Study on Design of Cavity Receiver of Concentrating Solar Power Plants—A Review

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Abstract The concentrating solar power technology has achieved rapid development in the world. One of the important components of such technology is cavity receiver as it affects the efficiency of the entire power plant. The solar cavity receiver is a photo-thermal conversion component of solar power plants, which heats the working fluid contained in it by absorbing solar radiation. In this paper, an effort has been made to review the work carried out by various researchers on different cavity receiver designs. Based on literature survey, it has been found that cavity geometry has a significant effect on overall flux distribution. The effect of rotation has been observed to be less than 1% for overall receiver efficiency calculations. The thermal losses occurring from the cavity receiver have been found to be affected by various parameters like thermal emissivity, mean fluid temperature, opening ratio and receiver inclination. The wind direction and fluid flow rate also have a considerable influence on the thermal performance of the cavity receiver. It has been realized that there is still scope for developing designs of an efficient cavity receiver which could minimize the losses and hence, enhances the overall efficiency of the plant. The identified gaps in this area for further research have also been discussed in this paper.

Keywords Solar energy · Cavity receiver · Heat loss · Radiation flux

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1 Introduction

The concentrating solar power technology plays a crucial role in conversion of solar energy into electricity. It has been used in parabolic trough, Fresnel system, central tower and dish. One of the key components of these solar thermal plants is receiver. Solar radiations are absorbed by the fluid contained in the receiver and then this fluid is further used for power production and heating applications. According to the type of concentrator, there can be a linear focus on receiver or a point focus on receiver. Parabolic trough collector and Fresnel system employs a linear focus on receiver while parabolic dish and central towers employ point focus on receivers. Among the various designs of existing receivers, one of the designs of concern is of cavity receiver. It consists of a large opening on the front face of the receiver which provides an advantage of increased surface area and reduced heat loss. Working fluid can attain higher temperature in cavity receiver. The performance of receiver affects the overall efficiency of the solar thermal power plants. It has been realized that the primary effect of cavity geometry is to vary the radiation flux distribution on the inside walls.

In this paper, a study on the various designs of receiver cavities used in both linear and point concentrators.

2 Cavity Receivers Used in Linear Focusing Concentrators

The linear focusing collectors track the sun along a single axis and focus irradiance on a single receiver. Linear parabolic trough collector and Fresnel system uses a line focusing receiver. The cavity receiver provides a well-insulated enclosure and a small aperture for absorption and reflection of solar energy on the heating surface of cavity. Various works done on these cavity receivers has been summarized in Table 1.

2.1 Cylindrical Cavity Receiver

One of the most common geometry of cavity receiver is a cylinder whose lower part comprising of a cavity receives the reflected solar radiation. Boyd et al. [1] designed a cavity in which the flow of heat transfer fluid (HTF) takes place through the annular channel in the cavity providing an advantage of low flux density and low thermal losses. The cavity design by Barra et al. [2] consisted of copper pipes soldered on the heating surface of the cavity and a removable Pyrex glass at the aperture entrance. Conversion efficiency was observed to be affected by the mean receiver oil temperature, mass flow rate, and inlet temperatures of heat transfer

Table 1 Summary of work on cavity receivers used in linear focus concentrators

Shape of cavity receiver	Work done	Conclusions
Cylindrical cavity receiver	Theoretical performance analysis	1. Low flux density of absorbed solar radiations 2. V-shaped entrance reduces convection and radiative losses
Triangular cavity receiver	Heat transfer analysis	1. High optical efficiency 2. Heterogeneous heat flux distribution 3. Enhanced heat transfer with rectangular fins 4. Outlet temperature of HTF depends on mass flow rate and direct normal irradiance
Trapezoidal cavity receiver	Thermal performance	1. Thermal efficiency decreased with increase in concentration ratio 2. Enhanced thermal performance with selective surface coated absorber 3. The efficiency with the round pipe (multi-tube) absorber was 2–8% higher as compared to rectangular pipe absorber

fluid. Bader et al. [3, 4] initially proposed a cylindrical shaped cavity receiver consisting of a tubular absorber with air as the working fluid which was further improved by incorporating corrugated absorber tube. It was found that increase in the HTF mass flow rate and use of a corrugated absorber tube both reduced the heat loss from the receiver and increased the collector efficiency.

2.2 *Triangular Cavity Receiver*

Chen et al. [5] designed a triangular cavity receiver and observed that the heat losses from the cavity increased with the increase of angle of inclination and wind speed. The heat lost from the designed cavity absorber has been found to be equivalent to that of the evacuated tube in windless conditions. The cavity design has been further improved by Xiao et al. [6, 26] by addition of glass cover at aperture which helped in reduction of heat losses. The triangular cavity shape facilitated reflections of the sunlight in the cavity. For complete utilization of solar energy, mass flow rate of heat transfer fluid should be changed with direct normal irradiance. Analysis of optical properties of cavity has been carried out by Chen et al. [7] and it was found that the optimal optical properties could be achieved with appropriate aperture width, depth-to-width ratio, and offset distance from focus of triangular cavity absorber.

2.3 Trapezoidal Cavity Receiver

Reynolds et al. [8] described experimental techniques for the investigation of the heat losses from the trapezoidal cavity absorber and the flow visualization technique for capturing the flow patterns inside the cavity. Singh et al. [9, 10] studied the effect of receiver shape, concentration ratio and surface coating on the thermal performance of trapezoidal absorber cavity. It was observed that thermal efficiency was enhanced by the surface coatings while it decreased with increase in concentration ratio of the collector. They also found that thermal efficiency increased by 2–8% using a round absorber tube over a rectangular absorber tube. Oliveira et al. [11] analyzed and optimized a trapezoidal cavity receiver for a linear Fresnel solar collector for four parameters, mainly number of absorber tubes, inclination angles of lateral walls of the cavity, cavity depth, and rock wool insulation thickness. The radiation losses were observed to increase with receiver depth as cover and lateral wall surface area increased and heat transfer coefficient decreased with insulation thickness. Mallick et al. [12] studied the effect of Grashof number, absorber angle, aspect ratio, surface emissivities, radiation–conduction number and temperature ratio through the proposed solar trapezoidal cavity model.

The effect of combined Nusselt number on Grashof number and absorber angle was found to be negligibly small. A decrease in Nusselt number has been observed with increase in aspect ratio (ratio of width and depth of cavity) and temperature ratio (ratio of bottom and top surface temperature of cavity), while an increases was observed with surface emissivity. Manikumar et al. [13] analyzed an inverted trapezoidal air cavity having a multi-tube absorber with plate and without plate underneath for various values of gaps between the tubes and depths of the cavity. The thermal efficiency in the case of plane surface was found to be more than that of tube surface. The value of overall heat loss coefficient and convective heat transfer coefficient were observed to increase with gaps between the tubes and the tube temperature.

3 Cavity Receiver Used in Point Focusing Concentrators

Collectors track the sun along two axes and focus irradiance at a single point receiver. This allows good receiver efficiency at a high temperature. The paraboloidal dish and central towers are the point focusing concentrators. Various works done on these cavity receivers has been summarized in Table 2.

Table 2 Summary of work on cavity receivers used in point focus concentrators

Shape of cavity receiver	Conclusions
Cylindrical cavity receiver	1. Cavity-aperture ratio and aspect ratio should be maximized within the limitations of cavity size and operating temperature to enhance the absorption efficiency 2. Convective loss increases with mean receiver temperature and decreases with increase in receiver inclination 3. Convective losses were higher for wind induced conditions than the no-wind conditions for all inclination angles of receiver 4. The temperatures of heat transfer fluid in laminar and turbulent conditions for tightly packed cavity receivers were higher than for medium and loosely packed cavity 5. Effect of rotation was observed to be less than 1% on receiver efficiency
Prism-shaped cavity receiver	1. Non uniform heat flux distribution in the cavity and boiling tubes 2. Change in the wind angle and wind direction directly affected the heat loss from receiver. Maximum heat loss observed when receiver exposed to side-on wind 3. A sharp increase in thermal efficiency was observed with major percentage of losses by convection during the early start-up period 4. As the depth of receiver increased, thermal efficiency increased followed by a decrease. An opposite variation trend has been observed with the heat losses 5. The radiative and convective heat losses decreased as thermal emissivity increased
Hemispherical cavity receiver	1. Natural convection heat loss affected by inclination and shape of the receiver 2. Convection heat losses reduced in modified cavity receiver 3. Maximum heat losses by head-on wind 4. Natural convection heat losses decreased with receiver inclination while opposite trend was observed with forced convection heat losses 5. Radiation heat losses varies with operating temperature and cover emissivity of cavity receiver

3.1 Prism-Shaped Cavity Receiver

Dong et al. [14] presented a combined calculation method for evaluation of the thermal performance of the cavity receiver under different wind environments for a typical shaped cavity. The change in the wind angle wind direction and the speed of air in the region of the boiling tubes affected the heat losses from the receiver. Tu et al. [15] studied the effect of depth of saturated water/steam cavity receiver on thermal performance and found uniformly distributed heat flux and wall temperature of the boiling panels with receiver depth. An increase followed by a decrease has been observed in thermal efficiency as the receiver gets stretched. Wei et al. [16] presented a modified combined method for simulation of the thermal performance of a saturated water/steam solar cavity receiver. Both the radiative and the convective heat losses from the cavity receiver were observed to reduce with increase in thermal emissivity.

Hence, an enhancement in receiver's efficiency was obtained. Fang et al. [17] studied numerically the thermal performance of prism-shaped solar cavity receiver during three kind of start-up process and observed a sharp increase in thermal efficiency and change in the temperature of air during the early start-up period.

3.2 Hemispherical Cavity Receiver

Kumar et al. [18] studied the natural convective heat loss from cavity receiver, semicavity receiver, and modified cavity receiver. It was observed that the orientation and geometry of the receiver strongly affected the natural convection heat loss. The modified cavity receiver was found to have less convection heat losses when compared with the other receivers.

Reddy and Kumar [19] proposed a three-dimensional numerical model for analyzing natural convection heat loss from modified cavity receiver without insulation of fuzzy focal solar dish concentrator. A comparison of two-dimensional and three-dimensional natural convection heat loss from the cavity receiver indicated that latter can be used for an accurate estimation of natural convection heat loss at lower inclination of the receiver while the former model can be used at higher angle of inclination of the receiver.

Veershetty et al. [20] developed a flux distribution model for a fuzzy focal solar dish concentrator system and analyzed the thermal performance of the modified cavity receiver at various wind conditions. The head-on wind was found to significantly influence the heat losses from the receiver. The maximum theoretical efficiency of solar dish collector was reported to be higher at no-wind conditions followed by side-on and head-on wind conditions at wind speed of 5 m/s.

Vikram et al. [21] studied the effect of various parameters on the combined natural convection and surface radiation heat losses from the modified cavity receiver. It was found that the natural convection heat losses were higher at receiver inclination angle, $\beta = 0°$ (receiver facing sideward) and lower at $\beta = 90°$ (receiver facing down) whereas an opposite trend was observed with the forced convection heat loss. The radiation heat losses were found to vary with operating temperature, cavity cover emissivity and marginal variation with inclination angle.

3.3 Cylindrical Cavity Receiver

Wang et al. [14] reported an inverse design method for cylindrical shaped cavity receivers with the cylindrical surface receiving major heat flux. In the peak flux regions, the peak temperatures found were mitigated by the use of a well-designed impinging system without any over pressure drop problem.

Hathaway et al. [22] carried out a numerical simulation based on the Monte Carlo Ray Tracing (MCRT) method to explore the performance of a cylindrical cavity receiver. It was observed that for the best performance in terms of absorption efficiency, the cavity-aperture diameter ratio and aspect ratio should be maximized within the limitations of size and operating temperature. Neber and Lee [23] proposed a receiver design for a Brayton engine-based solar power generation system. It was analyzed that with decrease in aperture diameter, an increase in concentration ratio was needed to produce the required amount of electricity. The increased in concentration ratio enhanced the total efficiency.

Singh [24] developed a simulation for investigating the heat transfer behaviour of a solar cavity receiver. It was observed that working fluid temperatures for both laminar and turbulent conditions were higher in tightly packed cavity receivers than in the medium and loosely packed cavity receivers. The working fluid temperatures and net heat flux has been found to vary with the aperture size of the cavity receiver.

Wu et al. [25] investigated the variation of natural convection losses with rotation of cavity receivers. The effect of rotation on heat transfer was dependent on the receiver orientation. The effect of rotation on the heat losses was observed to be less than 1%. Therefore, for calculating overall efficiency of receiver, it could be neglected.

Xiao et al. [6, 26] designed a tube-cavity solar receiver and conducted experiments for studying the effect of mass flow rate and flow direction on the performance of receiver. The counter current exhibited better performance than that of the parallel flow current and it was observed that the temperature can be controlled by increasing flow rate. The use of glass cover was found to have a positive influence on the air outlet temperature and hence, reduced heat losses.

4 Conclusions

In this paper, an attempt has been made to study the various designs of receiver cavities used in various concentrating solar power technologies. It has been found that inclination and design of the cavity receiver strongly affects the efficiency. The following points have been concluded from various designs studied.

(1) The cavity receivers provide the advantage of low flux density of absorbed solar radiations which reduces temperature gradients and thermal stresses.
(2) The selective surface coated absorber and provision of rectangular fins on the dorsal side of the cavity helped in enhancement of thermal efficiency.
(3) The triangular shaped cavity has highest optical efficiency with heterogeneous heat flux distribution.
(4) Natural convection heat loss from the receiver cavities tend to decrease as the inclination increases from 0 to 90° while an opposite trend was observed with forced convection heat losses. For all receiver inclination angles, convective losses were higher in wind induced conditions than in the no-wind conditions. Radiation heat losses vary with operating temperature and cover emissivity of cavity receiver.

5 Future Scope

(1) The future work involves the study and investigation on change in the structure and material of fins used in the receiver cavities of linear concentrators.
(2) The trapezoidal cavities have not been so far tested with the parabolic trough concentrator. A comparison between the thermal performance of the triangular and trapezoidal cavities has not been conducted so far.
(3) Fewer studies on estimation of optimum aperture size of cavity receiver have been conducted so far.
(4) More study on the effect of wind directions on the geometry of the cavity is required. As in some of literature reviews due to the variations of the opening ratios, head-on wind maximized the heat losses while in other side-on wind enhanced the losses.
(5) Various correlations predicted for the estimation of Nusselt number and heat loss coefficients have applications limited only to certain geometrical and operating conditions. Research on developing such correlations is required.

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