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Modified Solar Thermal Cavity Receivers for Parabolic Concentrating Collector: Review

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ABSTRACT

In India, we receive almost 80% of continuous solar radiation yearly. In order to make maximum use of this solar insolation, there are various solar thermal technologies of which one is concentrating solar power (CSP). Solar cavity receivers are more efficient technology as compared to solar trough technology. However, due to the complex design and losses in heat transfer in the form of convection, solar cavity systems have fallen behind in the world of alternative energy systems. In order to make cavity receiver technology more efficient, various energy losses are to be considered and efforts should be made to minimize them. The parabolic concentrator reflects the direct incident solar radiation onto a receiver mounted above the dish at its focal point. The conversion of concentrated solar radiation to heat takes place in the receiver. The heat transfer characteristics of the receiver changes during the rotation of the receiver which affects thermal performance. A heat transfer and flow simulation are performed for different solar cavity receiver's viz.: cylindrical, cubical, conical, dome and spherical receivers at various receiver inclinations at a constant temperature. The receivers are designed such that they have same surface area and aperture. It is observed that convective heat loss decreases as the inclination changes from 0° to 90°. Among these receivers, the convective heat loss for different geometries & different angle of inclinations is studied.

Keyword: Cavity Receivers, Heat Loss, Inclination Angles etc.

1. INTRODUCTION

Solar energy is very large, inexhaustible source of energy. 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. In addition to its size, solar energy has two other factors in its favor. First, unlike fossil fuels and nuclear power, it is an environmentally clean source of energy. Second, it is free and available in adequate quantities in almost all parts of the world where people live. The sun is a sphere of intensely hot gaseous matter with a diameter of $1.39x10^9$ m. The solar energy strikes our planet a mere 8 min and 20 s after leaving the giant furnace, the sun which is $1.5x10^{11}$ m away. The sun has an effective blackbody temperature of 5762K. The temperature in the central region is much higher and it is estimated at $8x10^6$ to $40x10^6$ K. In effect, the sun is a continuous fusion reactor in which hydrogen is turned into helium. The sun's total energy output is $3.8x10^{20}$ MW which is equal to 63 MW/m^2 of the sun's surface. This energy radiates outwards in all directions. Only a tiny fraction, $1.7x\ 10^{14}$ kW, of the total radiation emitted is intercepted by the earth. However, even with this small fraction, it is estimated that 30 min of solar radiation falling on earth is equal to the world energy demand for one year. [1]

The technology of tower-type solar power, which is one of the three primary solar power technologies, had been concerning and studying more and more all over the world, as it has many obvious advantages including a clean energy source, large-scale power generation, and low average cost. One possible configuration is to utilize a solar cavity receiver, which transforms light into heat in the tower-type solar power system. Its performance directly relates to the efficiency of the whole power generation system. So far, most of the studies on the thermal performance of tower-type solar cavity receiver are still focused on the heat loss of the receiver. [2]

Among the various solar collectors, the parabolic dish concentrating collector is the most suitable system for meeting medium and high-temperature process heat requirements. Generally, it consists of a reflector in the form of a dish and a receiver at the focus. The thermal and optical losses occurring from an open cavity solar receiver are less when compared to other types of receivers and hence, such receivers are preferred. Convective losses from cubical and rectangular open cavities have 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. [3]

Solar concentrators are used for many applications such as supplying process heat to industries, generating electricity, melting and processing of metals as in the case of solar furnaces, etc. Many varieties of concentrators are used in various parts of the world. Recently in India, Fresnel parabolic dish with a cavity receiver is being used for supplying low and medium temperature process heat. It consists of a mirror assembly in the form of a dish and a cavity receiver with a helical metallic coil. Such a system does not need any evacuated tube construction and uses simple float glass mirrors as reflectors. This makes the system cheaper in Indian scenario and durable in industrial environments. Working fluids used in such systems are thermic oil, air or pressurized water. [4]

A central cavity receiver system is a concept for a high-temperature solar concentrator that aims at the collection of large amounts of highly concentrated solar energy without requiring a piping. In this concept, it is expected to achieve economy-of-scale benefits because systems with several 1,00,000 m^2 of reflector surface area can focus on a single receiver approaching several 100 MW of power and thus use conventional power plant technology for the power cycle. Fig.1 shows the Schematic diagram of the dish solar concentrator/cavity receiver system [6], [7].

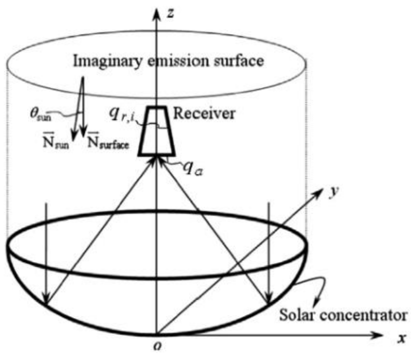


Fig.1. Schematic diagram of the dish solar concentrator/cavity receiver system [6]

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, it's 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.

2. PARABOLIC DISH REFLECTOR (PDR)

A parabolic dish reflector, shown schematically in Fig.2, is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must track fully the sun to reflect the beam into the thermal receiver. The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then either be converted into electricity using an engine-generator coupled directly to the receiver, or it can be transported through pipes to a central power-conversion system. Parabolic dish systems can achieve temperatures in excess of 1500°C. Because the receivers are distributed throughout a collector field, like parabolic troughs, parabolic dishes are often called distributed-receiver systems. [1]

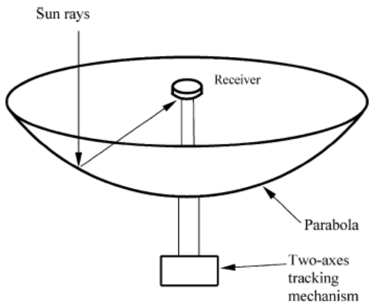


Fig.2. Schematic of a parabolic dish collector. [1]

Parabolic dishes have several important advantages:

1. Because they are always pointing the sun, they are the most efficient of all collector systems;
2. They typically have concentration ratio in the range of 600–2000, and thus are highly efficient at thermal energy absorption and power conversion systems;
3. They have modular collector and receiver units that can either function independently or as part of a larger system of dishes.

The main use of this type of concentrator is for parabolic dish engines. A parabolic dish-engine system is an electric generator that uses sunlight instead of crude oil or coal to produce electricity. The major parts of a system are the solar dish concentrator and the power conversion unit. Parabolic dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat-transfer fluid to the power-conversion systems. The need to circulate heat transfer fluid throughout the collector field raises design issues such as piping layout, pumping requirements, and thermal losses.

Systems that employ small generators at the focal point of each dish provide energy in the form of electricity rather than as heated fluid. The power conversion unit includes the thermal receiver and the heat engine. The thermal receiver absorbs the concentrated beam of solar energy, converts it to heat, and transfers the heat to the heat engine. A thermal receiver can be a bank of tubes with a cooling fluid circulating through it. The heat transfer medium usually employed as the working fluid for an engine is hydrogen or helium. Alternate thermal receivers are heat pipes wherein the boiling and condensing of an intermediate fluid are used to transfer the heat to the engine.

The heat engine system takes the heat from the thermal receiver and uses it to produce electricity. The engine-generators have several components; a receiver to absorb the concentrated sunlight to heat the working fluid of the engine, which then converts the thermal energy into mechanical work; an alternator attached to the engine to convert the work into electricity, a waste-heat exhaust system to vent excess heat to the atmosphere, and a control system to match the engine’s operation to the available solar energy. This distributed parabolic dish system lacks thermal storage capabilities but can be hybridised to run on fossil fuel during periods without the sunshine. The Stirling engine is the most common type of heat engine used in dish-engine systems. Other possible power conversion unit technologies that are evaluated for future applications are microturbines and concentrating photovoltaics. [1]

3. MODIFIED CAVITY RECEIVERS FOR PARABOLIC DISH COLLECTORS

3.1. Objectives

1. To study parabolic dish reflector.
2. To study different geometries of modified solar cavity receivers for parabolic solar collectors.
3. To study heat losses from the cavity receivers.
4. To study the effects of inclination angles on heat loss.
5. To study the effects of area ratio on heat loss

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, it's heated (or aperture) area and its operating temperature. Additional factors include the local wind velocity, ambient temperature, and the orientation of the receiver.

Clausing (1981) has developed a method for predicting the natural convective loss from cavity receivers. Radiation and convection losses are primarily functions of the size of the receiver and the operating temperature of the system. For most currently conceived central receiver system designs, the receiver operates at a constant temperature. Therefore, the rate of energy being lost from the receiver is essentially constant throughout the day (and year) and the percentage loss increases in the morning and evening. [9]

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 main objectives of this work to predict the convective heat loss from the different receiver is shown in Fig.3. [6]

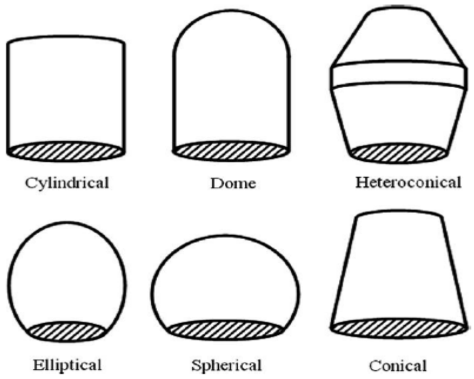


Fig.3. Six Classical Cavity Geometries [6]

3.2. Geometric Model of the Receiver

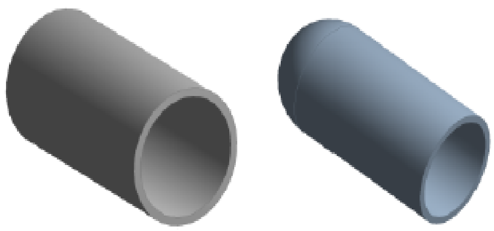


Fig.4. Geometric Model of Cylindrical Dome Receiver [6]

Initially, cylindrical geometry of cylindrical receiver is created as shown in Fig.4. For CFD analysis, the receiver is assumed to be placed in a sufficiently large enclosure with walls at ambient temperature. Due to the symmetrical flow geometry with respect to the middle vertical plane, the computational extent comprises only one-half of the physical domain. The size of the enclosure was determined in a preliminary study such that it showed the negligible effect on fluid and heat flows in the vicinity of the receiver. It was found that the height of the enclosure should be approximately twenty times the diameter of the receiver to achieve this. [6]

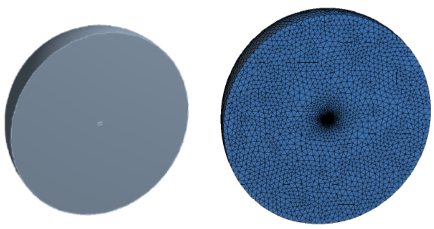


Fig.5. CFD Domain of Cylindrical Dome Receiver

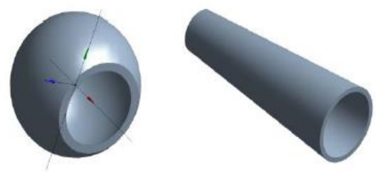


Fig.6. Geometric Model of Spherical and Conical Dome Receiver

For boundary conditions, the cylindrical enclosure wall was set to an ambient temperature of 27°C. The receiver's cavity and outer walls were assumed to be isothermal and adiabatic, respectively.

The cavity wall temperature for each receiver was set as follows:
For the model receiver, the average experimental values of cavity wall temperature data of 450°C is used for the cylindrical section, a similar setup is used for all the receivers. [6]

3.3. Analysis of the Modified Receivers

Temperature contours of the cylindrical receiver at a surface temperature of 450° C for inclinations of 0°, 30°, 60°, and 90° are shown in Fig.7.

Red color represents the stagnation zone that has a high temperature within the cavity whereas blue color represents the convective zone that is near ambient temperature. The zone boundary is the separation of red and yellow colors. Most of the receiver locations have air temperature gradients at 0° inclination (receiver facing sideways) of the cavity hence little stagnation zone exists for this particular orientation.

As the inclination of the receiver increases from 0° to 30° the stagnation zone size increases. As the inclination of the receiver increased to 90° (facing sideways) the stagnation zone size further increases. The convective heat loss is minimum at 90° inclination of the receiver as shown in Chart.1.

Fig.8.shows the temperature contours of the dome receiver for various inclinations at 450° C. It is observed that the inclination of the receiver increases from 0° to 90° of the receiver, the stagnation zone increases whereas the convective zone decreases. Hence the convective heat loss decreases as the orientation of the receiver changes from 0° to 90°

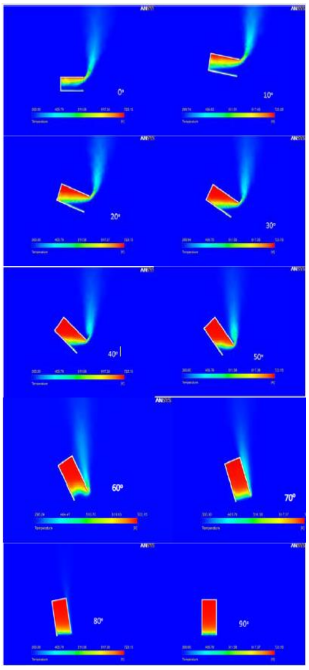


Fig.7. Cylindrical Receiver Temperature Contours at Inclination 0-90°C [6]

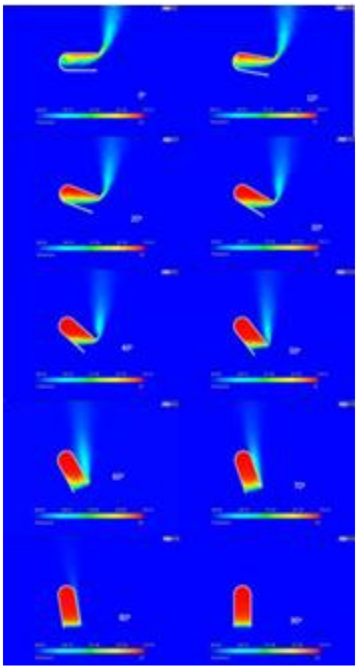
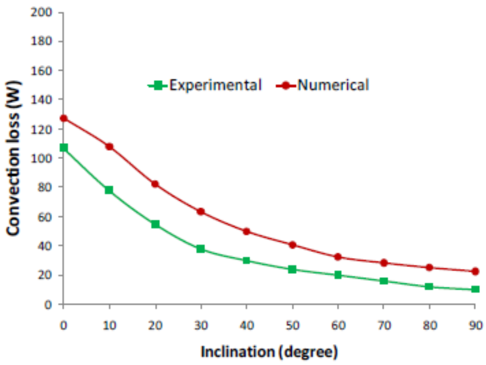


Fig.8. Dome Receiver Temperature Contours at Inclination 0-90°C [6]

Chart.1. Comparison of Experimental and Numerical Values for Cylindrical Receivers [6]



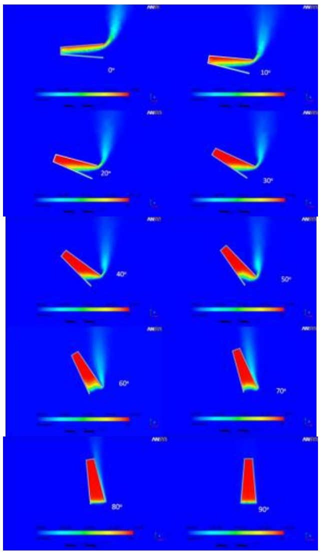


Fig.9. Conical Receiver Temperature Contours at Inclination 0-90°C [6]

Fig.9 shows the temperature contours of the conical receiver for various inclinations at 450° C. It is observed that at 0° inclination the convective heat loss is maximum. The convective heat loss reduces to a minimum as the orientation is increased to 90°. The stagnation zone increases within the receiver in both cases as the inclination of the receiver increases from 0° to 90°. The direct consequence of the increase in the stagnant zone is decreased in convective heat loss as the orientation changes from 0° to 90°.

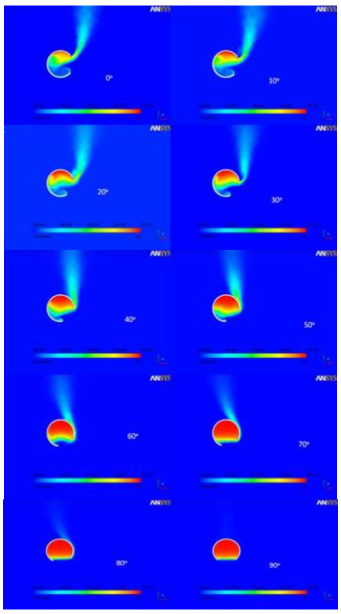


Fig.10. Spherical Receiver Temperature Contours at Inclination 0-90°C [6]

Fig.10. shows the temperature contours of the spherical receiver for various inclinations at 450° C. It is observed that the maximum convective heat loss occurs at 0° inclination. It is observed that the convective heat loss is minimum as the orientation changes to 90°.

Chart.2. Convection Heat loss comparison [6]

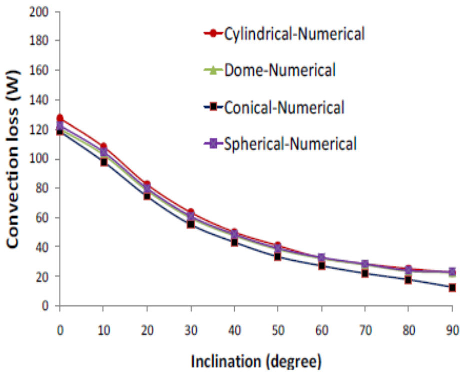


Chart.2 shows Comparison of convective heat loss with different inclinations among cylindrical, conical, dome and spherical receivers at 450°C. The receivers are designed such that they have same surface area and aperture. It is observed that convective heat loss decreases as the inclination changes from 0° to 90°. Among these receivers, the convective heat loss is least for conical receiver followed by a dome, spherical and cylindrical receivers.

5. CAVITY RECEIVERS FROM SEVERAL STUDIES

Three different cavity shapes namely cubical, spherical and hemispherical are analyzed in the present work (Fig.11). The effect of the opening ratio (a/H for cubical cavities and d/D for spherical and hemispherical cavities) of 0.5 and 0.25 on the convective loss is studied for the three cavity shapes. For a/H and d/D ratio of 1, the study is limited to cubical and hemispherical cavity shapes. The inner walls of all the cavities constitute the heat transfer surfaces and the cavity external walls are adiabatic. The area of the inner walls (heat transfer area) of all cavities is kept 1 m^2 though the diameters and sides of the cavity shapes are different. This facilitates comparison of the different cavity shapes on the basis of their convective loss at similar wall temperatures. [5]

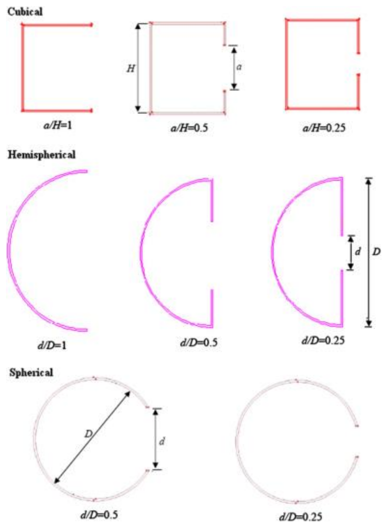


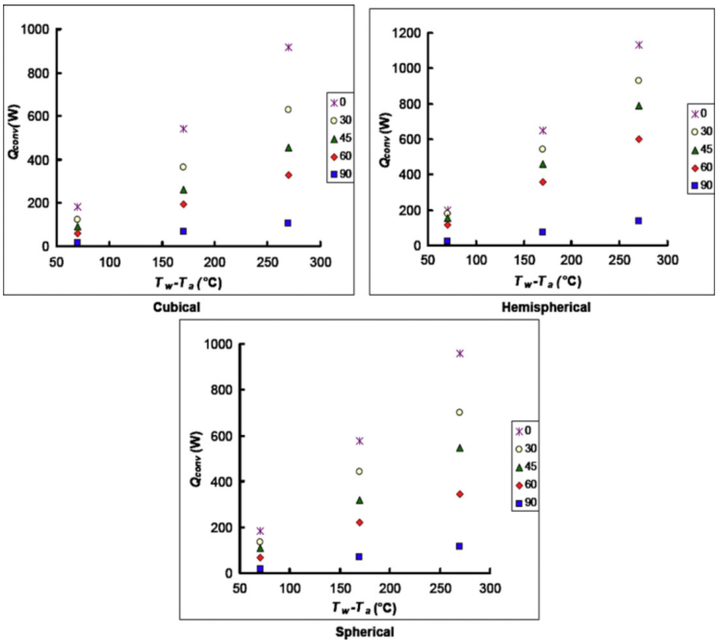
Fig.11. Open cavity analyzed [5]

The convective loss obtained for cubical, hemispherical and spherical cavity models with an opening ratio of 0.5 is depicted in Chart.3.

It can be seen that the convective loss increases with temperature difference (Tw - Ta). A linear trend is noticed. The convective loss is the least for the 90° inclination and is the highest for the 0° angle. [5] It can also be concluded from Chart.3. That the loss values are highest for the hemispherical cavity and lowest for the cubical cavity. An average increase of about 30% in the convective loss is observed for the hemispherical cavity when compared with the cubical cavity while the average convective loss increase is about 20% when compared to the spherical cavity for all opening ratios. This might be due to the fact that the depth of the hemispherical cavity is the lowest for all the models. This leads to reduced air stagnation within the hemispherical cavity leading to a higher convective loss. [5]

A reduced aperture size leads to a smaller aperture area that prevents the convective currents from exiting the cavity. The increase in natural convection loss for different inclinations is found to vary between 30% and 80% when the opening ratio is increased from 0.25 to 0.5 for all cavity shapes. A similar increase in natural convection loss is observed when the opening ratio is increased from 0.5 to 1 for the cubical and hemispherical cavities.

Chart.3. Convective loss for cavities having opening ratio of 0.5 [5]



The schematic of the solar fuzzy focal solar dish collector is shown in Fig.12. The receiver considered for simulation is made of copper tubing. The copper tubes are wound spirally to get the respective shape of the receiver as shown in Fig.13. The outer surface of the cavity receiver and the modified cavity receiver is completely covered with opaque insulation of 20 mm thickness, but in the semi-cavity receiver, the top half portion of the receiver is covered with opaque insulation. All the receivers are indented to capture the same reflected radiation and, therefore, have equal aperture area. For natural convection in the cavity receiver, the flow and heat transfer simulation is based on the simultaneous solution of the continuity, momentum and energy equations.[11]

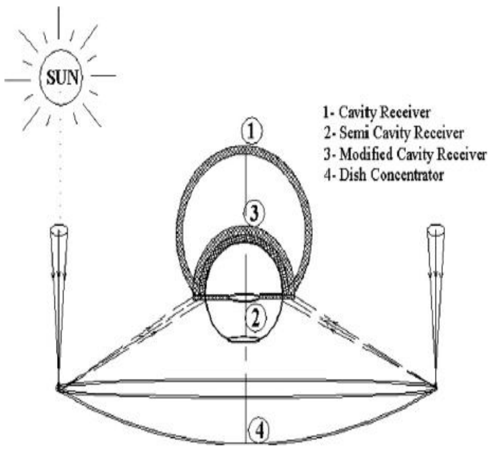


Fig.12. Schematic diagram of solar receivers in fuzzy focal solar dish [11]

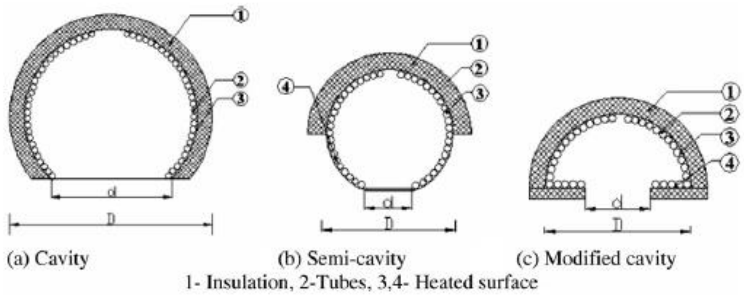


Fig.13. Enlarged view of different types of receivers [11]

The temperature contours of the cavity receiver at 400°C for various inclinations are shown in Fig.14. It is observed that at 0° inclination of the receiver, the fluid does not flow over the curved surface, whereas at 30°, 60° and 90° inclination, the fluid passes over the curved surface. At 90° inclination of the receiver, plume behavior has been observed. At 90° inclination of the receiver, a unique feature of three distinct flow regions is observed in the downstream: the attached boundary layer region, the separating region and the region of shed flow at the top. At the end of the shed flow, the flow develops toward an axisymmetric plume behavior. It is evident that the convection heat loss is minimum at 90° inclination of the receiver. [11]

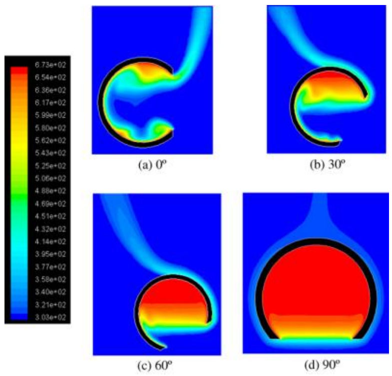


Fig.14. Temperature contours for various inclinations of cavity receiver at 400°C [11]

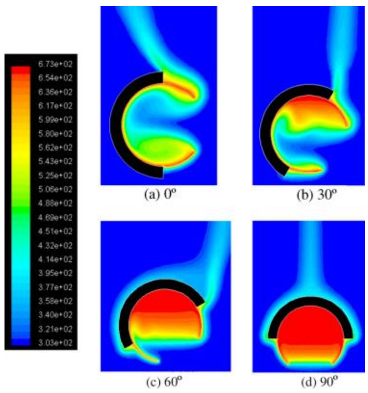


Fig.15. Temperature contours for various inclinations of semi-cavity receiver at 400°C [11]

The temperature contours of the semi-cavity receiver at 400°C for various inclinations are shown in Fig.15. The fluid passes over the curved surface starting from 0° to 90°inclination of the receiver. Beyond 30° inclination, the fluid from the left side portion of the semi-cavity receiver passes over more area when compared to the right side portion of the receiver. At 90° inclination, the phenomenon of plume formation has been observed, which resulted in higher convection heat loss. The existence of higher heat loss is due to the non-uniform boundary condition of the surface of the tubes, i.e. a portion of the surface area of the tube is exposed to the ambient. This leads to the formation of a non-effective stagnant air zone inside the receiver.

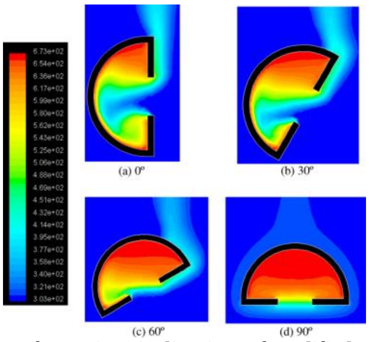
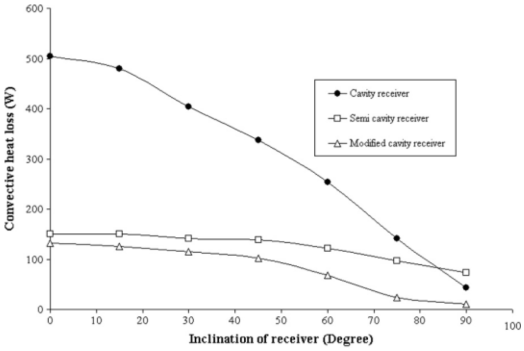


Fig.16. Temperature contours for various inclinations of modified cavity receiver at 400°C [11]

The temperature contours of the modified cavity receiver at 400°C for different inclinations are shown in Fig.16 The fluid passes over the entire curved surface at 90° inclination of the receiver, whereas it flows over somewhat less of the curved surface at 60°. An effective stagnant air zone is observed inside the modified cavity receiver. The convection loss decreases with an inclination of the receiver.

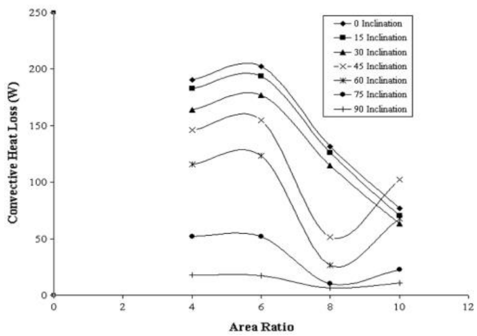
A comparison of cavity, semi-cavity and modified cavity receivers for different inclinations and at 400°C is shown in Chart.4. The maximum convection heat loss occurs at 0° inclination of the receiver and the value decreases up to 90° inclination of the receiver. This trend is observed for all three types of receivers. These natural convective heat losses from the cavity receiver decrease as the inclination of the receiver increases due to stratification of the flow. For all inclinations of the receiver, the cavity receiver gives higher convection heat loss than the other receivers, except at 90° inclination. This is due to the formation of effectively stagnant air inside the receiver. At 90°, low convection heat loss was observed when compared to the semi-cavity receiver. It is also observed that the variation of heat loss from the semi-cavity receiver with inclination is marginal.[11]

Chart.4. Variation of convective heat loss for different solar receivers.[11]



As A_w/A_1 increases from 4 to 10, the quantity of air trapped inside the receiver increases, thereby reducing the natural convection. The variation of the convection heat loss with area ratio for different inclinations of the modified cavity receiver is shown in Chart.5. Because of the ineffective stagnant air zone, the convection heat loss monotonically decreases up to 30°. It is observed that the stagnant air zone is highly stable beyond 30°. For the modified cavity receiver at greater than 30° inclination, the convective heat loss was found to be minimum for an area ratio (A_w/A_1) of 8. [11]

Chart.5. Variation of the convection heat loss with area ratio for different inclinations of the modified cavity receiver. [11]



6. CONCLUSION

The results of a numerical study of the problem of natural convection in cavity receivers of solar parabolic dish collector have been presented. The effect of cavity geometry, inclination, receiver temperature through the aperture of solar cavity receiver has been studied.

The comparison of convective heat loss with different inclinations among cylindrical, conical, dome and spherical receivers at temperature 450°C is presented. The receivers are designed such that they have same surface area and aperture. It is observed that convective heat loss decreases as the inclination changes from 0° to 90°. Among these receivers, the convective heat loss is least for conical receiver followed by a dome, spherical and cylindrical receivers.

A comparison of cavity, semi-cavity and modified cavity receivers for different inclinations and at 400°C shows that the maximum convection heat loss occurs at 0° inclination of the receiver and the value decreases up to 90° inclination of the receiver for the modified cavity receiver at greater than 30° inclination, the convective heat loss was found to be minimum for an area ratio (A_w/A_1) of 8.

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