafez et al. 2016; Castellanos et al. 2017). This will affect the total heat flux concentrating near the focal point or receiver. The aperture area is calculated using Eq. 7.

$$A_{con} = \frac{\pi}{4}D_{con}^2 \tag{7}$$
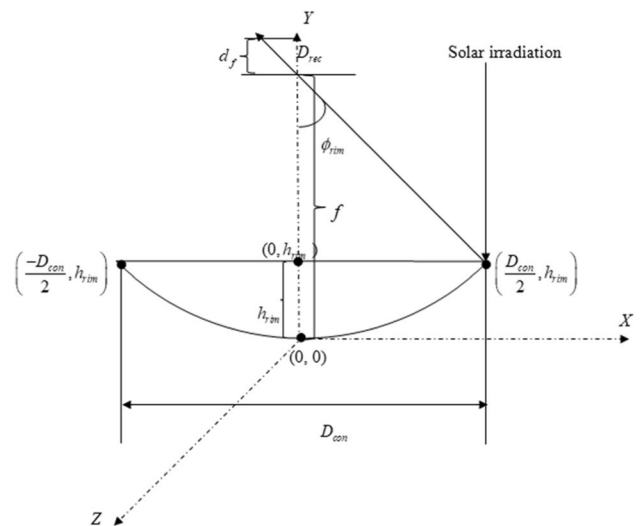
Fig. 13 Geometry of parabolic dish concentrator with focal length, focal point, and rim angle

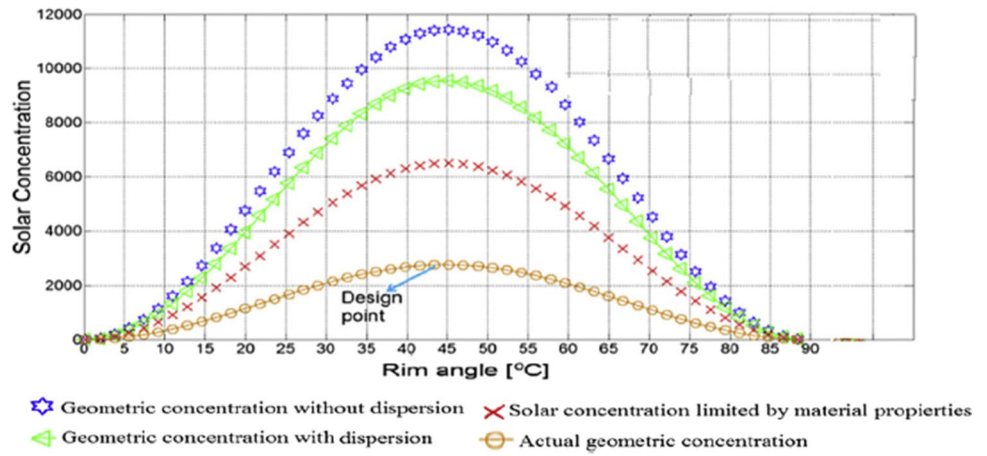**Fig. 14** Solar concentration as a function of rim angle (Castellanos et al. 2017)

Fig. 15 Focal length with respect to solar concentration and rim angle (Ruelas et al. 2013)
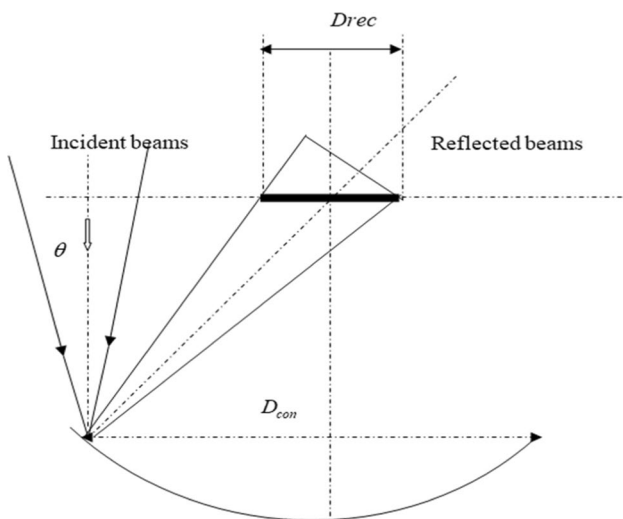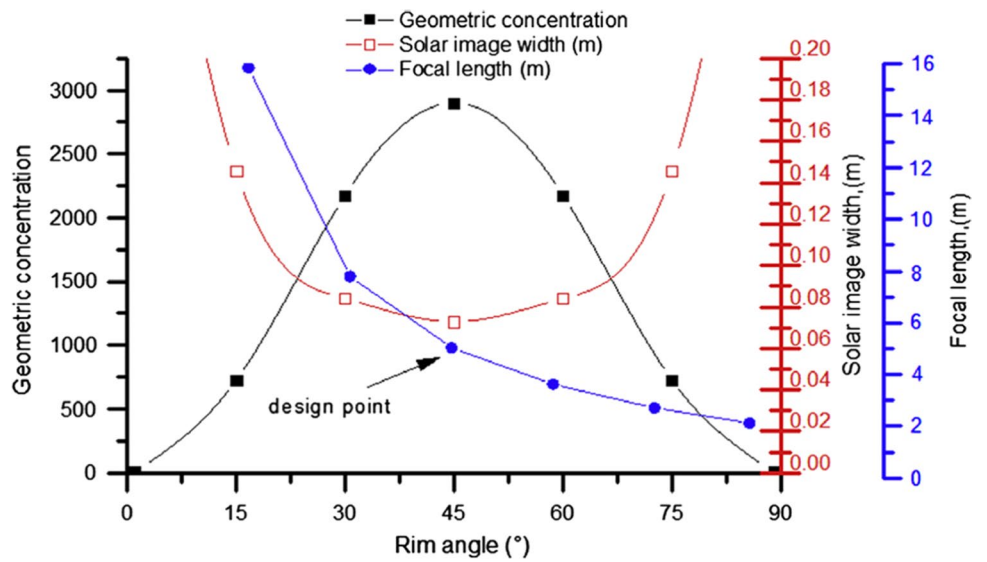

Fig. 16 Acceptance angle and receiver diameter of PDSC

Another notation for aperture area is given with Eq. 8 (Azzouzi et al. 2017; Roux and Meyer 2016).

$$A_{con} = \frac{8\pi}{3}f^2\left[\left(1+\left(\frac{D_{con}}{4f}\right)^2\right)^{\frac{3}{2}} - 1\right] \tag{8}$$

Aperture area of the receiver

Irradiation from the concentrator is focused at receive which can collect a high amount of energy for this aperture area of the receiver should be accurate. The aperture area of the receiver is calculated using Eq. 9 (Hafez et al. 2017; Azzouzi et al. 2015; Mendoza Castellanos et al. 2017).

$$A_{rec} = \frac{\pi}{4}D_{rec}^{\ 2} \tag{9}$$

Fig. 17 Thermal and optical efficiency with respect to height of the receiver (Bellos et al. 2019a)
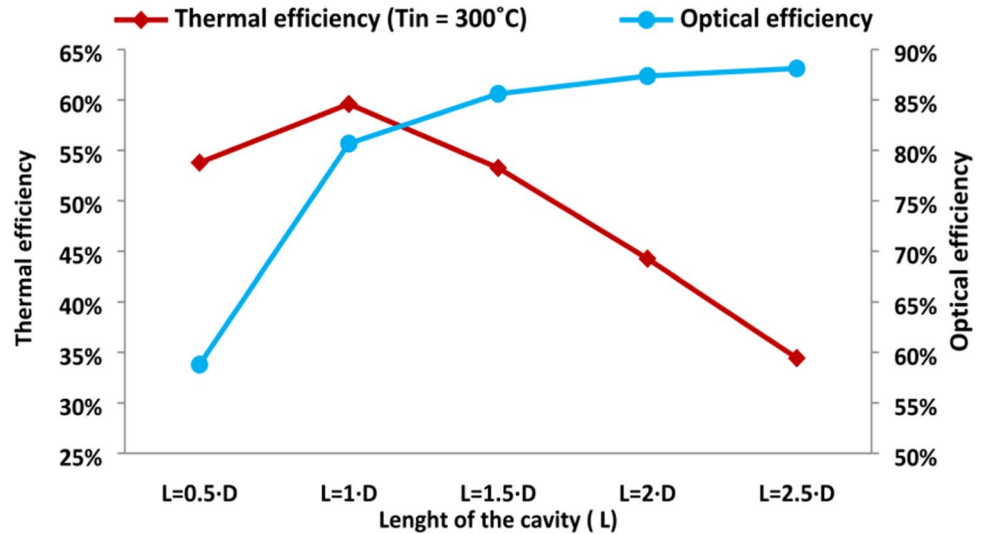
Fig. 18 Receivers surface temperature with respect to concentration ratio (Hafez et al. 2016)
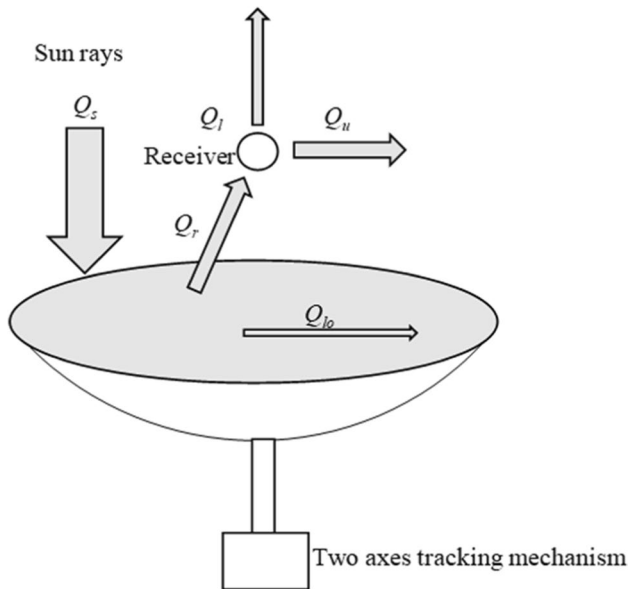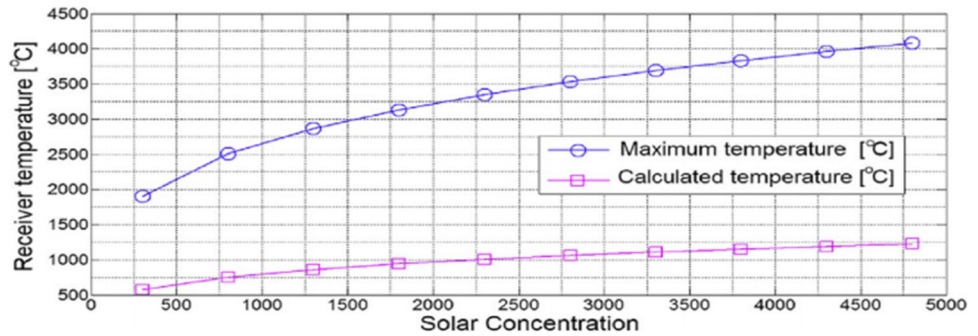

Fig. 19 Thermal efficiency of dish concentrator

Concentration ratio

It is a ratio of the aperture area of the concentrator to the aperture area of the receiver (Hafez et al. 2016; Roux and Meyer 2016). The concentration ratio is a main parameter to construct a solar dish concentration system; concentration ratio should be greater than 10. Concentration ratio is calculated using Eq. 10. Temperature at the focal point will change with respect to the concentration ratio we can observe it from Fig. 18.

$$C = \frac{A_{con}}{A_{rec}} \tag{10}$$

Thermal modelling for PDSC

Thermal efficiency of the collector is defined as the ratio of energy that is useful to the incident energy on the concentrator aperture (Thakkar 2015; Wu et al. 2010a); see Fig. 13. Thermal efficiency is calculated using Eq. 11 (Fig. 19).
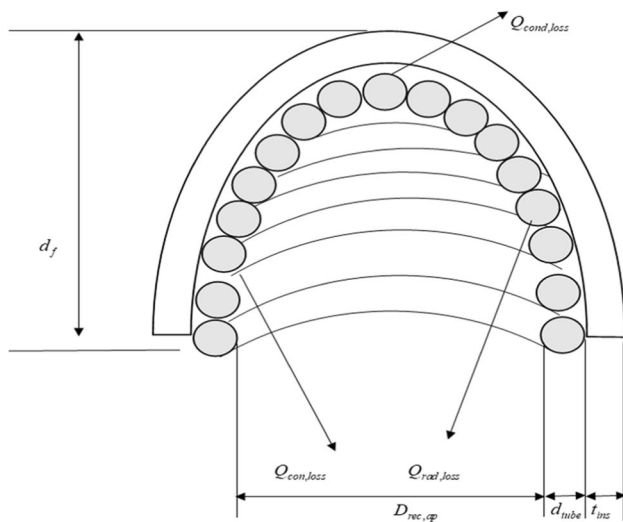
Fig. 20 Heat losses in cavity receiver (Loni et al. 2019b)

$$\eta_c = \frac{Q_u}{Q_s} \qquad (11)$$

Consider PDSC irradiation of Q_s its surface area of A_{con}, the direct normal irradiation I_s which will various from place to place and orientation of dish collector. For the system in steady state net solar heat transfer Q_s is given in Eq. 12.

$$Q_s = I_s A_{con} \qquad (12)$$

Useful heat delivered by the collector at steady-state condition is equal to the total heat absorbed by the heat transfer fluid in the receiver (Wu et al. 2010a). Useful heat delivered is calculated using Eq. 13.

$$Q_u = Q_r - Q_l \qquad (13)$$

The radiation falling on the receiver Q_r is a function of optical efficiency η_o. Radiation falling on the receiver can be calculated using Eq. 14 (Kaushika and Reddy 2000).

$$Q_r = I_s A_{con} \alpha_c \rho_c \tau s \qquad (14)$$

Optical efficiency η_o is defined as the ratio of energy falling on the receiver to the net solar heat transfer on to the collector's aperture area. Receiver efficiency η_r is defined as the ratio of useful heat delivered to the energy falling on the receiver. η_o and η_r are calculated using Eqs. 15 and 16.

$$\eta_o = \frac{Q_r}{Q_s} \qquad (15)$$

$$\eta_r = \frac{Q_u}{Q_r} \qquad (16)$$

Total heat loss from the receiver Q_l is given in Eq. 17.

$$Q_l = A_{rec} h_{ad} (T_{rec} - T_{amb}) \qquad (17)$$

Heat transfer coefficient (h_{ad}) represents the addition of convection and radiation heat transfer coefficients which is calculated using Eq. 18.

$$h_{ad} = h_{cov} + h_{rad} \qquad (18)$$

Convective heat transfer coefficient and radiative heat transfer coefficient is calculated using Eqs. 19 and 20.

$$h_{cov} = \frac{k_a}{D_{rec}} Nu \qquad (19)$$

$$h_{rad} = 4 \varepsilon \sigma T_a^{\ 3} \qquad (20)$$

To calculate the collectors' thermal efficiency, use Eqs. (11), (14)–(16).

$$\begin{aligned} \eta_c &= \frac{Q_u}{Q_s} = \frac{Q_r}{Q_s} \times \frac{Q_u}{Q_r} = \eta_o . \eta_r \\ &= \eta_o \frac{Q_r - Q_l}{Q_r} = \eta_o \left(1 - \frac{Q_l}{Q_r}\right) \\ &= \eta_o - \frac{Q_l}{\eta_o Q_r} = \eta_o - \frac{Q_l}{Q_s} \end{aligned}$$

$$\eta_c = \eta_o - \frac{Q_l}{Q_s} \qquad (21)$$

Collector's thermal efficiency is given in Eq. 21.

Heat flux at the receiver

In this thermal model, cavity receivers heat losses are determined namely conduction, convection and radiation losses. Figure 14 shows the heat losses from the receiver. The net heat transfer rate Q_{net} without losses at the receiver is calculated using Eq. 22 (Madadi et al. 2015) (Fig. 20).

$$Q_{net} = Q_r - Q_{cov,loss} - Q_{rad,loss} - Q_{cond,loss} \qquad (22)$$

$$Q_r = \eta_o . Q_s \qquad (23)$$

Equation (23) represents the energy absorbed by the receiver, and solar energy on the collector operator (Q_S) is taken from the Eq. 15.

Thermal efficiency of the receiver is determined as the ratio of net rate of heat transfer at the receiver to the incident solar heat rate from the collector. Thermal efficiency is calculated from Eq. 24 (Sendhil Kumar and Reddy 2008).

$$\eta_{th} = \frac{Q_{net}}{Q_s} \qquad (24)$$

Conduction heat loss

Total thermal resistance approach for conduction an external convection of the receiver at study state condition is calculated with Eq. 25. This approach is considered due to the specific cavity wall temperature and ambient temperature (Loni et al. 2018d).

$$
\begin{aligned}
Q_{\text{cond,loss}} &= A_{rec}.\frac{(T_{s,avg}-T_\infty)}{R_{\text{total}}} \\
&= \frac{A_{rec}.(T_{s,avg}-T_\infty)}{\frac{1}{h_{\text{outer}}}+\frac{t_{ins}}{k_{ins}}}
\end{aligned}
\tag{25}
$$

Convection heat transfer coefficient at the outer surface (h_{outer}) is calculated in Eq. 26.

$$
h_{\text{outer}} = \frac{k_\infty.Nu_{\text{combined}}}{D_{rec,\text{outer}}}
\tag{26}
$$

Heat transfer coefficient of air for external convection is investigated for both natural and forced convection conditions (Loni et al. 2018d). Nusselt number for forced convection is calculated using Eq. 27.

$$
Nu_{\text{foeced}} = 2 + \left[0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right]Pr^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{\frac{1}{4}}
\tag{27}
$$

$$
Re = \frac{\rho.V_{\text{wind}}.D_{rec,\text{outer}}}{\mu}
\tag{28}
$$

Reynolds number (Re) is given in the Eq. 28 and the Nusselt number for forced convection is calculated using Eq. 29 (Loni et al. 2018d).

$$
Nu_{\text{natural}} = 2 + \frac{0.589Ra_D^{\frac{1}{4}}}{\left[1 + (0.469/Pr)^{\frac{9}{16}}\right]^{\frac{4}{9}}}
\tag{29}
$$

Nusselt number for both natural and forced convection is calculated using Eq. 30.

$$
Nu_{\text{combined}} = \left(Nu_{\text{forced}}^{3.5} + Nu_{\text{natural}}^{3.5}\right)^{\frac{1}{3.5}}
\tag{30}
$$

Radiation heat loss

Radiation heat loss at the receiver is calculated by Eq. 31 (Loni et al. 2018d).

$$
Q_{rad,\text{loss}} = h_{rad}.A_{rec}.(T_s - T_\infty)
\tag{31}
$$

Heat transfer coefficient for radiation is given in Eq. 32.

$$
h_{rad} = \frac{Nu_{rad}.k_a}{D_{rec,\text{outer}}}
\tag{32}
$$

Nusselt number for radiation in hemispherical cavity is calculated using Eq. 33 (Loni et al. 2019b).

$$
Nu_{rad} = 9.650Gr_D^{0.068}(1 + cos\theta)^{0.001}\varepsilon^{0.546}(N_{RC})^{0.479}\left[1 - (T_R)^4\right]^{8.78}\left(\frac{D_{rec,ap}}{D_{rec,outr}}\right)^{0.493}
\tag{33}
$$

$$
N_{rc} = \frac{\sigma T_S^4\left(\frac{D_{rec,\text{outer}}}{2}\right)}{(T_S - T_\infty)k_a}
\tag{34}
$$

$$
T_R = \frac{T_\infty}{T_S}
\tag{35}
$$

$$
Gr_D = \frac{g\beta^l(T_S - T_\infty)D_{rec,\text{outer}}^3}{v^2}
\tag{36}
$$

Nusselt number for radiation in cylindrical cavity is calculated using Eq. 37 (Azzouzi et al. 2017).

$$
Nu_{rad} = 0.000154Gr^{0.627}(2 + cos\phi)^{-1.054}(1 + \varepsilon_p)^{0.313}\left(\frac{D_{rec,ap}}{D_{rec,\text{outer}}}\right)^{1.638}
\tag{37}
$$

Convection heat loss

Convection heat loss inside the receiver is considered for both natural and forced convection [28]. Total convective loss from the receiver is calculated by Eq. 38.

$$
Q_{cov,\text{loss}} = h_{\text{total}}.A_{rec}.(T_S - T_\infty)
\tag{38}
$$

Heat transfer coefficient for both natural and forced convection is given in Eqs. 39 and 40 (Loni et al. 2018d, 2018g).

$$
h_{\text{forced}} = 4.22\left(V_{\text{wind}}^{0.805}\right)
\tag{39}
$$

$$
h_{\text{natural}} = 1.45\left(T_S - T_\infty\right)^{0.333}
\tag{40}
$$

$$
h_{\text{total}} = h_{\text{forced}} + h_{\text{natural}}
\tag{41}
$$

Thermal properties of nanofluids

To increase thermal efficiency nanofluids are used in-place of regular working fluids to collect heat from the receiver (Chandrashekara and Yadav 2017; Pakhare et al. 2018; Khan et al. 2019; Abid et al. 2016; Bashir et al. 2020). Nanofluid application accuracy in the specification of nanoparticle is important. Thermophysical properties of nanofluids are calculated using Eqs. 42–48 (Chandrashekara and Yadav 2017).

Fig. 21 Absorbed energy for three shapes of receiver at different focal distances (Daabo et al. 2016b)
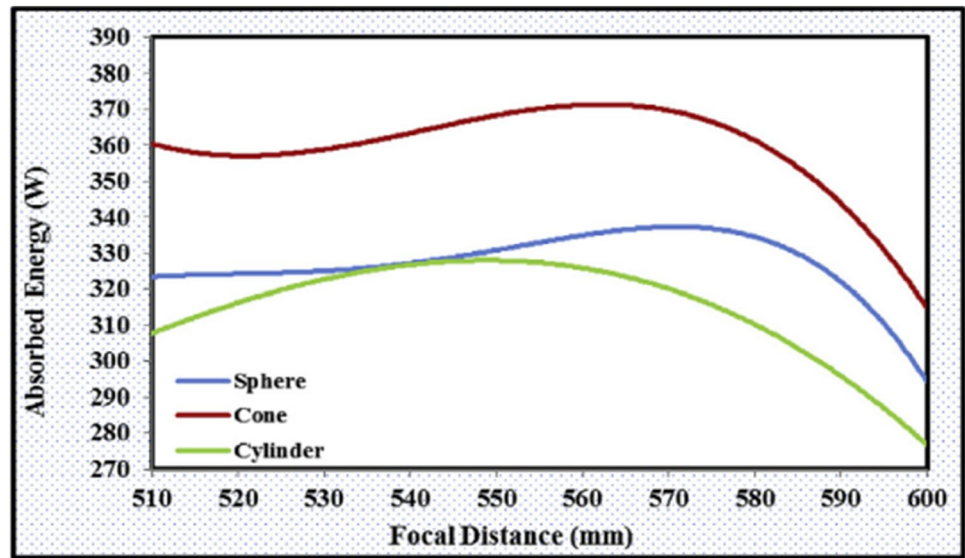
Thermo physical properties of nanofluids are derived as follows

Using the Maxwell model, thermal conductivity is calculated for effective suspension of nanoparticle in the base fluid. Mode for oil-based nanofluids is given in Eq. 42.

$$k_{nf} = k_f \left[\frac{k_{np} + 2k_f + 2(1 + \beta)^3 \phi (k_f - k_{np})}{k_{np} + 2k_f - (1 + \beta)^3 \phi (k_f - k_{np})} \right] \qquad (42)$$

β is the ratio of the thickness of nanolayer to the diameter of nanoparticle considered as 0.1 [66].

Thermal conductivity of oil as base fluid is calculated using Eq. 43.

$$k_f = 0.1882 - 8.304 \times 10^{-5}(T) W/mk \qquad (43)$$

Specific heat of nanofluid with oil as a base fluid is calculated using Eq. 44.

$$c_{p,nf} = (1 - \phi)c_{p,f} + \phi c_{p,np} \qquad (44)$$

Specific heat oil as a base fluid is calculated using Eq. 45.

$$c_f = 0.8132 + 3.706 \times 10^{-3}(T) kJ/kgK \qquad (45)$$

Density of the oil is calculated using Eq. 46.

$$\rho_{nf} = (1 - \phi)\rho_f + \phi \rho_{np} \qquad (46)$$

Density of the oil as a base fluid is calculated by Eq. 47.

$$\rho_f = 1071.76 - 0.72(T) Kg/m^3 \qquad (47)$$

Nanofluid viscosity is calculated using Eq. 48.

$$\mu_{nf} = (1 + 2.5\phi)\mu_f \qquad (48)$$

Observations

Overall performance of the PDSC system depends on efficiency of the receiver. Receiver efficiency alters with respect to its geometrical and optical properties. Geometrical properties affecting the efficiency of the receiver are.

Receiver shape

One of the geometrical properties which are affecting the receiver efficiency is shape of the receiver. Shape affects the absorption and reflection of the solar irradiation incident on the surface of the receiver. Good amount of research has done comparing three geometrical shapes of the receiver namely conical, spherical and cylindrical. Figure 21 shows comparison of three receiver shapes by Daabo et al. (2016b) who described the energy absorption in the receiver with respect to variation in focal lengths. In the figure, it can be clearly observed that receiver with conical shape absorbed more amount of energy compared with cylindrical and spherical shapes. Similarly, Idlimam et al. (2019) has done comparison for three different shapes of receiver as shown in Fig. 22. The figure describes the flux distribution on the surface of the receivers in which conical shaped receiver is having good

uniformity in flux distribution. Comparison of these three receiver shapes in terms of efficiencies is shown in Fig. 22. In this comparison, it is shown that conical receiver is having high thermal and optical efficiencies than other receivers. In other work done by Bellos et al. (2019a), shown in Fig. 23, it can be seen that comparison of different shapes of receiver in which receiver with cylindrical-conical shape has high thermal and optical efficiencies. In that work, it can be noticed that the authors have selected conical shaped receiver, which is having high efficiency that is observed from previous works and combined it with

cylindrical shaped receiver by which high thermal and optical efficiencies can be achieved. Over all studies done on receivers with different geometrical shapes, it can be concluded that receiver with conical shape is better suitable for PDSC system compared with other geometrical shapes (Fig. 24).

Receiver orientation

Following above section, other parameter that is affecting the efficiency of the receiver is orientation of the
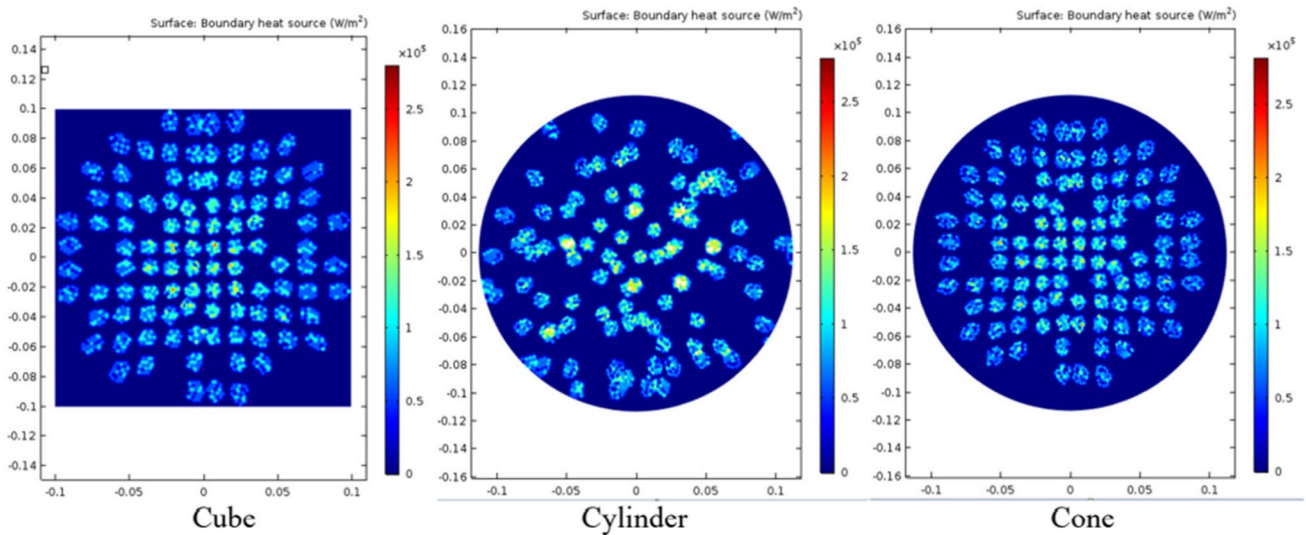

Fig. 22 Flux distribution over three different shapes of receiver (Idlimam et al. 2019)

Fig. 23 Optical and thermal efficiencies for three different receivers at varying focal lengths and absorption ratios (Daabo et al. 2016b)
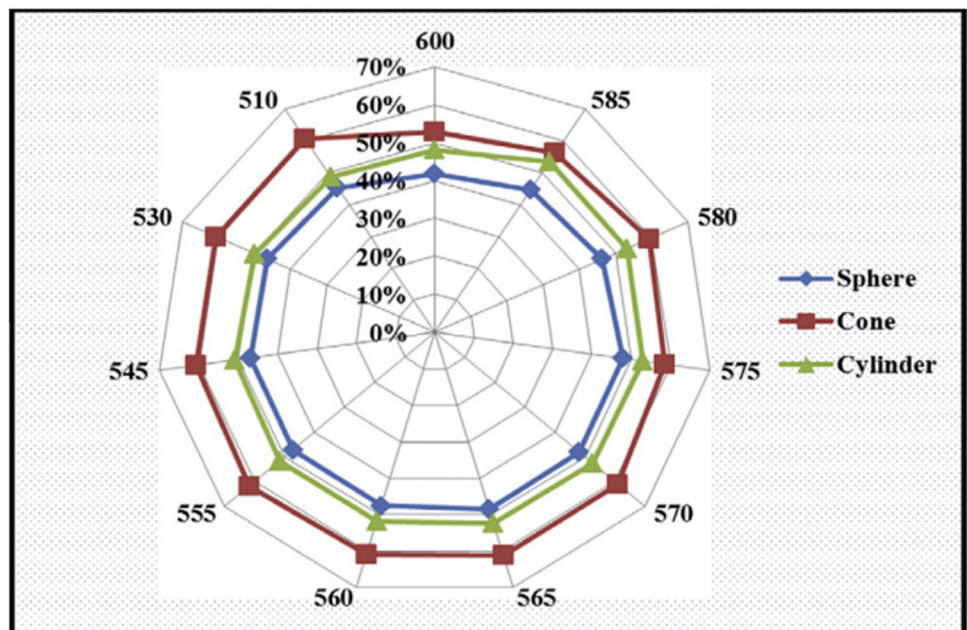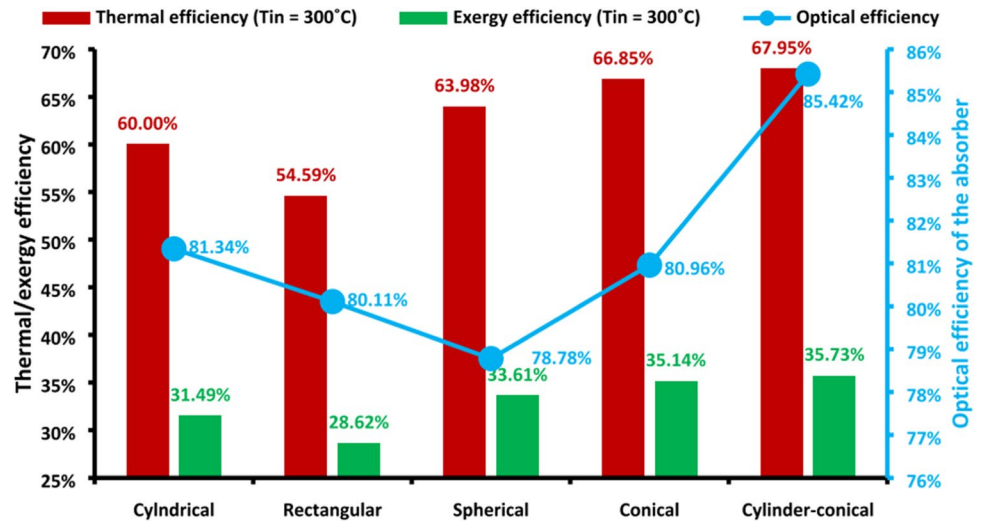
Fig. 24 Thermal, exergy, and optical efficiencies for different receiver shapes (Bellos, Bousi, et al. 2019a)


receiver. Reflected solar irradiation from the concentrator always points towards the receiver, while the orientation of the receiver changes the behavior of the fluid inside the receiver and also heat transfer characteristics. Natural convection and radiation heat losses are the important parameters which are not only affecting the receiver performance but also the entire system. Orientation of the receiver will alter the losses from the receiver that directly affects the thermal performance of the system. In Fig. 25, we can observe the comparison of convective and radiation heat losses at different orientating angles of the receiver done

by Reddy and Sendhil Kumar (2008). From the figure, it can be noticed how the convective heat loss is varying with respect to receiver orientation and its surface emissivity.

In other research work done by Sendhil Kumar and Reddy (2008), the author explained how the receiver inclination affects the convective heat loss as well as the total heat loss over the receiver, Fig. 26. In another work, Fig. 27, the same research team showed how the incident temperature and orientation of the receiver are affecting the convective heat loss in the receiver. It is clear that as the temperature increases, convective heat loss also

Fig. 25 Convective heat loss of receiver for different inclinations (Reddy and Sendhil Kumar 2008)
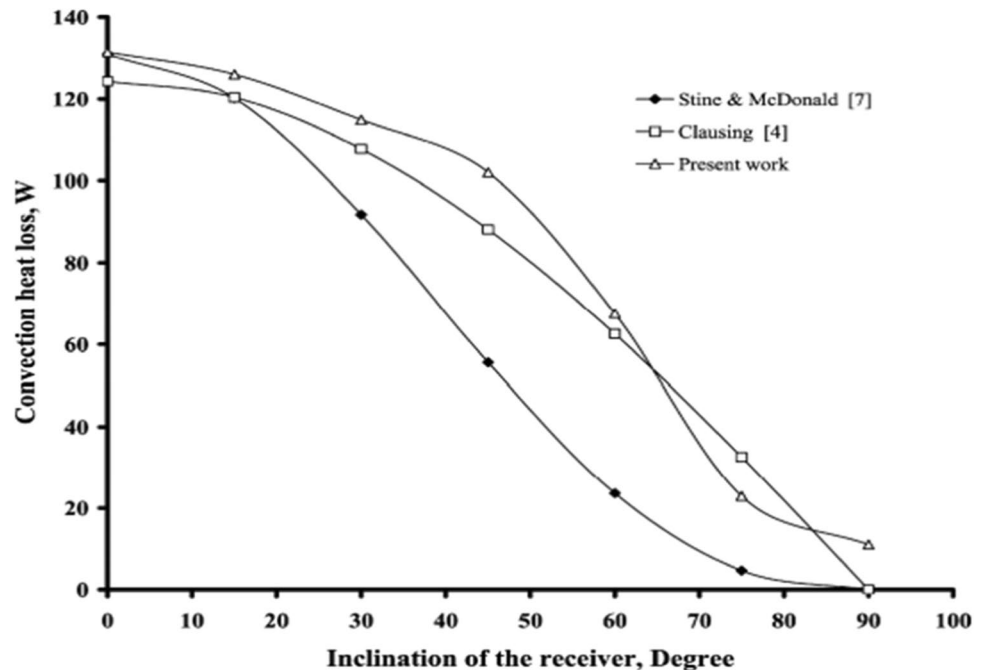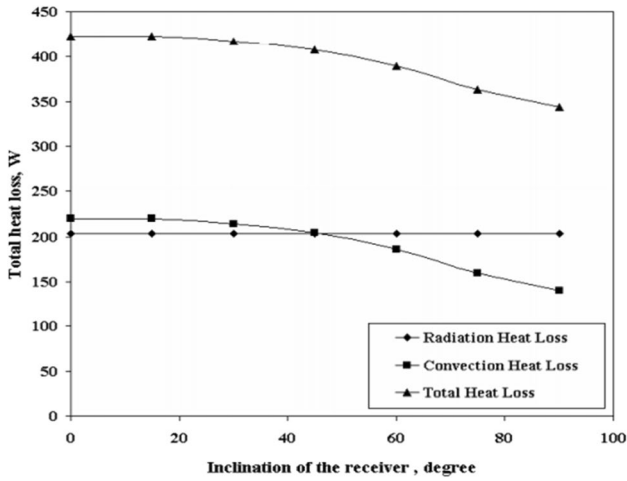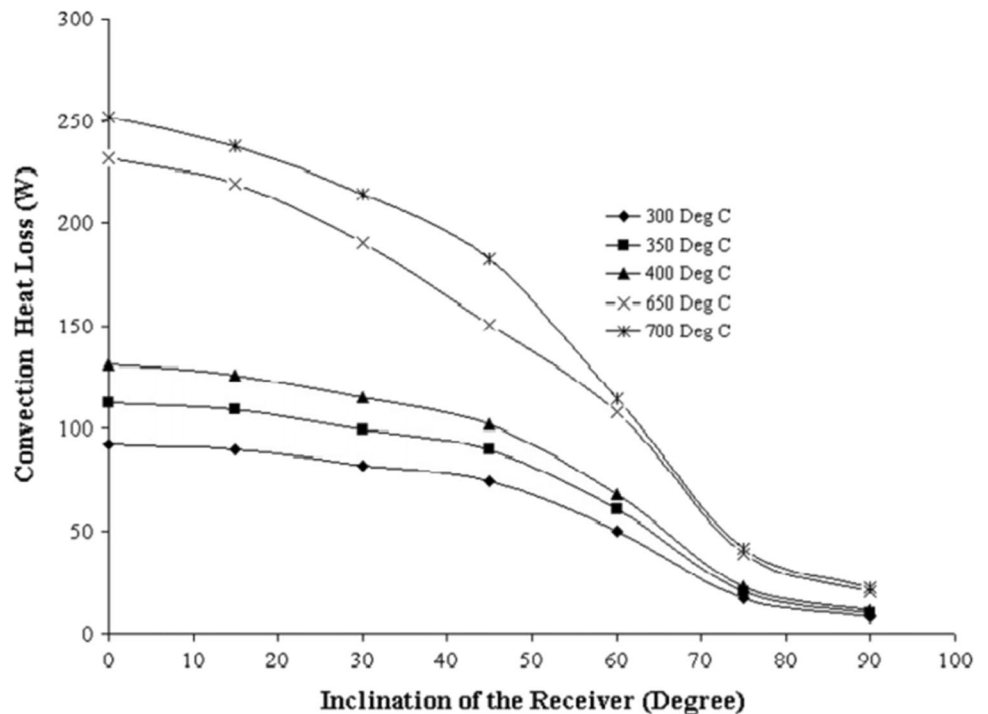
Fig. 26 Total heat loss at the receiver at different inclinations (Sendhil Kumar and Reddy 2008)

increases; also, less convective heat loss is generated at 90° inclination of the receiver.

Thermal losses in the receiver

Overall efficiency of PDSC depends up on the energy absorbed by the receiver and the receiver efficiency depends on the thermal losses that receiver undergone.

General thermal losses occur in receiver are convective heat loss and radiation heat loss. These losses mainly depend on some external conditions like wind flow over the receiver also the shape of the receiver and inclination of the receiver also affects the heat losses.

In the work done by Wu et al. (2014), they explained how the convectional flow is affected by the rotation of the cavity receiver in laboratory condition. It is found that rotation of the receiver affects the loss by ± 10%. In Fig. 28, we can observe the convectional flow with respect to the receiver orientation. Wu et al. (2010b) reviewed and discussed about the convectional heat losses from the cavity receiver. A Nusselt number correlation has been developed to predict the heat losses from receiver as well as wind effects on the receiver. In the same way, Avargani et al. (2020) analyzed the performance of the system with two different wind conditions. Inward wind condition affects the performance of the receiver compared with the outward wind condition. From Fig. 29, we can observe the graph showing thermal efficiency of the receiver decreasing with respect to wind velocity. Also, it is observed that efficiency is low at inward wind condition at 70° inclination angle of the receiver.

Zou et al. (2017) studied how the geometrical parameters like cavity length and aperture diameter affecting the thermal performance of the receiver. In Fig. 30, from the graphs, we can observe heat loss in the receiver with
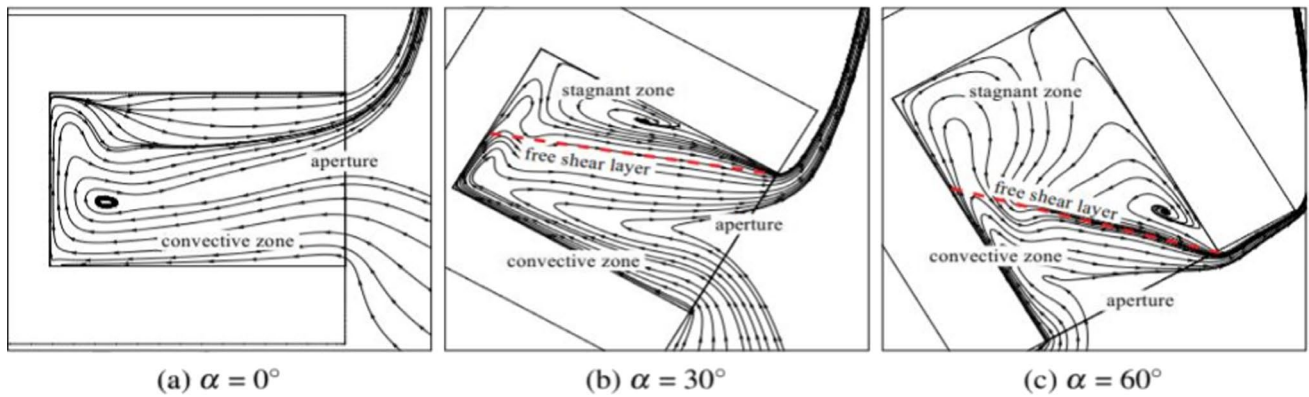
Fig. 27 Convective heat loss at the receiver for different temperatures and inclination of receiver (Sendhil Kumar and Reddy 2008)

(a) $\alpha = 0°$ (b) $\alpha = 30°$ (c) $\alpha = 60°$

Fig. 28 Convectional flow in cavity receiver with respect to receiver orientation (Wu et al. 2014)

varying cavity lengths and aperture diameter. Ngo et al. (2015) conducted a numerical study on combined natural convection and radiation heat loss. To enhance the efficiency of the receiver, they reduced amount of heat loss using plate fins in the receiver. It is observed that radiation heat loss is constant because of the surface properties of the receiver. Using the plate fins, it is found that reduction in convectional heat loss is achieved by 5%.

All the above studies reviewed on the receiver to explain the thermal heat losses in the receiver concludes two major points:

1. Heat losses from the receiver are depends on the geometrical properties of the receiver like receiver shape, cavity length, and aperture diameter.
2. Heat losses like convectional heat loss are due to the wind effects on the receiver and the receiver orientation. In case of radiation heat loss, it is due the surface properties of the receiver.

Conclusion and recommendations

In concentrating thermal systems, parabolic dish solar concentrator is having significant role because of its high concentration ratios. But the thermal losses from the system are decreasing the overall efficiency of the system. This review helps in designing parabolic dish solar concentrator system with improved thermal efficiency. Neuroma studies have been done on the design parameters of the system. This review will give an outlook of correlations that help modelling dish concentration system. One of the major components in the system is receiver; overall efficiency of the system depends on the receiver only. Properties that are affecting thermal performance like receiver geometry and receiver orientation are reviewed in this paper based on the literature available. It is also observed that conical shaped receiver is optimum for better heat flux distribution on the surface and also having high thermal performance (Daabo

Fig. 29 Changes in thermal efficiency with respect to wind velocity and wind condition (Avargani et al. 2020)
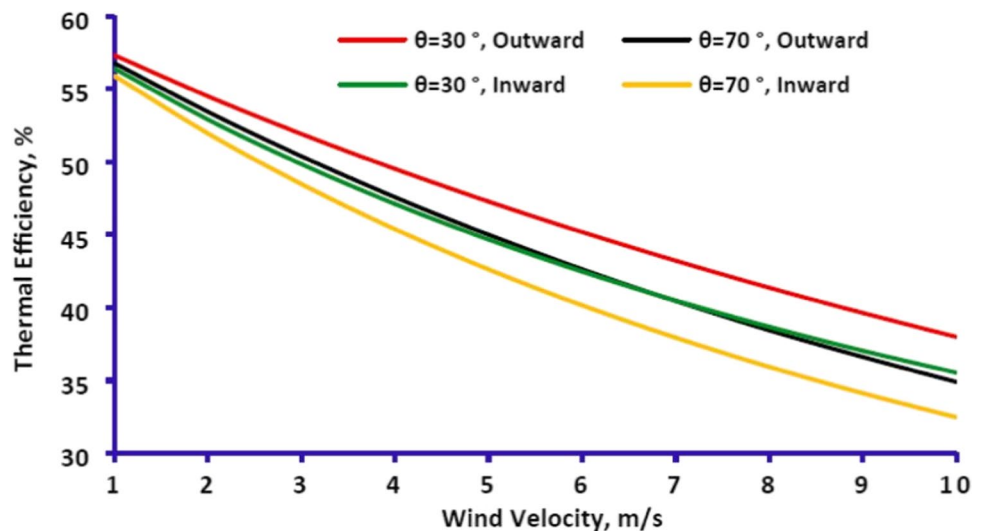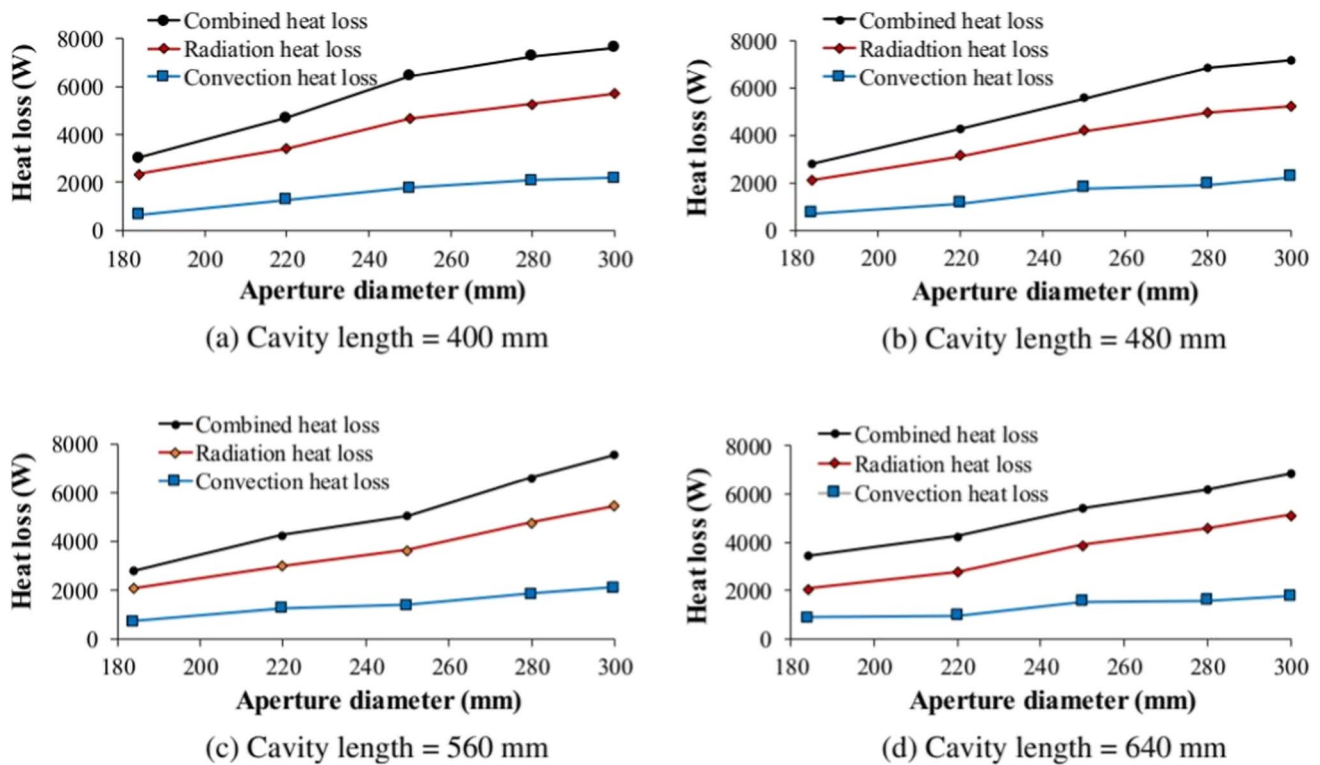
Fig. 30 Heat loss in receiver for varying cavity length and aperture diameter (Zou et al. 2017)

et al. 2016a). Also, it is observed that hemispherical shaped receiver is having high outlet temperature with use of nanofluids as heat transfer fluid. From the literature, it is found that nanofluids are used to improve thermal performance of the from 10 to 13% in place of regular heat transfer fluids (Loni et al. 2017). Few studies are also concentrated on the ray-tracing methods to estimate heat flux distributed on the receiver surface. This ray-tracing helps to reduce experimental coat and time to find out optimum design parameters. Applications that use parabolic dish solar concentrator as a heat source are also reviewed, and one of the major applications like desalination is discussed in the review.

Receiver orientation and receiver shape are the key points to improve the efficiency of the parabolic dish solar concentrator system. It is observed that research in this area is not focused into deep. There are some gaps in this area that should be focused. Based on the previous research work, some of the areas that are recommended for further research are as follows.

Recommendations.

- Minimize entropy generation for different shapes of cavity receiver at steady and unsteady weather conditions.
- Effects of solar irradiation distribution on the inner surface of receivers having varying shapes at different rim angles of concentrators.

- Study and comparison on the behavior of receivers having various shapes with respect to the convective heat losses at different positioning angles.
- To observe the changes in the output temperature of the working fluid in the receiver for different heat transfer fluids at different positioning angles of the receiver.

Abbreviations

A : Area, m²; C : Concentration ratio; D : Diameter, m; d_f : Height of the receiver, m; f : Focal length, m; g : Gravitational constant, m/s²; Gr : Grashof number; h : Heat transfer coefficient, W/m²K; I_s : Solar irradiation, W/m²; k : Thermal conductivity, W/mK; N_{RC} : Radiation-conduction number; Nu : Nusselt number; Pr : Prandtl number; Q : Heat transfer rate, W; Q_r : Solar heat available at receiver, W; Q_l : Heat loss from cavity receiver, W; Q_s : Solar heat available at concentrator, W; R : Thermal resistance, K/W; Ra : Raleigh number; Re : Reynolds number; S: Shape factor; t : Thickness, m; T : Temperature, K; V_{wind} : Wind speed, m/s

Greek symbols

α_c : Absoptivity; β^l : Volumetric expansion coefficient; ε : Emissivity; η : Efficiency; θ : Acceptance angle; μ : Dynamic viscosity, Pa s; ν : Kinematics viscosity, m²/s;

ρ : Density, kg/m³; ρ_c : Reflectivity; σ : Stefan Boltzmann constant, W/m²K⁴; τ : Transmittance; ϕ : Volume fraction

Subscripts

a : Air; ad : Addition; amb : Ambient; ap : Aperture; con : Concentrator; cond : Conduction; cov : Convection; D : Diameter; f : Base fluid; forced : Due to forced convection; ins : Insulation; natural : Due to natural convection; net : Net; nf : Nanofluid; np : Nanoparticle; o : Optical; outer : Outside of the receiver; rec: Receiver; rim : Rim; s : Surface; ∞ : Environment

Nomenclature

PDSC : Parabolic dish solar concentrator; FEM : Finite element method; CFD: Computational fluid dynamics; ORC: Organic Rankine cycle

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Conflict of interest The authors declare no competing interests.

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