Tuijin Jishu/Journal of Propulsion Technology
ISSN:1001-4055
Vol. 44 No.4 (2023)

Experimental Investigation to Improve Heat Transfer Rate of Transformer Oil Using Cuo Nanoparticles

[1]Mr. Manoj Damodar Salunke , [2]Dr. Eknath Raghunath Deore

Research Scholar S.S.V.P.S's B.S. Deore College of Engineering Dhule

Professor S.S.V.P.S's B.S. Deore College of Engineering Dhule

Abstract -In this research, we employed a statistical experimental design approach, specifically the Taguchi method using an L_9 orthogonal array robust design, to optimize experimental conditions. Our aim was to maximize the Heat Transfer coefficient of CuO-Transformer oil Nano fluid. We carefully selected three controllable factors with different levels: Concentration of Nanoparticles (0.1, 0.2, and 0.3g/lit), Size of nanoparticles (10, 15, and 20 Nm), and Ratio of Surfactant weight to Nano particles weight (0.1, 0.5, and 1).Our analysis of the results highlighted the significant role played by the Size of nanoparticles in influencing the heat transfer coefficient of the Nano fluid, accounting for approximately 88.852% of the variation. We determined the optimal settings for these three factors to maximize the heat transfer coefficient: Concentration of Nano particlesof0.2g/lit, Size of Nano particles of 10 Nm, and Ratio of Surfactant weight to Nano particles weight of 1. The Heat transfer coefficient predicted by ANOVA under these optimized conditions was 559.443W/m^2 K and by regression model was 549.45 W/m^2 K.To validate our findings, a confirmation test was conducted at these optimal conditions, and the results demonstrated a high degree of consistency between the experimental and predicted values.

Keywords: *Taguchi Method, Transformer oil, Nanoparticles, Heat Transfer coefficient, Regression analysis, Nano fluid.*

1. Introduction

The transformer is the heart of transmission as well as the distribution system, as it is the most important part of the transmission system; its performance affects the system considerably. It is used to step up the voltage in transmission lines and to step down the voltage in distribution lines. During the transformation of voltage, heat is generated inside the transformer core. For safe operation and to avoid overheating of a transformer, this heat needs to be dissipated to the surroundings. In a tropical country like India, the ambient temperature during summer rises above 400, so it becomes challenging to keep transformers cool. Sometimes extra desert coolers are used to maintain the required temperature of the transformers at substations. Recently researchers have found that the suspension of Nanoparticles in base transformer oil improves the heat transfer performance of transformer oil [1].

C. Choi et.al, investigated Al_2O_3 and AlNsuspension in transformer oil. Suspension of AlN (Aluminium Nitride) particles at a volume fraction of 0.5% showed increase in overall heat transfer coefficient by 20%. Spherical shaped Al_2O_3 nanoparticles at 4 % volume fraction also showed 20% rise in overall heat transfer coefficient [2]. Diaa-Eldin A. Mansour et.al, have tested Al_2O_3 nanoparticle suspension in transformer oil for its heat transfer performance by adding surfactant at weight percentage of 0.1% and 1%.. The heat transfer performance is observed at the concentrations of Al_2O_3 nanoparticle varying from 0.1 g/L to 0.6 g/L. The study revealed that the heat transfer performance is not only depends on the concentration of nanoparticles but also on the weight percentage of surfactants [3].B. X. Du, investigated the effect of Boron nitride (BN) and ferriferous oxide (Fe_3O_4) nanoparticles on thermal and dielectric properties on transformer oil. The experimentation concluded the improvement in both breakdown strength and the thermal properties like thermal conductivity and thermal diffusivity as compared to pure oil. The Nano-oil with BN particles showed better thermal conductivity than Fe_3O_4 Nano-oil [4]. Weimin Guan et.al. Analysed the numerical simulation of transformer filled with Nano-oil. The simulation results revealed that the heat transfer characteristics are improved under natural convection. In case of forced convection the results showed slight changes in heat transfer characteristics due to major influence of inlet velocity as the distribution of the Nano-oil is depending on temperature and flow velocity of oil [5]. Joyce Jacob et.al compared thermal resistance and thermal capacitance of pure transformer oil and AlN nanoparticles filled transformer oil using simulation model and the results are validated experimentally.An optimum nanoparticle concentration of 0.20% by weight, showed 1.54% reduction in thermal resistance as compared to pure transformer oiland 1.58% reduction in the value of capacitance as compared to pure transformer oil [6].BizhanMehrvarz et.al. Three dimensionally simulated the three-phase transformer and studied heat transfer performance of pure transformer oil and TiO_2 nanoparticles filled transformer oil. The simulation study revealed that the Nano-oil filled with TiO_2 particles has increased heat transfer coefficient as compare to pure transformer oil [7].Diaa-Eldin A. Mansour et.al made suspension of barium titanate (BT) nanoparticles in transformer oil by 0.01g/L and 0.02g/Lconcentration. The sample with 0.01 g/L concentration results in 28.3% increase in heat transfer coefficient and 2 % increase in breakdown voltage. Due to agglomeration of nanoparticles the sample with 0.02 g/L concentration given unsatisfactory results as compared to the sample with 0.01 g/L concentration [8]. Mansour et.al also studied the hybrid Nano-fluid sample with 0.01% volume fraction of TiO_2 nanoparticles and 0.005% volume fraction of BT nanoparticles which showed 33% increase in heat transfer coefficient and 45% rise in breakdown voltage [9]. Majority of researchers has found that suspension of the nanoparticles with the transformer oil increases heat transfer rate of the oil as compare to the pure oil. It can be clearly observed in the literature that the percentage increase in heat transfer rate depends on certain parameters such as concentration of nanoparticle, use of surfactant, size of nanoparticles, maximum temperature, type of nanoparticles etc. It is observed that there is lacuna of statistical analysis to find the most significant parameters and interrelationship between them. In the present work the effect of three factors, such as concentration of CuO nanoparticles, Size of these particles and concentration of surfactant on the heat transfer coefficient of transformer oil is analysed by using the Taguchi Method of Design of experiments.

To find the optimum level of selected factors, it is important to find the interrelationship between them and their influence on the output variable. Therefore to analyse such complex systems conventional approaches like full factorial experimentation are tardy and inefficacious. This kind of complex systems can be easily and effectively analysed by Taguchi method of design of experiments and ANOVA.In this approach experiments were planned according to the standard orthogonal arrays determined by Taguchi. Results obtained from experimentations were analysed by the standard method proposed by the approach [10-11]. The use of Taguchi orthogonal arrays minimizes the number of test experimentsconsiderably and gives best optimum combination of parameters [12].

The present investigates the factors like concentration of nanoparticles, size of nanoparticles and concentration of surfactant affecting on the heat transfer performance of the Copper oxide transformer oil Nano fluidby Taguchi method. The major aims of this study are 1) To investigate the impact of each factor on the heat transfer coefficient and 2) To find combination of optimum levels of factors to maximize the heat transfer coefficient.

2. Preparation of CuO Transformer oil Nano-fluid

In this study total nine samples were prepared with certain combination of factors like concentration of nanoparticles, size of nanoparticles and concentration of surfactant. The samples were prepared by dispersing CuO nanoparticles of average particle sizes 10nm, 15nm and 20nm with 99% purity in the transformer oil, and Sodium dodecyl sulphate (SDS) was used as a surfactant.

Two-step method of Nano fluid preparation was employed to obtain various samples of CuO transformer oil Nano-fluid as shown in figure 1, in which nanoparticles purchased from laboratory were mixed with the transformer oil. The required quantity of nanoparticles was measured by using sensitive weight balance and dispersed in the transformer oil. The mixture was stirred by magnetic stirrer for 20 minutes at 1800rpm. To improve the dispersion of nanoparticles in the transformer oil the mixture was processed under the ultrasonic disruptor for 60 minutes by giving 5 minutes interval after every 20 minutes. To remove the water content and gas bubbles formed during stirring the obtained sample was kept in vacuum oven at 50^0C for 24 hours. The sample was allowed to cool for 15 minutes before testing it for the heat transfer performance.

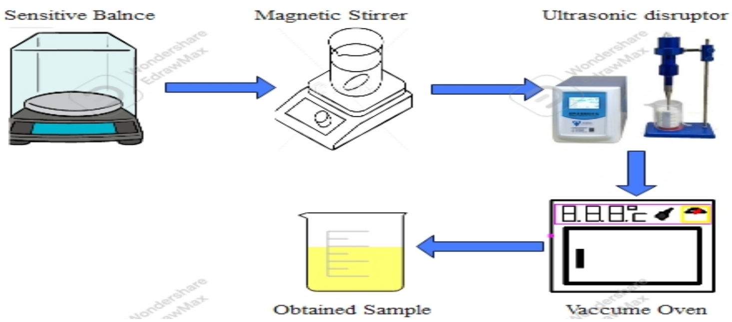

Figure 1. Nano fluidPreparation Procedure

3. Experimentation Setup

The setup utilized to conduct the heat transferability test is shown in Figure 2. An A.C. at 230V power supply was connected to the heater plate. The surface temperature at the heater plate ($T2$) and the temperature at the outer surface of oil T1 were both measured. The temperatures were monitored at intervals of 5 minutes until thermal stability was achieved. The heat transfer coefficient (H) was then calculated as the average of the last five recorded values. The following equation given by the Newton's law of cooling is used to calculate the heat transfer coefficient

$$H = \frac{Q}{A(T2-T1)} (1)$$

Whereas$H$ $(W/m^2\ K)$ is the heat transfer coefficient, Q (W) is the heat flux and A (m^2) is the surface area of heater plate.

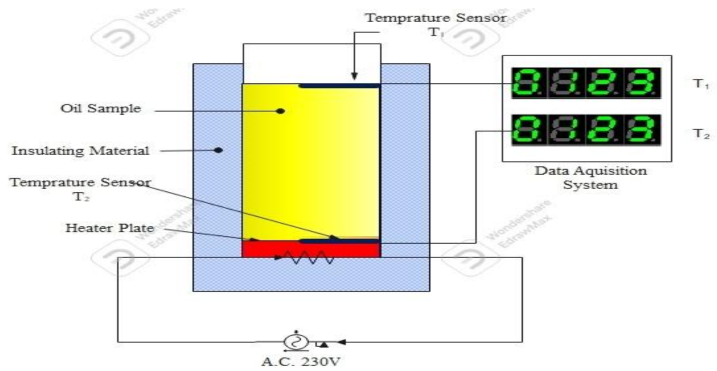

Figure 2. Experimental Arrangement to find Heat Transfer rate

3. Design of Experiments

Design of Experiments (DOE) is a systematic and efficient approach to planning, conducting, and analyzing experiments in order to optimize processes, improve product quality, and reduce costs. It encompasses a variety of methods and techniques such as General Full Factorial Design, Two-Level Fractional Factorial Designs, Taguchi's Orthogonal Arrays, Two-Level Full Factorial Designs,Plackett-Burman Designsand Response Surface Method (RSM) Designs etc [13].

The Taguchi method has been employed to enhance the quality of both processes and products by applying statistical principles. This approach finds widespread application in engineering analyses due to its versatility. It has been demonstrated that this technique can be highly effective when used with careful consideration of the relevant factors [14].Taguchi's approach is an experimental optimization method that leverages standard orthogonal arrays to construct a test matrix. This method facilitates the acquisition of a substantial amount of data while conducting the minimum number of tests, ultimately leading to the optimal values for each parameter [15].

The design of experiments (DOE) using the Taguchi method is a powerful statistical tool for optimizing input parameters and improving output function. In the context of the study mentioned, input parametersare (A) concentration of nanoparticles, (B) Size of nanoparticles and (C) Ratio of surfactant weight to nanoparticles weight and their three corresponding levels are crucial in determining the heat transfer performance of the Nano-transformer oil. The goal is to optimize these input parametersusing the Taguchi method as given in Table No. 1 to improve the output i.e. heat transfer coefficient (H).

The Taguchi Method categorizes desirable performance into three groups: "smaller-the-better," "larger-the-better," and "nominal-the-best." Signal-to-Noise analysis is employed to assess the quality characteristic, and it is expressed as follows:

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

Where MSD = Mead Squared Division

For Smaller the better characteristic

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

For Larger the better characteristic

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

For Nominal the best characteristic

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

In this study, where Y1, Y2, and Y3 represent the responses, n stands for the number of tests in a trial, and m represents the target value of the result, a "larger-the-better" quality characteristic was implemented and introduced. It's worth noting that larger valuesof heat transfer coefficient indicate improved heat transfer performance [16]

Table No. 1 Input parameters/factors and their levels

Sr.No	Factors	Levels		
		Level 1	Level 2	Level 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

As there were 3 control factors and three levels Taguchi suggests L9 orthogonal array to conduct experiments as given in table No. 2.

Table No. 2 L9 Orthogonal Array

Trial No.	A	B	C	H	SNRA1
1	0.1	10	0.1	539	54.6318

2	0.1	15	0.5	501	53.9968
3	0.1	20	1.0	489	53.7862
4	0.2	10	0.5	551	54.8230
5	0.2	15	1.0	521	54.3368
6	0.2	20	0.1	501	53.9968
7	0.3	10	1.0	560	54.9638
8	0.3	15	0.1	521	54.3368
9	0.3	20	0.5	489	53.7862

4. Results and Discussion

4.1 Taguchi Results

The results were analyzed and control factors were optimized using Qualitek-4 (QT4) software. QT4, version 4.75, is Windows-based software designed for the analysis and automated planning of Taguchi experiments.

Following the Taguchi method outlined in Table 2, experiments L-9 were conducted to assess the primary influence of control factors, representing the trends in their effects. Main effects were calculated using the average results.

Figures 3, 4, and 5 illustrate the impacts of concentration of nanoparticles, size of nanoparticles and ratio of weight surfactant to weight of nanoparticles on the heat transfer coefficient of transformer oil based Nano-fluid. Fig. 3 specifically depicts the influence of concentration of nanoparticles on the average response value. It is evident from the figure that as the concentration of nanoparticles increases from level 1 to 3 (ranging from 0.1 to 0.3g/Lit); the average heat transfer coefficient also increases. The highest average response, reaching 524$W/m^2 K$, is achieved at level 2 (0.2 g/Lit). Therefore, to attain the optimal response value, it is essential to optimize the concentration of nanoparticles.

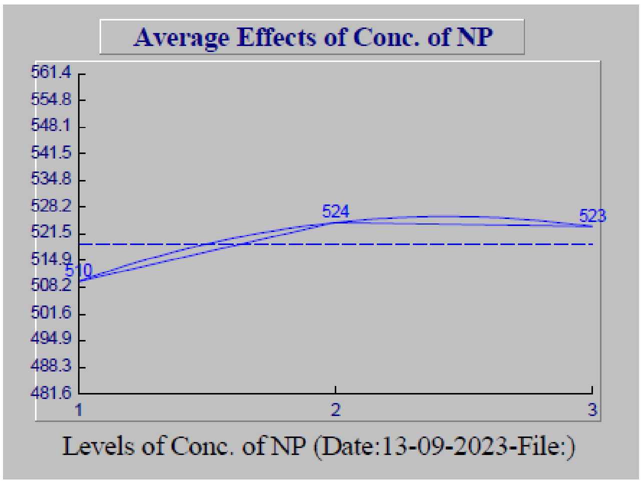

Figure 3:Effect of Concentration of Nanoparticles on Heat transfer Coefficient

Figure 4 illustrates that increasing the size of nanoparticles from level 1 to level 3 (from 10Nm to 20Nm) has a negative impact on the average response value. To achieve the maximum response value, it is essential to use the minimum size of nanoparticle i.e. 10 Nm.

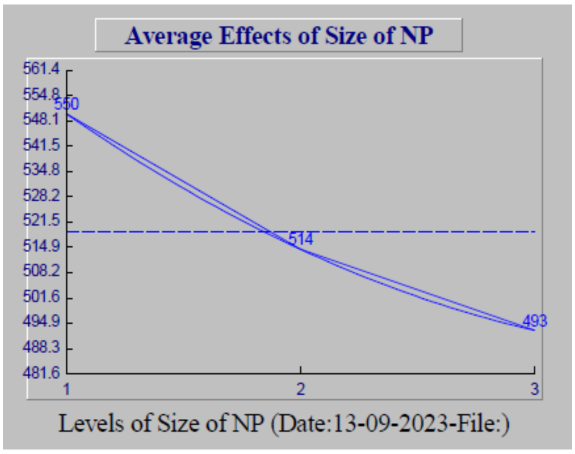

Figure 4: Effect of Size of Nanoparticles on Heat transfer Coefficient

Figure 5 provides insight into the influence of surfactant concentration on the average response value. As anticipated, raising the concentration level from 1 to 3 (from 0.1 to 1.0wt.% of nanoparticles) resulted in an increase in the average response value at level 3, reaching its peak (523W/m^2K) at level 3. This observation aligns with previous research findings, which have indicated that the enhancement of heat transfer in Nano fluids can be attributed to several factors.

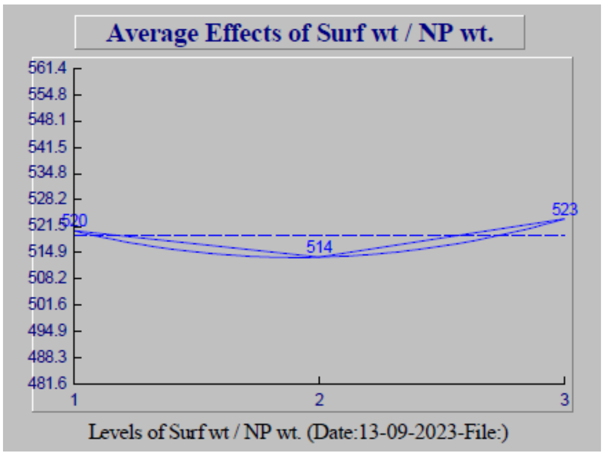

Figure 4: Effect of Ratio of surfactant weight to weight of Nanoparticles on Heat transfer Coefficient

4.2 Analysis of Variance (ANOVA)

An ANOVA analysis was conducted using Qualitek-4 software, which presents the significance of each factor as a percentage in the final column of Table 3.

Table 3: Analysis of Variance

Sr. No.	Factors	DOF	SS	Variance	F-Ratio	Pure Sum	%
1	Concentration of NP(A)	2	402.729	201.364	11.449	367.554	6.609
2	Size of NP(B)	2	4976.159	2488.079	141.467	4940.984	88.852
3	Ratio of Surfactant weight to NP weight (C)	2	146.824	73.412	4.174	111.648	2.007

Other/Error		2	35.174	17.587			2.532
Total		**8**	**5560.888**				**100%**

From ANOVA it is clear that Size of nanoparticles is the most significant factor. The Optimum conditions and the optimum results are calculated with the help of ANOVA and given in Table 4. Influence on significant factors on output parameter is shown in Figure 5.

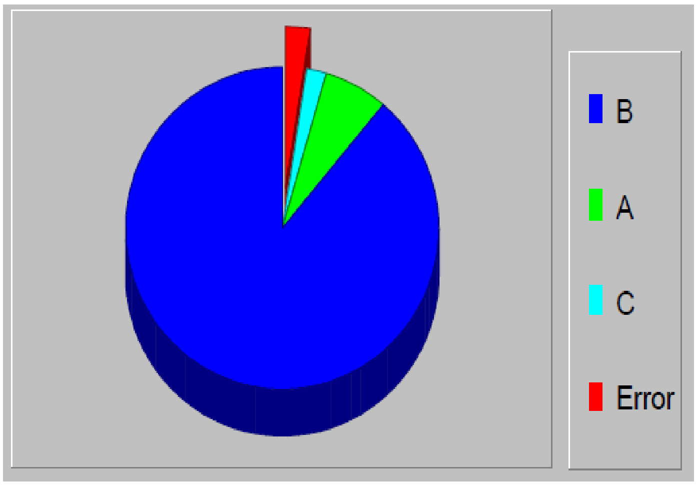

Figure 5: Significant factors and Interactions influences

Table 4 Optimum condition and Performance

Sr. no.	**Factors**	**Level Description**	**Level**	**Contribution**
1	Concentration of NP(A)	0.2	2	5.222
2	Size of NP(B)	10	1	30.888
3	Ratio of Surfactant weight to NP weight (C)	1	3	4.222

Total Contribution from all factors 40.332

Current grand average of performance 519.111

Expected result at optimum conditions **559.443 (**Predicted by ANOVA done in QT4 software)

4.3 Regression Analysis

Regression analysis of the test data reveals the relationship between controllable parameters and the average output, expressed in the form of the following linear equation.

H = 588.8 + 68.3 A - 5.700 B+ 3.99 C(6)

Where H = Response i.e. Heat transfer coefficient ($W/m^2\ K$)

A = Concentration of Nanoparticles g/Lit

B = Size of Nanoparticles (Nm)

C **=** Ratio of Surfactant weight to the weight of Nanoparticles

By substituting the optimum parameters derived through ANOVA into equation no. 6, we will obtain the optimal value for the quality characteristic. This optimal value is expected to maximise the heat transfer coefficient on the Nano fluid.

$H_{opt} = 588.8 + 68.3 * 0.2 – 5.700 * 10 + 3.99 * 1$

$H_{opt = 549.45}$ (Predicted by Regression equation)

4.4. Confirmation Experiment

To validate the predicted results, a confirmation experiment was carried out, involving an additional four trials. These trials were conducted under the optimal settings of the process parameters determined from the ANOVA, specifically CuO Transformer oil Nano-fluid was prepared by using Concentration of NP at 0.2 g/lit, Size of NP at 10Nm and Ratio of Surfactant weight to NP weight as 1 and tested in the experimental setup to find the heat transfer rate. Results of confirmation experiment are presented in Table 5.

Observation	Trial 1	Trial 2	Trial 3	Trial 4	Avg. Heat Transfer rate
Heat Transfer rate in (W/m^2 K)	553.62	556.55	547.86	545.01	550.01

From the results of confirmation experiments it observed that Average heat transfer rate i.e. 550.01 W/m^2 K falls within predicted 85% confidence interval.

5. Conclusions

An experimental investigation was conducted to evaluate the convective heat transfer coefficient of CuO-Transformer oilNano fluid. The study examined the influence of several controllable factors on the heat transfer coefficient using the Taguchi method, while considering the following parameters: Concentration of Nano particles (A) (0.1, 0.2, and 0.3g/lit), Size of nanoparticles (10, 15, and 20 Nm), and Ratio of Surfactant weight to NP weight (C) (0.1, 0.5, and 1).

The results revealed that the Heat transfer coefficient of the CuO-Transformer oilNano fluid increased with moderate Concentration of Nano particles, lower Size of nanoparticles, and higher Ratio of Surfactant weight to NP weight. Notably, the size of Nano particles emerged as the most influential parameter affecting the heat transfer coefficient. Optimal operational conditions for maximizing the heat transfer coefficient were identified as Concentration of Nano particlesof0.2g/lit, Size of NP (B) of 10 Nm, and Ratio of Surfactant weight to Nano particles weight of 1. Regression analysis also done to find the interrelationship between controllable parameters and the average output. The optimum value of output parameter predicted by the regression equation in good agreement with the output predicted by ANOVA A confirmation test was conducted, showing a prediction error of approximately 2.532%, demonstrating strong agreement between the experimental and predicted values. Leveraging the Taguchi method for test design allowed for achieving the optimal Heat transfer coefficient value with only 9 runs, significantly reducing the required experimental effort compared to 27 runs.

It's important to note that incorporating even a small quantity of nanoparticles into the working fluid to achieve marginal enhancements in heat transfer efficiency is cost-effective. OptimizingConcentration of Nano particles and Size of Nano particles presents a practical and cost-efficient alternative to achieve similar improvements in heat transfer coefficients. However, challenges, such as Nano fluid production cost and stability, remain significant obstacles to the widespread commercialization of Nano fluids. Addressing these issues is crucial to unlocking the full potential of Nano fluids as working fluids in transformer systems.

References

[1] Muhammad Rafiq, YuzhenLv, and Chengrong Li "A Review on Properties, Opportunities, and Challenges of Transformer Oil-Based Nano fluids", Hindawi Publishing CorporationJournal of Nano materials, vol. 2016, Article ID 8371560, 2016

[2] C. Choi, H. S. Yoo and J. M. Oh, "Preparation and heat transfer properties of nanoparticles in transformer oil dispersion as advanced energy efficient coolants", Current Applied Physics, Vol. 8 pp. 710-712, 2008

[3] Diaa-Eldin A. Mansour and Ahmed M. Elsaeed , " Heat Transfer Properties of Transformer Oil-Based Nano fluids Filled with Al_2O_3 Nanoparticles", IEEE International Conference Power & Energy (PECON), pp123-127, 2014.

[4] B. X. Du, X. L. Li and J. Li, "Thermal Conductivity and Dielectric Characteristics of Transformer Oil Filled with BN and Fe_3O_4 Nanoparticles", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, No.5, pp. 2530-2536, 2015.

[5] Weimin Guan, Miao Jin, Jiaqi Chen, Pan Xin, Yonghe Li. Kejie Dai, HailongZahang, Tao Huang and Ruan, "Finite Element Modelling of Heat Transfer in a Nano fluid Filled Transformer", IEEE Transactions on Magnetics, Vol. 50, No. 2, 2014

[6] Joyce Jacob, Dhanish Mon N and P Preetha, "Experimental Validation of Thermal Model of Unfilled and Nano Filled Transformer Oils", IEEEPES Asia-Pacific Power and Energy Engineering Conference, 2017

[7] BizhanMehrvarz, FatemehBahadori, SaeedZolfaghariMoghaddam, "Heat transfer enhancement in distribution transformers using TiO_2 nanoparticles", Advanced Power Technology, Vol. 30, Issue 2, pp 221-226, 2019.

[8] Diaa-Eldin A. Mansour, Essam A. Shaalan, Sayed A Ward and Adel Z. El.Dein"Effect of BT Nanoparticles on Dielectric and Thermal Properties of Transformer Oil", Proceedings of 4^{th} International Conference on Energy Engineering Faculty of Energy Engineering – Aswan University – Egypt, 2017

[9] Diaa-Eldin A Mansour, Essam A. Shaalan, Sayed A Ward, Adel Z. El Dein and Hesham S. Karaman, "Multiple Nanoparticles for Enhancing Breakdown Strength and Heat Transfer Coefficient of oil Nano fluids", Nineteenth International Middle East Power Systems Conference(MEPCON), Menoufia University, Egypt, pp-1406-1410, 2017.

[10] BehrouzRaei, "Statistical Analysis of Nano Heat Transfer in a Heat Exchanger Using Taguchi Method", Journal of Heat and Mass Transfer Research, Vol. 8, pp29-38, 2021

[11] Ravi Babu.S and SambasivaRao. G, "Experimental Investigation on Stability and Dielectric Break down Strength of Transformer Oil Based Nano-fluids", AIP Conf. Proc. 1952, pp 020075-1-020075-6, 2018.

[12] R. Rajesh, S.Sumathi, "Certain performance investigation on hybrid $TiO_2/Al_2O_3/MoS_2$ nanofiller coated 3ɷinduction motor: A Taguchi and RSM based approach", Energy Reports by Elsevier, Vol. 6, pp 1638-1647, 2020.

[13] Montgomery DC. Design and analysis of experiments: John wiley & sons; 2017

[14] Kotcioglu I, Cansiz A, Khalaji MN. "Experimental investigation for optimization of design parameters in a rectangular duct with plate-fins heat exchanger by Taguchi method", Appl Therm Eng. 2013;50(1):604-13.

[15] Sivasakthivel T, Murugesan K, Thomas HR. "Optimization of operating parameters of ground source heat pump system for space heating and cooling by Taguchi method and utility concept", Applied Energy. 2014;116:76-85.

[16] Roy, R. "A Primer on the Taguchi Method", New York: Van Nostrand Reinhold; 1990