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Artificial Neural Network Based Performance Assessment of Thermosyphon Solar Water Heating System

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ABSTRACT

The thermosyphon solar water heater receives the radiation energy from the sun and utilizes this energy to heat the water with the help of flat plate collector panel and transfers it to the domestic hot water storage tank. Knowledge of solar collector performance at any place in the world is essential for solar equipments design engineers and architects. In general, the performance of a solar water heater is affected by more number of climatological parameters; therefore its analysis is also a complex task. For the past twenty years, more number of numerical approaches are developed to obtain the thermal behavior of solar collector, without performing a set of complicated and expensive experimental tests as well as to improve the computing performance. Recently artificial neural network (ANN) models are most commonly used in all the fields, for fast and accurate computing performance. The principal aim of the present research work is, to design and develop an ANN model and suggest the most suitable algorithm to predict the outlet water temperature (T0) of solar water heater for the selected region in India. Initially an artificial neural network model was developed and trained with four different algorithms to predict the outlet temperature (T0) of water by using the measured parameters of weather and solar water heater. After training and testing, the results obtained from ANN model were compared by using minimum root mean square error (RMSE), minimum mean absolute error (MAE) and maximum linear correlation coefficient (R), to select the best algorithm. ANN model based on LM algorithm performs well to predict the outlet water temperature with minimum error in the present work. Hence, the developed ANN model trained with LM algorithm can be effectively utilized by the design engineers and architects to predict the performance of thermosyphon solar water heater on any day, by using global solar radiation, inlet water temperature and storage tank temperature without performing a complicated and expensive experimental test.

KEYWORDS: Solar water heater Artificial neural network Outlet water temperature

INTRODUCTION

Conventional fossil fuel resources will be diminishing within few more centuries and also the power generation technologies based on fossil fuel, has severe impact on global warming. To overcome this, nowadays most of the countries are interested to invest in non-polluting and inexhaustible energy sources like solar, biomass, wind and hydro power [11,13]. Among this the solar energy is available throughout the year and in all the regions of the world.

Sun is the biggest natural resource energy on the earth for millions of years. This energy source is abundant, free of cost and eco friendly. Therefore most of the countries are automatically attracted by this source and initiated more number of research works in the solar energy field, like water heating for domestic and industrial purpose, crop drying in agriculture field, space heating and electricity production, for effective and efficient utilization of this free source of energy.

The concept behind the solar radiation operated equipments is, to collect, convert the effective solar radiation falling on the earth surface in to useful energy and stored for later usage. Electrical energy can be produced with the help of photovoltaic (PV) cells to meet the growing energy demand of electrical power generation by fossil fuels. Solar hot water (SHW) system is used to produce the hot water by absorbing the energy available in the sunlight and it can be used for industrial and household applications [17,5].

Solar water heating is a growing popular technology being used for hot water applications both in industrial and domestic sectors. Hot water is essential for industries such as textile, paper, food processing, dairy, edible oil. Also, it is required in large quantities for public buildings such as hotels, hostels, hospitals, restaurants as well as for domestic purposes [7]. Therefore solar water heating systems can be used as an alternate for the electrical heating to save the cost of electric bill and fossil fuel resources.

In India, to meet the demand of growing population and developmental needs, various renewable energy initiatives have been taken up, by the Government of India with the help of ministry of new and renewable energy (MNRE) along with state level departments and also with private sectors. As a part of this revolution, they are encouraging the use of solar water heating systems (SWH) for domestic as well as industrial purposes by giving subsidies and free installation.

Artificial neural networks (ANN) are widely accepted latest technology offering an alternative approach for complex tasks. They can learn from examples, able to deal with non linear problems and once trained can perform prediction faster.

Kalogirou *et al*. [6] analyzed the temperature response of a solar steam generation system by developing an artificial neural network model. The actual measured data was compared with the predictions. Finally, the developed model of the system was able to predict the temperatures at various points of the system within minimum percentage of error. Sozen *et al*. [15] determined the efficiency of flat plate solar collectors by developing an artificial neural network technique. The results show that the minimum deviations between measured and predicted values. Esen *et al*. [4] proposed an artificial neural network and wavelet neural network for modeling of a solar air heater system. Comparison between predicted and experimental results shows that the neural network model can be used to find the efficiency of solar air heaters with reasonable accuracy.

Arekete [2] presented a feasibility study of solar water heater installed in Akure, South West, Nigeria. Here readings were taken from a flat plate collector with double glazing layers tilted at 20˚ to the horizontal surface. The outcome of the experiments accomplished the reality that due to high insolation, solar water heater is feasible in South West Nigeria and in most other parts of the country, particularly South East and the Northern regions of Africa. Kalogirou *et al*. [10] estimated the useful energy extracted and the temperature rise by implementing an artificial neural network (ANN) model in the solar domestic hot water system. The results for the useful energy extracted from the system and temperature rise in stored water clearly indicates that the ANN method can be used at different weather conditions and for completely unknown systems. Its performance can be improved by using more number of data sets for training and testing of ANN models.

Taherian *et al*. [16] studied the dynamic simulation of closed thermosyphon solar water heater in clear and partly cloudy days weather conditions of a city in north of Iran. The simulation results are compared with the experimental results. The result shows that the simulation program is also capable to predict the accurate performance of solar water heating system. Karaghouli and Alnaser [1] analyzed the thermal performance of the thermosyphon water heater installed in Bahrain and its applicability by using a sunny and cloudy day's data under various daily solar intensities. The experimental results support the thermal applicability of such a system in Bahrain weather conditions. Belessiotis and Mathioulakis [3] developed an analytical approach for thermosyphon solar water heaters and compared its ability to link the system design and constructional parameters with the expected energy output. Experimental results clearly represent that the proposed methodology can be used for energy optimization and also for evaluation of test results of an existing system for product improvement.

Most of the earlier studies investigated the performance of solar water heating system over a short period of time may be one/two days or for a week. Therefore it is necessary to improve the accuracy of estimation by using more number of data sets. To accomplish the above task an effort was taken to predict the performance of SWH by using a widely accepted artificial neural network technique.

The present work is carried out for the performance prediction of thermosyphon solar water heating (SWH) system with flat plate collector (FPC) using an ANN model. This artificial neural network model is trained by using four different algorithms. The following parameters month, date, year, time, inlet water temperature, solar radiation, storage tank temperature are used as the inputs of artificial neural network model to predict the outlet water temperature (T_o) as an output. The above mentioned all the readings were measured from the installed experimental setup in Thiagarajar college of engineering, Madurai, southern part of Tamilnadu (India) for different weather conditions. The readings were taken at every ten minutes interval from 10am to 5pm in each day. Large number of measured data is used to train the ANN model with four different algorithms. Finally

ANN model with best algorithm for the present work is found based on minimum root mean square error and mean absolute error and maximum linear correlation coefficient, to facilitate the work of solar system design engineers.

Methodology:

Experimental Setup:

The selection of solar collectors is influenced by the application, location, heat transfer characteristics and maintenance cost. Water heaters are selected based on the requirements of domestic and industrial purpose. For domestic purpose with temperature less than 100˚C, solar water heater with passive/non concentrating collectors are used. Similarly for the industrial processes of temperatures higher than 500˚C, concentrating SWHs are most commonly used. The flat plate solar collectors are considered as efficient in tropic regions due to its absorption of both direct as well as diffuse radiation. Thermosyphon or Passive solar water heating systems operates based on the concept of natural convection of water between the solar collector panel and the hot water tank.

In thermosyphon solar water heating system, flat plate solar collector panel and storage tank are considered as two major components. Main purpose of collector is to receive the radiation from the sun with the help of absorber plate and heats the working fluid. Here water is used as the working fluid due to its high specific heat capacity, high thermal conductivity, low viscosity, low thermal expansion coefficient, anti corrosive property and low cost.

The experimental setup of solar water heating system with flat plate collector manufactured by TATA BP solar is installed in Thiagarajar College of Engineering, Madurai (9^o 56’ N and 78^o 5’E), southern part of Tamilnadu, India. The experimental setup absorber plate is made up of 36SWG copper sheet. This absorber plate is coated with NALSUN (room temperature black chromium bath) for high absorptivity of greater than 0.95 and low emissivity of less than 0.16. The system comprises of 9 copper tubes with 12.9mm diameter and 0.57mm thickness, which are used to circulate the water. These copper tubes are attached to the absorber plate by ultrasonic welding. Glazing, made up of toughened clear glass having a length of 2080 mm and 1070 mm width, is used to transmit the solar radiation inside the system and minimizes the loss of heat from the absorber plate to the outside. Thermal insulation is done with rock wool to minimize the loss of heat from both sides and back of the collector. Rock wool is having 25mm thickness along the sides and 50mm thickness on the bottom side of the solar collector. Hot water produced in the collector is stored in a stainless steel of ASI 304 grade rectangular horizontal tank having a capacity of 100 liters is located on top of the collector. This stored hot water can be supplied for other utilities. To minimize the loss of heat, this storage tank is insulated with pre coated galvanized steel in outer side and high density CFC-Free PUF (Chlorofluorocarbon free polyurethane foam) insulation in inner side. Electrical back up is also built in the storage tank in the form of three heaters each 3 kW capacity in the experimental setup to manage the hot water shortage in winter and cloudy days. Experimental set up is shown in fig.1 and its specification is given in table 1.

Fig. 1: Experimental setup.

Working of SWH system:

The main reason for widest application of thermosyphon solar water heating system with flat plate solar collectors in industries, office and residential buildings for water heating is due to their reliable performance, low cost, minimal need for maintenance as compared with others. It is capable of absorbing both diffuse and the direct beam solar radiation, so that temperatures of 40ºC to 70ºC can be easily attained.

Water from the hot water storage tank enters into the flat plate collector at the lower end and gets heated by receiving energy from solar radiation while flowing through the absorber tubes. As a result of decrease in density with temperature of water, hot water moves up to the upend side of the collector and flows back into the hot water storage tank. Higher density cold water from the bottom of the hot water storage tank flows down and enters the flat plate collector again and thus water is recirculated until is heated to the desired temperature. Hot water from the hot water storage tank can be drawn for further utilization.

Table 1: Specification of experimental setup.

S.No	Parts	Material and dimension
1	Glazing	Toughened clear glass
2	Glazing transmissivity	0.88
3	Material of insulation	Rock wool
4	Bottom insulation thickness	50×10^{-3}m
5	Side insulation thickness	25×10^{-3}m
6	Absorber plate material	Copper
7	Absorber plate thickness	36 SWG
8	Absorber plate coating	NALSUN
9	Absorber area	$2m^2$
10	Number of absorber plate	9
11	Absorber plate coating absorptivity	0.95
12	Absorber plate coating emissivity	0.16
13	Riser tube material	Copper
14	Number of riser tube	9
15	Riser tube diameter	12.9×10^{-3}m
16	Riser tube thickness	0.57×10^{-3}m
17	Length of the collector	2080×10^{-3}m
18	Width of the collector	1070×10^{-3}m
19	Storage tank material	Stainless steel of ASI 304 grade
20	Capacity of storage tank	100

The inlet and outlet water temperatures are measured by temperature sensors. All the measuring instruments in solar water heater are connected with data acquisition system in ground. The ambient air temperature, amount of global solar radiation on the collector surface and wind speed of the same location were measured and recorded using a weather monitoring station with data logger.

Description of data:

The solar water heating system with flat plate solar collector having an absorber area of $2m^2$ is installed at a fixed tilt angle of 9.9˚ to absorb the maximum amount of solar radiation throughout the year. The following input parameters like month, date, year, time, inlet water temperature, storage tank temperature, solar radiation are used in artificial neural network model to predict the outlet water temperature (T_o) as an output. These parameters are measured from installed experimental setup for every ten minutes interval from 10 am to 5pm on each day and for twenty days in every month. This measurement process was carried out for a period of one year at different weather conditions from January 2014 to December 2014. Totally 43 readings was taken per day. Finally 10,320 readings were taken throughout the year which was randomly divided for the training and testing of a developed ANN model by using four different algorithms.

ANN Structure in the present work:

In the present work solar water heating system with single collector and single storage tank was installed to perform the assessment of outlet water temperature of thermosyphon solar water heating system for different weather conditions with the help of artificial neural network model.

The developed ANN model is trained and tested with the following input parameters month, date, year, time, inlet water temperature, storage tank temperature, solar radiation to predict an outlet water temperature (T_o) as an output. The measured input and output data sets are normalized based on the activation function used in the hidden layer. Here, tangent sigmoid activation function has been used in the hidden layer. Therefore the measured datasets are normalized within a range from -1 to 1, before applied in to the training algorithm. The testing process is carried out successively, after obtaining the best trained ANN model.

The ANN model was developed on 'Neural Network Toolbox' in MATLAB version 2012, to predict the performance of thermosyphon solar water heating system. After the normalization process, out of the total number of data collected 8268 data (80%) are used for training and the remaining 2052 data (20%) for testing.

After the random selection of training and testing data, it is necessary to select the appropriate number of neurons in hidden layer. In general, a trial and error method is used for selecting the hidden neurons. Initially a few random numbers of neurons are taken and samples are allowed to train, if the network fails to converge after a reasonable period, then training was restarted after adding a few more neurons in the layer. This process is repeated until the mean square error value converges in to minimum. Alternatively, the appropriate number of neurons in hidden layer was finalized, when mean square error (MSE) value reaches its minimum value and R value attains maximum. In the present work, the minimum MSE value and maximum R value were found at 18 neurons in both training and testing.

Training and testing was performed by using four different algorithms like gradient descent (GD), levenberg marquardt back propagation (LM), resilient back propagation (RP) and scaled conjugate gradient (SCG) to predict the outlet water temperature of solar water heating system. Thus, artificial neural network structure with seven inputs, 18 neurons in one hidden layer and one output was used to predict the outlet water temperature of solar water heating system with minimum error and also used to compare the performance of all the four algorithms. Artificial neural network structure for the present work is shown in figure 2. Finally ANN model with best algorithm is chosen based on the minimum root mean square error (RMSE), minimum mean absolute error (MAE) and maximum linear correlation coefficient (R) results produced during training and testing.

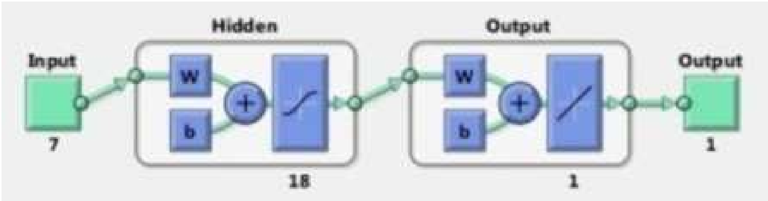

Fig. 2: ANN structure of the present work.

RESULTS AND DISCUSSION

Selection of ANN Algorithm:

The performance of ANN model was evaluated by using the MAE, RMSE and R. The mean absolute error (MAE) and root mean square error (RMSE) are expressed by the following equations [18,14]:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|X_i - Y_i|$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - Y_i)^2}$$

Where,
N = Total number of data.
X_i = Measured monthly average global solar radiation.
Y_i = ANN predicted monthly average global solar radiation.
i = Month

The performance results obtained from training and testing of ANN model with seven inputs, one hidden layer with 18 neurons and only one output, by using four different algorithms like gradient descent (GD), levenberg marquardt back propagation (LM), resilient back propagation (RP) and scaled conjugate gradient (SCG) algorithm are summarized in table 2. The results demonstrate that levenberg marquardt (LM) algorithm performs well with minimum root mean square error (RMSE), minimum mean absolute error (MAE) and maximum linear correlation coefficient (R) both in training and testing as compared to other algorithms. Therefore LM algorithm is selected as best algorithm for the present work.

Table 2: Performance results of the ANN model.

Name of the algorithm	Training results			Testing results		
	RMSE	MAE	R	RMSE	MAE	R
GD	4.6320	3.5845	0.8782	11.6437	9.6599	0.8851
LM	0.0083	0.0060	0.9999	0.0520	0.0254	0.9999
RP	1.3298	1.0092	0.9872	3.3773	2.6058	0.9859
SCG	0.2630	0.1946	0.9996	1.3294	0.9188	0.9996

Performance of ANN Algorithm:

Performance graph for the measured and ANN predicted outlet water temperature for some testing data by using the best algorithm (LM) in the present work is given in figure 3. From the performance graph also, it is clearly seen that almost all the predicted results are very close to the measured outlet water temperature values.

Generally, the outlet water temperature of solar water heater depends upon the many factors. Among this, time, day (Sunny/Cloudy) and global solar radiation are considered as important parameters to influence the performance of solar water heating system. Fig. 4 shows the variation of inlet water temperature and ANN predicted outlet water temperature of solar water heater with respect to time. The graph depicts that the outlet water temperature gradually increases from morning and reaches the maximum value around noon, when amount of solar radiation value is maximum.

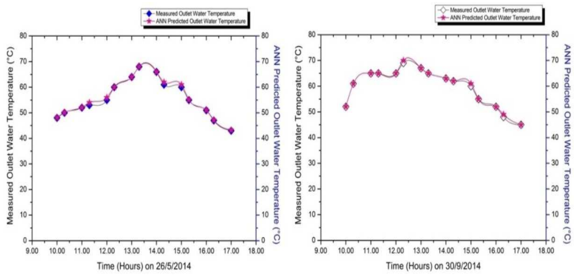

Fig. 3: Performance graph.

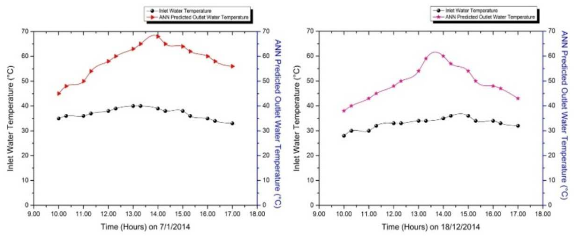

Fig. 4: Inlet and outlet water temperature variation with respect to time.

Regression and error Analysis:

Relation between the measured and ANN predicted outlet water temperature values of training and testing data for the best algorithm (LM) is shown in Figure 5, as regression plot. The R value for both training and testing data was 0.9999. The obtained R values also confirm that the proposed LM algorithm was best to predict the performance of solar water heating system.

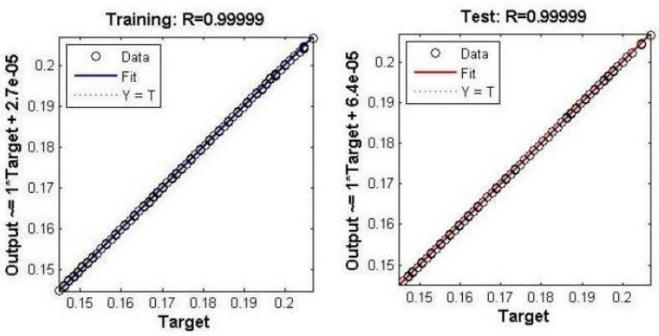

Fig. 5: Regression plot for training and testing data.

The formula for calculating the statistical error analysis terms i.e. mean absolute percentage error (MAPE) and coefficient of determination $(C_D^2)$was given below [12,1],

$$C_D^2 = 1 - \left(\frac{\sum_{i=1}^{N} (X_i - Y_i)^2}{\sum_{i=1}^{N} (Y_i)^2} \right)$$

$$MAPE - \frac{\sum_{i=1}^{N} \left| \frac{X_i - Y_i}{X_i} \right|}{N} \times 100$$

Where,

N : Total number of data.

X_i : Measured monthly average global solar radiation.

Y_i : ANN predicted monthly average global solar radiation.

The statistical error analysis result of testing data set for all the twelve months from Jan 2014 to Dec 2014 by the LM algorithm was given in table 3. The percentage of data closest to the line of best fit for a particular month is given by the term coefficient of determination. From the calculated results in table 3, the coefficient of determination results clearly indicates that the 99.99% of the predicted outlet water temperature values are very close to the measured values for all the months in a year by the ANN algorithm i.e. LM algorithm in the present work.

Table 3: Monthly testing data error analysis.

S.No	Month	(%)	MAPE (%)
1	JAN	99.99	0.0053
2	FEB	99.99	0.0648
3	MAR	99.99	0.0042
4	APR	99.99	0.0344
5	MAY	99.99	0.0693
6	JUN	99.99	0.0248
7	JUL	99.99	0.0093
8	AUG	99.99	0.0233
9	SEP	99.99	0.0019
10	OCT	99.99	0.0145
11	NOV	99.99	0.0094
12	DEC	99.99	0.1383

Accuracy of the testing data results are expressed in terms of mean absolute percentage error (MAPE). The calculated results of testing data error is within the range of 0.0019% to 0.1383% showing the high accuracy of MAPE, which confirms that LM algorithm performs well to predict the outlet water temperature with minimum error.

An ANN model developed, trained and tested by using LM algorithm in the present work, can be employed for the accurate prediction of outlet water temperature with minimum error for solar water heating system.

Conclusion:

Solar radiation from the sun is available everywhere in the world. In our society hot water requirements for most of the domestic purposes are below 60˚C. Solar water heating system can replace an electric heater in domestic applications and can serve as a pre heater when temperature is more than 60˚C as in industrial applications. So the solar water heating is the best option for meeting hot water requirements.

The present work focused on predicting the performance of solar water heating system associated with thermosyphon flat plate collector and horizontal hot water storage tank by using an ANN model. The data measured at various weather conditions for a period of one year was used for training and testing of an ANN model. Performance of four different algorithms like gradient descent (GD), levenberg marquardt back propagation (LM), resilient back propagation (RP) and scaled conjugate gradient (SCG) algorithm was evaluated based on minimum root mean square error (RMSE), minimum mean absolute error (MAE) and maximum linear correlation coefficient (R). Amongst the four algorithms, LM algorithm was identified as the best algorithm for the present work.

From the ANN model with LM algorithm, it was observed that the predicted outlet water temperature varies with global solar radiation as the measured values. In addition, the outlet water temperature results obtained from the ANN model was compared with the measured experimental results using regression and statistical error analysis. The regression R value was 0.9999 and the mean absolute percentage error value (MAPE) was in the range of 0.0019% to 0.1383%, in the present work. The high R value and the low MAPE values confirm the precise prediction of the collector performance by the proposed ANN model using LM algorithm. Thus, the artificial neural network model developed in the present work can be used to predict the outlet water temperature of solar water heating system with high accuracy.

In future the developed ANN model can be used to investigate the effect of different types of solar collector panels instead of flat plate solar collector or by using more number of solar panels instead of single panel or by using higher capacity storage tank in the performance analysis of solar water heating systems.

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