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Performance Analysis on Working Parameters of a Flat-Plate Solar Cavity Collector

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Abstract – Solar energy is being used over a long period of time for various purposes. Applications like air heating and water heating are the main usage of solar energy. It is globally accepted and being utilized in many countries. Still various types of research work are in progress throughout the world to improve the solar gadgets for more efficiency. It has been evident that every solar gadget needs a little bit of improvement in order to perform well. A better solution for the improvement of flat plate collector is the cavity collector. The objective of this work is to analyze a solar cavity collector experimentally for various working parameters. The outcome of the experiments has been presented in this article. An experimental analysis on solar cavity collector has been done to determine its optimal efficiency under various conditions. A parametric analysis has been carried out to find the optimal performance and effective utilization of the solar energy. Various length -to- diameter ratios have been experimented, viz. 40, 50 and 78.74, based on the commercially available pipe diameter. The gadget has been tested by changing the mode of flow as parallel and serpentine type with an L/D ratio of 78.74, as that L/D ratio has been performing better. Comparisons have been made for its optimal performance with circular- and rectangular- type cavity cover. The formation of eddies at the corners of rectangular casing (cavity cover) withstands or prevents some additional heat losses, thus it should be entertained and thereby the heat losses can be reduced to some extent. As in the case of circular cavities, the heat losses are more because of its simple construction and thereby no prevention of heat losses. But in the rectangular cavities, there is a possibility to hold up the heat in the corners of the cavity and thus the loss of heat can be prevented. Heat can be again radiated back into the cavities in the form of light. Also the collector has been tested with 5 and 7 cavities for the same L/D ratio of 78.74. It has been tested at various mass flow rates of water such as 0.002, 0.0025, 0.003, 0.0035, 0.00417 and 0.0067 kg/sec to investigate its optimal performance. Experimental results show that the L/D ratio of 78.74 of parallel flow mode gives better results than the others at the flow rate of 0.002 kg/sec.

Keywords – Cavity collectors, cavity shape, L/D ratio, mass flow rate, solar energy.

1. INTRODUCTION

Although solar radiation is a high-quality energy resource, its high temperature, exergy, and low flux density at the earth surface makes it not suitable to extract work or heat. By transferring the heat to a heat transfer fluid for heating applications, one can achieve temperatures adequate for general home or industrial applications. The utilization of the solar energy in an effective way plays a vital role in increasing the efficiency of the collector and also in reducing the initial and operating costs. Research works have been going on to optimize the solar collectors in all possible ways. Cavity collector is an improved version of the flat plate collector (FPC). Solar energy is utilized in the collector in two ways for air heating and water heating applications. The application of the cavity collector is to heat the water. To increase the operating temperature of a FPC more and more, one of the methods is a cavity type configuration. It is however useful to point out that the multi- reflection effect can be achieved through cavity which is called as the "cavity effect". As in the case of FPC, the absorber plate has been used to receive the irradiative energy from the sun. In this type, it has been replaced by the receiver tube.

Flores *et al.* [1] have reported that in the cubic cavity the radiative heat transfer plays a vital role than the convective heat transfer. They have developed a mathematical model and parametric study had been carried out with various solar control coating absorptances. The influence of the multi- reflector effect through a macro- cavity has been presented by Demichelis and Russo [2]. The optical design of the cavity and the cavity effect has been determined by them for solar concentrating collectors. The optical performance of non-isothermal flat plate solar collectors has been presented by Reyes and Salazar [3]. They reported the creation of a thermo-economic model and the determination of annual cost for solar air heater by means of dimensionless parameter such as mass flow number. The thermodynamic optimization procedure has been evaluated to determine the optimal performance parameters of an experimental solar cavity collector. Melchior *et al.* [4] developed a cavity-type receiver containing a tubular absorber model and validated with experimental results.

It has been reported that the solar chemical reactor containing a tubular ceramic absorber utilized in their thermo- chemical process has the capability for high-temperature applications such as the production of H_2. Bairi [5] had developed a numerical 2D parallelogrammic cavity and analyzed the parameters such as inclination angles (α) and heat exchange

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between active and passive walls with various Nusselt number correlations.

Hahm *et al.* [6] in their report focus 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. Singh *et al.* [7] have reported that the natural convective heat transfer in cavities is a complex function of cavity shape, aspect ratio and boundary conditions at the walls. Natural convection in regular shaped cavities, such as rectangular, square and cylindrical section has been analyzed and the results show that reducing convective heat transfer considerably improves the performance of Compound parabolic solar collectors. Also various correlations including Nusselt number have been analyzed. Prakash *et al.* [8] reported that the thermal as well as optical losses affect the performance of a solar parabolic dish-cavity receiver system. They have investigated the performance for fluid inlet temperatures varying 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 has been found that the convective loss increases with the mean receiver temperature and decreases with the increase in the receiver inclination. Kribus *et al.* [9] have done the experiment by using two heating stages: (1) high-temperature receiver stage called as Directly Irradiated Annular Pressurized Receiver and (2) low-temperature stage implemented as a partial ring of intermediate-temperature cavity tubular receivers which has been done by dividing the aperture into two stages. The results show reduced convective heat losses and minimized partitioning losses. Cruz *et al.* [10] have reviewed the design, construction and testing of a simple, low-cost passive water heater for the Portugal climate. They have reported that energy saving largely depends on thermal stratification within the storage cavity. A constant tilt angle of 45^o has been employed in their study.

Wang *et al.* [11] studied a taper annulus structure for the solar dish- cavity receiver which has been designed and optimized for dish parabolic collector having the same vertex and different taper angles. It has a high volume-to-surface ratio and relatively low flow resistance which can easily convert large power heat transfer to the working fluid. Parthipan *et al.* [12] have conducted an experimental and numerical study of parabolic solar dish collector water heater with the receiver. Experiments have been conducted with and without the glass cover. A small- scale aluminum cylindrical solar receiver with a spherical cavity has been installed at the focal point of the dish. Overall solar- to- heat efficiency between 45% and 70% has been attained for the solar collector using the open cavity receiver. About 4.19% increase in the efficiency of collector with a flow rate of 0.0075 kg/s has been obtained with the help of receiver covered with glass. Garcia *et al.* [13] have studied the geometric changes applied to flat plate solar collectors to improve its efficiency. Main idea has been to reduce the space for convection including baffles on air-glass gap, thus reducing the heat losses. The influence on heat losses for different baffle spacing and possible air leaks has been evaluated and discussed. The Nusselt number behavior has been shown by the positions on the flat plate for different geometries. The results of this study, if validated, may lead to an improvement in the performance of solar collectors without a significant increase in the cost.

Chen *et al.* [14] have used a theoretical method to analyze the optical properties of the cavity absorber. Optical design software Trace Pro has been used to analyze the optical properties of the triangular cavity absorber. It has been found that the optimal optical properties could be achieved with an appropriate aperture width, depth-to-width ratio and offset distance. The standard deviation of irradiance and optical efficiency for the optimized cavity absorber are 30528 W/m^2 and 89.23% respectively. Vijay Bhamre and Uday Wankhede [15] have studied the efficiency of a solar parabolic dish-cavity receiver system based on various parameters, viz., type of cavity receiver, geometry of cavity receiver, the orientation of cavity, the size and position of cavity receiver, working temperature, etc. They have found that convective and radiative heat losses are the major constituents of the thermal losses which affect the performance of a solar parabolic dish-cavity receiver system. Krishnavel *et al.* [16] have conducted an experiment with three modifications of a concrete collector, namely collector fabricated with concrete embedded with aluminum pipes, concrete embedded with PVC pipes and thermal conductive material added with concrete. Metallic scrap and wire mesh have been used as thermal conductivity materials to increase the thermal conductivity of the absorber plate. It has been inferred that the building integrated solar water heating (BISWH) system with cheaper PVC pipe has been capable of delivering moderate temperature hot water suitable for different domestic applications.

The performance of FPC with different geometries has been studied by Amrutkar *et al.* [17]. A test setup has been fabricated and experiments have been conducted to study these aspects under laboratory conditions (as per IS available for the FPC). Experiments have been done to find the possibility of obtaining higher thermal efficiency or higher water temperature using same collector space. They have concluded that by changing the geometric shape of FPC, the collector area and the number of tubes can be minimized which results in cost reduction. Madhukeshwara and Prakash [18] have studied the performance characteristics of solar FPC with three different selective surface coatings namely black chrome, matt black and sol chrome coatings. Results show that black chrome coating records maximum temperature of hot water in the storage tank and a higher thermal efficiency has been obtained at a tilt angle of 30^o, intercept of 0.746 and slope of 13.75 when compared to other two coatings. Uhliga *et al.* [19] have compared two different strategies to increase the receiver efficiency of a cavity receiver used to heat the compressed air of a 4.7 MWel turbine from 330°C up to

800°C, with a mass flow of 15.9 kg/s at 10 bar abs. The influence on the levelized cost of energy of different receiver sizes and one design option (transparent covering of aperture) for reducing the convection losses has been analyzed and compared. A CFD model has been used to analyze the convection losses in addition to the given correlations in the literature. The comparison has been made with three different receiver sizes and transparent covering of aperture to increase the efficiency of a cavity receiver, namely small receiver, large receiver and small receiver with window. They have reported that heat losses by radiation and convection to ambient depend on the aperture area, receiver inclination and the receiver temperature. Ruchi Shukla *et al.* [20] have presented a detailed review exclusively on the design aspects of solar water heating (SWH) systems. The development of various system components that included the collector, storage tank and heat exchanger has been summarized. Also it deals with alternative refrigerant technology and technological advancements in improving the performance as well as the cost-effectiveness of the SWH system. They have concluded that recent developments in heat pump-based solar collector technology exhibit a promising design to utilize solar energy as a reliable heating source for water heating applications in solar- adverse regions.

2. SOLAR CAVITY CONFIGURATION

The cavity structure of the collector enhances the heat availability within the FPC. In other words, the heat holding capacity of the FPC can be increased by the use of cavity configuration. The increase in heat availability can be effectively utilized to heat the working fluid (water) which flows inside the receiver tube which ultimately increases the efficiency of the collector system. The presence of cavity also makes the solar collector more effective during late afternoon hours due to multiple reflection effect of the light energy within the cavity (Figure 1).

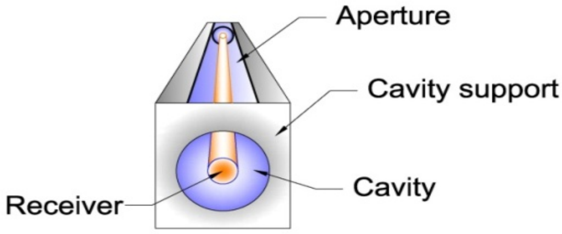

Fig. 1. Detailed view of a single cavity tube.

The conventional FPCs do not have the temperature stability which has been considered as a main concern. The fluctuations in the exit temperature of water during partly cloudy days are in-evitable. Cavity-type receivers are stable even at cloudy or partly cloudy days. The heat fluctuations are compensated by the cavity itself to meet the required outlet temperature of water, so that it ensures that there is no sudden drop in the exit temperature of water. In general, the cavity-type configuration can be applied to Fresnel lens collector and concentrating type collectors but it has been tried for the flat plate configuration. For better performance of the cavity collector, the experiments have been conducted with various L/D ratios.

2.1 Experimental Set-up

The solar cavity collector consists of a cylinder made-up of copper with the radius of 16 mm and insulated with glass wool insulation on the underside. Five such cavities are placed in a rectangular metal box at equidistance. The tubular absorber coated with the black paint with an outer radius of 6.35mm has been positioned concentrically within the cylindrical cavity. Figures 2 and 3 show the experimental arrangement of the cavity collector. The transport pipes in the cavities are connected in parallel and also in serpentine type. A single glass cover plate has been used to serve as a protective shield for spilled radiation and also it reduces the top heat loss from the collector to the surroundings. All the joints of the metal box have been well sealed. The bottom end of the collector tube has been connected to the fresh water tank. The setup is tilted at an angle of 11^o to the horizontal. Global radiation has been measured with pyranometer at the experimental site. Temperatures at different locations have been measured using thermocouples and a digital temperature indicator. The ambient temperature has been measured using a mercury thermometer with a precision of 0.1^oC. Thermocouples (copper-constantan type) are located at different locations, viz. at all cavities, glass plate, inlet and outlet pipes. The bottom and sides of the collector are properly insulated to reduce the heat losses.

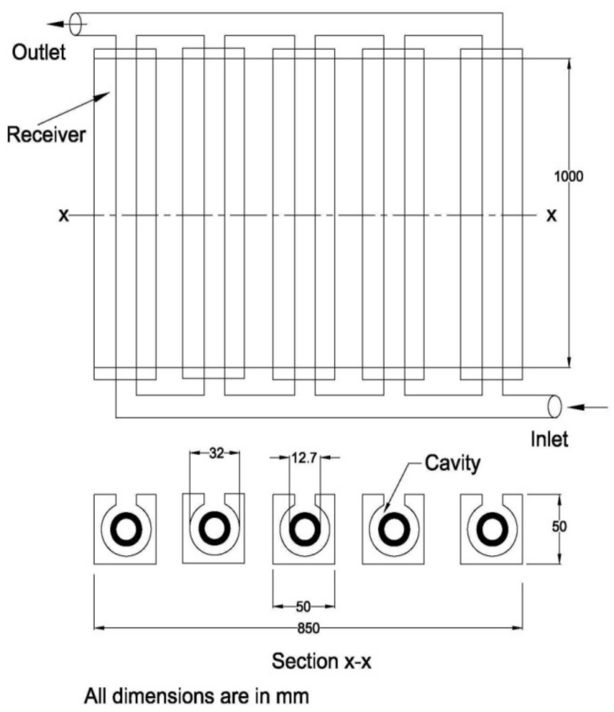

Fig. 2. Flat plate cavity collector.

2.1 Details of the Collector

Collector size : 1 × 0.85 × 0.05m
Cavity absorber material : copper
Absorber coating : Industrial mat black paint

Area of each cavity : 0.101 m^2
Thickness of glass plate : 0.004m
Collector insulation : Glass wool
Number of cavities : 5
Diameter of the tube : 0.0127m

The collector has been kept in open yard facing south and exposed to solar radiation. The experiments have been conducted from 9.30 AM to 5 PM. Observations have been made at a time interval of 10 minutes on different days with different mass flow rates of water. A performance investigation on the cavity collector has been made. To optimize the working parameters, experiments have been carried out for different L/D ratios of serpentine and parallel modes, rectangular and circular box covers (outside of the cavity) and the effect of number of cavities. A schematic diagram of a cavity collector is shown in Figure 4.

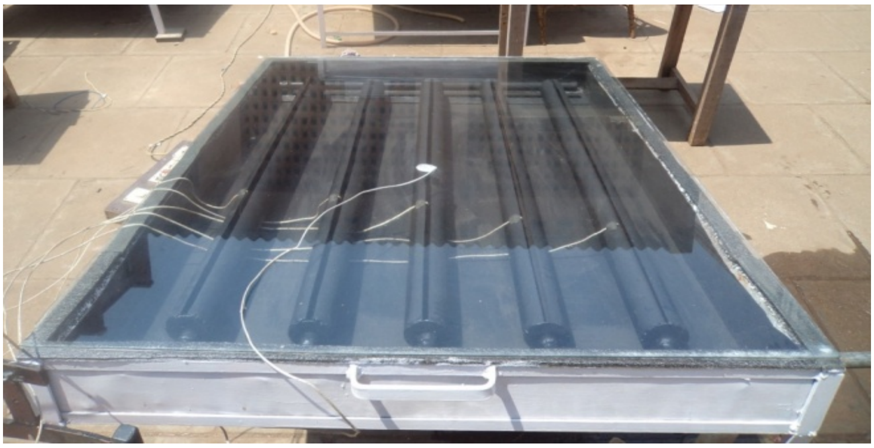

Fig. 3. Experimental setup of a circular solar cavity collector.

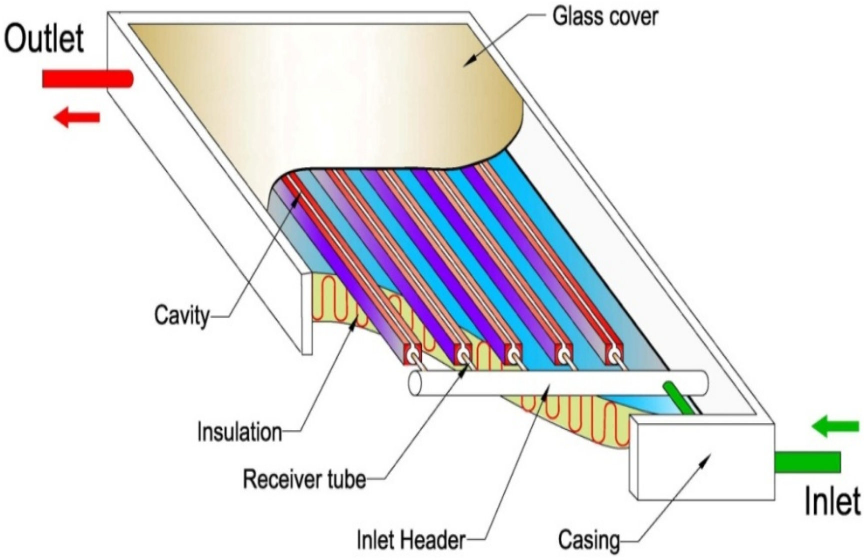

Fig. 4. Schematic diagram of a flat plate cavity collector.

3. 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, a proper design of the cavity makes effective capture of solar radiation entering through a 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 the multi-reflection effect is considered through the cavity and thus increases the heat holding capacity for a long time, particularly inside the cavity.

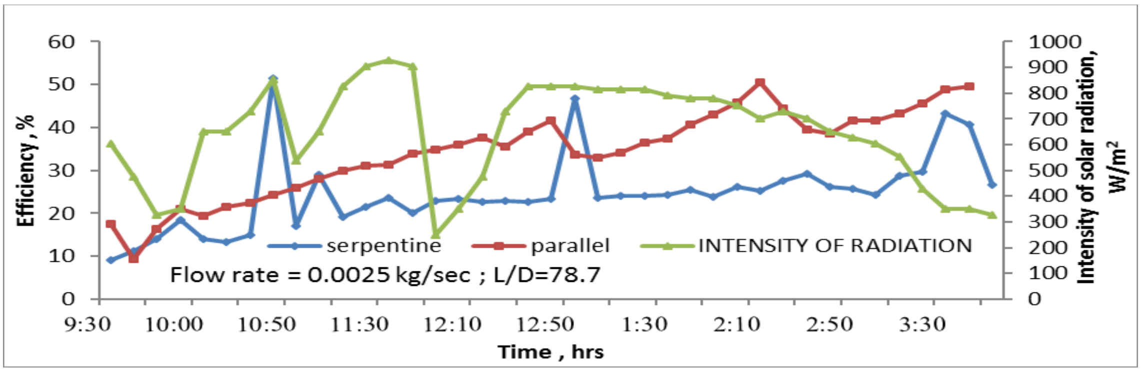

Fig. 5. Performance curve for two modes of flow.

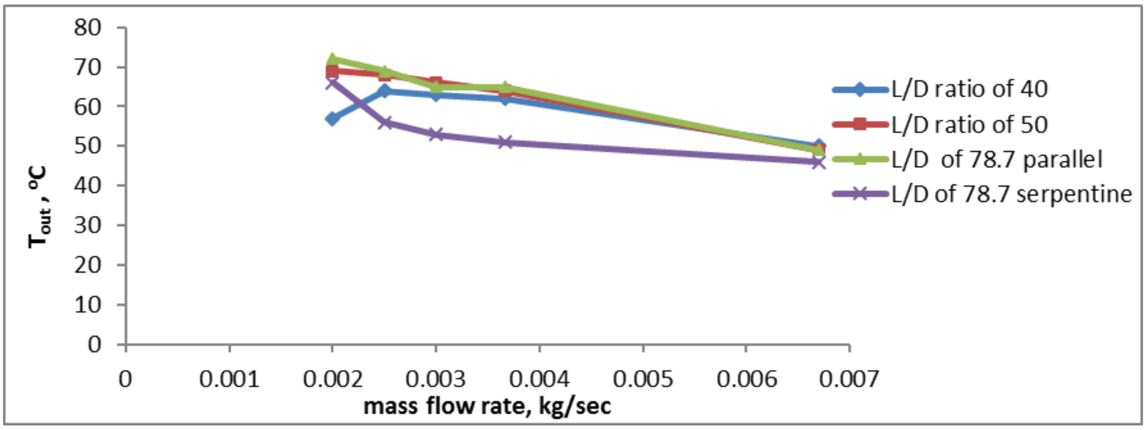

Fig. 6. Effect of L/D ratio on water outlet temperature.

Figure 5 shows the instantaneous efficiency comparison of the cavity collector in parallel and serpentine mode. It has been found that the efficiency is high in the case of parallel mode. Also it has been found that the efficiency is uniform when compared with serpentine mode. The efficiency of conventional FPC decreases immediately if the intensity of solar radiation falls after 12 noon or 1 pm. It has been inferred from Figure 5 that the efficiency has an increasing trend even at afternoon hours in the case of cavity-type collectors. It should be noted that there is no sudden drop in efficiency; as the cavity collector has the ability to collect and release the heat for a longer duration. The standard sizes of copper tubes available in the market have been taken into consideration. Accordingly, while fixing L/D ratios, the diameter is chosen. Though the length has been kept as constant, various diameters have been experimented. It is inferred from Figure 6 that the L/D ratio of 78.74 gives a better result rather than the L/D ratio of 40 and 50 and also that around 72°C water outlet temperature (maximum) has been obtained by the collector. It is known very well that if the mass flow rate of water increases, the outlet temperature of water will decrease, but the variation in the outlet temperature of water can be decided by the influence of the L/D ratio.

Cavity collector has been experimented with both parallel and serpentine mode of flows for an L/D ratio of 78.74. From the experimental results, parallel flow mode has been found to be more efficient than the serpentine type. Almost at all flow rates, the L/D ratio of 78.74 and parallel mode gives good results. A maximum temperature of 72°C (flow rate of 0.002 kg/sec) and a minimum temperature of 49°C (0.0067 kg/sec) have been achieved by the parallel mode. On the other hand, the L/D ratio of 78.74 under serpentine mode has found to give a maximum of 66°C and a minimum temperature of 46°C. Performance comparison between parallel and serpentine modes with L/D ratio of 78.74 shows that parallel mode is more efficient than the serpentine mode. Figure 7 clearly shows that cavity number 1 records a lower temperature for all the cases. It should be noted that there is no drastic change in the temperature of the individual cavities for the L/D ratio of 50. Moreover, cavity numbers 3, 4 and 5 reach the maximum temperature for all the cases except the L/D ratio of 78.74 under parallel mode. Even though all five cavities are exposed to solar radiation at the same time, there are some variations in the cavity temperatures. The slight variation in the pressure of the working fluid, restriction of flow inside the receivers, flow pattern of atmospheric air and water in the collector has an influence on the heat transfer phenomena that result in the variation in cavity temperatures.

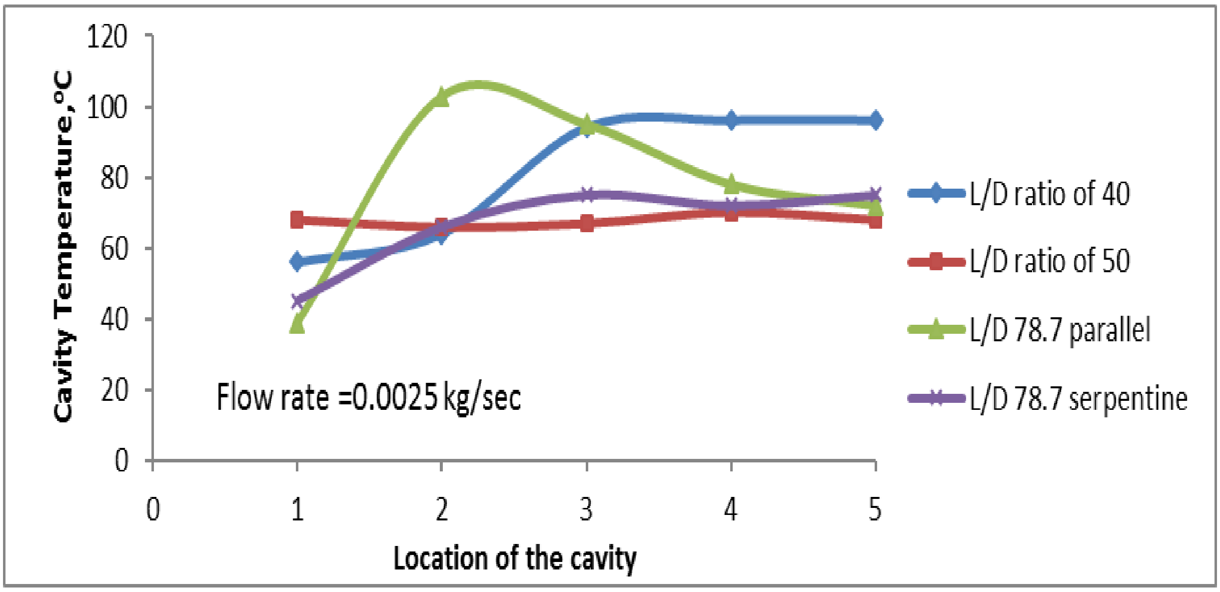

Fig. 7. Temperature distribution of cavities.

Figure 8 shows that the collector works in a more efficient way when the number of cavities has been increased. During the preliminary experimentation, the collector has been tested with five cavities. Later, a cavity collector with seven cavities has been tested to optimize the number of cavities. Based on experimentations, it has been found that the collector performance improve with the increase in the number of cavities. Further increase in the number of cavities is not possible since the pitch will get reduced, resulting in a shadow effect on the cavity.

For the flow rate of 0.002 kg/sec, the L/D ratio of 78.74 and five cavities reach a temperature of 72^{o}C (maximum), whereas on the other hand for seven cavities it is 70^{o}C. At higher flow rates (i.e. 0.003 kg /sec onwards), a collector fitted with seven cavities records higher temperature than the lower one. Increasing the number of cavities of the cavity collector is worthy and also it results in a better performance and the heat holding capacity of the collector also improves. Figures 6 and 8 clearly show that the temperature of water at outlet reaches around 70^{o}C in the cavity collector, when compared with the conventional flat plate in which it remains around 50–60^{o}C depending upon the configuration of the collector. In both parallel and serpentine modes, 0.002 kg/sec has been found to give better result. When compared with serpentine mode, the parallel mode gives better results with a minimum difference in temperature of 1-2^{o}C. Increasing the number of cavities to 7 (refer Figure 8) helps to hold the heat for a long time. The curve shows that with water flow rate from 0.003 to 0.0067 kg/sec, deviations are more when compared with five cavities. Mass flow rate of 0.003 kg/sec and increasing the number of cavities result in a more stable outlet temperature of water. Comparison has been made between two kinds of cavities, namely rectangular and circular. Inference from Figure 9 is that rectangular cavities retain heat energy for a longer time. During the morning time up to 12 noon, the increase in temperature gain of rectangular cavities is around 10^{o}C when compared with that of circular cavities. Between 1 pm and 2 pm, the variation increases to around 15^{o}C. That is, the thermal gain of rectangular cavities is considerably higher than that of circular cavities due to higher thermal retention at the corners of the rectangular cavities. Also a notable increase in the temperature is found in rectangular cavities when the temperature gain by circular cavities falls considerably after mid-noon due to the reduction of solar irradiation level. The rectangular cavities on an average maintain temperature by around 58^{o}C after mid-noon, thus indicating its suitability for SWH applications. The comparative study shows that the rectangular cavities have better thermal gain.

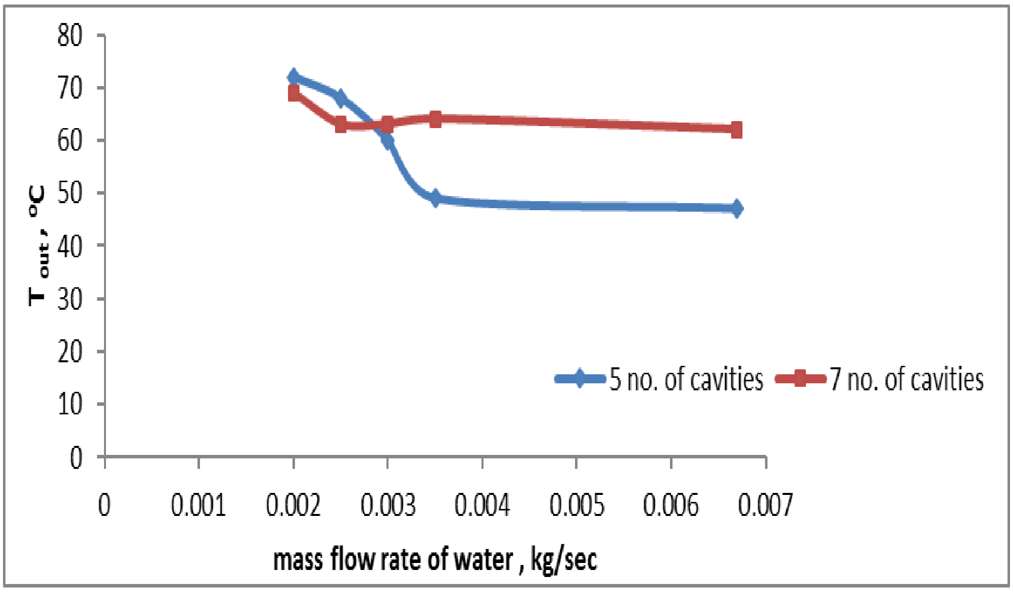

Fig. 8. Performance comparison of number of cavities.

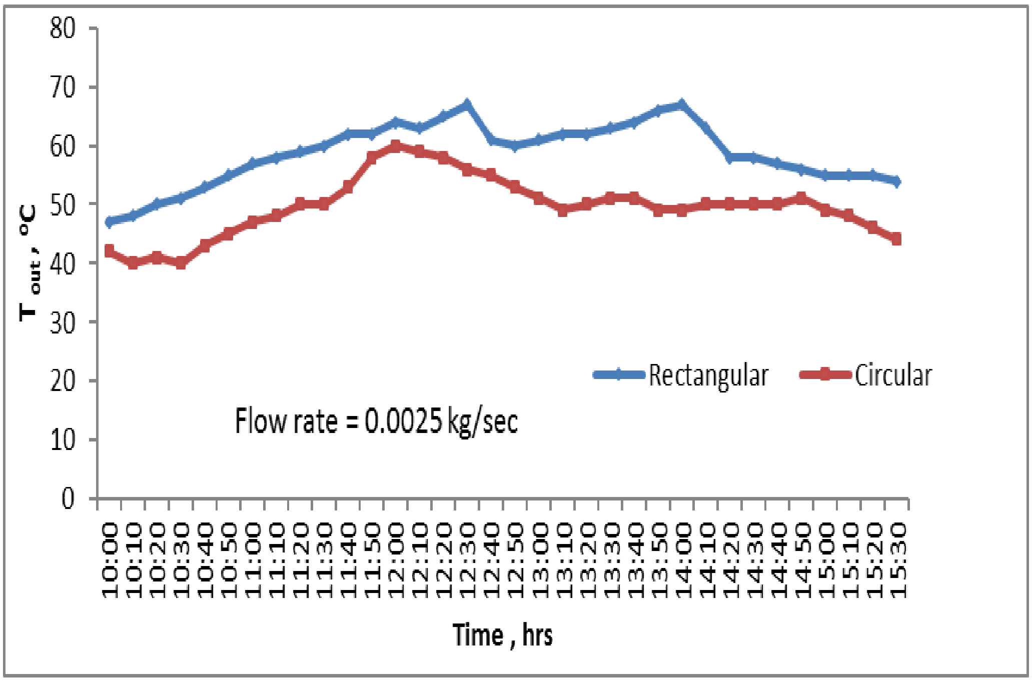

Fig. 9. Comparison of T_{out} for rectangular and circular cavities.

4. CONCLUSION

The objective has been to develop a new, more efficient and high heat-holding solar collector. The solution is a cavity-type collector or a receiver. The conventional FPC has found to be less efficient, concentrating-type configuration requires tracking mechanism and more costly too. Thus, it is clear that a cavity-type configuration is simple to construct which has numerous advantages and via- media between flat plate and concentrating-type collectors.

It also works more efficiently even at low radiation for a certain period of time and at partly cloudy days. Moreover, it gives a better performance at late afternoon hours. The efficiency of the collector does not suddenly drop during the afternoon hours. Both parallel and serpentine modes of flow with an L/D ratio of 78.74 have been tested; parallel mode has found to give better performance than the other. Various L/D ratios have been experimented, viz. 40, 50 and 78.74. The results show that the optimum L/D ratio among them is 78.74 under parallel mode. Water outlet temperature of 72°C has been obtained for an L/D ratio of 78.74 in the parallel mode. For all L/D ratios, cavity number 5 records the maximum temperature, and similarly cavity number 1 records the minimum temperature. It has been observed from the experimental results that the L/D ratio of 78.74 is preferable for all mass flow rates. There is a reasonable improvement with an increase in the number of cavities.

It has been observed from the experimental data that the efficiency of the cavity collector is better if rectangular cavities are used instead of circular cavities. Also it has been concluded that the rectangular cavities have the capability to withstand more heat inside the collector. It will act as a shield within the collector, thus reducing the losses considerably by not allowing the heat from individual cavity to the collector setup. Multi-reflection effect holds more amount of heat inside the cavity. Moreover, it has been concluded from the experimental results that if the L/D ratio increases, the temperature of the water at exit increases. If the diameter of the receiver decreases, the cavity area would increase. Although the cavity area increases, it would not entertain the incoming radiation. Thus, the cavity area plays a vital role for the improvement of cavity collector design and collector performance. Thus, it is concluded that the objective of the present study has been achieved.

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	Intensity of solar radiation, W/m^2
A_c	Collection area, m^2

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