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Original Article

Comparative Analysis of a Cost-Effective Solar Nano Al_2O_3 Coating Exhibiting Superior Solar Absorption Efficiency over Box-Behnken Design

Markndeyulu Vuggirala[1], N. Alagappan[2], CH V.K.N.S.N. Moorthy[3], N.V. Narasimrao Rao[4]

[1,2,4]*Department of Mechanical Engineering, Annamalai University, Tamil Nadu, India.*
[3]*Vasavi College of Engineering, Ibrahimbagh, Telangana, India.*

[3]*Corresponding Author : krishna.turbo@gmail.com*

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Abstract *- The study focuses on assessing the outcome attributes of solar flat plate collectors employing various preferable surface coatings. These collectors are pivotal in harnessing solar energy, utilizing air or water as the operative mediums. In both residential and commercial settings, flat plate collectors serve multiple purposes, generating heat adequate for warming swimming pools, domestic water, and edifices. They even possess the capability to power cooling systems, especially when sunlight exposure is amplified through reflectors. These collectors can effortlessly achieve temperatures up to 70 degrees Celsius. A newly developed cost-effective solar preferable coating, exhibiting superior solar absorption outcome in contrast to conventional black paint coatings used in typical Solar Water Heating Systems (SWHSs), has been introduced. This membrane involves the integration of metallic particles, predominantly* AL_2O_3*, into black paint, with variations in ratios (1g, 1.5g, and 2g), applied on three distinct flat plate collectors. Throughout this research, efficiency was evaluated for al203 nanocoating and keeping flat plate collectors at varying tilt angles (15°, 30°, and 45°) and diverse flow rates (60, 90, and 120 kg/hr).*

Keywords *- Collector performance, Heat transfer fluid, Optimum angle, Optimum flow rate, Selective surface coatings.*

1. Introduction

The world's energy dilemma appears to have a possible solution in solar energy. Its abundance and capacity to meet the Earth's energy demands are evident. By directly converting solar light into thermal energy, various equipment facilitates this process, mitigating environmental impacts, particularly in the domestic sector. Among these technologies, flat plate collectors stand out for their longstanding service. Serving as the pivotal component in solar energy systems, these collectors absorb radiation and transform it into usable energy to fulfil specific needs.

A variety of collector designs, including concentrating and stationary models like Heliostat Field Collectors, Parabolic Dish Reflectors, Cylindrical Troughs, Compound Parabolic, Evacuated Tube, Flat Plate, and Parabolic Collectors, have been developed to increase efficiency. Liquid flat plate collectors, particularly, find extensive application, serving as preheaters for collectors in oppressive heat industrial processes and residential heating systems. They are widely utilized in water and space heating installations, with coatings being a critical aspect. Traditionally, coatings comprised materials like Al, Cu, Fe, Zn, Cr, etc., but there is a growing shift towards high-performance nano coatings.

In Denmark, the number of plants that are based on solar heating that have been built or are currently being developed has significantly increased [1]. Flat plates frequently have variable volumetric flow rates. The volume flow rate increases with increasing solar irradiance and decreases with decreasing solar irradiance. There is frequently only one volume flow rate utilized when determining a solar collector's efficiency. In actuality, the volume flow rate affects the efficiency of the collector. The best operating plan for a solar collector field can only be determined if the impact on the efficiency of the collector is understood because of the volumetric flow rate.

Discussions were held regarding the assessment of the solar collector outcome test procedure and the impact of volume flow rate on solar collector outcome [2, 3]. Additionally, studies were conducted on the flow patterns in flat plate solar collectors under various circumstances [4, 5]. Additionally, analysis has been done on the effectiveness and performance of flat plates [6].

One crucial step in halting global warming is reducing greenhouse gas emissions. Reducing greenhouse gas emissions is one key step in the fight against global warming. As a result, there is more interest in Photovoltaic (PV) panels now that people are looking for a dependable, long-term, renewable, and ecologically friendly energy source to replace fossil fuels. The PV module selection and placement directly impact system output. It has been discovered that there is an ideal tilt angle for the best absorption of solar radiation for any place on Earth with certain radiation characteristics. The Japan Meteorological Agency has monitored solar radiation at over 60 locations in Japan, and the expanded AMeDAS Weather statistics can provide the computed radiation statistics.

Due to the sun's symmetry in its travel across the sky, the best strategy typically takes the geographical south into account. This claim has been adequately supported by prior research [6–10], While other methods for figuring out the ideal tilt angle have been put forth. Researchers and scientists have employed nanomaterials to enhance engineering qualities across a range of domains, such as solar energy [7, 8]. The unique qualities that nanomaterials exhibit above their parent materials have led scientists to utilise them for a wide range of technical applications. Because atom materials have different properties from bulk materials, the applications of nanotechnology have increased dramatically. With the use of thin-film technology, surface characteristics, including the absorption of solar radiation by mineral materials, have lately been enhanced. The biggest difficulty facing materials research today is using a nano description of the coats (1–100 nm), regardless of whether the coating thickness or structure is characterised in nanometers. The extraordinary properties and capacities of nanocoatings are a result of the quantum size effect.

2. Literature

The sun is the primary source of energy for most terrestrial sources. The sun produces 1.8 x1015 TW of energy or more than 99.9% of all energy sent to Earth today. The energy from the sun's radiation that reaches Earth each day is 100,000 times more than the total energy generated by all of the world's power plants combined. Because of this, there will never be a worldwide energy crisis because of the sun, and solar energy can power 20,000 times as many people as we do now. This quantity appears to be a great way to meet human requirements, especially since its use does not pollute the ecosystem or do harm to the environment [9-11].

Results on solution-derived NiO-Al_2O_3 coatings applied to solar absorbers for thermal absorption were published by Bostrom et al. (2007). A nickel concentration of 65%, a thickness of 0.1 m, and a particle size of 10 nm were found to be the ideal coating parameters. The absorbent layer reached a normal thermal conductance of 0.03 and a normal solar absorbance, sol, of 0.83. The absorber's performance was further improved by covering the initial absorbing layer with an anti-reflection layer. The sample with the best antireflection coating achieved a thermal emitance of 0.04 and a solar absorptance of 0.93 [12–19]. Sol-gel process was utilized to prepare matrices of carbon nanoparticles dispersed with NiO, ZnO and SiO_2 to study the functionality of solar selective absorbers, Katumba et al. (2008) [14]. Aluminium substrates were used for testing the coatings. FTIR, UV, and VIS [14].

3. Experimental Procedure

Figure 1 displays the tank under consideration, the schematic diagram of the solar flat collector, and the positions of the thermocouples. The flat plate collector is positioned next to a 100 litre tank, facing north-south. The experiment portion consists of a 2.0 m2 flat plate collector with nine riser tubes with an outer diameter of 1.27 cm, each measuring 6 feet in length and 1.2 cm in wall thickness. The tubes are composed of copper. These riser tubes are made of 0.20 mm-thick copper heat-collecting surfaces. By attaching thermocouples to riser pipes alternately, the wall temperature distribution of the collecting plate riser pipe was measured. Furthermore, the thermos couplings at the entrance and exit were fixed, with thermos couples at the intake and outlet were measured. With assistance, the water flow from the tank is regulated with a nob.

3.1. Box-Behnken Design

For the response surface approach, the Box-Behnken design works well because it allows for the following tasks:

- Estimating the quadratic model's parameters.
- Creating sequential designs.
- Identifying instances where the model does not suit the data.
- Usingblocks.

Doehlert matrix, Box-Behnken, and 3-level full factorial are the response surface designs that are compared with each other. The results show that the Doehlert matrix and Box-Behnken design are notably more ideal than the 3-level full factorial. However, the efficiency, when compared with the central composite method of design, is only marginal.

3.2. Specification of Flat Plate Collector

- Flat plate collector area = 1.8 m^2
- Two glass covers of 4 mm thickness are provided with pads. The absorber is of the tube and sheet type.
- Number of tubes = 9Tubes dimensions
- Outer diameter = 10mm
- Wall thickness = 1 mm
- Long = 2m (9 tubes of 10 mm ODI mm wall thickness and 2 m long are equipped, and 75 mm width corrugated black painted fins are embedded over the tube).
- The bottom and top headers' outer diameter = 25 mm.

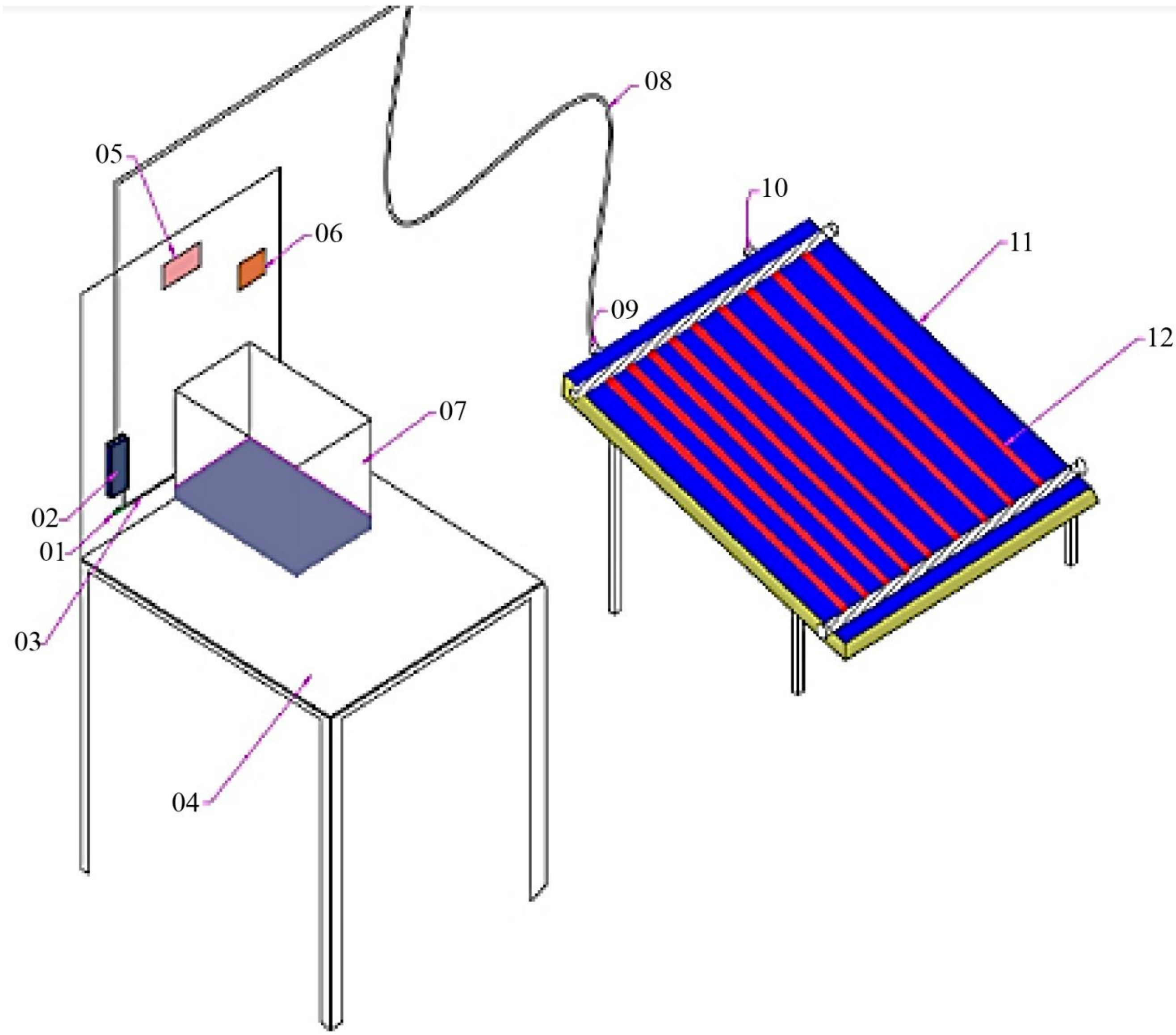

Fig. 1 Experimental setup
(1) External motor, (2) Rotameter, (3) Pipe, (4) Table, (5) Digital temperature indicator, (6) Thermocouple nob, (7) Water tank, (8) Water pipe connected to the collector, (9) Inlet value, (10) Out value, (11) Absorber plates, and (12) Copper tubes.

- Black paint is used as the coating on the absorber.
- 50 mm thick mineral wool insulation is used below the absorber and around the edges.

The collector was tested with a preferable coating of commercial black paint coated with a mixing of Al_2O_3 at different ratios (1%,1.5%and 2%) on the absorber plate and keeping the collector at different tilt angles (30^0,45^0 and 60^0. The collector utilized in this project is 1 x 1.2 m in size, with a copper thickness of 2 mm. It has nine copper tubes evenly distributed on it, each measuring 10 mm on the outside and 9 mm on the inside. The input and outlet headers, which have a diameter of 60 mm, were tested under various solar radiation conditions and collector tilts. Water is the working ingredient, and various flow rates were tested with it as different ratios of Al_2o_3 coating on three collectors and different tilt angles. Thermos couples were placed at different positions in the experimental setup.

The collector used in this project has a copper thickness of 2 mm and measures 1 x 1.2 m. Nine copper tubes, each measuring 10 mm on the outside and 9 mm on the interior, are evenly spaced throughout it.

The 60 mm-diameter input and output headers were tested in a range of solar radiation scenarios and collector tilts. The working ingredient is water, and several flow rates were tested using it.

3.3. Collectors with Nanocoating

Collector C1 coated with 1g of Al_2O_3 in commercial black paint.	Collector C2 coated with 1.5g of Al_2O_3 in commercial black paint.	Collector C3 coated with 2g of Al_2O_3 in commercial black paint.

Fig. 2 Collectors coated with nano particulars with different ratios

3.4. Data Reduction

The ratio between heat output and input determines thermal efficiency. The FPC's thermal efficiency (η%) is calculated using,

1. Heat gain by the working fluid or useful energy:

   $Q_c = m_c C_{pc} (\Delta T)$ watts

   m_c = Mass flow of cold fluid kg/s

   C_{pc} = Specific heat of cold fluid = 4186.8 j/kg-k.

2. Heat Energy absorbed by Collector:

   $Q_a = I \times A$ watts

   I = Intensity of solar radiation in w/m^2

   average solar power in India is 5kw.

   but I = 5 cos α (α= angle of tilt)

   FPC Surface Area of Collector = 0.1×2=0.2 m^2

   Total collector area (A) = Surface area x number of tubes (n) A = 0.2 × 9 =1.8 m^2

3. Efficiency of the unit:

   $$(\eta\%) = \frac{Qc}{Qa} \times 100$$

3.5. Expected Outcomes

Al_2O_3 nanoparticles should be combined with commercial black paint, applied to an absorber plate, and chosen for experiments that will lead to Improvements in the collector's performance could be revealed by both theoretical and experimental investigation.

- Nanoparticle utilization is done, expecting an increase in the absorbance capacity.
- Nano coatings will have a beneficial effect on the absorber's emissivity and absorptivity.

It is anticipated that the working fluid in the collector with the metallic coatings may warm up more at the output.

3.6. Process Parameters and their Levels

Table 1. Process parameters

Parameters	Levels		
	-1	**0**	**1**
Flow rate(kg/hr)	60	90	120
Angle (degrees)	15	30	45
Concentration (grams)	1	1.5	2

3.7. Design of Matrix

The Design of Experts (DOE) is a useful tool for organizing experiments and efficiently analyzing the collected data. The choice of the variables for the input and the corresponding output response that will be measured is the first step in the experimental task. As shown in Table 2, BBD produced 17 simulation runs grouped by three criteria for FPC coated with Al_2o_3 on the absorber plate. The DOE software 13.0 is utilized for the analysis in this work. First, the water mass flow rate is fixed using a rotameter and enters the collector through an inlet. The water passes through risers and comes out through the outlet. Meanwhile, water absorbs heat to absorb the plate, keeping the collector at different inclination angles at a fixed flow rate. Every trial's temperature is noted. Experiment planning and data analysis can be made more efficient with the use of Design of Experts (DOE). Starting with the selection of the response (output) to be assessed and the input factors, the experiment begins. As shown in Table 2, BBD produced 17 simulation runs for copper-absorbed plates with hybrid nanocoating that were grouped by three criteria.

Table 2. Design of matrix

		Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3
Std	**Run**	**A: Flow Rate**	**B: Angle**	**C: Concentration**	**Efficiency**	**Qa**	**Qc**
		kg/hr	**degrees**	**Gram**	**%**	**Kw**	**Kw**
6	**1**	120	30	1	39.25	7.79418	3.05913
4	**2**	120	45	1.5	52.65	6.3639	3.35048
5	**3**	60	30	1	26.04	7.79418	2.02947
12	**4**	90	45	2	46.13	6.3639	2.93549
9	**5**	90	15	1	25.01	8.6931	2.17444
14	**6**	90	30	1.5	36.27	7.79418	2.82677
10	**7**	90	45	1	35.88	6.3639	2.28316
7	**8**	60	30	2	39.06	7.79418	3.04421
3	**9**	60	45	1.5	31.89	6.3639	2.02947
13	**10**	90	30	1.5	36.27	7.79418	2.82677
16	**11**	90	30	1.5	36.27	7.79418	2.82677
11	**12**	90	15	2	31.27	8.6931	2.71805
15	**13**	90	30	1.5	36.27	7.79418	2.82677
1	**14**	60	15	1.5	24.18	8.6931	2.10195
17	**15**	90	30	1.5	36.27	7.79418	2.82677
8	**16**	120	30	2	52.33	7.79418	4.07884
2	**17**	120	15	1.5	38.54	8.6931	3.35048

4. Results and Discussions: ANOVA for Quadratic Model

4.1. Response 1: Efficiency (η%)

Transform: Square Root

Table 3. Response 1: Efficiency table using ANOVA

Source	Model	A-Flow Rate	B-Angle	C-Conctrn.	AB	AC	BC	A^2	B^2	C^2	Residual	Lack of Fit	Pure Error	Cor Total
Sum of Squares	7.01	3.18	1.97	1.54	0.0253	0.0079	0.0111	0.1318	0.1556	0.0008	0.1574	0.1574	0	7.16
Df	9	1	1	1	1	1	1	1	1	1	7	3	4	16
Mean Square	0.7785	3.18	1.97	1.54	0.0253	0.0079	0.0111	0.1318	0.1556	0.0008	0.0225	0.0525	0	
F-value	34.62	141.51	87.46	68.43	1.13	0.3518	0.4947	5.86	6.92	0.0342				
p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.324	0.5718	0.5046	0.046	0.0339	0.8585				

The model is highly significant with a p-value < 0.0001, indicating that it explains a significant portion of the variance in the data. Flow Rate (A), Angle (B), and Concentration (C) are all highly significant with very low p-values (< 0.0001), indicating strong effects on the response variable. Interaction terms (AB, AC, BC) are not significant, suggesting that the combined effects of these factors are not important. Quadratic terms show some significance, particularly for B^2 and A^2, indicating non-linear effects. The residual MS is 0.0225, and the lack of fit MS is 0.0525, indicating that there is some lack of fit in the model, but it is not substantial. The model fits the data well, with the significant factors explaining a substantial amount of the variation. The non-significant interaction terms and quadratic terms (other than B^2 and A^2) suggest that the primary factors are linear and do not interact significantly with each other.

In summary, the ANOVA table indicates that the model is robust and the primary factors (flow rate, angle, and concentration) significantly impact the response. The non-significant interaction terms suggest that these factors operate independently.

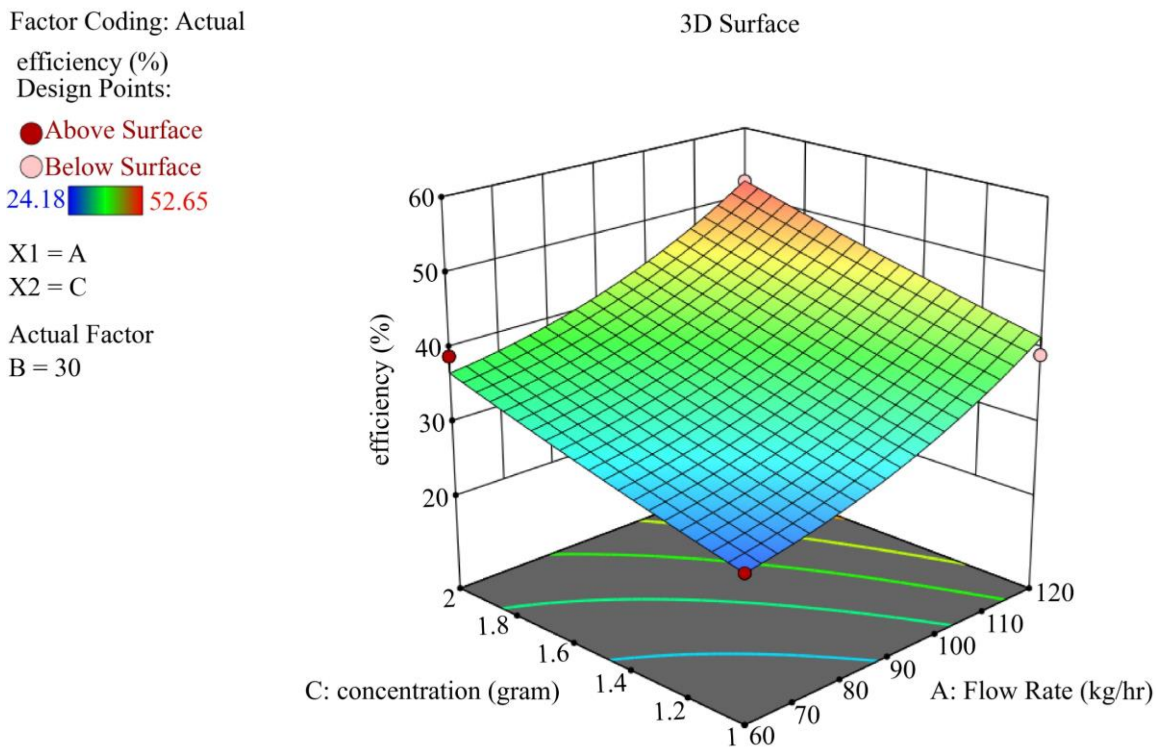

Fig. 3 Efficiency variation with respect to concentration and flow rate (Response 1)

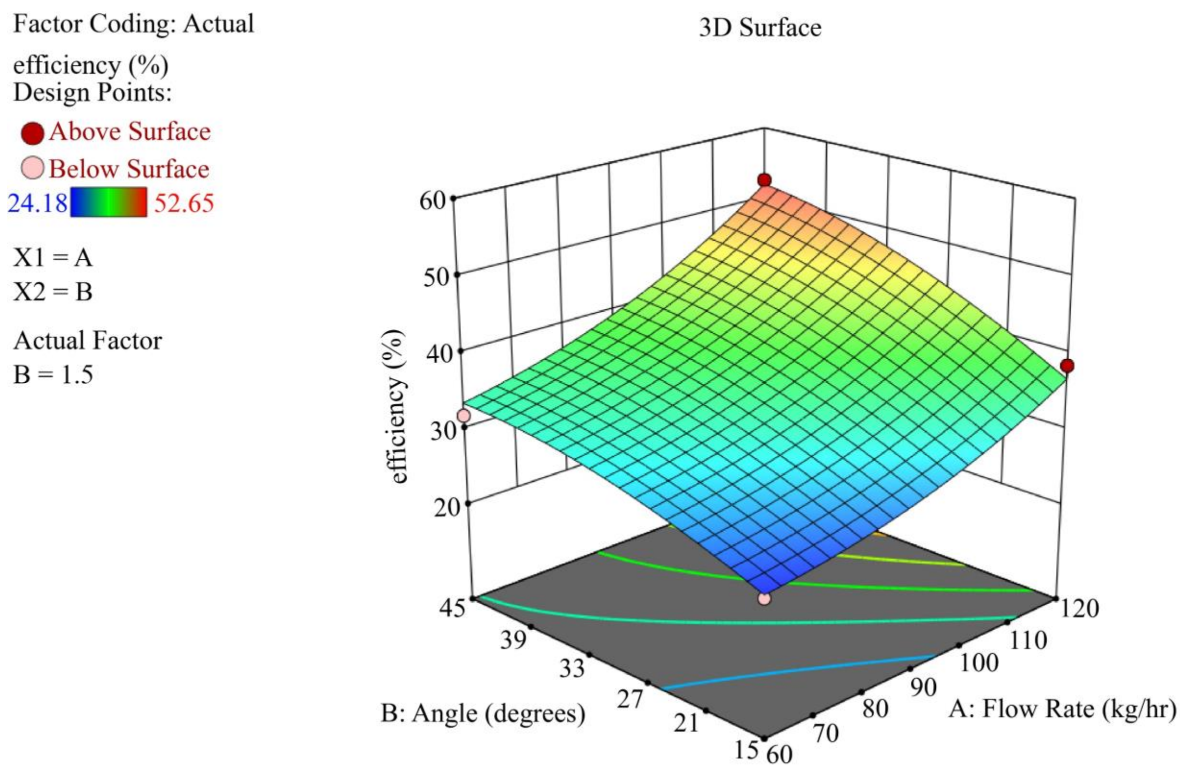

Fig. 4 Efficiency variation with respect to flow rate and angle (Response 1)

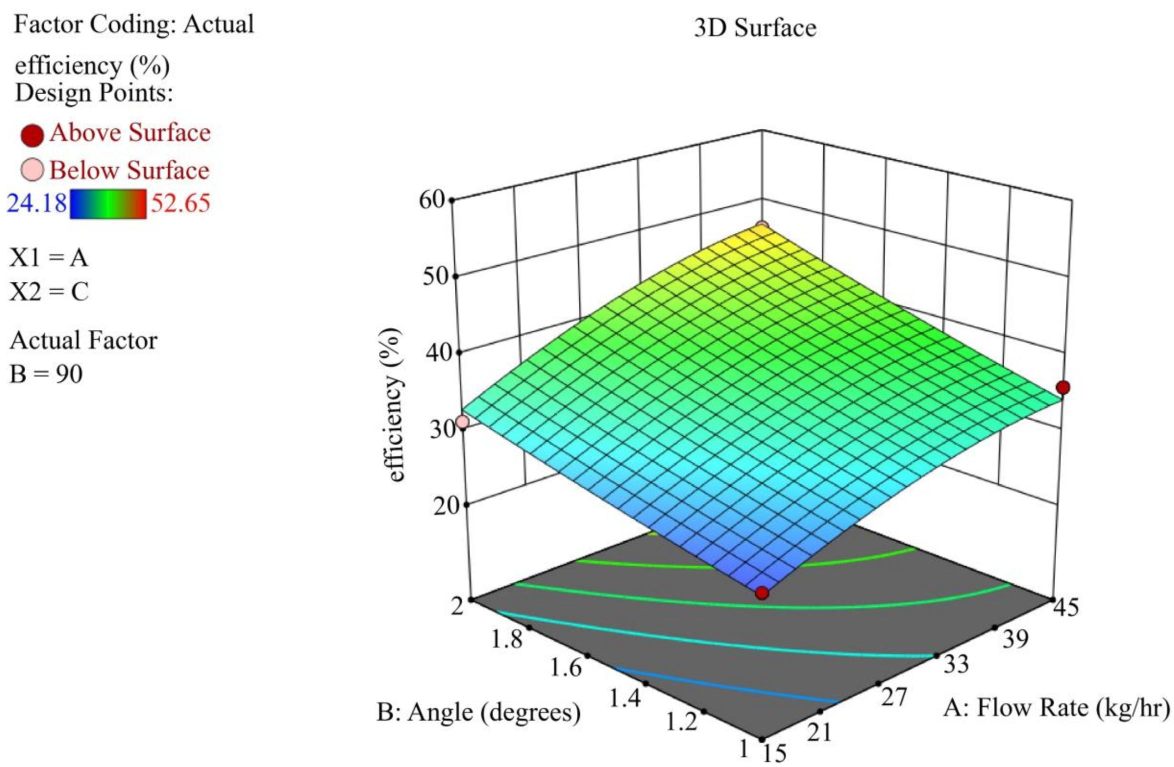

Fig. 5 Efficiency variation with respect to angle and concentration (Response 1)

It is evident from the previous figures that efficiency rises steadily as there is an increase in the flow rate and the angle of inclination. Efficiency gradually increases at a concentration coating of 1.5% due to the linear influence of the inclination angle. In comparison to the angle, the flow rate had a more linear effect on efficiency. There is more to the effect of interaction than just the flow rate and angle acting linearly. At high angles and flow rates, efficiency is at its peak. When compared, the effect of angle is minimum.

4.2. Response 2: Heat Energy Absorbed by the Collector (Qa)- ANOVA for Quadratic Model

Transform: Square Root

The model explains the total sum of squares (0.3759) with degrees of freedom 9. Since the residual SS is 0, the model fits the data perfectly, which suggests a perfectly fitting model with data. The only significant factor is Concentration (C) with a sum of squares of 0.3625, suggesting it has a substantial effect on the response.

Residual and Lack of Fit, both are 0, indicating no residual error and no lack of fit. This typically implies that the model predictions perfectly match the observed data points, which can be ideal.

The total degrees of freedom (16) are correctly partitioned among the different sources. The residual degrees of freedom being 1 indicates limited data points beyond those used to fit the model.

In summary, the model seems to perfectly explain the variation in the data with the Concentration (C) being the only significant factor.

Table 4. ANOVA table for heat energy absorbed by the collector (Qa Response 2)

Source	Model	A-Flow Rate	B-Angle	C-conc.,	AB	AC	BC	A^2	B^2	C^2	Residual	Lack of Fit	Pure Error	Cor Total
Sum of Squares	0.3759	0	0.3625	0	0	0	0	0	0.0133	0	0	0	0	0.3759
df	9	1	1	1	1	1	1	1	1	1	7	3	4	16
Mean Square	0.0418	0	0.3625	0	0	0	0	0	0.0133	0	0	0	0	

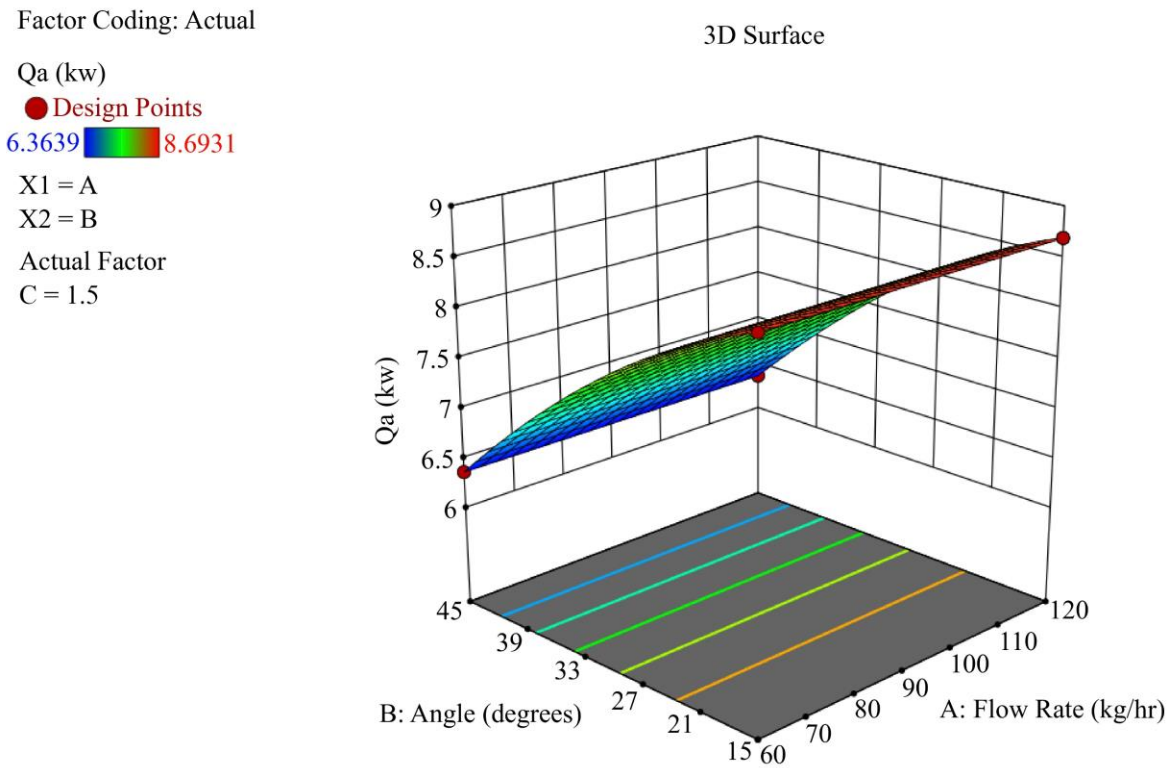

Fig. 6 Efficiency variation with respect to flowrate and angle (Response 2)

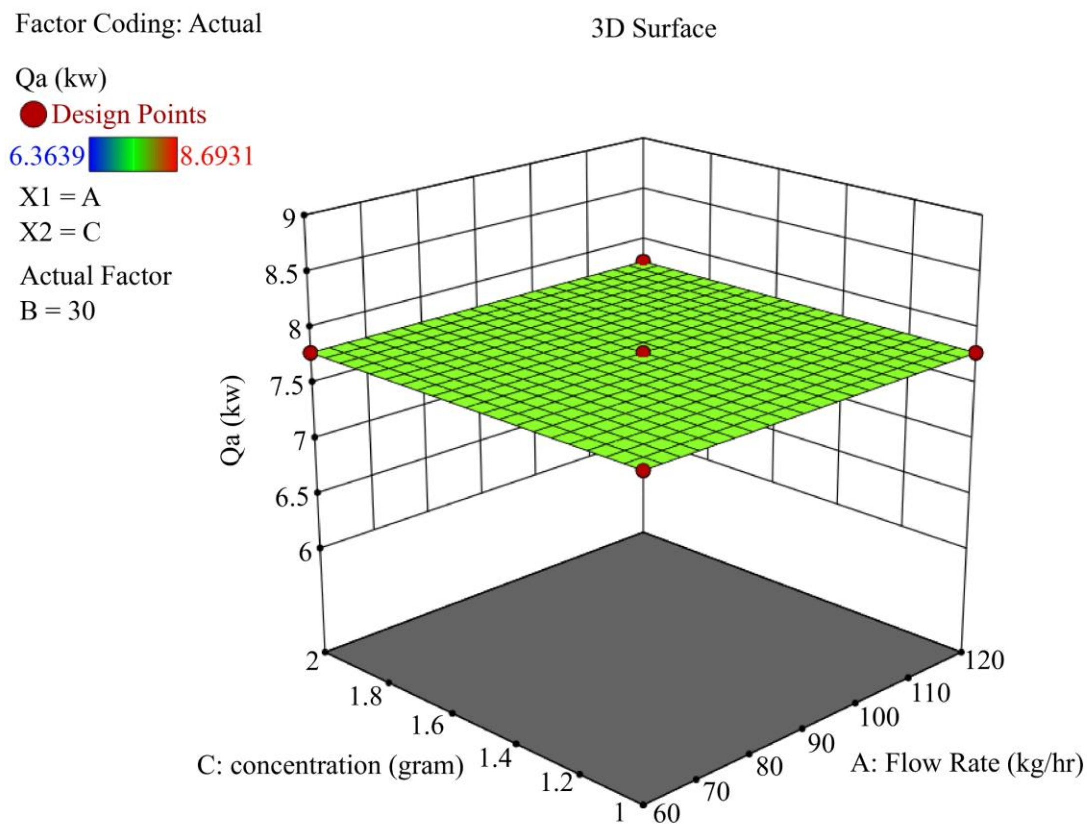

Fig. 7 Efficiency variation with respect to flowrate and concentration (Response 2)

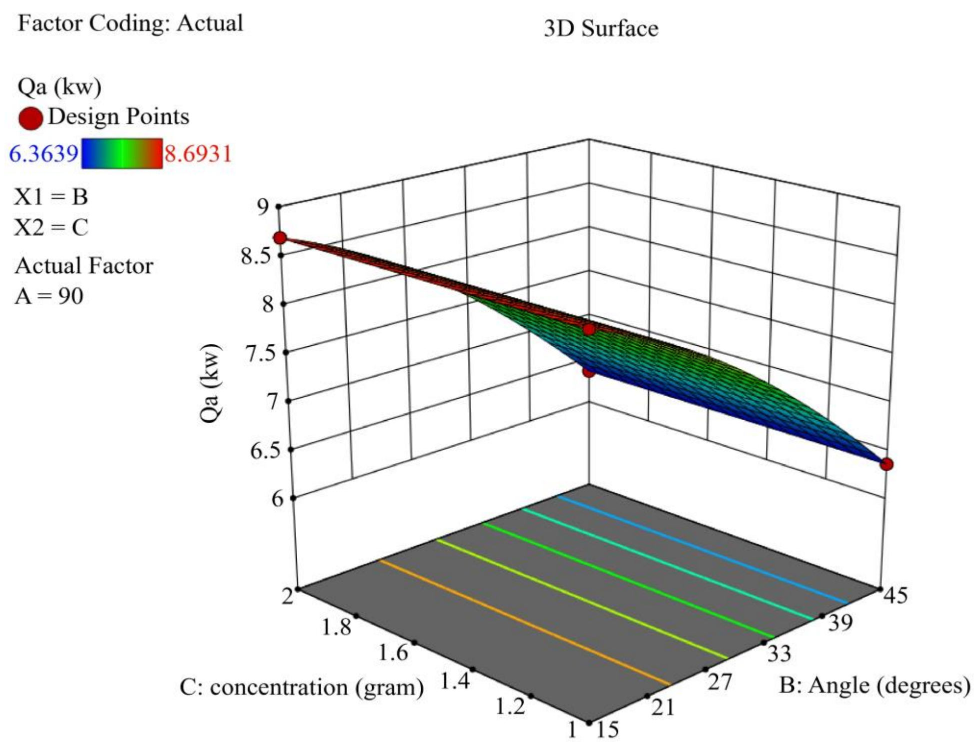

Fig. 8 Efficiency with respect to concentration and angle (Response 2)

4.3. Response 3: Heat Gain by the Cold Fluid or Useful Energy (Qc)- ANOVA for Quadratic Model

Transform: Square Root

The model is highly significant with a p-value < 0.0001, indicating that it explains a significant portion of the variance in the data. Flow Rate (A) and Concentration (C) are highly significant with very low p-values (< 0.0001), indicating strong effects on the response variable. Angle (B) is not significant, with a p-value of 0.5396. Interaction terms (AB, AC, BC) are not significant, suggesting that the combined effects of these factors are not important. Quadratic term B^2 is significant (p-value 0.0019), indicating a non-linear effect. The quadratic term A^2 is significant (p-value 0.0429) but to a lesser extent. Quadratic term C^2 is not significant.

The residual MS is 0.0017, and the lack of fit MS is 0.004, indicating some lack of fit in the model, but it is not substantial. The model fits the data well, with the significant factors explaining a substantial amount of the variation. The non-significant interaction terms and quadratic term C^2 suggest that these factors operate independently.

In summary, the ANOVA table indicates that the model is robust and the primary factors (Flow Rate and Concentration) significantly impact the response. The non-significant interaction terms and Angle (B) suggest that these factors do not have significant combined effects. The quadratic terms B^2 and A^2 indicate non-linear effects. Overall, the model explains the data well.

Table 5. ANOVA table for heat gain by the cold fluid or useful energy (Qc) (Response 3)

Source	**Model**	**A-Flow Rate**	**B-Angle**	**C-conc.,**	**AB**	**AC**	**BC**	**A^2**	**B^2**	**C^2**	**Residual**	**Lack of Fit**
Sum of Squares	0.4072	0.24	0.0007	0.1169	0.0002	0.0006	0.0002	0.0106	0.0401	0	0.0121	0.0121
df	9	1	1	1	1	1	1	1	1	1	7	3
Mean Square	0.0452	0.24	0.0007	0.1169	0.0002	0.0006	0.0002	0.0106	0.0401	0	0.0017	0.004
F-value	26.14	138.66	0.4157	67.54	0.0918	0.3552	0.1153	6.1	23.14	0.024		
p-value	0.0001	< 0.0001	0.5396	< 0.0001	0.7707	0.57	0.7441	0.0429	0.0019	0.8813		
	significant											

The efficiency progressively rises as the inclination angle and flow rate increase, as can be seen in the above table. Efficiency gradually increases at a concentration coating of 1.5% due to the linear influence of the inclination angle. In comparison to the angle, the flow rate had a more linear effect on efficiency. More than just the angle and flow rate, linear effects are present in the interaction effect. The highest efficiency is achieved at high angles and flow rates. Compared to the flow rate, an angle's linear influence is minimal.

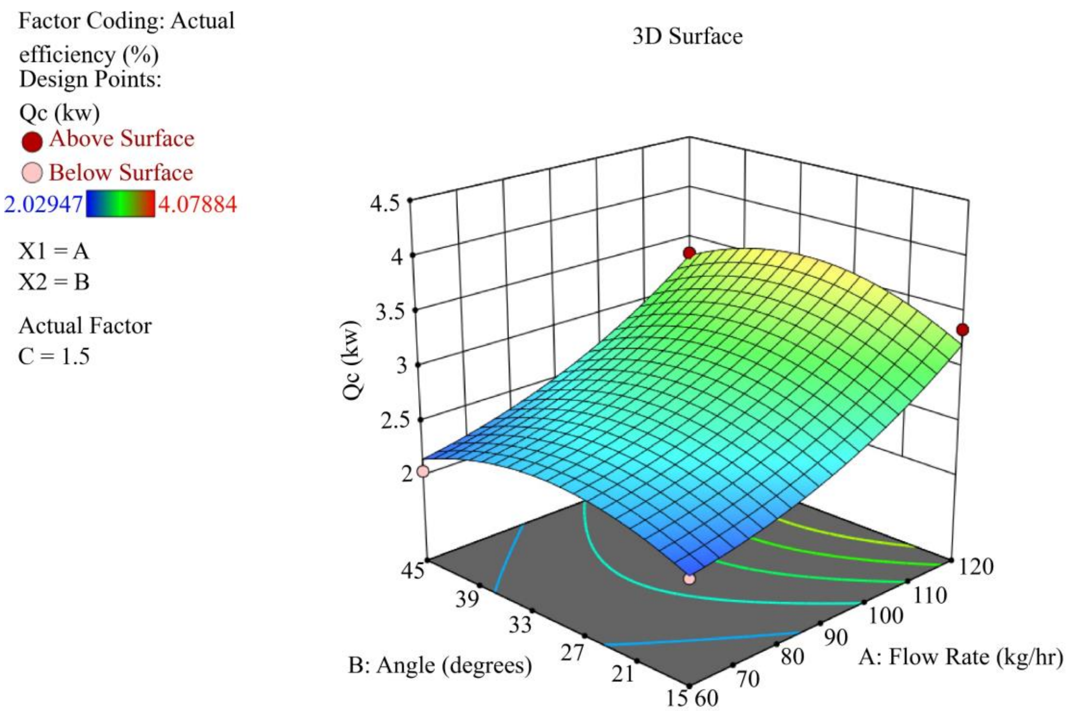

Fig. 9 Efficiency variation with respect to angle and flow rate (Response 3)

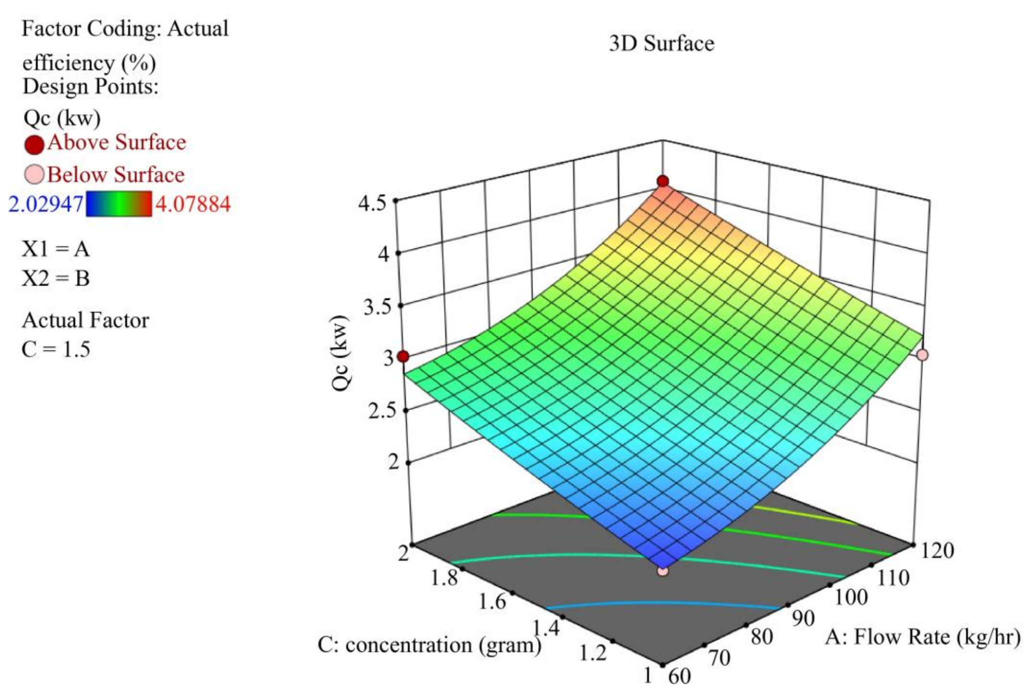

Fig. 10 Efficiency variation with respect to flowrate and concentration (Response 3)

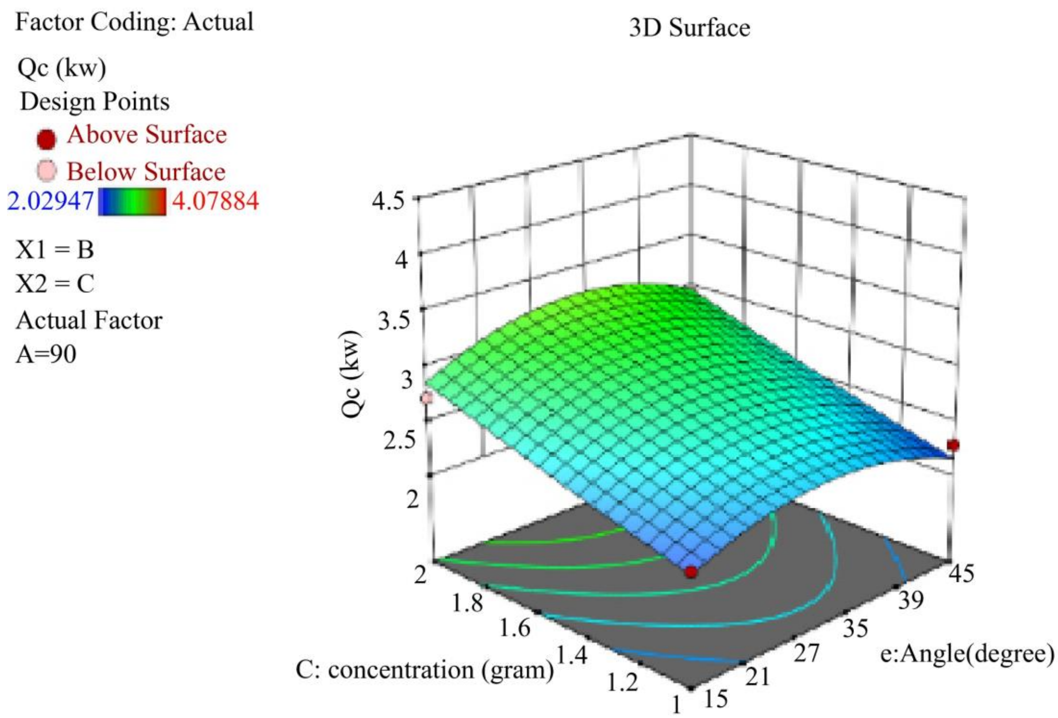

Fig. 11 Efficiency variation with respect to concentration and angle (Response 3)

Table 6. Factors

Factor	A	B	C
Name	Flow Rate	Angle	concentration
Level	90	30	1.5
Low Level	60	15	1
High Level	120	45	2
Std. Dev.	0	0	0
Coding	Actual	Actual	Actual

Table 7. Point prediction

Analysis	Efficiency	Qa	Qc
Predicted Mean	36.2925	7.79418	2.8285
Predicted Median*	36.27	7.79418	2.82677
Std Dev	1.8066	0	0.139929
SE Mean	N/A	N/A	N/A
95% CI low for the Mean	34.4075	7.79418	2.68248
95% CI high for the Mean	38.2278	7.79418	2.97839
95% TI low for 99% Pop	27.0523	7.79418	2.11249
95% TI high for 99% Pop	46.8367	7.79418	3.64488

4.4. Confirmation

Table 8. Efficiency table utilizing ANOVA (response 1)

Analysis	Efficiency	Qa	Qc
Predicted Mean	36.2925	7.79418	2.8285
Predicted Median*	36.27	7.79418	2.82677
Std Dev	1.8066	0	0.139929
n	1	1	1
SE Pred	N/A	N/A	N/A
95% PI low	31.742	7.79418	2.47598
95% PI high	41.0998	7.79418	3.20079

4.5. Comparison Table

Comparing experimental results with optimized value.

Table 9. Comparison table

	Parameters	Experiment Value	RSM Optimised Value
Optimized Operating Parameters	Flow Rate	**90**	**90**
	Angle	**30**	**30**
	Concentration	**1.5**	**1.5**
	Efficiency	**36.27**	**36.29**

5. Conclusion

This work proposes to use various nano-coating techniques to improve absorptivity and reduce emissivity when applied on liquid flat plate absorbers related to solar water collectors. It is a novel and cutting-edge approach in the field of solar systems that can be readily implemented at a reasonable cost. Potential research results are discussed, along with the setup requirements for the experiment and the coating techniques for the nanomaterials. Using these Nano coatings may, overall, greatly increase the effectiveness of the solar collector, according to the research done. To assess the heat increase of copper absorbers employing nano-coating of Al_2o_3, experiments are carried out using BBD and assessed using Design of Experiments (DOE) software.

Comparing the SWHS to regular black paint from the store, it is evident that the new coating, which contains Al_2o_3 particles, collects thermal energy more effectively. The above results were compared with experimental and RSM. Hence, the deviation is 0.2%.

Nomenclature

ID - Inner Diameter
RSM - Response Surface Methodology
BBD - Box-Behnken Design
Cu - Copper
OD - Outer Diameter
DOE - Design of Experiments
FPC - Flat Plate Collector

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