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Optimization Studies on the Performance Characteristics of Solar Flat - Plate Collector Using Taguchi Method

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Abstract: In this study an attempt is made to optimize the various operating parameters for enhancing the performance and heat transfer characteristics of solar flat plate collector using Taguchi method. An experimental investigation was carried out on solar flat plate collector while using silver/water nano fluid as working fluid. The operating parameters considered are Reynolds number (A), silver nano particle concentration (B) and incident solar heat flux (C). As these variables have major impact on the performance and heat transfer characteristics of solar flat plate collector, the test is conducted to study their influence and interactions on the performance and heat transfer characteristics. The experimental runs have been setup using Taguchi L9Orthogonal array based Design of Experiments (DoE)and the results of outlet temperature of the fluid, efficiency of collector and heat transfer rate for each run have been optimized in Design of Experiments (DoE) Taguchi method using MINITAB 17 software. The optimum combinations of parameter for each response have been predicted with respect to Signal to Noise Ratios (S/N). The Results have shown that the parameters chosen in this study have significant influence on the responses chosen and the validation results have shown significant improvement on the performance characteristics of the solar flat plate collector.

Key words: Solar Flat plate collector · Taguchi design of experiments · Optimization · Silver/water nano fluid

INTRODUCTION

Solar power is very important resource of renewable energy. Conversion of solar energy into useful form such as heat, electricity etc., is most important requirement in this era. Solar flux on the earth's surface provides energy which is greater than the energy requirement of all human beings in day to day life. It is necessary and convenient to switch over from conventional energy conversion method into new one to utilize the solar energy in efficient way.

Solar energy is the non-renewable energy resource with minimum environmental impact, Sharma *et al*. [1]. The advanced in nano technology provides an effective platform in the field of heat transfer. In heat transfer applications, nano fluid is used as heat transfer medium for effective heat absorption than base fluids. Nano fluid is a colloidal mixture of nano particles in base fluids such as water, ethylene glycol etc. The suspended nano particles improve thermal, physical, radiative and transport properties of the base fluid. Due to improved properties, better heat transfer characteristics are obtained in solar flat-plate collector. Sarit Kumar Das *et al*.[2] carried out experimental investigation on the temperature effect of thermal conductivity enhancement in nano fluids. It was observed that increase in thermal conductivity due to the temperature in the range of 21°C to 51°C using CuO and Al_2O_3nano particles and finer CuOnano particles show more enhancement of thermal conductivity with the increasing of temperature. Sang Hyun Kim *et al*. [3] studied the thermal conductivity of water-ethylene glycol based nano fluids containing size dependent alumina, zinc-oxide and titanium-oxide nano particles using transient hot-wire method. It was observed that the thermal conductivity is inversely proportional to the mean diameter of the suspended particles and also increase in the effective thermal conductivity due to high power laser irradiation.Aburba Kumar Santra *et al*. [4] analysed the effect of copper-water nanofluid as a cooling medium to identify the heat transfer characteristics in a 2D

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rectangular duct with laminar flow condition and nano particle volume fraction with a range of 0.00 to 0.050. The considerable increasing of heat transfer characteristics were observed with the increasing of solid volume fraction.

MATERIALS AND METHODS

Theoptimum input parameter combination was identified by using Taguchi method. The Taguchi method [5] is an experimental design technique which is used to reduce the number of experimental runs dramatically by using suitable orthogonal arrays. It reduces the duration of experimental time and cost. The objective is to reduce noise factors and increasing signal value to achieve higher values of Signal/Noise (S/N) ratio. As the mean decreases the standard deviation also decreases hence S/N ratio is required as measurable value instead of standard deviation. The goal in this experiment was to identify and to quantify those parameters, which have the greatest potential for increasing the performance characteristics such as outlet temperature, efficiency and heat transfer rate and to optimize selected design and operating parameters [6, 7].

Taguchi's Design of Experiments (DOE) were carried out in nine combination parameter tests, to determine the enhanced heat transfer characteristics of nano fluids that maximize the performance of solar flat-plate collector.

Selection of Orthogonal Array: An Orthogonal Array (OA) is a fractional factorial matrix, which assures a balanced comparison of levels of any factor (or) interaction of factors. It is a matrix of numbers arranged in rows and columns where each row represents the level of the factors in each run and each column represents a specific factor that can be changed from each run. This array is called orthogonal because all columns can be evaluated independently of one another. OA accommodates many design parameters simultaneously. In this experimental work, 3 parameters containing three levels control factors require 6 degrees of freedom. Mathematically,

Degrees of freedom = 3 (3-1) = 6

The smallest Orthogonal Array should have at least 6 degree of freedom. The L9can occupy 3 three level parameter. Table 1 shows design values of L9 orthogonal array.

Table 1: Design values of L9 orthogonal array.

Experimental number	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Parameter Selection: In parameter selection three key operating parameters, such as Reynolds number, nano particle concentration and incident solar flux were selected. These parameters were believed to have a significant effect on performance characteristics and could be tested using solar flat-plate collector. Three levels for all the parameters were considered for Taguchi design experiment.Reynolds number is an important parameter to maintain turbulent flow, mass flow rate and flow velocity. The physical properties of base fluid are abruptly altered due to the presence of nano particles to enhance the heat transfer characteristics. It is estimated that the collector performance depends on the incident solar flux. Hence Reynolds number, nano particle concentration and incident solar flux were selected as influencing characteristics.

The independent variables are chosen as follows.

Reynolds number-R_e (A)	: 5000, 15000, 25000.
Silver nano particle concentration-φ (B)	: 0, 0.01%, 0.03%.
Incident solar heat flux-I_T ©	: 800W/m^2, 900 W/m^2, 1000 W/m^2.

The engineering system behaves in such a way that the manipulated production and performance factors are classified into three categories [8]:

- Control factors, which affect process variability as measured by the S/N ratio.
- Signal factors, which do not influence the S/N ratio or process mean
- Factors, which do not affect the S/N ratio or process mean

The S/N ratio characteristics can be divided into three categories given by the following three equations, when characteristics are continuous [9].

- Nominal is the best characteristic,

$$\frac{S}{N} = 10\log\frac{\overline{Y}}{S_y^2} \quad (7)$$

- Smaller is the better characteristic,

$$\frac{S}{N} = -10\log\frac{1}{n}(\Sigma Y^2) \quad (8)$$

- Larger is the better characteristic,

$$\frac{S}{N} = -10\log\frac{1}{n}(\Sigma\frac{1}{Y^2}) \quad (9)$$

Where $\overline{Y}$, is the average of observed data, S_y^2 the variation of Y, n the number of experimental observations and Y the observed data? With the above S/N ratio transformation, the smaller the S/N ratio, the better result when considering heat transfer characteristics such as heat losses, logarithmic mean temperature, pressure drop etc. and the larger the S/N ratio, the better the result while considering outlet temperature, effectiveness, overall heat transfer coefficient etc. In this experiment larger is the better characteristic was considered since the responses such as outlet temperature, collector efficiency and heat transfer rate must be higher. Experiments were conducted based on the design values obtained from L9 orthogonal array [10].

Experimental Procedure: The experimental setup is shown in figure 1. The experiments were conducted as per ASHRAE 93-86[6] to determine the performance characteristics of solar flat-plate collector using silver/water nana fluid as heat transfer medium. The ASHRAE standard testing method stated that the collector must be tested under clear sky conditions to measure the performance characteristics. Data is recorded on any given data under steady-state conditions for fixed values of Reynolds number, nana particle concentration and incident solar heat flux with constant fluid inlet temperature. The experiment trials were conducted with three replicates. It is considered that the collector operating under steady-state conditions if the deviation of the experimental reading measured for a given Reynolds number is less than the following specified limits over a 15 minute period [7].

- Global radiation incident on collector plate ± 50W/m^2
- Ambient temperature±1°C
- Fluid flow rate ±1%
- Fluid inlet temperature ±0.1°C
- Temperature rise across the collector ±0.1°C

The wind speed between 3m/s and 6m/s and the flow rate at approximately 0.02 per square meter of collector gross area. The flat-plate collector is tested with above said Reynolds number. The block diagram of solar flat plate collector is shown in figure 2. After steady state condition prevails, the data for each test period are averaged and used in the MINITAB 17 for optimization [11-24].

As the inlet, outlet temperatures and mass flow rate are measured; the useful heat gain by the fluid is obtained by

$$Q = \dot{m}C_p(T_o - T_i) \quad (1)$$

Where $C_p$is the heat capacity of the fluid. The heat capacity of nano fluid is calculated by [6]

$$C_{p,nf} = C_{p,np}(\varphi)+C_{p,bf}(1-\varphi) \quad (2)$$

Where φ represents the volume of nano particles and $C_{p,np}$is the heat capacity of nano particles and $C_{p,bf}$ of the nano fluid.

Fig 1: Experimental setup of solar flat-plate collector

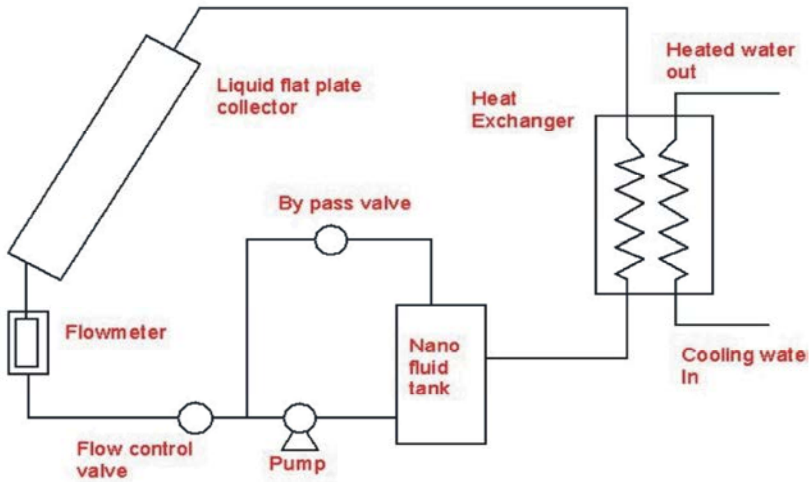

Fig 2: Block diagram of solar flat-plate collector with heat exchanger setup

Heat flux on the riser tube is given by

$$q_u = Q/A_l \quad (3)$$

Where, A_l is the lateral surface area of the riser tube. The convective heat transfer coefficient is given by,

$$h_{nf} = q_u/(T_{w(nf)} - T_{b(nf)}) \quad (4)$$

The efficiency of the collector is given by

$$\square = Q/A_c I_T \quad (5)$$

I_T is the total radiation is measured by pyranometer.

The relationship between Reynolds number and mass flow rate is given by

$$Re = \frac{4}{\pi D \mu} \quad (6)$$

Where, is mass flow rate, D is diameter of the riser tube and μ is viscosity of the nano fluid.

RESULTS AND DISCUSSION

Experimental runs were conducted as per Taguchi design with three replicates of each run on different days and the observed data were analyzed using Taguchi analysis. Signal/noise ratio is an essential part for analysing experimental data using Taguchi method. According to Taguchi method, maximum value of S/N ratio should be required to obtain optimum heat transfer characteristics.

Effect of R_e, φ and I_t on Outlet Temperature (T_o): Level values of the factors obtained for outlet temperature according to Taguchi design, are given in Table 2. Larger is the better characteristic was selected and the figure 3 shows the effect of input parameters on outlet temperature (T_o). Hence interpretations can be made based on the level values of A,B and C factors given in table 2 and figure 3 in determining optimum heat transfer parameters of experiments to be conducted under the same conditions.

The different values of S/N ratio between maximum and minimum are (main effect also) shown in table 2. The Reynolds number and nano particle concentration have the value of 2.4 and 2.39 are have more significant on outlet temperature (T_o). Hence it can be concluded that increasing Reynolds number will increase outlet temperature.

From table 2 it is observed that third level of a factor (Reynolds number), the third level of B factor (nano particle concentration) and the first level of C factor (heat flux) are higher. Consequently, the optimum output parameters determined under the same conditions for the experiments to be conducted will be 25000 for the Reynolds number, 0.03% for the nano particle concentration and 800W/m^2 for the heat flux for maximum outlet temperature.

From the Taguchi observation, it is concluded that when increasing Reynolds number the velocity of the flow will be increased. Due to this, increasing of Nusselt number leads to more convective heat transfer rate. Hence increasing the Reynolds number leads to increasing the outlet temperature.Increasing the concentration of nano particle in base fluid will increase the surface area. It leads to absorb more heat.

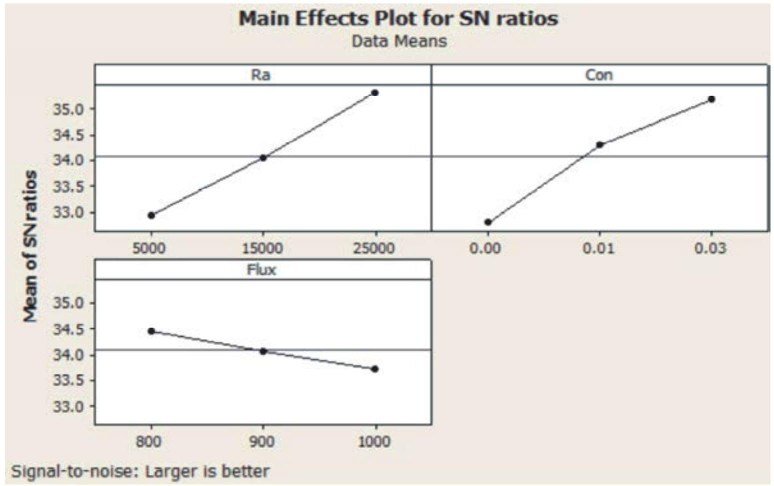

Fig 3: The graphic of mean of S/N ratios versus factor levels(T_O)

Table 2: Taguchi analysis: T_O versus Re, φ and heat flux

Level	A	B	C
1	32.92	32.79	34.46
2	34.03	34.29	34.06
3	35.31	35.18	33.74
Δ	2.40	2.39	0.72

Table 3: Analysis of variance: $T_O$vs Re, φ and heat flux

Source	df	Adj SS	Adj MS	F - value	P - value
A	2	324.67	162.33	15.71	0.060
B	2	312.67	156.33	15.13	0.062
C	2	38.00	19.00	1.84	0.352
Error	2	20.67	10.33		
Total	8	696.00			

The Taguchi prediction shows that the heat flux does not play significant role when compared with Reynolds number and nano particle concentration on outlet temperature of solar flat-plate collector using silver/water nano fluid as heat transfer medium.

The Taguchi method was used in determining optimum heat transfer conditions according to the S/N ratio, whereas the interaction between the heat transfer parameters were determined with the help of analysis of variance. MINITAB 17 was used for analysis of variance and the interactions between input parameters and outlet temperature were analysed. Table 3 shows the analysis of variance, T_O versus Re, φ and heat flux considering that, according to P (significant) values; φ and heat flux does not produce a significant level with the reliability interval of 95% and Reynolds number has some significant effect on response T_O.

The regression equation for outlet temperature considering Re, φ and heat flux is given by

$$T = 51.33 - 7.00xRe_1 - 0.67xRe_2 + 7.67xRe_3 - 7.67x\,\varphi_1 + 1.00x\varphi_2 + 6.67x\varphi_3 + 2.33xI_{T1} + 0.33xI_{T2} - 2.67xI_{T3}$$

Effect of R_e, φ and i_t on Efficiency (□): The Taguchi was also used to obtain efficiency values. Table 4 shows Taguchi design level values obtained from MINITAB 17 program. Graphical representation from figure 4 and the values from Table 4 show the S/N ratio for efficiency. The third level of factor A (Reynolds number), the third level of factor B (nano particle concentration) and the first level of factor C (heat flux) are higher. Hence optimum efficiency for the experiments to be conducted will be (3 3 1) 25000 Reynolds number, 0.03% nano particle concentration and 800W/m^2 for heat flux. From table 4 it is observed that nano particle concentration has significant effect on efficiency of solar flat-plate collector. While increasing nano particle concentration the surface area increases and it leads to have more fluid temperature difference between the inlet and outlet of the solar flat-plate collector. It is theoretically proved from equation (5). Hence the efficiency of solar flat-plate collector is increased while increasing nano particle concentration.

The variance analysis in table 5 shows the effect of input parameters on efficiency of the collector. The nano particle concentration has the P value less than 0.05. Therefore the P value is effective at the reliability level of 95%. The nano particle concentration has more significant effect on efficiency than Reynolds number. The regression equation for efficiency is given by

$$□= 44.39 - 8.36xRe_1 + 1.39xRe_2 + 6.97xRe_3 - 14.79x\varphi_1 + 3.59x\varphi_2 + 11.20x\varphi_3 + 4.31xI_{T2} - 2.37xI_{T2} - 1.93xI_{T3}$$

Table 4: Taguchi analysis? versus Re, φ and heat flux

Level	A	B	C
1	30.93	29.41	33.24
2	32.87	33.39	32.00
3	33.82	34.83	32.40
Δ	2.89	5.42	1.24

Table 5: Analysis of variance: ? vs Re, φ and heat flux

Source	df	Adj SS	Adj MS	F - value	P – value
A	2	361.51	180.76	8.35	0.107
B	2	1070.70	535.35	24.72	0.039
C	2	83.75	41.88	1.93	0.341
Error	2	43.32	21.66		
Total	8	1559.28			

Table 6: Taguchi analysis: Q versus Re, φ and heat flux

Level	A	B	C
1	56.31	58.10	57.58
2	58.37	58.63	58.97
3	60.84	58.80	58.98
Δ	4.53	0.70	1.40

Table 7: Analysis of variance: Q vs. Re, φ and heat flux

Source	do	Ad SS	Ad MS	F - value	P – value
A	2	309675	154837	19.99	0.048
B	2	8350	4175	0.54	0.650
C	2	36332	18166	2.35	0.299
Error	2	15489	7745		
Total	8	369845			

Effect of R_e, φ and I_t on Overall Heat Transfer Rate (Q): The Taguchi design was conducted to obtain over all heat transfer rate values too. Taguchi design values are given in table 6. Figure 5 shows the graphical representation of S/N ratios for overall heat.

Transfer rate. According to Taguchi design, third level of a factor (Reynolds number), third level of B factor (nana particle concentration) and third level of heat flux are higher. The optimum heat transfer.

Conditions for the experiments to be conducted will be (3 3) 25000 for Reynolds number, 0.03% for nana particle concentration and 1000W/m^2 for heat flux.

The analysis of variance to show the effect of input parameters on overall heat transfer rate of the collector is given in table 7. It shows the Reynolds number has more significant value on overall heat transfer rate because the p value is 0.048 when considering the reliability level of 95% than nana particle concentration and heat flux. The regression equation for overall heat transfer rate is given by

$$Q = 865.2 - 209.1xRe_1 - 32.6xRe_2 + 241.7xRe_3 - 38.0x\varphi_1 + 1.4x\varphi_2 + 36.6x\varphi_3 - 89.2xI_{T1} + 53.9xI_{T2} + 35.4xI_{T3}$$

When increasing the mass flow rate the overall heat transfer rate increases and it is theoretically realized from equation (1).

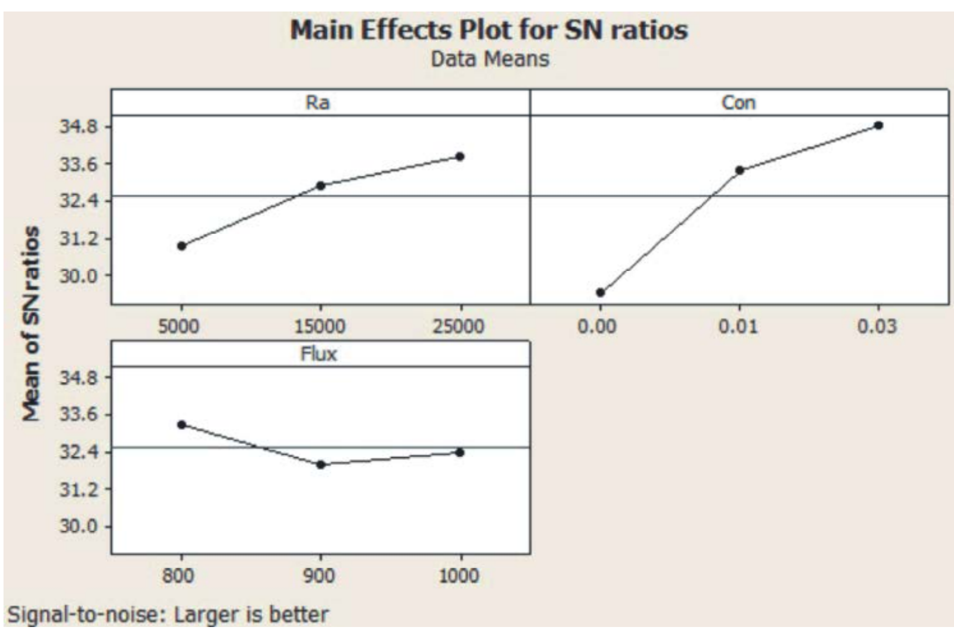

Fig 4: the graphic of mean of S/N ratios versus factor levels (□)

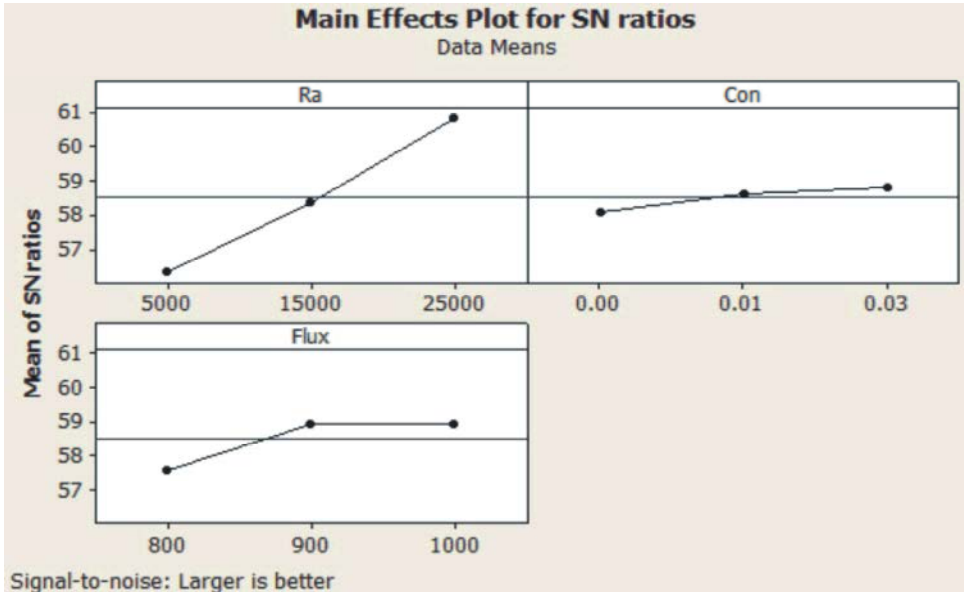

Fig 5: the graphic of mean of S/N ratios versus factor levels (Q)

CONCLUSION

The Taguchi experimental design was used to obtain optimum heat transfer characteristics of solar flat-plate collector. Experiments were conducted by using silver/nana fluid as heat transferring medium. Experiment results were analysed using ANOVA. The obtained results are summarised below.

Three different levels of Reynolds number, nana particle concentration and incident solar radiation, which were performance characteristics of the collector for which L9 orthogonal array was selected by using Taguchi method. As a result nine experiments were conducted with three replicates instead of full factorial. S/N ration were found to find the major influence factors. Larger is the better characteristic was selected. The maximum outlet temperature and maximum efficiency (3 3 1) were found to be 25000 for the Reynolds number, 0.03% for nana particle concentration and 800W/m^2 for the heat flux. But for maximum heat transfer (3 3) were found to be 25000 for the Reynolds number, 0.03% for the nana particle concentration and 1000W/m^2 for the heat flux.

Analysis of variance was applied to obtain S/N ratios to discover interactions between factor relating to outlet temperature, efficiency and heat transfer rate. According to the ANOVA analysis, the nana particle concentration and Reynolds number has an effect on outlet temperature, efficiency and heat transfer rate. Any variance was not observed for heat flux at the reliability level of 95%. In future the interaction between the factors may be obtained using Response Surface Methodology.

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