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RESEARCH ARTICLE

Engineering

Investigation of thermal conductivity enhancement of POE oil by the addition of nanoparticles

Investigación de la mejora de conductividad térmica de aceite POE mediante la adición de nanopartículas

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Abstract. Metallic or non-metallic nanoparticles are dispersed in the common heat transfer fluids to create nanofluids. In this study, the KD2 Pro instrument is used to experimentally measure the thermal conductivity of Polyol Easter Oil (POE) with varying concentrations of Al_2O_3, TiO_2, and SiO_2 nanoparticles. The findings of the experiment are compared with well-established correlations for estimating the thermal conductivity of nanofluids. The measurement showed that the thermal conductivity of nanofluids increases linearly with nanoparticle concentration. The highest thermal con-ductivity was achieved by a 0.1% concentration of Al_2O_3 in the base fluid, which was 1.4 times more effective than POE oil as the base lubricant with thermal conductivity of 0.188 $W.(mK)_{-1}$.

Keywords: Heat transfer fluids; thermal conductivity; nanoparticles; nanofluids

Resumen.
Las nanopartículas metálicas o no metálicas estan dispersadas en los fluidos de transferencia de calor comunes para crear nanofluidos. En este estudio, el instrumento KD2 Pro se usa para la medir experimentalmente la conductividad térmica del aceite de poliólester (POE) con concentraciones variables de Al_2O_3, TiO_2 y nanopartículas de SiO_2. Los resultados del experimento son comparados con correlaciones bien establecidas para estimar la conductividad térmica de los nanofluidos. La medición mostró que la conductividad térmica de los nanofluidos incrementa linealmente con la concentración de nanopartículas. La más alta conductividad térmica see logró por una concentración de 0.1% de Al_2O_3 en el fluido base, lo cual fue 1,4 veces mas efectivo que el aceite de poliólester (POE) como lubricante base con conductividad térmica de 0,188$W.(mK)_{-1}$.

Palabras clave: fluidos de transferencia de calor, conductividad térmica, nanopartículas, nanofluidos.

1 | INTRODUCTION

Anomalous increase in thermal conductivity of fluids by adding small amount of nano size solid particles has been established by many researchers [1, 2, 3, 4]. A homogenous colloidal solution of conventional heat transfer fluids and low concentrations of nanoparticles is known as a nanofluid. Developed for dramatically improving thermal conductivity and anti-wear properties, nanofluids are a revolutionary family of thermal flu-ids. [5, 6, 7]. Because the particles are so minute and are only supplied in very small quantities to the base fluids, serious problems like sedimentation, aggregation, and clogs are avoided. The primary factor affecting how effectively heat is transferred in conventional heat transfer systems is the working fluid's thermal conduc-tivity. Additionally, lubricating oils containing nanoparticles have superior lubricating qualities to base fluids, which would boost the components' durability [8, 9, 10, 11]. Numerous studies on the thermal conductivity of nanofluids have demonstrated that the thermal conductivity rises as the volume percentage of nanoparti-cles in the base fluid increases [12, 13]. Al_2O_3 nanoparticle and R134a/polyolester mixes were employed by Kedzierski [14] to test the performance of pool boiling on a rectangular finned surface. In comparison to the base fluids, the study found an increase in heat transmission of up to 113%. In a different study, Kedzierski et al. [13] looked into the dispersion of Al_2O_3 and ZnO in polyolester lubricant. They came to the conclusion that as the volume fractions of nanoparticles grew, so did the thermal conductivities of nanolubricants. The ther-mal conductivity of two distinct forms of TiO_2 nanoparticles dispersed in deionized water was compared by Murshed and Leong [15] using experimental and mathematical data. The thermal conductivity of the nanoflu-ids was measured using a transient hot-wire setup, and the results were then compared to those obtained from theoretical calculations by Hamilton and Crosser [1], Wasp, Kenny [16], and Bruggeman [17]. They dis-covered that the volume percentage of nanoparticles had a significant impact on the thermal conductivity of nanofluids. Additionally, particle size and shape have an impact on how well thermal conductivity is enhanced in nanofluids. The experimental results were substantially higher than the thermal conductivity predicted by theoretical models. The main finding from the literature was that the thermal conductivity was improved and the thermo-physical characteristics of the nanolubricant were enhanced. The application of composite nanolubricants in refrigeration systems has, however, only been the subject of a few small investigations. De-termining how thermal conductivity of nanolubricants, which can be utilised in refrigerators, are affected by nanoparticle volume concentration was the main goal of the current work. The purpose of the current work is to investigate the thermal conductivity of polyolester oil that contains Al_2O_3, TiO_2, and SiO_2 nanoparticles in two distinct concentrations. The results of the experiments are then contrasted with those predicted by vari-ous theoretical and empirical thermal conductivity models, including those of Maxwell, Hamilton and Crosser, Bruggeman, Yu, and Choi. Our research contributes to and expands the literature on the current debates on enhancement of thermal conductivity by addition of nano size particles in the base fluid.

2 | METHODOLOGY

2.1 | Preparation of nanolubricant

The high quality, fewer than 80 nm-sized nanoparticles used in this study were purchased. Field emission scan-ning electron microscopy is used to characterize nanoparticles (FeSEM). Al_2O_3, TiO_2, and SiO_2 were introduced as nanoparticles to the POE oil's base fluid. The FeSEM images of Al_2O_3, TiO_2, and SiO_2 nanoparticles are examined for size and aggregation. The physical properties of the nanoparticles are given in Table 1 [18].

TABLE 1 Thermophysical properties

Nanoparticles	Al_2O_3	TiO_2	SiO_2	POE Oil
Size (Nano-meter)	40 to 80	25	30	-
Thermal Conductivity (W/m K)	36	8.4	1.2	0.136
Density (kg/m3)	3700	3900	2600	840
Specific heat (J/kg K)	773	692	703	1994

The volume concentration (∅) of nanofluids can be estimated from equation (1) [19]. By knowing volume concentration, and using density from Table 1, Equation 1 can be used to estimate the mass of nanoparticles.

$$\varnothing = \frac{m_p}{\rho_p}/(\frac{m_p}{\rho_p} + \frac{m_b f}{\rho_b f}) \times 100 \qquad (1)$$

The nano lubricants were made using a two-step procedure [12, 20]. The POE oil was mixed with the 0.05% and 0.1% volume fractions of nanoparticles, and the mixtures were agitated for two hours using a magnetic stirrer, as shown in Fig.1 (a). After that, the mixtures were vibrated for 30 minutes in an ultrasonic homogenizer Fig.1 (b) to completely separate the nanoparticles and avoid their agglomeration and sedimentation.

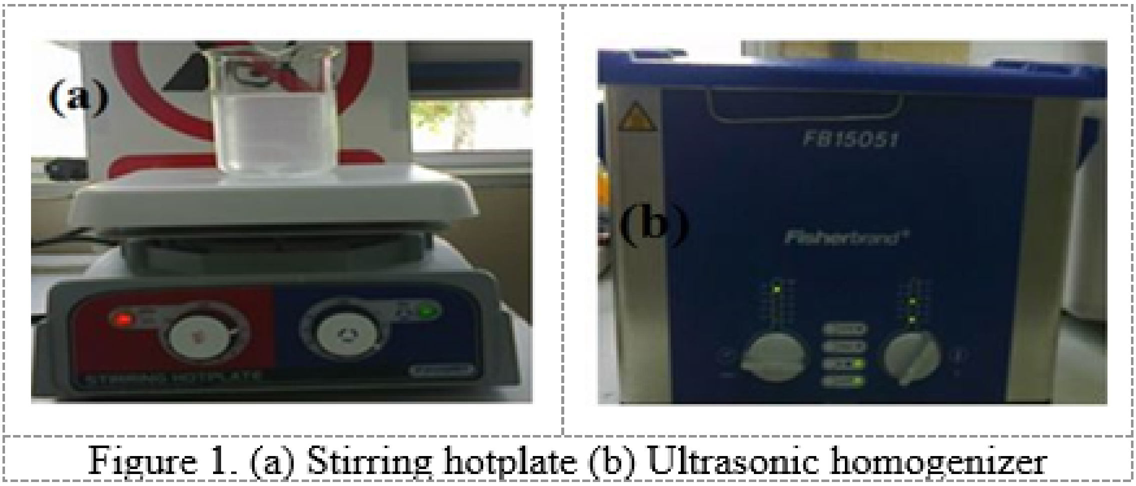

FIG. 1 (a) Stirring hotplate (b) Ultrasonic homogenizer

No surfactant was added to the mixtures as it can change the thermophysical properties of the nano lubricants. The nano lubricants were observed for sedimentation for forty-eight hours. The agglomeration or sedimentation did not occur and nano lubricants were stable during the observations, and this could be due to low volume fractions of the nanoparticles [21, 22].

2.2 | Thermal Conductivity measurement

Fig.2 illustrates an experimental measurement of the thermal conductivity of a nano lubricant using the transient hot-wires approach. First, the device was calibrated using the supplied reference fluid (glycerin). The transient hotwire method is more suitable for nanofluids as compared to steady-state parallel plate method and temperature oscillation methods since it is very difficult to apply these techniques directly to nanofluids or nano lubricant. The glycerin value was tested at 298 K and was 0.285 W m-1 K-1 with a precision of ±0.35%. Thus, the value matched the calibrated glycerin data, which was provided and is 0.286 Wm-1 K-1. To control the samples' temperature, a water bath was utilized. The probe was carefully positioned vertically without shaking or vibrating, which could have led to inconsistent readings.

FIG. 2 Thermal conductivity and specific heat measuring apparatus.

2.3 | Theoretical models of Thermal conductivity

There are a number of theoretical and empirical models that researchers have created over the years that can be used to predict the effective thermal conductivity of nanofluids or nanolubricants. In order to calculate the thermal conductivity, several of the most used models are employed in this study. Using the Effective Medium Theory, Maxwell and Thompson [23] created the first equation (Equation 2) describing the thermal conductivity of suspension with a spherical particle shape. In this model, low particle volume concentration is anticipated to cause particle dispersion.

$$\frac{K_eff}{K_L} = \frac{K_s + 2K_L + 2(K_s - K_L)\varphi s}{K_s + 2K_L - (K_s - K_L)\varphi s} \tag{2}$$

According to Maxwell's formula, the thermal conductivity of nanofluids is dependent on the thermal conductivity of the spherical particle, the base fluid, and the volume fraction of the solid particles. Using the Shape factor, Hamilton and Crosser [1] created their model (Equation 3). This model can be used to calculate the thermal conductivity of a fluid containing nanoparticles that are both spherical and cylindrical Bashirnezhad, Rashidi [19]. Hamilton and Crosser first unveiled this upgraded version in 1962. Based on this model, the suggested terms convey applications for nanoparticle size, shape, and volume fraction.

$$\frac{K_eff}{K_L} = \frac{K_s + (n-1)K_L - (n-1)(K_L - K_s)\varphi s}{K_s + (n-1)K_L + (K_L - K_s)\varphi s} \tag{3}$$

In which, n is the empirical shape factor and Ψ is the sphericity defined as the ratio of the surface area of a sphere to the surface area of the particle. The sphericity is 1 and 0.5 for the spherical and cylindrical shapes respectively. The notation K_eff is the thermal conductivity of the nanofluid, K_s is the thermal conductivity of the nanoparticles, K_L is the thermal conductivity of the base fluid and φ is the volume fraction of nanoparticles. A comparison of the Eqs (2) and (3) demonstrates that the Maxwell model with sphericity equal to one is a special case of the Hamilton and Crosser model. Bruggeman proposed a model to analyse the interactions of randomly distributed particles in 1935. Bruggeman thermal conductivity model (Equation 4) is used to predict the effective thermal conductivity of the binary mixture of homogeneous spherical and randomly dispersed nanoparticles [21].

$$\frac{K_eff}{K_L} = \frac{[(3\varphi s - 1)\frac{K_s}{K_L} + (2 - 3\varphi_s + \sqrt{\Delta})]}{4} \tag{4}$$

$$\Delta = (3\varphi_s - 1)^2(K_s/K_L)^2 + (2 - 3\varphi_s)^2 + 2(2 + 9\varphi_s - 9\varphi_s^2)(K_s/K_L) \tag{5}$$

When particle concentrations are low, the Bruggeman model produces nearly identical outcomes as the Maxwell model. The Maxwell model cannot well fit the experimental observations when the particle concentration is high enough. However, the Bruggeman model and the experimental data match pretty well Eastman, Choi [2].

The aforementioned classical models, which are derived from continuum formulations, assume diffusive heat flow in both liquid and solid phases and only include the particle shape and volume fraction as variables. The Maxwell model and its modification by Hamilton and Crosser seem to have overlooked several crucial nanofluid phenomena, which is why they were unable to account for the unusual rise in thermal conductivity of nanofluids. The size, clustering, and nano-layer between the nanoparticles and base fluids were some of the parameters that Keblinski, Phillpot [24] looked at as potential means of improving thermal conductivity in nanofluids. By substituting the modified thermal conductivity of particles, which is based on the so-called effective medium theory, for the thermal conductivity of nanoparticles in Eq. (2), Yu and Choi [25] suggested a modified Maxwell model to account for the effect of the nano-layer.

$$K_eff = [\frac{k_s + 2k_L + 2(k_s - k_L)(1 - \beta)^3\varphi}{k_s + 2k_L - (k_s - k_l)(1 + \beta)^3\varphi)}]k_L \tag{6}$$

Where the ratio of the original particle radius to the nanolayer thickness is denoted by the symbol β. The thermal conductivity of the nanofluid is typically calculated using $\beta = 0.1$.

The thermal conductivity of POE oil containing 0.01-0.10% of nanoparticles is calculated using the four models of thermal conductivity provided by equations 2 through 6, and the calculated values are compared to the experimental values.

3 | RESULTS AND DISCUSSIONS

The thermal conductivity of nano lubricant, with different volume fractions of nanoparticles, increased from 10% to more than 40% when compared to the base fluid. The lowest increase in thermal conductivity was 10% for 0.05% SiO_2 nano lubricant concentration and the maximum rise in thermal conductivity was 39% for 0.1% Al_2O_3 nano lubricant concentration. These results are comparable to [4] and [18]. Both studies found that adding nanoparticles in varying concentrations increases thermal conductivity. Thermal conductivity with a volume percentage of Al_2O_3 nanoparticles appended to POE oil are shown in Fig.3. The data points are average of five experimental readings. Along with the current experimental values, the thermal conductivity as calculated by four different correlations can be seen. The measured values lie within the predicted value range. The average value of thermal conductivity as determined by experiments, for 0.05% volume fraction is 0.164 and for 0.1% volume percent is 0.188 W/m K. Hence thermal conductivity nanolubricant increased by

21.5% and 39%. This enhancement in thermal conductivity of Al_2O_3 nano lubricant is in agreement with the experimental results of Lee, Hwang [26] and S. Lee [27]. Fig.4 presents the thermal conductivity values that were computed using the Maxwell, Hamilton, and Corsser correlations, Brugeman, and finally Yu and Choi for TiO_2 nanoparticles added to POE oil at various concentrations. The figure also represents the average of the experimental results for TiO_2 nanoparticle concentrations of 0.05% and 0.1%. The chart clearly shows that correlations overprojected the increase in thermal conductivity. The mean thermal conductivity of TiO_2 nano lubricant obtained by the hot wire method is 0.159 and 0.175 W/m K for volume concentrations of 0.05% and 0.1%, respectively. This shows a heat transfer augmentation of 18% and 30% respectively over the pure POE oil. These experimental outcomes of thermal conductivity of TiO_2 nano lubricant display good agreement with values measured by [28] and [29].

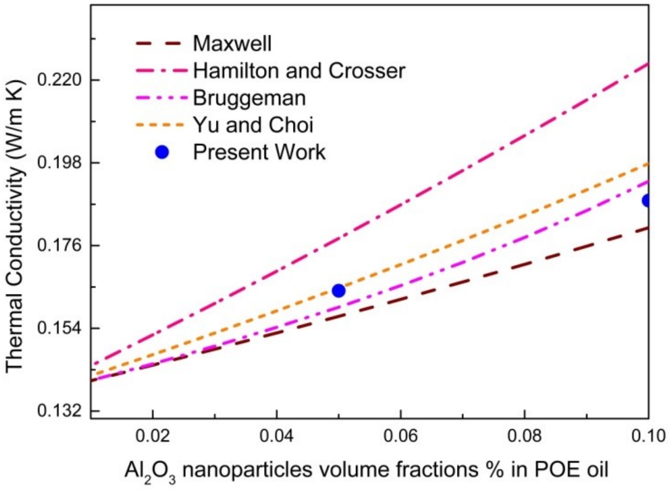

FIG. 3 Al_2O_3 nanoparticles suspended in POE oil

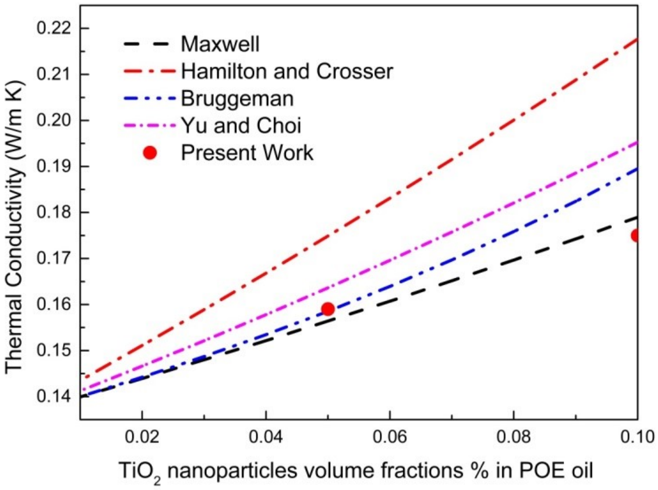

FIG. 4 TiO_2 nanoparticles suspended in POE oil

Figure 5 displays the predicted value of thermal conductivity from four mathematical models for different volume concentrations of SiO_2 nanoparticles in POE oil. The calculated thermal conductivity values from all four correlations are slightly higher than the mean experimentally measured value. The average thermal conductivity of 0.05% SiO_2 nano-lubricant is 0.149 W/m K, which is 10% higher than the base fluid. Similarly, the mean thermal conductivity of 0.1% SiO_2 nano lubricant is 0.168 W/m K, which is 24% higher than the POE oil base fluid. The thermal conductivity of SiO_2 nanoparticles measured during experiments is in good agreement with Sanukrishna, Vishnu [30] and Ohunakin, Adelekan [31].

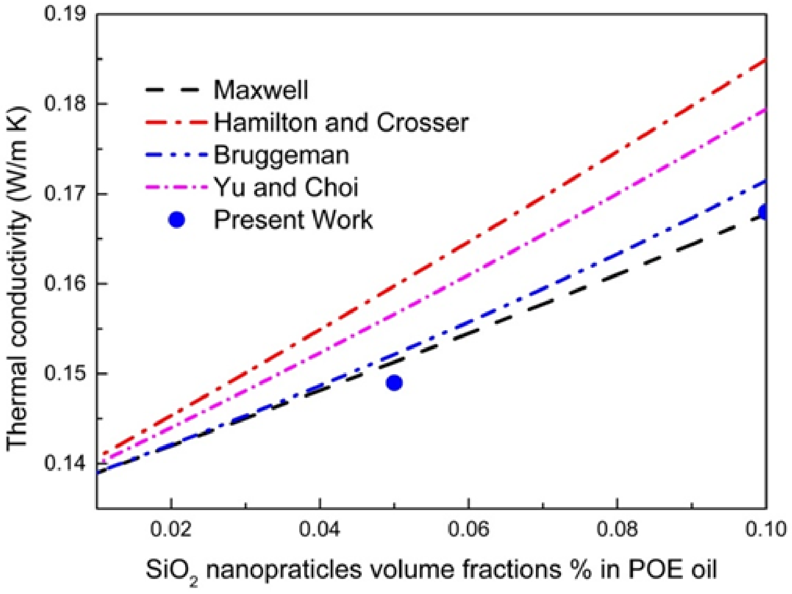

FIG. 5 SiO_2 nanoparticles suspended in POE oil

4 | CONCLUSIONS

The thermal conductivity of Al_2O_3, TiO_2, and SiO_2 in POE oil is calculated by various models. The different theoretical models of thermal conductivity of nanofluids have different results. With rising volume concentration, the discrepancy between calculated thermal conductivity from different models grows. Traditional theories are contrasted with the experimental findings for the thermal conductivity of Al_2O_3, TiO_2, and SiO_2 in POE oil It is discovered that the anticipated values of thermal conductivity of nanofluids are significantly impacted by the aggregation of nanoparticles. Based on comparison results, it can be inferred that more study is required to create a model that is suitable for predicting the thermal conductivity of nanofluids. The new model should take into account a number of potential factors that could improve the heat transfer performance of nanofluids, such as size, shape, and particle aggregation. In contrast to all other models, it is seen that the Maxwell model predicts regular fluctuations in thermal conductivity. The ideal model to utilise for the thermal conductivity of nanofluids, however, is still not entirely known. In comparison to Maxwell, the Bruggeman model provides slightly greater thermal conductivity models. The maximum value of heat conductivity is provided by the Hamilton and Crosser model. Also presented in this article is an experimental investigation of the thermal conductivity of nano lubricants. The experimental results support theoretical predictions in that the thermal conductivity of the nanolubricants rises with volume concentration.

In the present work the thermal conductivity of Al_2O_3-POE oil, TiO_2-POE oil, and SiO_2-POE oil nanolubricants also has been compared. Al2O3-POE oil is discovered to have a better thermal conductivity than the other two nanolubricants. The greatest experimental value of thermal conductivity is that of Al_2O_3-POE oil nano lubricant with the value of 0.188 W/m K. Additional thermo-physical research is required to come to a firm conclusion about how to improve the thermal conductivity between these three nanolubricants. Further research can be done to determine how temperature and volume concentration affect the viscosity of these nano lubricants. Only application-based research, which is currently in its infancy but is projected to evolve at a faster rate in the near future, will be able to determine the future of nanofluids and its current promises.

5 | ACKNOWLEDGEMENTS

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References

[1] R.L. and O. Crosser, “Thermal conductivity of heterogeneous two-component systems,” *Industrial Engineering Chemistry Fundamentals*, vol. 1, no. 3, p. 187–191.

[2] J., “Enhanced thermal conductivity through the development of nanofluids,” in *MRS proceedings*, Cambridge Univ Press.

[3] S., “Anomalous thermal conductivity enhancement in nanotube suspensions,” *Applied physics letters*, vol. 79, no. 14, p. 2252–2254.

[4] J.A., “Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles,” *Applied Physics Letters*, vol. 78, no. 6, p. 718–720.

[5] R. and J. Sunil, “Effect of nano sized garnet particles dispersion on the viscous behavior of extreme pressure lubricant oil,” *Journal of Molecular Liquids*, vol. 223, p. 643–651.

[6] R. and J. Sunil, “Relative anti-wear property evaluation of nano garnet gear lubricant,” *International Journal of Surface Science and Engineering*, vol. 11, no. 4, p. 320–343.

[7] R. and J. Sunil, “Experimental analysis of tribological properties of ultrasonically dispersed garnet nanoparticles in sn500 grade lubricating oil,” *Industrial Lubrication and Tribology*, vol. 70, no. 2, p. 250–255.

[8] S., *Performance analysis of mineral oil based nano-lubricants with sulphur impregnated reduced graphene oxide nanosheets*. Materials Today: Proceedings.

[9] P. R. and S. Kalaiselvam, “An experimental investigation and comprehensive modelling of thermal and rheological behaviour of graphene oxide nano platelets suspended mineral oil nano lubricant,” *Journal of Molecular Liquids*, vol. 347, p. 118357.

[10] M. Esfe, “Comparison of viscosity behavior of hybrid nano-lubricants containing al2o3-mwcnt nanoparticles dispersed in sae xwx engine oils to determine the optimal behavior of nano-lubricants based on experimental studies,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 641, p. 128446.

[11] Y., “Tribological performance of silicone oil based al2o3 nano lubricant for an mg alloy subjected to sliding at elevated temperatures,” *Tribology International*, vol. 175, p. 107779.

[12] G., “Synthesis, characterization, and thermal property measurement of nano-al95zn05 dispersed nanofluid prepared by a two-step process,” *International Journal of Heat and Mass Transfer*, vol. 54, no. 15-16, p. 3783–3788.

[13] M.A., “Viscosity, density, and thermal conductivity of aluminum oxide and zinc oxide nanolubricants,” *international journal of refrigeration*, vol. 74, p. 3–11.

[14] M., “R134a/al2o3 nanolubricant mixture pool boiling on a rectangular finned surface,” *Journal of Heat Transfer*, vol. 134, no. 12, p. 121501.

[15] K. S.M.S. and C. Yang, “Enhanced thermal conductivity of tio2—water based nanofluids,” *International Journal of Thermal Sciences*, vol. 44, no. 4, p. 367–373.

[16] J. E.J. and R. Gandhi, “Solid–liquid flow: slurry pipeline transportation.[pumps, valves, mechanical equipment, economics,” *Ser. Bulk Mater. Handl.;(United States*, vol. 1, no. 4.

[17] D.A.G., “Berechnung verschiedener physikalischer konstanten von heterogenen substanzen. i. dielektrizitätskonstanten und leitfähigkeiten der mischkörper aus isotropen substanzen,” *Annalen der Physik*, vol. 416, no. 8, p. 665–679.

[18] B.C. and Y. Cho, “Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles,” *Experimental Heat Transfer*, vol. 11, no. 2, p. 151–170.

[19] K., “A comprehensive review of last experimental studies on thermal conductivity of nanofluids,” *Journal of Thermal Analysis and Calorimetry*.

[20] H., “Nanocrystalline materials. progress in materials science.”

[21] S., “Application of tio2 nanoparticles as a lubricant-additive for vapor compression refrigeration systems – an experimental investigation,” *International Journal of Refrigeration*, vol. 35, no. 7, p. 1989–1996.

[22] N. O.A. and H. Mohammed, “A comprehensive review of fundamentals, preparation and applications of nanorefrigerants,” *International Communications in Heat and Mass Transfer*, vol. 54, no. 0, p. 81–95.

[23] J.C. and J. Thompson, *A treatise on electricity and magnetism*, vol. 2. Clarendon.

[24] P., “Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids,” *International Journal of Heat and Mass Transfer*, vol. 45, no. 4, p. 855–863.

[25] W. and S. Choi, “The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated maxwell model,” *Journal of Nanoparticle Research*, vol. 5, no. 1, p. 167–171.

[26] J.-H., “Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of al2o3 nanoparticles,” *International Journal of Heat and Mass Transfer*, vol. 51, no. 11-12, p. 2651–2656.

[27] S.-S. Lee, S. Li, and J. Eastman, “Measuring thermal conductivity of fluids containing oxide nanoparticles,” *Transaction of the ASME*, p. 121.

[28] K. S.M.S. and C. Yang, “Investigations of thermal conductivity and viscosity of nanofluids,” *International Journal of Thermal Sciences*, vol. 47, no. 5, p. 560–568.

[29] T. John, E. CONDUCTIVITY, V.I.S.C.O.S.I.T.Y., and S. NANOFLUIDS *International Journal of Innovative Research in Science, Engineering and Technology*.

[30] S. S.S. and M. Prakash, “Experimental investigation on thermal and rheological behaviour of pag lubricant modified with sio2 nanoparticles,” *Journal of Molecular Liquids*, vol. 261, p. 411–422.

[31] O.S., “Performance of a hydrocarbon driven domestic refrigerator based on varying concentration of sio2 nano-lubricant,” *International Journal of Refrigeration*, vol. 94, p. 59–70.