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Statistical analysis of the vacuum solar collector using the analysis of variance method

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ABSTRACT

Space and weight constraints, as well as the time lag between energy generation and consumption, are major obstacles to expanding solar water heating systems into existing structures with limited space. Collecting heat with this small, evacuated tube collector (ETC) is possible. It was found that the air inside the glass tube has poor thermal conductivity. An experimental and numerical study was performed on an evacuated tube solar collector, incorporating a heat tube with cylindrical fins to increase the contact surface between the air and the fin surface. Statistical analysis software is used to verify the results in practice. The temperature data was investigated using SPSS under the same flow conditions. These figures are from experiments examining the effect of variable volumetric flow rate, boost type, and variance analysis on temperature distribution. When analyzing the results of the trials, a significant threshold of 95% was used. Therefore, we compare the calculated significance to a value of 0.05 to evaluate the efficacy and capabilities of the components. The reliability and validity of the model depend on the presence of two components. If the resulting value is less than the significance level (0.05), then the model can be considered robust and efficient (flow rate and optimization type). If the estimated value is greater than that, the variables do not affect system performance. Flow rate and type of enhancement are the two factors considered in the analysis of variance.

1. Introduction

The need for energy is rising daily as technology and living standards improve. The high domestic use of diamonds and fossil fuels has necessitated the development of technology for an unlimited source of energy, or renewable energy [1]. Solar energy is the primary source of unlimited clean energy and has the potential to meet global energy requirements without endangering the environment [2]. Solar collectors come in various forms, such as flat panels, dish collectors, parabolic troughs, evacuated tubes, and so on. Evacuated tube collectors (ETC) are gaining popularity worldwide due to their superior thermal efficiency and operating temperature when compared to flat plate solar collectors. The vacuum between the absorber and the ETC cap greatly improves the efficiency of the ETC. This is mainly because convection and conduction limit heat loss. The high rate of energy absorption enhances instantaneous efficiency values. ETC has been observed to be much more efficient than conventional flat plate collectors (FPC), especially at lower temperatures [3]. Solar energy may be collected in two ways: directly using photovoltaic panels, which convert solar energy to electrical energy, and indirectly using solar thermal systems such as solar chimneys, solar collectors, and solar towers. Solar collectors are widely utilized in various applications because of their simple design, ease of installation, and low maintenance [4]. Several studies have been conducted to analyze and improve the performance of solar collectors.

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Nomenclature:

ANOVA	Analysis of Variance	*MS*	Mean Square
df	Degrees of Freedom	*PCTSL*	Thermal storage layer
ETC	Evacuated tube collectors	*SPSS*	Standard
F	F-value	*SS*	Stokes Number
F-critical	Critical statistics F	*Std*	Sum of Squares
FPC	Flat plate collectors	*ste*	Statistical Package for the Social Sciences
HP	Heat pipe	*TU1*	Red copper
HTC	Heat Transfer Coefficient		

Mirzaei (2021) [6] used ANOVA statistical analysis for a solar air heater; Abokersh et al. (2017) [7] presented a summary analysis of variance (ANOVA) for three regimens: A, B, and C. All significant factors were added to the regression models based on a standard P-value of less than 0.05 (Chen & Yang, 2022) [8]. Other studies focused on improving heat transfer and thermal performance. Ghoneim (2017) [9] expressed the temperature variation along the length of the fin. Abd-Elhady et al. (2018) [10] studied the effect of fins, oil minerals, and foam on the performance of heat pipe evacuated tubes. Supankanok et al. (2021) [11] improved heat transfer from the aluminum fin to the copper heat pipe by modifying the internal construction of the evacuated tube. Zakaria et al. (2022) [12] studied the influence of various factors, such as air contact with the surface area of the internal absorber. Shi et al. (2019) [13] performed an analysis of fin structure parameters (fin thickness and fin spacing) in an evacuated tube with phase change material. Wang et al. (2020) [14] used a thermal storage layer (PCTSL) and annular fins to improve the thermal performance of solar collectors. Dhaou et al., 2021 [15] discussed enhancing the thermal efficiency of a solar collector by using fine with two kinds of metal forms (copper and nickel). The purpose of this study is to determine the strength and effectiveness of two factors (volume flow rate and type of improvement) in increasing the thermal performance of a solar collector using the statistical analysis program ANOVA.

2. Experimental work

2.1. Evacuated tube-solar collector with heat pipe

The experimental research used a solar tube collector consisting of 10 individual evacuated tubes, each measuring 58 cm in length and 84 cm in width. Two borosilicate glass tubes are inside each, with a vacuum between them to retain heat. As can be seen from Figure 1, the outer diameter of the evacuated glass tube is 58 mm, and the length is 0.5 m.

The vacuum tube houses a copper heat pipe that is sealed off from the outside air. The collector's performance will improve because of this.

The evaporation portion will degas the tube and fill it with water and additives to prevent oxidation and corrosion, bringing the fill level to 50%. Any liquid may be drained away thanks to the tube's hollow design. At the same pressure, the inside of the evaporative heat pipe is cooler than that of the standard pipe. When sunlight strikes the heat pipe (HP) outer glass tube and inner absorption tube, the vacuum within the HP rapidly converts the liquid inside into a superheated vapor. The heated gas will climb to the top of the heat tube, where it will condense since it is lighter than the liquid.

The "manifold," mainly made of copper and known as the exchange thermocouple, connects the heat pipe's upper end to the evacuated tube. When the hot steam from within the heat pipe's obstructed tube reaches the heat exchange manifold, it transfers its thermal energy to the water that is flowing through the manifold. The vapor loses heat and condenses as the temperature rises, sinking to the bottom of the HP to be re-evaporated and re-circulated. Vacuum tube performance is measured using heat pipes constructed of TU1 red copper and filled with water.

2.2. Experimental setup

The experimental setup was designed to assess the effectiveness of an evacuated tube solar heat collector (ETHSC). An electric pump, heat tank, flow meter, and tubes with valves are just a few of the many parts that make up the experimental setup. The instruments and scales used in the experiments are shown in Figure 2. Four cases were used in the tests: a) heat pipe only with no fin, b) aluminum fin, c) copper fin, and d) perforated fin (Figure 3). The experimental investigation was conducted at a location 33° south of Baghdad, Iraq, corresponding to longitude 44.4803984 and latitude 33.3168805. The testing period spanned from December 2022 to February 2023, and tests were initiated at 10:00 AM on days with favorable weather conditions. The flow rate was adjusted to 0.5, 1.0, and 1.5 liters per minute using the valve control unit, and the system was operational until sunset. From sunrise until sunset, temperature and radiation intensity measurements were recorded at 10- and 30-minute intervals, respectively. Once the temperature difference reached a negligible value, the process was repeated for all test cases.

2.3. Analysis of data using statistical package for the social sciences

Analysis of variance (ANOVA) in the SPSS software is a series of statistical models and associated estimate procedures (such as "variation" between groups) used to analyze the variation between group means in a sample. It was created by the statistician Ronald Fisher. ANOVA is based on the total variance law, which divides the observed difference in a particular variable into components due to multiple causes of variation. In its most basic form, ANOVA provides a statistical test to determine if two or more population means are equal, thereby expanding the scope of the *t*-test beyond two means. The temperature values obtained from these tests may be used to investigate specimen variation and major treatment and factor influences [16]. Two-way analysis of variance (SPSS) can be used for these concerns.

Figure 1. A photograph showing the ten evacuated tubes used in the solar collector

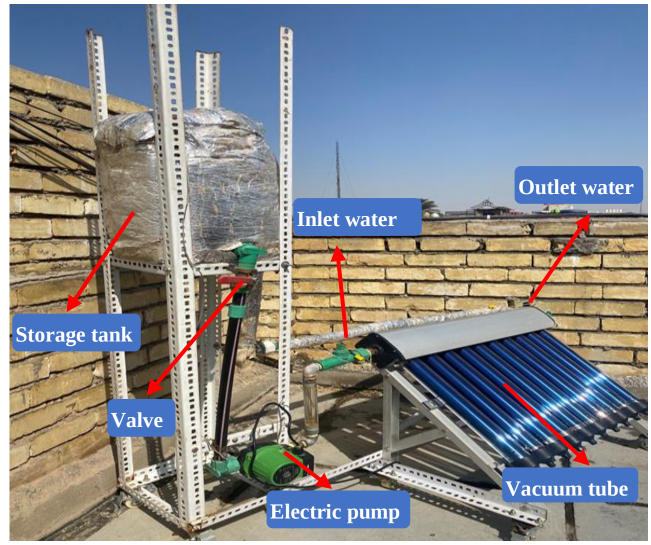

Figure 2. A photograph showing the basic components of the experimental setup

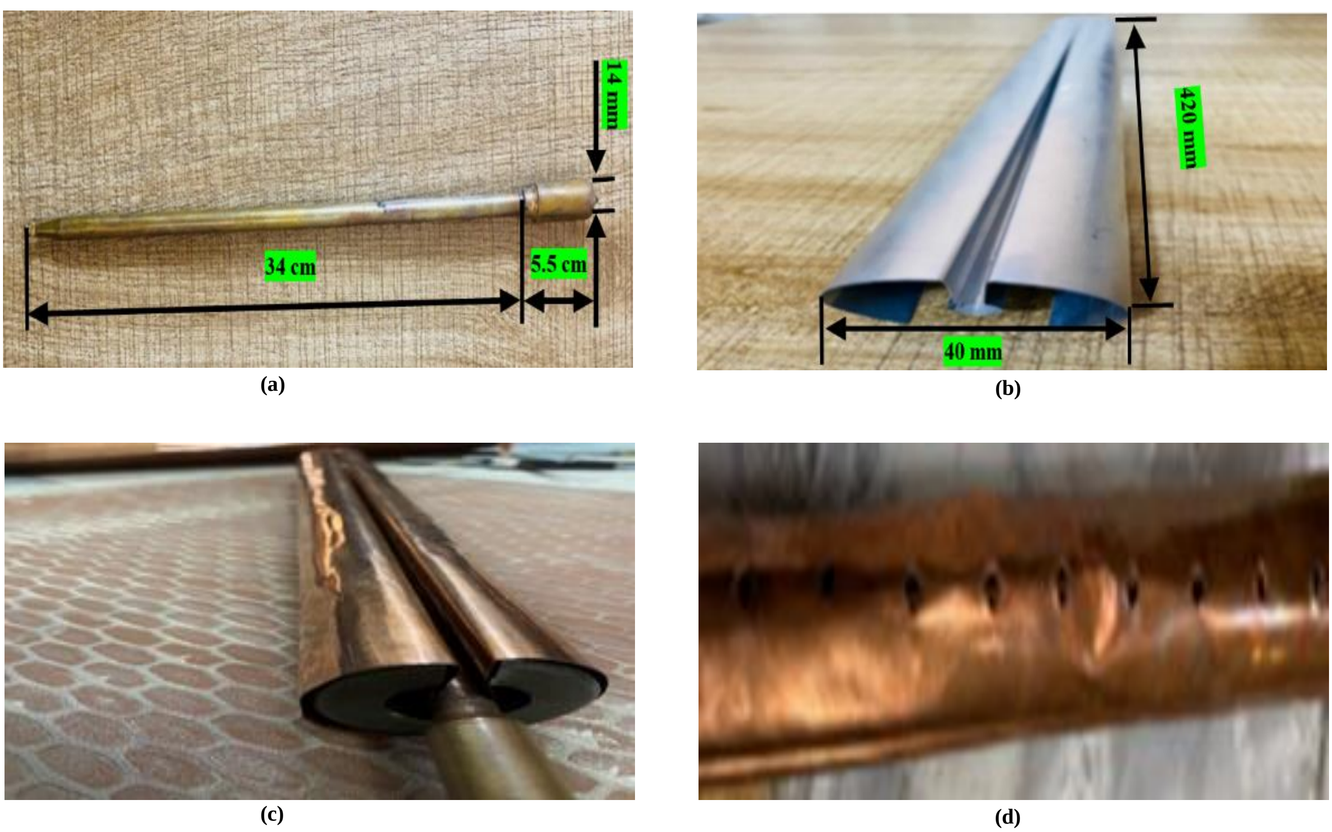

Figure 3. Photographs of experimental tests: (a) heat pipe only, without fin; (b) heat pipe with aluminum fin; (c) heat pipe with copper fin; (d) heat pipe with perforated fin.

2.4. The two-way analysis of variance

The two-way analysis of variance is an expansion of the one-way analysis of variance, and its name derives from the use of two independent variables.

The assumption of the two-way analysis

- The populations from which samples are drawn must be normally distributed or nearly normally distributed.
- Samples have to be independent.
- The variances of the populations must be equal.
- The groups must have the same sample size [17].

Advantage two-ways ANOVA

*The samples must be indecent. Exploring two variables (A and B) concurrently is more efficient than doing so separately.
*Interactions between variables can be investigated (complex relationships can also be investigated).
There are four causes of change in a two-way ANOVA (AB design):

1. Variables cause changes (A)
2. Variables cause changes (B)
3. Modifications because of the interaction effect of (A and B).
4. Changes within the cell (error)

Table 1 shows the two-way ANOVA rules, while Table 2 shows the analysis of variance ETSC with the FIN model. where the two-way ANOVA rationale is described in Figure 2.

Table 1. Two-way ANOVA summary.

Source of Changes	Degrees of Freedom	Sum of squares	Mean Square	F-value	F-critical
Main effect A	A-1	A Variance$^{2\times n}$	SSA/dfA	MSA/MSr	DFA, dfr
Main effect B	B-1	B Variance$^{2\times n}$	SSB/dfB	MSB/MSr	DFB/dfr
Residual (Error)	Total-(A+B)	SS total-(SSA+SSB)	SSr/dfr	N/A	N/A
Total	n-1	Std. Deviation $^{2\times(n-1)}$	N/A	N/A	N/A

Table 2. Analysis of variance in ETSC with the FIN model

(a) Between-Subjects Factors		n	(B) Between-Subjects Factors		n
Flow rate	1	21	Flow rate	1	21
	2	21		2	21
	3	21		3	21
Model	1	21	Perforation model	1	21
	2	21		2	21
	3	21		--	---

3. The hypotheses

With the two-way ANOVA, there are three hypothesis groups. The following are the null hypotheses for each set:

1. The starting parameter's means of population are equal.
2. The means of the population means of the second parameter are equal.
3. There is no interaction between the two factors.

$$F < \text{F-critical} = H_0$$
$$F > \text{F-critical} = H_1$$
$$SS = A\,Variance^{2\times N}$$
$$SS_{total} = Standard\ deviation^{2\times(N-1)}$$
$$MS = SS \div df$$
$$F = MS \div MS\ \text{residual}$$

4. Results and discussion

4.1. Descriptive statistics

After performing a statistical analysis of the outlet temperatures obtained from the experimental work, the following conclusions can be drawn: According to Table 3, the highest mean temperature occurred in Model 3, which was 38.7286 °C, with the lowest flow number of 0.5. This demonstrates the strength and effectiveness of the copper fin. While the average temperature was 34.5000 and 29.1429 degrees Celsius for aluminum and the heat pipe, respectively. Table 4 shows that the significance value (sig value) of the flow rate is (0.009), as it was the strongest in effectiveness after comparing it to the model, as it reached (0.017), which was also less than (0.05), and came in second place in strength and effectiveness, followed by the intersection between them, which reached (0.024).

Table 3. Descriptive statistics

Dependent Variable: The temperature				
Flowrate	**Model**	**Mean**	**Std. Deviation**	**n**
1	1	29.1429	3.15429	07
	2	34.5000	7.91960	07
	3	38.7286	**1**.43265	07
	Total	34.1238	7.09711	21
2	1	27.6857	1.91523	07
	2	32.6286	5.62782	07
	3	30.3429	6.90431	07
	Total	30.2190	5.40246	21
3	1	29.0000	0.00000	07
	2	32.8286	4.72360	07
	3	25.9571	5.14680	07
	Total	29.2619	4.78952	21
Total	1	28.6095	2.13000	21
	2	33.3190	5.97918	21
	3	31.6762	8.00868	21
	Total	31.2016	6.12834	63

Table 4. Between subject effects.

Dependent Variable: The temperature					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	853.3470 [a]	08	00106.668	3.905000	.001
Intercept	61332.960	01	61332.960	2245.162	.000
Flow rate	278.61000	02	00139.305	5.099000	.009
Model	239.98100	02	00119.991	4.39200	.017
Flow rate * Model	334.75600	04	00083.689	3.06400	.024
Error	1475.1630	54	00027.318		
Total	63661.470	63			
Corrected Total	2328.5100	62			

[a] R Squared = .366 (Adjusted R Squared = .273)

While it is clear in Table 5 that in the case of Model 3 perforation, the highest average occurred at a flow rate of 0.5, and its value was 43.6429

°C. The value of SIG in **Table 6** was zero for the perforation factor, and this indicates that the perforation model is highly effective and that effectiveness is rated with respect to dependent factors. It is followed by the flow operator, knowing that the intersection of these two factors is ineffective.

Table 5. Descriptive statistics

Dependent Variable: The temperature				
Flowrate	**Perforation**	**Mean**	**Standard Deviation**	**n**
1	1	38.7286	06.43265	07
	2	43.6429	07.39929	07
	Total	41.1857	07.13225	14
2	1	31.0143	06.98007	07
	2	43.1000	05.42187	07
	Total	37.0571	08068214	14
3	1	25.9571	05.14680	07
	2	40.0714	09.80777	07
	Total	33.0143	10.50032	14
Total	1	31.9000	07.99581	21
	2	42.2714	07.52955	21
	Total	37.0857	09.29462	42

Table 6. Tests between-subject effects

Dependent Variable: The temperature					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F-value**	**Sig.**
Corrected Model	1760.420 [a]	05	0352.084	007.115	.000
Intercept	57764.709	01	57764.709	1167.245	.000
Flowrate	0467.423	02	0233.711	004.723	.015
Perforation	1129.449	01	1129.449	022.823	.000
Flowrate * Perforation	0163.549	02	0081.774	001.652	.206
Error	1781.571	36	0049.488		
Total	61306.700	42			
Corrected Total	3541.991	41			

[a] R Squared = .497 (Adjusted R Squared = .427)

4.2. Profile plot

In the profile plot between the estimated marginals of the temperature and flow rate, the highest value occurred at flow rate 0.5 in the presence of Model 3, and it reached approximately 38.7286, as shown in **Figure 4**, while Figure 5 gives the perforated model, whose value amounted to 43.6429.

5. Conclusion

This research discussed the results of statistical analysis and experimental tests. The investigation was carried out to enhance the heat transfer of a solar collector using fins. These results show the effect of volumetric flow rate and fin type using differential statistical analysis by ANOVA, and the results showed that copper fins provide the greatest improvement, with an average temperature of 38.7286 °C at a flow rate of 0.5 L/min. Compared to aluminum fins with a temperature of 34.5000 and 29.1429 °C for the heat pipe, in the case of perforating the copper fin, it was found that there was a greater improvement in heat transfer up to 43.6429 °C at a flow rate of 0.5 liters per minute. The workers' flow rate (type of improvement) is less than 0.05, which indicates the workers' effectiveness in improving heat transfer. and increasing the thermal efficiency of the solar system.

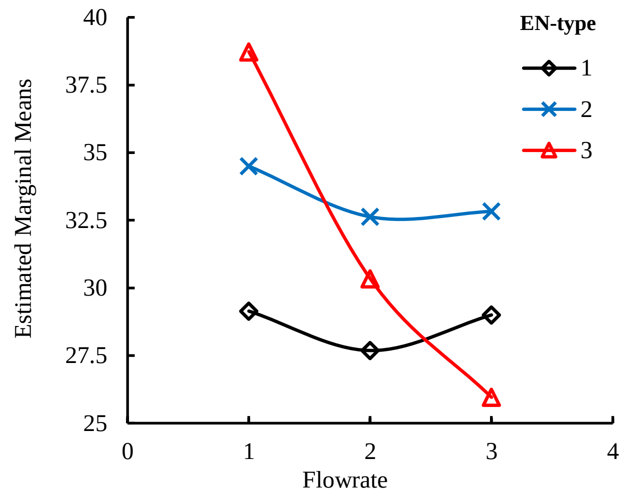

Figure 4. Profile plot showing the estimated marginal means of the temperature at flow rates of 0.5, 1, and 1.5 L/min.

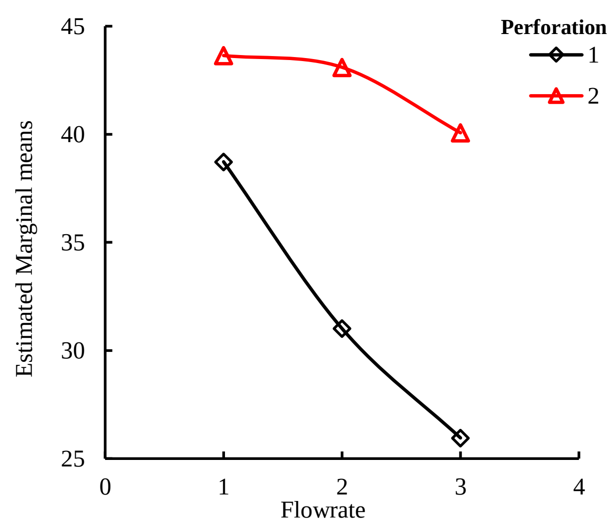

Figure 5. Profile plot showing the Estimated Marginal Means of the temperature at flow rates of 0.5, 1, and 1.5 L/min for the perforated model 3.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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