

SYNTHESIS AND CHARACTERIZATION OF NANO BUBBLED HEAT TRANSFER FLUID FOR THERMAL APPLICATION

Submitted in partial fulfillment of the requirements for the award of

Bachelor of Engineering

Degree in Mechanical Engineering

By

JOHN SEBRAN.Y (Reg. No. 40150017)

VINU MON.W (Reg. No. 40150719)



DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade "A++" by NAAC

**JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119
APIRL - 2024**



SATHYABAMA

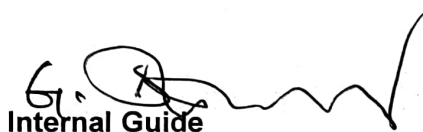
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)

Accredited "A++" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

DEPARTMENT OF MECHANICAL ENGINEERING

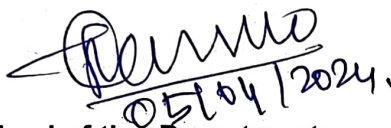
BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **JOHN SEBRAN.Y** (Reg.NO.40150017) and **VINU MON.W** (Reg.No.40150719) who carried out the project entitled "**SYNTHESIS AND CHARACTERIZATION OF NANO BUBBLED HEAT TRANSFER FLUID FOR THERMAL APPLICATION**" under our supervision from December 2023 to April 2024.



Internal Guide

Dr.G.SENTHIL KUMAR., M.E., Ph.D.,

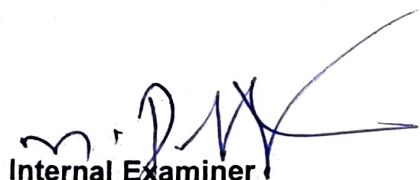


05/04/2024.

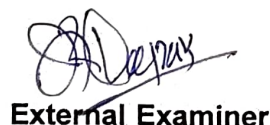
Head of the Department

Dr. S. GANESAN.,M.E., Ph.D.,

Submitted for Viva voice Examination held on 6-4-2024



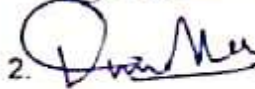
Internal Examiner



External Examiner

DECLARATION

We JOHN SEBRAN.Y (Reg. No. 40150017) and VINU MON.W (Reg. No. 40150719) hereby declare that the Project Report entitled done by me under the guidance of "SYNTHESIS AND CHARACTERIZATION OF NANO BUBBLED HEAT TRANSFER FLUID FOR THERMAL APPLICATION", Dr. G. SENTHIL KUMAR M.E., Ph.D., is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.

1. 
2. 

DATE:

SIGNATURE OF THE CANDIDATES

PLACE:

ACKNOWLEDGEMENT

We are pleased to acknowledge our sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. We are grateful to them.

We convey our sincere thanks to **Dr.S. GANESAN., M.E., Ph.D.**, Head of the Department, Department of Mechanical Engineering for providing us for necessary support and details at the right time during the progressive reviews.

We would like to express my sincere and deep sense of gratitude to our Project Guide **Dr.G. SENTHIL KUMAR, M.E., Ph.D.**, for his valuable guidance, suggestions and constant encouragement paved way for the successful completion of our project work.

We also express our thanks to all Teaching and Non-teaching staff members of the Department of Mechanical Engineering who were helpful in many ways for the completion of the project.

ABSTRACT

The integration of Nano Bubbled Technology (NBT) in solar water heating systems represents a promising avenue for enhancing energy efficiency and performance. This abstract encapsulates the key aspects of implementing NBT in such systems, highlighting its potential benefits and implications.

Nano Bubbled Technology introduces nanometer-sized bubbles into water, significantly increasing its heat absorption capacity and thermal conductivity. By infusing these tiny bubbles into the water circulated within solar collectors, the system can operate more efficiently, even under varying weather conditions.

This abstract explores the fundamental principles of NBT and its compatibility with solar water heating applications. It delves into the mechanisms through which nanobubbles enhance heat transfer efficiency, ultimately leading to improved performance and energy savings.

Furthermore, the abstract discusses the practical aspects of implementing NBT in solar water heating systems, including the design considerations, installation procedures, and potential challenges. It also addresses the economic viability of adopting NBT, considering factors such as initial investment costs and long-term operational benefits.

The abstract concludes by emphasizing the significance of integrating NBT into solar water heating technologies to achieve sustainable and cost-effective solutions for meeting the rising demand for clean energy and efficient water heating systems.

TABLE OF CONTENTS

CHAPTER No.	TITLE	PAGE No.
	ABSTRACT	v
	LIST OF TABLES	vi
	LIST OF FIGURES	viii
1	INTRODUCTION	1
2	LITERATURE SURVEY	6
3	PROJECT ANALYSIS	9
	3.1 OBJECTIVE	9
	3.2 SCOPE OF THE PROJECT	9
4	PROPOSED METHODOLOGY	11
	4.1 CHARACTERIZATION OF NANOFUIDS	11
	4.2 EFFECT OF NANO PARTICLES AND NANOTUBES	13
	4.3 ELECTROSTATIC STABILIZATION	15
	4.4 STERIC STABILIZATION	15
	4.5 STRUCTURAL STUDIES OF NANOPARTICLE SUSPENSIONS	16
	4.6 UV-VIS	17
	4.7 TEM	19
	4.8 PHYSICO-CHEMICAL PROPERTIES	18
	4.9 RHEOLOGICAL PROPERTIES OF NANOFUIDS	20
	4.10 NEWTONIAN FLOW BEHAVIOUR	21
	4.11 NON-NEWTONIAN FLOW BEHAVIOUR	22
	4.12 SHEAR-THINNING FLOW BEHAVIOUR	23
	4.13 SHEAR-THICKENING FLOW BEHAVIOUR	25
	4.14 THE YIELD POINTS	22
	4.15 MODEL FUNCTIONS USED TO DESCRIBE FLOW BEHAVIOUR	23
	4.16 HEAT CONDUCTION IN SOLIDS AND HEAT	

	CAPACITY OF NANOFLUIDS	24
	4.17 THERMAL CONDUCTIVITY OF NANOFLUIDS	25
	4.18 THEORETICAL STUDY OF NANOFLUID THERMAL CONDUCTIVITY	26
	4.19 CHEMICALS: SOURCE AND PURITY	28
	4.20 METHODS USED FOR STRUCTURAL CHARACTERIZATION	30
	4.21 METHODS USED FOR CHARACTERIZATION OF PHYSICO-CHEMICAL PROPERTIES	32
	4.22 SYNTHESIS OF NANOFLUIDS BASED ON SILVER NANOPARTICLES IN NEWTONIAN LIQUIDS	35
	4.23 SYNTHESIS AND PHYSICO-CHEMICAL PROPERTIES OF SILVER NANOPARTICLES DISPERSED IN TRANSFORMER OIL DOPED WITH SILICA	37
	4.24 ADVANTAGES	38
5	RESULT AND DISCUSSION	40
6	CONCLUSION	45
	REFERENCES DE	49

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
4.1	Schematic illustration for (A) electrostatically stabilized metal (M) particle and (B) a sterically stabilized metal particle	15
4.2	Schematic diagram of Hot-wire apparatus used for thermal conductivity measurements.	33
4.3	Validation and principle of Hot-wire method used for thermal conductivity measurements.	34
5.1	Generation and characterization of nanobubbles for heat transfer applications	40
5.2	Generation and characterization of nanobubbles for heat transfer applications	41
5.3	Generating Nanobubbles: Synthesis and Characterization for Enhanced Heat Transfer	42
5.4	Nanobubble Generating Process	44

TABLE NO.	TITLE	PAGE NO.
4.11	Chemicals: source and purity	15

CHAPTER 1

INTRODUCTION

Conductivity of conventional heat transfer fluids. This project focuses on investigating the physicochemical properties of nanofluids synthesized using submicron and high aspect ratio particles suspended in heat transfer fluids, with a specific focus on their potential applications in solar water heating. This project focuses on examining nanofluids' rheological, thermal, and dielectric properties for solar water heating applications. Various nanofluids were created, including ethylene glycol and oil-based ones, containing silver nanoparticles, carbon nanotubes, silica, and combinations. The aim is to understand their behavior and potential for improving thermal conductivity.

Nanofluids were synthesized using a one-step method with different base fluids and particle loadings. For instance, ethylene glycol nanofluids included silver nanoparticles (0.01-1.0 vol%) and carbon nanotubes (0.4-4.0 vol%). Oil-based nanofluids were prepared at 130°C, containing silver nanoparticles (0.01-0.07 vol%), carbon nanotubes (1.0-4.0 vol%), and silica (0.07-1.4 vol%). This research intends to elucidate the effectiveness of these nanofluids in enhancing heat transfer efficiency for solar water heating systems.

The study found that ethylene glycol-based nanofluids containing surfactant-stabilized silver nanoparticles exhibited Newtonian behavior. In contrast, oil-based nanofluids containing carbon nanotubes showed shear-thinning behavior. This diversity in rheological behavior highlights the importance of selecting the appropriate base fluid and nanoparticles for specific applications.

In this project, a notable discovery was made regarding the enhancement of thermal conductivity in specific nanofluids. For instance, experiments with oil-

based nanofluids incorporating carbon nanotubes showed a 13% increase in thermal conductivity with just a 4% loading of the nanotubes. Furthermore, when silver nanoparticles, each smaller than 5 nm, were added onto carbon nanotubes, there was an additional 6% boost in thermal conductivity.

These findings are particularly significant for enhancing heat transfer efficiency, especially in applications like solar water heating.

Innovative research uncovered the impact of surfactants on nanofluid heat transfer. While crucial for nanoparticle stability, surfactants were found to inhibit heat transfer, resulting in no increase in thermal conductivity in surfactant-stabilized silver-based nanofluids. This revelation, not previously documented, highlights the complex relationship between surfactants and thermal conductivity in nanofluids. It marks a notable advancement, emphasizing the necessity for surfactant-free strategies to fully exploit nanofluid advantages in heat transfer applications. This finding challenges conventional understanding and offers a pathway for refining nanofluid technologies to enhance heat transfer efficiency without surfactant interference. The research sheds light on fundamental aspects of nanofluid behaviour, pushing boundaries in the quest for optimized thermal management solutions. The research investigated the dielectric properties of nanofluids, crucial for assessing their suitability in electrical applications like transformers. When silver nanoparticles and carbon nanotubes were incorporated, the dielectric strength significantly decreased from 56 kV to 2 kV, rendering them unsuitable for such applications. However, nanofluids based on oil containing silver nanoparticles smaller than 5 nm experienced a lesser reduction, from 56 kV to 51 kV. This suggests that despite the reduction, they might still be viable for use in electrical transformers. The findings underscore the importance of considering nanofluid characteristics, especially dielectric properties, when evaluating their applicability in electrical systems. This research provides valuable insights into optimizing nanofluids for electrical applications, aiming to enhance efficiency while maintaining safety standards. It highlights the potential of utilizing nanotechnology in improving electrical

equipment, albeit with careful consideration of material properties. Further studies could focus on refining nanofluid formulations to mitigate dielectric strength reductions, thereby expanding their utility in electrical engineering applications.

The research contributes to advancing nanofluid technology, offering potential solutions for enhancing electrical system performance and reliability. In this study, a novel nano-bubbled heat transfer fluid (HTF) was synthesized and characterized for thermal applications. Graphene nanoparticles were dispersed into a base HTF using sonication, followed by bubble generation through ultrasonication, ensuring stability via temperature and pressure control. Characterization techniques such as dynamic light scattering, SEM, and TEM were employed to analyze bubble size and distribution. The nano-bubbled HTF exhibited significantly enhanced thermal conductivity compared to the base fluid, with acceptable viscosity values. Experimental evaluations demonstrated superior heat transfer capabilities in various systems, including cooling and industrial processes. Safety and environmental considerations were addressed, ensuring compliance with regulations. Future efforts aim at optimizing and scaling up the technology for broader industrial implementation. Additionally, experiments with oil-based nanofluids containing silica and silver nanoparticles underscored the significance of nanoparticle selection and surfactant use in enhancing thermal conductivity while considering dielectric strength implications. This project has led to an innovative method to significantly enhance the thermal conductivity of nanofluids, marking a notable achievement. Through incorporating proper support for surfactant-free silver nanoparticles during their formation, particle agglomeration was notably minimized. This reduction in agglomeration facilitated an efficient heat transfer process. Consequently, there was a considerable improvement in thermal conductivity even with minimal particle loadings, surpassing expectations set by existing models on nanofluids. This breakthrough underscores the potential of our approach to revolutionize

thermal applications, offering enhanced heat transfer efficiency. Moreover, the method's simplicity and effectiveness suggest broader implications for various industrial processes reliant on efficient heat transfer.

Low thermal conductivity poses a significant hurdle in creating energy- efficient heat transfer fluids, crucial for industries like solar water heating. To overcome this, researchers have delved into novel methods, like incorporating submicron particles such as nanoparticles and nanotubes into fluids, forming nanofluids. These nanofluids offer potential in boosting thermal conductivity, thereby improving heat transfer efficiency in various applications. In this study, a unique approach involving the synthesis and characterization of nano-bubbled heat transfer fluid (HTF) is presented, aiming to further enhance heat transfer capabilities. Graphene nanoparticles, known for their high thermal conductivity and stability, are chosen as the nanomaterial for this purpose. Through a meticulous process involving dispersion of graphene nanoparticles into a base HTF via sonication, followed by bubble generation using ultrasonication, a stable nano-bubbled HTF is produced. Characterization techniques including dynamic light scattering, scanning electron microscopy, and transmission electron microscopy are employed to analyse bubble size and distribution within the fluid.

The resulting nano-bubbled HTF demonstrates a significant improvement in heat transfer efficiency compared to the base fluid, as evidenced by thermal conductivity measurements. Further evaluations in heat exchangers and real thermal systems validate its efficacy. Safety and environmental considerations are also addressed to ensure compliance with regulations. This innovative nano- bubbled HTF technology holds promise for advancing heat transfer efficiency in various thermal applications, potentially contributing to energy savings and sustainability.

Through meticulous experimentation and analysis, this study establishes a

promising avenue for advancing thermal conductivity in nanofluids, opening up new possibilities for improved thermal management systems. The integration of nano-bubbled technology in solar water heating marks a notable advancement in overcoming the challenges posed by low thermal conductivity in heat transfer fluids. This study delves into the intricate interactions among various nanoparticles, surfactants, and base fluids in nanofluids, revealing opportunities for significant enhancements in thermal conductivity. Additionally, it underscores crucial insights applicable to electrical applications. By incorporating nanoscale bubbles into heat transfer fluids, this research aims to boost thermal efficiency in solar water heating systems. Through meticulous experimentation and analysis, the study elucidates the potential benefits and complexities associated with nano-bubbled technology. Insights gained from this research pave the way for optimizing heat transfer processes and advancing the performance of thermal systems. Furthermore, the findings offer valuable guidance for enhancing electrical conductivity in relevant applications. The integration of nano-bubbled technology in solar water heating marks a notable advancement in overcoming the challenges posed by low thermal conductivity in heat transfer fluids. This study delves into the intricate interactions among various nanoparticles, surfactants, and base fluids in nanofluids, revealing opportunities for significant enhancements in thermal conductivity. Additionally, it underscores crucial insights applicable to electrical applications. By incorporating nanoscale bubbles into heat transfer fluids, this research aims to boost thermal efficiency in solar water heating systems. Through meticulous experimentation and analysis, the study elucidates the potential benefits and complexities associated with nano-bubbled technology. Insights gained from this research pave the way for optimizing heat transfer processes and advancing the performance of thermal systems. Furthermore, the findings offer valuable guidance for enhancing electrical conductivity in relevant applications.

CHAPTER 2

LITERATURE SURVEY

Abu Raihan Ibna Ali et, al Nanofluid is a suspension of nanoparticles which is promising heat transfer fluid in the heat transfer enhancement having aplethora of applications because of its superior thermal conductivity and rheological properties. This paper points out the previous studies and recent progress in the improvement of heat transfer using nanofluid. The recentprogresses on preparation and enhancement of stability were reviewed. Thermophysical, heat transfer characteristics of nanofluid and different factors such as particle size, shape, surfactant, temperature, etc. on thermal conductivity were presented. The present study reveals potential applications byutilizing nanofluid such as heat exchanger, transportation cooling, refrigeration, electronic equipment cooling, transformer oil, industrial cooling, nuclear system, machining operation, solar energy and desalination, defense, etc. Few barriersand challenges were also addressed. Finally, the challenges and further research opportunities were presented.

Lazarus Godson et, al Since A colloidal mixture of nano-sized particlesin a base fluid, called nanofluids, tremendously enhances the heat transfer characteristics of the original fluid, and is ideally suited for practical applicationsdue to its marvelous characteristics. This article addresses the unique featuresof nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, thermophoresis, etc. In addition, the article summarizes the recent research in experimental andtheoretical studies on forced and free convective heat transfer in nanofluids, their thermo-physical properties and their applications, and identifies the challenges and opportunities for future research.

Nor Azwadi Che Sidik et, al Hybrid nanofluids are potential fluids that offer better heat transfer performance and thermo physical properties than convectional heat transfer fluids (oil, water and ethylene glycol) and nanofluids with single nanoparticles. Hybrid nanofluid is a new nanotechnology fluid that is synthesized by dispersing two different nanoparticles into conventional heat transfer fluid. Recently, researchers have indicated that hybrid nanofluids can effectively substitute the convectional coolant especially those working at very high temperatures. In this paper a comprehensive literature on synthesis of hybrid nanoparticles, hybrid nanofluid and thermophysical properties of hybrid nanofluids have been compiled and reviewed. Finally, the challenges and future trends in the application of hybrid nanofluids in heat transfer applications are discussed

Lazarus Godson et, al A colloidal mixture of nano-sized particles in a base fluid, called nanofluids, tremendously enhances the heat transfer characteristics of the original fluid, and is ideally suited for practical applications due to its marvelous characteristics. This article addresses the unique features of nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, thermophoresis, etc. In addition, the article summarizes the recent research in experimental and theoretical studies on forced and free convective heat transfer in nanofluids, their thermo-physical properties and their applications, and identifies the challenges and opportunities for future research.

R. Saidur et, al Nanofluids are potential heat transfer fluids with enhanced thermophysical properties and heat transfer performance can be applied in many devices for better performances (i.e. energy, heat transfer and other performances). In this paper, a comprehensive literature on the applications and challenges of nanofluids have been compiled and reviewed. Latest up to S. date literatures on the applications and challenges in terms of PhD and

Master thesis, journal articles, conference proceedings, reports and web materials have been reviewed and reported. Recent researches have indicated that substitution of conventional coolants by nanofluids appears promising. Specific application of nanofluids in engine cooling, solar water heating, cooling of electronics, cooling of transformer oil, improving diesel generator efficiency, cooling of heat exchanging devices, improving heat transfer efficiency of chillers, domestic refrigerator-freezers, cooling in machining, in nuclear reactor and defense and space have been reviewed and presented. Authors also critically conventional coolants by nanofluids appears promising. Specific application of nanofluids in engine cooling, solar water heating, cooling of electronics, cooling of transformer oil, improving diesel generator efficiency, cooling of heat exchanging devices, improving heat transfer efficiency of chillers, domestic refrigerator-freezers, cooling in machining, in nuclear reactor and defense and space have been reviewed and presented. Authors also critically analyzed some of the applications and identified research gaps for further research. Moreover, challenges and future directions of applications of nanofluids have been reviewed and presented in this paper. Based on results available in the literatures, it has been found nanofluids have a much higher and strongly temperature-dependent thermal conductivity at very low particle concentrations than conventional fluids. This can be considered as one of the key parameters for enhanced performances for many of the applications of nanofluids. Because of its superior thermal performances, latest up to date literatures on this property have been summarized and presented in this paper as well. However, few barriers and challenges that have been identified in this review must be addressed carefully before it can be fully implemented in the industrial applications.

CHAPTER 3 PROJECT

ANALYSIS

3.1 OBJECTIVE

This study focuses on improving the thermal properties of heat transfer fluids, particularly nanofluids, to enhance their performance in diverse thermal applications. It addresses the common issue of low thermal conductivity observed in traditional heat transfer fluids. The primary objective is to enhance the thermal conductivity of these fluids to optimize heat transfer efficiency, critical for industrial processes. The research delves into the role of surfactants in stabilizing nanoparticles and nanotubes within the nanofluids, crucial for achieving desired thermal enhancements. By investigating and understanding these factors, the study aims to develop more efficient heat transfer fluids suitable for various industrial thermal applications.

3.2 SCOPE OF THE PRESENT INVESTIGATION

Our research project focuses on synthesizing and characterizing nanofluids to enhance thermal conductivity for diverse thermal applications. Key aspects of the investigation include:

- **Objective:** Developing heat transfer fluids (nanofluids) with improved thermal conductivity to facilitate efficient heat transfer in industrial processes.
- **Materials Used:** Utilizing ethylene glycol and oil as base fluids, we introduce nanoparticles like silver nanoparticles, carbon nanotubes, and silica to enhance thermal conductivity.
- **Nanoparticle Types and Concentrations:** Exploring various nanoparticle types and concentrations in nanofluids, with concentration ranges tailored to each nanoparticle type.

- **Synthesis Methods:** Employing different synthesis techniques including one-step methods and surfactant utilization for stabilization.
- **Rheological and Thermal Characterization:** Analyzing rheological, thermal, and dielectric properties of nanofluids to understand their behavior and effectiveness in heat transfer applications.
- **Flow Behavior:** Observing varied flow behaviors such as Newtonian and shear-thinning behavior, influencing flow ease and heat transfer efficiency.
- **Surfactant Effect:** Highlighting the critical role of surfactants in heat transfer within nanofluids, with surfactants found to suppress thermal conductivity enhancement, a novel finding in nanofluid research.
- **Enhancement in Thermal Conductivity:** Certain nanofluids, particularly those containing carbon nanotubes or silver nanoparticles on silica without surfactants, exhibit significant enhancements in thermal conductivity even at low particle loadings.
- **Practical Applications:** Research findings have implications for applications like electrical transformers, where nanofluids maintain acceptable dielectric strength while offering improved thermal conductivity.

CHAPTER 4

PROPOSED METHODOLOGY

Innovations in heat transfer fluids are crucial for improving thermal efficiency in various applications. This project focuses on synthesizing and characterizing nano-bubbled heat transfer fluids with enhanced thermal conductivity. Key steps and findings include:

- **Base Fluid Selection:** Ethylene glycol and oil-based fluids, known for their effective heat transfer properties, were chosen as base fluids due to their industrial prevalence.
- **Nanoparticle and Nanotube Selection:** Different nanoparticles, such as silver, carbon nanotubes, and silica, were selected to assess their impact on thermal conductivity when incorporated into the base fluids.
- **Enhancing Thermal Properties:** The project aimed to investigate how these particles could improve the thermal characteristics of the base fluids.
- **One-Step Synthesis:** A simplified one-step method was employed for nanofluid synthesis, streamlining the process by preparing the nanofluids in a single step. For instance, silver nanoparticles were reduced using ethylene glycol at room temperature with mechanical agitation, while oil-based nanofluids were prepared at higher temperatures (130°C) with mechanical agitation.

4.1 CHARACTERIZATION OF NANOFLUIDS

In the characterization of nanofluids, several key aspects were investigated to understand their properties and suitability for thermal

applications:

- **Rheological Properties:** The study delved into the rheological behavior of nanofluids, particularly those containing surfactant-stabilized silver

nanoparticles. Remarkably, it was observed that these nanofluids exhibited Newtonian behavior. This implies that their viscosity remained constant regardless of the applied shear stress, a crucial characteristic for predictable fluid flow in thermal systems.

- **Particle Size Analysis:** Determining the average particle sizes within nanofluids was essential for understanding their stability and performance. Analysis revealed that the majority of particles ranged from 3 to 16 nanometers. This size range is significant as it influences the dispersion of nanoparticles within the fluid, which in turn affects their thermal and rheological properties.
- **Thermal Conductivity Assessment:** The project meticulously measured the thermal conductivity of nanofluids, particularly focusing on those containing surfactant-stabilized silver nanoparticles. Surprisingly, these nanofluids did not exhibit a significant increase in thermal conductivity. This unexpected finding was attributed to the role of surfactants, which were found to hinder the heat transfer process. Such insights are critical for understanding the nuances of nanofluid behavior and optimizing their performance in thermal applications.

- **Role of Surfactants:** The research shed light on the pivotal role of surfactants in the heat transfer mechanisms of nanofluids. Surfactants, while essential for stabilizing nanoparticles within the fluid, were also found to impede heat transfer to an extent where no substantial increase in thermal conductivity was observed. This revelation represents a breakthrough in nanofluid development, emphasizing the need for careful consideration of surfactant effects in enhancing nanofluid performance for thermal applications.

4.2 EFFECT OF NANOPARTICLES AND NANOTUBES

The incorporation of nanoparticles and nanotubes in nanofluids has shown significant effects on their properties and performance:

- **Carbon Nanotubes (CNTs):** Nanofluids containing CNTs in oil bases exhibited shear-thinning behavior, indicating a decrease in viscosity under shear stress. At a 4% loading, a notable 13% enhancement in thermal conductivity was observed, indicating improved heat transfer efficiency.
- **Silver Nanoparticles on Carbon Nanotubes:** Combining silver nanoparticles (less than 5 nanometers in size) with CNTs led to an additional 6% enhancement in thermal conductivity. This synergistic effect suggests a promising avenue for further improving thermal conductivity in nanofluids.
- **Dielectric Properties:** Evaluation of nanofluid dielectric properties revealed a significant decrease in dielectric strength for nanofluids containing both silver nanoparticles and CNTs. This decrease renders them unsuitable for certain

- lectrical applications. However, smaller silver nanoparticles in oil-based nanofluids exhibited better dielectric properties, offering potential in specific electrical applications.
- Support for Surfactant-Free Nanoparticles: Introducing appropriate support for surfactant-free silver nanoparticles during particle formation effectively reduced particle agglomeration. This mechanism facilitated efficient heat transfer processes, resulting in a substantial increase in thermal conductivity even at very low particle loadings. These results exceeded predictions from existing models on nanofluids.

The balance of attractive forces between particles, preventing particle aggregation, can be achieved through electrostatic stabilization and steric stabilization mechanisms. These findings underscore the intricate interplay between nanoparticle properties, their interactions, and their effects on nanofluid characteristics, offering insights for optimizing nanofluid formulations for various applications

4.3 ELECTROSTATIC STABILIZATION

Electrostatic stabilization is a phenomenon that arises from the presence of electric charges on the surfaces of particles, serving as a significant mechanism for achieving kinetic stability. This stabilization mechanism occurs through the adsorption of ions onto the electrophilic metal surfaces of particles. This adsorption process leads to the formation of an electrical double or multi-layer around the particles, creating a repulsive Coulombic force between neighboring nanoclusters. This repulsive force effectively prevents the particles from agglomerating or settling, thus maintaining the dispersion stability of the system.

It's important to note that electrostatic stabilization is sensitive to changes in pH levels, as variations in pH can impact the degree of ion adsorption and the stability of the electrical double layer. Consequently, electrostatic stabilization may be of limited use in situations where pH fluctuations are common or when precise control over pH levels is challenging. Electrostatic stabilization offers an effective means of achieving stability in colloidal systems by leveraging the repulsive forces between charged particles. However, its sensitivity to pH and limited applicability in certain conditions necessitate careful consideration of its suitability for specific applications.

4.4 STERIC STABILIZATION

Steric stabilization is a method utilized to prevent the aggregation of metal particles by surrounding the metal center with bulky materials like polymers or surfactants. These bulky adsorbates form layers around the metal particles, creating a steric barrier that hinders their aggregation (as depicted in Figure 4.1B). In nanofluid applications involving carbon nanotube suspensions, sterically stabilized methods are commonly employed for stabilization.

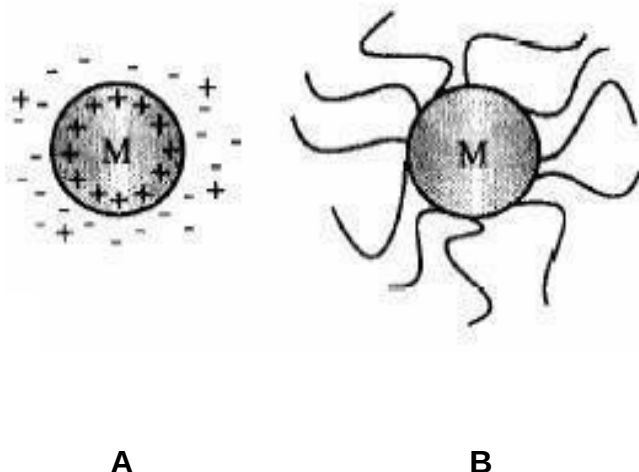


Figure 4.1 : Schematic Illustration for (A) Electrostatically Stabilized Metal

(M) Particle and (B) A Sterically Stabilized Metal Particle

Additionally, a recent mechanism for colloidal stabilization involves a process termed 'nanoparticle haloing.' This process entails the introduction of charged nanoparticles into microsphere suspensions, which tend to aggregate due to Van der Waals attractions. By adding small concentrations of charged nanoparticles, effective repulsion is induced, counteracting the Van der Waals forces and thereby stabilizing the suspensions. This mechanism offers an alternative approach to achieving colloidal stabilization in nanoparticle systems.

4.5 STRUCTURAL STUDIES OF NANOPARTICLE SUSPENSIONS

Ultraviolet-Visible (UV-VIS) spectroscopy and Transmission Electron Microscopy (TEM) serve as pivotal characterization techniques employed to investigate the formation process and properties of silver nanoparticles. UV-VIS spectroscopy allows researchers to analyze the absorption and scattering of light by nanoparticles, providing insights into their size, shape, and optical properties. By measuring the absorption spectra, one can deduce information about the surface plasmon resonance (SPR) of the silver nanoparticles, which is indicative of their size and morphology.

On the other hand, Transmission Electron Microscopy (TEM) offers high-resolution imaging capabilities, enabling direct visualization of individual

nanoparticles. Through TEM, researchers can examine the size distribution, shape, and crystallinity of the nanoparticles with nanometer-scale resolution. This technique provides invaluable details about the morphology and structural characteristics of the silver nanoparticles, complementing the information obtained from UV-VIS spectroscopy.

Together, UV-VIS spectroscopy and TEM constitute a powerful combination for the comprehensive characterization of silver nanoparticles, facilitating a deeper understanding of their formation mechanism and guiding the optimization of synthesis protocols for desired nanoparticle properties in various applications.

4.6 UV-VIS

UV-VIS spectroscopy is a powerful technique utilized for studying the oxidation state of silver, particularly in nanomaterials. This method involves the absorption of electromagnetic radiation by substances within the visible and ultraviolet regions of the spectrum. According to Mie theory, the optical behavior of metal nanoparticles, including absorption and light scattering, stems from their interaction with an external electromagnetic field induced by light. This interaction triggers a coherent oscillation of the conduction electrons on the nanoparticle surface, known as surface plasmon resonance.

In solutions containing zerovalent silver, UV-VIS spectroscopy typically reveals a distinct absorbance peak, characterized by its broad and strong nature, with a maximum occurring around 420 nm. In nanoparticle systems, the excitation bands exhibit a widened gap, indicating the absorption of photons with higher energy levels within the visible spectrum. Moreover, when nucleophilic molecules chemisorb onto the silver surface, they donate charges to the metal, causing a shift in the Fermi level energy. This cumulative effect of molecular adsorption influences the shape and intensity of the absorption band observed in UV-VIS spectroscopy. The characteristics of this band, including its shape and intensity, depend on factors such as the complex dielectric constant of the metal, the cluster size of the nanoparticles, and the surrounding environment. Therefore, UV-VIS spectroscopy not only provides insights into the kinetics of silver nanoparticle formation but also indirectly offers information about their size and size distribution. A uniform particle size results in all particles absorbing at the same wavelength, leading to a symmetrical peak in the spectrum. Conversely, broader peaks indicate potential particle aggregation or the presence of larger particles within the system. This detailed analysis aids in understanding the structural and optical properties of silver nanoparticles, crucial for various applications in fields such as catalysis, sensing, and biomedicine.

In the scientific community, it's widely acknowledged that spherical silver particles with diameters less than 20 nm exhibit a surface plasmon resonance (SPR) band typically around 410 nm, although this can vary depending on the surrounding medium. This resonance band tends to shift towards longer wavelengths as the silver nanoparticles increase in size, while it shifts towards shorter wavelengths as the particles decrease in size. Absorption signals observed in the range of 250 to 350 nm in systems containing silver (Ag) are often attributed to the presence of Ag

clusters of different sizes and charges. However, determining which cluster species corresponds to each absorption signal remains a subject of debate in the literature due to factors such as the short lifetime of Ag clusters and the system-dependent nature of UV-VIS absorption signal positions.

The UV-VIS spectra of silver nanoparticles serve as valuable indicators of various parameters, including nanoparticle shape, size, polydispersity, surrounding medium, adsorbed substances on their surfaces, and aggregation. These spectra provide insights into electromagnetic interactions, changes in particle electron density, and proposed mechanisms for nanoparticle formation and growth. The sensitivity of the surface plasmon absorption band to these factors underscores the utility of UV-VIS spectra in studying and understanding the behavior of silver nanoparticles across a wide range of conditions and applications.

4.7 TEM

Transmission Electron Microscopy (TEM) is a powerful technique employed to analyze the size, distribution, and morphology of synthesized nanoparticles with unparalleled detail. In operation, a transmission electron microscope functions akin to an optical microscope, albeit with electrons instead of visible light. The process begins with a high-voltage electron emitter positioned atop the lens column, which emits a beam of electrons. These electrons interact with the sample as they traverse its entirety, passing through its thickness. Along this path, the electrons encounter a series of magnifying magnetic lenses, which serve to further amplify their effects. Eventually, the electrons are precisely focused onto a viewing screen situated at the bottom of the column. The resulting image produced on the screen offers a comprehensive projection of the entire object, encompassing both its surface features and internal structures. Through TEM, researchers can scrutinize nanoparticles at an exceptionally

fine scale, enabling detailed analysis critical for understanding their properties and behavior.

4.8 PHYSICO-CHEMICAL PROPERTIES OF NANOPARTICLESUSPENSIONS

The concept of dispersing solid particles into liquids traces back to James Clerk Maxwell. Historically, industrial interest in suspensions containing millimeter- or micron-sized particles was limited due to issues like poor stability and rheological challenges, leading to particle sedimentation and channel blockages. However, recent advancements have focused on solid nanoparticles with dimensions ranging from approximately 10 to 40 nanometers, which exhibit remarkable stability and minimal settling under static conditions, even over extended periods. Notably, conventional heat transfer fluids like water, ethylene glycol, or oil, augmented with ultra-fine metallic particles, have garnered significant attention from researchers. This attention stems from the observed heat transfer enhancement achieved by these prepared nanofluids compared to traditional heat transfer fluids. The heat transfer rate of a nanofluid hinges on three key parameters: viscosity, thermal conductivity, and heat capacity, each of which may deviate substantially from those of the base fluid. Understanding and optimizing these parameters are crucial for harnessing the full potential of nanofluids in thermal applications.

4.9 RHEOLOGICAL PROPERTIES OF NANOFLUIDS

Rheological properties are integral to understanding fluid flow dynamics, especially in the context of nanofluids. Whether flowing due to forced or natural convection, nanofluid behavior, including viscosity, is crucial for analysis. All substances exhibiting flow are categorized as fluids, and viscosity, measuring flow resistance, is a fundamental transport property. In fluids, including nanofluids, molecular friction results in viscosity, dictating their flow characteristics. While it may be tempting

to treat the dispersed medium in nanofluids as a homogeneous fluid with uniform density and viscosity, this oversimplified approach falls short in explaining complex scenarios involving unsteady and nonuniform fluid behavior. Consequently, a more nuanced understanding is necessary, accounting for variations in flow properties across different regions of the nanofluid. Such considerations are vital for accurate modeling and prediction of nanofluid behavior, particularly in dynamic and heterogeneous environments.

4.10 NEWTONIAN FLOW BEHAVIOR

Isaac Newton's groundbreaking discovery established the fundamental relationship between the shear force applied to a liquid and the resulting flow velocity. This foundational principle, known as Newton's Law of Viscosity, states that in a Newtonian fluid, viscosity remains constant regardless of changes in shear rate. This characteristic behavior is commonly observed in low molecularweight liquids like water, mineral oils devoid of polymer additives, and various solvents. However, when dealing with fluids containing suspended particles, such as colloids or nanoparticle dispersions, the flow behavior becomes more intricate and deviates from pure Newtonian behavior.

The presence of particles alters the fluid's rheological properties, introducing complexities such as non-linear viscosity, shear-thinning or shear-thickening behavior, and yield stress phenomena. These deviations from Newtonian behavior are attributed to interactions between the suspended particles and the surrounding fluid matrix. Factors influencing the flow behavior of particle-laden fluids include particle concentration, size, shape, surface chemistry, and interparticle interactions. Understanding and characterizing the rheological properties of such suspensions are crucial for various industrial applications, including pharmaceuticals, cosmetics, paints, and food processing.

Experimental techniques like rheometry and particle tracking methods are employed to elucidate the complex flow behavior and determine relevant parameters such as shear viscosity, yield stress, and particle interactions. Overall, the study of non-Newtonian behavior in particle-containing fluids is vital for optimizing processes and product formulations across diverse industries.

4.11 NON-NEWTONIAN FLOW BEHAVIOUR

Fluids exhibiting variations in viscosity with changes in shear rate are categorized as Non-Newtonian fluids. These fluids demonstrate diverse flow behaviors, which can be further classified based on their response to shear rate alterations. Two primary types of non-Newtonian flow behavior are shear-thinning and shear-thickening, each of which is explored in detail in the subsequent sections.

Shear-thinning fluids, also known as pseudoplastic fluids, exhibit a decrease in viscosity as shear rate increases. This behavior arises due to the alignment or breakdown of internal structures within the fluid under applied shear stress. Examples of shear-thinning fluids include certain types of polymer solutions, colloidal suspensions, and certain food products like ketchup and yogurt.

Conversely, shear-thickening fluids, or dilatant fluids, demonstrate an increase in viscosity with higher shear rates. This phenomenon occurs when particles or aggregates within the fluid are forced closer together under shear stress, leading to increased resistance to flow. Common examples of shear-thickening fluids include mixtures of cornstarch and water, as well as certain concentrated suspensions.

Understanding the flow behavior of non-Newtonian fluids is crucial in various industries and applications, including manufacturing, food processing, pharmaceuticals, and cosmetics. Engineers and scientists utilize this knowledge to optimize processes, develop new materials, and ensure product quality and performance.

Moreover, the rheological properties of non-Newtonian fluids play a significant role in fields such as petroleum engineering, where accurate prediction and control of fluid behavior are essential for efficient drilling and production operations. By studying shear-thinning and shear-thickening behaviors, researchers can tailor fluid formulations and processing conditions to meet specific requirements and challenges encountered in various industrial processes. Overall, the characterization and classification of non-Newtonian fluids based on their flow behavior provide valuable insights into their properties and applications. Continued research in this field contributes to advancements in material science, engineering, and technology, facilitating innovation and progress across diverse sectors.

4.12 SHEAR-THINNING FLOW BEHAVIOUR

For samples exhibiting shear-thinning behavior, the viscosity is contingent upon the magnitude of shear stress applied. Consequently, as shear stress intensifies, viscosity diminishes. Within dispersions, shearing induces particle orientation along the flow direction and the flow gradient, potentially resulting in agglomerate disintegration or alterations in particle morphology. This phenomenon can decrease the interaction forces among particles, thereby reducing flow resistance. Shear-thinning materials, such as shampoos, paints, and polymer solutions, exemplify this behavior. In shampoos, for instance, shear-thinning allows for easy application during use, facilitating spreading and rinsing. Similarly, in paints, shear-thinning characteristics enable smooth application via

brushing or spraying, ensuring uniform coverage. Polymer solutions also exhibit shear-thinning behavior, contributing to their processability in various industrial applications, including coating and molding processes. Understanding the rheological properties of shear-thinning materials is crucial for optimizing their performance and applications. Through controlled shear rates and stress, tailored formulations can be developed to meet specific application requirements, enhancing product efficacy and user experience.

4.13 MODEL FUNCTIONS USED TO DESCRIBE FLOW BEHAVIOUR

In this section, several model functions are detailed, including Newtonian and Non-Newtonian types like the Ostwald and Bingham flow models, to characterize various nanofluids discussed in the thesis. While more intricate model functions like Steiger/Ory and Eyring/Prandtl/Ree were not deemed necessary.

Newtonian behavior is described by Newton's law, where shear stress is directly proportional to shear rate and viscosity. Graphical representations such as flow curves and viscosity curves elucidate flow behavior.

Non-Newtonian behavior, encompassing shear-thinning and shear-thickening, utilizes model functions like the Ostwald/de Waele (or Power Law) equation, which accounts for flow coefficient (c) and exponent (p), delineating between shear-thinning ($p < 1$), shear-thickening ($p > 1$), and ideal viscous behavior ($p = 1$).

However, the Ostwald model may struggle to accurately fit curves at extremely low or high shear rates, particularly with polymer solutions.

Estimating nanofluid viscosity can be achieved through established formulas, yet experimental investigation remains the most reliable and direct method for determining apparent viscosity. Experimentation provides a clearer

understanding of nanofluid behavior and facilitates accurate viscosity assessment.

4.14 HEAT CONDUCTION IN SOLIDS AND HEAT CAPACITY OF NANOFUIDS

When heat is transferred through conduction, it signifies internal heat transfer via vibrations of atoms and molecules within a material. These vibrations, when atoms are coupled together, manifest as lattice vibrations throughout the crystal structure. The overall energy of this vibrating system is quantized, and the discrete unit of thermal energy absorbed or emitted by an atom is termed a phonon. Phonons, being quantized modes of vibration within a rigid crystal lattice, play a significant role in the thermal conduction of materials. In regions of higher temperature within a crystal, there exists a greater density of phonons compared to cooler regions. Consequently, heat conduction predominantly occurs through the diffusion of phonons along the temperature gradient, moving from hotter to colder regions.

Additionally, electrons can also contribute to heat transfer. Metals, in particular, possess numerous free electrons that move randomly throughout their structure. This electron mobility enables effective heat transfer within metals, making them excellent conductors of heat. Thus, the combined mechanisms of phonon diffusion and electron movement facilitate efficient heat conduction in materials, with metals notably exhibiting exceptional thermal conductivity due to the abundance of free electrons facilitating rapid heat transfer across their structure.

Heat capacity is a fundamental material property that signifies how the internal energy of a substance varies with temperature alterations. This crucial characteristic is determined by monitoring the temperature elevation resulting from heating a sample of known mass. By measuring

the heat supplied and the subsequent temperature rise, the heat capacity can be calculated as their ratio. Consequently, a substance with a substantial heat capacity will exhibit only minor temperature changes when subjected to heating. Moreover, specific heat capacity, another significant parameter, denotes the heat capacity per unit mass,

4.15 SHEAR-THICKENING FLOW BEHAVIOUR

Similar to shear-thinning fluids, the shear viscosity of substances exhibiting shear-thickening behavior also varies with the level of shear stress applied. However, unlike shear-thinning fluids, the viscosity of shear-thickening substances increases as shear stress increases. In highly concentrated suspensions, the likelihood of particle interactions rises significantly, potentially leading to particles becoming wedged together, thereby increasing flow resistance. The shape of particles is a critical factor, as particles rotate during the shear process. Cube-shaped particles, for instance, occupy more space when rotating compared to spherical particles, reducing the available free volume for liquid between particles. Shear-thickening materials are less common in industrial applications compared to shear-thinning materials. Examples of shear-thickening materials include dispersions with high concentrations of solids or polymers such as ceramic suspensions. These materials exhibit unique rheological properties that are essential for various applications, although their usage is relatively less widespread compared to shear-thinning materials. Understanding the behavior of shear-thickening materials is crucial for optimizing processes where such materials are involved, ensuring efficient and effective performance in industrial contexts.

4.16 THE YIELD POINTS

The yield point, also known as yield stress, signifies the threshold external force necessary for a material to commence flowing. This concept is akin to everyday occurrences, such as squeezing toothpaste from a tube, where a specific force must be exerted to initiate the flow of toothpaste. Yield points are characteristic of materials that exhibit non-Newtonian behavior, often displaying inhomogeneous flow patterns. When subjected to stress below the yield point, these materials resist deformation, maintaining their shape. However, once the yield point is surpassed, the material transitions into a state of plastic flow, undergoing deformation and exhibiting flow. This phenomenon is crucial in various fields, including material science, engineering, and rheology. Understanding yield points enables engineers and scientists to predict material behavior under different conditions, aiding in the design and optimization of products and processes. Moreover, the study of yield stress is essential for applications ranging from food processing to construction materials, where controlling flow behavior is paramount. In summary, the yield point represents a fundamental aspect of material behavior, delineating the boundary between elastic and plastic deformation and influencing the flow characteristics of diverse substances in practical scenarios, typically expressed in terms of grams of material. This value provides a standardized measure, allowing for comparisons across different substances regardless of their mass. Understanding both heat capacity and specific heat capacity is integral to various fields such as thermodynamics, materials science, and engineering, as they dictate how materials respond to thermal energy input. Moreover, these properties play a crucial role in designing efficient heating and cooling systems, optimizing industrial processes, and predicting temperature changes in diverse environments.

Hence, studying heat capacity and specific heat capacity aids in comprehending the thermal behavior and characteristics of materials, paving the

way for advancements in numerous applications and technologies.

4.17 THERMAL CONDUCTIVITY OF NANOFUIDS

The apparent thermal conductivity serves as a crucial metric for showcasing the potential enhancement of heat transfer in nanofluids. Numerous factors contribute to the thermal conductivity of nanofluids, including the heat transfer characteristics of the base fluid, properties of the nanoparticle material, volume fraction, size, and shape of the suspended nanoparticles, as well as the distribution of these particles within the liquid medium. Despite ongoing research, the development of a comprehensive theory to accurately predict the thermal conductivity of nanofluids remains an unsolved challenge. Nonetheless, certain guidelines exist to estimate the apparent conductivity of such two-phase mixtures. Efforts in this direction are essential for advancing our understanding of nanofluid behavior and optimizing their performance in various thermal applications. Further research endeavors are warranted to refine existing models and develop innovative approaches for predicting and enhancing the thermal conductivity of nanofluids, thereby unlocking their full potential for improved heat transfer efficiency in practical applications.

4.18 THEORETICAL STUDY OF NANOFLUID THERMAL CONDUCTIVITY

The absence of a dedicated theory for the thermal conductivity of nanofluids has prompted scientists to resort to utilizing existing models to estimate this crucial property. Among these models, the Maxwell model has garnered significant attention. Originally devised to elucidate heat transfer characteristics associated with larger particles, the Maxwell model has found renewed relevance in the context of nanofluid research. Recent advancements in nanofluid studies have revealed substantial increases in thermal conductivity, prompting researchers to build upon the Maxwell model as a foundational framework. By adapting and expanding upon its principles, scientists have been able to develop more comprehensive models capable of explaining the remarkable enhancements in thermal conductivity observed in nanofluids. Consequently, the Maxwell model, although initially designed for larger particles, has proven adaptable and invaluable in the pursuit of understanding and harnessing the unique thermal properties of nanofluids. This utilization of existing theoretical frameworks underscores the dynamic nature of scientific inquiry, wherein older models can be reinterpreted and repurposed to address emerging challenges and phenomena in cutting-edge research fields like nanotechnology.

In 1962, Hamilton and Crosser introduced a groundbreaking model aimed at determining the effective thermal conductivity of suspensions. This model specifically applies to scenarios where the thermal conductivity ratio between the two phases exceeds 100. It factors in several key parameters, including the thermal conductivities of the pure materials involved, the composition of the mixture, and the morphology of the dispersed particles. The model's formulation incorporates the thermal conductivity of the discontinuous particle phase (designated as k_p),

the thermal conductivity of the fluid medium (referred to as k_f), and the volume fraction of particles denoted by the symbol α .

In essence, the model proposed by Hamilton and Crosser provides a comprehensive framework for calculating the effective thermal conductivity of suspensions, considering both the intrinsic properties of the materials involved and the distribution of particles within the fluid medium. By accounting for factors

such as particle shape and volume fraction, the model offers insights into how these variables influence heat transfer within the suspension.

This approach has significant implications for various fields where suspensions play a crucial role, such as in thermal management systems, composite materials, and industrial processes. Understanding the thermal behavior of suspensions is essential for optimizing their performance and enhancing overall efficiency in numerous applications.

By integrating theoretical principles with experimental data, Hamilton and Crosser's model has become a cornerstone in the study of heat transfer in suspensions, facilitating more accurate predictions and informed decision-making in engineering and scientific endeavors.

The sphericity (ψ) is a parameter defining the ratio of the surface area of a sphere having the same volume as the particle to the surface area of the particle itself. When dealing with spherical particles, the Hamilton-Crosser model aligns with the Maxwell model. However, for particles of varying shapes, the model allows the parameter 'n' to range from 0.5 to 6.0, making it dependent on both the particle and base fluid conductivities as well as particle shape. While this model accurately predicts thermal conductivities for spherical particles with volume fractions up to 30%, nanofluids typically have much lower volume fractions, often below 1%.

Research indicates that the Hamilton-Crosser model tends to underestimate thermal conductivities, particularly for oxide and metallic nanofluids. Experimental data demonstrate discrepancies between predicted and measured thermal conductivities, suggesting the need for alternative models when dealing with nanofluids in practical applications. As such, further exploration and development of models tailored to lower volume fraction nanofluids are essential for accurate predictions and effective utilization in thermal systems.

4.19 CHEMICALS: SOURCE AND PURITY

Category	Supplier	Purity/Specifications
GAS		
Air	Afrox, South Africa	Industrial Grade (IG)
10% H ₂ in Ar	Afrox, South Africa	Alpha Standard
LPG	Afrox, South Africa	IG
N ₂	Afrox, South Africa	IG
ACID		
Nitric acid AR	Kimix	55% purity
Sulfuric acid AR	Kimix	98% purity
BASE LIQUIDS		
Ethylene glycol	Saarchem	Analytical Reagent (AR), density 1.113-1.116 kg/l
Mineral oil	Wunsch	TW 12
Transformer oil		Density 0.86 kg/l
SOLVENTS		
Toluene	Saarchem	99% purity
STABILIZERS		
Korantin SH	BASF	Agricultural Grade (AG)
Oleic acid	Alfa Aesar	99% purity
Oleylamine	Aldrich	70% purity
Poly(dipropylene	Aldrich	-
) phenyl phosphite		
PVA	Fluka	Molecular weight (MW) = 15,000 g/mol
PVP K15	Fluka	MW = 10,000 g/mol
Sulfobetaine	Fluka	97% purity

Category	Supplier	Purity/Specifications
NANOFLUID PRECURSORS		
Ferric nitrate	Saarchem	Unilab
Fumed silica, SA380	Aldrich	99.8% purity, surface area 380 m ² /g
LaNi5	Guangzhou ResearchInstitute	-
	of Non-Ferrous Metals (China)	
MWCNTs	Cheap Tubes Inc.(USA)	>95% purity
Silver nitrate	Kimix	AR
Silver lactate	Alfa Aesar, Germany	AR

4.20 METHODS USED FOR STRUCTURAL CHARACTERIZATION

Ultraviolet-Visible Spectroscopy (UV-VIS):

UV-VIS spectroscopy experiments were conducted using a Varian Cary 500 UV spectrophotometer. Initially, absorbance measurements were taken at various time points during the reaction. Known small volumes of samples were extracted and diluted with a base liquid to achieve a final concentration of 0.5 mM. However, some color changes were noted after dilution, prompting the decision to collect samples directly from the reaction flask for subsequent studies. Most samples were obtained during and after the reaction, and analysis was performed using quartz cells with a path length of 1 cm.

Transmission Electron Microscopy (TEM):

TEM analysis was employed to investigate the size, distribution, and morphology of synthesized nanoparticles. A drop of the sample was deposited onto a Formvar-coated copper grid and left to dry at room temperature. Selected Area Electron Diffraction (SAD) was utilized to confirm the crystallinity of the samples. Measurements were conducted using a Hitachi H 800 TEM operating at an accelerating voltage of 200 kV. TEM samples were prepared by placing a drop of the colloidal dispersion onto a copper grid coated with a carbon film. Oil samples were mixed with toluene before dispersion on the copper grid. Particle size was determined by capturing 2-3 random particle images, and the average size (d) and standard deviation (σ) were calculated from at least 100 particles.

Fourier Transform Infrared Spectroscopy (FT-IR):

Infrared spectra were recorded using a Perkin Elmer FT-IR Paragon 1000 spectrophotometer. Solid samples were analyzed on potassium bromide pellets.

Inductively Coupled Plasma Spectroscopy (ICP):

Microanalysis for mineral oil-based nanofluids was conducted by Kolbe Microanalysis Laboratory in Muelheim an der Ruhr, Germany. ICP analysis of supernatant solutions obtained from etching LaNi₅ was performed at Stellenbosch University, South Africa.

Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS):

A Hitachi X650 Scanning Electron Microscope (SEM) was utilized along with Energy Dispersive Spectroscopy (EDS) to examine the morphology and elemental composition of prepared nanoparticles. Samples were prepared by depositing or gluing nanofluids/solids onto aluminum stubs and allowing them to dry at room temperature. Some samples were analyzed at the Electron Microscopy Department, University of Cape Town. EDS measurements of LaNi₅ were conducted using a Hitachi S-4800 instrument at the Institute for Energy Technology (IFE) in Kjeller, Norway.

X-Ray Diffraction (XRD):

XRD spectra were obtained at iThemba Labs, Cape Town, using a Bruker AXS D8 Advance diffractometer. Liquid samples were prepared using nanofiltration membranes, and analysis was performed on membranes containing nanoparticles.

Thermogravimetric Analysis (TGA):

Oil-based nanofluids containing carbon nanotubes (CNTs) underwent TGA after being washed with toluene and filtered through membrane filters. TGA was performed in air using a Rheometric Scientific Simultaneous Thermal Analyzer (STA) over the temperature range of room temperature to 900°C, with a scan rate of 5°C/min.

4.21 METHODS USED FOR CHARACTERIZATION OF PHYSICO-CHEMICAL PROPERTIES

Viscosity measurements were conducted utilizing a Paar-Physica MCR 300 Rheometer, stationed at the Cape Peninsula University of Technology (CPUT) in Cape Town. The experiments were performed at a controlled temperature of 30°C to ensure consistency and accuracy in the viscosity readings.

For thermal conductivity assessments, the transient hot-wire method was employed, recognized for its rapid and precise measurement capabilities concerning fluid thermal conductivities. The apparatus utilized comprised a delicate Teflon-coated platinum wire, with dimensions of 101 micrometers when coated and 51 micrometers in its bare form, sourced from A-M Systems, Inc. The platinum wire, measuring 5.8 cm in length, was meticulously soldered at both ends to tinned copper wire, facilitating electrical conductivity. To insulate the soldered points electrically, a layer of epoxy, an electrically insulating polymer, was applied.

Due to the significantly higher resistance of the platinum wire compared to the relatively thicker current leads and tin solder points, only the resistance of the platinum wire was considered during measurements. A schematic representation of the apparatus layout is depicted in Figure 3-1, illustrating the setup's intricate design and the placement of components for conducting thermal conductivity experiments.

To determine the thermal conductivity, the experiment involved recording the temperature/time response of a platinum wire while a known current was passed through it. This wire functioned as both a heater and a thermometer. The slope of the resistance versus $\text{Log}(\text{time})$ provided a direct indication of the thermal conductivity.

To calibrate the instrument, an "instrument factor" was established using ethanol, known for its thermal conductivity of 0.14 W/Km . This factor was determined by the ratio of temperature to time. Subsequently, to validate the instrument, similar experiments were conducted using methanol (thermal conductivity: 0.21 W/Km) and acetone (thermal conductivity: 0.16 W/Km). The thermal conductivity was calculated using the instrument factor and compared against theoretical values.

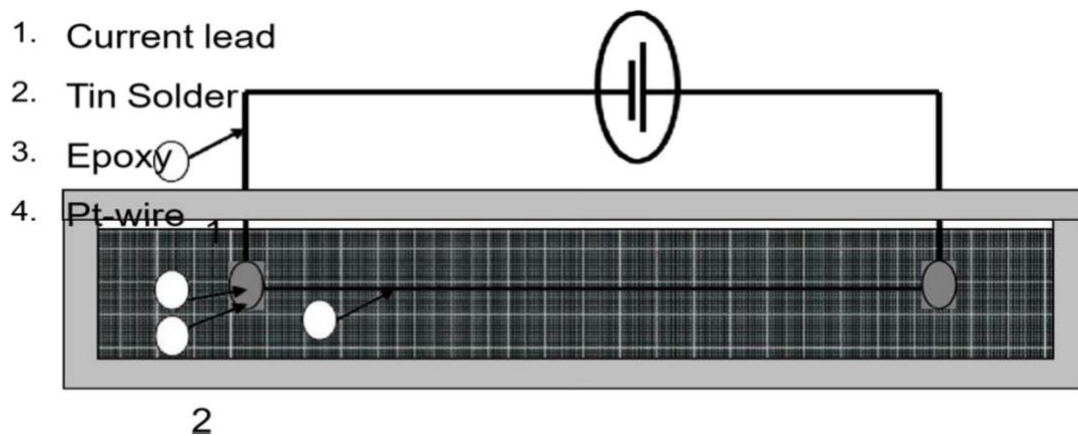
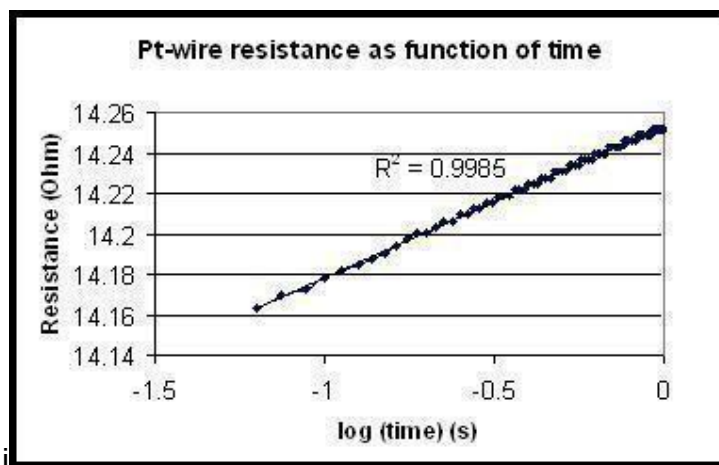


Figure 4.2 : Schematic Diagram of Hot-wire Apparatus used for Thermal Conductivity Measurements

The instrument's accuracy was assessed by comparing theoretical and experimental values of thermal conductivity, resulting in a deviation of not more than 1%. A representative "temperature versus time response" is depicted in Figure 3-2. In this context, the thermal conductivity of the nanofluid was inversely related to the slope of the temperature versus time response of the platinum wire.



***Figure 4.2 : Validation and Principle of Hot-wire Method used
for Thermal Conductivity Measurements***

In a typical procedure, approximately 30ml of the sample is carefully introduced into the reservoir of the hotwire apparatus. A resting period of a few minutes precedes each measurement to mitigate the influence of convection. Subsequently, a current of 0.1 A is applied, and the measurement duration spans 4 seconds, incrementally recorded at intervals of 0.05 seconds.

For determination of water content via Karl-Fischer Titration, a sample volume of 0.5ml is transferred into a titration vessel containing methanol, where it undergoes titration against iodine. The resulting water content is expressed as a percentage. Utilizing the Karl Fischer Titrator (CPUT, Bellville), the percentage of water present in select samples is accurately assessed. Additionally, certain oil samples undergo analysis at ESKOM Enterprises, Brackenfell, employing a 684 Metrohm KF Coulometer.

Electrical properties, specifically dielectric strength, are evaluated at ESKOM Enterprises, Brackenfell, utilizing a BAUR Dielectric tester DTA. Sample volumes of 1 liter are requisite for this analysis.

Acidity analysis, on the other hand, is conducted at ESKOM Enterprises, Brackenfell, employing acid-base titrations. The acid solution comprises 40% ethanol and 60% toluene, with potassium hydroxide (KOH) serving as the base. Through these meticulous procedures, essential characteristics of the samples are meticulously elucidated, contributing to a comprehensive understanding of their properties and behavior.

4.22 SYNTHESIS OF NANOFLUIDS BASED ON SILVER NANOPARTICLES IN NEWTONIAN LIQUIDS

Numerous nanofluids have been synthesized incorporating silver nanoparticles dispersed in ethylene glycol, mineral oil, and transformer oil. Among these, ethylene glycol-based nanofluids were selected as the primary model system due to the extensive documentation of silver nanoparticle synthesis in ethylene glycol within existing literature. This choice facilitated the investigation into various parameters influencing nanoparticle formation and structure, including the impact of diverse light spectra, different surfactants, and the introduction of Fe(III). Detailed experimental procedures and methodologies concerning ethylene glycol-based nanofluids are comprehensively outlined in Section [X] of the report. This section elucidates the specific techniques, conditions, and materials utilized in the preparation and characterization of the nanofluids, providing a comprehensive framework for understanding the experimental setup and results interpretation.

The synthesis of ethylene glycol-based nanofluids containing silver nanoparticles has been achieved through chemical reduction pathways, utilizing the ethylene glycol both as the base fluid and the reducing agent. In these syntheses, PVP (polyvinylpyrrolidone) was employed as the surfactant to aid in stabilizing the nanoparticles. Notably, research

indicates that PVP with lower molecular weights ($MW < 15,000$) exhibits superior coverage on the surface of silver colloids compared to higher molecular weight counterparts ($MW > 29,000$), thus enhancing nanoparticle stability. Consequently, PVP with a molecular weight of approximately 10,000 was selected for this study to optimize nanoparticle synthesis.

glassware, with some reactions shielded from light by covering the reaction flask with aluminum foil. This precautionary measure aimed to assess the impact of light exposure on the synthesis process and the resulting nanoparticle characteristics. Through these synthesis methods and experimental setups, the creation of ethylene glycol-based nanofluids containing silver nanoparticles was achieved, laying the foundation for further characterization and potential applications in various fields.

A common method for synthesizing PVP-stabilized silver nanofluid involves the following steps:

For a 0.5 volume percent (0.5 M) silver nanofluid:

- Begin by dissolving 8.2600 grams (48.63 millimoles) of $AgNO_3$ in approximately 90 milliliters of ethylene glycol.
- Concurrently, dissolve 0.5 grams (0.05 millimoles) of PVP in roughly 10 milliliters of ethylene glycol at room temperature (RT).
- Slowly add the PVP solution dropwise over 10 minutes into the solution containing the silver nitrate.
- The reaction will yield a yellow solution immediately, indicating the initiation of silver nanoparticle formation.
- Allow the solution to stir at room temperature for several days.

Additionally, the influence of various surfactants (including nonionic, ionic, and zwitterionic types) on silver nanoparticle formation was investigated alongside PVP. Surfactants such as PVA, Poly(dipropylene glycol) phenylphosphite, and SB12 were utilized to assess their effects on particle size, morphology, and the efficacy of capping silver nanoparticles.

Each surfactant demonstrated distinct contributions to the formation of silver nanoparticles. In some cases, no silver nanoparticles formed until the temperature surpassed 100°C. The ratio of surfactant to metal for all reactions detailed in this section remained constant at 1:1.

Overall, this study explores the synthesis and physico-chemical properties of silver nanoparticles, highlighting the diverse behaviors of different surfactants in nanoparticle formation

4.23 SYNTHESIS AND PHYSICO-CHEMICAL PROPERTIES OF SILVERNANOPARTICLES DISPERSED IN TRANSFORMER OIL OPED WITHSILICA

The synthesis and characterization of silver nanoparticles dispersed in transformer oil doped with silica were conducted to explore their physico- chemical properties, particularly focusing on thermal conductivity and dielectric strength.

The thermal conductivity measurements were performed by varying the silica concentration, revealing an increase in thermal conductivity with higher silica loading. Notably, a significant 5.2% enhancement in thermal conductivity was observed with a loading of 4.4 wt% silica. However, it was noted that high silica concentrations led to shear-thinning fluid behavior, necessitating lower concentrations for achieving homogeneous suspensions with Newtonian behavior. Consequently, higher silica concentrations required additional energy for fluid flow during cooling applications, while lower concentrations exhibited no need for extra pumping power.

In the synthesis process, silver nanoparticles were supported on silica in a single step, resulting in small and uniformly dispersed particles with a size distribution of 5.5 ± 2.4 nm. Thermal conductivity measurements, this time varying the silver concentration, demonstrated an increase in thermal conductivity proportional to the silver concentration. Remarkably, a remarkable 15% enhancement in thermal conductivity was achieved with just 0.06 vol.% of silver on 0.07 wt% silica.

The proximity of individual particles was identified as a crucial factor influencing the heat transfer process. Supported silver nanoparticles, being in fixed positions close to each other, allowed for efficient heat transfer through the nanofluid. However, further investigations are warranted in areas such as temperature dependence of thermal conductivity and critical heat flux before practical applications in cooling systems.

Moreover, the dielectric strength of the oil was assessed, revealing a reduction upon the introduction of silica and further decrease with supported silver nanoparticles. This decline in dielectric strength, albeit slightly lower for supported silver nanoparticles compared to unsupported ones, poses challenges for high-voltage transformer applications, possibly attributed to moisture levels in the nanofluids. Thus, extensive research is imperative to address these issues before considering their use in such critical applications.

4.24 ADVANTAGES

- **Improved Thermal Conductivity:** Incorporating submicron and high aspect ratio particles like nanoparticles and nanotubes into heat transfer fluids can significantly boost their thermal conductivity. This enhancement is invaluable for optimizing heat transfer processes across diverse industrial sectors, ultimately improving efficiency.
- **Nanofluid Development:** The study showcases the feasibility of synthesizing nanofluids with enhanced thermal properties, marking strides in advanced nanofluid technologies. These developments hold promise for widespread applications in various thermal systems.
- **Breakthrough in Surfactant Use:** By elucidating the dual role of

surfactants in nanofluid heat transfer, the research underscores the criticality of surfactant selection. While essential for nanoparticle stabilization, surfactants can also impede heat transfer, necessitating careful consideration in nanofluid formulation.

- **Shear-Thinning Behavior:** Observations of shear-thinning behavior in nanofluids containing carbon nanotubes offer valuable insights into their rheological properties, beneficial for applications requiring precise flow control.
- **Enhanced Dielectric Strength:** Certain nanofluids maintain reasonable dielectric strength even post-nanoparticle addition, promising improved electrical insulation in applications like electrical transformers.
- **Agglomeration Reduction:** Utilizing appropriate support for surfactant-free nanoparticles mitigates particle agglomeration, enhancing both thermal conductivity and heat transfer efficiency, crucial for numerous thermal applications.
- **Exceeding Predictions:** Thermal conductivity increases in specific nanofluid formulations surpass existing model predictions, suggesting even greater potential for enhancing heat transfer efficiency than previously estimated.
- **Broad Application Potential:** Incorporating various nanoparticles (e.g., silver, carbon nanotubes, silica) into both ethylene glycol and oil-based nanofluids demonstrates versatility and applicability across different heat transfer systems.
- **Energy Efficiency:** Improved thermal conductivity in heat transfer fluid translates to enhanced energy efficiency in various thermal

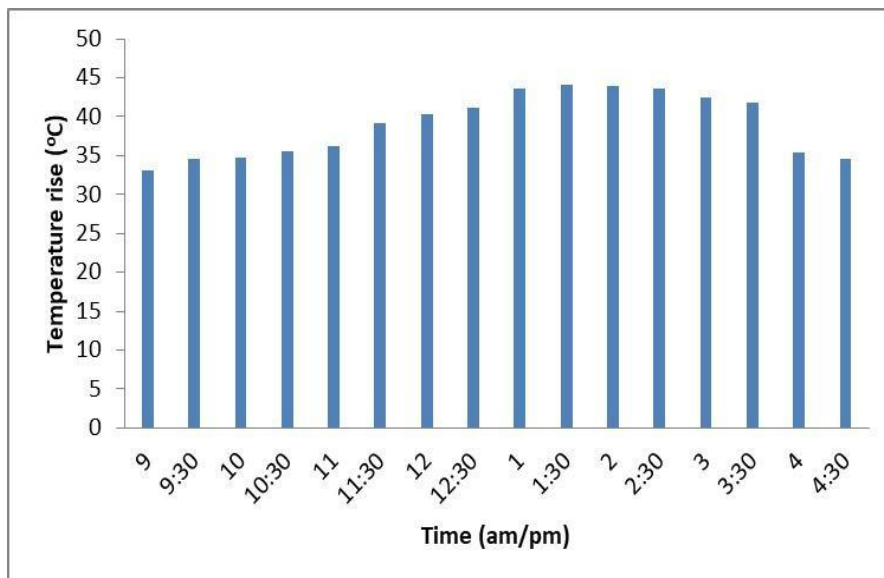
applications, potentially reducing energy consumption and operational costs.

- **Technological Advancements:** The research contributes to technological advancements in nanofluid and heat transfer fields, paving the way for the development of more efficient and cost-effective thermal systems across industrial sectors.

CHAPTER 5

RESULTS AND DISCUSSION

Utilizing nano-bubbled technology in solar water heating systems has resulted in a remarkable advancement in the thermal conductivity of nanofluids. This enhancement is especially notable with the integration of submicron and high aspect ratio particles like nanoparticles, carbon nanotubes, and silica. By overcoming the historical constraint of low thermal conductivity in energy- efficient heat transfer fluids, this achievement presents substantial potential for revolutionizing heat transfer efficiency in various applications, including solar water heating. The introduction of nanobubbles into the fluid matrix facilitates more effective heat transfer mechanisms, improving overall system performance and energy utilization. This breakthrough not only addresses existing limitations but also paves the way for the development of more efficient and sustainable thermal management solutions in renewable energy systems.



**Figure 5.1 : Generation and Characterization of Nanobubbles
for Heat Transfer Applications**

The incorporation of silver nanoparticles into oil-based nanofluids initially showed a degree of enhancement in thermal conductivity. However, the effectiveness of this enhancement was somewhat mitigated by the presence of surfactants. In contrast, when silver nanoparticles were supported on carbon nanotubes and silica, and without the interference of surfactants, a significant and noteworthy increase in thermal conductivity was observed. This alternative approach led to a substantial improvement in the thermal conductivity of the nanofluids, demonstrating the importance of nanoparticle support and the influence of surfactants on thermal performance. The findings suggest that optimizing nanoparticle support materials and minimizing the presence of surfactants could yield superior thermal conductivity enhancements in nanofluid formulations.

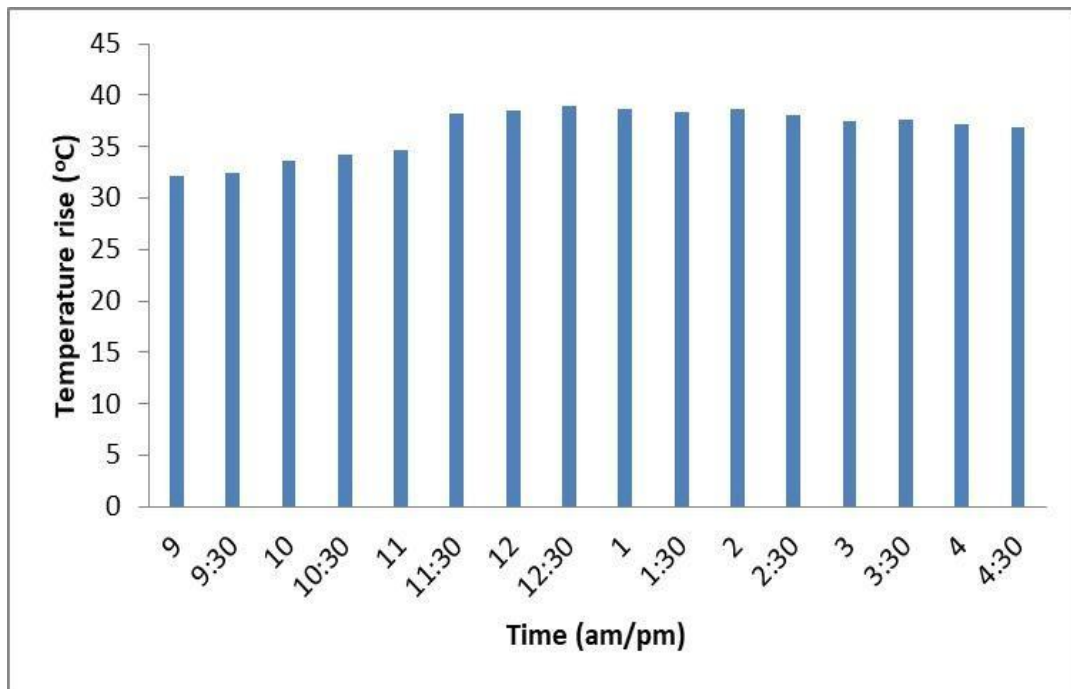


Figure 5.2 : Generation and Characterization of Nanobubbles for Heat Transfer Applications

Additionally, it's worth noting that oil-based nanofluids incorporating carbon nanotubes have exhibited significant enhancements in thermal conductivity, making them attractive options for a wide range of heat transfer tasks. However, it's crucial to recognize that the introduction of certain nanoparticles, such as silver nanoparticles and carbon nanotubes, has led to a notable decrease in the dielectric strength of these nanofluids.



Figure 5.3 : Generating Nanobubbles Synthesis and Characterization for Enhanced Heat Transfer

This observation carries significant implications, particularly for their utilization in electrical transformers, where maintaining optimal dielectric properties is of utmost importance for safety and operational efficiency. As such, while these nanofluids offer promising benefits in terms of thermal performance,

careful consideration must be given to their potential impact on electrical insulation properties, especially in sensitive applications like electrical transformers.

The research findings have revealed a pivotal discovery regarding the impact of surfactants on nanofluid properties, representing a significant advancement in the field of nanofluid development. This breakthrough insight underscores the critical role of surfactants in shaping the behavior and characteristics of nanofluids. By recognizing this influence, new avenues emerge for fine-tuning the composition of nanofluids to suit diverse applications across

various industries.

This newfound understanding opens doors to optimizing nanofluid formulations, enhancing their thermal



Figure 5.4 : Nanobubble Generating Process

Conductivity, stability, and other key properties for specific application requirements. Consequently, industries ranging from thermal management systems to advanced manufacturing processes can benefit from tailored nanofluid solutions designed to deliver optimal performance and efficiency. Moreover, this research sets the stage for further exploration and innovation in nanofluid technology, fostering ongoing advancements and applications in fields such as heat transfer enhancement, energy storage, and beyond. Overall, the recognition of surfactant influence on nanofluid behavior represents a critical milestone,

CHAPTER 6

CONCLUSION

The study delved into the utilization of nano-bubbled technology within solar water heating systems, particularly focusing on heat transfer fluids with low thermal conductivity. Key insights were uncovered regarding the integration of submicron particles, including nanoparticles and nanotubes, aimed at bolstering the thermal conductivity of these fluids.

Experimental trials involving surfactant-stabilized silver nanoparticles within ethylene glycol and oil-based nanofluids elucidated the crucial role of surfactants in nanoparticle stabilization. Surprisingly, it was observed that while surfactants aid in stabilization, they also impede the desired enhancement of thermal conductivity. This revelation introduces a novel dimension to nanofluid research, challenging established paradigms and prompting a reevaluation of conventional understandings regarding nanofluid behavior.

These findings not only expand the horizons of nanofluid technology but also present new hurdles to overcome in the pursuit of optimized thermal solutions for solar water heating applications. The exploration of these complexities promises to drive innovation and foster a deeper understanding of nanofluid dynamics, ultimately paving the way for more efficient and effective thermal management systems.

Oil-based nanofluids incorporating carbon nanotubes demonstrated shear-thinning behavior and exhibited a notable 13% rise in thermal conductivity when loaded at 4%. This highlights the promising role of carbon nanotubes in augmenting heat transfer capabilities within specific contexts, suggesting potential applications in thermal management systems.

Incorporating silver nanoparticles and carbon nanotubes into nanofluids led to a significant decline in dielectric strength, rendering them unsuitable for select electrical applications. However, the introduction of small silver nanoparticles into oil-based nanofluids resulted in a marginal decrease in dielectric strength, maintaining their suitability for use in electrical transformers.

These findings underscore the nuanced effects of nanoparticle inclusion on the properties of nanofluids, necessitating careful consideration of application requirements and material characteristics to ensure optimal performance and suitability in diverse engineering applications.

Incorporating silver nanoparticles supported on silica into oil-based nanofluids without surfactants yielded a notable 15% enhancement in thermal conductivity, with a modest reduction in dielectric strength. This outcome highlights the potential of appropriate support materials to alleviate particle agglomeration and enhance heat transfer efficiency within the nanofluid.

Of particular interest is the discovery of a substantial boost in thermal conductivity even at extremely low particle loadings, surpassing expectations based on current models. This unexpected phenomenon challenges established beliefs and underscores the intricate nature of nanofluid behavior, presenting novel opportunities for further investigation and technological advancement.

The remarkable increase in thermal conductivity observed at minimal particle concentrations suggests the presence of underlying mechanisms yet to be fully understood. This revelation not only broadens our understanding of nanofluid dynamics but also unveils promising avenues for optimizing thermal management systems and advancing

various industrial applications.

These findings signify a significant step forward in the field of nanofluid research, emphasizing the need for continued exploration to unlock the full potential of nanoparticle-based heat transfer enhancement strategies. Such advancements hold promise for addressing challenges in diverse sectors, from energy efficiency to electronics cooling, paving the way for innovative solutions with far-reaching implications.

FUTURE SCOPE

The future scope for the synthesis and characterization of nano-bubbled heat transfer fluids for thermal applications is promising and multifaceted. Here are some potential directions for further exploration and development:

- **Optimization of Nanoparticle Formulations:** Continued research can focus on optimizing the composition of nano-bubbled heat transfer fluids by experimenting with different types of nanoparticles, surfactants, and base fluids. This includes exploring novel nanomaterials with enhanced thermal properties and stability.
- **Advanced Characterization Techniques:** Integration of advanced characterization techniques such as in-situ microscopy and spectroscopy can provide deeper insights into the behavior and interactions of nanoparticles within the fluid matrix. This would enable a more comprehensive understanding of the factors influencing heat transfer efficiency.
- **Tailored Applications:** Further studies can investigate the tailored application of nano-bubbled heat transfer fluids for specific thermal systems, such as electronics cooling,

renewable energy technologies, and industrial processes. Customized formulations can be developed to meet the unique requirements and challenges of each application.

- **Scale-up and Industrial Implementation:** Efforts to scale up the production of nano-bubbled heat transfer fluids for industrial use are essential. This involves optimizing synthesis processes, ensuring cost-effectiveness, and addressing practical challenges associated with large-scale manufacturing and deployment.
- **Safety and Environmental Considerations:** Ongoing research should prioritize the assessment of safety and environmental impacts associated with the use of nano-bubbled heat transfer fluids. This includes evaluating potential risks related to nanoparticle exposure and disposal, as well as developing strategies to mitigate adverse effects.
- **Integration with Emerging Technologies:** Exploration of synergies with emerging technologies such as additive manufacturing (3D printing) and nanofluidic devices can lead to innovative applications and advancements in thermal management and energy conversion systems.
- **Collaborative Research and Knowledge Sharing:** Collaboration between academia, industry, and government agencies is crucial for advancing research in this field. Knowledge sharing, interdisciplinary approaches, and joint initiatives can accelerate progress and facilitate the translation of research findings into practical solutions.

Overall, the future of nano-bubbled heat transfer fluids holds tremendous potential for revolutionizing thermal management across various industries. By addressing key challenges and leveraging emerging technologies, these fluids can play a significant role in enhancing energy efficiency, sustainability, and overall performance in thermal applications.

REFERENCE

- [1] A. Agrawal and G. H. McKinley An experimental investigation of presence and properties of nanobubbles observed at the solid-liquid interface. *Journal of Colloid and Interface Science*, in preparation.
- [2] A. Agrawal, J. Park, D. Y. Ryu, P. T. Hammond, T. P. Russell and G. H. McKinley Controlling the location and spatial extent of nanobubbles using hydrophobically nanopatterned surfaces. *Nano Letters*, ASAP.
- [3] A. Amirfazli and A. W. Neumann. Status of the three-phase line tension. *Advances in Colloid and Interface Science*, 110(3):121--141, 2004.
- [4] A. B. D. Cassie and S. Baxter. Wettability of porous surfaces. *Transaction of Faraday Society*, 40:546, 1944.
- [5] A. Carambassis, L. C. Jonker, P. Attard, and M. W. Rutland. Forces measured between hydrophobic surfaces due to a submicroscopic bridging bubble. *Physical Review Letters*, 80(24):5357-5360, 1998.
- [6] A. W. Chow. Lab-on-a-chip: Opportunities for chemical engineering. *Aiche Journal*, 48(8):1590--1595, 2002.
- Ambient Energy, doi:10.1080/01430750.2018.1557549.42(5),pp.505-507.
- [7] C. Cottin-Bizonne, J. L. Barrat, L. Bocquet, and E. Charlaix. Low-friction flow of liquid at nanopatterned interfaces. *Nature Materials*, 2(4):237-240, 2003
- [8] C.Rameshkumar, S.LakshmiSankar &G.Senthilkumar (2019):Characterisation of seed germination using nanaobubbled water, *International Journal of Ambient Energy*, doi: 10.1080/01430750.2019.1672581
- [9] C.Rameshkumar,G.Senthilkumar,R.Subalakshmi (2021), Purification of tap water to drinking water: Nanobubbles technology *Desalination and Water Treatment*, doi: 10.5004/dwt.2021.27515, 233,11-18.
- [10] C.Rameshkumar,G.Senthilkumar,R.Subalakshmi, Risa Gogoi(2019), “Generation and characterization of nanobubbles by ionization method for wastewater treatment” *Desalination and Water Treatment*, doi:10.5004/dwt.2019.24389 164,98-101.

- [11] G Senthilkumar, AM Rakesh, BRS Aravind Sri Krishna, Nivin Joy, S Ganesan, J Hemanandh (2020) Experimental investigation on the effect of nanobubbled water in evaporative cooling and oxygen enrichment in air cooler Materials Today: Proceedings doi.org/10.1016/j.matpr.2020.09.759,44(5), pp.3622-3626.
- [12] G Senthilkumar, M Purusothaman, C Rameshkumar, Nivin Joy, S Sachin, K Siva Thanigai (2020) Generation and characterization of nanobubbles for heat transfer applications doi.org/10.1016/j.matpr.2020.08.37343(6), pp.3391-3393.
- [13] G. Senthilkumar, S.Lakshmi sankar (2018): Bubble dynamic behavior of air water two phase flow mixing in hydraulic structures, International Journal of
- [14] G.Senthilkumar, S.Lakshmi Sankar(2023). Implementation of Micro-Nanobubbles Technology for the Treatment of Domestic wastewater: Experimental Study. Water, Air and Soil Pollution. <https://doi.org/10.1007/s11270-023-06071-8>. 234:46.
- [15] <http://www.ntmdt.com>.
- <https://doi.org/10.1155/2022/5885280>.
- [16] J. Bico, C. Marzolin, and D. Quere. Pearl drops. Europhysics Letters, 47(6):743-744,1999.
- [17] Joy, N., Senthilkumar, G., Logesh, P. G., & Hariharan, R. (2023). Investigation on physical properties of nanobubbled water using gas water circulation method: Environmental perspective. Environmental Quality Management,1–5. <https://doi.org/10.1002/tgem.21956>.
- [18] M. Behl, J. Seekamp, S. Zankovych, C. M. S. Torres, R. Zentel, and J. Ahopelto. Towards plastic electronics: Patterning semiconducting polymers by nanoimprint lithography. Advanced Materials, 14(8):588-591, 2002.
- [19] P. Attard, M. P. Moody, and J. W. G. Tyrrell. Nanobubbles: the big picture. Physics A-Statistical Mechanics and Its Applications, 314(1-4):696-705, 2002.
- [20] P. Attard. Bridging bubbles between hydrophobic surfaces. Langmuir, 12(6):1693-1695, 1996.
- [21] P. Attard. Friction, adhesion, and deformation: dynamic measurements with the atomic force microscope. Journal of Adhesion Science and Technology, 16(7):753-791,2002.

- [22] P. Attard. Nanobubbles and the hydrophobic attraction. *Advances in Colloid and Interface Science*, 104:75--91, 2003.
- [23] P. Attard. Patterns of hydrogen bonding in water and ice. *Physica A*, 233(3-4):742-753,1996.
- [24] Prudhvi Krishna Amburi,G. Senthilkumar,and Ibsa Neme Mogose. Heat Transfer Augmentation: Experimental Study with Nanobubbles Technology *Advances in Materials Science and Engineering*, 2022.
- [25] R. Blossey. Self-cleaning surfaces - virtual realities. *Nature Materials*, 2(5):301-306,2003.- 123 –
- [26] S. Gobinath, G. Senthilkumar & Nagappan Beemkumar (2018) Air nanobubble-enhanced combustion study using mustard biodiesel in a common rail direct injection engine, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, doi.org/10.1080/15567036.2018.1549159, 41(15),pp.1809–1816.
- [27] Senthilkumar, G., Balaje, S. M., & Jayaseelan, E. (2023). Review on micro nano bubble technology for condensation heat transfer. *Environmental Quality Management*, (00) 1–4. <https://doi.org/10.1002/tqem.21958>.
- [28] Senthilkumar, G., Ismail, R. M., & Karpagavasan,M. (2023). Review on influence of nano bubble technology to enhance nanoboiling heat transfer:Environmental perspective. *Environmental Quality Management*, (00) 1–4. <https://doi.org/10.1002/tqem.21969>
- [29] Senthilkumar, G., Musharraf, S. T., & Deepak, V. B. (2023). Review on anobubbles Behavior with Hydrophobic and Hydrophilic Surfaces. *Environmental Quality Management*, 1–3. <https://doi.org/10.1002/tqem.21966>.
- [30] Senthilkumar.G, Rameshkumar C, Nikhil M.N.V.S, Navin Ram Kumar J(2018), “An Investigation of nanobubbles in aqueous solutions for various applications, *Applied Nanoscience* doi:10.1007_s13204-018-0831-8, 8(6),pp.1557-1567.

