International Journal of Research in Advent Technology (IJRAT) Special Issue
E-ISSN: 2321-9637
SharadchandraPawar college of Engineering, Dumbarwadi, Pune 410504,
Organizes
National Conference "MOMENTUM-17", 14th& 15th February 2017
Available online at www.ijrat.org

Investigations of cascaded solar thermal cavity receiver for concentrating collector

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Abstract-Thermal and optical losses affect the performance of a solar thermal cavity receiver used in parabolic concentrating collector system. The constituents of thermal losses in solar thermal receiver areconductive ,convectiveand radiative losses. Radiative heat losses and convective heat losses are the major constituents as compared to conductive losses. The thermal efficiency and cost effectiveness of the whole system is affected by the convection losses occurring in the receiver.The determination ofsolar thermal cavity receiver convective loss is of great concern to system designers, researchers due to its direct effect on the thermal efficiency. It is necessary to determine this convective heat loss accurately and subsequently which will improve the thermal performance of the thermal cavity receiver. A recent technical designof cascaded solar receiver is proposed to reduce convective heat losses using computational and experimental investigations.This paper present a comprehensive review and systematic summarization of the state of the art in the research and progress in this area. The efforts include the numerical and experimentalinvestigations andconvection heat loss mechanism in the cavity receivers with varied shapes that have been considered up to date..

Index Terms- Cavity receiver, Convection heat loss, Wind effect, Parabolic dish.

1. INTRODUCTION

Developing solid engineering design requirements is crucial to the success of any design project. An engineer mustbegin the design process reviewing research, have a talk with the people in the industry, and discuss about how their research could be translated into measurable design requirements. In addition to cost and technical requirements, the engineer must create ambitious but achievable technical requirements. For developing constraints and design requirements, one straightforward method is to simply identify gaps in current solutions. The solar radiation available in abundant, cleanliness character of solar energy, very high cost of fossil fuels and negative emission consequences of fossil fuel consumption along with large requirements for process heat below 250^{o}C are the key drivers of the strong focus on the development of solar thermal applications in India. In addition to itshuge size (inexhaustible source of energy, 1.79 X 10^{11} MW), solar energy has two other factors in its favor. First unlike nuclear power andfossil fuels, it is clean and an environmentally source of energy. Second the availability of solar energy is free and available in adequate quantities in almost each corner of the world where people live.

In India the energy problem is very serious. In spite of discoveries of oil and gas off the west coast, the import of crude oil continues to increase and the price paid for it now dominates all other expenditure. Every year the country is spending more than thousand crores for the import of oil. This amount forms a major part of India's import bill. The need for developing energy alternatives is thus evident and considerable research and development work is needed in this direction.

One of the promising options is to make more extensive use of renewable sources of energy derived from the sun.Solar energy is very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.79 X 10^{11} MW which is many thousands of times larger than the present consumption rate on earth of all commercial energy sources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the unconventional energy sources.

The concentrated solar radiation is absorbed in the receiver of the solar-thermal system and the same is converted in to usable energy. Once absorbed, this useful solar thermal energy is transferred as heat to a heat-transfer fluid, such as air, water, ethyl-glycol, or molten salt, to be stored and/or used in a power conversion cycle. The main two types of solar thermal cavity receiver are external receiver and cavity receivers usually cylindrical in shape.

In external type, the solar flux from number of panels (which is also known as heliostats) is directed onto the outer surface of the cylinder and the solar energy is absorbed by the receiver fluid flowing through closely spaced tubes fixed on the inner side. Whereas in cavity type receiver, a cavity receiver has an aperture through which the concentrated/reflected solar radiation passes. Once absorbed inside the solar cavity, the internal reflections ensure that the majority of thereflected radiation that has entered the cavity receiver is absorbed on the internal absorbing surface.

The solar thermal cavity receiver contains a suitable material tube configuration through which the receiver fluid flows according to process heat temperature requirement. In large scale solar concentrator projects, and commercially available solar concentrators, it is found that the solar thermal cavity type receiver is most commonly used. This is due to the lower heat-loss rate compared to that of an external receiver; however, they are more expensive than external receivers. The concentrated solar radiation entering the aperture of the cavity spreads inside and is absorbed on the internal walls where the heat is then transferred to a working fluid. Any radiation that is reflected or re-radiated from the walls inside the cavity is also absorbed internally on the cavity walls resulting in a higher absorptance value of the receiver. This spreading of the solar radiation causes a reduction in the incident flux within the cavity, thus helping to prevent thermal cracking or smelting of the internal walls. Also, because of the design of the cavity receiver, it is easier to insulate to aid in avoiding radiant and convective heat loss to the environment.

The performance of a solar paraboloidalconcentratingdish-cavity receiver system is affected by the thermal and optical losses. The thermal losses of a solar cavity receiver include convective and radiative losses to the air in the cavity and conductive heat loss through the insulation used behind the helical tube surface. The inner convective and radiative heat losses form the major constituents of the total thermal losses. In the proposed research work, the design of central cavity receiver will be analyzed and a new design of cascaded solar thermal cavity receiver will be proposed to reduce heat losses using computer software shown in Fig. 1.

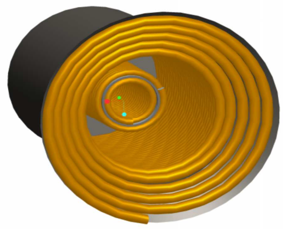

Fig. 1.Proposed Cascaded solar thermal cavity receiver

A heat transfer and flow simulation will be proposed for solar thermal cavity receiver at various receiver inclinations and at different temperatures. The numerical study of combined laminar natural convection, surface heat conduction and surface radiation heat transfer in a modified cavity receiver of solar paraboloidal dish collector is also proposed in research work. An experimental setup will be proposed to investigate the performance of the cascaded solar thermal cavity receiver. Measurements of energy losses, temperature drops, wind speed, working fluid flow rate, and inlet/outlet temperatures of the working fluid inside the cascaded solar thermal cavity receiver will bedone to collect and will be employed in studying the performance of cascaded solar thermal cavity receiver.

2. LITERATURE REVIEW

The literature on convection heat transfermechanism in open cavities mainly involved cubical, rectangular and square shaped cavities. Cylindrical, cylindrical with a conical frustum, spherical and hemispherical shaped cavities used for specific applications like solar thermal receivers were also studied.The detailed study on the combined convection and radiation from a modified hemispherical solar thermal cavities have been reported by Reddy and Sendhil Kumar (2008).A two dimensional numerical analysis of combined natural convection (laminar) and surface radiation in the modified solar cavity receiver of a solar dish was presented. Two separate Nusselt numbers were proposed for both natural convection and surface radiation. The incorporation of the radiation in a modified cavity receiver completely alters the heat loss rate. It was observed that the convective loss mechanism significantly influenced by the orientation of the receiver. The convection heat loss was dominated by the radiation heat loss for higher receiver inclination angle (>45˚). The radiation heat loss was considerably influenced by the area ratios. The receiver showed better performance at an area ratio of 8. The model was used to estimate the convection and radiation heat losses from the cavity receiver of solar parabolic dish collector system. The total heat loss from the receiver has been estimated for operating temperatures varying from 300˚C to 700˚C.

A heat transfer and flow simulation was performed by Dr. Umashankar and Ravi Kumar D S (2012) for four different solar cavity receiver's viz.: cylindrical, conical, dome and spherical receivers at various receiver inclinations at constant temperature. The receivers are designed such that they have same surface area and aperture. It was observed that convective heat loss decreases as the inclination changes from 0^0 to 90^0.Among these receivers, the convective heat loss is least for conical receiver followed by dome, spherical and cylindrical receivers

The natural convection occurring from open cavities was analyzed by M.Prakash et al (2012). Three solar cavity shapes were studied namely cubical, spherical and hemispherical geometries with equal heat transfer area. The numerical analysis was performed on three dimensional (3-D) cavity models using the Fluent CFD software. The highest convective loss was observed for the hemispherical open cavity and the lowest for the cubical open cavity for opening ratios of 0.25 and 0.5. The convective loss for all temperature and inclination cases is the least for the opening ratio of 0.25.There was a decrease in the convective loss as the cavity inclination angle increases. The highest loss is noticed for the 0^0angleand the least for the 90^0. The stagnation zone area is found to increase with cavity inclination. This leads to the decrease in convective loss with increase in inclination. This was true for all cavity shapes.

Radiation performance of dish solar concentrator/ cavity receiver system was studied using Monte-Carlo method coupled with optical properties by Yong Shuai et al (2008). Limb darkened sun was given to investigate the influence of sun shape on the flux distribution in the parabolic concentrator. The circumsolar values had little effect on the peak of concentration ratio, but radius of the focal spot increases with the CSR value. The probability model of surface slope error was introduced by the Gaussian distribution. Surface slope error broadens the flux distribution and reduces the peak value of the distribution to maintain the energy balance. The directional distribution of sunlight and its effect on the performance of a cavity receiver were performed. All cases examined in different sampling locations of the focal zone show a similar trend. The peak value of the percent directional distribution of radiation flux occurs where the zenith angle θ_P is equal to the rim angle if $\psi_{rim}\leq45^0$; otherwise, it occurs where the zenith angle is less than the rim angle if $\psi_{rim}>45^0$. Furthermore, this value increases with the sampling location away from the focus. The five different cavity geometries were evaluated on the uniformity of wall radiation flux; the results indicated that cavity geometry had a significant effect on overall flux distribution. Based on the concept of equivalent heat flux, the spherical receiver with relatively good radiation performance provides a starting point for the shape optimization; thus, a desirable shape (upside-down pear) may be achieved with almost uniform distribution. More study was needed to better quantify multi-reflection losses and free and forced convection losses from cavity receivers.

Convective losses from cubical and rectangular open cavities had been extensively studied. The general assumptions in these investigations are that the cavity walls are either uniformly heated or one wall is heated and others are maintained in adiabatic condition. Consequently the results cannot be directly used for solar cavity receivers used for process heat applications, which are mainly cylindrical in shape and have non-uniform wall temperatures.

Different wall boundary conditions were studied; all the cavity walls having same wall temperatures, only one wall having constant temperature and the remaining walls were kept adiabatic, one wall having constant heat flux and other walls are adiabatic, a flow exists in the cavity leading to non isothermal wall temperatures. Chakroun studied the effect of different wall boundary conditions on the heat transfer from an open cavity. The convection flow patterns and loss mechanisms have been reported. Nusselt number correlations have been proposed for different cavity shapes and wall boundary conditions.

The important energy loss for the receiver originates from convection and radiation heat transfer to the surroundings. These losses depend on the design of the receiver, whether it is a cavity or external receiver, its heated (or aperture) area, and its operating temperature. Additional factors include the local wind velocity, ambient temperature, and the orientation of the receiver. Studies had been made on the combined radiation, free and forced-convection losses from large surfaces, and tilted cavities.

Robert Y. Ma (1993) performed the tests to determine the convective heat loss characteristics of a cavity receiver for a parabolic dish concentrating solar collector for various tilt angles and wind speeds of 0-24 mph. Natural convective heat loss from the receiver is the highest for a horizontal receiver orientation (facing side) and negligible with the reveler facing straight down. Convection from the receiver is substantially increased by the presence of side-on wind for all receiver tilt angles. For head-on wind, convective heat loss with the receiver facing straight down is approximately the same as that for side-on wind. Overall it was found that for wind speeds of 20-24 mph, convective heat loss from the receiver can be as much as three times that occurring without wind.

The researchers in Centre of Sustainable Energy System, Department of Engineering, Australian National University made great efforts to develop more general correlations for predicting the receiver convection heat loss. Taumoefolau and Lovegrove (2002) as well as Paitoonsurikarn and Lovegrove (2002) experimentally and numerically investigated the natural convection heat losses from a 70 mm cylinder receiver (model cavity receiver) with cavity temperatures ranging from 350^0C to 500^0C. It was reported that the experimental and numerical results obtained were in good agreement qualitatively with those predicted by various correlations proposed by previous researchers.

Lovegrove et al. (2003) have attempted to develop a correlation that can reliably predict natural convection heat losses from cavity receivers employed in solar parabolic dishes at all tilt angles. A correlation was developed using the concept of the ensemble cavity length Ls as the characteristic length to account for the combined effect of the cavity geometrical parameters and the inclination.

Paitoonsurikarn and Lovegrove (2003) undertook the numerical investigation of natural and combined convection heat loss from cavity receivers. A new correlation in the form $Nu = CRa^n f(Pr)$ was developed for prediction of heat transfer coefficients. The ensemble cavity length Ls was modified to include the aperture geometry. Later, they (Paitoonsurikarn et al., 2004) carried out a parametric study of several relevant parameters in natural convection heat loss from open cavity receiver in solar dish application. The previously proposed correlation model in Paitoonsurikarn and Lovegrove (2003) has been modified to take into account the variation of additional parameters. Moreover, a correlation based on the modified Stine and McDonald model was developed. Both models are quite promising in the natural convection heat loss prediction in most cases. Based on the numerical simulation results of three different cavity geometries and the previous works (Paitoonsurikarn and Lovegrove, 2003; Paitoonsurikarn et al., 2004), an improved version of correlation was presented by Paitoonsurikarn and Lovegrove (2006a).

Taumoefolau et al. (2004) experimentally investigated the natural convection heat loss from an electrically heated model cavity receiver for different inclinations varying in $-90–90^0$ with temperature ranging from 450 to 650^0C. It was found that the Clausing model showed overall the closest prediction for both numerical and experimental results with downward-facing angles despite its original use for big scale central receivers. For upward-facing angles, the modified Stine and McDonald model showed the closest agreement to the experimental results. The inclination, for which maximum convection heat loss occurs, increases as the opening ratio decreases, which was also observed by Leibfried and Ortjohann (1995).

Most recently, an experimental and numerical study of the steady state convective losses occurring from a downward facing cylindrical cavity receiver of length 0.5 m, internal diameter of 0.3 m and a wind skirt diameter of 0.5 m was carried out by

M. Prakash et al (2008).The effects of fluid inlet temperature, receiver inclination angle and external wind on the total thermal loss and the convective losses were studied experimentally as well as numerically for a downward facing cavity receiver made up of helical coil tube having cavity diameter less than the depth as well as the aperture diameter. The highest total and convective losses were obtained for the head-on wind condition at 0^0inclination of the receiver. The losses were higher than the side-on wind convective loss. The no-wind convective loss at 0^0inclination is greater than that due to 1 m/s and 3 m/s side-on wind as the side-on wind presumably prevents the hot air from flowing out of the cavity. At 3 m/s wind speed, the total and convective losses are independent of wind direction for all inclination except 0^0receiver inclination. The effect of inclination on losses due to the side-on wind condition was very small when compared to the no-wind and head-on wind conditions.

The objective of proposed research study is to evaluate the thermal performance of parabolic dish solar collector thermal cavity receiver with different geometric configuration. It is expected that with the same collector space higher thermal efficiency or higher fluid temperature can be obtained. In this proposed research study the design of thermal cavity receiver is analyzed to reduce heat losses using computer software. A heat transfer and flow simulation is performed for thermal cavity receiver at various receiver inclinations and at different temperatures. The prototype of thermal cavity receiver is manufactured using material and equipments available and tested at research center. The research work elaborates in detail the steps undertaken in the fabrication of the thermal cavity receiver and other accessory parts used in the experimental setup such as tube design and working

4. OBJECTIVE OF STUDY

In India the energy problem is very serious. In spite of discoveries of oil and gas off the west coast, the import of crude oil continues to increase and the price paid for it now dominates all other expenditure. Every year the country is spending more than thousand crores for the import of oil. This amount forms a major part of India's import bill. The need for developing energy alternatives is thus evident and considerable research and development work is needed in this direction. The objective of this study is to make a well awareness among the engineers to carry out more and more research and make more extensive use of renewable sources of energy derived from the sun. The other objectives related with the proposed study are:

- The objective of present study is to evaluate the thermal performance of parabolic dish solar collector central cavity receiver using computer software.
- To achieve higher thermal efficiency and higher fluid temperature with the same cavity receiver space.
- To analyze the design of thermal cavity receiver thermally in order to reduce heat losses using computer software.
- To design a new cascaded solar thermal cavity receiver using computer software to improve the thermal and optical performance of the system.
- To test the heat transfer and flow simulation performanceof cascaded solar thermal at various receiver inclinations and at different temperatures to reduce heat losses.
- To manufacture the prototype of central cavity receiver using material and equipments available and to test the same prototype at research center.
- To collect and employ to study the performance of the cascaded solar thermal cavity receiverby taking the measurements of energy losses, temperature drops, wind speed, working fluid flow rate, and inlet/outlet temperatures of the working fluid inside the central cavity receiver.
- To calculate the efficiency,this is used as a measure of performance of parabolic central cavity receiver.
- To compare the experimental results with the result obtained using a computer model.

5. SCOPE OF THE PROBLEM

The heat losses from the receiver include three contributions: conductive heat loss from the receiver walls and radiative and convective heat losses through the receiver aperture. Among these contributions, natural convective heat loss contributes a significant fraction of energy loss. The natural convective heat loss in the receiver is an important factor for determining the performance of a fuzzy the overall focal solar dish concentrator. In order to improve system efficiency, natural convection characteristics need to be studied extensively.

The important energy loss for the receiver originates from convection and radiation heat transfer to the surroundings. These losses depend on the design of the receiver, its heated (or aperture) area, and its operating temperature. Additional factors include the local wind velocity, ambient temperature, and the orientation of the receiver. The design of solar thermal cavity receiver need to be analyzed to reduce heat losses.

6. REASONS FOR SELECTING PROBLEM

- Energy is one of the building blocks of the country. The growth of the country has been fueled by cheap, abundant energy resources. Solar energy is a form of renewable energy which is available abundantly and collected unreservedly.
- In India the energy problem is very serious. In spite of discoveries of oil and gas off the west coast, the import of crude oil continues to increase and the price paid for it now dominates all other expenditure.
- Every year the country is spending more than thousand crores for the import of oil. This amount forms a major part of India's import bill. The need for developing energy alternatives is thus evident and considerable research and development work is needed in this direction.

7.CONCLUSION

The need for developing energy alternatives is evident and considerable research and development work is needed in this direction .It's need of today to make a well awareness among the engineers to carry out more and more research and make more extensive use of renewable sources of energy derived from the sun.

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