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Effect of CuO and SiC Nanoparticles on Thermal Performance of Transformer Oil: Taguchi Method Approach

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ABSTRACT

Efficient thermal management is vital for reliable transformer operation, especially in tropical climates like India where high ambient temperatures challenge conventional cooling systems. This study examines the enhancement of heat transfer performance in IS335 transformer oil by incorporating copper oxide (CuO) and silicon carbide (SiC) nanoparticles, forming nano-transformer oils (NTOs). A systematic Design of Experiments (DOE) approach using the Taguchi method (L9 orthogonal array) was adopted to optimize three key parameters: nanoparticle concentration (0.1–0.3 g/L), nanoparticle size (10–20 nm), and the surfactant-to-nanoparticle weight ratio (0.1–1). The results indicate that for CuO NTO, nanoparticle size is the most influential factor, contributing 89.04% to the heat transfer enhancement. In contrast, for SiC NTO, both nanoparticle size and concentration significantly impact performance, each accounting for approximately 34% of the variation. Under optimized conditions, CuO NTO demonstrated a 17.19% improvement, while SiC NTO showed a 13.06% improvement in heat transfer performance compared to base transformer oil. The outcomes were validated through confirmation tests and regression analysis, confirming the robustness of the optimization. While the findings underscore the potential of NTOs for advanced transformer cooling, further research is recommended in areas such as cost-effective formulation, long-term stability, environmental assessment, and commercialization strategies.

Keywords – *Heat transfer, Nanoparticle, SiC (Silicon Carbide),CuO, Taguchi Method, Transformer.*

1. INTRODUCTION

In modern electrical power systems, transformers are critical components that ensure efficient transmission and distribution of electrical energy. The performance and longevity of transformers heavily depend on effective thermal management and insulation properties of the insulating fluids used. Conventional transformer oils, while widely employed, face limitations in thermal conductivity and heat dissipation, which can lead to overheating, reduced efficiency, and shortened operational lifespan [1].

Recent advancements have demonstrated that incorporating nanoparticles into transformer oil—forming nanofluids—can significantly enhance its thermo-physical properties, particularly thermal conductivity and heat transfer efficiency. Among various nanoparticles studied, copper oxide (CuO) and silicon carbide (SiC) have attracted considerable interest due to their high thermal conductivities and compatibility with transformer oil matrices. These nanomaterials hold promise for improving the thermal performance of transformer oils, thus addressing critical challenges related to transformer overheating and efficiency [2] [3].

However, the benefits of nanofluids are highly dependent on factors such as nanoparticle size, concentration, and dispersion stability. Optimizing these parameters is essential for maximizing thermal performance while maintaining electrical insulating properties. To systematically analyse and optimize these factors, experimental design techniques like the Taguchi Method have been effectively employed, enabling a reduction in experimental trials and providing statistically significant insights into process parameters [4] [5].

Despite growing interest, comprehensive studies evaluating the impact of CuO and SiC nanoparticles on transformer oil's thermal behaviour—using robust statistical approaches—remain limited. This research aims to fill this gap by investigating the influence of these nanoparticles on the thermal performance of transformer oil through a systematic Taguchi-based experimental approach. The study seeks to determine optimal nanoparticle concentrations and dispersion conditions that enhance heat transfer, thereby contributing to the development of more efficient and reliable transformer systems.

2. SYNTHESIS OF SIC AND CUO NANOFLUID-BASED TRANSFORMER OIL

In this study, nine distinct nanofluid samples were synthesized by systematically altering three critical parameters: nanoparticle concentration, particle size, and surfactant content. Silicon carbide (SiC) and copper oxide (CuO) nanoparticles, each with a purity of 99%, were individually dispersed into transformer oil to prepare the samples. The SiC nanoparticles had average diameters of 10 nm, 15 nm, and 20 nm. Sodium dodecyl sulfate (SDS) was selected as the surfactant to aid in stabilizing the nanoparticle dispersion within the oil matrix.

A two-step synthesis approach was employed for the preparation of both SiC and CuO nanofluids, as illustrated in Figure 1. In the first step, a precise amount of nanoparticles was measured using a high-accuracy analytical balance and then introduced into the transformer oil. The resulting mixture was stirred using a magnetic stirrer for 20 minutes at 1800 rpm to achieve preliminary dispersion.

The second step involved subjecting the mixture to ultrasonic agitation for a total of 60 minutes, divided into three cycles of 20 minutes each, with 5-minute rest intervals in between. This ultrasonication process played a crucial role in breaking down any particle agglomerates and ensuring homogeneous distribution throughout the base fluid.

Following dispersion, the samples were placed in a vacuum oven at 50°C for 24 hours to remove any residual moisture and entrapped gas bubbles that may have formed during the mixing stages. After vacuum drying, the nanofluids were allowed to cool at room temperature for approximately 15 minutes. These prepared samples were then ready for subsequent heat transfer and dielectric performance testing.

Figure 1 provides a schematic overview of the two-step synthesis process used for preparing SiC and CuO nanofluid transformer oils.

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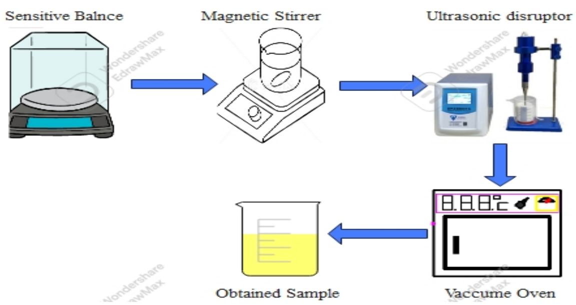

Fig. 1. Nano-Oil Synthesis Process

3. EXPERIMENTAL CONFIGURATION

The experimental setup designed to evaluate the heat transfer performance of the nanofluids is systematically illustrated in **Figure 2**. This configuration incorporated a 230V alternating current (A.C.) power supply, which was securely connected to a heating plate, serving as the primary heat source. The key objective of this setup was to assess thermal behavior through precise temperature monitoring.

Two specific temperature points were tracked throughout the experiment. The first, labeled **T2**, corresponded to the temperature at the surface of the heating plate, while the second, **T1**, denoted the temperature at the external surface of the fluid sample. Temperature readings were logged every five minutes, and this process continued until thermal equilibrium was achieved.

Upon reaching steady-state thermal conditions, the **heat transfer coefficient (H)** was determined—a critical parameter reflecting the efficiency of thermal energy transfer within the system. The calculation was based on **Newton's law of cooling**, expressed by the following relation:

$$H = (1/A) * Q/\Delta T \qquad (1)$$

Where $\Delta T = T_2 - T_1,$

Q is the heat flux,

A represents the surface area across which heat transfer takes place.

To ensure accuracy and consistency, the value of **H** was computed as the average of the last five recorded temperature values. This approach guaranteed that the derived heat transfer coefficient reflected a stabilized thermal condition, thereby offering a dependable measure of the system's heat transfer capability under the given experimental conditions.

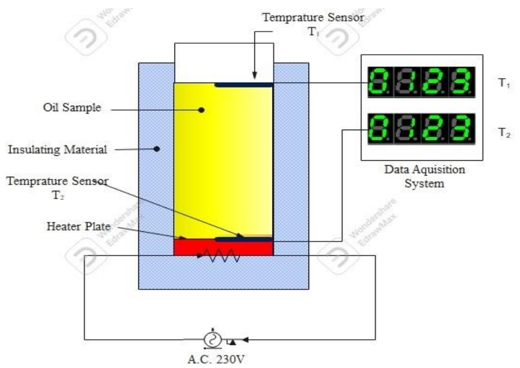

Fig 2. Experimental Configuration

4. EXPERIMENTAL DESIGN AND METHODOLOGY

The Design of Experiments (DOE) is a rigorous, systematic framework used to plan, conduct, and analyse experiments for optimizing processes, improving product quality, and minimizing costs. This approach incorporates various statistical techniques, including General Full Factorial Design, Two-Level Fractional Factorial Designs, Taguchi's Orthogonal Arrays, Plackett-Burman Designs, and Response Surface Methodology (RSM) [6].

Among these techniques, the Taguchi method stands out for its effectiveness in enhancing process efficiency and product quality through statistical analysis. Widely utilized in engineering applications, this method strategically employs orthogonal arrays to construct an efficient test matrix, enabling extensive data collection with minimal experimental runs while identifying optimal parameter configurations [7][8].

In this research, the Taguchi method serves as a powerful statistical tool for optimizing input parameters to maximize the output response—**heat transfer coefficient (H)**. The key input variables under investigation include:

- **A) Nanoparticle concentration**
- **(B) Nanoparticle size**
- **(C) Surfactant-to-nanoparticle weight ratio**

Each parameter is tested at three distinct levels to assess their influence on the thermal performance of nano-enhanced transformer oil. The experimental design, as detailed in Table 1, follows the Taguchi optimization approach to determine the most effective parameter combination for enhancing heat transfer.

The Taguchi Method classifies desirable performance into three categories: "smaller-the-better," "larger-the-better," And "nominal-the-best." Signal-to-Noise (S/N) analysis is employed to assess the quality characteristic, and it is expressed as follows:

$S/N=-10\log_{10}(MSD)$ (2)

Where MSD = Mead Squared Division

For Smaller the better characteristic

$MSD=(Y_1^2+Y_2^2+Y_3^2+\ldots\ldots)/n$ (3)

For Larger the better characteristic

$MSD=[(1/Y_1^2)+(1/Y_2^2)+(1/Y_3^2)+\ldots\ldots]/n$ (4)

For Nominal the best characteristic

$MSD=[(Y_1-m)^2+(Y_2-m)^2+(Y_3-m)^2+\ldots.]/n$ (5)

Through the systematic application of the Taguchi method, this study seeks to efficiently explore and optimize the interplay between input parameters and their impact on the heat transfer coefficient (H), thus contributing to a deeper understanding of the underlying processes and improving overall performance.

Within the scope of this study, we introduced a framework for assessing the responses, denoted as Y1, Y2, and Y3, which are critical indicators of the experiment's outcomes. In this context, 'n' signifies the total number of tests conducted in each trial, and 'm' represents the desired or target value that we aim to achieve in our results.

For this particular investigation, we adopted a specific quality characteristic known as "larger-the-better." This quality characteristic aligns with the notion that achieving larger values of the heat transfer coefficient (H) is indicative of superior heat transfer performance [9]. In other words, we aim to maximize the heat transfer coefficient, as larger values signify more effective heat transfer processes.

By embracing the "larger-the-better" quality characteristic, we set the stage for an in-depth analysis of how various factors and parameters affect the heat transfer coefficient. Our objective is to identify the optimal conditions that result in the highest possible heat transfer coefficient values, ultimately leading to improved heat transfer performance in the context of this study.

Table No. 1 Specification of Input Parameters and Corresponding Levels

Sr.No	*Factors*	*Levels*		
		1	*2*	*3*
1	Concentration of Nanoparticles (A) g/Lit	0.1	0.2	0.3
2	Size of Nanoparticles(B) (Nm)	10	15	20
3	Ratio of Surfactant weight to the weight of Nanoparticles (C)	0.1	0.5	1.0

Since there were three control factors, each with three levels, Taguchi recommended employing the L9 orthogonal array for conducting experiments, as presented in Table No. 2.

Table No. 2 L_9 Orthogonal Array

Trial No.		*A*	*B*	*C*
1		0.1	10	0.1
2		0.1	15	0.5
3		0.1	20	1.0
4		0.2	10	0.5
5		0.2	15	1.0
6		0.2	20	0.1
7		0.3	10	1.0
8		0.3	15	0.1
9		0.3	20	0.5

4. RESULTS AND DISCUSSION

4.1 Experimental Results

Nine formulations each of CuO NTO and SiC NTO were tested. The heat transfer coefficients (HTCs) and signal-to-noise (S/N) ratios were calculated using Newton's law of cooling and Taguchi's "larger-the-better" approach

Table 3: Average Heat Transfer Coefficient and S/N Ratio

Sample	CuO NTO HTC (W/m^2K)	S/N Ratio	SiC NTO HTC (W/m^2K)	S/N Ratio
1	539	54.63	480	53.62
4	551	54.82	490	53.80
7	560	54.96	520	54.31
9	489	53.78	530	54.48

4.2 Taguchi Analysis and ANOVA

Main effect analysis and ANOVA identified key influencing factors,
For CuO NTO, nanoparticle size had the most significant effect ($\Delta Y = 0.942$; 89.04% contribution). For SiC NTO, both concentration and size had moderate influence (~34% each).

Table 4: ANOVA Summary

Factor	CuO NTO % Contribution	SiC NTO % Contribution
NP Concentration (ς)	6.46%	34.38%
NP Size (σ)	89.04%	34.19%
Surfactant Ratio (ρ)	1.91%	28.37%
Error	2.59%	3.06%

4.3 Optimum Conditions

Optimization using Qualitek 4 software predicted the best configurations for heat transfer performance.

Table 5: Predicted Optimum Heat Transfer Rate

Oil Type	Optimum Settings (ς, σ, ρ)	Predicted HTC (W/m^2K)
CuO NTO	0.2, 10, 1	559.31
SiC NTO	0.3, 20, 1	545.57

4.4 Regression Analysis

Regression models validated the findings:

CuO NTO: $HTC = 588.8 + 68.3\varsigma - 5.7\sigma + 3.99\rho$

$R^2 = 93.03\%$

SiC NTO: $HTC = 437.35 + 116.7\varsigma + 2.33\sigma + 22.68\rho$

$R^2 = 95.98\%$

4.5 Confirmation Tests

Validation experiments confirmed predicted results.

Table 6: Confirmation Test Comparison

Oil Type	Taguchi (W/m²K)	Regression (W/m²K)	Confirmed (W/m²K)
CuO NTO	559.31	549.45	550.01
SiC NTO	545.57	541.70	530.60
Pure Oil	-	-	469.30

5. CONCLUSION

This study experimentally evaluated the heat transfer performance of CuO and SiC-based Nano Transformer Oils (NTOs). Using Taguchi design and regression analysis, it was found that **nanoparticle size is the most influential factor for CuO NTO**, whereas **both concentration and size significantly affect SiC NTO**. The optimal configurations led to a **17.19% improvement in heat transfer for CuO NTO** and **13.06% for SiC NTO**, compared to pure transformer oil. The close agreement between predicted and confirmed results validates the reliability of the models and optimization approach. These findings demonstrate the potential of NTOs to enhance thermal performance in power transformer applications.

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