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Preparation and Characterization of Nanofluids as a Dielectric Fluid for Sustainable Machining Applications

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Abstract
This study investigates the experimental, characterization, and optimization of CNT-based nanofluids to obtain desired outcomes for machining applications. Process parameters, such as CNT concentration, sonication time, and surfactant quantity percent, were optimized for the usage of ANOVA strategies. The highest zeta size of 98.5 nm was received with a mixture of 1 g/L CNT attention, 60 mins of probe sonication, and 0.2 vol% SDS surfactant, indicating improved nanofluid stability through reduced particle agglomeration. The very best zeta potential of - 46.5 mv, determined in experimental run 2, reflects robust repulsive forces between particles and progressed stability, even as the lowest zeta potential was -39 mv. Thermal conductivity values ranged from 0.324 W/mk to 0.421 W/mk, with the best outcomes observed in experimental run 12, demonstrating the potential of the nanofluid for the manufacturing field. The experimental results reveal the thermal strength of CNT-based nanofluids, making them useful and appropriate as dielectric fluids for sustainable advanced machining procedures. The findings affirm the effectiveness of tailor-made nanofluids in improving performance in sustainable advanced machining applications.

Keywords: Nanofluids, Carbon nanotubes, Dielectric fluids, Thermal conductivity

1. Introduction

Nanofluids are fluids containing suspended nanoparticles within a base fluid, designed to enhance the fluid's properties for various applications. Properties that include thermal conductivity, dynamic viscosity, electric conductivity, density, and lubrication conduct can be advanced by incorporating nanoparticles into the base fluid. The enhancement of those properties in nanofluids can be executed through one-step or two-step mixing strategies. The two-step blending technique is most preferred to achieve the favored properties. In this technique, ultrasonication and probe sonication processes happen. **Figure 1** explains the illustration of the preparation of nanofluids. The nanoparticles utilized in nanofluid preparations are commonly metallic-primarily based, carbon-primarily based, or ceramic-primarily based. The variety of the scale of the nanoparticles lies between the 0 to 100 nm [1].

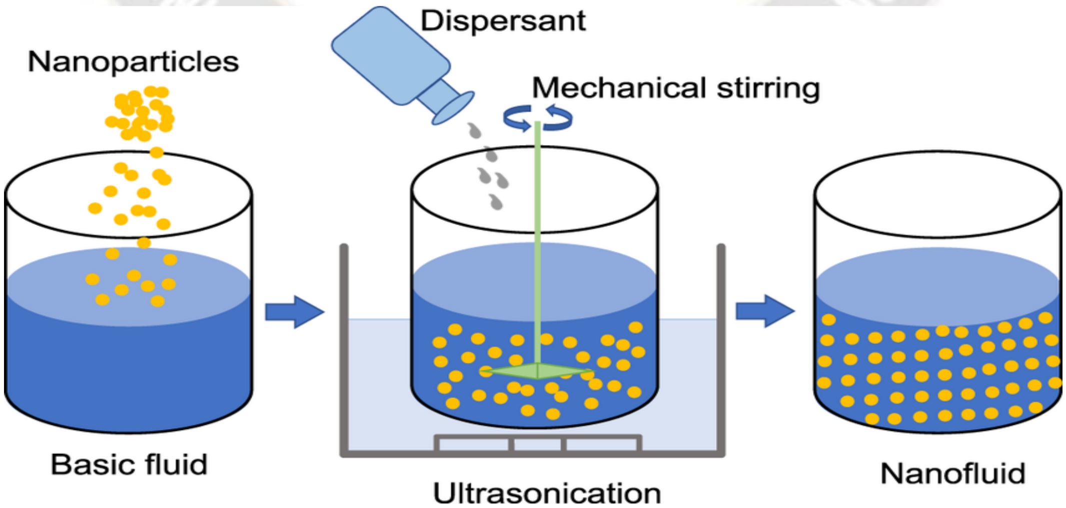

Figure 1: Two-step methodology for nanofluid preparation [2]

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Within the two-step method, nanoparticles are first synthesized one after the other and then introduced into the base fluid. This technique allows for higher control over nanoparticle characteristics and supports a broader variety of materials. For example, Mutuku et al. [3] employed this technique to create Al2O3/water nanofluid. To begin with, nanoparticles are synthesized in a solvent, allowing control over their size and extraordinary properties. After that, it is separated from the synthesis medium using processes that incorporate centrifugation or filtration. After isolation, the nanoparticles are dispersed into the base fluid, regularly with the addition of dispersants to enhance stability. To ensure uniform distribution, the mixture is stirred, and stabilizers may be added if crucial. Even though this technique entails more steps compared to the one-step method, it is preferred while unique nanoparticle properties are critical. The selection to apply a one-step or -step device depends on factors much like the shape of nanoparticles, the preferred properties of the nanofluid, and the properties available. Moreover, the base fluid desires to be determined on based the software's requirements, operating conditions, and compatibility with nanoparticles to keep stability and obtain the desired properties [4].

Nanofluids are used as a dielectric media in numerous superior machining strategies like electric discharge machining (EDM), grinding, electrochemical, ultrasonic machining, and so forth. This work focuses on the potential applications of nanofluids as dielectric fluids in EDM machines. EDM is a specialized way used for reducing tough geometries with immoderate precision. It works by removing materials via a sequence of electrical discharges that arise between an electrode and the workpiece, every immersed in a dielectric fluid. This dielectric fluid is vital as it gives electric insulation, cools the tool, and flushes away particles created during machining. The selection of a dielectric fluid is predicated upon elements like the component being machined, specific machining necessities, and environmental troubles. Essential applications of dielectric fluids encompass their capability to insulate undesirable electrical contact, compatibility with the workpiece and machine components, and sufficient dielectric strength to preserve controlled spark generation. Effective heat dissipation via thermal conductivity prevents overheating, while considerations like flammability, environmental protection, and the fluid's feature in achieving precise finishes are vital for the productivity of EDM. **Figure 2** shows the entire setup of the EDM methodology. Schematic exhibits that dielectric fluids circulate and filter the debris and play an essential role among the electrodes. Dielectric fluids provide dielectric strength, thermal and electric conductivity, and stability for spark erosion during the machining of components [5].

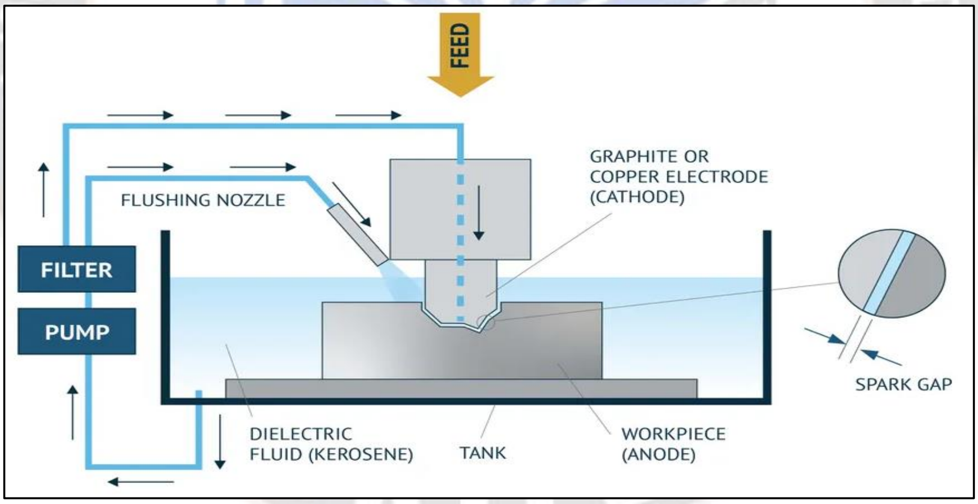

Figure 2: Schematic of EDM setup [5]

2. Literature Survey

Pyarimohan et al. [6] worked to predict the thermophysical properties of prepared nanofluids and implemented machine-learning methods for optimization. It has far observed that 8 percent of thermal conductivity and 34 percent of heat capability are more suitable due to the addition of nanoparticles as compared to nanofluids. Praveen et al. [7] attention to studying the hybrid fluids to enhance the cooling properties of the organized nanofluids. The authors have applied diverse machine studying equipment and experimentation to obtain the outcomes. It has far found that the addition of Al2O3 and copper within the based fluids efficiently enhanced the 55 %of LIB temperature at about 349 milli lire in keeping with the minute flow rate. Emmanuel et al. [8] work with ML strategies and optimize the various method parameters to have an effect on on results parameters. It is determined that Al2O3 nanoparticles of 5 nm size outcomes the properties of nanofluids substantially. Machine learning techniques along with Random forests provide the best expected performance. It has also been observed that size and nanoparticles and Reynolds number significantly enhance

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the heat transfer properties of the nanofluids. Tao et al. [9] optimize the diverse machine learning hybrid machine learning equipment and multiobjective optimization tools to enhance thermal residences, viscosity, and particular warmth capability. The authors have developed the regression models and affirm with Pareto factors tools. It has been found that 45 % of the effects of advanced nanofluids were obtained at 45 to 55 levels of temperature. Hasan et al. [10] used the finite elements strategies techniques to observe the warmth switch and fluids dynamics conduct of the prepared nanofluids. The author's effects show that the Hartmann number lies between 0 to 20 and NV friction lies among the 0 to 0.04 the enormous variety for preferred results. Support vector machine, neural network, and random forest advanced machine learning tools applied the computational value throughout the experimentation. Ramazan et. al [11] monitor that the addition of copper oxide and Al_2O_3 nanoparticles considerably enhance the lubrication properties of nanofluids. The authors carried out the vibration-assisted machining to technique the titanium-based superalloys. It has been noted that the reducing pressure of 35 % and average surface roughness of 38 % systematically decreased with the aid of making use of the nanofluids MQL strategies. Moreover, various authors' work with specific nanofluids, techniques, and techniques are demonstrated in **Table 1.**

Table 1: Key findings of nanofluids, processes, and techniques

Authors	Workpiece materials	Nanofluids types	Potentials applications
Ashutosh et al. [12]	Ti-6Al-4V, Titanium based superalloy	CuO nanoparticles mixed	nano-MQL
Teng et al. [13]	Titanium-based alloy	NMQL	Grinding zone, sustainability
Jun et al. [14]	Graphene oxide	Water and ethanol-based	Dielectric fluid
Bizhan et al. [15]	AL6061-T6	Iol based nanofluids	Milling machine, dielectric fluids
D. X. Peng et. al. [16]	Superalloys	SO_2 based, paraffin mixed	Tribological properties, machined materials

In this work, nanofluids are prepared, characterized, and optimized to their potential applications in the fields of advanced machining area. The development of the properties of dielectric fluids for numerous applications is suggested with the aid of various researchers. The preceding work insights that researchers have made massive research to show that the enhancements in the properties of the dielectric fluid play a vital role within the fields of sustainable machining. It has been revealed via research that method parameters drastically affect required performance parameters. The selection of preparation methods together with the one-step approach and step method for nanofluids play a crucial role in obtaining its desired properties. Most researchers found that 2-step methods remain suitable for obtaining better mixing of nanoparticles with in-base fluid. Moreover, ANOVA and BBD optimization tools were utilized to set up and observe the vital connections among the system and required parameters. The subsequent work will discuss the materials and methods used in this work.

3. Materials and processes used

3.1 Materials details

Commercial market available EDM oil, a hydrocarbon-based fluid, used as a base dielectric fluid for mixing the nanoparticles. Carbon nanotubes (CNTs) are used as a nanoparticle and their specifications are defined in Table 2. Sodium dodecyl sulfate (SDS) was used as a surfactant and blended with the based fluid to keep proper blending. These materials for nanofluid preparation have been procured from ABX industry Gujarat. A two-step method is applied to ensure proper mixing of nanoparticles. Their detail is furnished in the following section.

Table 2: Specification of the carbon nanotubes and EDM oil [17]

CNTs			
Melting point (C)	Tensile strength	Density	Modulus of Elasticity
2800–3000°C	50–200 GPa	1.3–1.4 g/cm³.	1–1.5 TPa
EDM oil			
100–200°C Flash point		0.8–0.9 g/cm³	

3.2 Process and equipment

Glass beakers are used to mix the nanoparticles in the base fluid of 100 ml quantity. CNTs were mixed in three concentration levels, i.e., 0.5 gm/L, 1 gm/L, and 1.5 gm/L. SDS as a surfactant has been combined within the ratio of 0.1, 0.2, and 0.3 of volume %. These prepared solutions are mixed by ultrasonication at a frequency of greater than 22 kHz for 40, 60, and 80 minutes. Transparency and coloration of prepared solutions have been altered after sonication time indicating the nanoparticle's solubility in the base fluids. Sonication time, nanoparticle concentration, and surfactant concentrations are the process parameters to prepare the desired properties of nanofluids. These process parameters and their levels are mentioned in **Table 3**.

Table 3: Process parameters level and concentration

Process parameters	Level		
CNTs	.5 gm/L	1 gm/L	1.5 gm/L
SDS	0.1 volume %	0.2 volume %	0.3 volume %
Sonication Time	40 minutes	60 minutes	80 minutes

A probe sonication technique was carried out to ensure the proper distribution of nanoparticles. This ultrasonication is performed for 40, 60, and 80 minutes at room temperature. After the synthesis of nanofluids, the stability of nanofluids characterization by various techniques. The thermal conductivity of nanofluids (NFs) changed into measured using a KD2 pro thermal property analyzer. This tool consists of sensors inserted into the medium and a transportable controller. The KD2 pro operates primarily based on the transient hot wire (THW) approach. The particle size distribution and zeta potential of the nanofluid had been analyzed using a Malvern Zetasizer. This instrument has been widely used by researchers to evaluate particle size distribution in nanofluids. The nanoparticle size distribution in the nanofluids was determined using the Dynamic light Scattering approach. Furthermore, this study utilized design of experiments (DOE) techniques to establish the foremost relationship between input and output parameters. The experiments were structured using the box-Behnken layout (BBD) approach, resulting in 17 experimental runs. Design Expert 13 software facilitated the improvement of the experimental design. A second-order polynomial equation was used to model the process, incorporating linear, quadratic, and interaction results between the parameters.

4. Results and Discussion

In this segment, experimental effects for Z-size, Z-potential, and Thermal conductivity are mentioned. The outcomes received for these overall performance parameters are described in **Table 4**. Box Behnken techniques were used to lay out the experiments run. This method is appropriate to make a significant relation between the process and performance parameters. The obtained outcomes were analyzed through the usage of ANOVA and analysis of variance approach [18]. ANOVA explains how variables are considerable to each other and essential to achieve the preferred outcomes.

Table 4: Experimental results for Z-size, Z-potential and Thermal conductivity

Experimental run	CNTs concentrations (gm/L)	Probe sonication time (minutes)	Surfactant concentrations (gm/L)	Z-size (nm)	Zeta-potential (mV)	Thermal conductivity (W/m.K)
1	1.25	75	0.2	90	-45.5	0.27
2	1	60	0.2	85	-46.5	0.289
3	0.75	45	0.2	75	-40.5	0.28
4	1.25	60	0.1	82	-42.5	0.26
5	0.75	60	0.1	95.5	-44	0.291
6	1.25	45	0.2	90.5	-45.2	0.271
7	1	45	0.3	83.5	-41.5	0.262
8	1	60	0.2	72.5	-39	0.24
9	1	60	0.2	98	-43.5	0.3
10	1	75	0.3	90.2	-45.3	0.271
11	1	60	0.2	84.5	-46	0.249
12	1	45	0.1	90.3	-45.4	0.271
13	1.25	60	0.3	85.5	-44.5	0.25
14	0.75	60	0.3	90.4	-45.3	0.271
15	1	75	0.1	96	-43	0.29
16	0.75	75	0.2	88.5	-42	0.27
17	1	60	0.2	98.5	-43.8	0.301

4.1 Zeta size analysis

Table 4 indicates the zeta size results for prepared nanofluids along with a specific combination of process parameters. The highest zeta size of 98.5 nm was determined in experimental run 17, while the lowest zeta size of 72.5 nm changed into found in run eight. A better zeta size is required for improved nanofluid stability, as it shows higher dispersion and reduced agglomeration. **Table**

5 indicates the ANOVA outcomes for zeta-length and model precise statistics. All measurements were performed at room temperature, and each sample was examined three times; the mean values were reported. The nanofluid was prepared with the use of specific surfactant concentrations, sonication times, and nanoparticle concentrations. For each sample, 100 ml of hydrocarbon oil was utilized and subjected to probe ultrasonication. Terms with P-values lower than 0.0500 suggest importance, and in this case, A, B, C, BC2, A^2, and B^2 are significant. Conversely, terms with P-values above 0.1000 are taken into consideration as insignificant. If many model terms are insignificant simplifying the model should enhance its performance. The F-value of 32.34 indicates that the model is statistically considerable and that such a large F-value is due to noise. The predicted R^2 cost of 0.6267 deviates appreciably from the Adjusted R^2 value of 0.9463. this may suggest a potential block effect or information/model issues, including the presence of outliers or the need for response transformation. It is recommended to explore version reduction and conduct confirmation runs to validate the empirical model. Adequate Precision, which measures the signal-to-noise ratio, must preferably exceed 4. All residuals fall inside applicable limits, confirming the model's suitability, as proven in **Figure 3** [19].

Table 5: Analysis of variance results for Zeta-size

	SOS	Degree of freedom	Mean	F-value	p-value	
Model	829.93	9	92.21	32.34	< 0.0001	**significant**
A-CNTs	578.00	1	578.00	202.70	< 0.0001	
B-Sonication Time	63.28	1	63.28	22.19	0.0022	
C-Surfactant	30.03	1	30.03	10.53	0.0141	
AB	12.25	1	12.25	4.30	0.0769	
AC	0.2500	1	0.2500	0.0877	0.7757	
BC	22.56	1	22.56	7.91	0.0260	
A^2	20.43	1	20.43	7.16	0.0317	
B^2	88.23	1	88.23	30.94	0.0008	
C^2	15.56	1	15.56	5.46	0.0521	
Residual	19.96	7	2.85			
Lack of Fit	19.81	3	6.60	178.49	0.0001	**Non-significant**

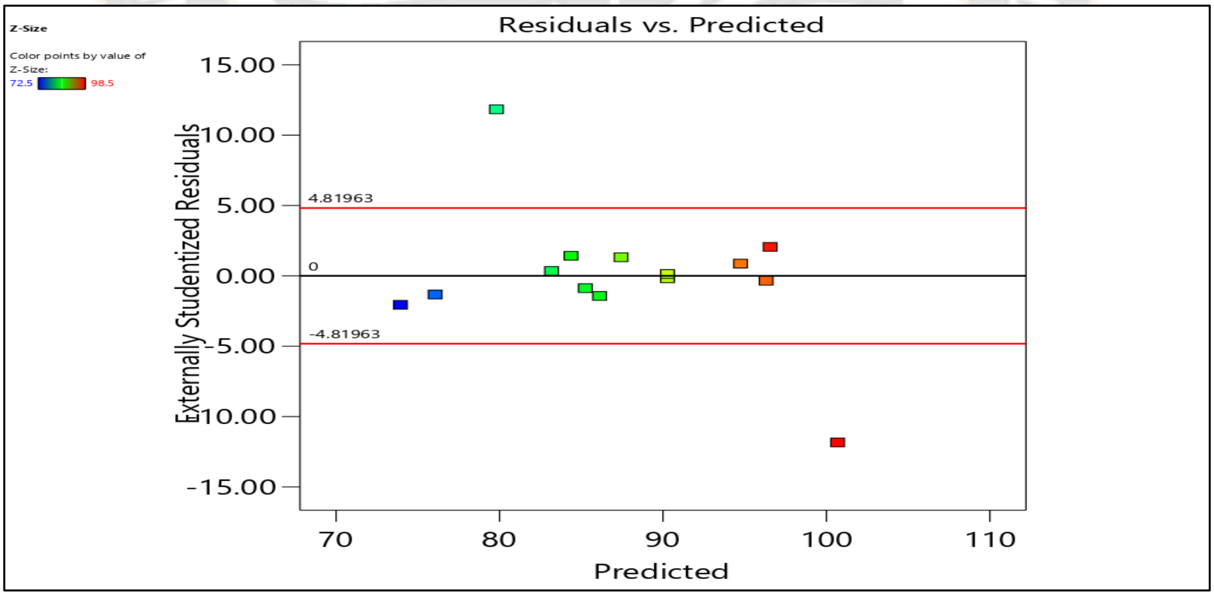

Figure 3: Model stability for zeta size results

4.2 Zeta potential analysis

Table 4 suggests the consequences for the highest zeta potential of -46.5 mV were determined in experimental run 2, while the lowest zeta potential of -39 mV turned into found in run 8. A greater negative zeta capacity is favored for higher nanofluid stability because it indicates stronger

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repulsive forces between particles, preventing agglomeration. **Table 4** indicates the zeta potential effects for prepared nanofluids along with numerous combinations of process parameters. The highest zeta potential of -46.5 mV was observed in experimental run 2, even as the lowest zeta potential of -39 mV was observed in run 8. A higher absolute value of zeta ability is desired for higher nanofluid stability, as it suggests more potent repulsive forces between particles, minimizing aggregation. **Table 6** gives the ANOVA results for zeta potential and model precise data. All measurements were performed at room temperature, and each sample was tested three times, with the mean values reported. The nanofluid was prepared with the use of different surfactant concentrations, sonication instances, and nanoparticle concentrations. For each sample, 100 ml of hydrocarbon oil was used, followed by using probe ultrasonication. Terms with P-values decrease than 0.0500 indicate significance, and in this example, A, B, A^2, and B^2 are significant. Terms with P-values above 0.1000 are deemed insignificant. Simplifying the version by removing these insignificant terms could enhance its performance. The F-value of 11.88 suggests that the model is statistically significant, with a low probability (0.18%) that such a huge F-value could be due to noise. The anticipated R^2 of 0.6267 deviates appreciably from the Adjusted R^2 of 0.9463, which may indicate ability issues with the version or statistics, such as the presence of outliers. It is recommended to explore model reduction and conduct confirmation runs to validate the empirical model. Adequate Precision, which measures the signal-to-noise ratio, needs to ideally exceed four. With a ratio of 10.779, the model is deemed suitable for navigating the design space. All residuals fall within desirable limits, confirming the model's suitability, as shown in **Figure 4** [20].

Table 6: Analysis of variance results for Zeta-potential

	SOS	Degree of freedom	Mean	F-value	p-value	
Model	65.12	9	7.24	11.88	0.0018	significant
A-CNTs	9.68	1	9.68	15.90	0.0053	
B-Sonication Time	1.13	1	1.13	1.85	0.2162	
C-Surfactant	2.21	1	2.21	3.62	0.0988	
AB	0.0000	1	0.0000	0.0000	1.0000	
AC	0.8100	1	0.8100	1.33	0.2866	
BC	0.2500	1	0.2500	0.4106	0.5421	
A^2	46.41	1	46.41	76.22	< 0.0001	
B^2	2.50	1	2.50	4.10	0.0825	
C^2	1.95	1	1.95	3.20	0.1169	
Residual	4.26	7	0.6089			
Lack of Fit	4.21	3	1.40	107.95	0.0003	significant

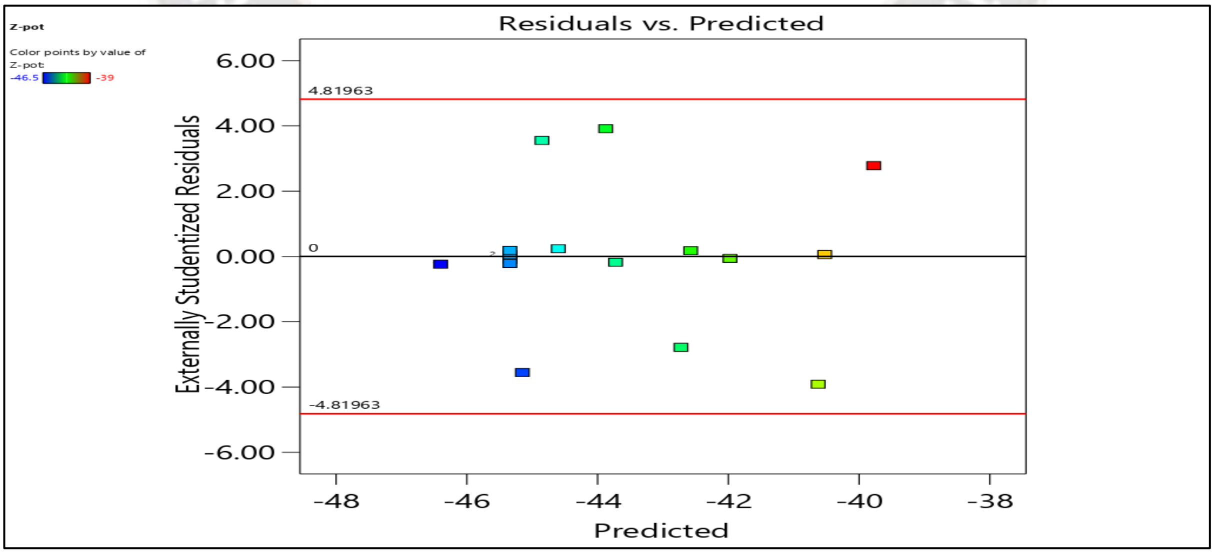

Figure 4: Model stability for zeta size results for zeta potential

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4.3 Thermal conductivity analysis

Table 4 shows the thermal conductivity outcomes for prepared nanofluids together with diverse combos of process parameters. The highest thermal conductivity of 0.421 W/mK was determined in experimental run 12, while the lowest thermal conductivity of 0.324 W/mK was found in run 5. A better thermal conductivity is desired for stepped-forward heat transfer performance in nanofluids. **Table 7** presents the ANOVA results for thermal conductivity and model summary data. All measurements were achieved at room temperature, and each sample was tested in 3 instances, with the mean values reported. The nanofluid changes into prepared using different surfactant concentrations, sonication times, and nanoparticle concentrations. For every sample, 100 ml of hydrocarbon oil was applied and subjected to probe ultrasonication. Terms with P-values lower than 0.0500 indicate importance, and in this case, A (CNT concentration), A^2, and B^2 are significant. Terms with P-values above 0.1000 are considered insignificant. Simplifying the version by removing these insignificant terms could enhance its predictive performance. The F-value of 11.88 indicates that the model is statistically substantial, with a low opportunity (0.18%) that this kind of large F-value may be because of noise. The predicted R^2 cost of 0.6267 deviates significantly from the Adjusted R^2 value of 0.9463, indicating potential problems which include the presence of outliers or the need for response transformation. Adequate Precision, which measures the signal-to-noise ratio, should ideally exceed 4. In this model, a ratio of 10.779 confirms its suitability for navigating the design space. All residuals fall within acceptable limits, confirming the reliability of the model, as shown in **Figure 5** [21].

Table 7: Analysis of variance results for Thermal conductivity

	SOS	Degree of freedom	Mean	F-value	p-value	
Model	0.0049	9	0.0005	51.54	< 0.0001	significant
A-CNTs	0.0018	1	0.0018	168.47	< 0.0001	
B-Sonication Time	0.0029	1	0.0029	271.26	< 0.0001	
C-Surfactant	0.0000	1	0.0000	3.05	0.1245	
AB	0.0000	1	0.0000	2.38	0.1669	
AC	0.0000	1	0.0000	1.93	0.2076	
BC	2.500E-07	1	2.500E-07	0.0238	0.8818	
A^2	0.0001	1	0.0001	10.42	0.0145	
B^2	0.0000	1	0.0000	4.63	0.0684	
C^2	0.0000	1	0.0000	2.21	0.1804	
Residual	0.0001	7	0.0000			
Lack of Fit	0.0001	3	0.0000	121.25	0.0002	significant

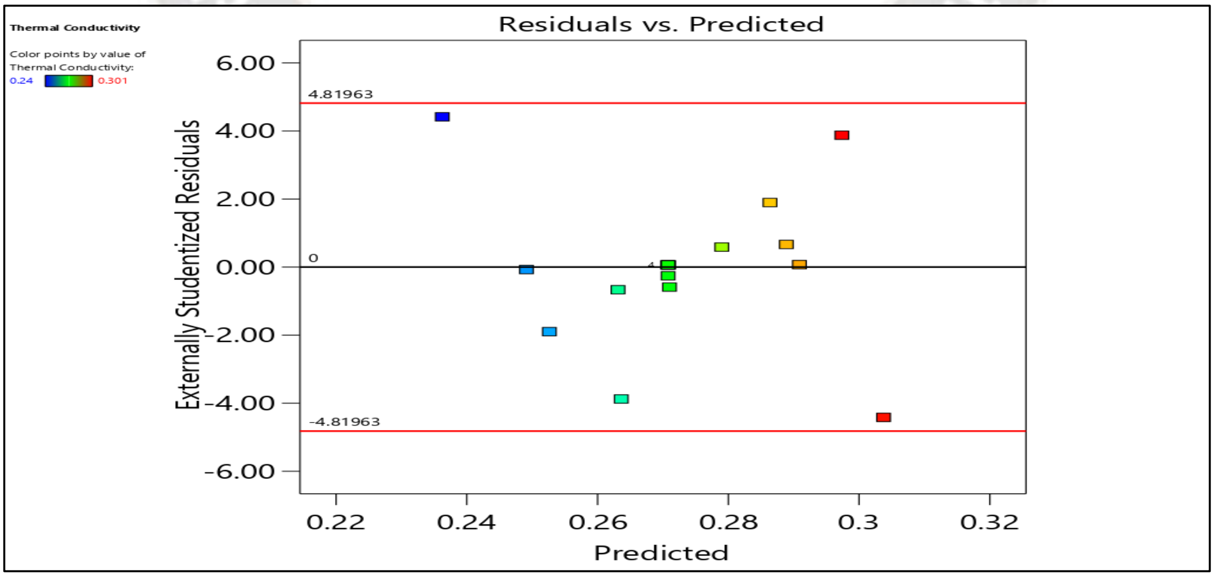

Figure 5: Model stability for zeta size results for thermal conductivity

5. Conclusions

In this work, CNTs-based nanofluids are prepared, characterized and optimized in terms to acquire the preferred properties. The process parameters were optimized using ANOVA strategies and thermal conductivity, zeta size and zeta potential are characterized and their results are as follows:

1. The results show that the highest zeta size (98.5 nm) was obtained with the combination of 1 gm/L CNTs concentration, 60 minutes probe sonication time, and 0.2 volume % of SDS surfactant. The highest zeta size suggests the advanced stability of nanofluids.
2. The highest zeta potential of -46.5 mV was determined in experimental run 2, even as the lowest zeta potential of -39 mV was determined in run 8. A greater negative zeta potential is preferred for higher nanofluid stability, as it suggests stronger repulsive forces between particles, preventing agglomeration.
3. The highest thermal conductivity of 0.421 W/mK was determined in experimental run 12, even as the lowest thermal conductivity of 0.324 W/mK was determined in run 5. A higher thermal conductivity is preferred for progressed heat transfer efficiency in nanofluids.
4. The experimental results indicate that the improved properties of nanofluids are most suitable as dielectical fluids for sustainable advanced machining processes.

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