HEAT TRANSFER IN NANOFLUIIDS (TiO_2-Water)

TERM PAPER 2024 report submitted to

Indian Institute of Technology Delhi

in partial fulfilment for the award of the degree of

Bachelor of Technology

in

CHEMICAL ENGINEERING

by

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(2023CH10161, 2023CH71178, 2023CH10170, 2023CH70679)

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2023-24 SEMESTER 1

November 27, 2024

Abstract

Nanofluid is an innovative heat transfer fluid with superior potential for enhancing the heat transfer performance of conventional fluids. Research studies have indicated that nanofluids, a suspension of a nanoparticle in a base fluid, exhibits enhanced thermal conductivity. Various attempts have been made to study the thermophysical properties of nanofluids. This article examines the curve fitting of experimental data of thermal conductivities of nanofluid consisting of TiO2 as nano particle and water as the base fluid. Transient hot wire technique has been used to measure conductivities at various temperatures and study the values in the temperature range 15 C to 35 C. The results obtained using the numerical models have been compared to results of the existing models. It was observed that an increase in the volume fraction of nanoparticles, results in a significant increase in the thermal conductivity. This in turn enhances the heat transfer properties of the fluid.

Contents

INTRODUCTION

0.1 Introduction

Conventional heat transfer fluids such as water, oil and ethylene glycol have low thermal conductivities as compared to most of the solids. These fluids are widely used in industries for cooling systems, power generation and transportation. Poor thermal conductivities were an obstacle for achieving effectiveness in heat exchangers. Therefore, many attempts have been made to enhance the heat transfer properties by creating new kinds of fluids.

To evaluate the heat transfer performance of nanofluids and their practical applications, it is essential to first investigate its thermal conductivity, which is a key thermophysical properties. In this paper an attempt has been made to study the thermal conductivity increase with volume fractions of nano particles and optimal nanoparticle concentration after obtaining plots using our numerical methods to show industrial importance and application respectively.

The transient hot-wire (THW) gives scattered points which is not very suitable for studying the variations in thermal conductivity with respect to temperature and volume fraction while the wasp, Yu and Choi Model, Bruggeman, Hamilton-Crosser etc. models give results with high inaccuracies. Hence, the introduction of a quadratic regression model, which covers the data points more accurately as compared to the linear curve fitting as suggested in reference[1] results in highly accurate curve fitting of measured values, allowing the proper study of comparison with earlier models and advanced numerical integral analysis is also done in order to find further useful results.

0.2 Literary Review

H. Masuda and others examined thermophysical properties of metallic oxides dispersed in water. Measuring of thermal conductivity was done by employing Transient heat wire method. Their studies reported a significant rise in thermal conductivity of nano fluids as compared to the base fluid.

The Transient Hot Wire (THW) method has been used to find experimental data of thermal conductivity and compare it with predicted results. It involves heating a thin wire and placing it in a nanofluid where it acts as a line source of heat.The rise in temperature is recorded. The estimation of thermal conductivity is done by measuring the rate of temperature. This model is believed to measure thermal conductivities more accurately.

0.2.1 Models used for comparison

1. Yu and Choi model: This model estimates the effective thermal conductivity of nanofluids by using the concept of an interfacial layer around the nanoparticle. According to this model the effective thermal conductivity (k_{eff}) of the nanofluid is expressed as:

$$k_{\text{eff}} = k_f \left[1 + \phi \left(\frac{k_p + 2k_f + 2\beta(k_p - k_f)}{k_p + 2k_f - \beta(k_p - k_f)} \right) \right]$$

Where:

1. k_f: Thermal conductivity of the base fluid.
2. k_p: Thermal conductivity of the nanoparticles.
3. β: A dimensionless parameter related to the interfacial layer, calculated as:

$$\beta = \frac{3(k_i - k_f)}{k_i + 2k_f}$$

4. k_i: Thermal conductivity of the interfacial layer.

2. Bruggeman Model: This model considers the nanofluid to be a homegeneous mixture of two phases and the interaction between the two phases determines the overall effective thermal conductivity

For a two-phase system, the effective thermal conductivity (k_{eff}) of the composite is given by:

$$\sum_i \phi_i \frac{k_i - k_{\text{eff}}}{k_i + 2k_{\text{eff}}} = 0$$

Where:

1. k_i: Thermal conductivity of phase i.
2. ϕ_i: Volume fraction of phase i.
3. k_{eff}: Effective thermal conductivity of the mixture.

3. Effective Medium Theory: This model attempts to replace a heterogeneous mixture with a homogeneous mixture and accounts for the resultant physical property

(which is Thermal Conductivity in our case) as the averages of the constituent phases.

In nanofluids, EMT can estimate the effective thermal conductivity (k_{eff}) of a base fluid with dispersed nanoparticles. Using the Maxwell Garnett Approximation:

$$k_{\text{eff}} = k_f \left[1 + \frac{3\phi_p(k_p - k_f)}{k_p + 2k_f - \phi_p(k_p - k_f)} \right]$$

Where:

1. k_f: Thermal conductivity of the base fluid.
2. k_p: Thermal conductivity of the nanoparticles.
3. ϕ_p: Volume fraction of nanoparticles.

0.3 Plan

This research aims to study the thermal conductivity of nanofluids via the application of advanced numerical methods to perform curve fitting through regression models and integral analysis to:

1. Plot Thermal Conductivity vs. Volume Fraction graphs: the relationship between thermal conductivity and nanoparticle volume fraction at various conditions will be studied through a quadratic regression model obtained. The results of the regression of the experimental data will be compared with the existing theoretical models to study the deviation of the existing theoretical models with the regression model;

2. Plot Thermal Conductivity vs. Temperature graph: a quadratic regression model is obtained in K and T and plotted to assess the increment in thermal conductivity relative to that of base fluid(water);

3. Find optimal concentration range: The areas under each interval of the thermal conductivity vs. volume fraction graph represents the cumulative thermal conductivity contribution of the nanofluid over that specific volume fraction range. Normalizing the areas by division by respective range sizes aims to remove interval size dependency, ensuring fair comparisons across different volume fraction-ranges;

4. Obtain a multilinear regression expression in K, T, and phi to study the simultaneous effect of temperature and volume fraction on change in thermal conductivity.

The parameters used and will be analyzed in the paper are:

1. K_{water} : thermal conductivity of water
2. $K_{nanofluid}$: thermal conductivity of nano fluid
3. T : temperature
4. ϕ : volume fraction

NUMERICAL ANALYSIS

0.4 Numerical Methods used

0.4.1 Quadratic Regression

Quadratic regression equations(in variable form) have been used for the k vs t, k vs phi and formula for finding the coefficients.

$$k_{\text{nanofluid}}(T) = a_n T^2 + b_n T + c_n$$

$$k_{\text{nanofluid}}(T) = a_w \varphi^2 + b_w \varphi + c_w$$

Polynomial Regression Model

$$C_p = a_0 + a_1 T + a_2 T^2 + a_3 T^3$$

→ Dependent variables are non-linear functions of independent variables

Data: $(T_1, C_{p1}), (T_2, C_{p2}), \ldots, (T_3, C_{p3}), (T_N, C_{pN})$

This gets converted to:

$$y_1 = a_0 + a_1 x_1 + a_2 u_1 + a_3 w_1$$

$$\mathbf{y} = \begin{bmatrix} C_{p1} \\ C_{p2} \\ \vdots \\ C_{pN} \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} 1 & T_1 & T_1^2 & T_1^3 & \cdots & T_1^m \\ 1 & T_2 & T_2^2 & T_2^3 & \cdots & T_2^m \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & T_N & T_N^2 & T_N^3 & \cdots & T_N^m \end{bmatrix}$$

Extend to m^{th} order polynomial:

$$\begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_N \end{bmatrix} = (X^T X)^{-1} X^T Y \quad \to \text{left inverse of matrix } X$$

0.4.2 Multilinear Regression

$$\text{Model: } \hat{y} = a_0 + a_1 x + a_2 u + a_3 w$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} 1 & x_1 & u_1 & w_1 \\ 1 & x_2 & u_2 & w_2 \\ 1 & x_3 & u_3 & w_3 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_N & u_N & w_N \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ \vdots \\ e_N \end{bmatrix}$$

$$Y = X\Phi + e$$

$$\text{Least Square: } \Phi = (X^T X)^{-1} X^T Y$$

Multilinear regression has been used for studying the dependence of thermal conductivity on temperature and volume fraction simulatneously

0.4.3 Simpsons 1/3rd rule

Simpson's 1/3rd rule is a method used for numerically approximating the integral of a function by dividing th interval into two sub intervals and using parabolic arcs.

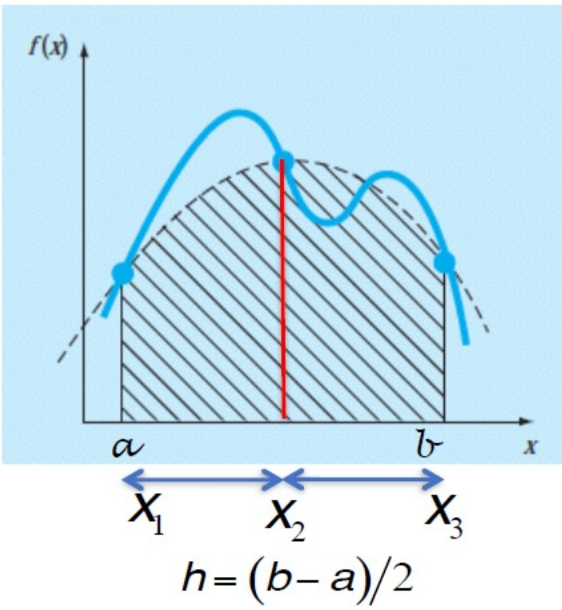

FIGURE 1: Simpsons 1/3rd rule

The formula used is:

$$= \frac{h(y_1 + 4y_2 + y_3)}{3}$$

0.5 Calculation of Δk

The average percentage increase in thermal conductivity of nano-fluids as compared to that of water has been studied by using the following equation which calculates the mean of infinite thermal conductivity increments across the temperature profile using Simpson's 1/3rd rule.

$$\text{Average Percentage Increase} = \frac{1}{T_{\max} - T_{\min}} \int_{T_{\min}}^{T_{\max}} \left(\frac{k_{\text{nanofluid}}(T) - k_{\text{water}}(T)}{k_{\text{water}}(T)} \times 100 \right) dT$$

Simpsons 1/3rd rule has been employed to solve the above equation.

0.6 Determination of optimal concentration range

1. The curve is divided into Sub-intervals

- Volume fraction interval $[\varphi_{\min}, \varphi_{\max}]$ is divided into multiple shorter intervals. For instance:
  - Subinterval 1: $[0, \varphi_1]$
  - Subinterval 2: $[\varphi_1, \varphi_2]$
  - Subinterval 3: $[\varphi_2, \varphi_3]$
  - ... and so on.

2. Normalization of the Areas

Divide each subinterval's area by the respective width of the volume fraction range:

$$A_{\text{normalized},i} = \frac{A_i}{\varphi_{i,\max} - \varphi_{i,\min}}$$

The above denotes the **average contribution** of thermal conductivity per unit volume fraction in each subinterval.

3. Comparison of Normalized Contributions

The subinterval with the highest normalized contribution refers to the range where the addition of nano-particles most effectively enhances thermal conductivity. This range contains the optimum nano-particle concentration, as it will refer to the most efficient use of TiO2.

In this way, the Optimal concentration subinterval is determined.

RESULTS AND DISCUSSION

0.7 Plot 1

Plot of thermal conductivity vs particle fraction at 25°C using different numerical models like Yu and Choi Model, Wasp Model, Bruggeman Model, and Effective Medium Theory. The plot compares how these models predict thermal conductivity enhancement in nanofluids as a function of particle volume fraction (ϕ) to the curve obtained by quadratic regression model.

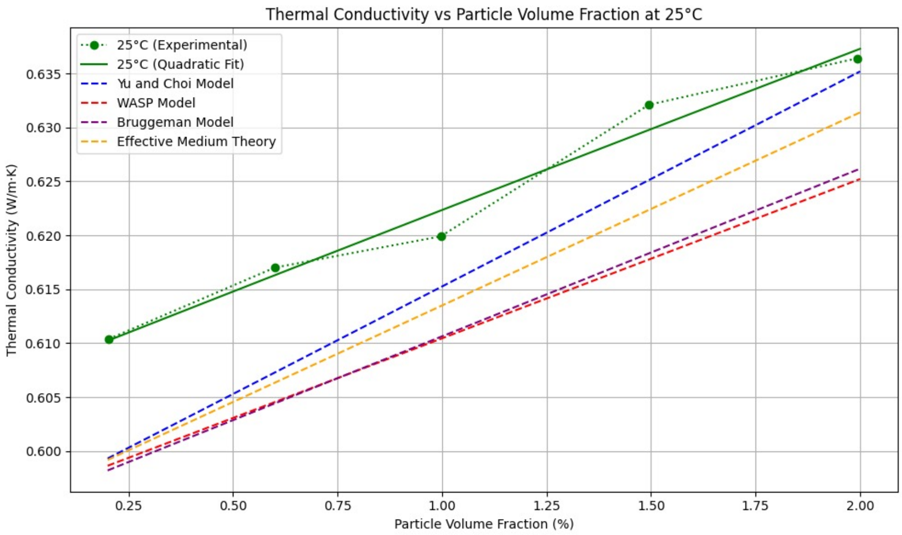

FIGURE 2: Thermal conductivity vs. particle fraction at 25°C for different models.

The quadratic model used for the prediction is given by:

$$K_{\text{eff}} = 0.607165 + 0.0152923 \cdot \phi - 0.000116901 \cdot \phi^2 \tag{1}$$

General Quadratic Model for Thermal Conductivity

$$K_{\text{eff}} = a + b \cdot \phi + c \cdot \phi^2 \tag{2}$$

where a, b, and c are constants determined for a specific temperature.

TABLE 1: Quadratic Model Parameters for Thermal Conductivity at Different Temperatures

Temperature (°C)	a	b	c	R^2
15	0.599311	0.0096344	0.00295217	0.99854
25	0.607165	0.0152923	-0.000116901	0.99398
35	0.610719	0.0248748	-0.00436021	0.99393

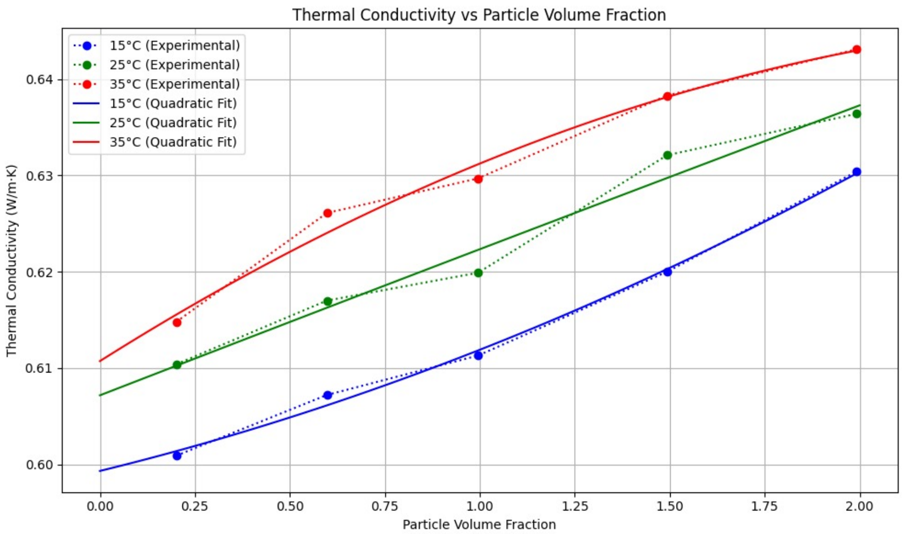

FIGURE 3: Thermal conductivity vs. Particle Fraction at different temperatures

TABLE 2: Normalized Areas for Different Subregions of Particle Fraction at Different Temperatures for finding the optimal concentration range

Particle fraction (ϕ)	15°C	25°C	35°C
0.2 to 0.38	0.602361	0.61159	0.617554
0.38 to 0.56	0.604499	0.614326	0.621435
0.56 to 0.74	0.606829	0.617055	0.625034
0.74 to 0.92	0.609349	0.619777	0.62835
0.92 to 1.1	0.612061	0.622491	0.631383
1.1 to 1.28	0.614964	0.625197	0.634134
1.28 to 1.46	0.618059	0.627896	0.636602
1.46 to 1.64	0.621345	0.630587	0.638788
1.64 to 1.82	0.624822	0.63327	0.640691
1.82 to 2	0.62849	0.635947	0.642312

Since the normalized areas, which represents the cumulative thermal conductivity contribution, show an increasing trend as the volume fraction increases without showing any peak show that optimal volume concentration range cannot be determined.

0.8 Plot 2

Plot of quadratic models for thermal conductivity as a function of temperature for different particle fractions to facilitate the study of percentage increase of thermal conductivity as compared to base fluid water.

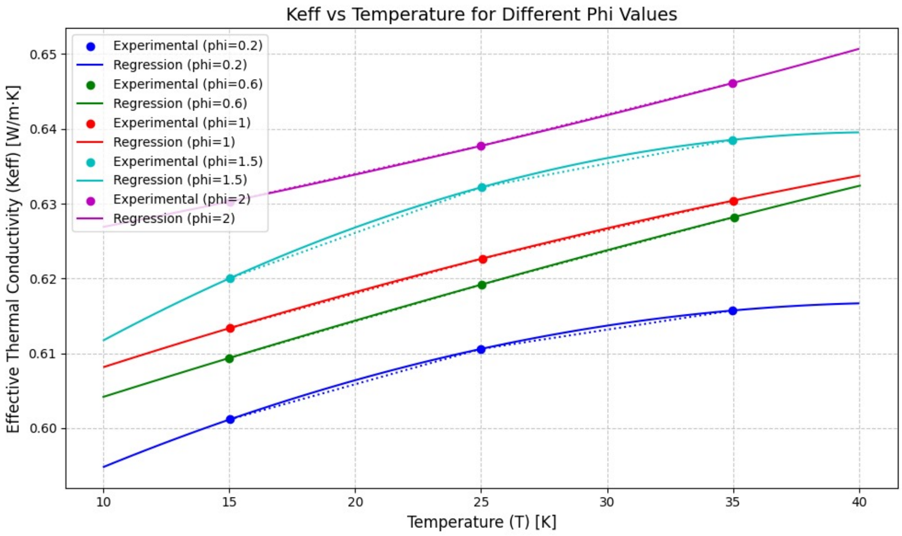

FIGURE 4: Thermal conductivity vs. Temperature at different Particle fractions

General Quadratic Model for Thermal Conductivity

$$K_{\text{eff}} = a + b \cdot T + c \cdot T^2 \tag{3}$$

where a, b, and c are constants determined for a specific particle fraction.

TABLE 3: Quadratic Model Parameters for Thermal Conductivity at Different Particle Fractions

Particle Fraction (ψ)	a	b	c
0.2	0.578876	0.00180755	-2.15614e-005
0.6	0.593177	0.0011397	-3.99363e-006
1	0.596603	0.00122932	-7.53218e-006
1.5	0.590801	0.00238324	-2.91219e-005
2	0.620853	0.000557327	4.71455e-006

0.9 Plot 3

The plot of average $\Delta K\%$ (average enhancement in thermal conductivity percentage relative to that of water) vs. temperature for different particle fractions. The plot illustrates how the percentage of thermal conductivity enhancement varies with temperature for different nanoparticle concentrations.

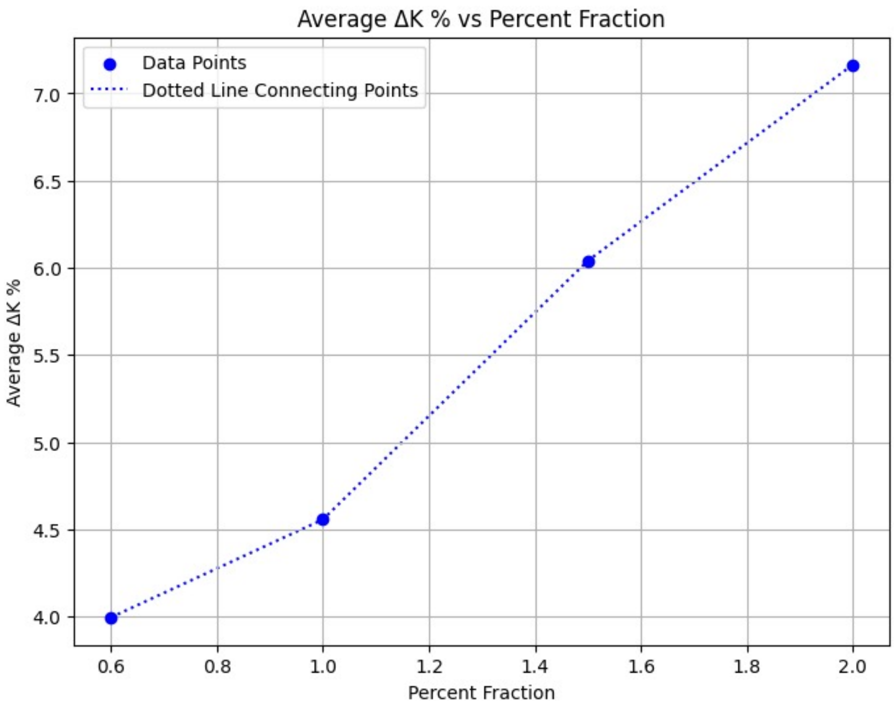

FIGURE 5: Average increase in thermal conductivity relative to base fluid ($\Delta K\%$) vs. Temperature at different particle fractions

0.10 Plot 4

The plot shows the experimental data of Effective Thermal Conductivity of Nano-Fluid plotted against multi-variables Temperature and Particle fraction.

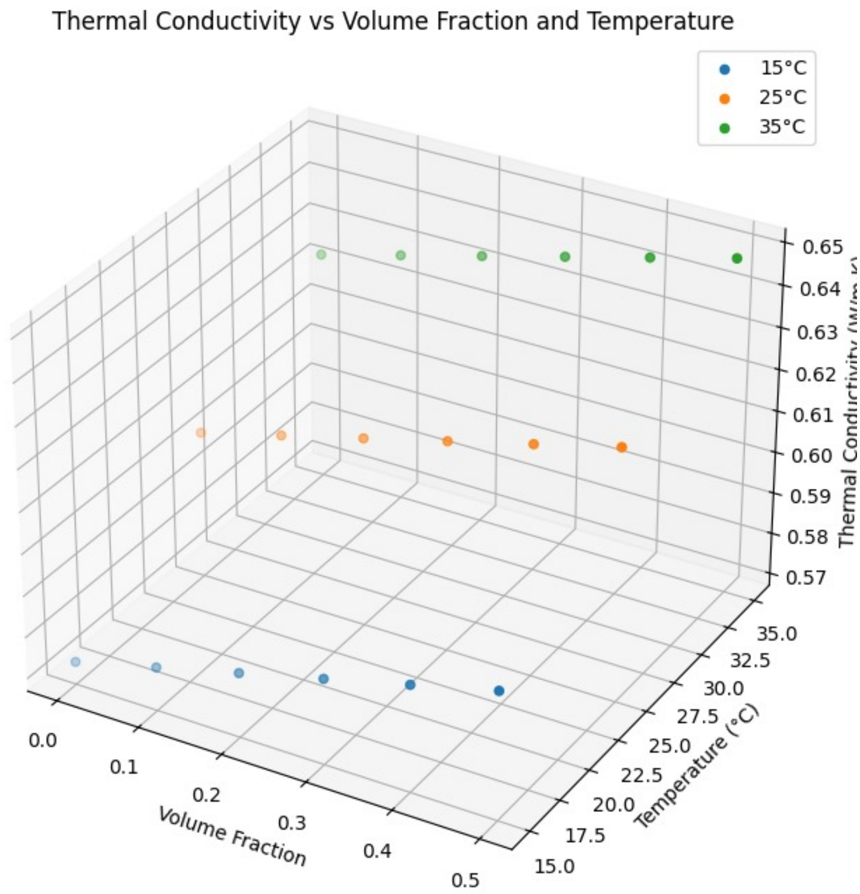

FIGURE 6: Thermal conductivity vs. Temperature and Particle Fractions

0.11 Plot 5

This plot shows how our multilinear regression model for thermal conductivity tries to fit the experimental data for Thermal Conductivity as function of temperature and Particle fraction.

Multivariable Model for Thermal Conductivity

$$K_{\text{eff}} = 0.536635 + 0.0503896 \cdot \phi + 0.0025 \cdot T \tag{4}$$

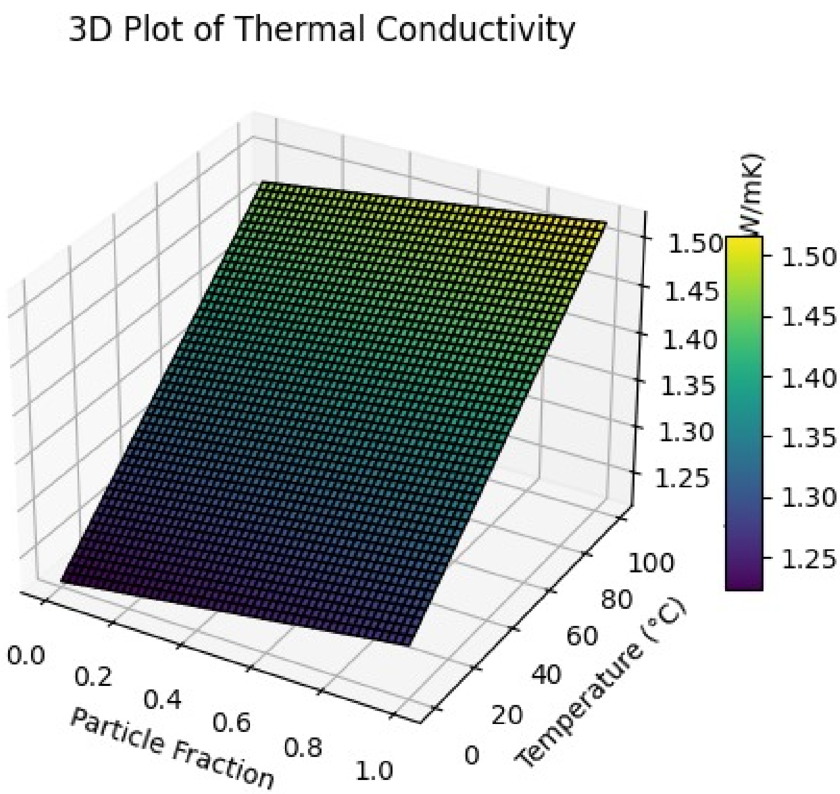

Figure 7: Thermal conductivity vs. Temperature and Particle Fractions

PATH FORWARD

While we have limited the research on spherical shape of nanoparticles, we perceive the promising potential of other shapes such as cylindrical,plate shaped, tubular in affecting heat transfer properties of nanofluids can employ the Hamilton Crosser Model to take into account the effects of different shapes using particle sphericity. We can also incorporate Brownian motion effects(as it contributes to micro-scale convection) and how they affect the heat transfer properties of nanofluids where can implement Koo-Klenstreur and Jang Choi models to predict heat transfer properties in this case.

Also we have prepared the models using particle fraction between 0.2 percent and 2 percent and temperature range between 15℃ to 35℃ we may be unable to predict behaviour of nanofluids at high temperature (e.g. heat exchanger systems) and at low temperatures (e.g. cryogenic systems). At volume fractions more than 2 percent particle aggregation, sedimentation may affect heat transfer phenomena, So there is a scope to extend experimental studies and create a model that covers a wider temperature range and concentration range.

CONCLUSION

In the investigated volume fraction range of 0–2%, titanium dioxide (TiO) nanoparticle dispersion demonstrated a consistently progressive enhancement of thermal conductivity. The normalized area analysis revealed a continuous improvement in thermal transfer characteristics without observable saturation, suggesting sustained nanofluid performance within this concentration spectrum. Since there is no peak in the rise it suggests that there is minimal nanoparticle agglomeration, which is critical for maintaining nanofluid stability and thermal efficiency. This structural stability indicates that the nanoparticles remain uniformly distributed throughout the base fluid.

These findings are of great importance in thermal energy applications, as they show that TiO nanofluids have the potential to offer enhanced heat transfer performance without loosing its thermal stability over a certain concentration range. The continuous rise in thermal conductivity suggests that concentrations up to 2% can be used without facing any issues of agglomeration. Thus it can be concluded that further research studies should focus on investigating concentration ranges beyond 2% to determine potential performance limits.

SELF ASSESSMENT

0.12 Level o

We did level 0 as we did complete literature assessment of the formulae and prediction models used in our referred research paper. We carefully examined the existing theoretical models for prediction of thermal conductivity. We compared them with our own results by plotting it and examined the inaccuracies in our results.

0.13 Level 1

1. We developed the code for quadratic regression to predict values of thermal conductivities as a function of volume fraction and temperature separately.

2. We also developed the code for multi-linear regression that uses volume fraction and ϕ simultaneously to approximate the values of thermal conductivity.

3. We developed the code for Simpsons 1/3rd rule which was employed in finding the optimal concentration of nanoparticle in the base fluid and Δk calculation.

0.14 Level 2

0.14.1

Calculation of Δk : In the reference research paper that we used showed the effect of enhancement of thermal conductivity in comparison to that of water only through a graphical representation of K vs T graph for various volume fraction. But in our term paper, we obtained the quantified analysis of increment in k with respect to water by calculating the percentage increase over the entire range of temperatures 15-35 by applying the concept of integral analysis of Simpson's 1/3rd method. We also compared the relative thermal conductivity percentage increase for different volume fractions by plotting the graph for the same, resulting in a visual analysis of enhancement in heat transfer due to addition of nanoparticles in water.

Optimal concentration range: We further extended our research by using the k vs phi plot to determine optimal thermal conductivity, which is the point of diminishing returns, where adding more TiO no longer results in significant thermal conductivity gains, by comparing the normalized areas. In the investigated volume fraction range of 0–2 percent, titanium dioxide (TiO) nanoparticle dispersion demonstrated a consistently progressive enhancement of thermal conductivity. The normalized area analysis revealed a continuous improvement in thermal transfer characteristics without observable saturation, suggesting sustained nanofluid performance within this concentration spectrum.

REFERENCES USED

1. Measurement of temperature-dependent thermal conductivity and viscosity of TiO2-water nanofluids Weerapun Duangthongsuk, Somchai Wongwises * Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Department of Mechanical Engineering, King Mongkut's University of Technology Thonburi, 126 Bangmod, Bangkok 10140, Thailand

2.Nanofluid Thermal Conductivity and Effective Parameters Sarah Simpson, Austin Schelfhout, Chris Golden and Saeid Vafaei * Mechanical Engineering Department, Bradley University, Peoria, IL 61625, USA; ssimpson@mail.bradley.edu (S.S.); aschelfhout@mail.bradley.edu (A.S.); Chris.Golden.ME@gmail.com (C.G.)

3.Heat transfer and fluid flow of pseudo-plastic nanofluid over a moving permeable plate with viscous dissipation and heat absorption/generation Hamid Maleki1 , Mohammad Reza Safaei2,3 , Hussein Togun4

4. Thermal Conductivity and Viscosity: Review and Optimization of Effects of Nanoparticles Kevin Apmann, Ryan Fulmer, Alberto Soto and Saeid Vafaei

5. A Comprehensive Review of Non-Newtonian Nanofluid Heat Transfer Hossam A. Nabwey 1,2,* , Farhad Rahbar 3, Taher Armaghani 3, Ahmed. M. Rashad 4 and Ali J. Chamkha 5

6 Prof. Jayati Sarkar, Slides of CLL-113 Course