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Research Article

Performance Characterization of a Solar Cavity Collector Using Artificial Neural Network

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It is mandatory to improve the design of the flat plate collector (FPC) used for solar thermal applications to perform well. One way to improve the performance characteristics of FPC is to retain the heat energy available inside the collector. That is, a collector should be capable to give more heat energy to working fluid for a longer duration. It has been implemented in such a way in an entertained and improved model which is known as solar cavity collector (SCC). It consists of 5 numbers of cavities equipped with inlet and outlet tubes. The same having with an enclosure has been constructed and investigated to find the optimal performance. In general, the physical dimensions of the collector influence more the functioning behaviors of SCC. The performance variables that are considered for the present study are the comparison between 5 and 7 numbers of cavities and the effect of aperture entry. Collector angle of tilt, two types of flow mode, and water mass flow rates are the other performance variables that are also considered. The data from the experimentations are trained, tested, and validated with the help of the artificial neural network (ANN). The accuracy of the model is 96%, and the end results revealed the same trend followed by both experimental and ANN simulation results. Also, the variations that occur between ANN and experimented results are ±4%.

1. Introduction

For general home and industrial heating utilization, the heat energy needed is more to fulfill the requirements. If the desired temperature has achieving means, the heat is transferred to any kind of heat transfer fluid (HTF). The heating can be achieved by any kind of collection method that is available with specific requirements. Flesch et al. [1] have numerically analyzed the effect of angle of tilt at 0° to 90° cavity position and heat losses with the wind blowing on the cavity applied for cavity receivers. Also, they explain the effects of wind with these positions and how the huge impact on heat losses occurs in the particular environment. The cavity receivers designed with aperture transparent covering and reduction methods of convection losses have been analyzed and compared by Uhlig et al. [2]. Also, they analyzed the methods for enhancing collector efficiency. They conclude that the convection and radiation losses are decided by receiver tilt angle, the area of the aperture which is visible to the sun, and the temperature of the cavity receiver. The central receiver technology with low cost and high-performance scenarios has been reviewed by Zhu and Libby [3]. They discuss the thermal storage combined with the central receiver and its design considerations. It operates at higher temperatures and also delivers higher efficiency power generation and a cost-effective approach.

Samanes and Garcia-Barberena [4] have developed a transient simulation model numerically. The developed model was used to simulate the solar cavity receivers. They analyzed the performance-influencing parameters considering all major heat loss mechanisms in the cavity. For finding the thermal behavior, heat transfer fluid was utilized in different ways in the cavity receiver setup. Cutting tool wear estimation has been calculated by using an artificial neural network (ANN) by Rajeev et al. [5]. Various factors were considered for input parameters, and only one output was taken as tool wear. Both experimental and ANN values are matched together. The average error for their comparative analysis was below 10%, and the accuracy of their model was 93%. A three-dimensional numerical study focused on cavity receivers of different shapes with forced convective heat loss carried by Jilte et al. [6]. They studied cylindrical, conical, cone-cylindrical, and dome cylindrical-shaped receiver heat loss mechanisms under wind conditions. Yuting et al. [7] had conducted one experimental investigation on a semispherical in shape cavity receiver for the heat loss calculations. It is applicable for the solar dish-type collector. Experimental analysis has been conducted for inclination angles, various types of fluid inlet temperatures, and aperture sizes.

The modeling investigations with different approaches for FPC and evacuated tube collector, namely, Sydney type, have been analyzed and compared by Fischer et al. [8].Comparison of analysis includes the parameter identification for training the model and resembles measured and modeled output scenarios. They explained and recommend to use the simulated collector which can be used yearly. It yields for both models of solar-based hot water collectors eventually for domestic usages. The prediction of solar-based thermal energy systems with the help of ANN technology and its applications has been explained by Wahiba and Evgueniy [9]. The system performance is used for space heating and water heating solar applications. Their results showed better agreement with the input data and final outputs with higher accuracy of 97% and also has more effectiveness. The usages of HTF in SCC have been explained by Lakshmipathy et al. [10]. They experimented different kinds of water flow rates ranging from 0.002 kg/s to 0.007 kg/s and concluded that the inclusion of HTF has an impact on the performance of SCC. The effect of various kinds of tilt angle inclinations with respect to datum for a parabolic type cavity collector has been enumerated by Prakash et al. [11]. They analyzed the efficiency improvements of parabolic dish cavity system including the optical and thermal losses which have been taken into consideration. The fluid inlet temperatures vary from 50°C and 75°C, and the cavity inclinations at 0°, 30°, 45°, 60°, and 90° have been tested by using the Fluent CFD software. They conclude that the convective heat losses decreases with the increase in receiver inclination angles, and similarly, it increases with the mean receiver temperature.

The performances of cavity collectors with various working parameters have been elaborately analyzed by Lakshmipathy et al. [12]. Various energy storing materials and techniques involved for the improvement of SCC have been discussed. Singh and Eames [13] have tested on more number of cavity shapes such as rectangular, square, and cylindrical cross-sections with varying the aspect ratio of the collector. They applied certain boundary conditions which are more suitable for their research for different cavity shape geometries. The experiments have been carried out by Kribus et al. [14] on cavity receiver system. The aperture is divided into two parts and, the cavities have also been splitted up accordingly. They uses two stages of heating process, namely, high- and low-temperature receivers. Their result enumerates the reduced rate of convective heat losses by the partition. Also, it helps to improve the efficiency of the whole system. Venkatachalam et al. [15] have reviewed the different solar collectors from an economic point of view. Also, they analyzed three kinds of collectors, namely, FPC, parabolic trough collectors (PTC), and evacuated type extended tubular collectors. They suggested the application of a solar water heater with various nano and heat transfer fluids. Thermal performances of cavity-type receivers accompanied by various depths have been numerically studied by Tu et al. [16]. Also, they inspected the solar receiver in connection with geometrical effects and analyzed the receiver with suggested suitable cavity depth. Further, the analysis has been made with the combined numerical and computational model. The influential factors with different depths of the cavity receiver are also studied.

The objectives of this research work may be stated into the following points which are as follows:

(i) Conducting the performance test on cavity collector

(ii) Testing the gadget experimentally with different kinds of working parameters such as (a) collector angle of tilt, (b) two types of flow mode, and (c) comparison of 5 and 7 numbers of cavities

(iii) By comparing the operating parameters with better solutions

(iv) ANN simulation analysis has been made with working parameters

(v) Comparison of experimental end results with ANN-simulated results

2. Design and Construction Details of SCC

The chapter of the literature review clearly shows that there is a lag in the research in connection with SCC applicable for the improvement of FPC. Almost all reviews enumerate the investigations towards the development of concentrating collection techniques applied to cavity collectors. Therefore, there is a scope to develop the cavity collector with enhanced performance than the FPC. The design and construction details are as follows.

The design procedure of a single solar cavity has been carried out with a receiver of cylindrical contour in shape. Initially, the outer radius of 16 mm made with a copper receiver tube has been constructed. It has a gap on the top external surface often called aperture gap and is located on the cavity support, and the same is placed in a square enclosure outer box of 50 mm size. Then, a tubular receiver covered with black-colored paint has been spray-painted for better entrap of solar radiation. It has an outside radius of 6.35 mm concentrically fixed and making a correct position at the center of the cylindrical cavity. This comprises a single cavity design. Furthermore, all five numbers are fabricated with the same procedure to make a whole setup. At last, it has been situated into a rectangular enclosure at an equidistance. To protect from the spilled radiations, the cavity collector uses a single glass plate mounted at the top. Also, it minimizes the top and side heat loss coefficient values, thus preventing the spilled radiations get away from the collector to the atmosphere. Each cavity has a common header at both inlet and exit sections. The conduit pipelines in each cavity are joined with two kinds of flow modes namely parallel and serpentine types. The metal box enclosure joints are tightly sealed up to avoid leakages and insulation made with glass wool material. The top end of SCC has been connected to a tank provisioned for hot water collection, and the bottom end has fastened to the tank which supplies the freshwater to the SCC.

2.1. Investigation Framework of SCC. SCC has been laid over in the open yard facing south direction. It is left out for the exposure to solar radiation. All the experimentations have been conducted with the help of a data logger in a laboratory environment and the data's stored in a laptop. The working substance used for the investigation is water. The observations are noted down with timings from 9.30 AM to 4 PM Indian Standard Time (IST) every 10 minutes of time duration. The observations have been made along with various water flow rates on different days. The location of the experimentation is Annamalai Nagar, near Chidambaram, India (11.396° N, 79.716° E).Thermocouples are affixed at various locations of SCC to read the temperatures and connected to a digital temperature indicator. The detailed assembly drawing of SCC has been presented in Figure 1. It shows the dimensions of SCC and also a view of the cross-section at xx. Figure 2 displays the overall diagrammatic illustration of SCC. Table 1 shows the technical details of SCC which helps to know about the overall materials used and dimensional details of SCC.

3. ANN Simulation

For ANN analysis, some parameters are considered which are listed below.

(i) Angle of tilt

(ii) The value of thermal conductivity of the receiver materials

(iii) The temperature of the glass cover plate

(iv) Intensity of radiation

(v) Entry point temperature of the water

(vi) The temperature recorded at ambient condition

(vii) Air blowing velocity at nearer to the gadget

(viii) Water flow rates

(ix) The developed ANN model has only one output, that is, water exit temperature

To obtain the maximized performance from the ANN, different network architectures have to be selected from the available content. Also, the transfer and training functions have to be selected properly for their optimized operation. Based on the different strategies of these functions, the better one has to be picked out, and selected architecture has to be used finally for all interpretations. In this research, the model uses two-layered feed-forward networks. Also, it operates with eight numbers of inputs and only one output. The first layer of the network utilizes log sigmoid, whereas the other utilizes the positive linear neuron. After the collection of experimented data, the simulation has been carried out with the help of the ANN tool of MAT LAB software. For training, conjugate gradient back propagation is used in connection to the functional operation Powell-Beale training function that is utilized in this present study. For training, around 595 numbers of data are used. Similarly for testing, around 170 numbers of data are used in the network structure. The network starts with some initial weights during training the network. Also, it picks up biases randomly and data used for training possess good accuracy. Mean square error is so important so that the best performance of the system can be evaluated. It has been calculated for the set of testing data, and the regression (R) value has been found as 0.9188. The accuracy of the developed model is 96% and the coefficient of correlation is 0.9. Though various kinds of models has been tried for its best performance, this current model is selected and it seems to be better than the other models.

4. Results and Discussion

The experimental and ANN simulations have been carried out, and the final results are listed down.

4.1. Efficiency and Water Outlet on Different Inclination Angles. Inclination tilt angle for SCC must be experimented to perform better heat transfer mechanism prolonged inside the collector. Therefore, before going to the other parameters, the effect of inclination angle has been analyzed for SCC. The deviation in T_{out} and η has been shown in Figure 3 for various inclination tilt angles. The experiments have been carried out with different tilt angles such as 11°, 15°, 20°, and 25°. For FPC, the globally accepted and foremost inclination tilt is 11° which is widely used by others. But for SCC, it has not been established yet. At an inclination angle of 11°, both efficiency and water exit temperature are obtained, the maximum of 57% and 68°C, respectively. It has been inferred that an angle of 11° is best suited among all.

4.2. Effect of Water Outlet Temperatures with Time in Apertures. Figure 4 shows the curve for the variations in T_{out} for three aperture entry gaps 5, 8 and 11 mm, respectively. It should be noted down that the aperture gap is too short; it limits the incoming radiations entering inside into the collector. Similarly, if the gaps are too large means, it freely allows the radiation to get away from the collector to the surroundings. Therefore, it needs to optimize the aperture gaps with reduced losses and availability of radiation at the maximum possible level. Around 72°C of maximum

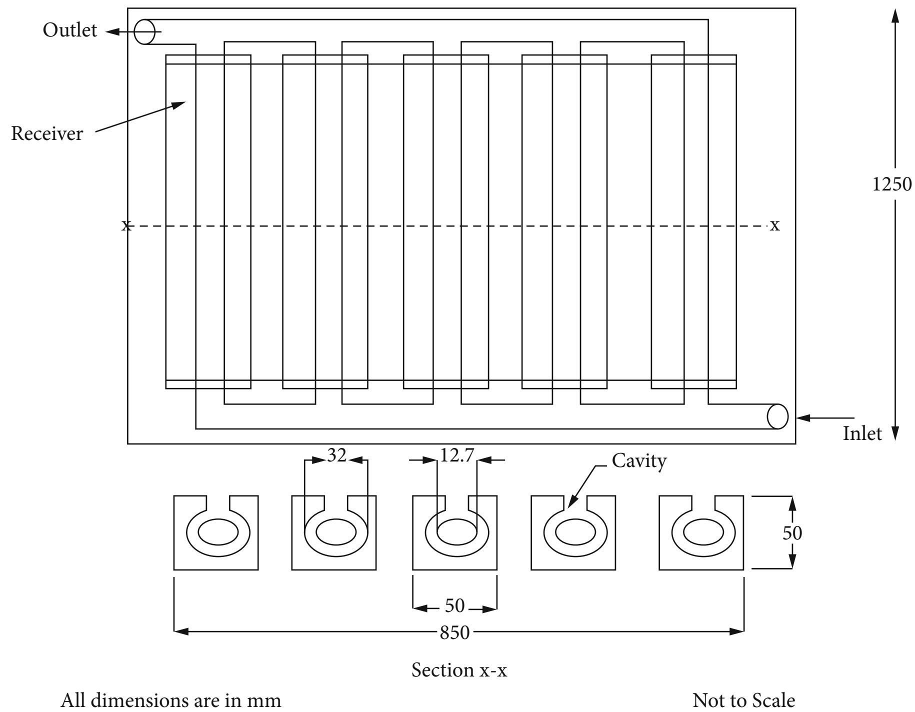

FIGURE 1: Assembly drawing of cavity collector.

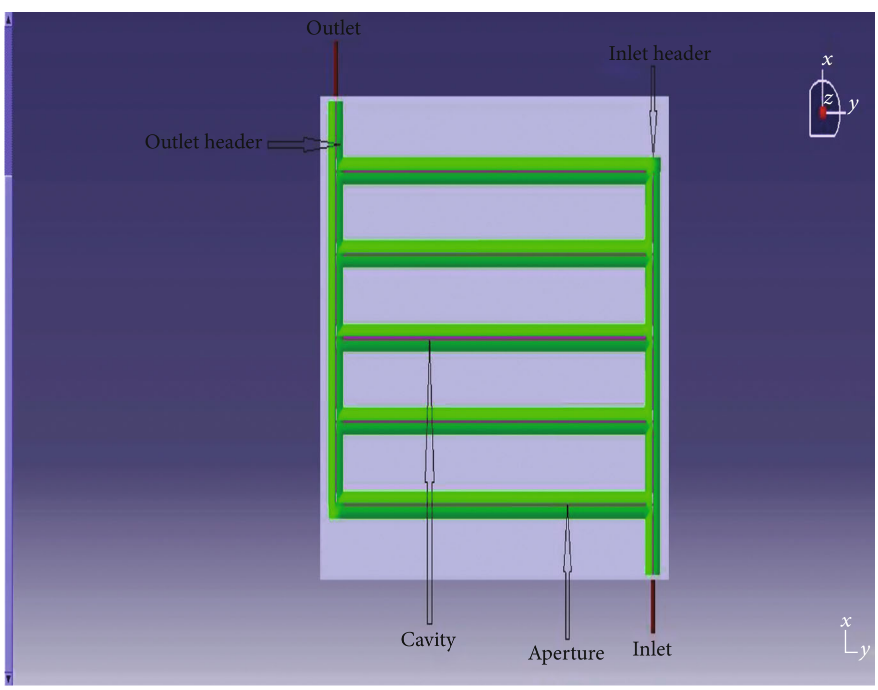

FIGURE 2: Diagrammatic illustration of SCC.

temperature at 2:15 PM has been performed by the SCC with an 8 mm aperture. SCC records 64°C of temperature at the time of 3:30 PM if an 11 mm aperture is being used. Similarly, a temperature of 48°C at 1:30 PM has been obtained by SCC with a 5 mm aperture maintained. 8 mm aperture is well suitable for SCC for the achievement of best performances.

4.3. Effect of Efficiency on Time in SCC and FPC. The effect of variation in efficiency curves for both SCC and FPC is indicated in Figure 5. In general, the efficiency of FPC goes on decreasing trend during late afternoon hours as the sunshine is gradually reduced with time. But in the case of SCC, the heat energy once absorbed from the sun has been holding up in the cavity. Therefore, the

Table 1: Technical overall details of SCC.

Size of the collector	1.25 × 0.85 × 0.05 m
Area of each cavity	0.101 m^2
Number of receivers and cavities	5
Receiver coating material	Matt black paint of industrial use
Diameter of inlet and exit tube size	0.013 m
Material used for receiver	Copper
Collector insulation material	Glass wool
Insulation thickness	0.025 m
Thickness of glass cover	0.004 m
Header diameter size for both inlet and exit	0.019 m

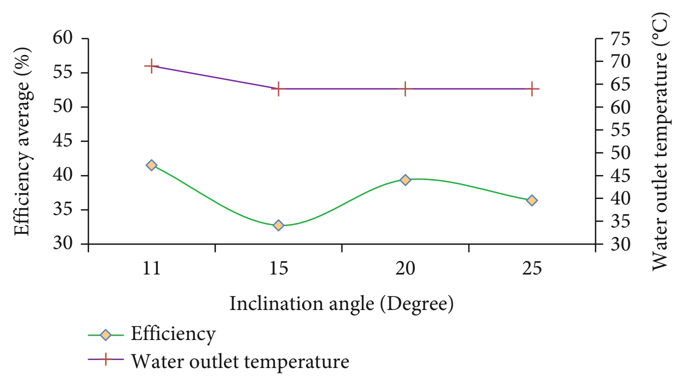

Figure 3: Efficiency and T_{out} comparison for different inclination angles.

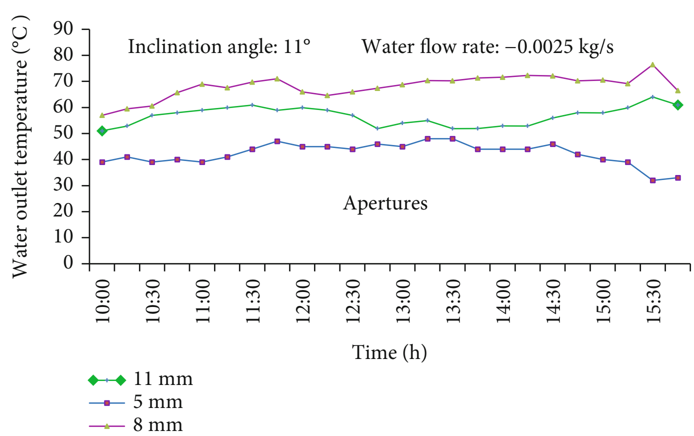

Figure 4: Variation in T_{out} with the three aperture entries.

efficiency of the system has been improved eventually. It has been observed from Figure 5 that the maximum efficiency of 77.7% during 1 : 40 PM has been achieved with SCC. At the same time, FPC records only a maximum temperature of 41.3% during 1 : 00 PM. Also from the figure, it is noted that the efficiency of the SCC has been more appreciable even during the afternoon time between 1 : 50 PM and 4 : 00 PM. There is no larger variation observed in the case of SCC when compared to FPC, due to the heat energy-absorbing capacity that has been deployed by SCC.

4.4. Efficiencies and Radiation with Time for Two-Mode of Flow. Figure 6 shows the performance comparison of instantaneous efficiencies for a parallel and serpentine mode of flow. An observation from the figure shows the efficiency for the parallel mode edge over the other, that is, serpentine mode. Also, the efficiency curve for the parallel flow model is uniform and attains a maximum efficiency of 79.49% at a 0.0025 kg/s water flow rate. It has been experienced from the graph afternoon; both efficiency curves have an increasing trend. It has been inferred that the parallel mode of flow has to be entertained in SCC to perform well.

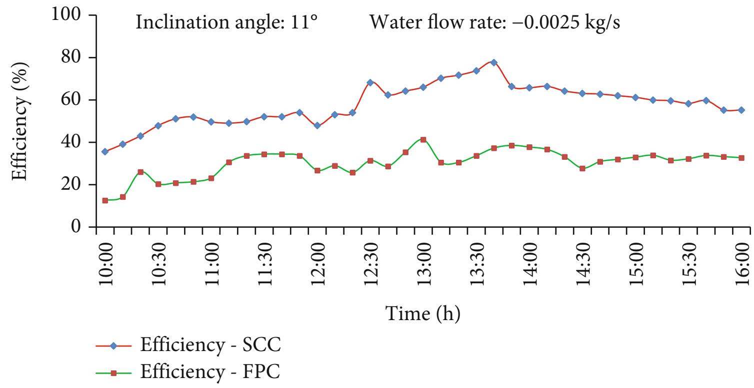

Figure 5: Effect of efficiency for both FPC and SCC.

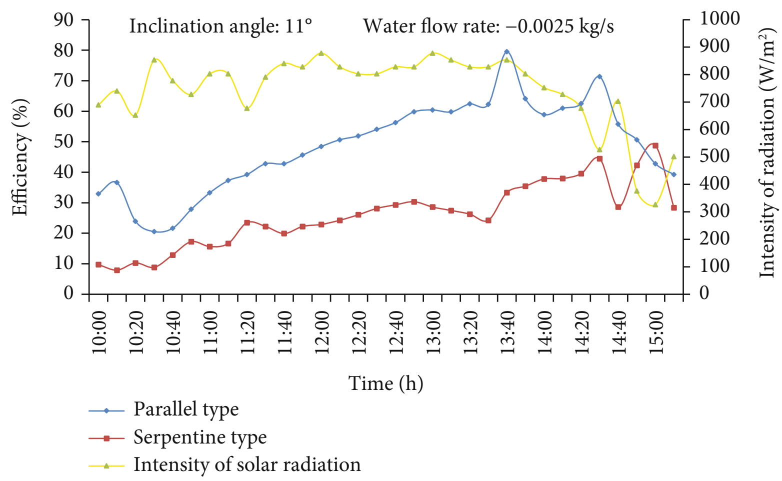

Figure 6: Performance comparison for two modes of flow.

4.5. Efficiencies with Time for Different Cavity Cover Box Materials. The time versus efficiency for the cavity cover box materials like GI and MS sheet metals has experimented in SCC as shown in Figure 7. A uniform water flow rate of 0.0025 kg/s has been kept for both cases. As far as concerning the GI material, the SCC obtains a maximum efficiency of 47%, and if SCC utilizes MS material, the efficiency was reduced to 43%. That is, a difference in the efficiency of 4% deviation has been experienced by these cavity cover materials. Even though the variation is small, the maximized performance has been achieved by the GI material. The reason is that the heat withstanding capability is quite high with GI when compared with MS.

4.6. Effect of Cavity Temperature with Cavity Number. Figure 8 illustrates the distribution of cavity temperature by its locations. Also, the graphical representation shows the huge impact on the cavity temperature variations to the locations. The 7 numbers of cavities configuration register a better temperature range for all the cavity numbers. But more variations have been seen in the case of 5 no. of cavity configuration. Cavity location 3 achieves a maximum temperature of 80.5°C with 7 no. of cavities configuration. This is the maximum temperature recorded by any cavity location. Of course, all numbers of cavities are exposed to sunshine uniformly; the deviations may occur due to the following conditions: (a) the shadow effect takes place between the cavities themselves, (b) the variations on heat transfer phenomenon, and (c) the flow conditions of the transport fluid. All these factors influence the temperature distributions in the locations.

4.7. Effect of Different Water Flow Rates vs. Exit Temperature of the Water on SCC. Figure 9 represents the water flow rate vs. exit temperature of water for both experimental and ANN-simulated results. During the experimentations and ANN, the solar radiation intensity value of 1267.35 W/m^2 has been recorded by the Pyranometer. While comparing both the ANN and experimented results, it came to know that they closely match with each other. That means, the present generated ANN model has the greater agreement with experimented results. Therefore, this model has been practiced for simulating the experimented results in SCC. It has the same trend as Rajeev et al. [5] measured vs.

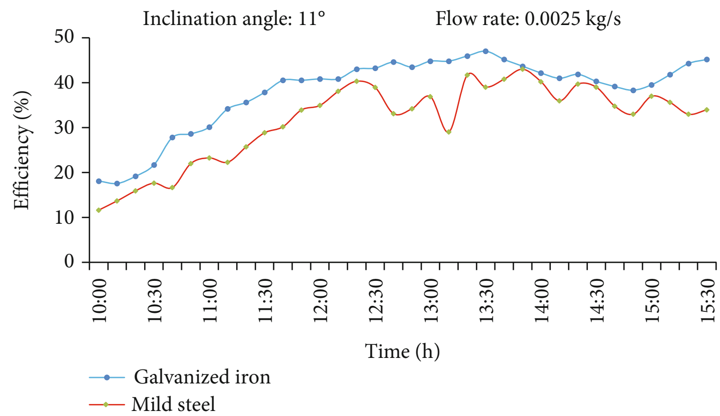

Figure 7: Efficiencies with time for various cavities cover box materials.

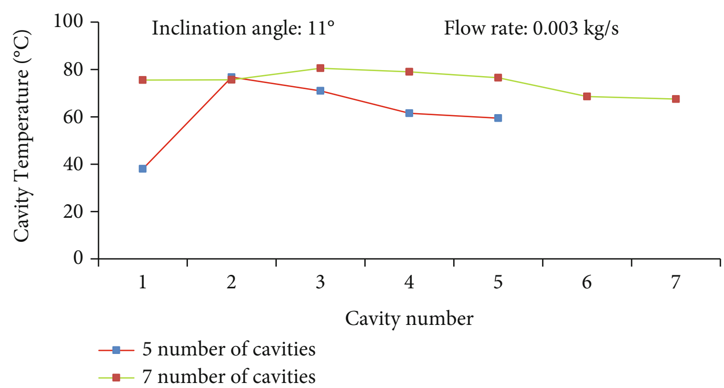

Figure 8: Distributions of cavity temperature by its location.

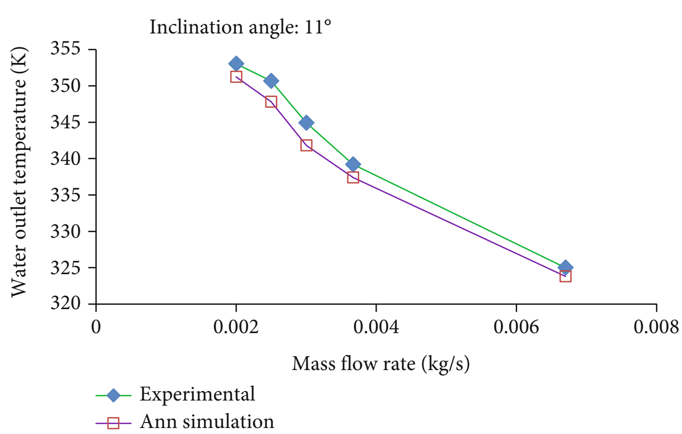

Figure 9: Effect of different water flow rates vs. exit temperature of the water.

predicted for experimental and ANN prediction results. The value of R obtained is 0.9188.

4.8. Effect of Inclination Tilt Angle on Exit Water Temperature in SCC. Figure 10 shows a plot of inclination tilt angle versus exit temperature of water for the comparison of ANN and experimental results. The trials have been carried out for various inclination tilt angles starting from 11° to 25°. It seems both the experimented and ANN results are matched together with lesser variations found at an angle of 11° and more at 25°. The deviation in temperature between these ANN and experimented results is 2 K.

4.9. ANN on Exit Water Temperature and Radiation with Time. A graphical sketch display of ANN on exit temperature of the water to time and corresponding intensity of solar radiation has been shown in Figure 11. The readings are taken with a uniform flow rate of water maintained at

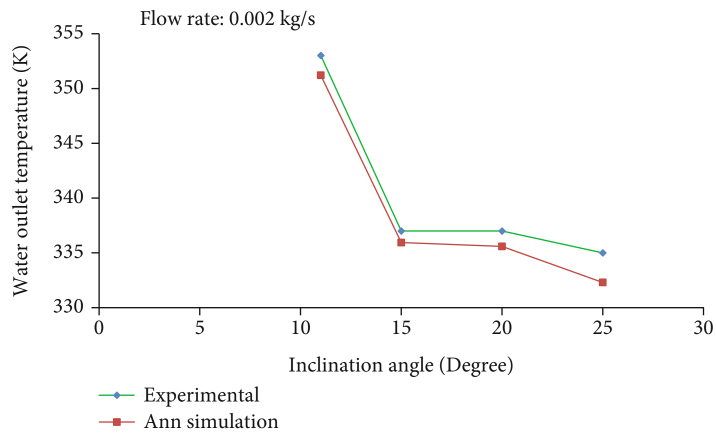

Figure 10: Effect of inclination tilt angle on exit water temperature in SCC.

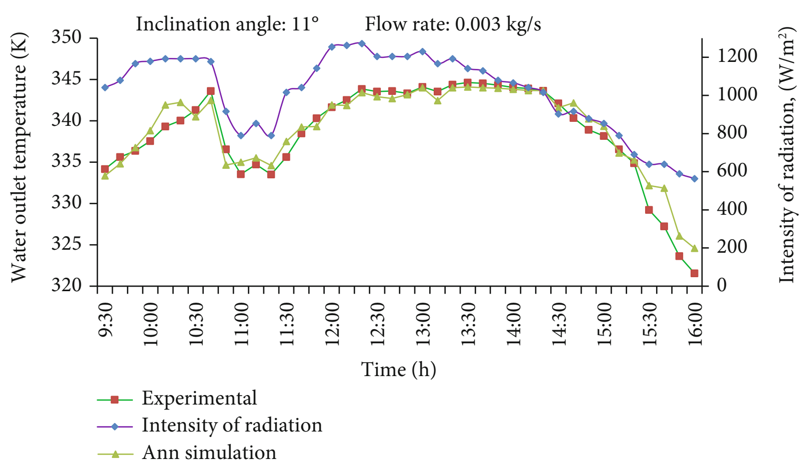

Figure 11: ANN on exit water temperature and radiation to time.

0.003 kg/s. The experimented result follows the same trend as that of the ANN values. Both are well-matched with each other correspondingly to the respective solar intensity of radiation values. The maximum deviation in temperature recorded by both experimented and ANN values are 4 K at any instant.

5. Conclusion

SCC has been tested experimentally and also simulated with ANN for various kinds of parameters, and the best results are summarized as follows.

(i) The optimized aperture gap for SCC is 8 mm. Out of 5, 8, and 11 mm aperture gaps, 8 mm gap records 68°C as the maximum temperature of water at the exit. Also, the maximum efficiency of 57% has been fetched out

(ii) The parallel mode of flow has a greater impact on the performance of SCC than the serpentine flow mode. The maximum temperature of 72°C at 2 : 15 PM has been obtained

(iii) When comparing SCC with FPC, SCC performs well during the afternoon time and late afternoon hours rather than FPC. It has been proved that the SCC curve for efficiency goes on an increasing trend even in the midnoontime. Also, the net heat transfer rate increased remarkably

(iv) The gadget has been tested with two types of cavity cover box materials used such as galvanized iron and mild steel. The results reveal that the galvanized iron fitted to SCC proves better than the mild steel material

(v) Performance of SCC with 5 and 7 no. of cavities configurations has been analyzed to examine which cavities will get more amount of heat. The results ensure that the centermost cavity location for both cases experiences maximum temperatures. This is due to the minimized heat losses at the center of SCC

(vi) ANN has been used as an effective tool to simulate the experimented results. Variations that occur between ANN and experimented results are ±4%.

ANN simulation has the same trend and also reveals that of experimental values

(vii) This current model has an accuracy of 96%. It has a coefficient of correlation of 0.9 and suits more better than the other models

(viii) SCC has the potential to heat the water preliminary before entering into any kind of concentrating collectors in the power plant applications

(ix) In solar-powered utilizations like solar power plants, water has to be converted into steam. It requires more amount of energy, and this can be fulfilled by SCC with more benefits

(x) If SCC has been utilized to heat the water at the initial stage, it leads to time-saving and reduces the dependence on solar concentrating collectors to some extent

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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