Chapter 18
Optimization of Multi-Parabolic Profile Flat-Plate Solar Collector for Space-Heating Application

Vikas Verma

Abstract In the recent decades, the demand for energy in India is growing at a very high rate such that the conventional energy sources are not sufficient to meet the demand. However, renewable energy have also been harnessed to some extent. In this work, an efficient multi-parabolic flat-plate solar collector is optimized for maximum efficiency. This collector simple is in construction and 39% more collector surface area as that of a flat-plate collector of 8 m^2. Solar collector is designed and optimized for 1.5 ton heat capacity of GSHP system during winter season for Roorkee, India, climatic condition. Theoritical analysis has been carried out for optimizing the design and performance parameters. Eight parameters at mixed levels have been considered using L_{18} (2^1, 3^7) orthogonal array in the Taguchi method, and the results indicate that 52.34% of maximum collector efficiency has been achieved with 6.8 m^2 of minimum collector area.

Keywords Multi-parabolic profile flat-plate solar collector · Area and efficiency · Taguchi method · S/N ratio · Space heating

Nomenclature

A_c	Area of solar collector (m^2)
C_f	Specific heat capacity (J/kg K)
CR	Concentration ratio
d	Diameter of collector pipe (mm)
FR	Heat removal factor
h	Heat transfer coefficient (W/m^2K)
I	Solar radiation (W/m^2)
L	Length (m)
m	Mass flow rate (kg/s)

V. Verma (✉)
Department of Energy, Tezpur University, Tezpur Assam, India
e-mail: vikas@tezu.ernet.in

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r	Radius of pipe (mm)
S	Absorbed flux by MPPFPSC (W/m^2)
SAGSHPS	Solar-assisted ground-source heat pump system
GCHP	Ground-coupled heat pump
T	Temperature (°C)
U	Overall loss coefficient (W/m^{2}K)

1 Introduction

This solar collector is well understood system to convert solar energy to thermal energy. The sole aim of solar collector is to achieve higher energy conversion efficiency by using different shapes of concentrator for production of hot water, electricity, and space heating. In general, around 29% of energy spent for space-heating/cooling demand is met by conventional system. In order to overcome the uses of conventional system, solar collector plays a major role in space-heating applications such as solar-assisted ground-source heat pump system (SAGSHP). Bertram [1] simulated a SAGSHP system with ground heat exchanger using TRNSYS simulation to understand the impact of seasonal performance of solar energy on the system performance. They studied the solar energy impact by varying the flat-plate collector area from 0 to 30 m^2. Huajun Wang and Wang and Qi [2] carried out an experimental study to analyze the performance of an underground thermal storage system using a 25 m^2 area of evacuated tube solar collector and 50 m depth ground-coupled heat pump system for residential building—and they reported about 70% efficiency for the evacuated tube collector. Chen et al. [3] performed a study on 21 m depth ground-coupled heat pump with 13.6 m^2 evacuated tube solar collector for space-heating applications. Based on their experimental results, they found that the SAGSHP system is more efficient as compared to conventional system for space heating. Bakirci and Yuksel [4] investigated the thermal performance of a solar source heat pump system for residential heating through 19.68 m^2 flat-plate solar collector. Based on the experimental results, they found that the solar collector efficiency varied from 33 to 47%, while the COP of heat pump and whole system were found to be 3.8 and 2.9, respectively. Chen et al. [5] simulated long-term solar-assisted ground-coupled heat pump system with 45 m^2 area of flat-plate solar collector. They found 26.3% of improvement as compared to traditional GSHP system, also the collector efficiency varied from 55 to 58% and reported 22% energy saving of the total heating load. Wang et al. [6] showed that injection of heat into the borehole was very important to improve the overall COPsys of SAGSHPS and HSGSHPS, and he could reach 3.42 and 2.99 from 3.17 and 2.95 and proposed a hybrid ground source heat pump system which can reduce electrical energy demand by 32%. Chen and Yang et al. [7] carried out a simulation on solar-assisted ground-coupled heat pump system under specified load condition for a collector area of 40 m^2 with bore-hole length of 264 m. System performance could be reached to 3.55. Bi et al. [8]

demonstrated that the average COP of the SGSHP system is 2.78, and the vertical double-spiral coil (VDSC) GHX was also justified in decreasing the temperature interference between the interior and exterior coil pipe. Yang et al. [9] performed a short time simulation by different combination modes of solar collector and GHXs, based on 20-day simulation, and the highest COP of 3.46 and energy saving rate of 14.5% were achieved when solar collector and GHX both are connected in series mode. Yumrutas and Kaska [10] reported annual heat pump COP values between 2.5 and 3 based on experimental investigation of thermal performance of a solar-assisted heat pump system with energy storage. Trillat-Berda et al. [11] carried out an experimental study of GCHP with 180 m^2 solar collector area. After 11 month in operation, the average value of power extraction and injection into the ground were 40.3 and 39.5 W/m, respectively, and the average COP of heat pump was 3.78. Han et al. [12] designed and simulated a solar-assisted ground-source heat pump (SAGSHP) heating system with latent heat energy storage tank (LHEST) in Harbin. They also obtained an average performance around 3.28 over the whole heating period. Jilin University and Hebei Engineering University also carried out some research on the design simulation and experiments using the SAGCHP system [13, 14].

In this work a multi-parabolic profile flat-plate solar collector has been proposed with GSHP system for space-heating application for minimum solar collector area and maximum efficiency through Taguchi method for Indian climatic condition. The main objective is to understand the effect of solar collector in GSHP system for space-heating applications. Solar-assisted ground-source heat pump system is one of the best energy utilization technology for higher energy saving and environmental protection.

2 System Description

SAGSHP system consists of two different components, one is solar collector, and the second one is ground coupled heat exchanger as shown in Fig. 1. In this system, heat pump consists of a compressor, condenser, expansion valve, evaporator, and fan coil unit. In the SAGSHP system, water is considered as the working fluid for extracting heat from the solar collector and GHX unit from where it is transmitted to the heat pump through refrigerant R-22. In SAGSHP system for heating mode, the evaporation of the refrigerant takes place in the evaporator using the heat absorbed from heat sources such as ground heat exchanger and solar collector. The heat rejected in the condenser is then used for space heating by means of a fan coil unit, and then, the refrigerant is sent back to evaporator through an expansion valve, where hot water becomes cold and again sent back to solar collector and ground heat exchanger.

The performance of the MPPFFP solar collector mainly depends on factors such as collector area (m^2), solar intensity, and absorbed heat flux. As the solar insolation available during winter season is less, it is essential to optimize the solar collector to obtain maximum heat output. In the present research work, Taguchi method has been implemented to optimize the area and efficiency of the MPPFP solar collector

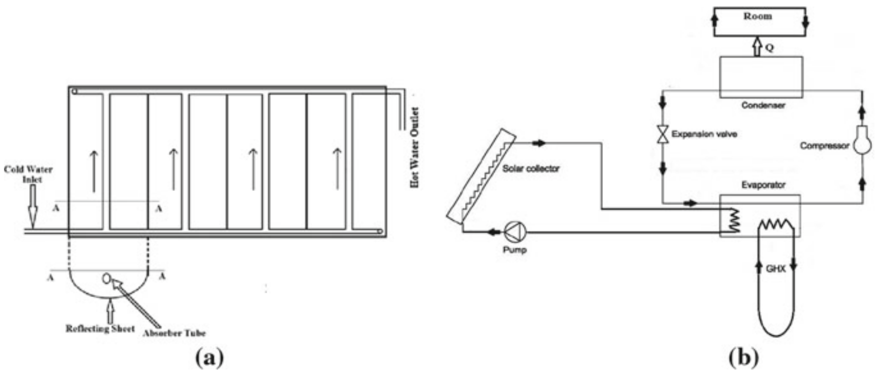

Fig. 1 Schematic diagram of **a** Multi-parabolic profile flat-plate solar collector, **b** solar-coupled heat pump system

using thermodynamic analysis. The following temperatures were measured at various points in the MPPFP solar collector during experiments in winter: water inlet temperature into the collector = 14 °C, average ambient temperature = 13.8 °C, average sky temperature = 7.8 °C.

3 Thermal Design of MPPFP Solar Collector

Multi-parabolic profile solar collector consists of four number of aluminum sheets bent in parabolic shape and are stacked in series on a support, resembling a flat-plate collector. The absorber tube is located exactly at the focal point of the parabola. All the absorber tubes are connected to inlet outlet header tubes which finally interacts with an intermediate heat exchanger. Solar collector efficiency directly depends on different factors such as outlet temperature, energy gain by collector, area of collector, and material of collector, but the important uncontrollable parameter is solar intensity. MPPFP solar collector gives high output temperature as compared to flat-plate solar collector, while solar intensity is minimum. Solar collector efficiency can be calculated by using the following relations [15]:

$$\eta_{\mathrm{i}} = \frac{Q_u}{A_{sc} I_b} \tag{1}$$

$$A_{sc} = \frac{F_R(\tau\alpha)I_b - F_R U_{\mathrm{Total}} \Delta T}{I_b\left(\frac{\tau\alpha}{1-(1-\alpha)\rho_g}\right) - \left\{\frac{1}{h_i} + \frac{r_i}{k}\mathrm{In}\left(\frac{r_o}{r_i}\right) + \left(\frac{r_i}{r_o}\right)\frac{1}{h_o}\right\}(T_{\mathrm{in}} - T_a)} \tag{2}$$

where Ţ = 0.88 and $\alpha = 0.95$. These values correspond to the test results for thermodynamic relations [16], r_i and r_o represent the inner and outer radii of solar collector absorber tube, respectively. Total energy gain (Q_U) and total heat loss by MPPFP solar collector system are written as

$$Q_u = F_R(W - d_0)L\left[S - \frac{U_{Total}}{CR}(T_{in} - T_a)\right], \quad (3)$$

$$U_{\text{Total}} = U_{FP} + U_{PC} \quad (4)$$

In this calculation, overall loss based on the convection and re-radiation losses is considered. Total loss of multi-parabolic profile flat-plate solar collector can be calculated as

$$U_{PC} = \frac{\frac{q_L}{L}}{\pi d_0(T_{pm} - T_a)} \quad (6)$$

$$U_{FP} = U_t + U_b + U_s \quad (7)$$

where U_t, U_b, and U_s indicate the top losses, bottom losses, and side losses, respectively.

4 Optimization of MPPFP Solar Collector

4.1 Taguchi Technique

Taguchi method is efficient and systematic approach to optimize design for performance and quality using standard orthogonal array in matrix form of experiments. Taguchi method calculates certain typical models according to the orthogonal array instead of all the possible models. The main objective of Taguchi method is to select the optimal combination of control factors. Finally, the results are analyzed from each trial runs using signal-to-noise ratio (SN), analysis of variance (ANOVA), and response table. There are three different types of performance characteristics for analysis using the S/N ratio: lower-the-better, higher-the-better, and nominal-the-best. The use of ANOVA is to find out the percentage contributions of individual parameters, and based on the above results, one will be able to find out the influential parameters and their levels that contribute for the performance parameter selected in a particular analysis.

4.2 Taguchi—Design of Experiments

In the present research, eight parameters at mixed levels are used in the Taguchi method for the experimental trial runs. Before selecting an orthogonal array, the minimum number of experiments to be conducted can be fixed by using the following relation [15]:

$$N_{\text{Taguchi}} = 1 + NV(X - 1)$$

In the present analysis where N_{Taguchi} = number of experimental trial runs, total number of parameters ($NV = 8$) and mixed level (X) was used with L_{18} (2^1, 3^7) orthogonal array. As the main aim of the present research is to optimize the MPPFP solar collector area and efficiency, lower the better criterion is used for solar collector area, whereas higher the better criterion is selected for the collector efficiency. These ratios can be computed using the following expressions:

$$\text{Lower the better } S/N(db) = -10\log\left(\frac{1}{r}\sum_{i=1}^{r} X_i^2\right)$$

$$\text{Higher the better } S/N(db) = -10\log\left(\frac{1}{r}\sum_{i=1}^{r} X_i^2\right)$$

where X_i = performance value at a given observation and i = number of repetitions in a trial.

5 Results and Discussion

The main focus of this work is to find out the levels of parameters for optimum solar collector area and efficiency of multi-parabolic profile flat-plate solar collector system for space-heating application. Mostly the performance of collector depends on both controllable and uncontrollable parameters such as solar radiation, thermal conductivity of solar collector pipe, mass flow rate of collector fluid, diameter of collector pipe, thermal conductivity of fluid, heat transfer coefficient of fluid, reflectivity and transmissivity of glass cover, absorptivity of the material, emissivity of reflecting sheet and collector pipe, heat removal factor, concentration ratio of solar collector, overall losses by solar collector, insulation thickness, energy gain by solar collector, wind velocity, ambient temperature, sky temperature, specific heat capacity of collector fluid. However, for the purpose of optimization of the MPPFP solar collector, only eight controllable parameters have been considered. These parameters are thermal conductivity of fluid (A), diameter of pipe (B), number of glass cover (C), solar intensity (D), mass flow rate of water (E), emissivity of absorber pipe (F), height of side cover (G), reflectivity of glass cover (H), and considered an L_{18}(2^1, 3^7) orthogonal array for experimental trial runs with mixed levels, considering one parameter at two levels and seven parameters at three levels are given in Table 1.

Table 1 Parameters and their levels

Label	Parameters	Level		
		1	2	3
A	Thermal conductivity of fluid (W/m K)	0.65	0.26	-
B	Diameter of pipe (inch)	1	1.5	2
C	Number of glass cover	1	2	3
D	Solar intensity	302	368	447
E	Mass flow rate of water (kg/s)	0.3	0.4	0.5
F	Emissivity of absorber pipe (−)	0.85	0.90	0.95
G	Height of side cover (mm)	300	350	400
H	Reflectivity of glass cover (−)	0.12	0.16	0.24

5.1 Taguchi Method—Signal-to-Noise Ratio

In Taguchi method, the important step after the selection of the experimental plan is to determine the signal-to-noise ratio (S/N) for all the experimental trial runs. The term signal illustrates the preferable effect for the output. In the present case, solar collector area and efficiency of MPPFPSC system and the term noise represents the undesirable effects on the outputs. In the present analysis, signal-to-noise ratios are calculated by using lower the better and higher the better concepts, respectively, for solar collector area and efficiency of MPPFPSC system. Based on the matrix of random experimental trial runs for calculating the solar collector area, efficiency, and S/N ratio of MPPFPSC system for space-heating application, the computed values are given in Table 2.

Using the values of Table 2, a response Table 3 for solar collector area and efficiency are computed to demonstrate the order of influencing parameters on the respective output on behalf of the rank of parameters defined on the basis of delta, which is the difference between the maximum and minimum values of each parameter. For example, ranks 1 and 8 indicate the most and least influencing parameter, respectively. The data given in Tables 3 are also depicted in Fig. 2 to highlight the final optimum influencing parameters. The levels of optimum parameters are A2B1C1D1E3F1G3H3 and A2B1C2D2E3F2G1H2 based on lower the better and higher the better concept, respectively, for solar collector area and efficiency.

5.2 Taguchi Method—ANOVA Analysis

ANOVA is used to formulate the relative significance of each parameter in terms of percentage contribution of overall response. The ANOVA Table 4 computed for both solar collector area and collector efficiency contain the data for Degree of Freedom

Table 2 Area and efficiency of MPPFP solar collector

Ex. no	SN ratio of MPPFPSC area	Area of MPPFPSC	SN ratio of MPPFPSC efficiency	Efficiency of MPPFPSC
1	−18.23	8.16	26.98	22.35
2	−18.04	7.98	29.46	29.73
3	−18.08	8.02	29.13	28.61
4	−17.94	7.89	28.12	25.49
5	−17.81	7.78	30.42	33.21
6	−18.65	8.57	25.95	19.84
7	−18.43	8.35	26.10	20.19
8	−18.28	8.21	26.55	21.28
9	−17.89	7.85	29.98	31.57
10	−17.21	7.26	33.86	49.36
11	−17.40	7.42	33.09	45.18
12	−17.12	7.18	33.89	49.51
13	−17.01	7.09	34.23	51.48
14	−17.75	7.72	31.94	39.56
15	−17.36	7.38	33.69	48.37
16	−17.45	7.46	33.05	44.96
17	−17.08	7.15	34.03	50.32
18	−17.60	7.59	32.50	42.17

Table 3 Response table for MPPFP solar collector area

Levels	1		2		3		Delta		Rank	
	(m^2)	(η%)	(m^2)	(η%)	(m^2)	(η%)	(m^2)	(η%)	(m^2)	(η%)
A	−18.14	28.08	−17.35	31.97	–	–	0.81	3.89	3	2
B	−17.72	31.08	−17.76	30.74	−17.79	30.54	0.07	0.54	7	6
C	−17.68	30.43	−17.73	30.93	−17.79	30.86	0.11	0.50	4	8
D	−17.09	31.00	−17.67	31.11	−17.91	30.49	0.82	0.62	2	5
E	−18.37	29.43	−17.70	30.80	−17.52	33.83	0.85	4.4	1	1
F	−17.67	30.30	−17.74	31.11	−17.76	30.92	0.09	0.0.81	6	3
G	−17.76	31.05	−17.80	30.53	−17.72	30.62	0.04	0.52	8	7
H	−17.75	30.67	−17.75	31.08	−17.65	30.8	0.10	0.70	5	4

(DF), sum of squares (SS), and mean of squares (SS); F is a ratio of the mean square error to the residual error and is traditionally used to determine the significance of a factor, and P is the ratio that indicates the percentage contribution by different control factors. The parameters with higher percentage contributions are ranked higher in terms of importance in the experiment and also have significant effects in controlling

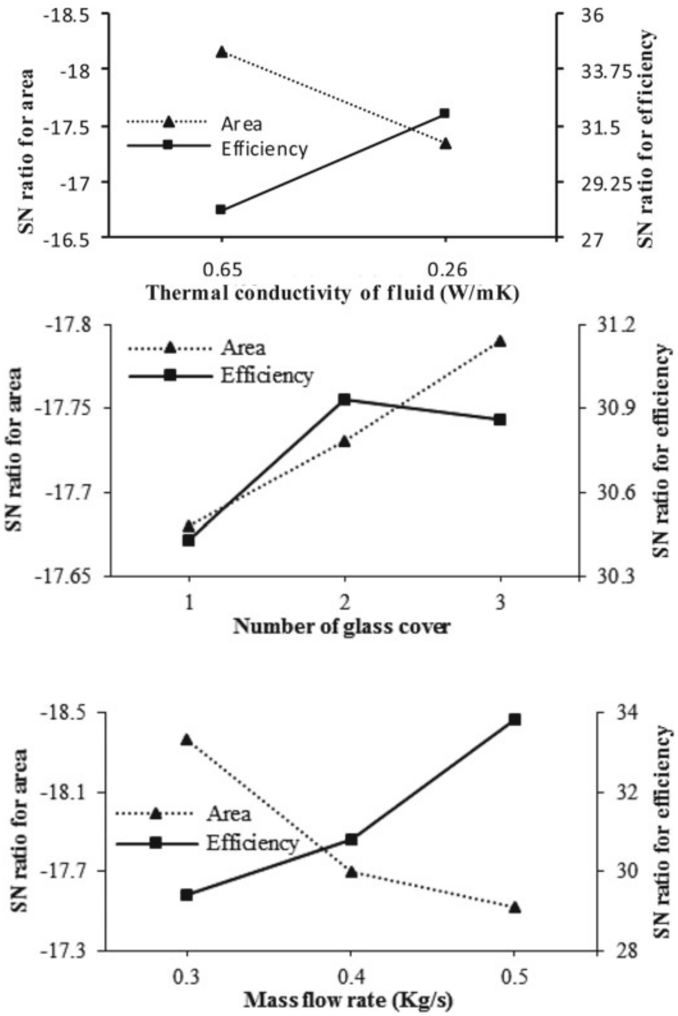

Fig. 2 Mean of S/N ratios for efficiency and area of MPPFP solar collector

the overall response. The variance and percentage contribution and sum of squares of the control factors, A, B, C, D, E, F, G, and H were computed for space-heating application with condition of maximum efficiency and minimum solar collector area of MPPFP solar collector system. The sum of squares (SS) and degree of freedom (DF) have been calculated by using the following equations:

$$SS = \frac{1}{2}\left\{(\text{sum of } S/N \text{ ratio level I})^2 + (\text{sum of } S/N \text{ ratio level I})^2 - C.F\right\},$$

$$\text{Correction factor } (C.F) = \frac{\left(\text{sum of } \frac{S}{N}\right)^2}{N}$$

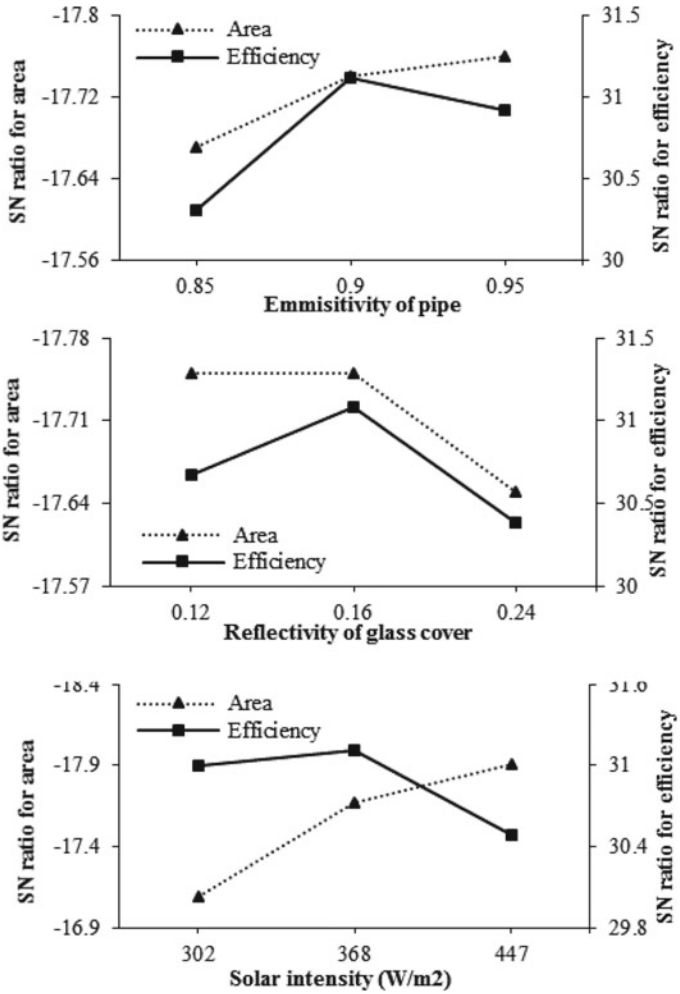

Fig. 2 (continued)

where N = total number of experiments ($N = 18$), and degree of freedom = level − 1.

5.2.1 Area of MPPFP Solar Collector

In the present analysis, the optimum levels of important parameters of solar collector have been selected to achieve the optimum area of collector. The parameters of influence considered are solar intensity and mass flow rate of fluid in collector tubes which flows inside the solar collector for extracting the heat from solar energy and

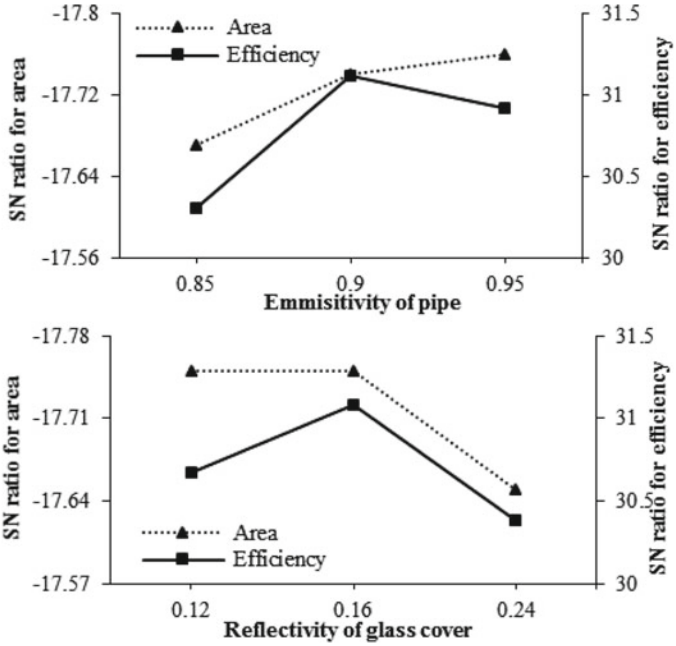

Fig. 2 (continued)

Table 4 ANOVA: Optimization of MPPFPSC area and efficiency

Source	DF	Sum of square (SS)		Mean of square (MS)		% of contribution	
		Area	Efficiency	Area	Efficiency	Area	Efficiency
A	1	6.3841	7.1532	6.3841	7.1532	13.6133	18.4083
B	2	3.4252	2.8796	1.7126	1.4398	7.8427	7.6103
C	2	5.9741	2.5486	2.98705	1.2743	12.8826	6.6577
D	2	9.2764	3.1543	4.6382	1.5771	19.4736	8.5174
E	2	12.7683	10.8275	6.4759	5.4137	26.7534	27.8487
F	2	3.8472	4.9587	1.9236	2.4793	7.9538	12.7609
G	2	1.3751	2.6759	0.68755	1.3379	2.8272	6.8853
H	2	4.2175	4.3567	2.10875	2.1783	8.6524	11.3114
Error	2	1.275	0.304	0.6375	0.152		
Total	17	48.6347	38.8585			100	100

converting in to heat energy, and the other parameters are taken as ambient temperature (Ta), transmittance of the cover ($Ţ = 0.88$), and absorptivity ($\alpha = 0.95$). The average ambient temperature of the given location [17] for heating period is assumed to be 13.8 °C, and also, it is assumed that the solar collector contributes heat energy around 3.5 kW, that is 50% of the total heating load. The calculated solar collector area varies from 7.09–8.57 m^2. The main aim of ANOVA results is to predict the percentage contribution of each parameter that are used to calculate the optimum solar collector area. From Table 4, it can be noticed that the highest contribution comes from the mass flow rate of fluid (E) with 26.7% contribution followed by the solar intensity (D) with 19.47% contribution.

5.2.2 Efficiency of MPPFP Solar Collector System

In order to achieve the optimum efficiency of the MPPFPSC system, it is required to select the appropriate levels of all the contributing parameters. Table 4 shows the ANOVA results for the efficiency of MPPFPSC system. The ANOVA tabular values show that all the parameters contribute for calculating the efficiency of MPPFPSC system in the form of percentage contribution value. It can be observed that the mass flow rate of fluid (E) contributes the highest percentage (27.84%) value among all the parameters. From this table, the higher percentage contributing parameters ranking can be found as EAFHDBGC.

5.3 Taguchi Method—Confirmation Test

The solar collector area was predicted based on different parameters like heating load and average ambient temperature for Indian climatic conditions. Taguchi conformation test has been carried out from 18 experimental trial runs. Based on these calculations, the computed values of solar collector area and efficiency of MPPFP solar collector system are given in Table 2. From these results, it is observed that the solar collector area and efficiency of MPPFPSC system varies from 7.09 m^2 to 8.57 m^2 and 19.84 to 51.48, respectively. The efficiency of MPPFPSC system directly depends on the area of solar collector. Based on the best set of operating parameters among the L_{18} Taguchi array, the optimum area of solar collector and efficiency of MPPFPSC system are found to be 6.8 m^2 and 52.34%, respectively. Thus, implementation of Taguchi method has made it possible to determine the optimum values of solar collector area and efficiency of MPPFPSC system using the control factors at different levels listed in 18 experimental trial runs.

6 Conclusion

Solar-assisted ground-source heat pump is an important alternate technology for utilization of renewable energy for space-heating applications. In this study, an attempt has been made to find out the optimum area and efficiency of MPPFP solar collector for space-heating application using Taguchi method through L_{18} orthogonal array at mixed levels. Simulation results were obtained for all the 18 trial runs for optimum solar collector area and efficiency. Based on the optimization, solar collector area is found to be 6.8 m^2 using the Taguchi method for space-heating application. Also found that mass flow rate and solar intensity are to be more influencing parameters for optimizing the solar collector area. They contributes around 26.75 and 19.47%, respectively, but for the term of efficiency, mass flow rate also contributes a more percentage around 27.84% and thermal conductivity of pipe contributes around 18.4%. Finally, it was found that with the predicted levels of parameters, the MPPFP solar collector could achieve maximum efficiency of 52.34%.

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