Optical Modeling of a Cylindrical-Hemispherical Receiver for Parabolic Dish Concentrator

Kolli Harish Kumar
Central Mechanical Engineering Research Institute CSIR
Desireddy Shashidar Reddy
Indian Institute of Technology Bombay
Malay Karmakar (malay@cmeri.res.in)
Central Mechanical Engineering Research Institute CSIR https://orcid.org/0000-0002-8541-2391

Research Article

Keywords: Solar thermal energy, parabolic dish concentrator, cylindrical-hemispherical receiver, optical efficiency, ray tracing

Posted Date: November 7th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2174608/v1

Abstract

Among all sub-systems ofa solar thermal energy system, thereceiverplays a major role while getting the heat energy from the concentrator. The reliability of such systems depends on the amount of solar energy being collected by the receiver, which ismainlycharacterised by the optical parameters likefocal length, aperture diameter, surface absorptivity and slope error. In this paper,the optical analysis of a cylindrical-hemispherical type receiver coupled with a3m diameter parabolic dish concentrator has been discussed. The studyhas been carried out using SolTracesoftware by varying the parameters likereceiver aperture diameter (D_a) ranging from 0.125 to 0.162 m, surface error of the concentrator from 1.7453 to 34.907mrad and also surface absorptivity (α) from 75% to 95%for different receiver distances(H) ranging from 1.7 to 1.95m. From the simulation results, it is observed that the optical efficiency is maximum when the receiver distance is 1.85m for receiver aperture diameter of 0.150 m for the given system. Increase in the slope errors from 1.7453 to 17.453 mrad decreases the average optical efficiency by almost 50% for all receiver diameters.It is alsonoticed that uniform heat flux distribution can be achieved when the position of the receiver is maintained at H = 1.85 m from the concentrator for the given receiver diameterand surface absorptivity of the receiver of 0.150 m and 95% respectively.The simulated results of heat flux intensity on the receiver surface are then compared and validated by the experimental results available in literature. The simulatedoptical efficiency of the presentreceiver is also found to be 8% higher when it is compared with a conventional cylindrical receiver having similardimensions.

Highlights

1. The manuscript investigates the various performance parameters affecting the optical efficiency of a cylindrical-hemispehrical type receiver used in a solar thermal system having a parabolic dish concentrator, as there is very limited information available specially on this type of receiver in published literature.
2. The present investigation is based on simulation study considering the present system and the obtained results are briefly highlighted below –

a. The effect of receiver aperture diameter was investigated with varying receiver diatances from the concentrator and it was observed that the optical efficiency is maximum when the receiver is maintained at 1.85m for receiver aperture diameter of 0.150 m.
b. It was observed that higher slope error of the concentrator deteriorates the optical efficiency. The simulated results show that the average decrease in the optical efficiencies is about 50% for increase in slope errors from 1.7453 to 17.453 mrad for all receiver diameters.
c. The receiver absorptivity was also found to influence the optical efficiency and it was seen that the receiver having 95% absorptivity has the optical efficiency is 62.31%.

3. The simulated results of heat flux intensity on the receiver are compared and validated by the experimental results available in literature.

4. In this manuscript, the performance of the cylindrical-hemispherical receiver has also been compared with a conventional cyldrical receiver with similar dimensions and it was observed that the present receiver is 8% more optically efficient than a conventional cylindrical receiver for the given range of parameters.

1. Introduction

Nowadays, the solar energy is considered asthebest alternative source to the fossil fuels which mainly causes global warming. Concentrating solar energy collectors are one of the emerging ways for harnessing solar thermal energy. According to Kumar et.al. (2022), the parabolic dish concentrator (PDC) is in top position due to its high concentration ratios.In such systems, the concentrator helps to collect and concentrate the solar rays at the focal point. Comparing with other solar concentrating systems, PDC system can generate higher temperature of the fluid flowing through the receiver placed at the focal point.The receiver acting like a heat exchanger is placed at the focal point of the concentratorand absorbs the heat energy from the concentrated rays and releases heat to the heat transfer fluid. The exchange of heat energyto the heat transfer fluid to receiver determines the overall efficiency of the PDC system, and this is why proper optical modelling is important for the system.

The optical modelling helps to reduce the experimental expenditure and time. In recent times,Sagadeet.al (2013)had done the optical analysis of a parabolic dish solar water geyser systemusing SolTrace software where the distribution of heat flux on the individual coils has been shown for the conical shaped receiver.Le Roux et.al (2014)used ray tracing and receiver modelling technique method to find the optimum area ratio of receiver to concentratorhaving rim angle of 45° with optical error as 10 mrad and tracking error of 1°. The rectangle cavity receiver in a small scale solar thermal Brayton cycle is used for this study. And the optimum receiver to concentrator area ratio is obtained as 0.0035. Reddy et.al (2015)usedSolTrace software to study the focal image characteristics of a fuzzy focal solar dish collector. The results of this study is useful to design a suitable receiver for the dish collector system.Ken J Craig et.al (2016)also studied tubular receiver used in Brayton cycle using combined CFD and SolTrace to evaluate absorbed solar radiation on the surface of the tubes. They explained the approach of importing complex geometries generated in CFD to Monte Carlo Ray Tracing Method (MCRTM).Li et.al (2016)studied optical performance of a PDC and cavity receiver system using MCRTM. Effects of geometrical and surface properties like diameter ratio, height ratio and absorptivity of the cavity receiver are analyzed with respect to its optical performance. From the results, it is observed that optical efficiency of simulated results and results obtained from correlations are complimenting each other.Zou et.al (2017)studied the effect of geometric parameters on the thermal performance for a cylindrical cavity receiver. The distribution of heat flux on the receiver surface was shown using Soltracesoftware and the heat losses are calculated using ANSYS.Pavlovic et.al (2017) investigated PDC system with a spiral receiver numerically and experimentally. They used OptisWorks ray tracing software to analyze solar ray distribution on the receiver surface. The developed thermal model is solved by using Engineering Equation Solver (EES). In other research work,Pavlovic et.al (2018) analyzed optical, thermal and exergetic performance of spiral and conical cavity receivers. An optical tool was used to simulate the PDC and they combined it with the thermal modelling and then validated them with the experimental results. Optical efficiency of the conical receiver is found to be 1.38% more than spiral receiver's optical efficiency.

Soltaniet. al (2019)have combined the computational fluid dynamics (CFD) and raytracing method for estimating optical thermal modelling of cylindrical receiver with helically baffled annular space. They used ANSYS for the CFD modelling and SolTrace as primary software for ray tracing. They have shown that thermal performance of the receiver was increased up to 65% with respect to change in aperture diameter and focal length. Cherif et.al (2019)conducted the parametric study of a PDC system using SolTrace software to find out the best configuration for achieving the optimal performance.Craig et. al (2020)usedSolTrace software to analyse the total heat flux distribution on a tubular cavity receiver and also found out the amount of heat that is absorbed by the receiver walls at various inclination angles. It is observed that optical efficiency of the receiver was around 70%.Sasidharan and Dutta (2021) have also done characterization of flux distributed at focal point for a shuffler type concentrator. They showed that the average flux density generated from the experimental setup is matched with the flux value which is spatially resolved from numerical analysis. LeivaButtiet.al (2021)modeled a solar biomass gasifier using MCRTM where the heat flux distribution on the cylindrical cavity receiver was evaluated using SolTrace software. Effect of variables like solar absorptance, reflection type of the receiver and tracking error on the flux distribution is explained.

Few research works are also focussed on the variation of optical efficiency with respect to the receiver geometry. Johnston (1998) had done experimental and theoretical analysis of a 20 m^2 PDC to characterize the focal image of the system. Experimentally measured flux distribution is compared with the fluxes generated by ray tracing algorithm for different slope errors.Daabo et.al (2016)compared thermal and optical behavior of three different geometries of the receivers. OpticWorks software was used for raytracing analysis and CFD was for thermal modeling. Analysis was done on the basis of two optical parameters like shape of the receiver and absorption ratio which were affecting the focal point region of the concentrator.Daabo et.al (2017),in other work, used similar shaped receiver geometries used in previous work and analyzed optical efficiency using raytracing and CFD. In this work the optical parameters considered were pitch of the tube coil used in the receiver and the tube diameter.Zou et. al (2017)used MCRTM to solve heat flux distribution and absorptancy of a cylindrical cavity receiver. The analysis has been done on three critical properties of the cavity receiver like aperture diameter, focal length and number of coil loops in the receiver.Si-Quan et.al (2019)analyzed spherical cavity receiver using MCRTM for optical performance of the receiver. Reflected ray losses and optical efficiency with respect to the focal length region have been analyzed with the ray tracing analysis.

Xiao et.al (2019) had done optical efficiency of a conical receiver using TracePro software. Effects of geometrical parameters like cone angle of the receiver, number of loops in the helical tube and the focal point of the concentrator were studied. Zhang et.al (2020)had done performance optimization of a conical receiver using both optical and thermal modelling. Optical analysis is done using TracePro software and then coupled with ANSYS for CFD analysis. Parameters like receiver's cone angle, insulation thickness and number of loops influencing optical efficacy are analyzed in this work. From the data it was observed that with increase in the cone angle and number of loops of the receiver, the optical efficiency is decreased by around 1%.MadadiAvargani et.al (2020)had done thermal analysis of cylindrical cavity receiver using CFD and ray tracing methods. Influence of optical parameter like slope error on the heat flux distribution on the receiver surface is explained in this work. Increase in the slope error of the concentrator from 10 to 35mrad heat flux distribution is reduced by 60% Rajan and Reddy (2022)investigated optical performance of a corrugation cavity receiver used for 1000m^2 PDC. They used ASAP software to study the heat flux distribution and internal reflection of the rays at different optical parameters like focal length, aperture diameter, absorptivity and the tapered angle of the corrugation cavity receiver. Maximum optical efficiency of the receiver is observed as 82.93% at a specific receiver position.

In the available literature, it isseen that how the geometrical and optical parameters of receiver determine the efficiency of the receiver used in PDC system. Most of these studies are focussed on the parameters like shape, height and absorptance of receivers. However, there are only very few papers which are focused on hemispherical-cylindrical typereceiverand the availableinformation are notsufficient. Apart from this, theslope error of the concentrators, also an important parameter that affects uniformity of the heat flux, has not been discussed much in previous literature.

In the present work, the focus has been given to study theeffect of parameters like aperture diameter (D_a), receiver distance from the concentrator(H), surface absorptivity (α) and slope error (θ_s) on the optical efficiency of a cavity receiver havingcylindrical-hemispherical type shape.In this type of receiver, the upper part of the receiver is hemispherical in shape and the lower portion is cylindrical.Since the present study focuses on the optical efficiency of the receiver, the work primarily highlights the helical coil tube without considering insulation on its outer surface. The optical efficiencies of such hemispherical-cylindrical typereceiveristhencompared with that of conventional cylindrical receiver having similar dimensions.In addition, the slope error which is also an important characteristic of the concentrator surface and is less discussed in the previous research works, has also been considered for finding out its effect on the optical efficiency.

2. Methodology

In this study, the solar thermal system consists of a parabolic dish concentrator (PDC) with a cavity receiver of cylindrical-hemispherical typeas shown in Fig. 1. Such a cylindrical-hemispherical type receiver has a cylindrical body with a hemispherical top. This type of cavity receiver is very unique in shape when it is compared with other receiver geometries described in published literature.

The aperture diameter of the concentrator is taken as 3m and therim angle is considered as 45^{o}in order to achieve the maximum efficiency (Daabo et.al 2016a). The direct normal irradiation (DNI) is taken as 1000W/m^2. The height of the receiver is taken as 0.152m and the receiveraperture diameter is varied from 0.125m to 0.162m as shown in Fig. 2.The receiver has 12 turns of coils with inner and outer coil diameters of 10 mm and 11 mm respectively. Since the focal length of the present system is 1.8 m, the receiver distance from the concentrator hasbeen maintained in the range from 1.7m to 1.95m.

The surface reflectivity of the concentrator is set at 96% and three different slope errors 1.7453, 17.453, 34.907mrad (MadadiAvargani et.al 2020) for the concentrator have been considered in the optical analysis. Other optical parameters like surface absorptivity of the receiver has been considered ranging from 0.75 to 0.95. For this work, the concentrator errors like specular, sun shape, tracking error, etc. have not been consideredas per Daabo et.al 2016(b).The design parameters of the present solar thermal system is given in Table 1.

Table 1
Parameters considered in present study

Parameters	Symbol	Value	Units
Concentrator diameter	D_c	3	m
Focal length	f	1.8	m
Rim angle	φ	45	o
Reflectivity of dish	ρ_c	0.96	-
Slope error of the dish	θ_s	1.7453–34.907	mrad
Receiver distance from the concentrator	H	1.7–1.95	m
Receiver diameter	D_a	0.125–0.162	m
Receiver height	h	0.152	m
Receiver absorptivity	α	75%- 95%	-
Irradiation	DNI	1000	W/m^2

3. Mathematical Formulation

This section describes the basics of mathematical model and the optical efficiencyfor the PDC system coupled with a cylindrical-hemispherical typereceiver. The parabolic dishconcentratesthe solar irradiation at a point where the receiver is placed to collect that radiation. The distance between the concentratorbase to the focal point, known as focal length,is an important parameter to determine the efficiency of the overall system (Kumar et.al 2022). With respect to the aperture diameter of the concentrator (D_c) and the rim angle (φ), the focal length (f) of the concentrator can be presented as per Eq. 1.

$$f=\frac{D_c}{4\tan\left(\frac{\phi}{2}\right)}$$

1

The receiver, being the core of the system, plays a major role in determining the overall efficiency. The Eq. 2 gives the relation of receiver aperture diameter (Da)with acceptance angle (θ), focal length (f) and rim angle (φ) as shown below.

$$D_a=\frac{f\times\theta}{\cos\phi\,(1+\cos\phi)}$$

2

Again, the amount of heat absorbed by the fluid while flowing through the annular space of receiver with respect to the total solar radiation heat that concentrates on the receiver surface defines the efficiency of the receiver. This energy conversion helps to find out the optical efficiency ($\eta_{optical}$) of the receiver which is calculated from Reddy et.al 2022 using Eq. 3 as stated below.

$$\eta_{optical}=\frac{Q_{absorber}}{Q_{total}}$$

3

Where, $Q_{absorber}$and Q_{total} are thetotal solar radiation absorbed by the receiver surface and solar energy input from the concentrator.The total heat flux absorbed by the receiver using direct and indirect solar radiation concentrating on its surface is represented by Eq. 4.

$$Q_{absorber}=Q_d+Q_{ref}$$

4

Where, Q_d and $Q_{ref}$are the solar radiation absorbed by the receiver surface directly and indirectly respectively.Since the receiver surface is not a perfect absorber, there are other characteristics like reflection phenomenon on the surface and as a result, the reflected radiation is measured on the surface for single and multiple times using Eq. 5 as given below.

$$Q_{ref}=Q_{1,ref}+Q_{n,ref}$$

5

Where, $Q_{1.ref}$ and $Q_{n,ref}$ are the reflections of the indirect radiation for the first and multiple times on the receiver surface.

4. Optical Analysis

In this work, SolTrace ray tracing software,for it’s high accuracy and low computational cost, has been used for optical analysis of the receiver.This SolTrace softwareuses MCRT method to perform the analysis shown in Fig.3(K.J.Cragi et.al 2020). This method is very useful which involves tracing the vectors through the space, where it calculates the ray direction until it hits the surface and absorbed by the surface (K.J.Cragi et.al 2016).Pillbox sunshape distribution has been considered in this study for distributing and analyzing the solar irradiation.

Since the constructionof complex geometries like circular shape concentrator usingSolTracesoftwareis not easy, MATLAB or Python codeis used to convert such complex geometries into finite number of elements(K.J.Cragi et.al 2016). The process flow chart for modeling of optical efficiency isshown in Fig.4. TheCAD model of the receiver is exported to ANSYS to generate mesh file and the generated data is reinterpreted using MATLAB before exporting it into SolTrace software which works on MCRTM. The surface properties of the receiver and the concentrator are consideredas perrequirement of themodel.

While carrying out the optical modeling, it is important to determine the number of rays that interacts with the receiver surface.Fig. 5 shows the ray sensitivity analysis of the receiver geometry and it is observed that the absorbed heat flux is0.53% more in case of 0.2 million rays.So, the number of rays that have been considered for the present analysis is 0.2 million. During the analysis, the data file of ray interactions is generated using SolTrace software which is further converted into heat fluxdata file of individual ray using MATLAB script. The heat flux ray data is then exported to ANSYS fluent to give rise the total heat flux absorbed on the receiver surface.

5. Validation Of The Presentoptical Model

The results obtained by the presentoptical simulation, which needs to be validated, have been comparedwith the data available in literature (Johnston, 1998).In order to do this, the geometry of the present model having 3m concentratordiameter wasmodified to suit the dimensions of the experimental prototype. The modified diameter of the concentrator was 5m keeping the constant receiver distanceas 1.8m. Moreover, the receiver of the present model was also modified to a circular copper plate having 0.5m diameter to match the dimensions of the experimental set up as mentioned in Johnston, 1998. The modified geometry of the present model thus becomes similar to the Johnston’s experimental model except to the fact that the concentrator in the present study is considered as single reflector unlike facetted mirrors used in experimental model. The value of DNI is taken as 1000W/m^2 in both cases.

Thesimulated results from the present work have been compared with the experimental data (Johnston, 1998) as shown in Fig. 6 (a). This figure also shows that the comparison of present simulation results with simulation results from published literature (Rajan and Reddy, 2022) which are found to be good in agreement. The Fig. 6(b) shows thatthe solar heat flux ishigher at the center and gradually decreasing towards the periphery. The values of total heat flux for the experiment, literature and the present study are found to be 14.8kW, 14.781kW and 14.768 kWrespectively. It isalso observed that simulation results of heat flux values for both the present work and the work done by Rajan and Reddy, 2022are very much similar in natureand the percentage deviation is 0.09%. However,the experimental results done by Johnston, 1998 showsfewminor peaks near the focal point and the percentage deviation between experimental and present simulation work is found to be 0.22%.The reasons to such deviations may be due to the errors in experimental setup like tracking error, slope error, limb darkening effect error, etc. Wind conditions and environment effects could be the other reasons for such deviations. Therefore, it may be concluded that the results of presentmodelare validatedwith experimental data.

6. Results And Discussion

The present work has been carried out to analyse the effects of receiver aperture diameter,slope errorand the surface absorptivity on the optical efficiency of the receiver with respect to receiver distance from the concentrator. The details of the study are discussed below.

6.1 Influenceof receiver aperture diameter

The proper mounting and appropriate position of the receiver enhances it’s optical efficiency. As the distance from the concentrator increases, the intensity of the heat flux increases upto a certain distance and then it gradually decreases. Fig.7 shows the heat flux distributions on the receiver with varying receiver distance from the concentratorranging from 1.7 to 1.95m.

In Fig. 8, the variations of optical efficiency have been highlighted with varying receiver distance from 1.7m to 1.95m when the receiver aperture diameters are 0.162, 0.150, 0.138 and 0.125m.In the figure, the maximum optical effeicncy is noticed for 0.150 m receiver diameter ata receiverdistance of 1.85m. It is seen that the largerreceiver diametercaptures more solar irradiation with high heat loss from the receiver. Similarly, decrease in aperture diameter also results less absorption of solar irradiation withsignificant heat loss.Maximum optical efficacy is observed as 82.1% for the receiver with the aperture diameter of 0.150m comparing with all the other cases.

6.2 Influence of slope error of concentrator surface

One of the important parameters affecting the optical efficiency is the slope error of concentrator surface. The concentrator with irregular surface causes non uniformity of the rays on the receiver surface and some of the rays are escaped from the receiver to the outer space, which results in non-uniformity in the heat flux distribution. Surfaces with slope error of 0 mrad are also called as ideal surfaces where the solar rays hit the concentrator surface and reflect back perfectly to a point on the receiver surface. Similarly surfaces with slope errors, called real surface, irregularly reflect the solar rays towards the receiver surface. Heat flux distributions of ideal surfacealong with real surface with slope errors 1.7453, 17.453 and 34.907mrad are analysed and shown in Fig.9 for a given receiver distance of 1.7 m.

The Fig. 10(a/b/c/d)show how the optical efficiencies vary with different receiver distances for slope errors of 0, 1.7453, 17.453, 34.907 mrad and also receiver aperture diametersof 0.125, 0.138, 0.150, 0.162

m. It is observed from Fig. 10(c) that the concentrator with ideal surface gives the highest optical efficiency of 82.1% at receiver distance *H* = 1.85m for the receiver aperture diameter of 0.150 m,. On the other hand, from Fig 10(d) it is evident that, for a real surface with slope error of 1.7453 mrad,the receiver's highest optical efficiency is 63.94% at a height of 1.8m for receiver aperture diameter of 0.162m. It isalsoobserved that, at this point, the optical efficiency of a real surface is 2% higher than the ideal surface because of increased ray interactions. It is further noticed that there is a significant drop in the optical efficiencies of the receiverwith increase in the slope errors. Fig. 10(d) shows that, for 1.8m receiver distance, the peak and the lowest optical efficiencies are found to be 63.94% and 4.7% for real surfaces with slope errors 1.7453and 34.907 mrad respectively which shows that almost 59% drop is occurred for variations in slope errors.

The phenomena of absorptivityof a cavity receiver is assessed by the amount of received, reflected and absorbed rays by it'ssurface. With the help of simulation,the distribution pattern of heat flux on the receiver surface can not only be studied, but also it becomes easier to find out the high and dead intensity areas of heat flux on the receiver. In order to get better optical efficiency, the high and dead intensity areas should be eliminated from the receiver. Due to the high concentration of the heat flux, the tube material used in the receiversometimes getsdamaged whichfinally affects the overall performance. Consequently, it becomes necessary to find out the optimal position of the receiver to avoid such phenomena.6.3Influence of absorptivity of the receiver surface

The optical efficiencies of the receiver have been evaluated for different receiver distances (*H*) with receiver diameters (D_a) varying from 0.125 to 0.162 mand also with absorptivity (α) ranging from 75%, 85% and 95%. FromFig.11(a/b/c), it is observed that the nature of simulated results are all similar and the maximum optical efficiency in each case is found to be at *H* = 1.85m for 0.150 m receiver diameter. The simulated optical efficiencies are given in Table.2.

Table.2 Optical efficiency varying with respect to absorptivity

S.No	Absorptivity (%)	Aperture Diameter (m)	Receiver distance from the concentrator (*H*)	Optical efficiency (%)
1	75	0.150	1.85	52.32
2	85	0.150	1.85	54.97
3	95	0.150	1.85	62.31

7. Efficiency Comparison Of Present Receiver With A Conventional Cylindrical Receiver

In the present study, the geometrical parametersof a cylindrical-hemispherical type receiver have beenevaluated to find out its optimized design parameters and these parameters are further compared with a conventional cylindrical receiver having similar overall dimensions. The optical efficiencies of these two type receivers having 0.150 m diametershave been simulated, compared and represented in Fig.12 for different receiver distances varying from 1.7m to 1.95m.From the simulation results,it is observed that the efficiencies of the present cylindrical-hemispherical receiver and the conventional cylindrical receiver are 82.1% and 76.3% under this study which shows that it is nearly 8% higher in case of the cylindrical-hemispherical receiver at H = 1.85m.

This enhancement in the efficiency of cylindrical-hemispherical receiver could be due to more number of internal reflections of the rays with higher absorption of the heat flux, while in case of cylindrical receiver, the internal reflections of the raysare less because of it's open/hollow space at the top, leading to loss of optical efficiency. Therefore, it may be concluded that the cylindrical-hemispherical receiver could be a better alternative option over the conventional cylindrical receiver. Table.3 , however, summarizes the optical efficiencies of other types of receivers found in available literature along with the present receiver.

Table.3 Optical efficiency comparison of present study with literature

Study	Receiver shape	Max. Optical efficiency
Wang et.al (2013)	Cylindrical receiver	72%
Daabo et.al (2016a)	Conical receiver	75.3%
Pavlovic et.al (2016)	Spiral receiver	80%
Dahler et.al (2018)	Solar reactor receiver	59.6%
Bellos et.al (2019)	Cylindrical receiver	81.34%
	Rectangular receiver	80.11%
	Spherical receiver	78.78%
	Conical receiver	80.96%
Hassan et.al (2021)	Cylindrical receiver	67.6%
Present study	Cylindrical-hemispherical receiver	82.1%

8. Conclusions

In this present study, the optical modeling of a cylindrical-hemispherical cavity receiver, which is used in solar thermal systems, has been performed. In order to do the modeling analysis, SolTracesoftware has been used that adoptsthe MCRT Method to evaluate the heat flux distribution over the receiver surface. Three optical parameters - aperture diameter of the receiver, surface absorptivity of the receiver and slope error of the concentrator are considered to investigate the optical efficiency at different receiver distances. The obtained results from the simulation study are briefly highlighted below.

i. The optical efficiency of the cylindrical-hemispherical receiver for an ideal surface is found to be maximum as 82.1% at $H = 1.85$mtaking it's aperture diameter of 0.150m.

ii. It has been observed that the slope errors of the concentrator largely effect the heat flux distributions on the receiver surface. It has been seen that the concentrator with1.7453 mrad slope error has the highest optical efficacy of 63.94% for 0.150m receiver aperture diameter when the receiver distance is maintained at1.85 m. However,the simulated results show that the average decrease in the optical efficiencies is about 50% for increase in slope errors from 1.7453 to 17.453 mrad for all receiver diameters.

iii. It is alsoobserved that uniform heat flux distribution can be achieved when the positionof the receiver from the concentrator is maintained at H = 1.85m for 0.150 m receiver diameterconsidering 95% surface absorptivity of the receiver.

The simulated results of heat flux intensity on the receiver are compared and validated by the experimental results available in literature where about 0.22% deviations has been noticed. In this study, the performance of the cylindrical-hemispherical receiver is also compared with a conventional cyldrical receiver with similar dimensions. 8% increase in the efficiency of the present receiver is observed over the conventional cylindrical receiver. The findings from the present investigation may be useful to the researchers for further evaluatingof the performace of the cylindrical-hemispherical receiver.

Nomenclature

D_c	**Aperture diameter of the concentrator (m)**
D_a	Aperture diameter of the receiver (m)
f	Focal length (m)
H	Receiver distance from the concentrator (m)
I	Incident solar heat flux (W/m^2)
$Q_{absorbed}$	Absorbed heat by the receiver (W)
Q_{solar}	Solar energy input for receiver (W)
Q_d	Radiation absorbed by the receiver directly (W)
Q_{ref}	Radiation absorbed by the receiver indirectly (W)
Greek Symbols	
Θ_s	Slope error of the concentrator (mrad)
φ_{rim}	Rim angle
α	Absorptivity
ρ_c	Reflectivity of the concentrator
$\eta_{optical}$	Optical efficiency
Abbreviations	
ASAP	Advanced System Analysis Program
CFD	Computational Fluid Dynamics
DNI	Direct Normal Irradiation
MCRTM	Monti Carlo Ray Tracing Method

Declarations

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material.

Authors' Contribution:

Kolli Harish Kumar: Conceptualization and writing - original draft preparation

DesireddyShashidar Reddy: Writing - review and editing

Malay K. Karmakar: Advising - review and editing

“K H K analyzed the data regarding optical efficiency of the Cylindrical – Hemispherical receiver this is the major contribution in writing the manuscript. D S R and M K K reviewed and done the constructive editing for the manuscript. All authors read and approved the final manuscript”.

Ethical Approval:

Not Applicable

Consent to Participate:

Not Applicable

Consent to Publish:

Not Applicable

Acknowledgments: The authors thankfully acknowledge Director, CSIR-CMERI, for kind support and encouragement. CSIR- HRDG, New Delhi may also be acknowledged for granting theCSIR-SRF(2021) Fellowship.

Competing Interests:

The authors declare that they have no competing interests.

References

1. Bellos, E., Bousi, E., Tzivanidis, C., &Pavlovic, S. (2019). Optical and thermal analysis of different cavity receiver designs for solar dish concentrators. Energy Conversion and Management: X, 2(June), 100013. https://doi.org/10.1016/j.ecmx.2019.100013
2. Cherif, H., Ghomrassi, A., Sghaier, J., Mhiri, H., & Bournot, P. (2019). A receiver geometrical details effect on a solar parabolic dish collector performance. *Energy Reports*, *5*, 882–897. https://doi.org/10.1016/j.egyr.2019.07.010
3. Craig, K. J., Slootweg, M., Le Roux, W. G., Wolff, T. M., & Meyer, J. P. (2020). Using CFD and ray tracing to estimate the heat losses of a tubular cavity dish receiver for different inclination angles. *Solar Energy*, *211*(October), 1137–1158. https://doi.org/10.1016/j.solener.2020.10.054
4. Craig, Ken J., Marsberg, J., & Meyer, J. P. (2016). Combining ray tracing and CFD in the thermal analysis of a parabolic dish tubular cavity receiver. *AIP Conference Proceedings*, *1734*(May 2016). https://doi.org/10.1063/1.4949061
5. Daabo, A. M., Mahmoud, S., & Al-Dadah, R. K. (2016a). The effect of receiver geometry on the optical performance of a small-scale solar cavity receiver for parabolic dish applications. *Energy*, *114*, 513–525. https://doi.org/10.1016/j.energy.2016.08.025

6. Daabo, A. M., Mahmoud, S., & Al-Dadah, R. K. (2016b). The optical efficiency of three different geometries of a small scale cavity receiver for concentrated solar applications. *Applied Energy*, *179*, 1081–1096. https://doi.org/10.1016/j.apenergy.2016.07.064
7. Daabo, A. M., Mahmoud, S., Al-Dadah, R. K., & Ahmad, A. (2017). Numerical investigation of pitch value on thermal performance of solar receiver for solar powered Brayton cycle application. *Energy*, *119*, 523–539. https://doi.org/10.1016/j.energy.2016.12.085
8. Dähler, F., Wild, M., Schäppi, R., Haueter, P., Cooper, T., Good, P., Larrea, C., Schmitz, M., Furler, P., & Steinfeld, A. (2018). Optical design and experimental characterization of a solar concentrating dish system for fuel production via thermochemical redoxcycles.*SolarEnergy*,*170*(May),568–575.https://doi.org/10.1016/j.solener.2018.05.085
9. Hassan, A., Quanfang, C., Abbas, S., Lu, W., & Youming, L. (2021). An experimental investigation on thermal and optical analysis of cylindrical and conical cavity copper tube receivers design for solar dish concentrator. *Renewable Energy*, *179*, 1849–1864. https://doi.org/10.1016/j.renene.2021.07.145
10. Johnston, G. (1998). Focal region measurements of the 20 m2 tiled dish at the Australian National University. *Solar Energy*, *63*(2), 117–124. https://doi.org/10.1016/S0038-092X(98)00041-3
11. Kumar, K. H., Daabo, A. M., Karmakar, M. K., & Hirani, H. (2022). Solar parabolic dish collector for concentrated solar thermal systems: a review and recommendations. In *Environmental Science and Pollution Research* (Vol. 29, Issue 22). Springer Berlin Heidelberg. https://doi.org/10.1007/s11356-022-18586-4
12. Le Roux, W. G., Bello-Ochende, T., & Meyer, J. P. (2014). The efficiency of an open-cavity tubular solar receiver for a small-scale solar thermal Brayton cycle. *Energy Conversion and Management*, *84*, 457–470. https://doi.org/10.1016/j.enconman.2014.04.048
13. Leiva Butti, J. M., Tripp, N. G., Núñez Mc Leod, J. E., & Rivera, S. S. (2021). Effect of surface material properties and operating conditions on the heat flux and temperature distributions in the cavity receiver of a solar-dish-coupled biomass gasification reactor. *Energy Conversion and Management*, *244*. https://doi.org/10.1016/j.enconman.2021.114303
14. Li, S., Xu, G., Luo, X., Quan, Y., & Ge, Y. (2016). Optical performance of a solar dish concentrator/receiver system: Influence of geometrical and surface properties of cavity receiver. *Energy*, *113*, 95–107. https://doi.org/10.1016/j.energy.2016.06.143
15. Madadi Avargani, V., Rahimi, A., Divband, M., & Zamani, M. A. (2020). Optical analysis and heat transfer modeling of a helically baffled cavity receiver under solar flux non-uniformity and windy conditions. *Thermal Science and Engineering Progress*, *20*(February), 100719. https://doi.org/10.1016/j.tsep.2020.100719
16. Pavlović, S. R., Bellos, E., Stefanović, V. P., Tzivanidis, C., & Stamenković, Z. M. (2016). Design, simulation, and optimization of a solar dish collector with spiral-coil thermal absorber. *Thermal Science*, *20*(4), 1387–1397. https://doi.org/10.2298/TSCI160213104P

17. Pavlovic, S., Daabo, A. M., Bellos, E., Stefanovic, V., Mahmoud, S., & Al-Dadah, R. K. (2017). Experimental and numerical investigation on the optical and thermal performance of solar parabolic dish and corrugated spiral cavity receiver. *Journal of Cleaner Production*, *150*, 75–92. https://doi.org/10.1016/j.jclepro.2017.02.201
18. Pavlovic, S., Loni, R., Bellos, E., Vasiljević, D., Najafi, G., & Kasaeian, A. (2018). Comparative study of spiral and conical cavity receivers for a solar dish collector. *Energy Conversion and Management*, *178*(December), 111–122. https://doi.org/10.1016/j.enconman.2018.10.030
19. Rajan, A., & Reddy, K. S. (2022). Optical modeling of corrugation cavity receiver for large-aperture solar parabolic dish collector. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *44*(2), 3330–3348. https://doi.org/10.1080/15567036.2022.2063458
20. Reddy, K. S., Natarajan, S. K., & Veershetty, G. (2015). Experimental performance investigation of modified cavity receiver with fuzzy focal solar dish concentrator. *Renewable Energy*, *74*, 148–157. https://doi.org/10.1016/j.renene.2014.07.058
21. Sagade, A. A. (2013). Comparative experimental analysis of the effect of convective heat losses on the performance of parabolic dish water heater. *International Journal of Sustainable Engineering*, *6*(3), 258–266. https://doi.org/10.1080/19397038.2012.691566
22. Sasidharan, S., & Dutta, P. (2021). Optical characterization of a fixed focus Scheffler reflector for pressurized solar receiver testing. *Solar Energy*, *227*(September), 89–100. https://doi.org/10.1016/j.solener.2021.08.078
23. Si-Quan, Z., Xin-Feng, L., Liu, D., & Qing-Song, M. (2019). A numerical study on optical and thermodynamic characteristics of a spherical cavity receiver. *Applied Thermal Engineering*, *149*, 11–21. https://doi.org/10.1016/j.applthermaleng.2018.10.030
24. Soltani, S., Bonyadi, M., & Madadi Avargani, V. (2019). A novel optical-thermal modeling of a parabolic dish collector with a helically baffled cylindrical cavity receiver. *Energy*, *168*, 88–98. https://doi.org/10.1016/j.energy.2018.11.097
25. Wang, F., Lin, R., Liu, B., Tan, H., & Shuai, Y. (2013). Optical efficiency analysis of cylindrical cavity receiver with bottom surface convex. *Solar Energy*, *90*, 195–204. https://doi.org/10.1016/j.solener.2013.01.017
26. Xiao, H., Zhang, Y., You, C., Zou, C., & Falcoz, Q. (2019). Effects of critical geometric parameters on the optical performance of a conical cavity receiver. *Frontiers in Energy*, *13*(4), 673–683. https://doi.org/10.1007/s11708-019-0630-2
27. Zhang, Y., Xiao, H., Zou, C., Falcoz, Q., & Neveu, P. (2020). Combined optics and heat transfer numerical model of a solar conical receiver with built-in helical pipe. *Energy*, *193*. https://doi.org/10.1016/j.energy.2019.116775
28. Zou, C., Zhang, Y., Feng, H., Falcoz, Q., Neveu, P., Gao, W., & Zhang, C. (2017). Effects of geometric parameters on thermal performance for a cylindrical solar receiver using a 3D numerical model. *Energy Conversion and Management*, *149*, 293–302. https://doi.org/10.1016/j.enconman.2017.06.088

Figures

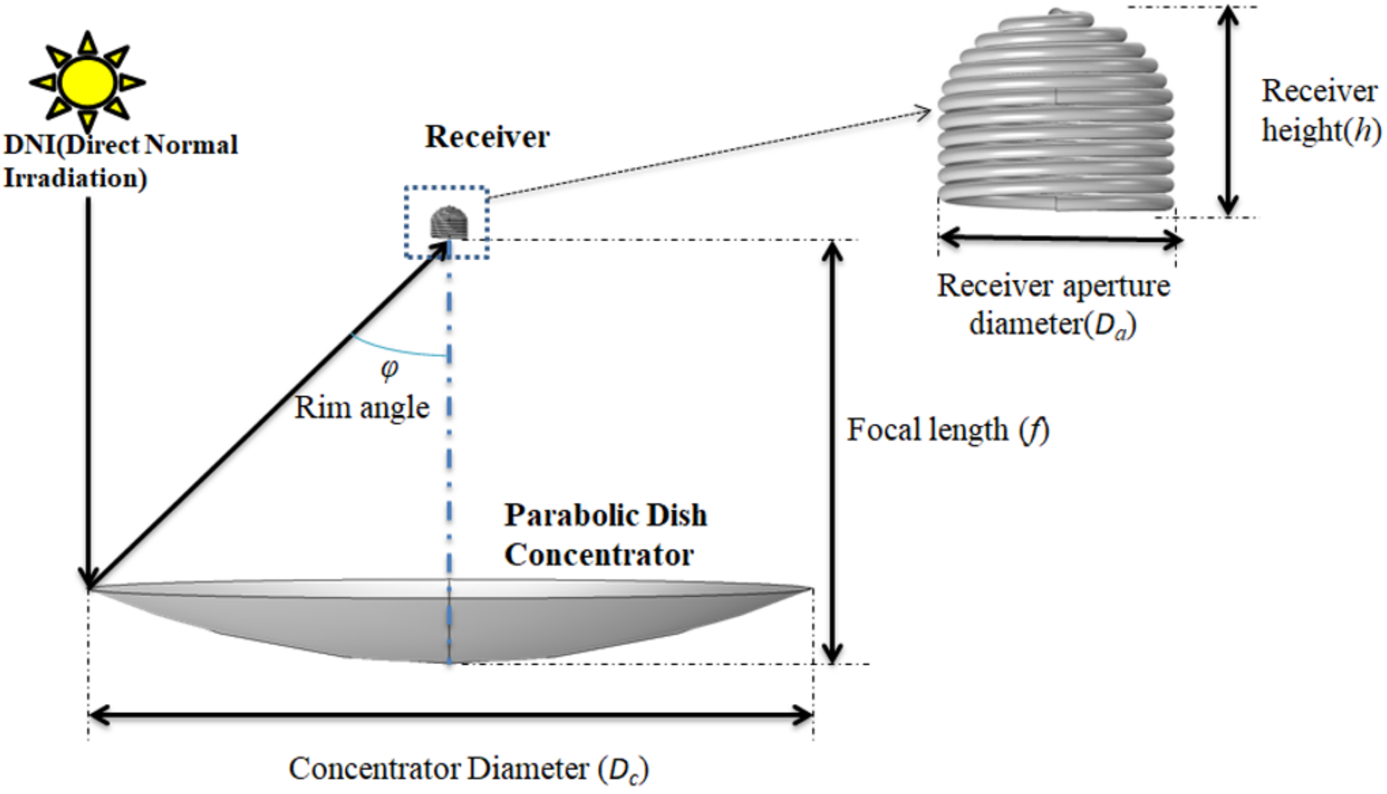
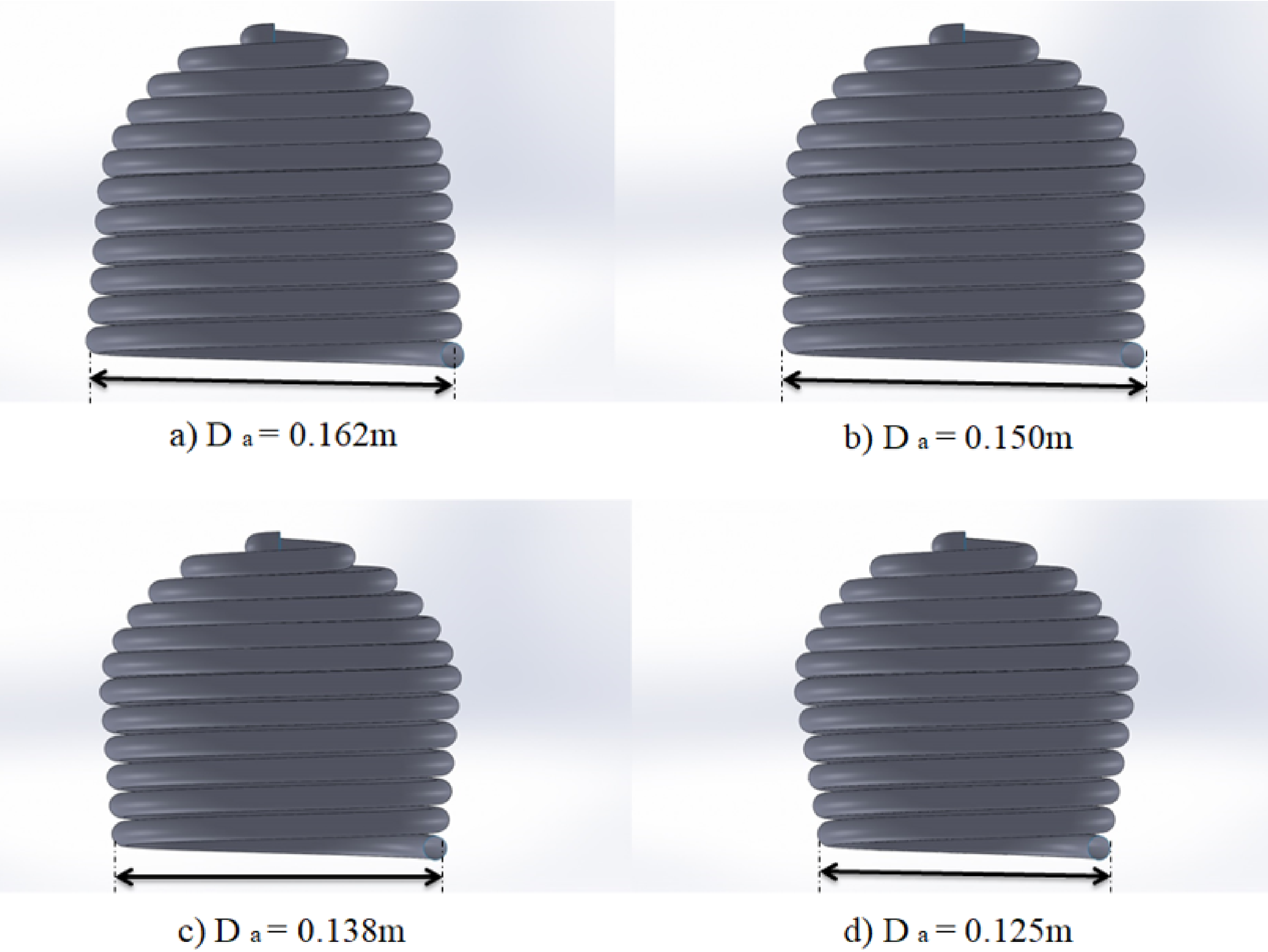


Figure 1

Schematic diagram of parabolic dish and cavity receiver



a) $D_a = 0.162$m

b) $D_a = 0.150$m

c) $D_a = 0.138$m

d) $D_a = 0.125$m

Figure 2

Receiver geometry with varying aperture diameters

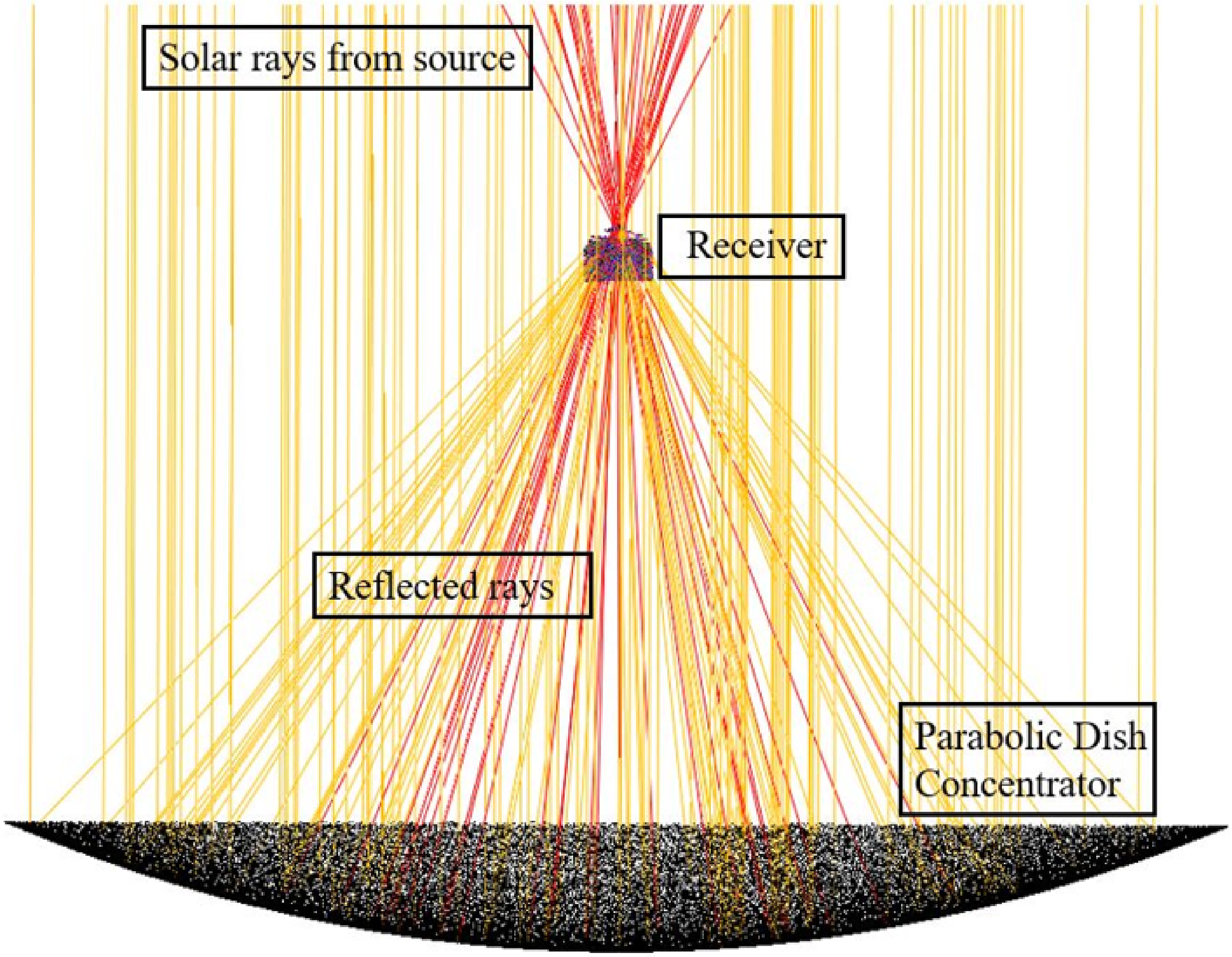


Figure 3

Optical simulation using SolTrace

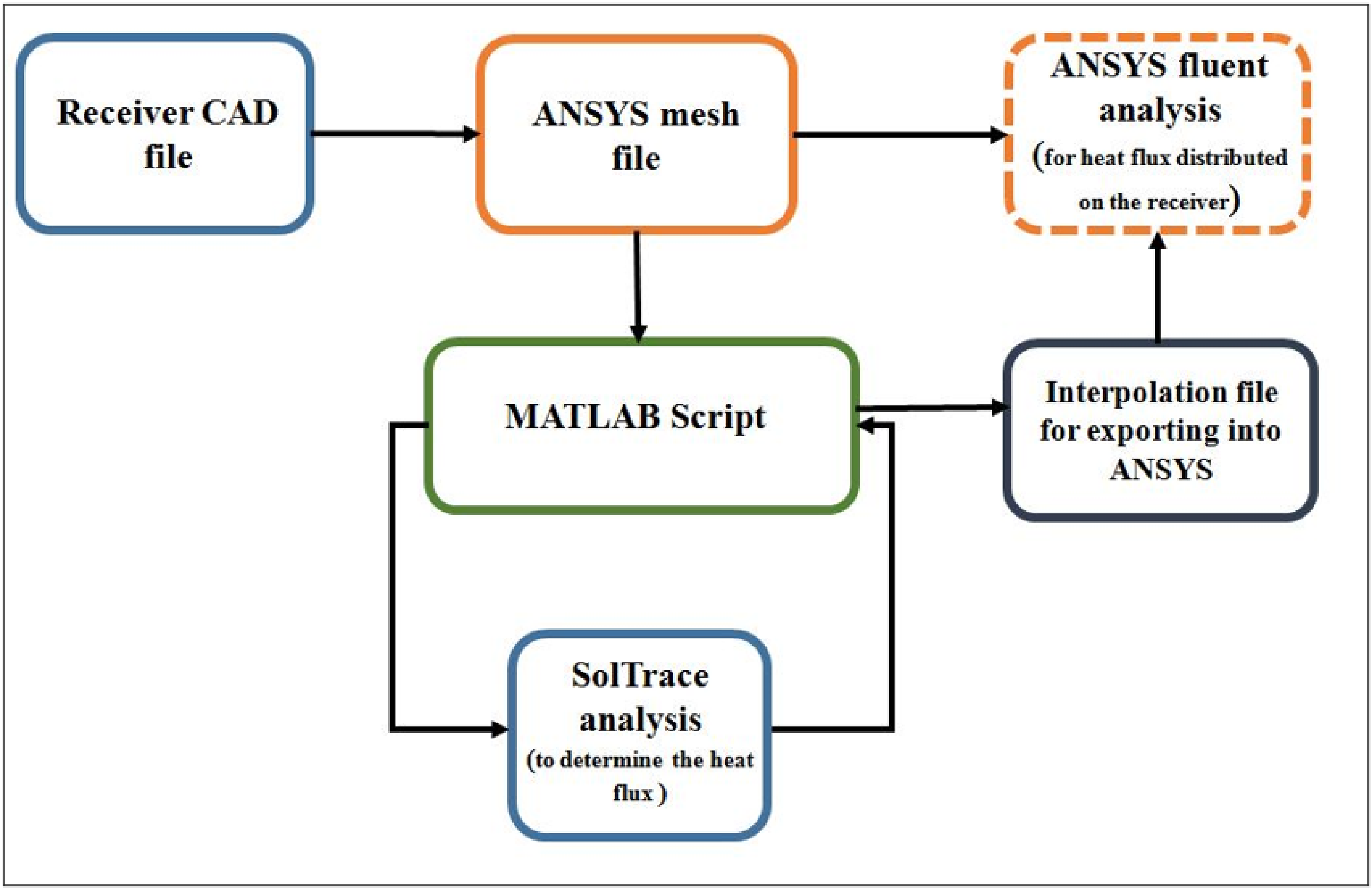


Figure 4

Process flow chart of optical efficiency using ANSYS &SolTracesoftware

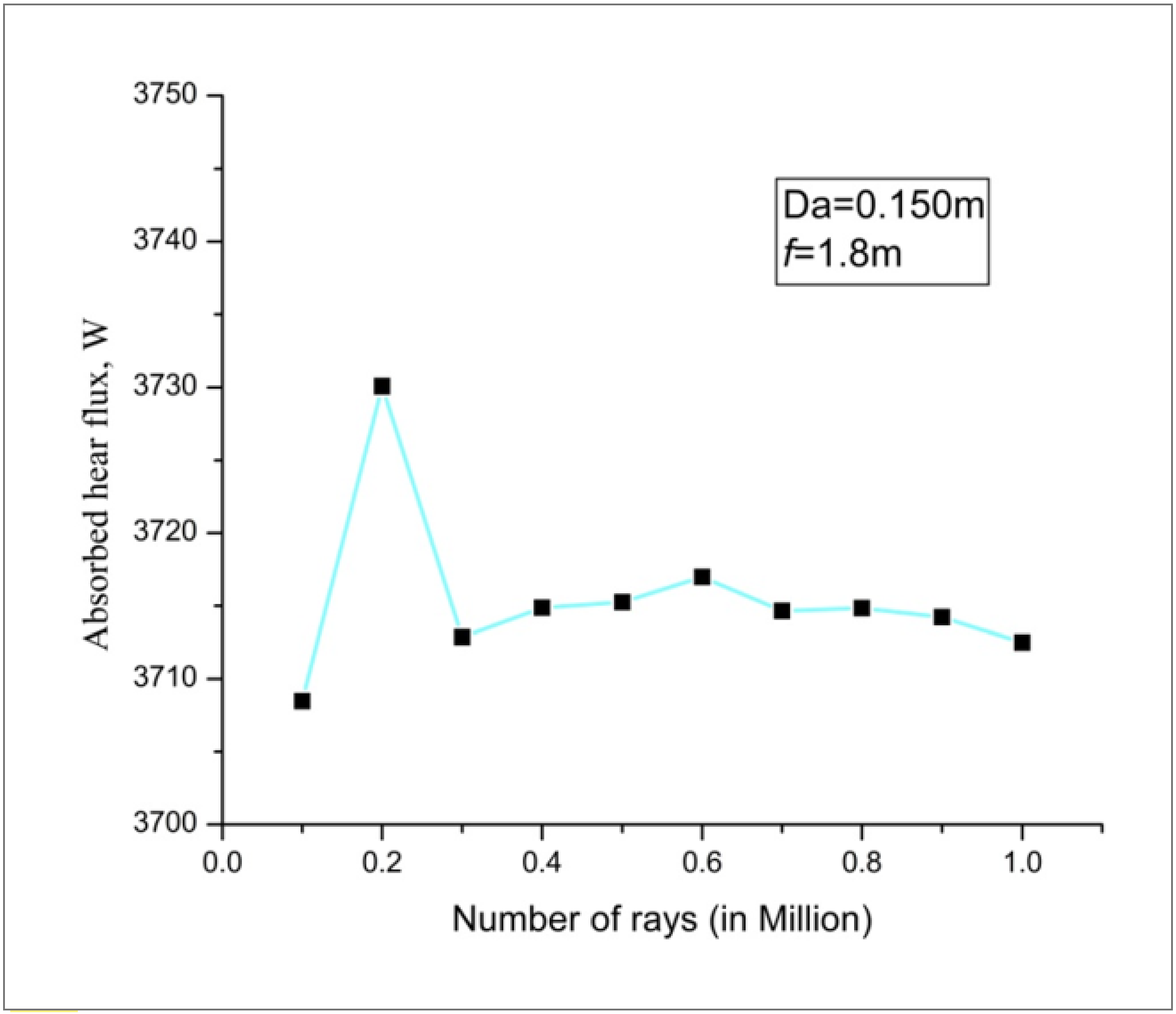
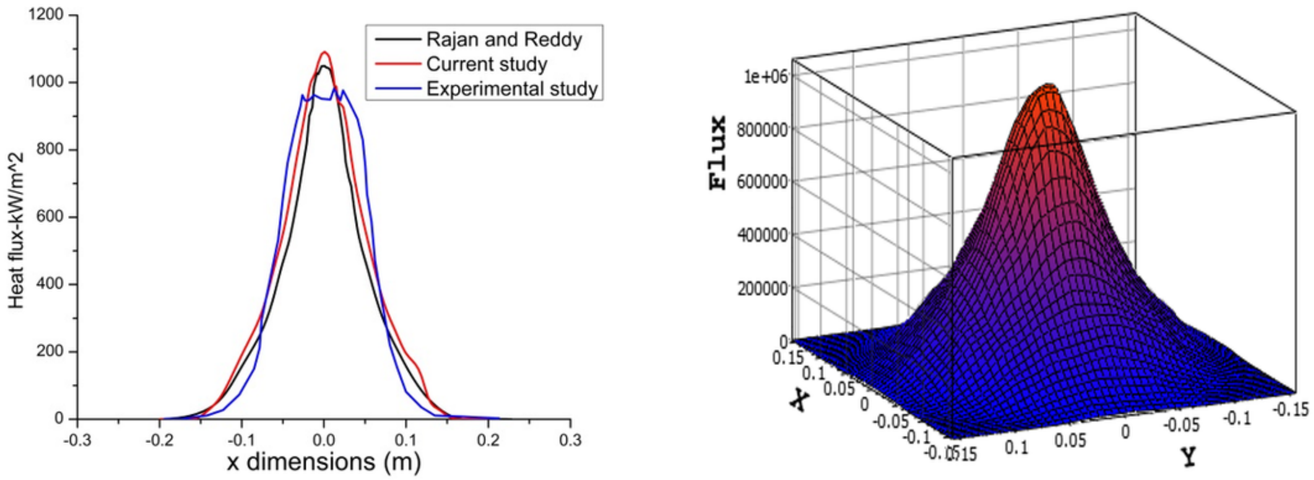


Figure 5

Ray sensitivity analysis for the receiver geometry

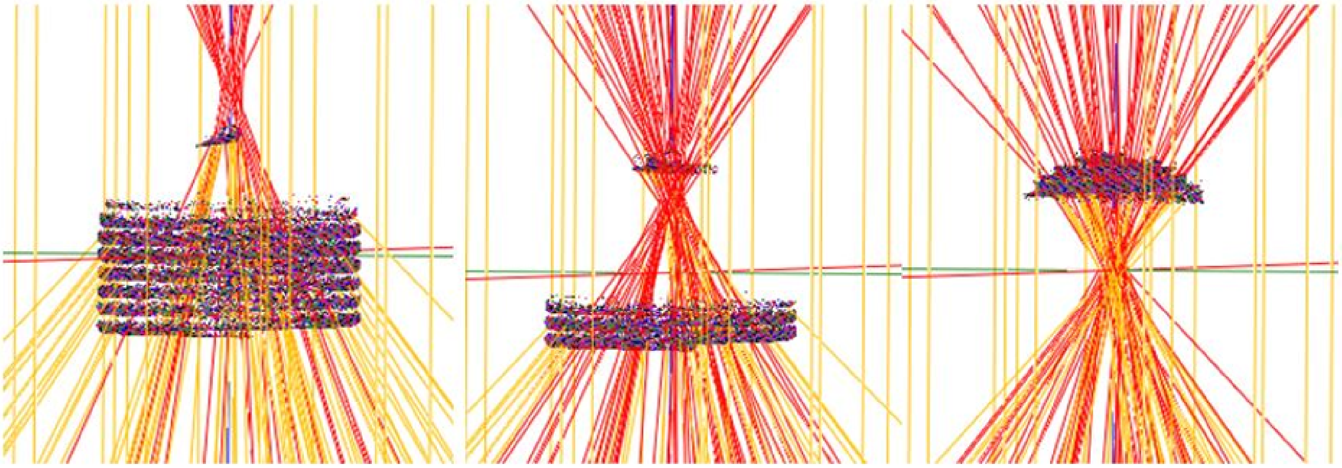


(a)

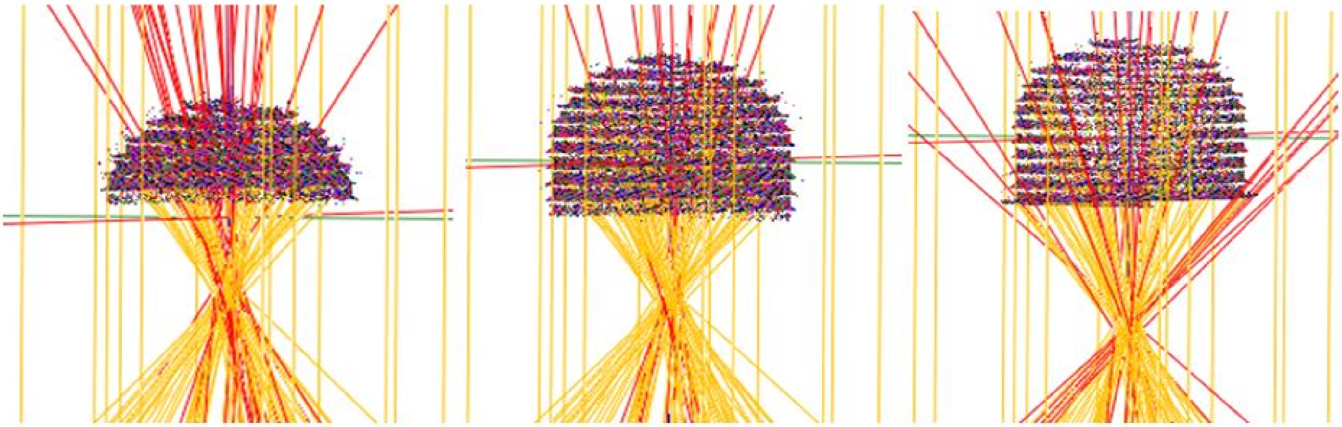
(b)

Figure 6

(a) Comparison between present study, Johnston’s experimental data (1998) & Rajan and Reddy simulation results (2022) (b) Flux mapping of present study usingSolTrace



a) H = 1.7m b) H = 1.75m c) H = 1.8m



d) H = 1.85m e) H = 1.9m f) H = 1.95m

Figure 7

Heat flux distributions for different receiver distance with receiver diameter 0.150 m

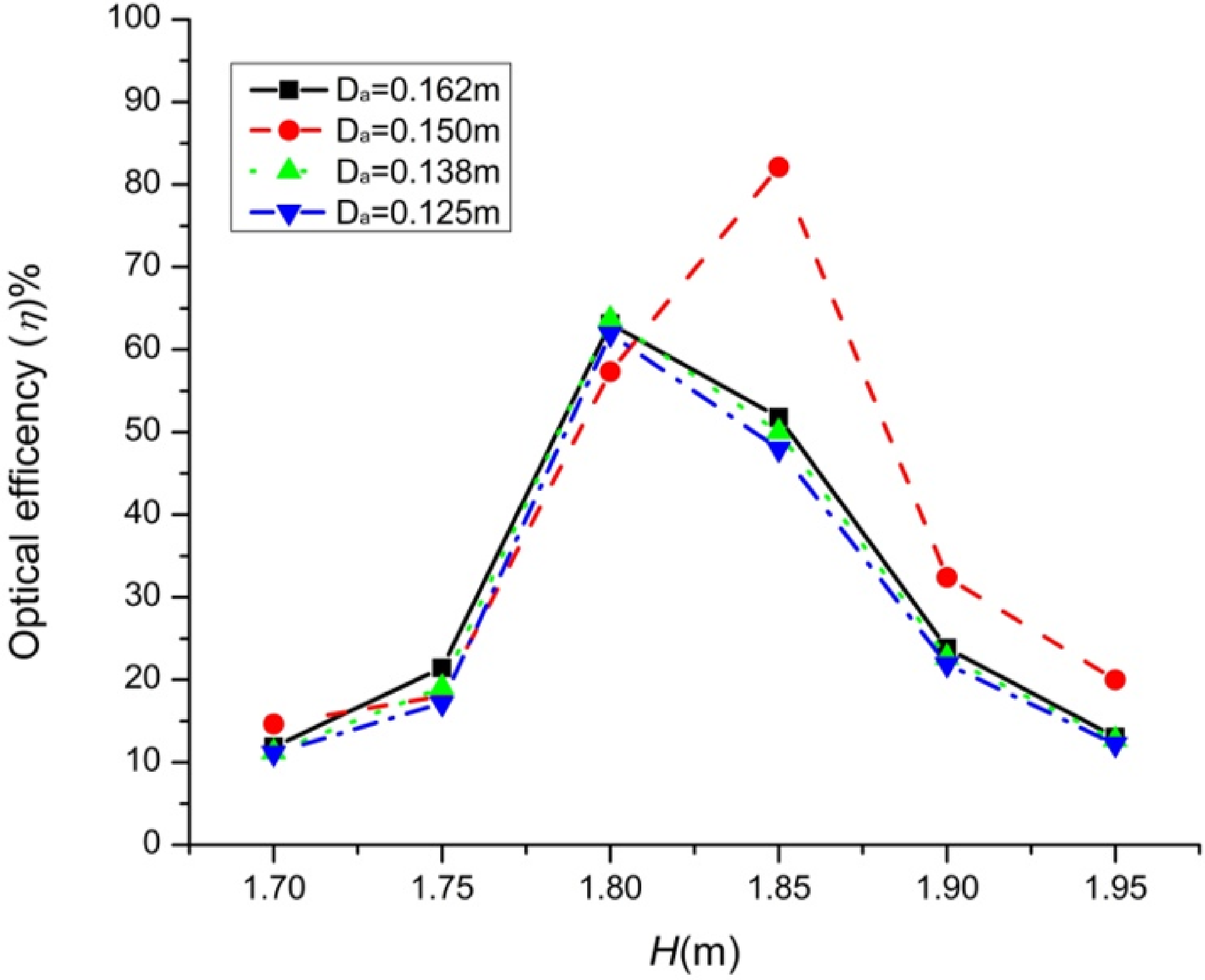


Figure 8

Optical efficiency vs receiver distance for varying receiver aperture diameters

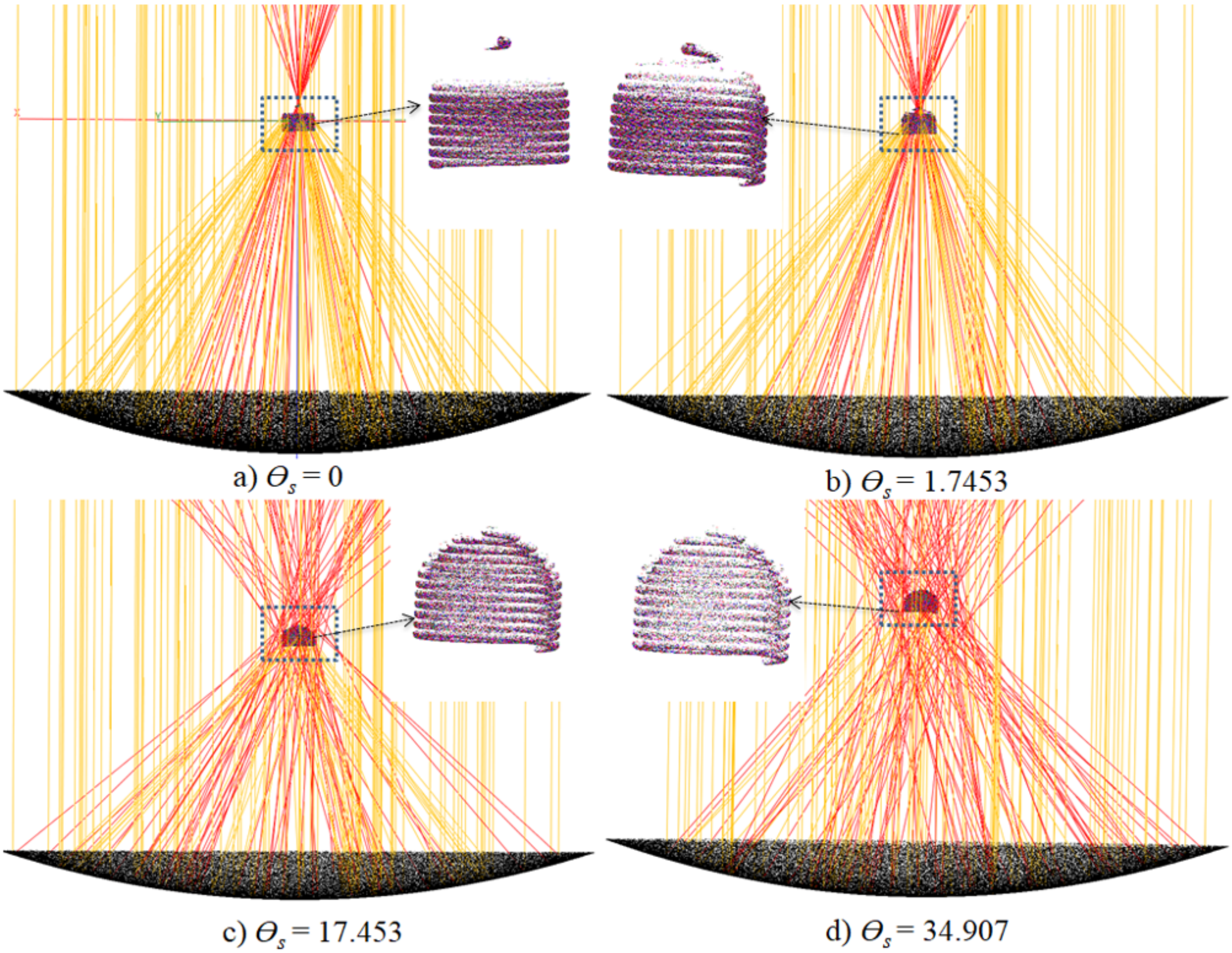
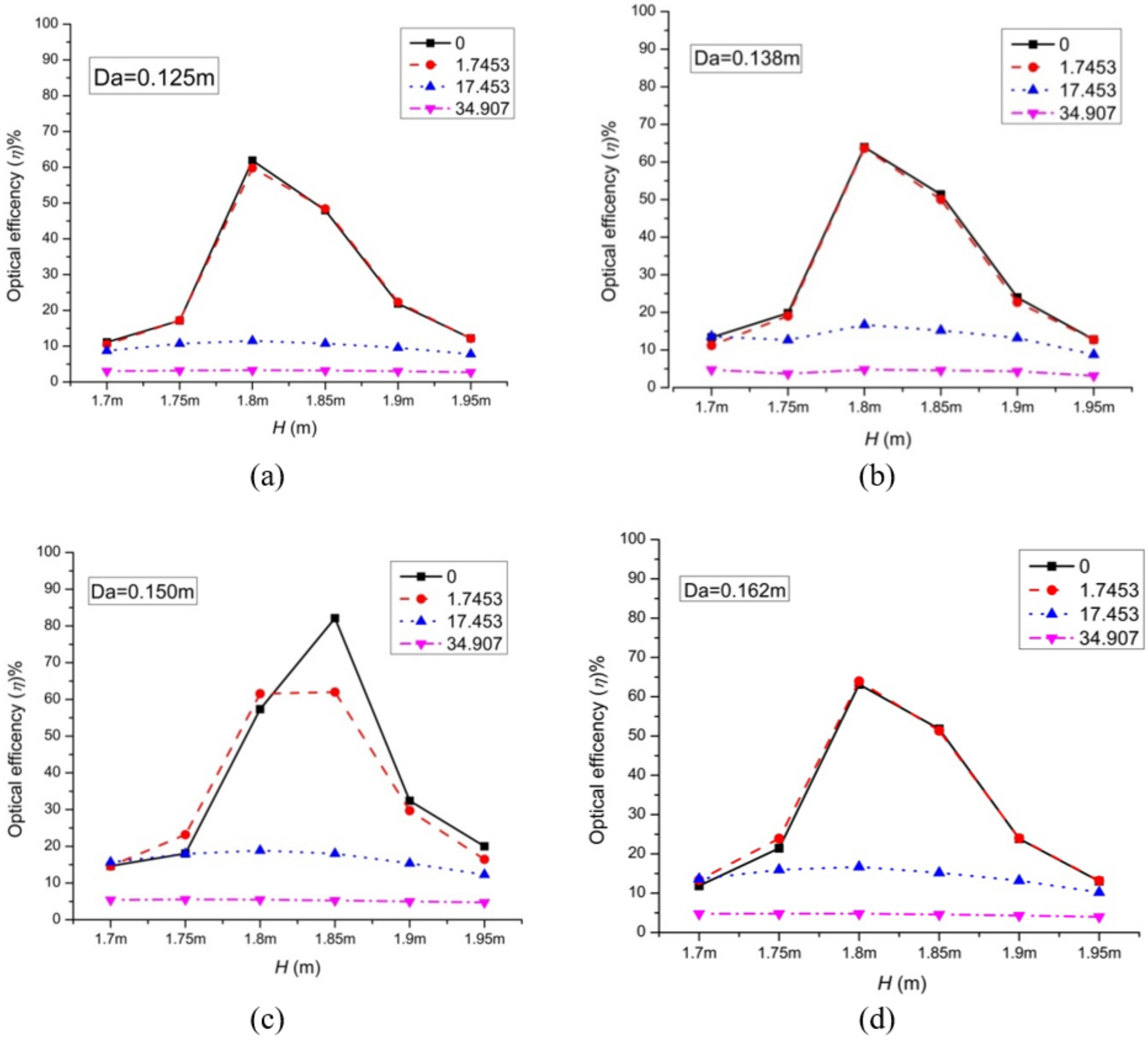


Figure 9

Heat flux distribution with varying slope errors at *H*= 1.7m

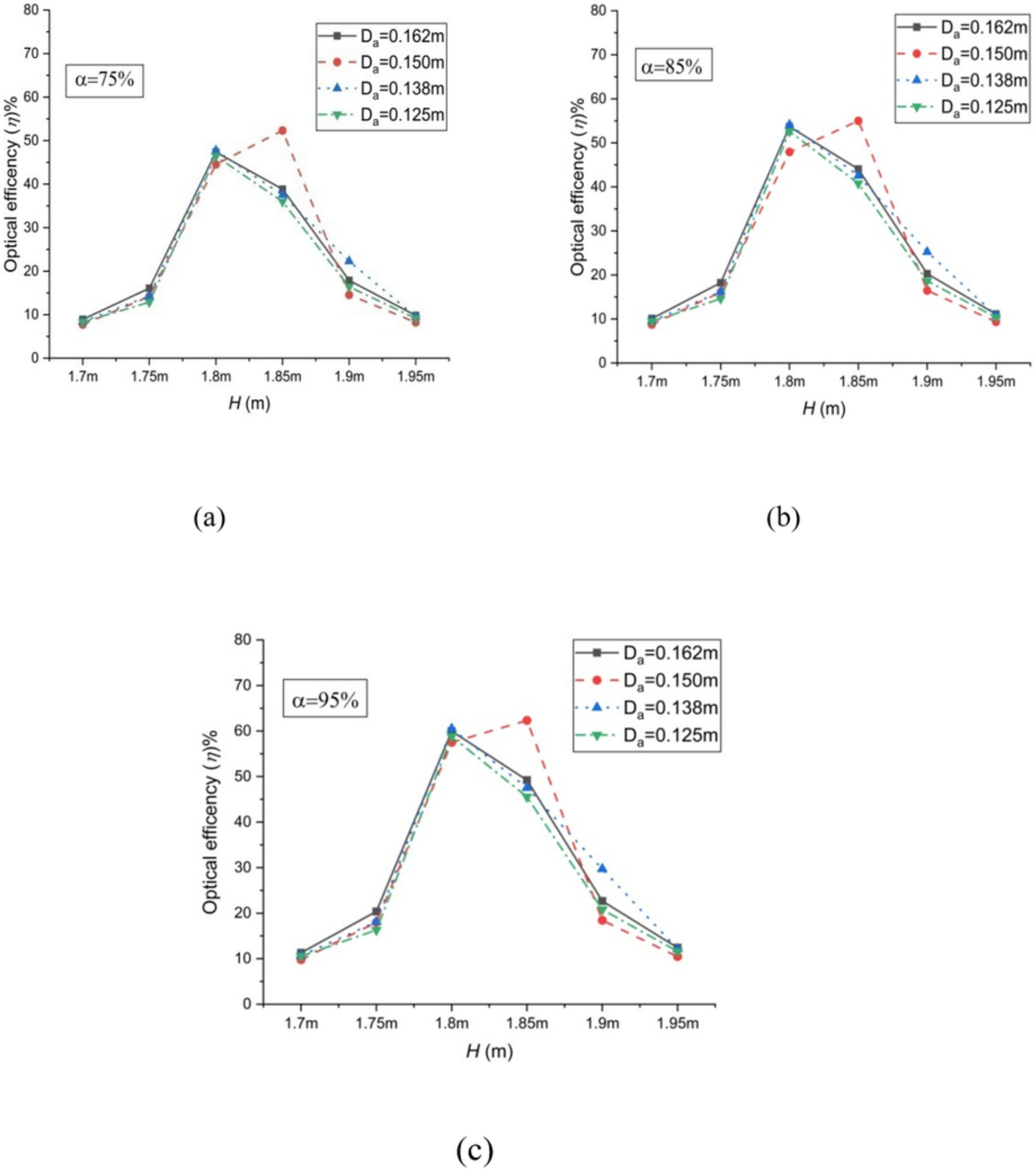


(a) (b)

(c) (d)

Figure 10

Optical efficiency vsreceiver distance for different slope errors ofconcentrator and different receiver aperture diameters



(a)

(b)

(c)

Figure 11

Optical efficiency vs receiver distance for varying absorptivity of the receiver at different receiver aperture diametres.

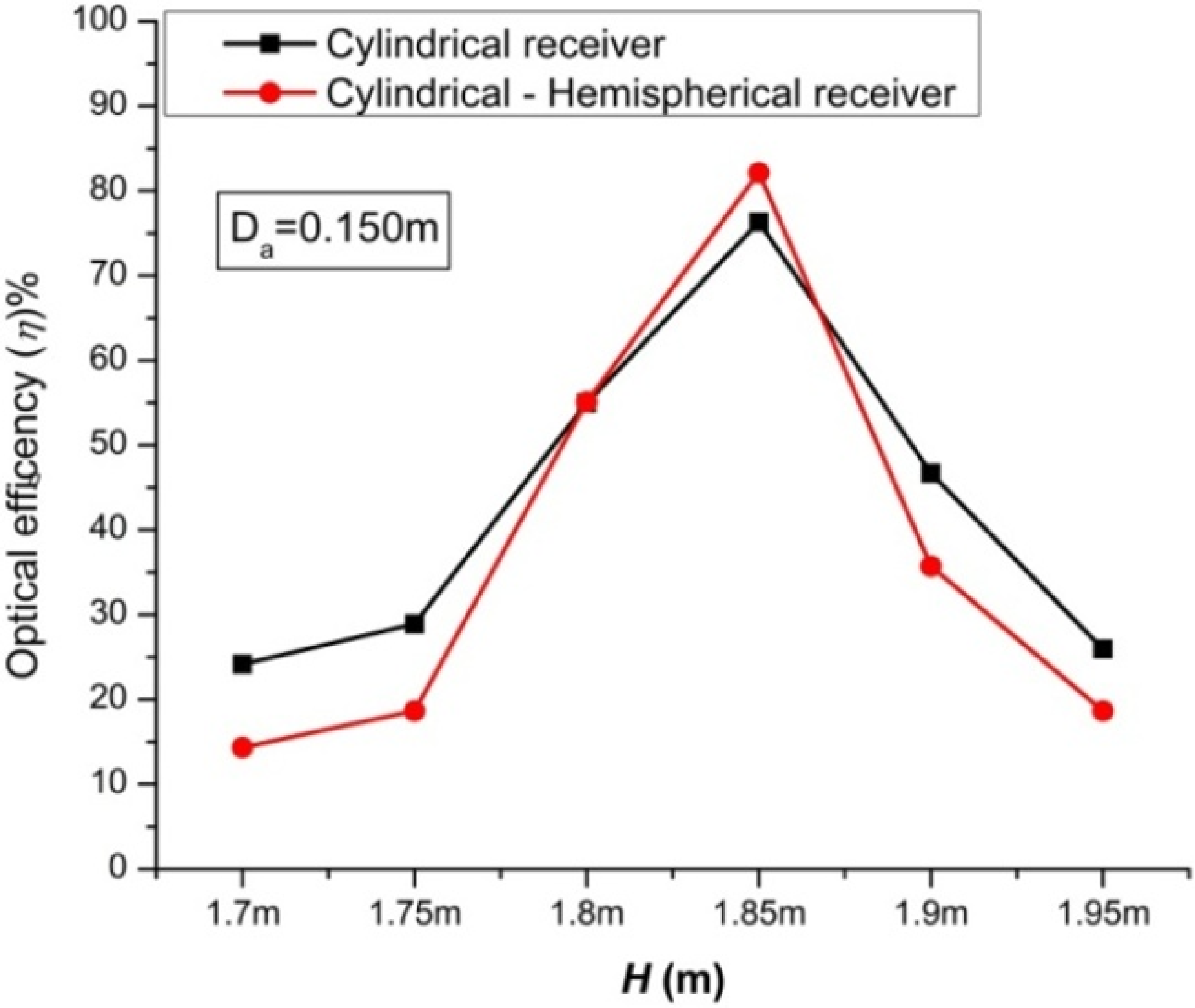


Figure 12

Optical efficiency of cylindrical &cylindrical-hemispherical receivers