Novel designs of cavity receiver for a solar parabolic dish concentrator

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Abstract. To enhance the performance of a parabolic dish concentrator, it must achieve the maximum thermal performance of the receiver. Hence the optimization of the receiver performance will play an essential role in optimizing the system of solar parabolic dish concentrator. Lot of studies investigated many configurations and designs for receivers and compared the performance among them. Study of new and novel designs will enrich this field of study and pave the road to reach optimal receiver. The objective of this study is to develop the existing design further towards the best design. Cavity receivers, especially conical receivers are known for high thermal efficiency. This study investigate four designs of conical receivers, three of them are novel designs using Ansys Fluent software. The investigated receivers are helical conical, pentagon conical, rectangular conical, and triangle conical respectively in the order of their performance. At 300 K the thermal performance of the best receiver which is helical conical is 66.68%, and the optical efficiency are 89.2%.

Keywords: Receiver, Thermal performance, Dish concentrator, Conical cavity, Energy, Efficiency

1. Introduction

Finding new technologies in generating energy from renewable energy sources is a base stone in order to reduce the dependent on conventional energy sources [1]. Solar energy is one of the most important renewable sources which covering the need of the humanity in clean way [2]. Increasing of the consumption of fossil fuel which emits CO₂ and other harm gases which are the main reason for greenhouse effects, motivates many researchers to focus on solar energy [3][4]. The useful energy is obtained from solar thermal collector which convert the incident radiation into thermal energy [5]. Solar parabolic dish is pioneer technology which promises best performance and efficiency comparing with other solar thermal system. Concentrated solar power is the solar irradiation incidents on the reflector (mirror) and concentrated to be absorbed by receiver [6]. The special thing about solar dishes that it can works in different applications which required high temperature unlike the normal types of collectors such as flat plate or evacuated tube collectors [7]. Many researchers have been doing lots of studies and have investigated the ability to improve and develop the solar concentrating systems by comparing between different types of receivers [8], or studying the effect of inlet or outlet position on thermal and optical performance [9]. These studies have been done numerically, but even experimentally this field has been enriched with lots of studies. And the energy and exergy performance of the receiver has been investigated for solar parabolic dish concentrator. [10] As mentioned before solar dish is useful for high temperature applications. This design containing a dish which is reflector, this reflector concentrate the solar irradiation to the focal point, receiver which fixed to this focal point (or in some cases closer to focal point), and tracking mechanism which track the sun in two axis to ensure optimal reflection for all sun irradiation [11]. Many studies have dealt with solar dishes and receivers. Cavity receivers and external types of receiver has been investigated heavily. There is lots of
configurations of cavity receivers such as: Cylindrical receiver [12,13], Conical receiver [14], Rectangular receiver [15], and spherical receiver [16]. In term of external types of receiver it is also has been investigated especially flat receiver [17]. Some of these studies are really good and pave the road for other researchers, and the others are examples for poor performance receivers. Poor configurations and designs give ideas to avoid this losses or failures. This field has numerous studies either experimentally or numerically, but tell reaching to the optimal design this vast area will still attract researchers, and lots of aspects are waiting to be investigated.

2. Material and methods

2.1. Configurations and geometry

ANSYS FLUENT software [18] has been used in the numerical simulation, this geometry can be modeled in Ansys in Design Modeler or Space Claim on the other hand it can be imported to the program. The configuration has been modeled in Solidworks software and then imported to Ansys. This configuration will be meshed later and used in the numerical simulation. In this case the meshed configuration will investigated especially thermally. Figure 1 shows the reflector and receiver geometry developed in Solid Works software. The front view and plan of the helical conical, triangular, rectangular and pentagonal cavity receivers are shown in Figure 2, Figure 3, Figure 4 and Figure 5 respectively. Table 1 shows the geometric and simulation parameters chosen for the present study.

![Figure 1. Reflector and receiver geometry by SOLIDWORKS.](image-url)
Figure 2. Front and plan view for helical conical receiver.

Figure 3. Front and plan view for triangular receiver.
Figure 4. Front and plan view for rectangular receiver.

Figure 5. Front and plan view for pentagonal receiver.
Table 1. Geometric and simulation parameters.

| Parameter                          | Value          |
|-----------------------------------|----------------|
| Aperture of the collector         | 1 m²           |
| Aperture of the receiver          | 0.2 m          |
| Concentration ratio               | 28             |
| Reflectivity                      | 90%            |
| Absorptivity of the receiver      | 87%            |
| Solar radiation                   | 1000 W/m²      |
| Tube inner diameter               | 9 mm           |
| Tube outer diameter               | 10 mm          |
| Heat transfer coefficient for convection | 10 W/m²k     |
| Mass flow rate                    | 0.03 kg/s      |
| Ambient temperature               | 27°C           |

2.2. Configuration mesh

Mesh has been generated through Ansys Mesh with tetrahedron method. Six cases has been investigated, each case represent number of mesh. Number of mesh will be essential factor in term of accuracy. The element size has been used is 0.0124 mm which represent 519204 elements. This is the optimal mesh which ensure accuracy with respect to time consumption required for the process. Figure 6 shows the variation of element size with number of elements. Figure 7 shows the generated mesh for various receivers in Ansys.

![Figure 6](image_url)

**Figure 6.** Variation of Element size with Number of Elements.
2.3. Boundary condition

After importing the geometry from solid works to design modeler, and after meshing and choosing the optimal mesh, adding boundary conditions had done. In boundary condition both energy and radiation model have been enabled. Then the surfaces has been named in mesh process has been to be dealt with in this boundary conditions. The inlet and outlet of the flow has been choose with corresponding to the flow rate required. The insulated surface which has been considered as adiabatic wall, which means that no losses or heat flux occur on such surface. And the absorber which is the wall which participate in solar loading. The absorber wall will exposed to the solar radiation which will be defined through radiation model. This wall will be exposed to heat flux equal to the solar radiation concentrated. Convection and radiation losses will occur only from absorber surface and will not occur from insulated surface. In order to make this simulation less complex the pattern of heat flux distribution has been considered constant through all the surface. This uniform pattern is not different from the actual pattern which has been validated with [8].

Boundary conditions has been chosen in the simulation and is given below:

(a) The absorber surface which has been exposed to the reflector is participated in solar loading and heat losses too.

(b) The insulated surface has been assumed to be perfectly insulated and there is no heat losses and this surface has not participated in solar loading.

(c) The flow inlet of the tube has been chosen as “mass flow inlet” as 0.03 kg/s and the flow outlet has been chosen the same of the inlet by chosen the flow rate weighting as 1.

(d) Rosseland has been chosen as the radiation mood. And the concentration ratio has been considered into solar ray tracing mode in radiation.

(e) The gravity effect has been considered, and steady-state flow too.

(f) Solar radiation distribution has been considered as uniformly distributed on the aperture of the receiver.

Figure 7. Conical, triangular, rectangular, pentagonal receivers mesh by ANSYS.
2.4. CFD simulation

Fluent software uses conservation equations. Mass, energy and momentum equation have been solved by ANSYS.

The equations of the simulation that has been used by ANSYS:

**Continuity Equations:**
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}
\]

**Momentum Equation:**
\[
\frac{\partial u}{\partial t} + \rho \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + 2 \frac{\partial^2 u}{\partial y \partial z} \right) \tag{2}
\]
\[
\frac{\partial v}{\partial t} + \rho \left( u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = - \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + 2 \frac{\partial^2 v}{\partial y \partial z} \right) \tag{3}
\]
\[
\frac{\partial w}{\partial t} + \rho \left( u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = - \frac{\partial p}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial x^2} + 2 \frac{\partial^2 w}{\partial y \partial z} \right) \tag{4}
\]

**Energy Equation:**
\[
\frac{\partial T}{\partial t} + u \left( \frac{\partial T}{\partial x} \right) + v \left( \frac{\partial T}{\partial y} \right) + w \left( \frac{\partial T}{\partial z} \right) = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{5}
\]

Rosseland mode has been used in the numerical simulation [19].

\[
q_r = - \Gamma \nabla G \tag{6}
\]
\[
q_r = - 16 \Gamma n^2 T^3 \nabla T \tag{7}
\]

Where: \( \Gamma = \frac{1}{(3(\alpha + \sigma s) - \cos)} \)

G: incident radiation
a: absorption coefficient
\( \sigma s \): the scattering coefficient
n: medium refractive index
\( \sigma = 5.67 \times 10^{-8} \) W/m² K⁴: Stefan – Boltzmann constant
T: Temperature
C: Coefficient of linear – anisotropic phase function

2.5. Energy analysis

Solar radiation power can be calculated from [17]:
\[
Q_S = I_o A_{ap} \tag{8}
\]

where \( A_{ap} \) Aperture area

Dish power can be determined from [17]:
\[
Q_D = \eta_{opt} Q_S \tag{9}
\]

Where \( \eta_{opt} \) optical efficiency

Receiver power is given by (which is useful energy gained by the receiver) [17]:
\[
Q_R = m C_p (T_{out} - T_{in}) \tag{10}
\]

Thermal efficiency is given by the following expression [17]:
3. Results and Discussion

3.1. Validation of the numerical model

In order to validate the results of this study, it has to be validated in the same conditions of the reference chose for validation. The conical receiver of this study has been validated for the same condition for a similar study done by Bellos et al. [8]. This study is comparing between five types of receivers and the heat transfer fluid is Thermoil VP1. In same condition such inlet temperature, ambient temperature and intensity of solar radiation. Not forgetting the same absorptivity, reflectivity, and emissivity. For the mass flow rate the inlet mass flow rate has been chosen to be the same and the heat transfer coefficient has been chosen the same too. The outlet temperature which is the results of the simulation has been used to calculate the thermal efficiency which compared with the results of the reference. The outlet temperature was very close to the reference and the thermal efficiency results were 4% average deviation which considered acceptable range. For that this study considered to be validated.

3.2. Results of the simulation

Figure 8–11 shows the temperature distribution in the helical conical, triangular, rectangular and pentagonal receivers respectively.

\[ \eta_{th, t} = \frac{\dot{m}C_p(T_{out} - T_{in})}{\eta_{opt}A_{ap}I_b} \]  

(11)
Figure 9. Temperature distribution in the triangular receiver.

Figure 10. Temperature distribution in the rectangular receiver.
3.3. Comparison of thermal efficiency
The comparison between the 4 types of studied receivers shown in figure 12 indicates that the conical receiver is the best receiver, in term of thermal performance and the least heat losses. With the best optical efficiency. With 66.68% thermal efficiency for conical receiver, the simulation and the numerical analysis shown that this efficiency is the best efficiency comparing with other cavity receivers. Triangular receiver shown the least performance with 60.27% thermal efficiency. Rectangular receiver has 63.19% thermal efficiency and pentagonal receiver has 64.71% thermal efficiency. And the heat losses for the conical is the least with 25.24%

Figure 11. Temperature distribution in the pentagonal receiver.

Figure 12. Thermal efficiency for the four types of cavity receivers.
3.4. Comparison of outlet temperature
In order to understand the thermal performance of the receiver is to compare the outlet temperature of the 4 types of receivers. The highest outlet temperature is for conical receiver which has the best thermal performance too. The result is aligned with the thermal efficiency result. The next highest outlet temperature is pentagonal receiver. The next two outlet temperature is for rectangular and triangular receiver respectably ordered. Increasing the mass flow rate will affect the outlet temperature. As shown in figure 13, increasing mass flow rate will decrease the outlet temperature for that choosing the optimal mass flow rate is very important in term of level of the temperature required for the application.

![Outlet temperature for the four types of cavity receivers.](image)

3.5. Comparison of heat losses
Figure 14 shows the heat losses for four different types of cavity receivers studied. Corresponding with the previous discussed results the heat losses is matching with the thermal performance. The best thermal efficiency receiver has the least heat losses. And the least thermal efficiency receiver has the maximum heat losses. Investigating the heat losses deeply will help to improve the efficiency of the receiver. Convection losses and radiation losses are the desired losses for investigations. Reducing the heat losses is the first step to enhance the performance of the receiver. Enhancing the area of the receiver surface will increase the absorptivity but in the same time increase the capability of losses.
4. Conclusion
The present study compares the performance of 4 types of cavity receivers numerically. The simulation has been done by ANSYS tool. And the geometry model by SOLIDWORKS software. The output of the simulation was the outlet temperature which will represent the thermal efficiency for each receiver. The temperature distribution pattern has been shown in this study, it will start increasing from the inlet till reaching the maximum at the outlet of the receiver. The effect of mass flow has also been dealt with through this paper, and the heat losses has been noticed too.

1. Among the four types of cavity receivers (helical, triangular, rectangular, and pentagonal): the best thermal performance is for the conical receiver with 66.7% while other receivers showed reduced performance in the order: triangular 60.3%, rectangular 63.19%, and pentagonal 64.6%.
2. Among the heat losses from the four receivers (helical, triangular, rectangular, and pentagonal): the least losses is observed for the conical with 25.2%, while other receivers showed higher values in the order: triangular 28.2%, rectangular 27.2%, and pentagonal 26%.
3. Increasing the mass flow rate showed an increasing trend for the performance for all the type of cavity receivers.

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