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Experimental investigation and optimization of parameters of a new design flat plate cavity collector

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ABSTRACT

This paper deals with the performance analysis and optimization of working parameters of a flat plate solar cavity collector. Cavity type configuration is an improved version of a flat plate collector. It is evident that every solar gadget need a little bit of improvement in order to perform well. Various experiments both theoretical and experimental are going on in various countries to achieve better performance of flat plate collector. Hence the better choice for the improvement of flat plate collector is the cavity collector. Usually the cavity type configuration is utilized for focusing, solar tower and Fresnel lens collectors. But it was experimented for the flat plate improvement and hence it is proved to be a one of the alternate solution for the flat plate collector. It also works more efficiently even at low radiation source for a certain period of time and at part cloudy days. Solar Cavity Collector (SCC) has been experimented with various working parameters like change of receiver material (Copper and Aluminum), various L/D ratio, change of inclination angle, change of mode of flow (parallel and serpentine), collector packed with pebble bed and metal chips to enhance the heat transfer phenomena in the collector, by increasing the number of cavities and Collector with end plates. End plates were welded at entry and exit of the receiver pipes to stagnate the water for a while inside the collector.

Introduction

Flat-plate solar collector uses diffuse and direct component of solar radiation for fluid heating. Usually it operates in low temperature levels (<373 K) for heating of water, air and other aqueous solutions. It has numerous advantages over concentrating type which includes simple in construction, cheaper, requires less maintenance, ease to operate, etc. Solar energy is utilized in the collector for air heating and water heating applications. Solar water heating is one of the effective methods to extract heat from the collector with available solar radiation. The utilization of the solar energy in an effective way plays a vital role to increase the efficiency of the collector and also to reduce the initial and operating costs. Research works are going on to optimize the solar collectors in all possible ways to minimize the losses and also to improve the optimal performance. Cavity collector is an improved version of the flat plate collector. The application of the Cavity collector is used to heat the water. In general to obtain maximum efficiency, one of the methods is to increase the operating temperature of a flat plate collector and also to convert the available radiation into heat energy with minimum heat losses. Hence, one of the methods to achieve this phenomenon is a cavity type configuration. The intermittent characteristic of the solar radiations necessitates improvement of suitable collection and storage technologies. Thermal energy storage is simple and effective method to store and extract the high or low temperature energy for later use. Because of its simplicity sensible heat storage has an advantage of storing and extracting heat energy as ease as much and no complicated design and implementation required as compared to latent heat storage.

Bairi [1] formed a numerical 2D parallelogrammic cavity which explains about the several inclination angles (α) and heat exchange between active and passive walls with various Nusselt number correlations. Influence of multi reflector effect through a macro cavity was presented by Demichelis and Russo [2].The optical design of the cavity and the cavity effect was determined by them for solar concentrating collectors. Flores et al. [3] reported that in the cubic cavity the radiative heat transfer plays a vital role than the convective heat transfer. They developed a mathematical model and parametric study was carried out from various solar control coating (SCC) absorptances. Hahm et al [4] focused on the performance of a cone in conjunction with a cavity-receiver. A cone with a small exit aperture suffers from a high amount of rejected rays. A larger aperture on the other hand increases the thermal losses of the cavity. Harjit Singh et al, [5] reported that, natural convective heat transfer in cavities is a complex function of cavity shape, aspect ratio, boundary conditions at the walls. Natural convection in regular shaped cavities, such as those of rectangular, square, and cylindrical section were analyzed and results show considerable reduction in convective heat transfer, thus improves the performance of CPC solar collectors. Various correlations including Nusselt number have been used for the analysis. Jose et al [6] reviewed the design, construction, and testing of a simple, low-cost passive water heater for Portugal climate. They have reported that, energy saving largely depends on thermal stratification within the storage cavity. A constant tilt angle of 45o was actually employed in their study.

Kribus et al [7] did the experimental analysis by using two heating stages namely, high-temperature receiver stage

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which is Directly Irradiated Annular Pressurized Receiver (DIAPR) and Low-temperature stage which consists of intermediate temperature cavity tubular receivers. Results show that convective heat losses and partitioning losses have been reduced. Prakash et al [8] reported that the thermal as well as optical losses affect the performance of a solar parabolic dish-cavity receiver system. The experiments were conducted for fluid inlet temperatures between 50^{o}C and 75^{o}C and for receiver inclination angles of 0^o, 30^o, 45^o, 60^o and 90^o using the Fluent CFD software. It was found that the Convective loss increases with mean receiver temperature and decreases with increase in receiver inclination. The optical performance of Non-isothermal flat plate solar collectors was presented by Torres and Ibarra [9]. They reported the creation of thermo-economic model and determination of annual cost for solar air heater by means of dimensionless parameter such as mass flow number. The thermodynamic optimization procedure was evaluated to determine the optimal performance parameters of an experimental solar cavity collector. Tom Melchior et al. [10] explain about a cavity type receiver containing a tubular absorber model, developed and validated experimentally. The solar chemical reactor containing a tubular Ceramic absorber which utilizes thermo chemical process has the capability of high temperature applications such as the production of H_2.

Cavity collector – An introduction

Fig.1 and Fig.2 explains about a single cavity tube in detail. They explain about the basic components like receiver, cavity support structure and aperture. Also the location of cavity, energy transfer to receiver through the cavity. The aperture is a small opening which admits the solar radiation into the cavity. Solar radiation enters through aperture, gets reflected by cavity and reradiated back to the receiver tube. Again and again the reflection prolongs inside the cavity and part of it escapes from the cavity through aperture opening. The reflected light rays have been effectively absorbed by the receiver and thus the working fluid gets heated up. In conventional flat plate collector the absorber plate was used to collect the solar radiation; which has been replaced by a receiver tube for cavity type configuration.

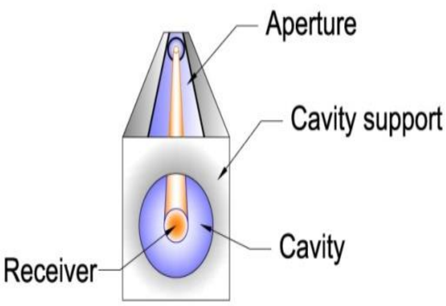

Figure1. Detailed view of a single cavity tube

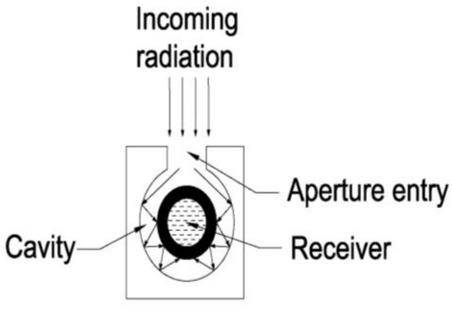

Figure 2. Multi reflection process of a solar cavity collector

The cavity receiver suffers from high amount of rejected rays if the aperture is made too small, on the other hand a larger aperture increases the thermal losses of the cavity. Therefore an optimum size of the aperture has to be found to get the maximum incoming radiation to be absorbed by the cavity collector. Thus the incidental solar energy can be transformed into thermal energy for various applications such as heating and production of hot water by using solar collectors. Hence cavity collector has the capacity to hold the heat for a long time. Therefore the better solution for the improvement of flat plate collector was the cavity type configuration. In the case of a flat plate collector, the absorber plate is used to receive the irradiative energy from the sun. For cavity collector, it has been replaced by the receiver tube. In this research work water was used as a working fluid. . It is however useful to point out that the multi reflection effect can be achieved through cavity which is called as the" Cavity effect" and hence the heat holding capacity of the collector has been enhanced to an optimum level.

Experimental set-up

The solar cavity consists of a cylinder made-up of Copper with the radius of 16 mm. Five numbers of such cavities were placed in a rectangular metal box at equal distance. The tubular receiver coated with the black paint having an outer radius of 6.35mm was positioned concentrically within the cylindrical cavity. Fig.3 shows the experimental arrangement of the cavity collector. The transport pipes in the cavities were connected in parallel and also in serpentine type. A glass plate mounted on the top serves as a protective shield for spilled radiation and also it reduces the top heat loss from the collector to the surroundings. Simply, it can be more effective for reducing the convective and radiative losses from the collector to the surroundings. All the joints of the metal box were well sealed. The bottom end of the collector tube was connected to the fresh water tank. The setup was tilted at an inclination angle of 11^o with respect to the horizontal. Global radiation was measured with the help of Pyranometer. Temperatures at different locations were measured by digital temperature indicator with the use of thermocouples. The ambient temperature was recorded using mercury thermometer. Thermocouples were located at different locations such as, at all cavities, glass plate, inlet and outlet pipes. The bottom and sides of the collector were properly insulated with glass wool to reduce the heat losses. The collector was kept in open yard facing south and exposed to solar radiation. The experiments were conducted from 9.30 AM to 4 PM. Observations were made with a time interval of 10 minutes on different days with different mass flow rates of water.

Table 1. Details of cavity collector

Collector size:	1 x 0.85 x 0.05 m
Number of cavities	5
Area of each cavity	0.101 m^2
Diamter of the tube	0.0127 m
Thickness of glass plate	0.004 m
Cavity receiver material	Copper
Collector insulation	Glass wool
Recivier coating	Industrial mat black paint
Aperture entry gap	0.006 m
Pitch distance of the cavity	170 mm

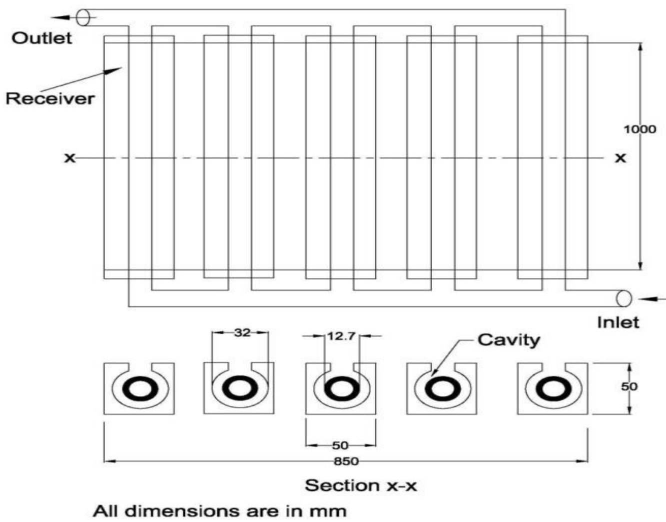

Figure 3. Flat plate cavity collector

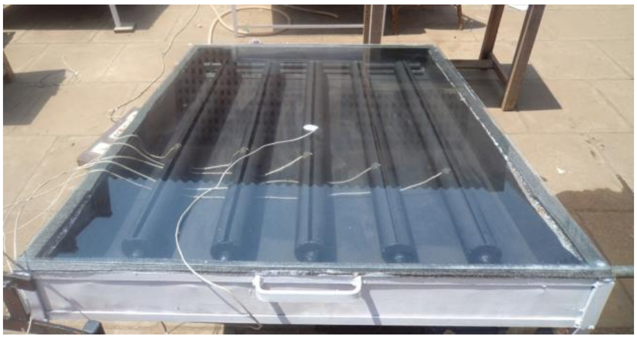

Figure 4. Experimental setup of a solar circular cavity receiver

Experimental analysis

This section explains about the parametric analysis of the solar cavity collector which includes the mode of flow [parallel and serpentine], change of receiver material as aluminum and copper, various tilting positions that is, changing the inclination of the collector as 11^o, 15^o, 20^o, 25^o, collector packed with and without pebble bed and metal scrap chips, increasing the number of cavities from 5 to 7, and End plates welded at top and bottom of the collector. Further more for optimizing the working parameters various experimental works have also been carried out such as , a) L/D ratio of 78.7 was tested for both serpentine and parallel modes, b) Tests were carried out with various L/D ratios of the collector as 40,50 and 78.7, c) Rectangular and circular box covers (outside of the cavity) for same L/D ratio of 78.7 were tested, d) Effect of number of cavities has also been tested with 5 and 7 for L/D ratio of 78.7. The observations were made for every 10 minutes interval of time.

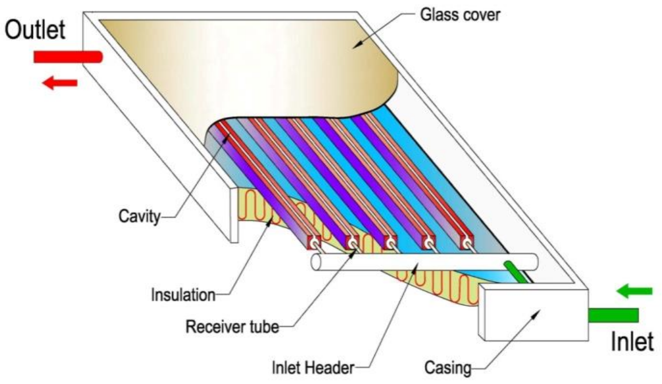

Figure 5. Schematic diagram of a flat plate cavity collector

Results and discussion

Solar collectors usually can employ the cavity type configuration for highly concentrated solar applications. The cavity receiver has an advantage of multiple reflection of radiative energy inside the cavity itself. That-is proper design of the cavity makes the effective capture of solar radiation entering through small opening, called aperture. Cavity type collectors are also well suited for the solar radiation of intermittent type. The radiative energy once absorbed by the air inside the cavity can withstand the temperature and distribute it to the surrounding working fluid either air or water. It is however useful to point out that multi reflection effect is considered through the cavity and it increases the heat holding capacity for a long time in the cavity.

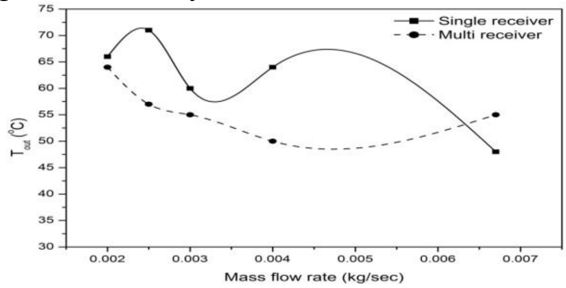

Figure 6. Comparison between single and multi receiver

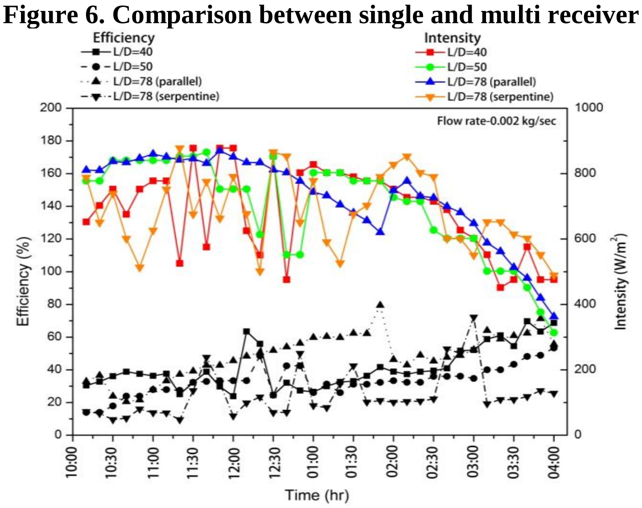

Figure 7. Effect of L/D ratio on the performances of solar cavity collector

Initially, the cavity collector was experimented with single and multi receiver. The receiver was splitted into three numbers instead of a single one. From Fig .6 the maximum outlet temperature of water around 72^{o}C was achieved by single receiver configuration at a mass flow rate of 0.0025 kg/sec. The temperature curve for multi receiver shows gradually decreasing trend with respect to the flow rate of water, 0.0067 kg/sec be the exception. Fig .7 shows the performance analysis of cavity receiver with different length to diameter ratios (L/D ratio) such as 40, 50, and 78.

The experiment was conducted for a L/D ratio of 78 and the mode of flow of water as parallel and serpentine to find the better performance of the collector which gives maximum efficiency among the two modes. The results furnished here are for all L/D ratios, the experiments have been conducted only for parallel mode of flow. It was found that the maximum efficiency has been obtained with the L/D ratio of 78 in parallel mode. It was evident from the graph that the efficiency curve for L/D of 78 gives better results than the others and there were no sudden ups and downs on efficiency and it was uniform when compared to serpentine mode. Almost all the points of L/D ratio of 78 in parallel approaches higher values. The lower most location was for L/D radio of 78 in serpentine mode of flow. Efficiency curves for L/D ratios of 40 and 50 lies between L/D ratio of 78 in parallel and serpentine mode of flow. For comparison the corresponding values of solar intensity were also furnished. It should be noted that the efficiency curve for all L/D ratios approaches a higher value at late afternoon hours, at that time solar intensity was low. There was no sudden drop in efficiency as in the case of conventional flat plate collector.

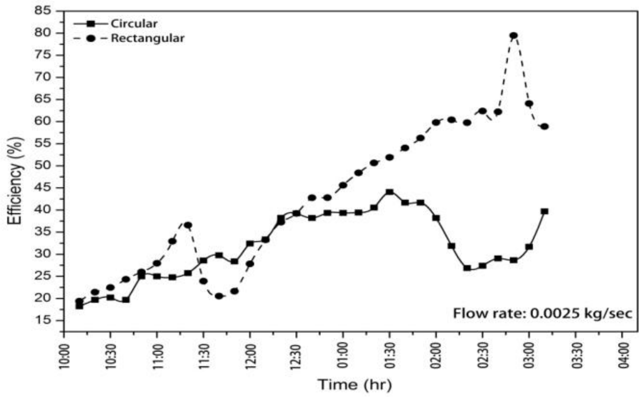

Figure 8. Variation in efficiency with respect to circular and rectangular cavities

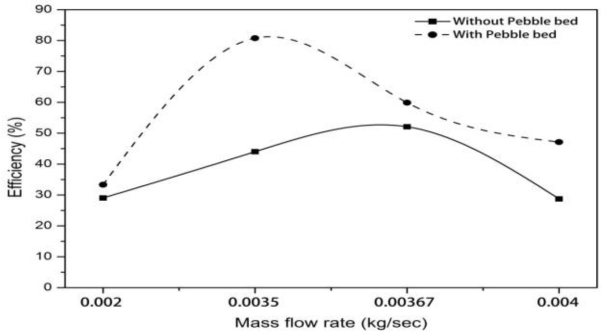

Figure 9. Effect of peddle bed on the performance of cavity collector

Figure 8 shows the comparison between circular and rectangular cavities for a mass flow rate of water at 0.0025 kg/sec. The usage of rectangular cavities was better when compared to the circular one. It was clear that in late afternoon hours the efficiency goes on increasing trend for rectangular cavities, at the same time the efficiency curve for circular cavities moves down. Thus from this experimental results, the usage of rectangular cavities would be a better choice. The inference from Fig.9 was the usage of heat enhancing medium like pebbles influences more in the performance of cavity collector. The experiment was conducted with and without packing of pebble bed for different mass flow rates of water from 0.002kg/sec. to 0.004 kg/sec. cavity collector packed with pebble bed gives better performance than the collector without pebble bed. From the figure, the efficiency curve for collector with pebble bed was far better when compared with collector without having pebbles. The variation in efficiency between these two was more at flow rate of 0.0035 kg/sec.

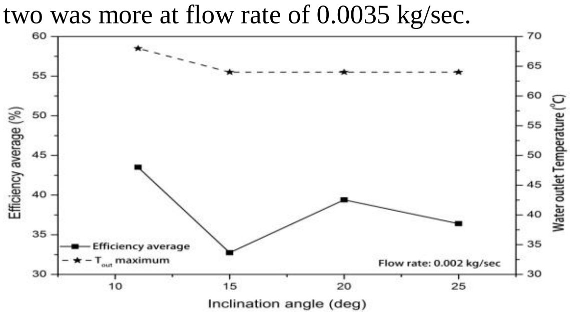

Figure 10. Efficiency and T_{out} comparison for different inclination angles

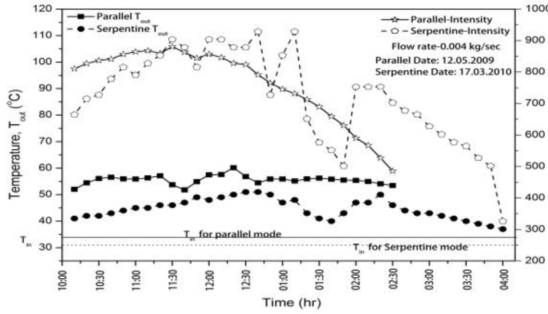

Figure 11. Comparison between parallel and serpentine mode of flow

The effect of inclination angle on the performance of cavity receiver has been analyzed in Figure.10. The experiments were conducted with tilted angle of 11°, 15°, 20°, 25° to find out the optimal performance. Even though the optimal inclination angle of a flat plate collector of 11° was well known; the better inclination angle for a solar cavity collector has not been established yet. Therefore it has been experimented to obtain a better inclination angle for SCC. Experimental results show that, inclination angle of 11° was best suited among the all for SCC. For both efficiency and water exit temperature, inclination angle of 11° records the maximum value. When looking for the water exit temperature except inclination angle of 11° it remains constant. For average efficiency it obtains a maximum value of 43.51 % for inclination angle of 11°, on the other hand a minimum value of 32.74 % for 15° inclination angle. For inclination angle of 20° and 25°, the values of efficiency were obtained as 39.4 % and 36.4 % respectively for a mass flow rate of 0.002 kg/sec.

Figure 11 compares the performance of parallel and serpentine flow for a flow rate of 0.004 kg/sec. Parallel mode of flow has been found to give better results when compared to serpentine mode of flow. Corresponding values of inlet water temperature have been given for both mode of flow so that the variation in inlet to outlet temperature of water can be viewed easily. As the intensity of radiation decreases, there was no sudden change in outlet temperature of water for parallel mode, which remains constant. The variation in intensity curve is due to a partly cloudy at that moment. Because of the cloud, Pyranometer records the lower value. Around 60° C has been achieved by the parallel mode of flow for a flow rate of 0.004 kg/sec. Also the curve for parallel mode of flow looks smoother when compared to serpentine mode.

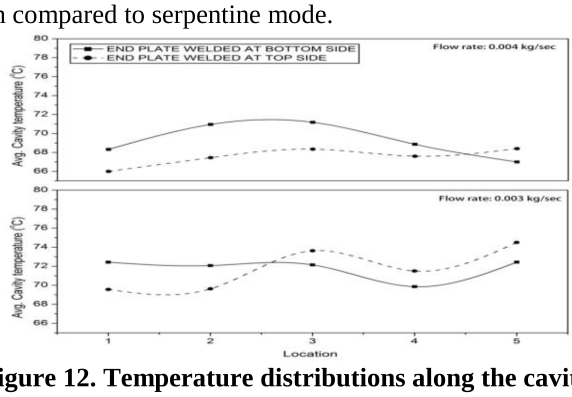

Figure 12. Temperature distributions along the cavities

It has been inferred from Fig.12, end plates help the working fluid to stagnate inside the receiver for a while and thus more heat exchange takes place between the receiver and water flowing inside it. Moreover it gives better performance when the endplates were welded at bottom side than at the top side of the SCC. In the cavity type configuration, cavity location at 2 and 3 records the maximum temperature. It's clearly shown by the graph; the 3rd cavity location records the maximum temperature for all curves irrespective of the flow rate. This is because of the shadow effect of the other cavities inside the cavity collector. It should be noted that fluctuations in cavity temperature was more at the flow rate of 0.003 kg/sec for both curves and on the other hand, both curves for the water flow rate of 0.004 kg/sec were more stable.

Conclusion

The objective was to develop a new, economical, more efficient and high heat holding capacity type of solar collector. Thus a Cavity type collector or receiver has been thought of. Moreover the conventional flat plate collector does not give more efficiency and on the other hand, concentrating type configuration requires tracking mechanism which costs more. Thus it is simple to construct a cavity type configuration which has the advantages of both flat plate and concentrating type collectors. SCC is an intermediate version of flat plate and concentrating type collectors. Efficiency of SCC was better than that of the conventional flat plate collector. The efficiency of the collector was not suddenly dropped during the afternoon hours. More over it gives better performance at late afternoon hours. Both parallel and serpentine mode of flow for L/D ratio of 78.7 was tested, parallel mode gives better performance than the other. Various L/D ratios were experimented viz, 40, 50 and 78.7. Results show that optimum L/D ratio among them was found to be 78.7.

SCC is much effective at partly cloudy days since the temperature of the collector is well maintained by the cavity and temperature would not drop down immediately as in the case of conventional flat plate collector. Copper as the receiver material gives more efficiency than the Aluminum. At higher flow rates multi receiver would be a better choice. As L/D ratio increases, the efficiency also increases. The formation of eddies at the corners of rectangular cavities prevents the heat loss from the collector to the surroundings. In the case of circular cavities the construction is so simple thus it further increases the heat flow to the surrounding. That is heat losses are more in the case of circular cavities. Pebbles store the heat from the solar radiation and the heat losses from the collector to the surrounding gets transferred to the pebbles. Thus it acts as a medium by which some heat energy can be utilized by the collector. Improvement in the energy transfer was achieved around 10% by the use of Pebbles was. The end plates welded at entry and exit of the receiver helps more heat interaction between the working fluid and receiver.

Nomenclature

η Efficiency, %
α Inclination angle with respect to the horizontal axis , ^{o}
$\dot{m}$ Mass flow rate, kg/sec
L Length of the collector, m
B Breadth of the collector, m
H Height of the collector, m
l Length of the single cavity, m
h Height of the single cavity, m
I_t Total intensity of solar radiation, W/m^2
A_c Collector area, m^2

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