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Experimental and Artificial Neural Network (Ann) Simulation of a Solar Cavity Collector

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Abstract: Solar cavity collector (SCC) is an improved version of flat plate solar collector (FPC). A SCC of outer radius 16mm positioned concentrically and placed in a 50 mm metal box. Five numbers of such cavities with a provision of inlet and outlet water pipes has been fabricated and experimented for its optimal performance. This experimental gadget is used to heat the water. As the physical dimensions of solar cavity collector influence the performances of the cavity collector, it includes the comparison of 5 numbers of cavities and 7 numbers of cavities, effect of aperture entry have been taken as investigation parameters in the present study. Inclination angle of the collector, water mass flow rates and mode of flow are the other parameters taken for the present study. Experimental data are trained and tested using Artificial Neural Network (ANN) tool of MATLAB software and ANN simulation results have been validated and verified with the available experimental data. Simulations for other set of variables have been predicted with the developed ANN model.

Key Words: solar energy, Cavity receivers, different shapes of cavity, Length to Diameter ratio, water mass flow rates, ANN.

I. INTRODUCTION

In general, the radiation from the sun is a primary resource of energy in a high quality form. It has numerous disadvantages which include high temperature, higher energy phenomena, and lower flux density at the surface of the earth makes complication to covert the available radiation into useful work or heat. To extract the heat energy for home and industrial heating applications by transferring the heat to any kind of heat transfer fluid (HTF) is a better way to achieve it. The proper utilization of solar energy in the Collector increases the efficiency and also reduces operating costs and lesser the payback period. Air and water heating are the most common applications of the solar energy. Still there are many more researches going on to improve the collector efficiency and reduce the losses to a minimum possible level.

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Flat-plate solar collector uses diffuse and direct component of solar radiation for liquid heating applications. Usually it operates in a low temperature levels (< 373 K) for heating of water, air and other aqueous solutions. It has numerous advantages over concentrating type; In general to obtain maximum

The absorber plate in the FPC has a temperature greater than its environment, unrecoverable heat losses occur from the whole absorber surface to environment. Consequently, efficiency, many methods are available to increase the operating temperature of a flat plate collector and also to convert the available radiation into useful heat energy with minimum heat losses. the collector efficiency gets reduced to a minimum level. Therefore FPC absorber has to be modified or avoided so as to reduce the heat losses. With use of cavity configuration the above said heat losses are alleviated. Since SCC have a cavity configuration instead of an absorber plate. Hence the heat losses are prevented by the use of cavity structure and it holds the heat inside the collector thus improves the overall efficiency of the collector.

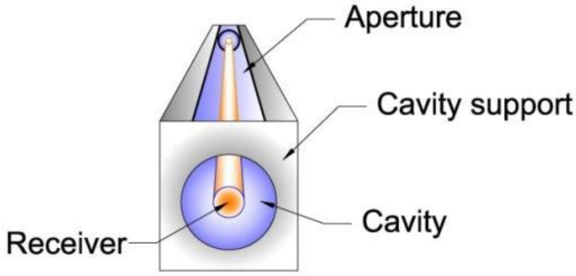

Fig.1 Sketch of a single cavity in detail

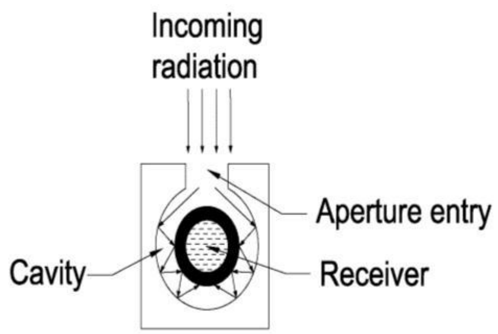

Fig.2 Multi reflection process of a solar radiation in SCC

Fig. 1 shows a single cavity tube in detail and Fig.2 describes how the multi reflection is functioning inside the cavity.

The location of cavity and energy transfer to receiver through the cavity can be understood based on the illustration. It has basic components like receiver, cavity support structure and aperture. The aperture is a small opening which admits the solar radiation into the cavity. Solar radiation enters through the aperture, gets reflected by cavity and re-radiates back to the receiver tube.

The reflection prolongs inside the cavity and part of it escapes from the cavity through aperture opening. The receiver absorbs energy from reflected light rays; thus the working fluid gets heated up.

II. INTRODUCTION TO ANN SIMULATION

To predict the solar collector performance, numerical models can be used. Energy balance equations of the collector system are solved either numerically or analytically in the traditional models. The traditional models are time-consuming and cumbersome and use number of empirical correlations and sometimes convergence may not be achieved. In the recent times, Artificial Neural Network (ANN) has been widely used for solving engineering problems. Speed, fault tolerance and non-linearity are some of the characteristics that make this network as an efficient alternative to the traditional modelling procedures. The mimic of artificial neural network somewhat is similar to a function of human brain it is also a multi dimensional domain which is able to handle the incomplete data successfully. ANN (or) neural network is a construction of group of artificial neurons that are interconnected. Fig.3 shows the constructional view of an ANN in detail.

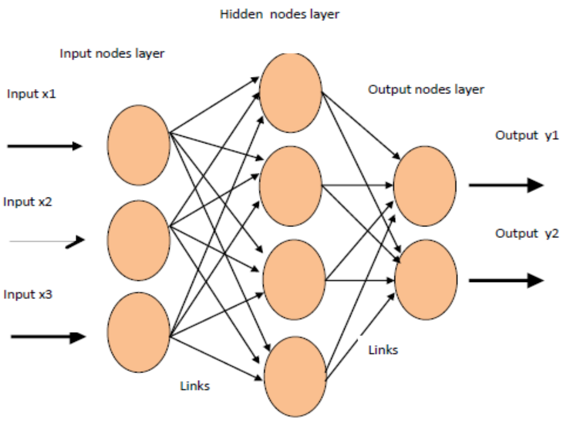

Fig. 3 Constructional view of an ANN in detail

III. REVIEW OF LITERATURE

A simple, semi-empirical method, in determining the size of aperture at optimized level and operational temperature inside the cavity collector has been developed by Steinfeld and Schubnell [1]. Diver, [2] has explained about the cavity-type configuration used for highly concentrated solar systems. They developed a cavity type receiver having an enclosure which is completely insulated and having a lesser opening called aperture entry through which the radiation entered inside. They concluded that due to the multiple reflections which are possible through inside surface of the wall and cavity absorbs a little bit of scattered solar radiation inside on it. Hunt *et al*, [3] have reported about the solar radiation heating of the gas particle mixtures, and they explained about new receiver concepts which substitute the existing cavity collector. Steinfeld and Fletcher, [4] have examined a receiver in spherical shape which has a reflection arrangement inside the cavity for solar furnace since it holds high temperature inside the receiver. They found that the cavities prevented by infrared rays which is absorbed or escaped by the walls of cavity and redirect it to the surface of the reactor. Siegel and Howell, [5] have described the thermal radiation heat transfer on cavity receiver configurations, and concluded that the cavity type configurations were implemented to exposure of hot surface considered with the radiation losses in the small opening. The thermal performance of concentrated system has been analyzed by Harris and Lenz, [6]. They concluded that the geometrical shape of cavity seriously affects the power distribution on walls of the cavity Tu *et al*, [7] have probed the performance of the receiver is based on the geometrical consideration. Saturated steam and water inside the cavity receiver with various depth has been studied numerically and also by computational model. Flores *et al*, [8] has found that inside the cubical cavities, radiation mode of heat transfer is more dominated when compared to the convection mode. Based on this conclusion, they studied and form a mathematical model which suites for their study. Jilte *et al*, [9] have numerically explored a three dimensional (3D) study for various shapes of receiver particularly suitable for forced convectional losses. Receiver shapes which includes conical, cylindrical, cone cylindrical and dome cylindrical under the wind conditions. Experimental investigations are made on the solar collector heat loss mechanism in semi spherical shaped cavities by Tan *et al*,[10]. Experiments are conducted for different fluid inlet temperatures, inclination angles and aperture sizes. Bairi, [11] developed a two dimensional numerical model applicable for parallelogram shaped cavity and analysation have been made for inclination angles, heat exchange between passive and active walls by using different correlations of Nusselt number.Hahm *et al*, [12] reported that in a cone cavity receiver, rejection of solar rays will be more if the aperture gap is too small, similarly, more losses from cavity will occurs if there is a larger aperture gap . Singh and Eames, (2011) explains about the convection mode of heat transfer in cavity depends on shape of the cavity, aspect ratio and given boundary condition of wall. Yaici and Entchev, [13] have applied the ANN for prediction of Solar Thermal Energy Systems (STES) performance. ANN model is used to predict the heat exchanger with various heat inputs and stratification temperatures of tank constructed inside and another tank utilizes propane firing method. Their result confirms that the applied method has a better accuracy and be more effective even the input data is in distorted form with various noise levels.Fischer *et al*, [14] have compared two type of models namely Sydney type evacuated model and a flat plate collector. They use the measuring equipments which confirms European standard EN 12975-2. Results shows the same level of output achieved between the calculated and measured one with state of art model. A concentrated type solar collector has been considered for its optimal shape at the heater surface is analyzed by Demichelis and Russo [15]. Multiple reflectional effects in a macro cavity for cylindrical and truncated cone cavities were examined in detail. The cavity design has been made optically and the cavity effect is also derived.

IV. CONSTRUCTIONAL DETAILS OF SCC

A single solar cavity of a cylindrical contour made out of copper with an outer radius of 16 mm has been fabricated having an aperture at top surface and placed in a metal box of size 50 mm. A tubular receiver coated with the black paint of outer radius 6.35 mm is concentrically positioned inside the cavities (cylinder in shape).

Five such cavities has been fabricated and placed in a rectangular enclosure at equidistance. Parallel and serpentine mode of flow connection has been made to connect the transport pipes within the cavity. To protect heat losses from top side to environment, a single glass plate is used. Glass wool insulation has been made at the bottom of the collector to prevent heat losses to the surroundings. The metal box is well sealed to prevent leakages. Collector bottom is connected with a source of fresh water. The thermocouples used for this research work are K-type thermocouples which are used to measuring temperatures of water at the inlet pipe and outlet pipe of the collector. The accuracy of the thermocouples is ± 0.4°C and the response time in still air is 1s. The thermocouples are also located to measure the temperature of all five numbers of cavities.

V. OVERVIEW OF SOLAR CAVITY-COLLECTOR

SCC has been placed in an open space with an exposure to sun rays. Usually it should face in south direction for better entrapment of solar radiation. All the experimentation has been made by using Agilent data logger in the solar energy laboratory from 9.30 AM to 4 PM Indian Standard Time (IST) at Annamalainagar location, Chidambaram, India (11.396°N, 79.716°E). During experimentation, all the observations had made at an interval of time of 10 minutes. Water is used as a working fluid throughout the research. Different kinds of water flow rates on various days have been experimented. Whole experimental setup has been tilted at 11° inclination angle referred to horizontal plane.

TABLE 1 - CONSTRUCTIONAL DETAILS OF SCC

Temperatures at different locations have been measured by the use of thermocouples.These thermocouples have been connected to a digital indicator which shows the temperature accurately. Ambient temperature was recorded with the help of a hospital thermometer (Mercury) whose precision is 0.1°C. Fig.4 and Fig.5 illustrates the detailed view of SCC and overall Schematic view of SCC respectively. Table 1 shows the constructional details of SCC.

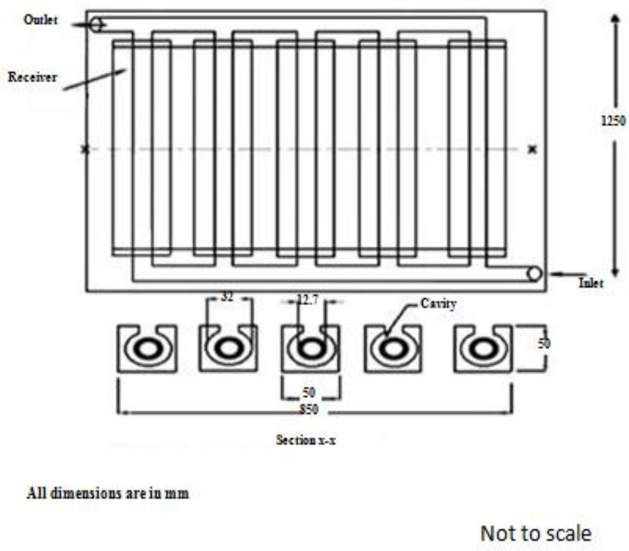

Fig. 4 Details of SCC

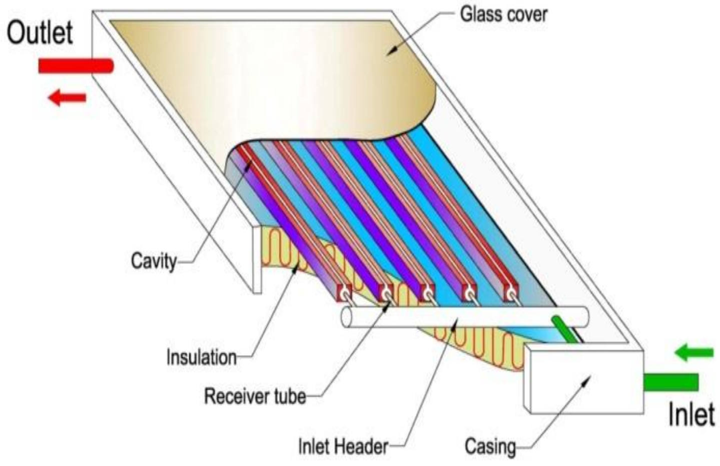

Fig. 5 Overall Schematic view of SCC

Collector size	1.25 m× 0.85m × 0.05 m
Material used for receiver	copper
Coating of the absorber	Matt black coloured paint of industrial use
Area of each cavity	0.101 m^2
Inlet and outlet pipe diameter	0.013 m
Glass plate thickness	0.004 m
Insulation material used	glass wool
Insulation thickness	0.025 m
Number of cavities	5
Inlet and outlet header diameter	0.019 m
Distance between glass plate to cavity top surface	0.04 m

VI.RESULTS AND DISCUSSION

The experiments have been conducted with different kind of parameters that has been discussed in detail in this chapter.

A. Effect of Inclination Angle

Effect of the inclination angle on the performance of SCC has been analyzed experimentally. Fig.6 shows that variation of T_{out} and η for different inclination angles. In order to optimize the performance, the experiments are conducted with various tilt angles such as 11°, 15°, 20° and 25°. Even though the inclination angle (optimum) for FPC of 11° is 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. For both efficiency and water exit temperature, inclination angle of 11° records the maximum value of 68°C at a flow rate of 0.002 kg/s. For all inclination angles the water outlet temperature remains constant, except the inclination angle of 11°. Experimental results show that, inclination angle of 11° is best suited among the all.

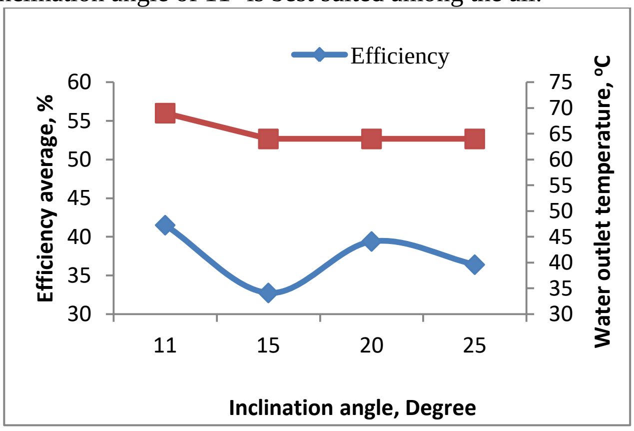

Fig.6 Efficiency and T_{out} comparison for different inclination angles

B. Effect of Aperture Gap

Fig. 7 shows water outlet temperature curve for the aperture gaps of 5 mm, 8 mm and 11 mm. Small apertures in the SCC restricts the incoming solar radiation to the collector and thereby it reduces the performance parameter. On the other hand a large aperture allows more amount of solar radiation into the collector, at the same time it also permits the re-radiation to escape quickly from the collector to the surroundings. For 8 mm aperture the collector records a maximum temperature of 72°C at 2:15 PM. For 11 mm aperture a maximum temperature of 64°C at 3:30 PM has been obtained. 5 mm aperture records a maximum temperature of 48°C at 1:30 PM and comparatively it records lower temperature. 8 mm aperture gap has been found to give better performance.

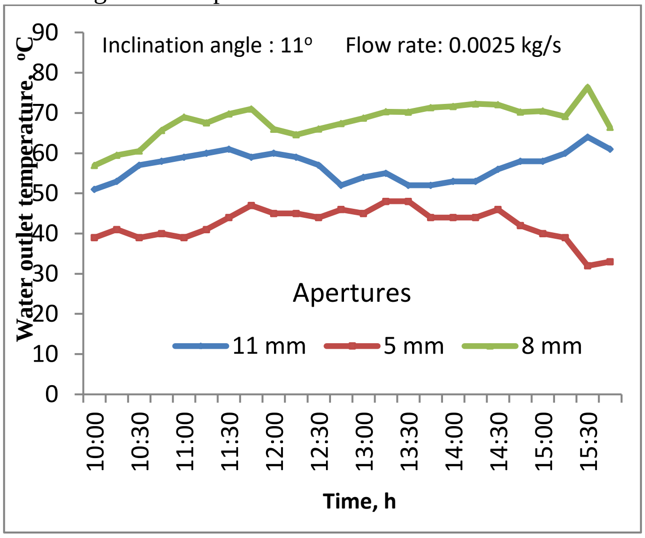

Fig. 7. Comparison of T_{out} for different aperture gaps

C. Comparison of FPC and SCC

The efficiency curve for both SCC and FPC are shown in Fig.8. Maximum and minimum efficiency of 77.7 % at 1:40 PM and 35.65 % at 10:00 AM has been achieved for SCC, while it has been 41.3 % at 1:00 PM and 12.6 % at 10:00 AM for FPC respectively. It is noted from the efficiency curve for SCC that even during afternoon hours the efficiency of the SCC is appreciable between 1:50 PM to 4:00 P.m. While at the same time for FPC it is not appreciable. When the intensity of the radiation reduces means efficiency of the flat plate collector also deceases suddenly after 1 PM which means there is no major improvement in efficiency after 1 PM. Whereas in case of SCC, no immediate drop occurs in the efficiency curve even the radiation is at lower level (say after mid noon). SCC has the special ability to with stand the fluctuations while the radiation is intermittent type. It can hold the heat inside and releases heat when ever needed.

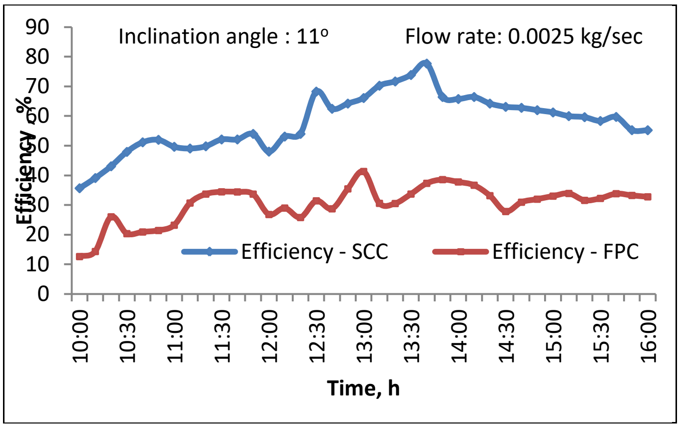

Fig.8. Efficiency comparison of SCC and FPC

D. Effect of modes of flow - Parallel and serpentine

Fig.9 shows the comparison of efficiency in parallel and serpentine mode of flow. The efficiency is more in parallel mode when compared to serpentine mode. From the experimental analysis, the parallel mode attains an instantaneous average efficiency (minimum to maximum) of 56 % is achieved at the water mass flow rate of 0.0025 kg/s. On the other hand, serpentine mode attains on an instantaneous average efficiency of 27 %. The instantaneous efficiency of parallel mode of flow has a maximum value of 79.49 % and a minimum value of 20.55 % as shown in Fig.9. In serpentine mode it has attained a maximum of 48.76 % and a minimum of 7.92 %. It should be noted that, for both mode of flow the instantaneous efficiency goes on increasing trend after 12.00 noon.

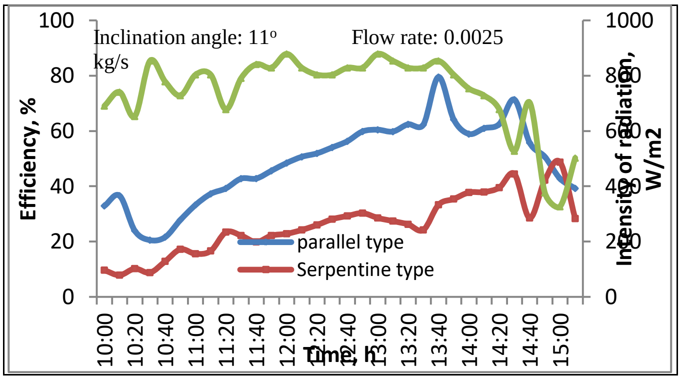

Fig. 9. Performance curve for two modes of flow

E. Investigation on Cavity box Materials

Cavity collector is experimented with two different cavity box materials such as G.I and M.S sheets. For both the cases a constant mass flow rate of 0.0025 kg/s has been maintained for investigation. It is inferred from the Fig.10, a gradual increase in efficiency with respect to the time is achieved by the collector with the use of G.I sheet. There are drastic variations are seen in efficiency curve after 12:20 PM in the case of M.S sheet. Maximum efficiency of 43 % is obtained when M.S sheet is used while it is 47% when G.I sheet is used. When comparing to M.S sheet, the efficiency curve for GI sheet increases gradually up to 1:30 PM and thereafter it starts decreasing.

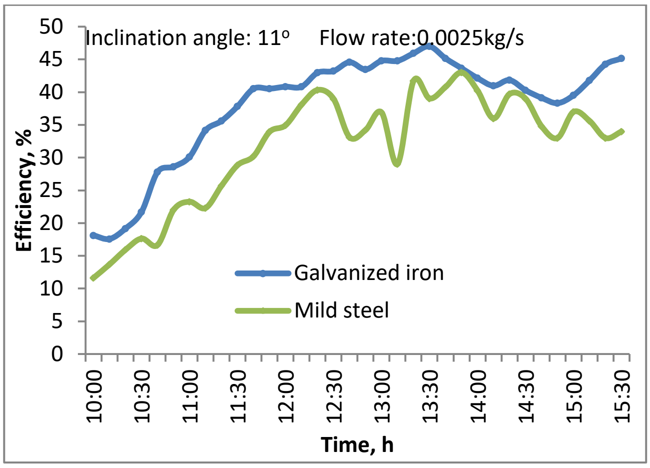

Fig.10 Efficiency comparisons of different cavity box materials

A time versus water outlet temperature plot for both cavity box materials has been shown in Fig.11 at a water flow rate of 0.0035 kg/s. Same trend have been experienced in this case also. A maximum temperature of 64°C at 2:10 PM has been achieved. At the same time if M.S sheet is used the collector achieves a maximum temperature of 60°C at 1:20 PM. This happens because Mild Steel releases the heat quickly and also it absorbs the incoming solar radiation slowly when comparing to G.I sheet. Furthermore, the heat holding capacity of G.I sheet is more when compared to mild steel if it is being used as a cavity box material.

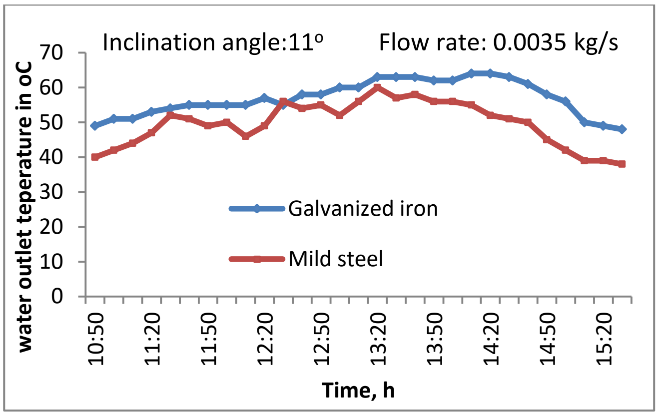

Fig. 11 Comparison of T_{out} for different cavity box materials

F. Effect of Number of Cavities on the Performance of SCC

Fig.12 shows mass flow rate versus water outlet temperature for five numbers of cavities and seven numbers of cavities. During preliminary experimentations, SCC has been tested with five numbers of cavities. At later stage, it has been tested with seven numbers of cavities to optimize the number of cavities. At lower flow rates, the collector with five numbers of cavities is more efficient and a maximum water outlet temperature of 72°C has been obtained at a water mass flow rate of 0.002 kg/s. On the other hand, SCC with 7 numbers of cavities records a maximum water outlet temperature of 69°C at the same flow rate. The collector with 7 numbers of cavities, records a maximum temperature of 63°C at water mass flow rate of 0.003 kg/s; but the collector with 5 numbers of cavities intends to give only a maximum temperature of 60°C. When comparing both the 5 and 7 numbers of cavities at a water mass flow rate of 0.0067 kg/s, they give a maximum temperature of 47°C and 62°C respectively. Based on the experimentation results, it has been conclude that the performance of SCC improves with an increase in number of cavities. More stability of water outlet temperature has been achieved with 7 numbers of cavities. For SCC, further increase in the number of cavities is not practically possible. If the pitch is further reduced to some extent it will results in a shadow effect on the cavity. Also it directly affects the performance of SCC. Fig.13 shows a graphical representation of temperature distribution of cavities with respect to the cavity location for the water mass flow rate of 0.003 kg/s. All 7 numbers of cavities records a better temperature range when compared to 5 no. of cavities. For 7 no. of cavities cavity number 3 records a maximum temperature of 80.5°C and a minimum temperature of 67.5°C is recorded at cavity number 7. For five no. of cavities, a maximum temperature of 76.5°C is achieved by cavity number 2 and a minimum temperature of 38.02°C is recorded at cavity number 1. Due to the shadow effect, the cavity number 2 and 3 always records a maximum temperature when compared to other locations of cavity. That is the centre most cavity records maximum temperature but various factors influences the cavity temperature. Due to these factors, the maximum temperature achieved by the location of cavity may vary.

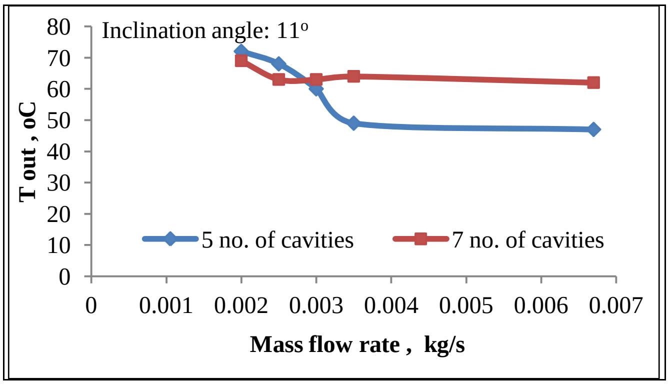

Fig.12 Performance comparison with number of cavities

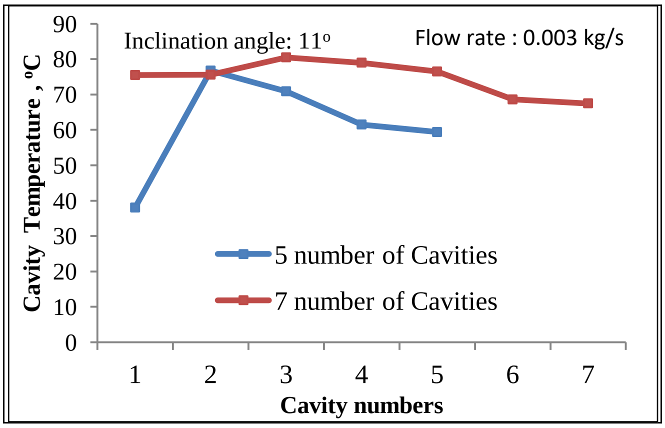

Fig.13. Temperature distributions of cavities along with the location

VII. ANN SIMULATION RESULTS

ANN simulation has been made for this present study. The following parameters were used for ANN analysis:

- Tilt angle
- Thermal conductivity of receiver material
- Water inlet temperature
- Solar intensity of radiation
- Glass plate temperature
- Ambient temperature
- Velocity of air
- Mass Flow Rate
- The output parameter of ANN model is water outlet temperature.

Various network architectures and a number of training and transfer functions have been investigated to obtain the best performance. The architecture that gives the better result from those tested is finally adopted in the present research. It has a two-layer feed-forward network with eight inputs and an output. The first layer uses log-sigmoid and the second layer use one positive linear neuron. The training and simulation are carried out with the ANN tool of MAT LAB software. For training the data, Conjugate gradient back propagation with Powell- Beale training function is used. While 675 data are used for training the network and 160 are used for testing the network. The training of the network is started with some initial weights and biases randomly chosen and the training data are learned with good accuracy. The evaluation of the best performance is based on the mean square error calculated for the test data set and R^2 value obtained is 0.9088. The performance of SCC has been simulated using the model described in the chapter with the help of ANN simulation. Fig.14 shows a comparison of mass flow rate versus water outlet temperature for both experimental and ANN simulation results for intensity of radiation is 1267.35 W/m^2 at an inclination angle of 11°. It shows that the experimental values are very closer to that of ANN simulated values. That is the result presented here justifies that the present model is in good agreement with the experimental results and hence, this model has been used for the simulation of SCC.

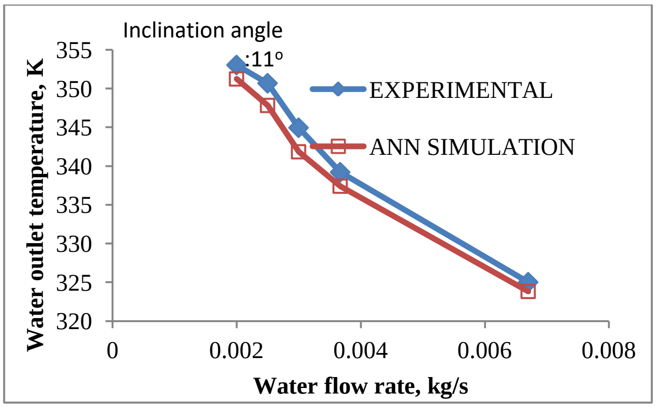

Fig.14. Water flow rate vs. Outlet water temperature for experimental and ANN simulation results

Fig.15 shows a plot of inclination angle versus water outlet temperature for experimental and ANN simulation results for the water flow rate of 0.002 kg/s. The curve of the plots also follows the same trend as reported for the experimental trials. The deviation from experimental and simulated value is very less at an inclination angle of 11° and it is more at an inclination angle of 25°.

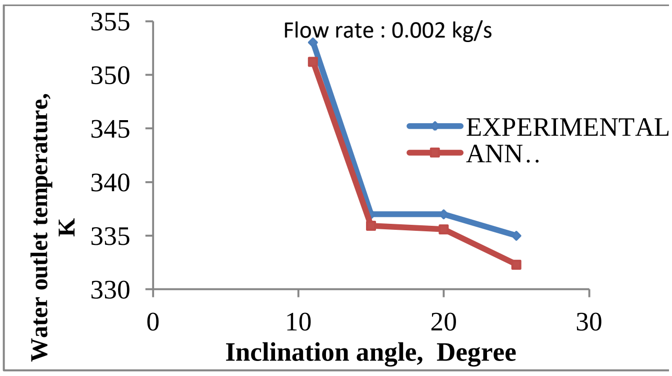

Fig.15. Inclination angle vs. water outlet temperature for experimental and ANN simulation results

Fig.16 shows a graphical representation of time versus experimental and ANN simulated water outlet temperature for a day for the flow rate of 0.003 kg/s at an inclination angle of 11°. Corresponding intensity of radiation has also been included. It is inferred from the Fig.16, the water outlet temperature curve for both experimental and ANN simulated values are very closer. Also, the ANN simulated results are having the same trend as the intensity of radiation curve.

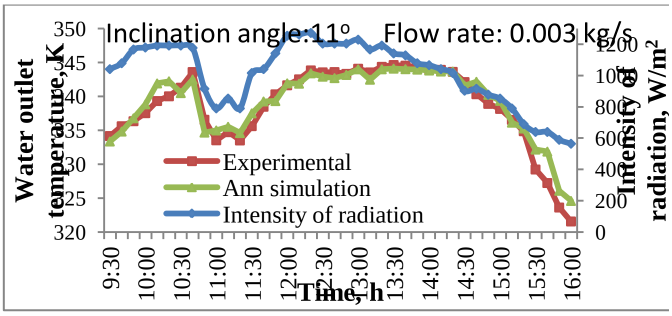

Fig.16. Time vs Experimental and ANN simulated water outlet temperature

VIII. CONCLUSION

The review of literature of existing researches shows that many parametric studies on solar cavity collector for flat plate configuration have not been investigated. Almost all the researchers are explaining about the investigations of solar cavity collector which is applicable for concentrating type solar collectors. Solar cavity collector have been designed, fabricated and tested for different working parameters. The cavity collector is experimented for various parameters and their end results are listed below.It has been found out that the better inclination angle for SCC is 11°. Three different types of aperture entry gaps of 5 mm, 8 mm and 11 mm are experimented. Out of these three aperture gap, the best suited for SCC is 8 mm. Two kinds of flow mode, parallel and serpentine mode has been experimented. Of which Parallel mode gives better results than the serpentine mode of flow. When comparing SCC with FPC, SCC proved to give better performance at late afternoon hours. Consequently, a better heat transfer rate has been achieved. The efficiency of SCC has an increasing trend, even in afternoon hours when compared to conventional flat plate collector.SCC has been experimented with two kinds of cavity box material viz., galvanized iron and mild steel. Galvanized iron as a cavity box material gives a better performance than Mild Steel. ANN can be effectively used to simulate the performance of SCC. The deviation of the results from experimental values is of the order of ± 4 %. The analysis of ANN simulation reveals the same trend as that of experimental simulations. SCC can be used to heat the water at initial stage before entering into the concentrating type collectors. In applications like solar power generating plants, the water has to be heated in concentrating type collectors to convert it into steam. If SCC heats the water at initial stage which can lead in time saving, water retention time inside the concentrating collector and reduces operating cost of concentrating collectors. Thus it improves overall efficiency of the plant.

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