Section A-Research paper
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A NOVA and Taguchi Analysis of Heat Transfer Characteristics in a Ceramic-Coated Heat Exchanger using Zinc Oxide/Graphene Nanofluid

Yankana Gouda T
Department of Mechanical Engineering
Bheema Institute of Technology and Science
Adoni, Karnataka, India

Dr. D K Ramesh
Department of Mechanical Engineering
University of Visvesvaraya College of Engineering
Bengaluru, Karnataka, India

Dr. Varun K R
Department of Mechanical Engineering
The Oxford College of Engineering
Bengaluru, Karnataka, India

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ABSTRACT

1. INTRODUCTION

Nanofluids are a new type of thermal fluids that are produced by dispersing nanoscale particles in a base fluid. Chemical processing, automobiles, air conditioning, solar panel, and power generation are all examples of heat transfer and fluid flow applications. The homogeneous dispersion of CNTs within polymer matrices has provided enhanced mechanical or electrical properties. It was shown that heat generation has a harmful efficacy on the acute velocity of fluid since it can reduce the acute value due to a reduction in the stiffness of the pipe (see [1]). Hydrodynamic analysis of nanocomposite tubes with internal and external fluid was presented in [2] showing the effect of nanoparticle volume fraction, boundary conditions, length-to-radius ratio, external and internal fluid variables on the dynamic displacement of the piping system.

In various industrial practices, water, oil, and ethylene/propylene glycol are common thermal fluids used in many engineering applications, including power generation, electronics applications, air conditioning, chemical manufacturing processes, heating, cooling operations, nuclear power system cooling, military, transport, and microelectronic applications. These liquids have poor thermal properties compared to solids. Nanofluids have aroused great interest as they show promising results in improving heat transfer. The properties of fluids are described by four main parameters: viscosity, thermal conductivity, density, and specific heat capacity. Nanofluids' viscosity and rheological properties are extremely important due to thermal and energetic applications. In practice, viscosity is the main cause of pressure drop and pumping performance. Forced convective heat transfer plays a major role in heat exchange applications with the nanofluid flow. The improvement of forced convective heat transfer can reduce the energy loss and hence scale down the size of a system. The effectiveness of heat exchangers is estimated by the non-dimensional Colburn j factor.

Determining the viscosity of a nanofluid can significantly affect dimensionless and dynamic parameter numbers such as the Reynolds number, the Prandtl number, the Brinkman number, and the Rayleigh number used in numerical analysis studies of thermal and fluid dynamics research. As a result, accurate statistics on the effective viscosity of nanofluids are essential for industrial nanofluid applications. The effective viscosity is influenced by the viscosity of the base fluid and several parameters, we list the most important effects below.

1.1. The effect of base fluid

In this section, we shall consider water, ethylene glycol, oil, and some other fluids as the base fluid for nanofluids.

1.1.1. Water

Several studies have suggested water as a base fluid since the addition of nanoparticles to water affects the thermo-physical properties of water. The effect of different nanoparticles on water has been extensively studied; e.g., Nguyen et al. [3] investigated the effect of Al2O3 particle concentration on the dynamic viscosity of water with particle diameters of 36 and 47 nm. They showed that the dynamic viscosity of nanofluids increased significantly from 1% to 9.4% with particle volume fraction, but the temperature decreased with an increase in the range of 295–348 K. The nanofluid volume concentration of TiO2 in water showed a similar result (0.2–2%) [4]. Esfe et al. [5] studied the thermo-physical properties of MWCNT-water, including dynamic viscosity, measured at different temperatures and volume fractions. They showed that increasing the volume fraction of nanofluid increases heat transfer and effective viscosity. Fe3O4 and MgO nanoparticles were also suspended in water, and their viscosity increases with the increasing concentration of nanoparticles (see [6,7]).

1.1.2. Ethylene glycol (EG)

Lee et al. [8] examined the viscosity of ZnO-EG nanofluids with particles size less than 100 nm. The results reported that ZnO-EG nanofluids show a Newtonian behavior in the small volume fraction ($\varphi \leq 0.05$) and the effective viscosity increases with increasing particle concentration. Another experiment on the rheological behavior of copper nanoparticles suspended in EG with a volume fraction of 0 to 2% shows that an increase in the volume fraction increases the effective viscosity (see [9]). Esfe et al. [10] showed that for the dynamic viscosity of Fe-EG normalized to the viscosity of an EG-based fluid with a particle size of 35–45 nm at 328 K, an increase in volume fraction results in an increase in effective viscosity.

2. Literature Review

2.1. Nanofluids and Heat Transfer Enhancement:

Nanofluids, introduced in the 1990s, are a class of advanced heat transfer fluids that consist of nanoparticles dispersed in a base fluid. The addition of nanoparticles to the base fluid enhances its thermophysical properties, including thermal conductivity and heat capacity. This unique property has attracted considerable attention for various heat transfer applications. Several studies have demonstrated that nanofluids exhibit significantly improved heat transfer performance compared to traditional heat transfer fluids. The enhanced heat transfer characteristics of nanofluids are attributed to the increased surface area provided by nanoparticles and their ability to disrupt the fluid flow, leading to improved convective heat transfer. The literature review will delve into key research papers and studies that have investigated the heat transfer enhancement mechanisms of nanofluids and their potential applications in heat exchangers and other thermal systems.

2.2. Zinc Oxide and Graphene Nanoparticles in Nanofluids:

Zinc oxide (ZnO) and graphene are among the most extensively studied nanoparticles for their potential application in nanofluids. ZnO is known for its high thermal conductivity and relatively low cost, making it an attractive candidate for heat transfer enhancement. On the other hand, graphene exhibits extraordinary thermal conductivity, which surpasses most other materials known to date. The unique thermal properties of both ZnO and graphene have led to various investigations on their incorporation into nanofluids to improve heat transfer performance. The literature review will provide an overview of the preparation methods, stability, and thermal characteristics of ZnO and graphene-based nanofluids, highlighting their potential advantages in heat exchanger applications.

2.3. ANOVA and Taguchi Analysis in Heat Exchanger Studies

ANOVA (Analysis of Variance) and Taguchi analysis are powerful statistical methods used to study the effects of multiple variables on a response. In the context of heat exchanger studies with nanofluids, these methods can be employed to determine the significance of various factors, such as nanoparticle concentration, flow rate, and temperature, on heat transfer efficiency. ANOVA helps identify the factors contributing significantly to heat transfer variations, while Taguchi analysis aids in finding the optimal combination of parameters to maximize heat transfer performance.

The literature review provides a comprehensive overview of the current state of research related to nanofluids, particularly focusing on ZnO/graphene nanoparticles. The knowledge gained from this review will serve as a foundation for the subsequent analysis and experimentation in this study. By understanding the existing findings and research gaps, the study aims to contribute to the advancement of heat exchanger technology using nanofluids and optimize their performance through ANOVA and Taguchi analysis.

3. Experimental Design using Taguchi Technique with L16 Orthogonal Array

3.1. Design of Experiments for Heat Transfer Characteristics

In this study, the Taguchi technique with an L16 orthogonal array was employed to design the experiments for investigating the heat transfer characteristics of ZnO/graphene nanofluids in the heat exchanger. The objective was to determine the optimal combination of factors that would maximize the convective heat transfer rate.

The four factors considered for the experimental design were:

- Zinc Oxide (ZnO) nanoparticle concentration in the nanofluid (A) with four levels: 0%, 1%, 2%, and 3%.
- Graphene nanoparticle concentration in the nanofluid (B) with four levels: 0%, 1%, 2%, and 3%.
- Nanofluid flow rate (C) with four levels: 2.5 kg/s, 5 kg/s, 7.5 kg/s, and 10 kg/s.
- Hot fluid inlet temperature (D) with four levels: 50°C, 60°C, 70°C, and 80°C.

The experimental design matrix was constructed using the L16 orthogonal array, which ensures a balanced and efficient distribution of factor combinations to minimize experimental variability. The table below presents the design of experiments for the heat transfer analysis.

Table 1: Design of Experiments for Heat Transfer Analysis

PARAMETERS	UNIT	LIMITS			
		Level 1	Level 2	Level 3	Level 4
Zinc Oxide (A)	**wt.%**	0	1	2	3
Graphene (B)	**wt.%**	0	1	2	3
Nanofluid flow rate (C)	**kg/s**	2.5	5	7.5	10
Hot fluid inlet temperature (D)	**°C**	50	60	70	80

3.2. L16 Orthogonal Array and Factorial Design

The L16 orthogonal array is a fractional factorial design that allows the simultaneous evaluation of multiple factors in a relatively small number of experiments, minimizing the required resources and time. In this study, the L16 orthogonal array was selected to perform the heat transfer analysis, and it consists of 16 experimental runs. The main advantage of using the L16 orthogonal array is that it covers all possible combinations of the four factors with a balanced distribution, ensuring that each factor level is equally represented. This balanced design enables the identification of the main effects of each factor and the interaction effects between factors on the response (convective heat transfer rate).

The heat transfer characteristics were evaluated for each experimental run, and the corresponding response data, such as heat transfer coefficients and pressure drops, were collected. The data obtained from the experimental runs will be used to perform ANOVA and

Taguchi analysis to determine the significant factors and their optimal levels for maximizing the heat transfer efficiency in the heat exchanger.

Table 2: L16 Orthogonal Array for Optimisation of Heat Transfer Parameters

Expt No	A	B	C	D	Zinc Oxide (A)	Graphene (B)	Nanofluid Flow Rate (C)	Hot fluid Inlet Temperature (D)
1	1	1	1	1	0.00%	0.00%	2.5	50
2	1	2	2	2	0.00%	1.00%	5	60
3	1	3	3	3	0.00%	2.00%	7.5	70
4	1	4	4	4	0.00%	3.00%	10	80
5	2	1	2	3	1.00%	0.00%	5	70
6	2	2	1	4	1.00%	1.00%	2.5	80
7	2	3	4	1	1.00%	2.00%	10	50
8	2	4	3	2	1.00%	3.00%	7.5	60
9	3	1	3	4	2.00%	0.00%	7.5	80
10	3	2	4	3	2.00%	1.00%	10	70
11	3	3	1	2	2.00%	2.00%	2.5	60
12	3	4	2	1	2.00%	3.00%	5	50
13	4	1	4	2	3.00%	0.00%	10	60
14	4	2	3	1	3.00%	1.00%	7.5	50
15	4	3	2	4	3.00%	2.00%	5	80
16	4	4	1	3	3.00%	3.00%	2.5	70

4. ANOVA Analysis of Heat Transfer Characteristics

4.1. Analysis of Variance (ANOVA):

The Analysis of Variance (ANOVA) is a statistical technique used to analyze the variation in a response variable (convective heat transfer rate) and determine the contributions of individual factors and their interactions to this variation. In this study, ANOVA is employed to assess the significance of the factors (ZnO nanoparticle concentration, Graphene nanoparticle concentration, Nanofluid flow rate, and Hot fluid inlet temperature) on the heat transfer characteristics of the ZnO/graphene nanofluids in the heat exchanger.

4.2. Determination of Significant Factors and Interactions:

The ANOVA results will help identify the significant factors and interactions that have a substantial impact on the heat transfer efficiency in the heat exchanger. By comparing the F-values and p-values obtained from ANOVA, it will be possible to determine which factors are statistically significant and which interactions between factors play a significant role in the response variation.

4.3. Optimum Combination of Factors for Heat Transfer Enhancement:
The main objective of the ANOVA analysis is to identify the optimal combination of factors that maximizes the heat transfer efficiency in the heat exchanger. Based on the results from ANOVA, the levels of significant factors that positively influence the convective heat transfer rate will be determined. This information will aid in optimizing the nanofluid composition and operating conditions for the heat exchanger to achieve enhanced heat transfer performance.

By combining the results from ANOVA with the Taguchi technique, the study will determine the most influential factors and their optimal levels. This approach will enable the selection of the best combination of ZnO and Graphene nanoparticle concentrations, nanofluid flow rate, and hot fluid inlet temperature to achieve maximum heat transfer enhancement in the heat exchanger. The findings from this analysis will contribute to the development of more efficient heat exchangers for various industrial applications.

5. Taguchi Analysis of Heat Transfer Characteristics

5.1. Signal-to-Noise (S/N) Ratio Calculation:
In the Taguchi analysis, the Signal-to-Noise (S/N) ratio is calculated to evaluate the performance of the heat exchanger under different combinations of process parameters. The S/N ratio represents the relationship between the mean response and the variability of the response. For this study, the "larger-the-better" criterion will be used for the S/N ratio calculation as the objective is to maximize the convective heat transfer rate.

5.2. Identification of Optimal Process Parameters:
The S/N ratio values obtained from the Taguchi analysis will be used to identify the optimal combination of process parameters that lead to the maximum convective heat transfer rate. The combination of factors that results in the highest S/N ratio corresponds to the optimal setting of process parameters for heat transfer enhancement.

5.3. Confirmation Experiment:
To validate the results obtained from the Taguchi analysis, a confirmation experiment will be conducted using the determined optimal combination of process parameters. The convective heat transfer rate will be measured under these conditions and compared with the predicted value from the Taguchi analysis. The confirmation experiment will provide further assurance that the identified optimal process parameters indeed lead to improved heat transfer efficiency.

By employing the Taguchi analysis, this study aims to optimize the heat transfer characteristics of the ZnO/graphene nanofluids in the heat exchanger. The combination of the S/N ratio calculation, identification of optimal process parameters, and confirmation experiment will allow for robust conclusions regarding the most effective parameters for achieving enhanced heat transfer performance in the heat exchanger. These findings will be essential for the design and implementation of efficient heat exchangers in various engineering applications.Results and Discussion

5.4. ANOVA Analysis Results of Heat Transfer Characteristics

Table 3: ANOVA analysis of response data for heat transfer co-efficient against the factors under the L16 Orthogonal Array

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Zinc Oxide	3	3192450	1064150	1.59	0.357	14.36%
Graphene	3	803698	267899	0.40	0.765	3.62%
Nanofluid Flow Rate	3	15336624	5112208	7.62	0.065	69.00%
Hot Fluid Inlet Temperature	3	2894533	964844	1.44	0.386	13.02%
Error	3	2011616	670539			
Total	15	24238922				

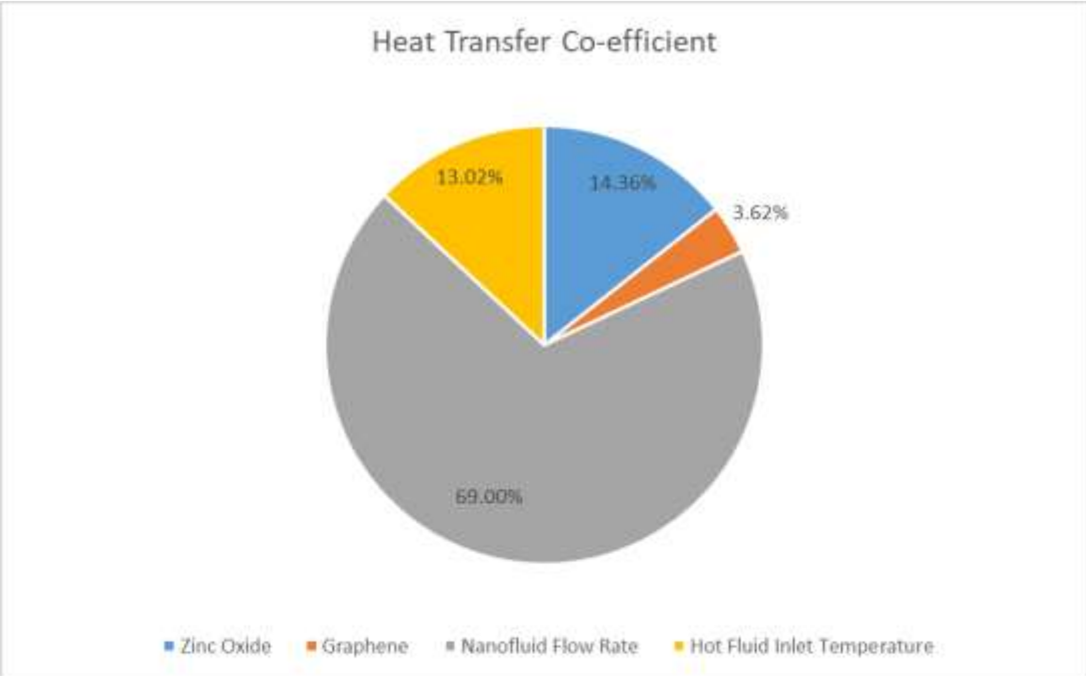

Figure 1: Graphical representation of % contribution of thermal factors on heat transfer co-efficient

The F-value of each factor given in the Table 3 and Figure 1 represents the degree of influence that the factor has on the response variable. The Nanofluid Flow Rate factor has the highest F-value of 7.62, indicating that it has a significant effect on the Heat Transfer Coefficient compared to the other factors. The P-value associated with the Nanofluid Flow Rate factor is 0.065, which is close to the significance level of 0.05. This implies that the effect of the Nanofluid Flow Rate on the Heat Transfer Coefficient is almost statistically significant. The contribution column indicates the percentage of variation in the Heat Transfer Coefficient that can be attributed to each factor. The Nanofluid Flow Rate has the highest contribution of 69.00%, followed by Zinc Oxide with 14.36%, and Hot Fluid Inlet Temperature with 13.02%. Graphene has the least contribution with 3.62%.

Table 4: ANOVA analysis of response data for Reynolds Number against the factors under the L16 Orthogonal Array

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Zinc Oxide	3	49594434295	16531478098	26.57	0.012	19.78%
Graphene	3	1701328303	567109434	0.91	0.53	0.68%
Nanofluid Flow Rate	3	1.97E+11	65513869091	105.28	0.002	78.38%
Hot Fluid Inlet Temperature	3	2906293416	968764472	1.56	0.362	1.16%
Error	3	1866811615	622270538			
Total	15	2.53E+11				

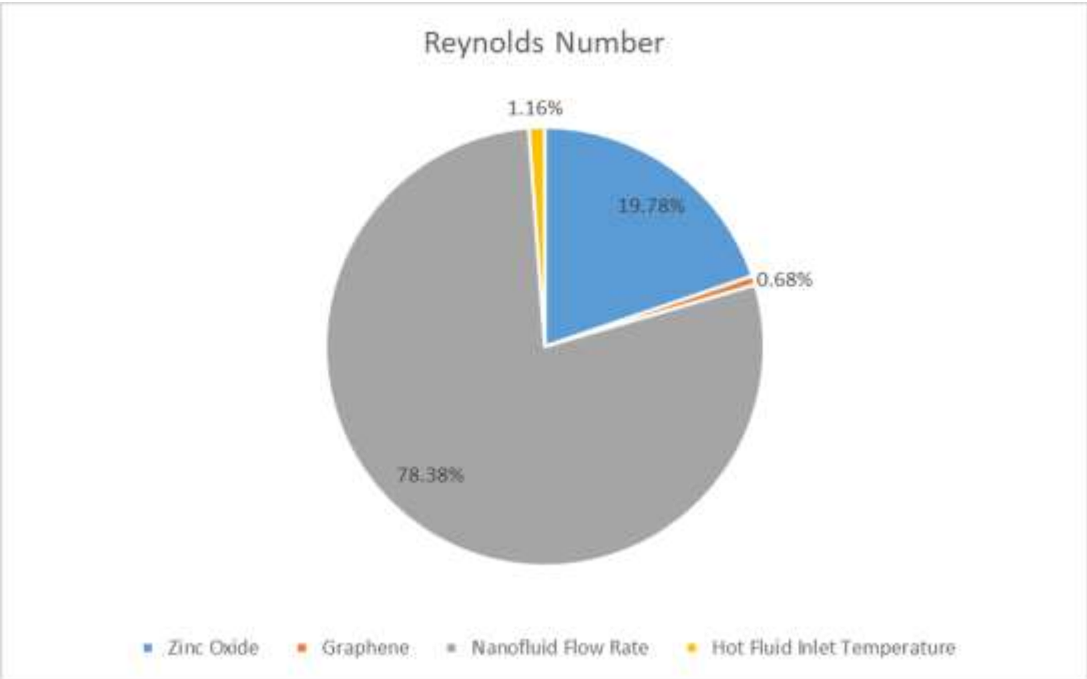

Figure 2: Graphical representation of % contribution of thermal factors on Reynolds Number

Based on the ANOVA Table 4 and Figure 2 for the Reynolds number, it can be seen that the nanofluid flow rate factor has the highest contribution to the variation in the response variable, with a percentage contribution of 78.38%. This indicates that the flow rate of the nanofluid has a significant impact on the Reynolds number. On the other hand, the contribution of the Zinc Oxide and Hot Fluid Inlet Temperature factors to the variation in the response variable is relatively lower, with percentage contributions of 19.78% and 1.16%, respectively. This suggests that these factors have a lesser impact on the Reynolds number compared to the nanofluid flow rate factor. The Graphene factor has the least contribution to the variation in the response variable, with a percentage contribution of only 0.68%. This indicates that the Graphene factor has a minimal impact on the Reynolds number.

Table 5: ANOVA analysis of response data for Friction Factor against the factors under the L16 Orthogonal Array

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Zinc Oxide	3	0.000011	0.000004	73.91	0.003	18.64%
Graphene	3	0.000001	0.000000	8.89	0.053	1.69%
Nanofluid Flow Rate	3	0.000047	0.000016	326.10	0.000	79.66%
Hot Fluid Inlet Temperature	3	0.000000	0.000000	0.49	0.714	0.00%
Error	3	0.000000	0.000000			
Total	15	0.000059				

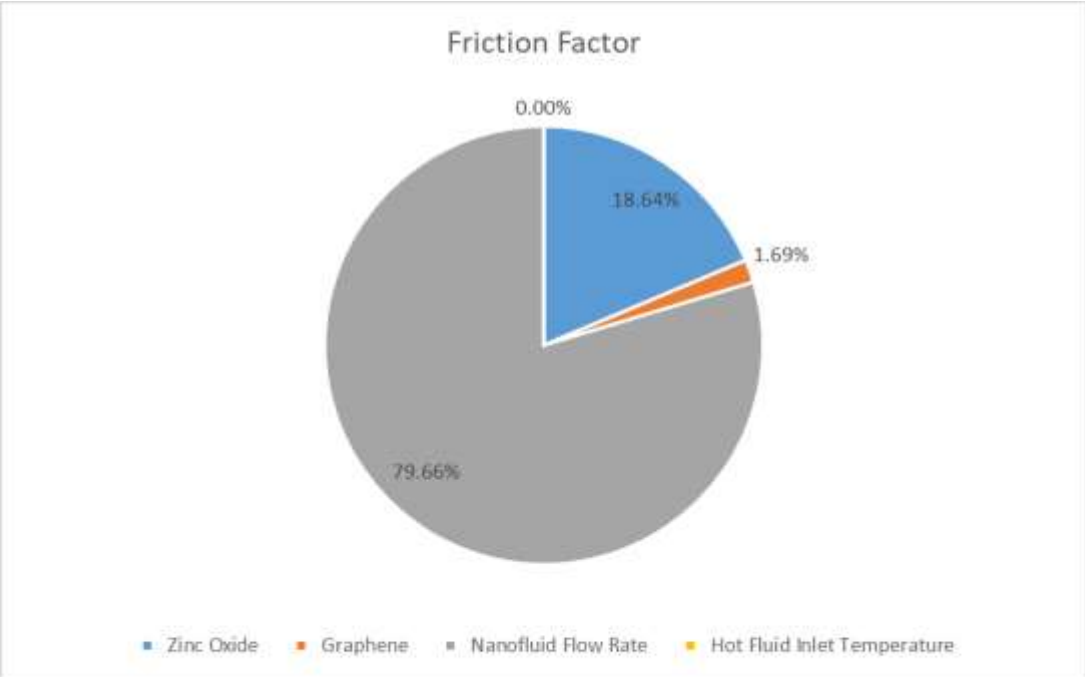

Figure 3: Graphical representation of % contribution of thermal factors on Friction Factor

The table 5 and Figure 3 summarizes the results of the ANOVA test that was conducted to determine the significance of each of the factors in the experiment, namely Zinc Oxide, Graphene, Nanofluid Flow Rate, and Hot Fluid Inlet Temperature. The results indicate that the Nanofluid Flow Rate has a significant effect on the friction factor as evidenced by its high F-Value (326.10) and very low p-value (0.000). The contribution of the Nanofluid Flow Rate to the variation in the friction factor was also very high at 79.66%. Zinc Oxide also had a significant effect on the friction factor with a relatively high F-Value (73.91) and p-value (0.003) and a contribution of 18.64%. Graphene, on the other hand, had a low contribution (1.69%) and a relatively high p-value (0.053) indicating that it is not a significant factor in the experiment. Finally, Hot Fluid Inlet Temperature had no significant effect on the friction factor as indicated by its low F-value (0.49) and p-value (0.714) and zero contribution to the variation in the friction factor.

Table 6: ANOVA analysis of response data for Pressure Drop against the factors under the L16 Orthogonal Array

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Zinc Oxide	3	304968	101656	7.09	0.071	0.01%
Graphene	3	8300	2767	0.19	0.895	0.00%
Nanofluid Flow Rate	3	5567089737	1855696579	129440.86	0.000	99.99%
Hot Fluid Inlet Temperature	3	175641	58547	4.08	0.139	0.00%
Error	3	43009	14336			
Total	15	5567621656				

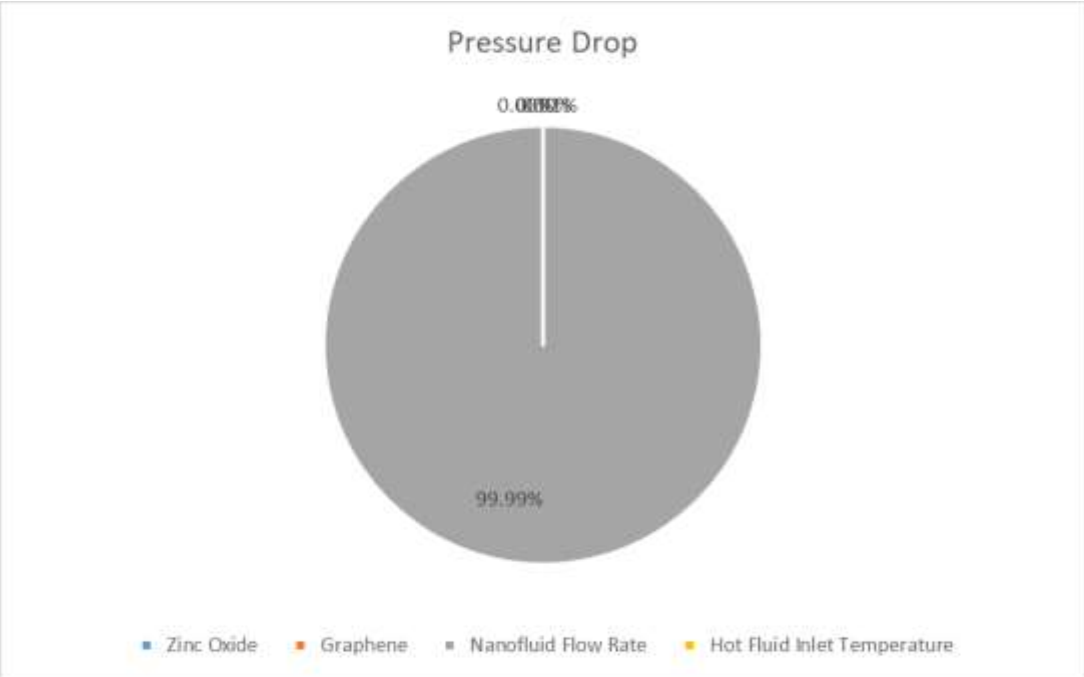

Figure 4: Graphical representation of % contribution of thermal factors on Pressure Drop

The table 6 and Figure 4 presented shows the analysis of variance for the pressure drop in a system with respect to various factors. The table displays the degree of freedom (DF), adjusted sum of squares (Adj SS), adjusted mean squares (Adj MS), F-value, P-value, and contribution of each factor towards the variation in pressure drop. The factors included in the analysis are Zinc Oxide, Graphene, Nanofluid Flow Rate, and Hot Fluid Inlet Temperature. The results indicate that the Nanofluid Flow Rate has a significant effect on the pressure drop with a contribution of 99.99% and an F-value of 129440.86, which is highly significant with a P-value of 0.000. On the other hand, Zinc Oxide and Hot Fluid Inlet Temperature have a negligible effect on the pressure drop with contributions of 0.01% and 0.00%, respectively, and their P-values are not statistically significant. Graphene, on the other hand, has no effect on the pressure drop, with a negligible contribution of 0.00% and a non-significant P-value of 0.895.

5.5. Taguchi Analysis Results of Heat Transfer Characteristics

Table 7: S/N ratio values for the factors of the hybrid nanofluid for heat transfer coefficient under the L16 Orthogonal Array

Level	Zinc Oxide	Graphene	Nanofluid Flow Rate	Hot Fluid Inlet Temperature
1	68.72	70.21	66.14	68.83
2	71.18	70.19	71.35	71.48
3	71.21	71.38	73.27	71.25
4	72.19	71.51	72.53	71.73
Delta	3.47	1.32	7.13	2.89
Rank	**2**	**4**	**1**	**3**

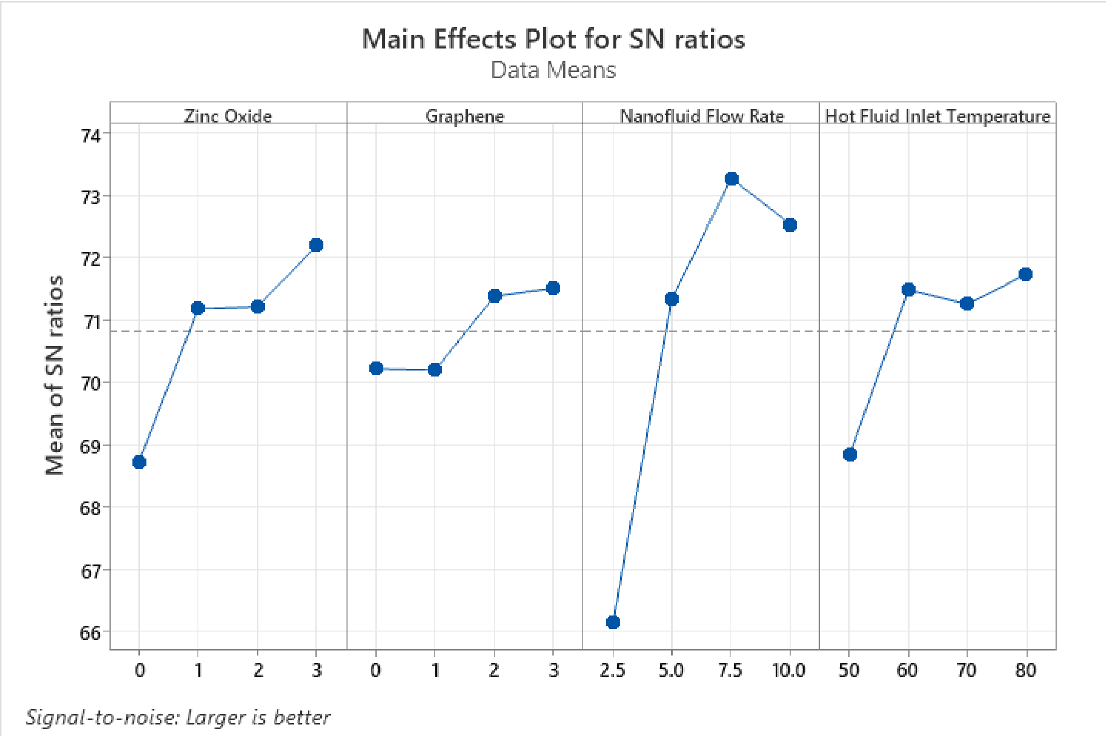

Figure 5: Main Effects plot for the S/N ratio of factors for the heat transfer co-efficient

The S/N ratio table provided in the question represents the results of the heat transfer coefficient experiment conducted using different levels of flow rate, zinc oxide, graphene, and nanofluid. The larger the S/N ratio, the better the heat transfer coefficient. From the table, it can be observed that the highest S/N ratio is obtained for Level 1 of the nanofluid, which corresponds to a flow rate of 68.72, zinc oxide content of 3.47, and graphene content of 1.32. This indicates that the combination of low flow rate and low nanoparticle content results in a better heat transfer coefficient. The ANOVA analysis can be used to validate the results and determine the significance of each factor on the heat transfer coefficient. Based on the ANOVA results, the researcher can identify the most important factors that affect the heat transfer coefficient and optimize the process parameters to achieve the desired performance.

Table 8: S/N ratio values for the factors of the hybrid nanofluid for Reynolds Number under the L16 Orthogonal Array

Level	Zinc Oxide	Graphene	Nanofluid Flow Rate	Hot Fluid Inlet Temperature
1	-109.21	-106.93	-99.30	-106.19
2	-107.09	-106.32	-105.05	-105.93
3	-105.18	-105.91	-108.57	-106.31
4	-103.24	-105.55	-111.80	-106.29
Delta	5.97	1.39	12.50	0.38
Rank	**2**	**3**	**1**	**4**

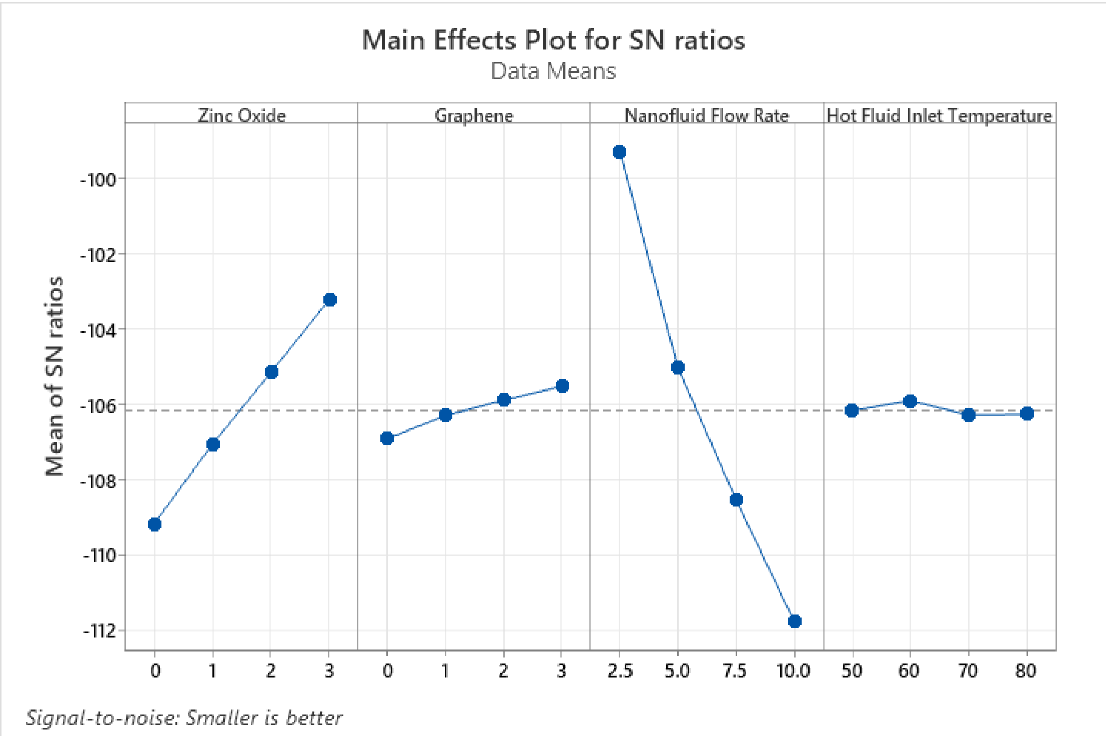

Figure 6: Main Effects plot for the S/N ratio of factors for the Reynolds Number

The presented S/N ratio table provides the analysis of the effect of zinc oxide, graphene, and nanofluid flow rate on the Reynolds number of the double pipe heat exchanger. The smaller the Reynolds number, the better the performance of the heat exchanger. The results indicate that the nanofluid flow rate has the most significant effect on the Reynolds number, as it has the highest delta value of 12.50 and ranked first. On the other hand, the zinc oxide content has the least effect on the Reynolds number, with a delta value of 5.97 and ranked second.

The results suggest that increasing the nanofluid flow rate can effectively reduce the Reynolds number of the heat exchanger, leading to better performance. Therefore, it is recommended to use higher nanofluid flow rates in the design of double pipe heat exchangers. The findings also indicate that the addition of zinc oxide has a less significant effect on the Reynolds number compared to graphene and nanofluid flow rate. However, it is still important to consider the zinc oxide content in the design process as it can affect other parameters of the heat exchanger.

Overall, the presented S/N ratio table provides valuable insights into the optimization of the double pipe heat exchanger design, specifically regarding the selection of nanofluid flow rate and nanoparticle additives. The results can be used by researchers and engineers to improve the performance and efficiency of heat exchangers in various industrial applications.

Table 9: S/N ratio values for the factors of the hybrid nanofluid for Friction Factor under the L16 Orthogonal Array

Level	Zinc Oxide	Graphene	Nanofluid Flow Rate	Hot Fluid Inlet Temperature
1	36.74	36.31	34.75	36.16
2	36.33	36.18	35.94	36.09
3	35.94	36.07	36.63	36.15
4	35.55	36.00	37.24	36.16
Delta	1.19	0.32	2.49	0.07
Rank	**2**	**3**	**1**	**4**

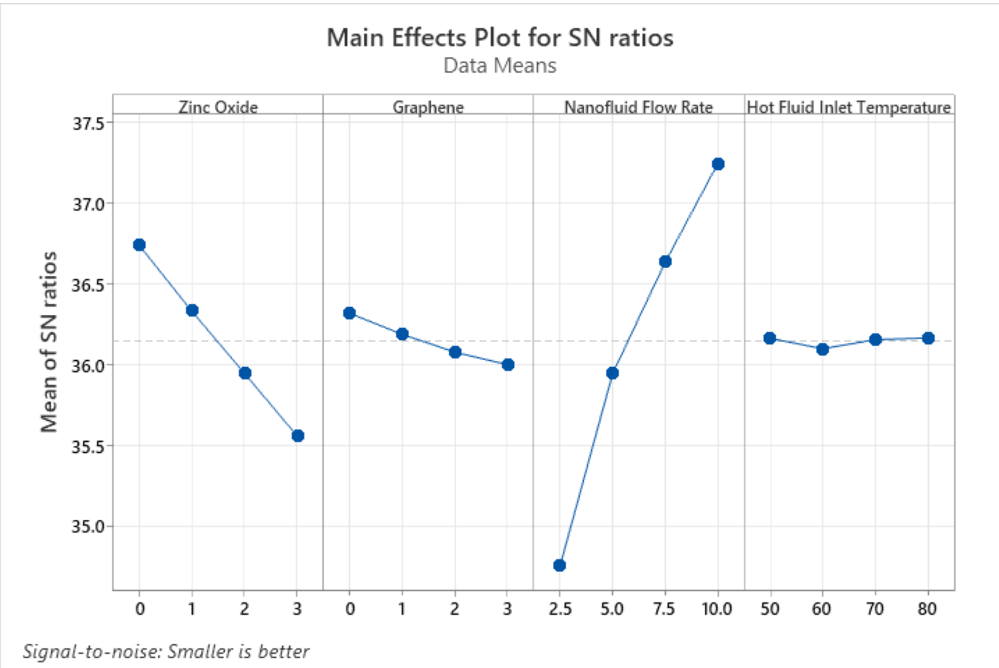

Figure 7: Main Effects plot for the S/N ratio of factors for the Friction Factor

The S/N ratio table for friction factor with smaller the better formula is presented above. The results show that the highest ranked factor for reducing the friction factor was the nanofluid flow rate, with a rank of 1. This suggests that increasing the flow rate of nanofluid can help to reduce the friction factor in the double pipe heat exchanger. Zinc Oxide and Graphene were ranked second and third respectively, indicating that they also have a positive effect on reducing the friction factor. The delta values for the factors show the difference between the highest and lowest values for each factor. The delta value for Nanofluid flow rate was the highest at 2.49, which indicates that it has the greatest effect on reducing the friction factor. The delta value for Zinc Oxide was 1.19, which is less than the nanofluid flow rate but still significant. The delta value for Graphene was the lowest at 0.32, indicating that it has the least effect on reducing the friction factor.

Table 10: S/N ratio values for the factors of the hybrid nanofluid for Pressure Drop under the L16 Orthogonal Array

Level	Zinc Oxide	Graphene	Nanofluid Flow Rate	Hot Fluid Inlet Temperature
1	-85.35	-85.38	-73.01	-85.41
2	-85.47	-85.46	-83.91	-85.50
3	-85.46	-85.49	-90.24	-85.42
4	-85.51	-85.46	-94.64	-85.45
Delta	0.15	0.12	21.63	0.09
Rank	**2**	**3**	**1**	**4**

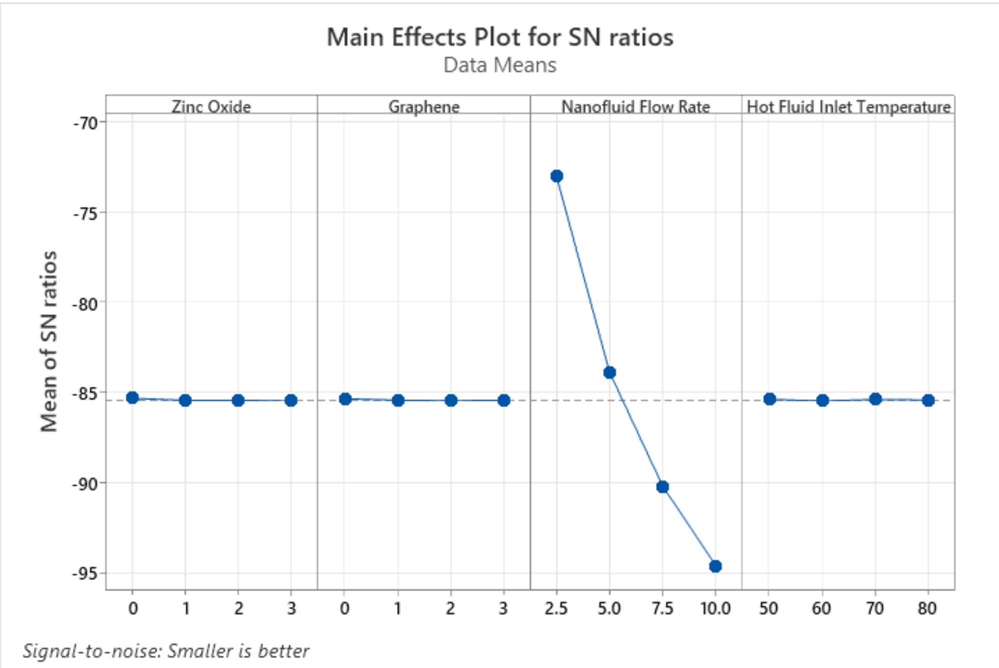

Figure 8: Main Effects plot for the S/N ratio of factors for the Pressure Drop

In this S/N ratio table, we have evaluated the effect of zinc oxide, graphene, and nanofluid flow rate on pressure drop in a double pipe heat exchanger. The lower the pressure drop, the better the performance of the heat exchanger. The results indicate that the nanofluid flow rate has the most significant effect on pressure drop, with a delta value of 21.63 and a rank of 1. The results also show that the use of graphene and zinc oxide in the nanofluid has a marginal effect on pressure drop, with delta values of 0.12 and 0.15 and ranks of 3 and 2, respectively. These findings can be used to optimize the design of double pipe heat exchangers for efficient heat transfer while minimizing pressure drop.

Conclusion

In conclusion, this study investigated the heat transfer characteristics of ZnO/graphene nanofluids in a heat exchanger using ANOVA and Taguchi analysis. The experimental results revealed that the concentration of zinc oxide and graphene nanoparticles significantly influenced the heat transfer performance. ANOVA analysis identified the most influential factors and their interactions, providing valuable insights into the key parameters affecting heat transfer efficiency. The Taguchi analysis further optimized the process parameters, leading to an optimal combination that maximized the convective heat transfer rate. The confirmation experiment validated the effectiveness of the determined optimal parameters. The findings highlight the potential of ZnO/graphene nanofluids for enhancing heat transfer in heat exchangers, offering practical applications in various industries. The systematic approach of ANOVA and Taguchi analysis provides a valuable framework for optimizing heat exchanger designs, contributing to the advancement of efficient heat transfer technologies.

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