

**A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF ÇANKIRI KARATEKİN UNIVERSITY**

**PREPARATION AND CHARACTERIZATION OF ALUMINIUM
OXIDE NANOFUIDS, POLYURETHANE NANOCAPSULES
NANOFUIDS AND HYBRID NANOFUIDS**

**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CHEMICAL ENGINEERING**

BY

ALI RAHMAH ALI ALBURGHEEF

ÇANKIRI

2023

PREPARATION AND CHARACTERIZATION OF ALUMINIUM OXIDE
NANOFLUIDS, POLYURETHANE NANOCAPSULES NANOFLUIDS AND
HYBRID NANOFLUIDS

By Ali Rahmah Ali ALBURGHEEF

August 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

Advisor : Asst. Prof. Dr. Semahat DORUK

Examining Committee Members:

Chairman : Prof. Dr. Ahmet YARTAŞI
Chemical Engineering
Çankırı Karatekin University

Member : Asst. Prof. Dr. Semahat DORUK
Chemical Engineering
Çankırı Karatekin University

Member : Asst. Prof. Dr. Eda KELEŞ GÜNER
Chemical Engineering
Erzincan University

Approved for the Graduate School of Natural and Applied Sciences

Prof. Dr. Hamit ALYAR
Director of Graduate School

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Ali Rahmah Ali ALBURGHEEF

ABSTRACT

PREPARATION AND CHARACTERIZATION OF ALUMINIUM OXIDE NANOFUIDS, POLYURETHANE NANOCAPSULES NANOFUIDS AND HYBRID NANOFUIDS

Ali Rahmah Ali ALBURGHEEF

Master of Science in Chemical Engineering

Advisor: Asst. Prof. Dr. Semahat DORUK

August 2023

Nanofluids attract the attention of researchers due to their unique physical and chemical properties. These physical and chemical properties, which vary with the morphology, size, and chemical nature of the nanoparticles used, cause nanofluids to exhibit unique characteristic properties. Nanofluids prepared using various basic fluids are widely used in heat transfer applications due to their increased heat conduction coefficients and convection coefficients. The high cooling rates, low pumping power, and abrasion resistance they provide are used in many fields of industry, such as manufacturing, energy, transport, and electronics. Compared to the secondary fluids classically used in heat transfer applications, their longer life and their ability to be used repeatedly make them advantageous in application. In summary, nanofluids obtained by dispersing nanoparticles in a base fluid are preferred for heat transfer enhancement due to their high heat transfer coefficients and the advantages they provide in use. The idea of using FDM for thermal energy storage usually involves the use of a phase change between the solid and liquid phases as latent heat. The use of latent energy storage systems using phase change materials is the most effective way to store thermal energy and has the advantages of isothermal storage processes and high energy density. The depletion of fossil energy resources has led to a shift towards alternative energy sources. Phase-change materials provide an advantage in terms of their use as an alternative energy source in the form of renewable energy sources. For this reason, in this study, nano-sized capsules were obtained by nano-encapsulation of a phase change agent, and mono and hybrid nanofluids were prepared, in which pure water was the basic fluid, Al_2O_3

and nanocapsules with polyurethane shells containing phase change agents were used as nanoparticles, and the effect of surfactant amount on the stability of nanofluids was investigated. The thermal conductivity (heat conduction coefficient) and viscosity values of the nanofluids were determined. The volumetric solid ratios of the nanofluids were selected as 0.01, 0.05, and 0.1%. The amount of surfactant was determined to be 0.05g, 0.1 g, and 0.15g. NP-10 (Tergitol) was preferred as a surfactant. Thermal conductivities were measured with a KD2 Pro thermal conductivity meter. The KD2 Pro thermal conductivity meter measures with the Hot Wire method. Thermal conductivity values were found in the range of 0.604 W/m.K.–0.628 W/m.K. for Al₂O₃ / water nanofluids, 0.540 W/m.K.–0.596 W/m.K. for polyurethane nanocapsules / water nanofluids, and 0.604 W/m.K.–0.609 W/m.K. for hybrid nanofluids. Viscosities were determined using a Vibro brand viscometer. Viscosity values were obtained in the range of 0.97 cp–1.09 cp for Al₂O₃/water nanofluids, 0.94 cp–1.07 cp for polyurethane nanocapsules/water nanofluids, and 1 cp–1.03 cp for hybrid nanofluids. All measurements were carried out at room temperature. In general, it was observed that thermal conductivity and viscosity values increased as the amount of solid and surfactant increased.

2023, 61 pages

Keywords: Nanofluids, Aluminum oxide nanoparticles, Polyurethane nanocapsule, Hybrid, Viscosity, Thermal conductivity, Zeta potentiall

ÖZET

ALÜMİNYUM OKSİT NANOAKIŞKANLARIN, POLİÜRETAN NANOKAPSÜLLÜ NANOAKIŞKANLARIN VE HİBRİT NANOAKIŞKANLARIN HAZIRLANMASI VE KARAKTERİZASYONU

Ali Rahmah Ali ALBURGHEEF

Kimya Mühendisliği, Yüksek Lisans

Tez Danışmanı: Dr. Öğr. Üyesi Semahat DORUK

Ağustos 2023

Nanoakışkanlar kendilerine özgü fiziksel ve kimyasal özellikleri sebebi ile araştırmacıların ilgisini çekmektedir. Kullanılan nanoparçacıkların morfolojisi, boyutu ve kimyasal doğası ile değişen bu fiziksel ve kimyasal özellikler nanoakışkanların kendine özgü karakteristik özellikler sergilemesine sebep olmaktadır. Çeşitli temel akışkanlar kullanılarak hazırlanan nanoakışkanlar, artan ısı iletim katsayıları ve taşınım katsayıları sebebi ile ısı transferi uygulamalarında oldukça fazla kullanılmaktadır. Sağladıkları yüksek soğutma oranları, düşük pompalama gücü ve aşınma direnci imalat, enerji, ulaşım ve elektronik gibi sanayinin bir çok alanında uygulamalarda yer almaktadır. Isı transferi uygulamalarında klasik olarak kullanılan ikincil sıvılara kıyasla daha uzun ömürlü olmaları, tekrar tekrar kullanılabilme özellikleri uygulamada avantajlı olmalarını sağlamaktadır. Özet olarak nanoparçacıkların bir temel akışkan içerisinde dağıtılması ile elde edilen nanoakışkanlar, yüksek ısı iletim katsayıları, kullanımda sağladıkları avantajlar sebebi ile ısı transferi artırımı amacıyla tercih edilmektedirler. Termal enerji depolamak amacıyla FDM kullanımı fikri genellikle katı ve sıvı faz arasında bir faz değişiminin gizli ısı olarak kullanımını sağlamaktadır. Faz değiştiren malzemeler kullanılarak gizli enerji depolama sistemlerinin kullanımı termal enerji depolamanın en etkili yoludur ve depolama proseslerinin izotermal doğası ve yüksek enerji yoğunluğu gibi avantajlara sahiptir. Fosil enerji kaynaklarının tükenmesi alternatif enerji kaynaklarına yönelmeye sebep olmuştur. Faz değiştiren malzemeler alternatif enerji kaynağı olarak yenilenebilir enerji kaynağı şeklinde kullanımı açısından kullanımda avantaj sağlamaktadır. Bu nedenle bu çalışmada bir faz değiştiren maddenin nano enkapsulasyonu ile nano boyutta kapsüller elde edilerek, Al_2O_3 ve faz

değiştiren madde içeren poliüretan kabuğa sahip nanokapsüllerin nanoparçacık olarak kullanıldığı, saf suyun temel akışkan olduğu mono ve hibrit nanoakışkanlar hazırlanmıştır ve nanoakışkanların kararlılıkları üzerine yüzey aktif madde miktarının etkisi incelenmiştir. Nanoakışkanların termal iletkenlik (ısı iletim katsayısı) ve viskozite değerleri belirlenmiştir. Nanoakışkanların hacimsel katı oranları % 0.01, %0.05 ve % 0.1 olarak seçilmiştir. Yüzey aktif madde miktarı 0.05g, 0.1g ve 0.15g olarak belirlenmiştir. Yüzey aktif madde olarak NP-10 (Tergitol) tercih edilmiştir. Termal iletkenlikler KD2 Pro termal iletkenlik ölçüm cihazı ile yapılmıştır. KD2 Pro termal iletkenlik ölçüm cihazı Hot Wire metodu ile ölçüm yapmaktadır. Termal iletkenlik değerleri Al₂O₃ / su nanoakışkanlar için 0,604 W/m.K-0.628 W/m.K, poliüretan nanokapsül /su nanoakışkanlar için 0.540 W/m.K - 0.596 W/m.K, hibrit nanoakışkanlar için 0.604 W/m.K - 0.609W/m.K aralığında bulunmuştur. Viskoziteler Vibro marka viskozimetre kullanılarak belirlenmiştir. Viskozite değerleri Al₂O₃ / su nanoakışkanlar için 0.97 cp -1.09 cp, poliüretan nanokapsül/su nanoakışkanlar için 0.94 cp - 1.07 cp, hibrit nanoakışkanlar için 1 cp - 1.03 cp aralığında elde edilmiştir. Yapılan tüm ölçümler oda sıcaklığında gerçekleştirilmiştir. Genel olarak katı miktarı ve yüzey aktif madde miktarı arttıkça termal iletkenlik ve viskozite değerlerinin de arttığı gözlemlenmiştir.

2023, 61 sayfa

Anahtar Kelimeler: Nanofluids, Alüminyum oksit nanopartiküller, Polyüretan nanokapsül, Hibrit, Viskosite, Termal iletkenlik, Zeta potansiyeli

PREFACE AND ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Asst. Prof. Dr. Semahat DORUK, for her patience, guidance and understanding.

Ali Rahmah Ali ALBURGHEEF

Çankırı-2023



CONTENTS

ABSTRACT	i
ÖZET.....	iii
PREFACE AND ACKNOWLEDGEMENTS.....	v
CONTENTS.....	vi
LIST OF SYMBOLS	viii
LIST OF ABBREVIATIONS	ix
LIST OF FIGURES	x
LIST OF TABLES	xi
1. INTRODUCTION	1
1.1 Nanoscience and Nanotechnology.....	3
1.2 Nanoparticles	6
1.2.1 Types of nanoparticles	7
1.3 Methods of Nanoparticle Synthesis	8
1.4 Nanofluids	9
1.4.1 Types of nanofluids	11
1.4.2 Mono nanofluids.....	11
1.4.3 Hybrid nanofluids	11
1.4.4 Production methods of nanofluids.....	12
1.4.5 Properties of nanofluids.....	14
1.4.6 The stability evaluation methods for nanofluids	16
1.4.7 Stability enhancement procedures.....	19
1.4.8 Thermophysical properties of nanofluids	19
1.4.9 Potential features of nanofluids	24
1.4.10 Applications of nanofluids.....	24
2. LITERATURE REVIEW	28
2.1 Metallic Nanoparticles Nanofluids	28
2.2 Metal Oxide Nanoparticles Nanofluids	29
2.3 Non-metallic Nanoparticles Nanofluids	30
3. MATERIALS AND METHOD	31
3.1 Synthesis of PU/Nonadecane Nanocapsules.....	31

3.2 Preperation of Nanoparticles / Water Nanofluids	33
3.3 Thermophysical Properties of Nanofluids	35
3.3.1 Thermal conductivity.....	35
3.3.2 Viscosity	36
4. RESULTS AND DISCUSSION.....	38
4.1 Preperation of Polyurethane Nanocapsules.....	38
4.2 Preperation of Nanofluids	44
4.3 Thermal Conductivity.....	48
4.4 Viscosity	50
5. CONCLUSIONS AND RECOMMENDATION.....	53
REFERENCES.....	54
CURRICULUM VITAE.....	61

LIST OF SYMBOLS

k_{bf}	Basefluid thermal conductivity
k_B	Boltzmann's constant
F_B	Buoyant force
$^{\circ}C$	Celsius degree
β	Constant of hydrodynamic interaction of nanoparticles and fluid
k	Constant of thermal conductivity
cm^3	Cubic centimeter
mm^3	Cubic millimeter
ρ	Density
ρ_f	Density of fluid
ρ_p	Density of particle
F_D	Drag force
k_{eff}	Effective thermal conductivity
μ_{eff}	Effective viscosity
g	Gravitational acceleration
F_G	Gravitational force
$>$	Greater than
$<$	Less than
m	Meter
mV	Millivolt
\pm	More or less
nanofluid	Nanofluid
nm	Nanometer
k_{np}	Nanoparticle thermal conductivity
ϕ	Nanoparticle volume ratio
$\%$	Percent
π	Pi
r	Radius
γ	Ratio of particle radius to matrix thickness
Re	Reynolds number
C_p	Specific heat
$C_{p,bf}$	Specific heat of basefluid
$C_{p,nanofluid}$	Specific heat of nanofluid
ψ	Sphericity coefficient
U_0	Velocity
μ_{bf}	Viscosity of basefluid
$\mu_{nanofluid}$	Viscosity of nanofluid
ζ	Zeta potential

LIST OF ABBREVIATIONS

CNT	Carbon nanotube
CVD	Chemical vapor deposition
DIW	Deionized water
DLS	Dynamic light scattering
EG	Ethylene glycol
FTIR	Fourier-transform infrared spectroscopy
HeNe	Helium-neon
MWCNTs	Multi-walled carbon nanotubes
Nanofluids	Nanofluids
pH	Potential of hydrogen
PVD	Physical vapor deposition
SEM	Scanning electron microscopy
SI	International system of units
TEM	Transmission electron microscopy
TGA-DSC	Thermo gravimetric analysis-Differential scanning calorimetry
UV-VIS	Ultraviolet-visible spectroscopy

LIST OF FIGURES

Figure 1.1 On display at the British Museum the Lycurgus cup, contains gold and silver nanoparticles (Poole 2003).....	4
Figure 1.2 At the Cathédrale Notre-Dame de Chartres (France), the Rosace nord stained glass, the colors shift according on the sizes and shapes of gold and silver nanoparticles from ref (Jin et al. 2001).....	5
Figure 1.3 Classification of nanoparticles based on diameter (Oyeleke et al. 2021).....	7
Figure 1.4 Classification of nanoparticles based on properties (Oyeleke et al. 2021).....	7
Figure 1.5 Material thermal conductivity data (Shanthi et al. 2012)	9
Figure 1.6 Production methods (1) One-step method (2) Two-step method (Babar et al. 2019).....	14
Figure 1.7 Types of colloidal stabilization (Mostafa and Yahia 2017).....	16
Figure 1.8 The set-up used for measuring the sedimentation rate of Nanofluids	17
Figure 1.9 Zeta potential of nanofluids (Mukherjee and Paria 2013)	18
Figure 1.10 Some of Nanofluids potential applications in different areas.....	25
Figure 3.1 Production stages of nanocapsules	32
Figure 3.2 Nanocapsule containing PCM.....	33
Figure 3.3 (1) Ultrasonicator device (2) Experimental setup for ultrasonication	35
Figure 3.4 (1) Thermal conductivity meter (2) Experimental setup for thermal conductivity measurement.....	36
Figure 3.5 Viscometer device	37
Figure 4.1 SEM images of nanocapsules	38
Figure 4.2 TEM images of nanocapsules	39
Figure 4.3 Particle diameter distribution of nanocapsules	40
Figure 4.4 FTIR analysis of nanocapsules	41
Figure 4.5 DSC curves of nanocapsules	43
Figure 4.6 Aluminum-oxide/water nanofluids samples	45
Figure 4.7 Polyurethane / water nanofluids samples	46
Figure 4.8 Hybrid nanofluids samples	47
Figure 4.9 Thermal conductivity of Al ₂ O ₃ /Water nanofluids.....	48
Figure 4.10 Thermal conductivity of PU nanocapsules/Water nanofluids	49
Figure 4.11 Thermal conductivity of Hybrid nanofluids	50
Figure 4.12 Viscosity of Al ₂ O ₃ /Water nanofluids	51
Figure 4.13 Viscosity of PU nanocapsules/Water nanofluids.....	52
Figure 4.14 Viscosity of Hybrid nanofluids.....	52

LIST OF TABLES

Table 1.1 Viscosity models of nanofluids.....	23
Table 3.1 Chemicals used in the production of nanocapsules	31
Table 3.2 Chemicals used in the experiment	33
Table 3.3 Specification of the sample Al ₂ O ₃ /water nanofluids	34
Table 3.4 Specification of the sample polyurethane/water nanofluids	34
Table 3.5 Specification of the sample hybrid (Al ₂ O ₃ + polyurethane)/water nanofluids	34



1. INTRODUCTION

Since the energy crisis of the 1970s, the world has been suffering the worst lack of energy resources and facing economic decline cumulatively. Scientists are researching diverse energy storage technologies based on sustainable and renewable resources to fulfill future energy needs (Salunkhe and Shembekar 2012).

The importance of energy continues to rise in the modern world. By 2035, experts expect demand will have expanded by a third (Xu *et al.* 2015). Since the start of the Industrial Revolution, fossil fuels have been man's primary source of power. Eighty-six percent of the world's energy consumption in 2001 came from fossil fuels (Lewis and Nocera 2016). Coal, oil, and natural gas have had massive effects on the environment, but their resources are limited. Rapid climatic changes and ocean acidification have occurred over the last 250 years because of the high concentrations of greenhouse gases in the atmosphere. Wild life behavior already shows the effects of environmental shifts on the allocation of these species (Walther *et al.* 2002, Thuiller *et al.* 2008).

One of the most vital functions in manufacturing is heat transmission. Adding, reducing, or relocating heat in the appropriate areas is essential for every manufacturing facility. Water, ethylene glycol (EG), pumping oil, and other traditional heat transfer fluids have inadequate thermal performance for use in cooling applications (Nikkam 2014). Increasing the heat transfer surface or the heat transfer coefficient between the fluid and the surface are two methods that may be used to achieve more heat transfer in a constrained space. Microelectronics, transportation, solid-state lighting, and manufacturing are just a few of the areas where cooling is a major technological difficulty. So, the development of cutting-edge coolants that significantly outperform existing options is of the utmost importance. The thermal conductivity of the resulting fluids increases when solid metal or metal oxide particles, on the order of micrometers or millimeters in size, are added to the base fluids. However, having milli- or micro-sized particles in a fluid presents a number of difficulties. When mixed with base fluids, microparticles help increase the thermal conductivity and convective heat transfer of liquids. However, they don't form a stable solution and tend to settle out (Maxwell,

1873). However, sedimentation, excessive wear, and blockage owing to microscopic particles cause a significant decrease in pressure and a disruption in the flow of fluid. Using nanofluids allows for the elimination of difficulties and the enhancement of thermal characteristics.

In nanofluids, the nanoparticles (1–100 nm) and base fluid mixed thoroughly were identified by Choi in 1995 (Choi and Eastman 1995, Godson *et al.* 2010) at the Argonne National Laboratory. Nanotechnology and nanoscience have shown new solutions by presenting nanofluids in the latest decade, which may help to increase heat transfer fluids' implementation, particularly in modern-technology applications. It has already been proven that adding solid nanoparticles to fluids could increase their thermal effects (Choi and Eastman 1995).

Solid nanoparticles with typical diameters below 100 nm are suspended in liquids like water, oil, ethylene glycol, etc. to create nanofluids. When guest nanoparticles are evenly distributed and maintained in a stable suspension in the base fluid, they may drastically enhance the thermal characteristics of the host fluid. Typically, one-step and two-step manufacturing processes are used to create stable and highly conductive nanofluids. Agglomeration of nanoparticles is a major problem in all nanopowder technologies, and it affects all methods of producing nanoparticle suspensions. In recent years, nanofluids have caught more and more attention. The main driving force for nanofluids studies lies in a wide range of applications of engineering, including solar and power plant cooling, automotive and air conditioning cooling, cooling of transformer oil, improving diesel generator efficiency, nuclear reactors, defense, and space, as reported by Wang and Mujumdar (2008).

The heat transmission capability of a fluid may be greatly enhanced by suspending nanophase particles in it. The following are some of the more important ones: (Xuan and Li 2000).

1. As a result of being floating in the fluid, the nanoparticles increase both their surface area and their heat capacity,

2. The nanoparticles in suspension improve the fluid's perceived thermal conductivity,
- 3: Increased contact and collision between particles, fluid, and flow passage surface,
- 4: The fluid's turbulence and mixing fluctuations are amplified,
- 5: The fluid's transverse temperature gradient is reduced due to the dispersion of nanoparticles.

1.1 Nanoscience and Nanotechnology

Nanoscience is the new science that talks about materials on a nanoscale through the production, characterization, exploration, or exploitation of nanostructured materials. Nanostructured materials are those including the smallest active unit (clusters, crystallites, or molecules) with a size between 1 and 100 nanometers (Buzea *et al.* 2007).

Nanotechnology is specified as a practical science capable of manipulating matter on an atomic and molecular scale to solve diverse troubles (Rivas-Cruz *et al.* 2022).

When exactly humans started making use of nanosized materials is unclear. Roman glassmakers were producing glasses with nanosized metals as early as the fourth century A.D. The Lycurguscup, a relic from this time period, is on display in London's British Museum. Soda lime glass with silver and gold nanoparticles was used to create the cup depicting King Lycurgus's tragic demise. When a light is put within the cup, its color changes from green to a dark red (Poole 2003).

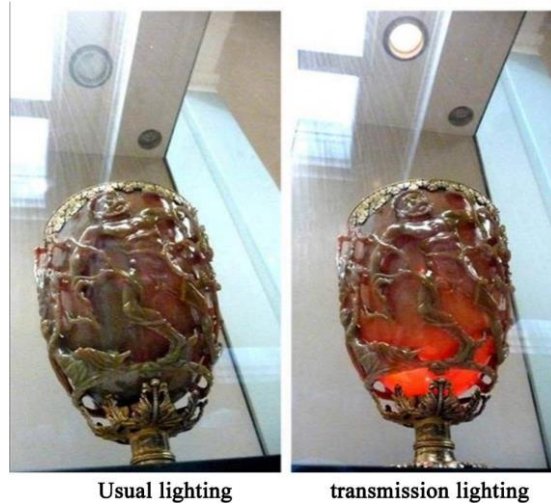


Figure 1.1 On display at the British Museum the Lycurgus cup, contains gold and silver nanoparticles (Poole 2003)

It appears green when it is lit from its sides. It appears red when it is lit from the inside, in other words, in “transmission” (the object is then between the lamp and the eye).

In many historic churches, nanotechnology is clearly visible. Several Gothic European cathedrals include stunning instances of these uses in their stained glass windows. Stained glass windows in the Middle Ages often had a ruby-red hue made possible by early nanotechnology, the Leon Cathedral (Spain), situated on the ancient French pilgrimage route to Santiago de Compostela, is one such unique masterpiece.

Michael Faraday published a paper in the Philosophical Transactions of the Royal Society in 1857 attempting to explain the effect of metal particles on the color of church windows. Gustav Mie was the first to explain why different colored glasses are produced by different sizes and types of metals. His paper was published in the German journal *Annalen der Physik* (Innovation and Ziche 2005).

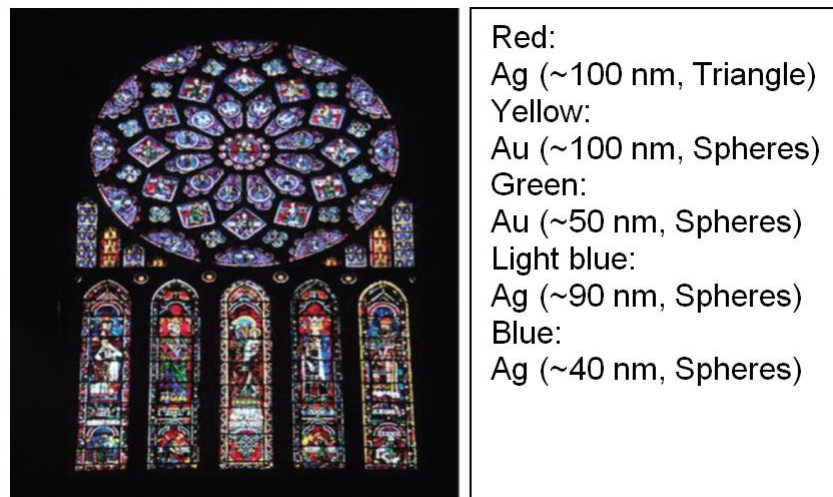


Figure 1.2 At the Cathédrale Notre-Dame de Chartres (France), the Rosace nord stained glass, the colors shift according on the sizes and shapes of gold and silver nanoparticles from ref (Jin *et al.* 2001)

The subject of intense studies, applications, and a certain amount of media coverage are nanotechnologies, nanoparticles, and nanomaterials, which are part of human life today. The applications of nanotechnology are increasingly important in the lives of every human being, for industrial and trade, health, and community. In several disciplines, including computing, engineering, and medicine, nanotechnology has proven to be priceless. Currently, nanotechnology is used in distinguished energy industries such as hydrogen, fuel cells, photovoltaic, nuclear, tidal, wind, and geothermic technologies. In an elaborated review of these industries (including theoretical and experimental works) of nanotechnology concerning the power fields and industry of nanotechnology in these areas, nanotechnology has a large field of potential applications such as energy efficiency, energy saving, energy storage, etc. (Hussein 2015). Nanotechnology is widely regarded as one of the most significant emerging technologies, with the potential to profoundly alter and enhance every facet of human life over the next decade. The nanotechnology study is enhancing high expectations due to the particular characteristics of matter at the nanoscale that lead to a new function that is imagined to be conceived (Ferlier 2019).

The main problems scientists must solve to develop numerous and important industries, but in a controlled manner, include observing, manufacturing, and manipulating nano-objects, studying and understanding their characteristics and interactions with their environment, in particular with living organisms, modeling and simulating them, and integrating them into communicating systems.

1.2 Nanoparticles

The typical definition of a nanoparticle is a particle having at least one dimension less than 100 nm. Because, compared to their volume, nanoparticles have an extremely large surface area. This is what gives them their unique characteristics. The surface of a nanoparticle is a crucial part of the material due to its high surface area.

The nanoparticles that exist today on the market and in industrial business are produced in large-scale manners, directly related to the synthesizing processes of macroscopic materials: cosmetics, materials with high mechanical quality, smart glasses, etc., lithium battery electrodes, etc. In terms of tonnage, these mainly concern the following products (examples of application fields are shown in the following brackets): titanium dioxide (cosmetics), silica nanoparticles (tire reinanofluidorcement, food additive), alumina (adjuvant in the medical field, food additive), carbon nanotubes (mechanical reinanofluidorcement for sporting goods), zinc oxide (cosmetic) and cerium (paint), silver nanoparticles (anti-bacterial, low energy loss glasses), fullerenes and carbon black (inks, battery electrodes in lithium), and iron (soil decontamination), dendrimer (Haruta *et al.* 1987).

Nanoparticles are defined as spherical particles with a size between 1 and 100 nm and an interfacial layer. The interfacial layer of nanoscale matter affects all of its properties. Typically, ions, inorganic molecules, and organic molecules make up the interfacial layer.

1.2.1 Types of nanoparticles

Nanoparticles can be classified based on different characteristics.

The classification of nanoparticles based on diameter is shown in Figure 1.3.

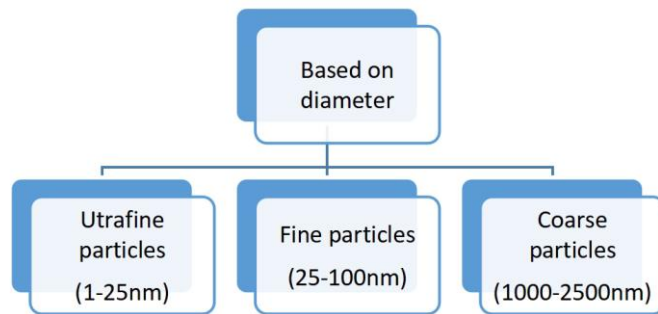


Figure 1.3 Classification of nanoparticles based on diameter (Oyeleke *et al.* 2021)

In heat transfer applications, the utilization of fine particles is essential, owing to the fact that the use of larger-sized particles has been reported, leading to constraints such as sedimentation, fouling, pressure drop across the working system, clogging of channels, and erosion caused by abrasion by the nanoparticles (Allahyar *et al.* 2016).

Figure 1.4 illustrates how properties can be used to categorize different types of nanoparticles.

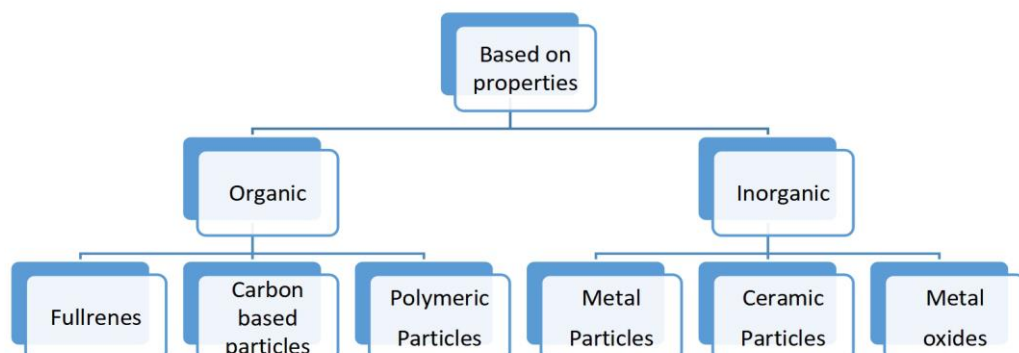


Figure 1.4 Classification of nanoparticles based on properties (Oyeleke *et al.* 2021)

Commonly used core nanoparticles include metallic particles (Fe, Ag, Au, Al, and Cu), metal oxides (Al₂O₃, SiO₂, ZnO, CuO, Fe₃O₄, TiO₂), nitrides (AlN, SiN), carbon-based particles (nanodiamond), single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (MWCNT), graphene nanoplatelets (GNanoparticles), and graphite metal carbides (SiC) (polymeric nanocomposite blends containing HDPE, paraffin wax, fatty acids, etc.) as additive particles into the base fluids (Sajid and Ali 2018, Ilyas *et al.* 2017). Nanoparticles are used to improve the thermal and heat transfer properties of base fluids. They are also linked to better antibacterial activity, mass transfer, and chemical reactivity (Selvam *et al.* 2017).

1.3 Methods of Nanoparticle Synthesis

Nanoparticles may be made using either a top-down or bottom-up approach. The former dealt with the process of "cutting" larger portions of material down to the size of a nanoparticle in order to create nanoparticles. This is often done using etching or lithography, however, ball mill grinding may also be utilized. The second step is to suspend the resulting nanoparticles in their carrier fluid. Two-step processes are common in real-world applications and are utilized to create nanofluids.

Using a bottom-up strategy, in which a nanoparticle is "grown" from simple molecules, is the most practical way for creating nanoparticles on a commercial scale. Since nanoparticles are created from atomic or molecular components that grow up in size, becoming nanometer-sized particles, this technique is also known as the single-step method. The size of the nanoparticle can be controlled in a number of ways, including by limiting the concentration, functionalizing the surface of the particle, or using a micelle to stimulate growth. In this method, the base fluids are made at the same time as the nanoparticles. This approach is primarily used on a small scale in the lab (Zhang 2013).

As the additional nanoparticles have better thermal conductivity than base fluids, their inclusion attempts to boost the nanofluid's thermal conductivity. As can be seen in

Figure 1.5, the thermal conductivity of water and other typical HTFs is much lower than that of ordinary metallic and non-metallic solids.

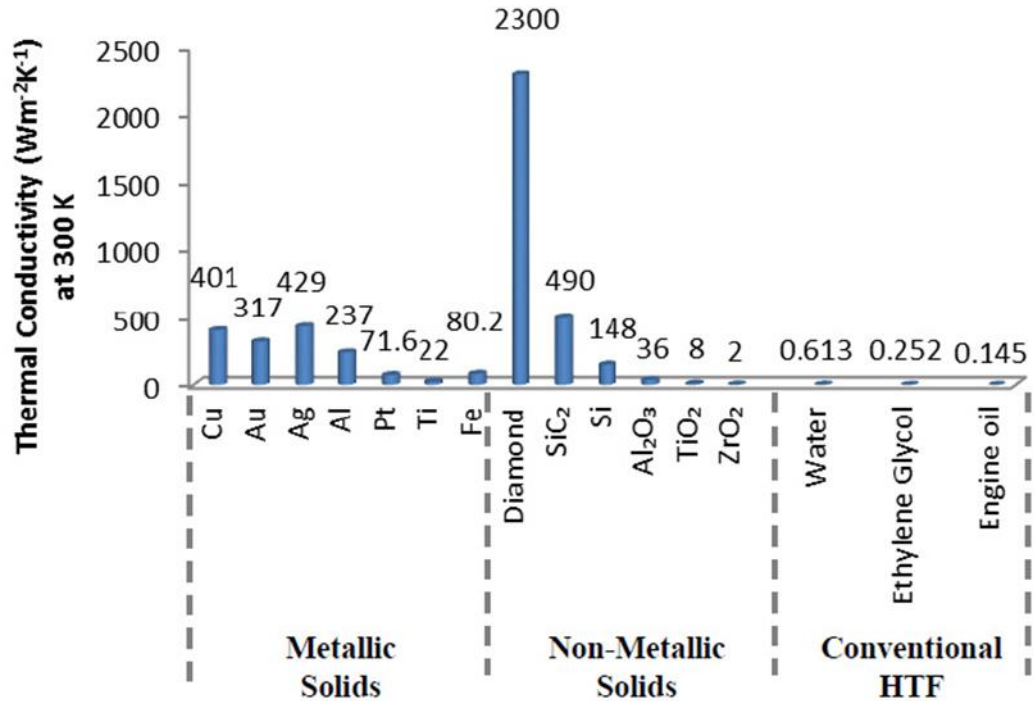


Figure 1.5 Material thermal conductivity data (Shanthi *et al.* 2012)

1.4 Nanofluids

There are massive efforts being made to enhance fluids' heat transmission characteristics. It is well known that many nanoparticles, both metallic and non-metallic, have much greater thermal conductivities than water. The anticipated heat transfer capability of a nanofluid improves as the thermal conductivity of the nanoparticles increases. Nanofluid concentration, nanoparticle type, temperature, and nanoparticle shape are only a few of the variables that affect the thermal conductivity enhancement (Maxwell 1873).

More work has been done to create blends from the outset. Micron- and millimeter-sized solid particles were mixed with the base fluids to create suspensions or slurries. Nevertheless, the practical applications are severely constrained by the fact that big

solid particles generate bothersome difficulties, including abrasion of the surface, clogging the microchannels, eroding the pipeline, and swelling the pressure drop. Nevertheless, liquid suspension was only of mild theoretical interest at best, and later tests by other researchers had little results. Most notably, manufacturing difficulties and particle size made it impossible to use in many applications. When researchers Choi and Eastman from Argonne National Laboratory introduced their novel concept of nanoscale metallic particles and carbon nanotube suspensions, the situation turned around for the better. While the results of their experiments with metal and metal oxide nanoparticles suspended in diverse base fluids were encouraging, many questions remained unanswered (Prasher *et al.* 2005).

Researchers have spent a lot of time looking at many different kinds of nanoparticles. Hence, standard base fluids (water, ethylene glycol, propylene glycol, motor oil, etc.) may include nanoparticles of oxides (Al₂O₃, CuO, TiO₂, Fe₂O₃, SiO₂, etc.), metals (Cu and Ag), and carbon nanotubes (CNTs) (Ganvir *et al.* 2017).

Mono-nanofluids, also known as simple nanofluids, are colloidal suspensions formed by combining a single type of nanoparticle with any base fluid in a one- or two-step method.

Hybrid nanofluids are a new type of nanofluid developed to solve the problems of stability and low thermal conductivity. They are fluids created by colliding multiple types of nanosized solid particles of two or more different materials into a base fluid.

The most recent approach in more than a century of work is shown by increasing the thermal conductivity of fluids, modeling suspensions, and concepts of nanofluids. Due to their capability to strengthen the poor thermal conductivity of conventional heat transfer fluids, nanoparticles may improve the efficiency of these fluids (Nikkam 2014).

1.4.1 Types of nanofluids

Suspensions of nanoparticles in a fluid, known as nanofluids, offer intriguing thermal properties compared to normal base fluids and undeniably improved heat transfer properties. Certain nanofluids have far greater heat conductivity than traditional liquids. A critical factor in preparing a nanofluid is the choice of appropriate base fluids, as they ensure stability over time and prevent aggregation. The type of nanofluid depends on the materials used, such as nanoparticles and base fluids. However, they are generally classified into mono- and hybrid nanofluids (Bumataria *et al.* 2019).

1.4.2 Mono nanofluids

Mono-nanofluids, also known as simple nanofluids, are colloidal suspensions formed by combining a single type of nanoparticle with any base fluid in a one- or two-step method. They were the first nanofluids to improve a suspension's thermal properties. The type of base fluid, size, shape, kind of nanoparticles, and concentration of the fluid influence their high thermal conductivity. However, mono-nanofluids lack overall hydrothermal features, including increased stability and thermal conductivity. On the other hand, metal nanofluids (e.g., copper nanofluids) have high thermal conductivity but low stability. Moreover, clogging, fouling, sedimentation, and system failures are all conceivable because of their standard strength. These factors make such nanofluids inadequate for applications involving heat transfer (Chandravadhana *et al.* 2020).

1.4.3 Hybrid nanofluids

Hybrid nanofluids are a new type of nanofluid developed to solve the problems of stability and low thermal conductivity. They are fluids created by colliding multiple types of nanosized solid particles of two or more different materials into a base fluid. They can optimize heat transfer rates in many applications by providing a higher heat transfer rate than standard nanofluids and reportedly exhibiting higher thermal conductivity. Due to its synergistically improved thermal properties and enhanced

overall hydrothermal characteristics, it is now a prospective candidate for the management of heat transfer applications (Sarkar *et al.* 2015).

1.4.4 Production methods of nanofluids

It is essential for high-quality nanofluids to be produced that the nanoparticles be dispersed evenly and suspended stable in the host liquid. The study of nanofluid characteristics and their applications requires good dispersion and stable suspension. Dispersing monosized nanoparticles before they agglomerate is the key to making exceptionally stable nanofluids. Nanofluids may be produced using a wide variety of physical and chemical methods, some of which only require a single step. Scientists are also developing other strategies for producing nanofluids. The following is a brief overview of these steps: It is essential in making high-quality nanofluids to disperse the nanoparticles evenly and suspend them stably in the host liquid. For researchers interested in the characteristics and potential uses of nanofluids, a stable suspension and uniform dispersion are essential starting points. Dispersing monosized nanoparticles before they agglomerate is the key to making exceptionally stable nanofluids. Nanofluids may be produced using a wide variety of physical and chemical methods, some of which only require a single step. Researchers are also developing new methods for producing nanofluids. In a nutshell, the following describes these procedures:

1.4.4.1 One-step method

The physical vapor deposition (PVD) technique or the liquid chemical method are both used to directly produce nanoparticles in the one-step procedure, which then combines the process with the synthesis of nanofluids. The aggregation of nanoparticles is decreased, and the stability of fluids is increased since this technique avoids desiccating storage, transit, and discrete distribution procedures. Nanoparticles are produced and then dispersed into the base fluid all at once. Nanoscale vapor from metallic source material, for instance, may be immediately distributed into low-vapor pressure fluids using a one-step manufacturing technique developed by Argonne (Eastman *et al.* 2001).

The van der Waals forces between nanoparticles were overcome using this unique one-step approach, resulting in stable suspensions of Cu nanoparticles without the need for dispersants. Wet grinding technology using bead mills is another example of a one-step physical process. Because of the prohibitive cost and limited scalability of one-step physical methods, one-step chemical methods are fast gaining ground. One-step chemical reduction methods are used for producing stable metallic nanofluids (Zhu *et al.* 2006, Liu *et al.* 2006).

Phuoc *et al.* (2007) produced Ag-water nanofluid using one-step optical laser ablation in liquid. The primary benefit of a one-step procedure is the increased purity and uniformity in size of the nanoparticles produced. The one-step approach does not come without its drawbacks. Most importantly, inadequate reaction or stabilization leaves leftover reactants in the nanofluids. Also, only low-vapor-pressured base fluids are compatible with this process.

1.4.4.2 Two-step method

The first phase in the two-step procedure involves the physical or chemical production of nanoparticles as a dry powder by techniques including inert gas condensation and chemical vapor deposition. Since the 1930s, ultrafine metal particles have been manufactured by the process of inert gas evaporation-condensation (nanoparticles are synthesized by the evaporation of a metallic material in an inert gas). Adding to that, the basic chemical procedure to produce nanoparticles is to have some compound, typically a halide, holding a metal atom, as well as a decreasing agent that takes out the other parts of the compound. After this, the powder is mixed into the liquid. The primary benefit of the two-step technique is the fact that nanoparticles may be manufactured independently using an industrial technology that enables their large and cheap manufacturing. For oxide nanoparticles, this method works about as well as it does for metallic nanoparticles. Nanoparticle aggregation is the main issue with the two-step technique (Kwak and Kim 2005).

It is shown that particles substantially aggregated before dispersion and also after dispersion in ethylene glycol after 9 hours of sonication. Scientists frequently purchase the nanoparticles as powder, which they then dilute with the solvent. However, using surfactant and controlling pH in these nanofluids may improve stability. There are scientists who choose to buy nanofluids from private companies. Nevertheless, these nanofluids do not conform to vendor criteria in terms of the purity and size of the nanoparticles they contain.

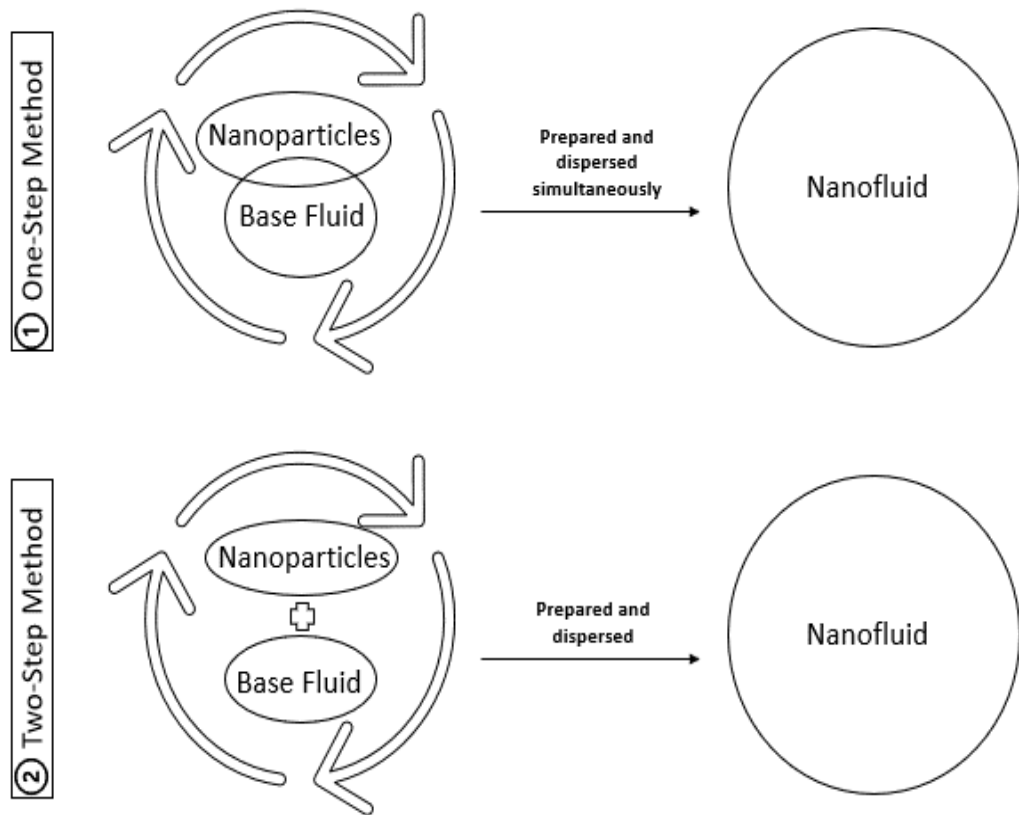


Figure 1.6 Production methods (1) One-step method (2) Two-step method (Babar *et al.* 2019)

1.4.5 Properties of nanofluids

Nanofluids may be characterized by their stability, thermal conductivity, viscosity, and specific heat. These characteristics are crucial in the production of nanofluids. This section will go through the properties.

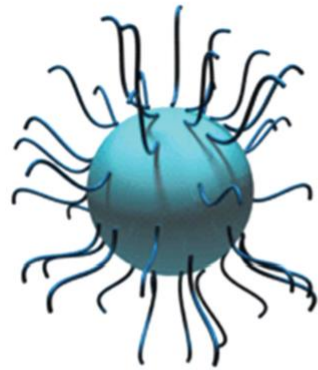
1.4.5.1 Stability of nanofluids

Nanofluids tendency to coagulate can cause them to lose their ability to transfer heat. For this reason, research on stability is an inevitable issue that can change the thermo-physical characteristics of nanofluids for application and is also substantial in analyzing the factors that affect the stability of such suspensions. This part includes the stability development methods and the stability strengthening method, along with details about the stability mechanisms regarding nanofluids.

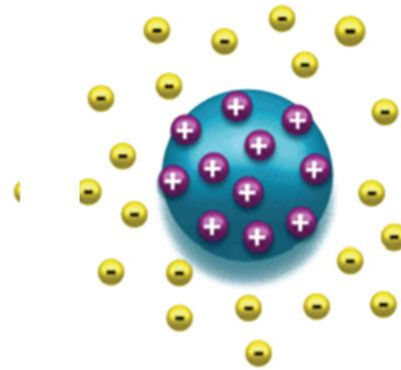
1.4.5.2 Stability mechanisms of nanofluids

Dispersed particles may agglomerate together, expand in size, and finally drown at the bottom. When particles are stable, they do not clump quickly. The collision rate and the cohesiveness likelihood during collision typically define the rate of agglomeration. The DVLO hypothesis was created by Derjaguin, Verway, Landau, and Overbeek to explain the stability of colloids (Missana and Adell 2000, Popa *et al.* 2010).

According to DLVO theory, the incorporated attractive vander Waals interactions and electrical double layer repellent forces between particles as they approach one other owing to Brownian motion determine a particle's stability in solution. When the appealing force exceeds the repellent force, the two particles will agglomerate and the suspension will be lost. Suspensions will be stable if the particles repulse each other strongly enough. repellent forces between particles must predominate in order for nanofluids or colloids to remain stable. Figure 1.7 illustrates the distinction between steric repulsion and electrostatic (charge) repulsion as the two primary processes that in nanofluid influence colloidal stability. Polymers are always present in the suspension system for steric stabilization, they adsorb onto the particles' surfaces, where they exert a steric repulsive force (Mostafa and Yahia 2017).



Steric stabilization



Electrostatic stabilization

Figure 1.7 Types of colloidal stabilization (Mostafa and Yahia 2017)

1.4.6 The stability evaluation methods for nanofluids

1.4.6.1 Sedimentation and centrifugation methods

The stability of nanofluids can be measured in a variety of ways. Sedimentation is the simplest technique. The stability of nanofluids was evaluated using a sedimentation balance technique, in which the accumulation of nanoparticles in a nanofluid sample on a tray placed in the suspension was weighed using a precision scale. The amount of nanoparticles remaining scattered in the nanofluids may be calculated from the weight of the nanoparticles on the submerged tray. When the concentration or particle size of the supernatant particles remains constant, we say that the nanofluids are stable. Another common technique for gauging the stability of nanofluids is to photograph their sedimentation in a test tube (Li *et al.* 2009).



Figure 1.8 The set-up used for measuring the sedimentation rate of Nanofluids

It should be mentioned that two factors can be measured using this technique: the sedimentation rate and the time at which no more nanoparticles settle on the platform.

The set-up presented in Figure 1.8 was used to measure the sedimentation rate of nanoparticles (evaluation of nanofluid stability). The submerged tray in the samples was indirectly connected to the scale pin. Consequently, the scale could measure the weight of the sedimented nanoparticles on the tray continuously. Due to the extensive amount of time spent observing, the sedimentation process is exceedingly slow. Hence, a centrifuge technique was created for assessing stability.

1.4.6.2 Measurement of spectral absorbency

One such useful technique for gauging nanofluid stability is spectral absorbency analysis. The absorption intensity is linearly related to the concentration of nanoparticles in the fluid. To assess the stability of nanofluids, UV-vis spectral analysis may be used if the nanomaterials disseminated in the fluid show distinctive absorption bands in the wavelength range of 190–1100 nm. Using a UV-vis spectrophotometer, they looked at the durability of nanofluids. Nanofluid stability was previously thought

to be heavily influenced by factors including particle shape and the base fluid (Hwang *et al.* 2012).

1.4.6.3 Zeta potential analysis

The zeta potential is defined as the potential difference between the dispersal medium and the fluid layer that remains attached to the particle at rest. The zeta potential quantifies the attractive force between dispersed particles of different charges (Figure 1.9). To put it another way, low-zeta potential colloids tend to coagulate or flocculate, whereas high-zeta potential ones are electrically stabilized. The zeta potential of nanofluids in the 40–60 mV range is thought to be optimal for stability. Several scientists have conducted zeta potential analysis of nanofluids. (Mukherjee and Paria 2013).

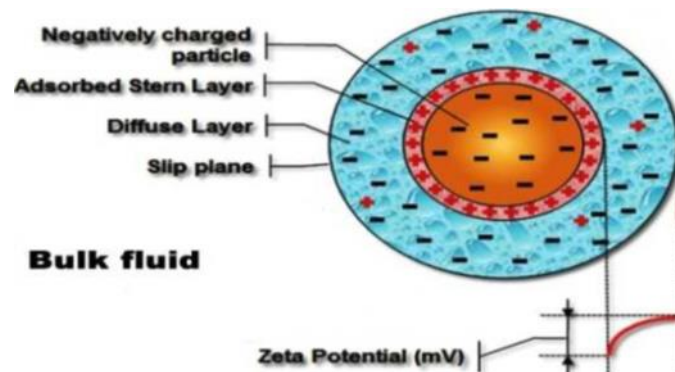


Figure 1.9 Zeta potential of nanofluids (Mukherjee and Paria 2013)

1.4.6.4 Scanning electron microscopy (SEM)

SEM (Scanning Electron Microscopy) allows you to see elements at the atomic level, including their sizes, shapes, and distributions. SEM analysis was done to examine the microstructure and morphology of nanoparticles and nanostructured materials (using the FEG-HR Zeiss Ultra 55 SEM system). For implementing SEM analysis for NANOFLUID samples, around 2 ml of each suspension was dried for around 8 hours at 80°C, which was then used for SEM analysis. (Nikkam 2014).

1.4.7 Stability enhancement procedures

1.4.7.1 Addition of surfactants

Generally, surfactants or dispersants are used to enhance the stability of the nanofluids. The addition of surfactants decreases the surface tension of host fluids and increases the immersion of particles. Surfactants can be defined as chemical components added to nanofluids in order to decrease the surface tension of liquids and increase the immersion of particles. Several studies in the literature talk about adding surfactant to nanoparticles to avoid fast sedimentation (Mukherjee and Paria 2013).

Nonetheless, it's a cheap and simple way to make nanofluids more stable. Little amounts of dispersants may have a huge impact on the surface properties of a system. One part of a dispersant is hydrophobic, often a long-chain hydrocarbon, while the other part is hydrophilic and polar. Dispersants are used to improve wettability (the ability of two materials to stick together) between them (Yu and Xie 2012).

1.4.7.2 Ultrasonic agitation

After nanofluids have been prepared, agglomeration may develop over time, leading to the rapid sedimentation of nanoparticles as a consequence of an increase in the gravitational pull between them.

1.4.8 Thermophysical properties of nanofluids

1.4.8.1 Thermal conductivity

To prove the efficacy of these novel designed suspensions for heat transfer applications, it is necessary to investigate thermal conductivity, the most important thermophysical parameter of nanofluids. The transient hot wire method is one of the various methods for estimating the thermal conductivity of nanofluids (THW) (Groot *et*

al. 1974), the transient plane source (TPS) (Wan *et al.* 2012), the temperature oscillation technique (Santucci *et al.* 1986), and the optical methods (Kleinstreuer and Feng, 2011). The two first methods have gotten the most concern. The thermal conductivity of the nanofluid is estimated using the following equation (1.1).

$$k = \left[\frac{q}{4\pi(T_2 - T_1)} \right] \ln \left(\frac{t_2}{t_1} \right) \quad (1.1)$$

where the thermal conductivity of the suspension, T_1 and T_2 are the temperatures at time t_1 and t_2 , and q is the constant heat rate (applied electric power), respectively. Groot *et al.* (1974) first introduced the transient hot wire method, and Nagasaka and Nagashima (1981) later developed and improved it. In the literature, there are diverse models and equations that have been applied to estimate the nanofluid thermal conductivity. Some traditional models and equations are Maxwell (1873), the Hamilton-Crosser model (Hamilton and Crosser 1962, Davis 1986, and Jeffrey 1973).

1.4.8.2 Maxwell correlation

This equation was introduced to anticipate the thermal conductivity of nanofluids (Maxwell, 1873). The thermal conductivity is calculated from Equation (1.2).

$$\frac{K_{nf}}{K_{bl}} = 1 + \frac{3(\alpha - 1)\phi}{(\alpha + 2) - (\alpha - 1)\phi(2)} \quad (1.2)$$

where α is K_p/K_{bl} and K_{bl} , K_p , and $K_{nanofluid}$ are the thermal conductivity of the base liquid, nanoparticles, and nanofluid, respectively, and ϕ is the volume fraction of the particles.

1.4.8.3 Viscosity

The ability of a fluid to flow is defined by its viscosity. Due to its capability of affecting the pressure drop during forced convection, it is known as an essential parameter for

practical purposes. One of the most important characteristics of nanofluids is their viscosity. In engineering systems, viscosity is considered just as important as thermal conductivity due to the nanofluid's potential to exhibit improved thermal conductivity without correspondingly higher pressure drops. Many researchers have discussed the viscosity of nanofluids in relation to the factors influencing the nanofluids. Nanoparticle share rate, concentration, temperature of nanofluids, size, etc. are all pertinent variables. One way to describe the viscosity of a suspension is in comparison to the viscosity of the liquid phase.

$$\mu_{nf} = \mu_{bf} \mu_r \quad (1.3)$$

where $\mu_{nanofluid}$ and μ_{bf} are respectively the dynamic viscosities of the suspension and base fluid, and μ_r is the relative viscosity. Several models exist to represent the relative viscosity as a function of the volume fraction, f , of solid particles, which varies with particle size and concentration. Almost all of the associations stem from Einstein's ground-breaking research (Einstein 1906).

It assumes a linearly viscous fluid with tiny suspended particles, spherical particles. The effective viscosity of the mixture is underestimated above this point. Considering non-interacting suspension, the suggested equation (1.4) is as follows:

$$\mu_{nf} = \mu_{bf} (1 + 2.5\varphi) \quad (1.4)$$

Where φ is the particle volume fraction in the base fluid. The nanofluid viscosity increases linearly with the percentage of solid particles. Although the particle volume fractions may not be so small, and as the structure and interactions of the particles inside the continuous phase may also impact the viscosity of the suspension, it has been shown that these aspects are limits of this formula. Since Einstein's paper was released, many researchers have added to and developed upon the formula. In the case of higher concentrations, a modified equation was proposed by Guth and Simha (1936), which takes into account the interaction between the solid particles and defines.

$$\mu_r = 1 + 2.5\varphi + 14.1\varphi^2 \quad (1.5)$$

so that the Equation (1.6) becomes

$$\mu_{nf} = \mu_{bf} (1 + 2.5\varphi + 14.1\varphi^2) \quad (1.6)$$

Brinkman (Guth and Simha 1936) proposed a more elaborated model that is currently used in the literature. For particle concentrations less than 4%, (Brinkman 1952) Equation (1.7) is as follows:

$$\mu_{nf} = \mu_{bf} (1 - \varphi) - 2.5 \quad (1.7)$$

Over a wide range of particle volume fractions, Kruger and Dougherty (1959) obtained a semi-empirical equation (1.8) for the shear viscosity.

$$\mu_{nf} = \mu_{bf} (1 - \varphi/\varphi_m)^{[\mu] \varphi_m} \quad (1.8)$$

where I is intrinsic viscosity, and φ_m is the maximum packing percentage of particles (often between 0.495 and 0.54 at rest and around 0.605 at high shear rates for monodisperse suspensions of hard spheres). Using the maximum particle volume concentration φ_m as determined through experiment, Frankel and Acrivos (1967) presented the following equation for the viscosity of nanofluids:

$$\mu_{nf} = \mu_{bf} (1 + 2.5\varphi + 10.05\varphi^2 + A \cdot e^{B \cdot \varphi}) \quad (1.9)$$

For an essentially isotropic suspension of stiff and spherical particles, Batchelor takes into account the impact of Brownian motion on the bulk stress (Batchelor 1977) and proposes the following equation (1.10):

$$\mu_{nf} = \mu_{bf} (1 + 2.5\varphi + 6.25\varphi^2) \quad (1.10)$$

It is clear from the above two equations that if the terms of the second or higher order of ϕ are neglected, the above relation decreases to that of Einstein's formula. Equation (6.24) has been established for a particle volume fraction up to $\phi < 0.1$, where the motion of single particle and pair particle interactions is predominant.

Table 1.1 Viscosity models of nanofluids

(Einstein 1906)	$\mu_{nanofluid} = \mu_{bf}(1+2.5\phi)$ $\mu_{nf} = \mu_{bf}(1 + 2,5\phi)$
(Hatschek 1913)	$\mu_{nf} = \mu_{bf}(1 + 4,5\phi)$
(De Bruijn 1942)	$\mu_{nf} = \mu_{bf} \left(\frac{1}{1 - 2.5\phi + 1.552\phi^2} \right)$
(Batchelor 1977)	$\mu_{nanofluid} = \mu_{bf}(1+2.5\phi+6.25\phi^2)$
(Krieger <i>et al.</i> 2000)	$\mu_{nanofluid} = \mu_{bf}(1-\phi/\phi_m)(\mu_i)\phi_m$
(Brinkman 2004)	$\mu_{nanofluid} = \mu_{bf}(1-\phi)^{-2.5}$
(Wang <i>et al.</i> 2007)	$\mu_{nf} = \mu_{bf}(1 + 7,3\phi + 123\phi^2)$

1.4.8.4 Specific heat

Specific heat is the amount of energy needed to increase the temperature of an object by one degree Celsius per unit of mass. The below form, where C_p is the specific heat, is often used to illustrate the connection between heat and temperature change. If a phase transition occurs, the connection is invalid since the heat provided or withdrawn does not affect the temperature. So, we define a mathematical equation as $Q = C_p m \Delta T$, where Q is the amount of heat added, C_p is specific heat, m is mass, and ΔT is the temperature difference. Thus, for nanofluid, we can define it as $(\rho C_p)_{nanofluid} = \rho_{nanofluid} (Q/m\Delta T)_{nanofluid}$ which turns to an equation (1.11).

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_{bf} + \phi(\rho C_p)_p \quad (1.11)$$

Therefore, the specific heat of nanofluids can be defined as:

$$(C_p)_{nf} = \frac{(1-\phi)(\rho C_p)_{bf} + \phi(\rho C_p)_p}{(1-\phi)\rho_{bf} + \phi\rho_p} \quad (1.12)$$

1.4.9 Potential features of nanofluids

Nanofluids have some infrequent applications, which makes them very peculiar for several engineering applications. Some of the special advantages of nanofluids are:

- I. The rise in thermal conductivity is beyond expectation and much higher than theoretical anticipations.
- II. Ultrafast capability of heat transfer.
- III. Better stability than other suspensions.
- IV. Decreasing erosion and clogging in microchannels.
- V. Decreasing pumping power.
- VI. Decrease the friction coefficient.
- VII. Better lubrication.

1.4.10 Applications of nanofluids

Nanofluids are liquids containing nanoparticles suspended in low concentrations, and the properties of nanofluids have been greatly developed. Since the emergence of the concept of nanofluids more than a decade ago, the wide range of applications of nanofluids in various fields has captured more and more interest. For this reason, many scientists are researching the fields of nanofluids for various purposes and industries. The potential of applications for nanofluids in various fields, such as biomedical applications, food, surface coating, lubrication, and heat transfer enhancement, is paramount in many industrial applications, including the petroleum industry, nuclear

reactors, transportation, and electronics. Figure 1.10 shows several nanofluids wide range of applications in various fields.



Figure 1.10 Some of Nanofluids potential applications in different areas

1.4.10.1 Heat transfer intensification

Transportation: Cooling rates in heavy-duty engines (cars and trucks) might be a great advantage of the use of nanofluids by improving efficiency, saving weight, and facilitating thermal management systems.

Electronic applications: The production of microelectronic components makes heat wasting more complicated because of the increased density of chips. Because of their

massive heat productivity and small surface area, modern electronic appliances present unique problems for thermal control.

Industrial cooling: By using nanofluids in industrial cooling applications, savings in both energy and pollutants are expected to occur.

Heating buildings: minimizing environmental impact Nanofluids have potential for use in HVAC systems.

Nuclear systems cooling: In order to advance nanofluid technology for the nuclear energy sector, the Massachusetts Institute of Technology has developed a multidisciplinary center. They are looking at three distinct nuclear uses for nanofluids (Buongiorno *et al.* 2008).

Space and defense: There is an urgent need for a lightweight, compact, and energy-efficient cooling system because of the constraints imposed by space station and aircraft design (You *et al.* 2003).

1.4.10.2 Mass transfer enhancement

Although many studies have focused on how nanoparticles might improve mass transfer in nanofluids, Demirbas (2006) was the first to investigate the impact of nanoparticles on bubble-type absorption in an NH₃/H₂O absorption system. When nanoparticles are present, the performance of absorption may increase by a factor of 3.21. Then, they used visualization to examine how nanoparticles and surfactants alter the absorption properties of NH₃/H₂O bubbles (Vekas *et al.* 2007).

1.4.10.3 Energy applications

Nanofluids' superior thermal conductivities, which improve heat transmission, and their exceptional absorption qualities are both put to use in energy-related applications.

Energy storage: Thermal energy storage in the form of sensible and latent heat has become a substantial part of energy management, with a focus on effective use and conservation of waste heat and solar energy in industry and buildings (Popa *et al.* 2010).

Solar absorption: Solar power is among the most environmentally friendly renewable energy options.

2.4.10.4 Mechanical applications

To explain why nanofluids are so effective in lowering friction, certain nanofluids have good lubricating capabilities because the nanoparticles in them create a protective coating with low hardness and elastic modulus on the worn surface.

2.4.10.5 Biomedical application

Certain nanoparticles, such as those with antibacterial activity or drug-delivery features, may be found in nanofluids, which then display these same characteristics.

2. LITERATURE REVIEW

Choi and Eastman (1995) first used the term "nanofluid" to describe mixes of solid nanoparticles with diameters less than 100 nm that are suspended in a liquid, with average solid volume fractions of less than 4%. In comparison to typical heat transfer fluids, metals like silver, copper, and iron, as well as nonmetals like aluminum oxide (Al_2O_3), copper oxide (CuO), titanium dioxide (TiO_2), zinc oxide (ZnO), SiC, and carbon nanotubes (graphene), have higher thermal conductivities.

Easman *et al.* (2001) were the first to offer the idea that nanofluids may improve their thermal conductivity. Several study teams from across the world have since published a plethora of studies, both experimental and theoretical. Based on the nanoparticles investigated, this research may be broken down into three distinct groups.

2.1 Metallic Nanoparticles Nanofluids

They proposed using metallic nanoparticles to enhance the fluid's thermal conductivity and develop heat transfer. Researchers presented research proving that thermal conductivity increases with volume fraction. The thermal conductivity ratio of Cu (35 nm)/water nanofluid to base fluid goes up by 44% when 0.05 % of the nanoparticles are present (Eastman *et al.* 1996).

In 2000, a study showed that thermal conductivity increases with volume fraction. The thermal conductivity ratio of Cu (100 nm)/water nanofluid to base fluid increases by 78% for the volume fraction of nanoparticles (7.5%) and Cu (100 nm)/HE-200. Oil nanofluid to base fluid increases by 43% for the volume fraction of nanoparticles (7.5%) (Xuan and Li 2000).

In 2003, a study showed that thermal conductivity increases with volume fraction. The thermal conductivity ratio of Au (10–20 nm)/water nanofluid to base fluid increases by 21% for volume fractions of nanoparticles (0.00026% and Ag (10–20 nm)/water

nanofluid to base fluid increases by 16.5% for volume fractions of nanoparticles (0.001% (Patel *et al.* 2003).

The thermal conductivity ratio of Fe (10 nm)/water nanofluid to base fluid increases 18% for the volume fraction of nanoparticles (0.55%) (Hong *et al.* 2005).

In 2008, the thermal conductivity ratio of Al (80 nm)/EG nanofluid to base fluid increased by 45% for the volume fraction of nanoparticles (0.5%) (Murshed *et al.* 2008).

In 2015, the thermal conductivity ratio of Ag (5–25 nm)/DI nanofluid to base fluid increased by 16% for the volume fraction of nanoparticles, 0.5% (Parametthanuwat *et al.* 2015).

2.2 Metal Oxide Nanoparticles Nanofluids

Masuda *et al.* (1993) published the first study on aluminum oxide and improving thermal conductivity (nanoparticles of SiO₂ (12)/water). They found that for a fraction $\phi = 2.3\%$, heat conductivity went up by 1.1%.

Another study from 1997 found that nanoparticles of CuO (36 nm) had a 60% higher thermal conductivity when they made up 5% of the volume (Xuan and Li 2000).

In 1998, they evaluated the heat transfer coefficients of spherical and cylindrical TiO₂ nanoparticles. They discovered that a nanofluid containing 27 nm spherical nanoparticles improves heat conductivity by 11.6% for a volume fraction of 4.35% (Ch and Cho 1998).

In 1999, we improved thermal conductivity by 12% for a volume fraction of 3.41% by dispersing 24 nm nanoparticles in water. This value is inferior to the 12% obtained (Lee *et al.* 1999).

Experiments were also done in 2002 using CuO nanoparticles with a diameter of 33 nm and a volume percentage of 4% in pure water. The thermal conductivity of the nanofluid was found to have increased by 17%, and that of TiO₂ (40nm) by 13%, at a volume fraction of 4% (Kleinstreuer and Feng 2011).

Nanofluids' thermal conductivity was analyzed in a study in 2006. Specifically, Al₂O₃ (36 nm) and CuO were used. These particles were dispersed in pure water. The thermal conductivity of the Al₂O₃/water nanofluid went up by 30% when the volume fraction was 10%, and it went up by 52% when the volume fraction was 6% for CuO in water (Li and Peterson 2006).

In 2007, they studied the thermal conductivity of nanofluids. They employed Al₂O₃ (38nm) and TiO₂ (10nm). These particles are dispersed into ethylene glycol and pure water. They achieved an 8% improvement in thermal conductivity for the Al₂O₃/water nanofluid and 10.6% for Al₂O₃ in ethylene glycol, both with a volume fraction of 3%, and an 11.4% enhancement for TiO₂/water and 15.4% for TiO₂/ethylene glycol for $\phi = 3\%$ volume (Kim and Choi 2007).

2.3 Non-metallic Nanoparticles Nanofluids

In 2007, MWCNTs were suspended in water. They found the thermal conductivity of the nanofluid increased by 7% for $\phi = 1\%$ (Hwang *et al.* 2007).

In 2012, SWCNT was suspended in water. They found the thermal conductivity of the nanofluid increased by 12.1% for $\phi = 0.3\%$ (Pang and Kang 2012).

In 2016, SWCNT was suspended in EG. They found the thermal conductivity of the nanofluid increased by 15.5% for $\phi = 0.21\%$ (Harish *et al.* 2016).

In 2012, MWCNT was suspended in water. They found the thermal conductivity of the nanofluid increased by 5% for $\phi = 0.48\%$ (Xing *et al.* 2012).

3. MATERIALS AND METHOD

In this study, two types of nanofluids were prepared: mono nanofluid and hybrid nanofluid, by using water as the base fluid with aluminum oxide nanoparticles and polyurethane nanocapsules.

Three different volumetric ratios of nanomaterial, 0.01%, 0.05%, and 0.1%, were used in the experiments. 100 mL of nanofluid was prepared for each experimental run. Nanofluids were prepared at three different ratios of surfactant: 0.5%, 1%, and 1.5%, which are used for the stabilization that helps nanofluids remain stable. Tergitol NP-10 was used as a surfactant.

3.1 Synthesis of PU/Nonadecane Nanocapsules

In this study, nanocapsules with a polyurethane shell material containing n-nonadecane as PCM were synthesized. The production method of nanocapsules is the interfacial polymerization of oil and water emulsions. A substance called tergitol (NP-10) was used as a surfactant, and DETA and TDI were used as building blocks for the polymerization. The chemicals used for the production of nanocapsules are given in Table 3.1.

Table 3.1 Chemicals used in the production of nanocapsules

N	Chemical Name	Purity	Manufacturer
1.	Cyclohexane	≥ 99,8%	SIGMA-ALDRICH
2.	Toluene 2,4-diisocyanate	≥ 98,0%	SIGMA-ALDRICH
3.	Tergitol	NP-10	SIGMA-ALDRICH
4.	n-nonadekan	99%	SIGMA-ALDRICH
5.	Diethylenetriamine	99%	ALFA AESAR

Figure 3.1 shows the production of nanocapsules containing PCM in stages. The oil-water emulsion for the synthesis of nanocapsules consists of two phases. For the oil phase, n-nonadecane was dissolved in cyclohexane, and TDI was added. The water phase contained surfactant NP-10 (surfactant) and purified water. The oil and water

phases were mixed separately in a magnetic stirrer to ensure homogeneity of the oil phase and water phase separately. The mixing speed of the oil and water phases is a parameter that significantly affects the size and diameter of the particles obtained. In this study, after mixing the two phases, the emulsion droplets were kept in the ultrasonic mixer for 5 minutes to reduce the diameter of the emulsion droplets. Then, the reaction was started by adding DETA as an initiator, drop by drop, to the emulsion at a 1500 rpm magnetic stirrer. The reaction was allowed to complete at 60 °C for 2 hours. At the end of 2 hours, the solvents remaining in the nanocapsules obtained were evaporated, washed with distilled water, and dried in a vacuum oven at 40 °C.

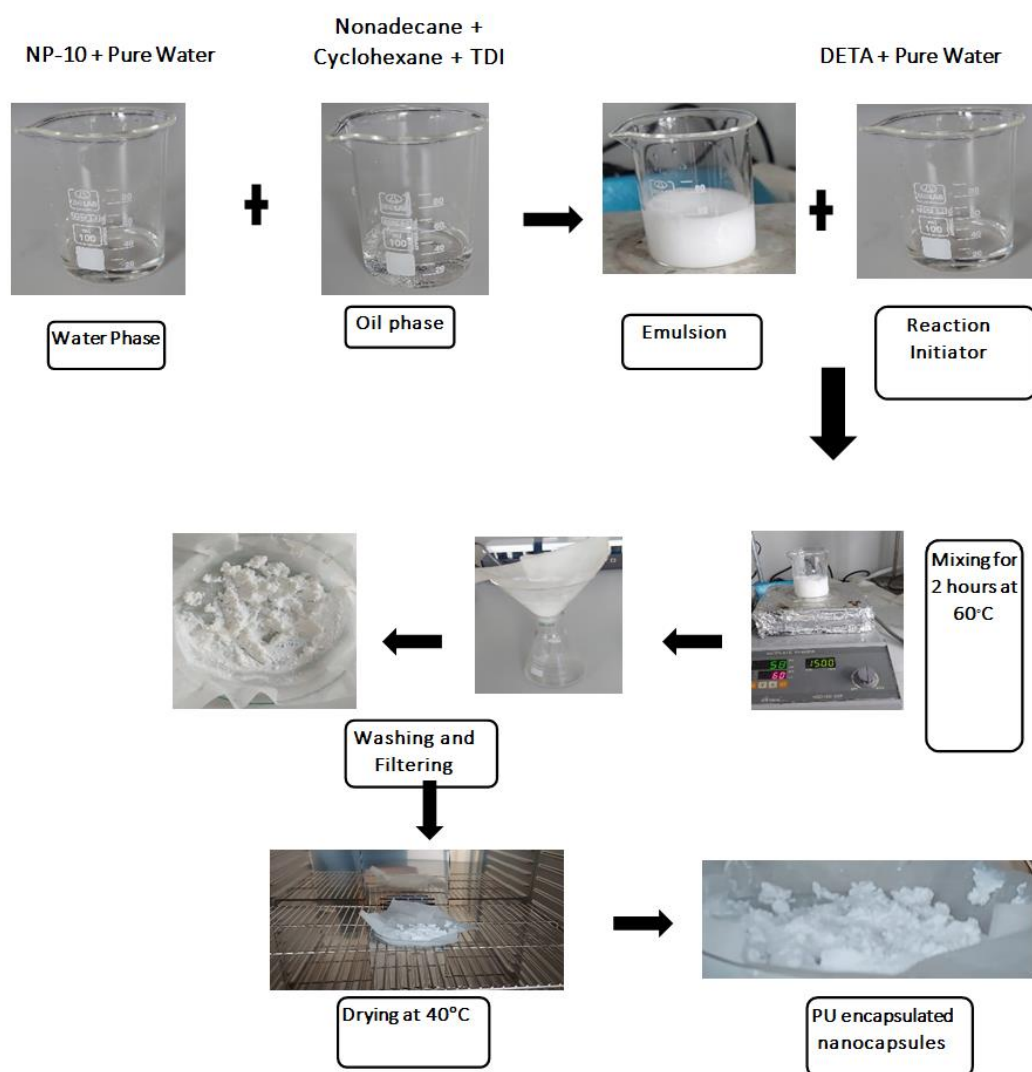


Figure 3.1 Production stages of nanocapsules

SEM, TEM, FTIR, DSC, and Zeta Sizer all participated in the characterization of the nanocapsules. A typical capsule containing PCM is shown in Figure 3.2. While the capsule has an outer shell, it traps the PCM inside. SEM and TEM analysis helped to visualize the capsules. FTIR determined the content of the shell materials of the capsules and the presence of PCM. DSC was used to determine the melting and freezing temperatures, latent heat, and enthalpy of melting of the capsules. With the help of a zeta sizer, it was concluded whether the synthesized capsules were nano-sized or not.

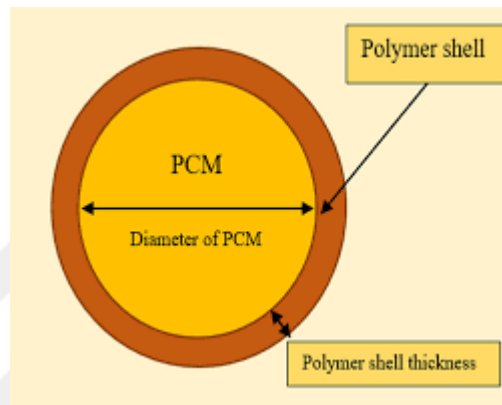


Figure 3.2 Nanocapsule containing PCM

3.2 Preparation of Nanoparticles / Water Nanofluids

Chemicals for preparation of nanofluids are shown in the Table 3.2.

Table 3.2 Chemicals used in the experiment

Chemical Name	Formula	Supplier	Purity Rate (%)
Aluminum oxide	Al_2O_3	Sigma Aldrich	99.99
Tergitol NP-10	$C_2H_4O)_n \cdot C_{15}H_{24}O$	Sigma Aldrich	99.99
Deionized water	H_2O	Çankırı Karatekin University	99.99

As stated in the second chapter, there are two ways of making nanofluids: one-step and two-step. This study employed the two-step method. The phases of preparation for the two-step approach are as follows:

- Nanoparticles were weighed in accordance with the specified volumetric ratios and mixed with up to 100 mL of deionized water.
- For 30 minutes, the ready mixture was stirred at 1000 rpm using a magnetic stirrer.
- After being agitated in a magnetic stirrer for 30 minutes, each sample in Tables 3.3, 3.4, and 3.5 underwent 60 minutes of ultrasonic stirring.

Table 3.3 Specification of the sample Al₂O₃/water nanofluids

Experiment No	Al ₂ O ₃ % V	Surfactant g
1	0.01	0.05
2	0.01	0.1
3	0.01	0.15
4	0.05	0.05
5	0.05	0.1
6	0.05	0.15
7	0.1	0.05
8	0.1	0.1
9	0.1	0.15

Table 3.4 Specification of the sample polyurethane/water nanofluids

Experiment No	polyurethane % V	Surfactant gr
1	0.01	0.05
2	0.01	0.1
3	0.01	0.15
4	0.05	0.05
5	0.05	0.1
6	0.05	0.15
7	0.1	0.05
8	0.1	0.1
9	0.1	0.15

Table 3.5 Specification of the sample hybrid (Al₂O₃+ polyurethane)/water nanofluids

Experiment No	A ₂ O ₃ % V	Surfactant g
1	0.05	0.05
2	0.05	0.1
3	0.05	0.15
4	0.1	0.05
5	0.1	0.1
6	0.1	0.15
7	0.15	0.05
8	0.15	0.1
9	0.15	0.15

Ultrasonic mixing was done with 8/2 pulses at 400 W power. As the temperature rise during mixing is high and high temperatures affect the stability of the nanofluid, a cooling jacket was formed by using a circulating water bath, as seen in Figure 3.3. Moreover, the temperatures of the nanofluids were kept at room temperature.

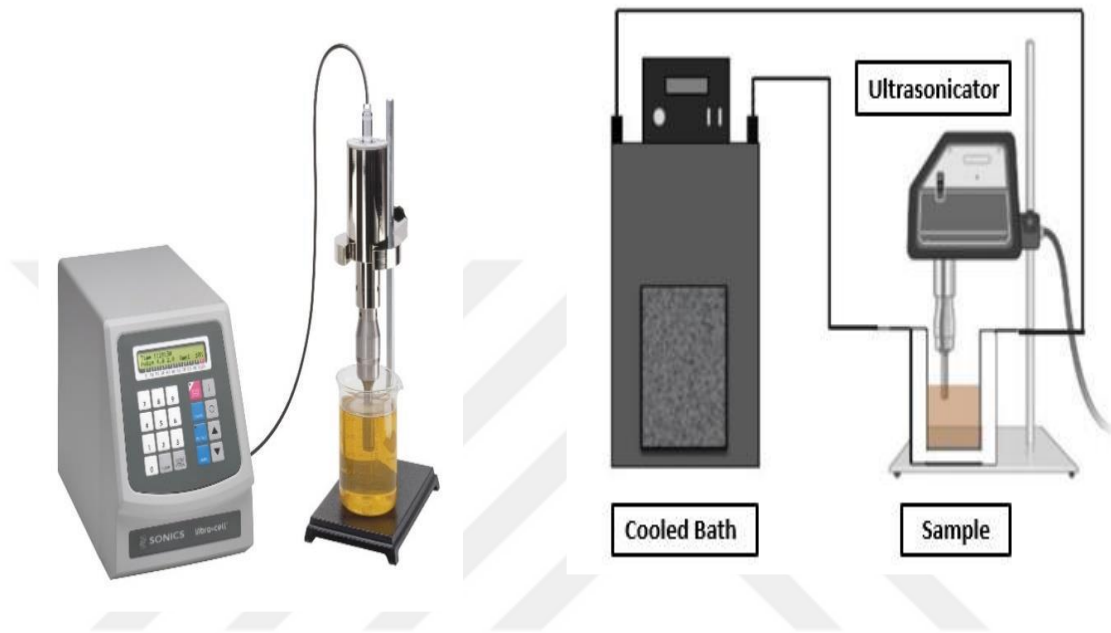


Figure 3.3 (1) Ultrasonicator device (2) Experimental setup for ultrasonication

As was previously indicated, the produced nanofluids' physical characteristics were determined by measuring their viscosity and thermal conductivity. All thermodynamic characteristics were determined at ambient temperatures.

3.3 Thermophysical Properties of Nanofluids

3.3.1 Thermal conductivity

The literature has adopted various methods for measuring the thermal conductivity of liquids, and some of these techniques have also been applied to actual nanofluids. The experimental setup for measuring thermal conductivity is shown in Figure 3.4. We used a transient hot-wire method and a KD2 pro thermal properties analyzer (Decagon

Devices, Inc., USA) to look at the thermal conductivities of nanoparticles and water nanofluids. The apparatus had a thermal resistor, a microprocessor, and a probe measuring 60 mm in length and 1.3 mm in diameter for controlling and measuring probe conduction. The required precision was 5%.

The sample was covered in parafilm to prevent air penetration and ensure reliable results. After temperature equilibrium was achieved, we took ten readings from each sample to get an average.

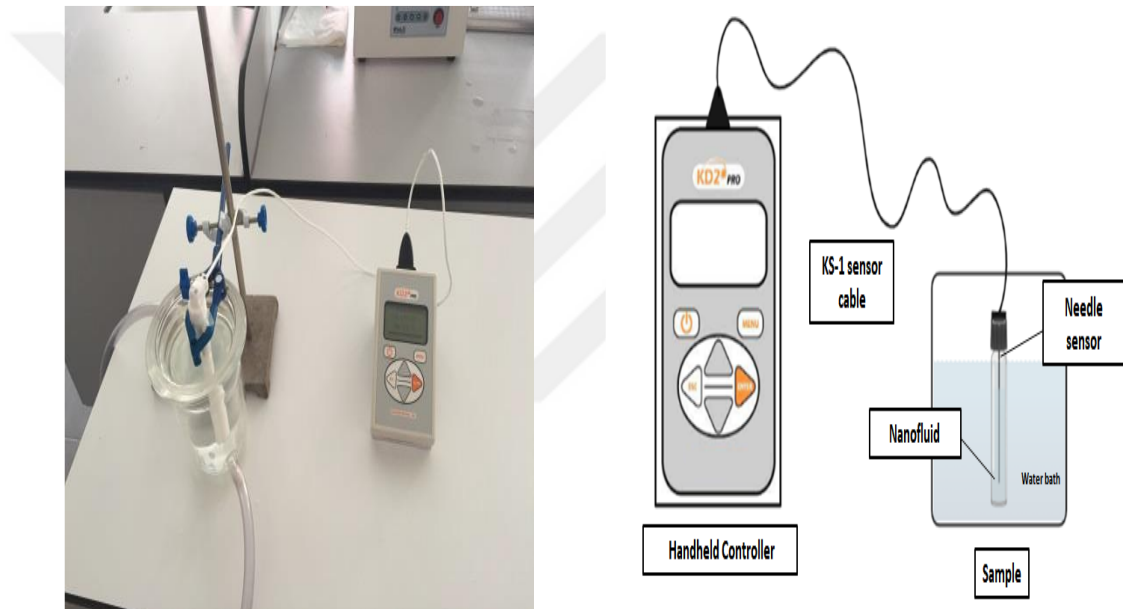


Figure 3.4 (1) Thermal conductivity meter (2) Experimental setup for thermal conductivity measurement

3.3.2 Viscosity

For the measurement of viscosity data, a Vibro-viscometer SV-10/SV-100, with which a wide range of measurements can be made continuously, was used (Figure 3.5). The ranges are for SV-10: 0.3–10000 mPa.s. and for SV-100: 1000–100000 mPa.s. The precision of the device in question is within 1%, and it measures viscosity by sensing the electric driving current required to cause the two sensor plates to vibrate at a constant frequency of 30 Hz and an amplitude of less than 1mm. For each sample, three

different values of viscosity and temperature were noted. The viscosity was measured at ambient pressure and a temperature between 10°C and 40°C. The suspension was deposited into the glass container of the viscometer with the help of a Pasteur pipette, avoiding the air bubbles. Before any of these measurements were made, the viscometer was carefully calibrated manually.

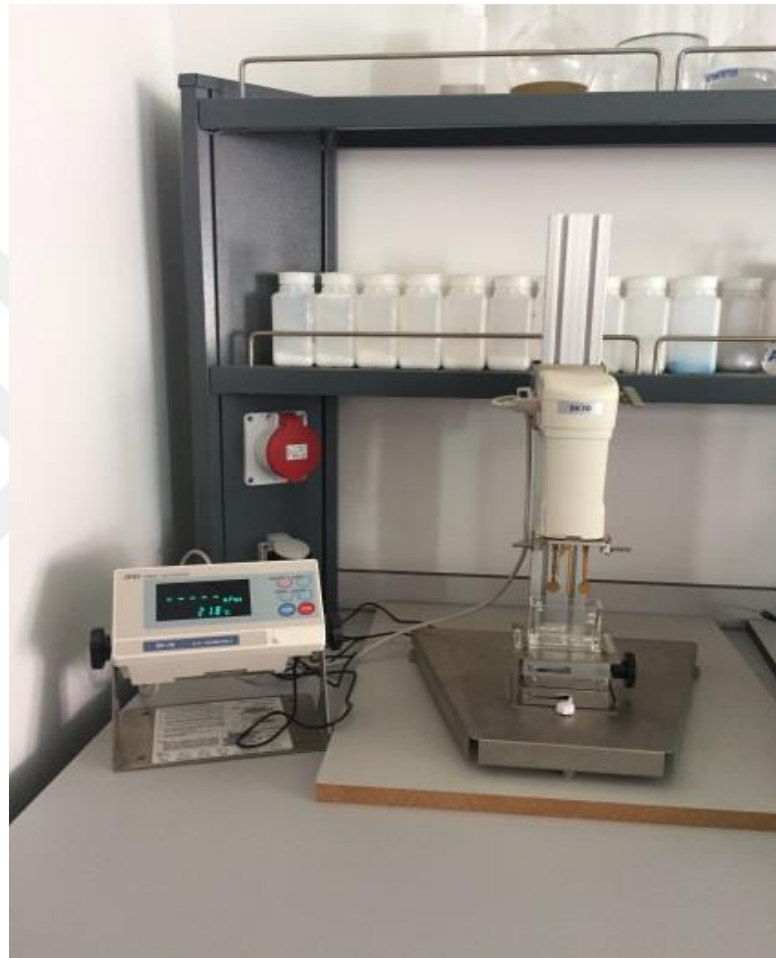


Figure 3.5 Viscometer device

4. RESULTS AND DISCUSSION

4.1 Preperation of Polyurethane Nanocapsules

In order to determine the geometries of the synthesized nanocapsules, scanning electron microscopy (SEM) images were taken at the Çankırı Karatekin University Central Research Laboratory. Figure 4.1 shows the SEM images of the nanocapsules. When PCM-filled nanocapsules are made by interfacial polymerization of the emulsion, the nanocapsules should have a spherical shape. SEM images show that the obtained nanocapsules are spherical in shape.

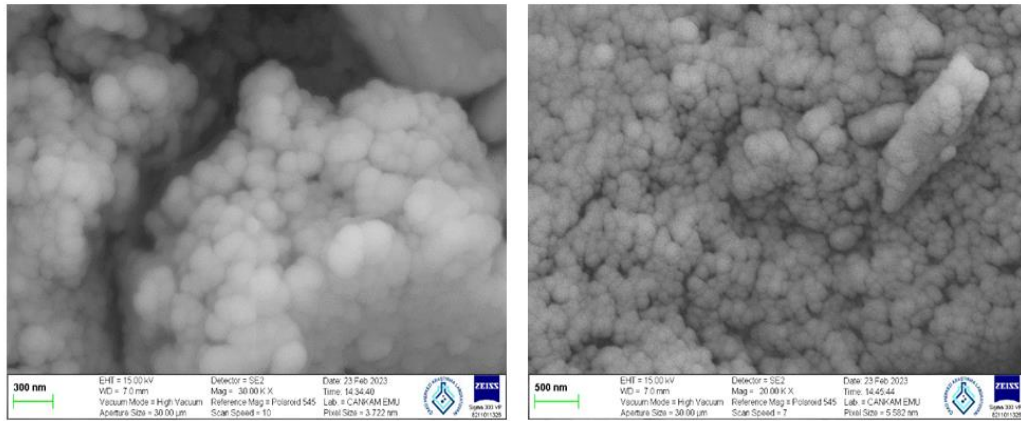


Figure 4.1 SEM images of nanocapsules

Capsules that appear as stacks on top of each other in SEM images separate from each other when dispersed in water. This can be observed through TEM analysis. Figure 4.2 shows images of TEM analysis performed at METU MERLAB.

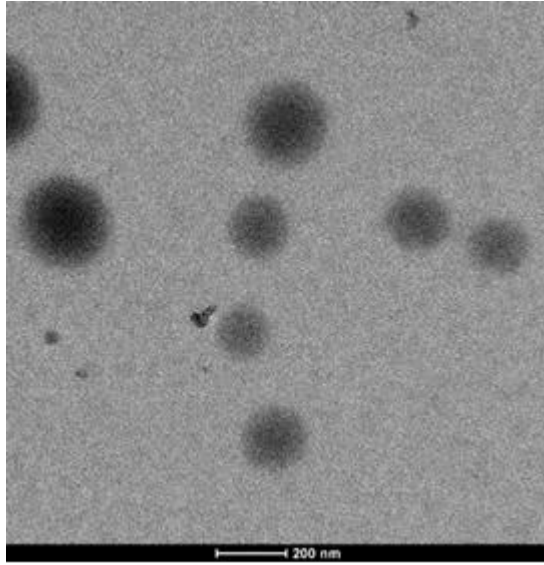


Figure 4.2 TEM images of nanocapsules

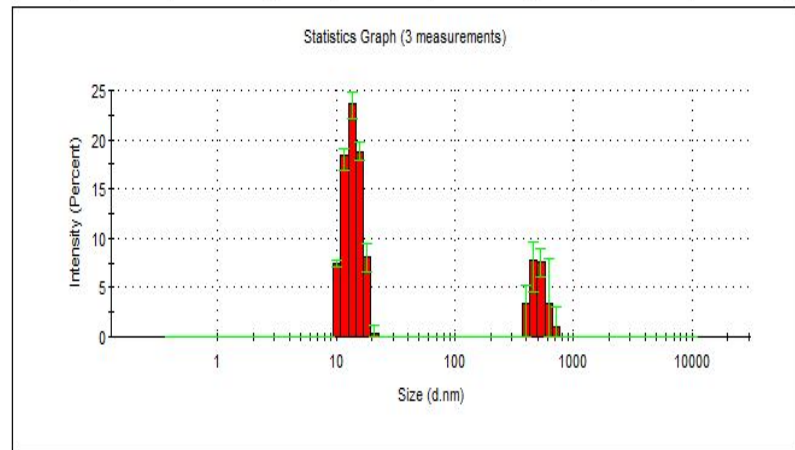
SEM and TEM images show that the geometry of the nanocapsules is spherical. Nanocapsules, which have a high tendency to stick to each other in powder form, are homogeneously dispersed in water due to their hydrophilic shell structure. In addition, carboxylic acid groups on the surface of the shell prevent the agglomeration of nanocapsules by electrostatic repulsion.

The particle diameters of the capsules were determined at Çankırı Karatekin University Central Research Laboratory using the 'Malvern zetasizer nano zs zeta potential and zeta size' measuring device. Figure 5 shows the distribution of particle diameters. Peak 1 is seen at 11.92 nm. When agglomerated particles are removed from the distribution, the average particle diameter is 11.92 nm. Figure 4.2 shows the percent particle diameter density. As can be seen from Figure 4.3, particle diameters are mostly around 10 nm.

Results Table

Size d.nm	Intensity Percent	Size d.nm	Intensity Percent
0.4000	0.0	68.06	0.0
0.4632	0.0	78.82	0.0
0.5365	0.0	91.28	0.0
0.6213	0.0	105.7	0.0
0.7195	0.0	122.4	0.0
0.8332	0.0	141.8	0.0
0.9649	0.0	164.2	0.0
1.117	0.0	190.1	0.0
1.294	0.0	220.2	0.0
1.499	0.0	255.0	0.0
1.736	0.0	295.3	0.0
2.010	0.0	342.0	0.0
2.328	0.0	396.1	0.0
2.696	0.0	458.7	4.6
3.122	0.0	531.2	8.9
3.615	0.0	615.1	8.0
4.187	0.0	712.4	3.1
4.840	0.0	825.0	0.0
5.615	0.0	955.4	0.0
6.503	0.0	1106	0.0
7.531	0.0	1281	0.0
8.721	0.0	1484	0.0
10.10	7.0	1718	0.0
11.70	16.0	1990	0.0
13.54	22.1	2305	0.0
15.69	18.8	2669	0.0
18.17	9.4	3091	0.0
21.04	1.2	3590	0.0
24.36	0.0	4145	0.0
28.21	0.0	4801	0.0
32.67	0.0	5560	0.0
37.84	0.0	6439	0.0
43.82	0.0	7456	0.0
50.75	0.0	8635	0.0
58.77	0.0	1,000e4	0.0

a

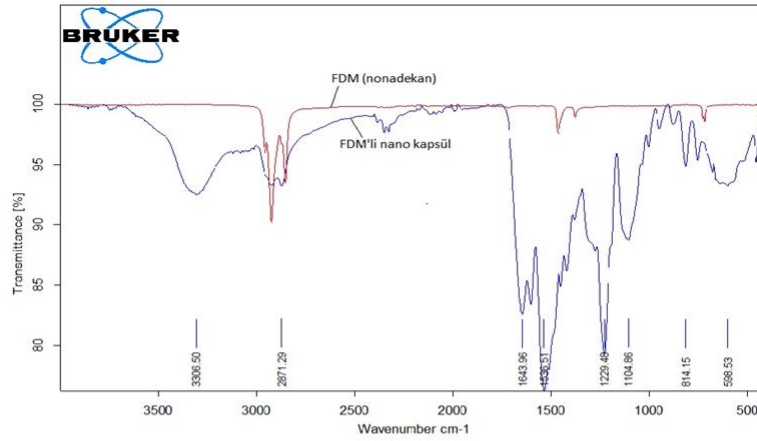


b

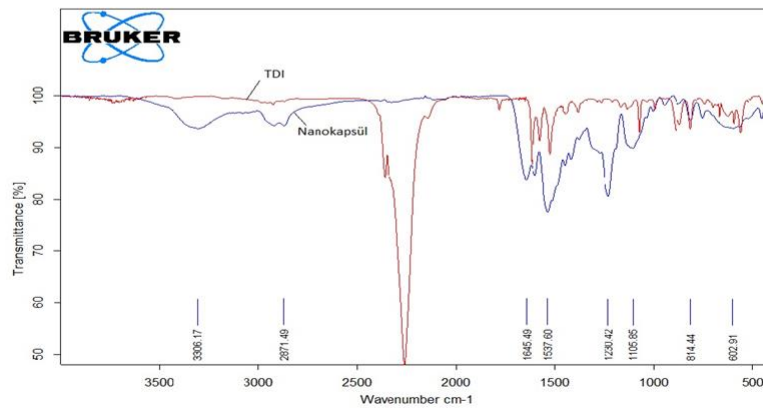
Figure 4.3 Particle diameter distribution of nanocapsules

FTIR analysis is necessary to determine the content of the shell of polyurethane nanocapsules containing PCM. In this study, the content of the capsule shell, the degree of reaction of TDI, and the content of the capsules were determined by FTIR analysis. Figure 4.4 shows the FTIR peaks of nanocapsules with and without PCM. In Figure 4.4a, you can see the FTIR peaks of PU nanocapsules that have nonadecane and PCM (nonadecane) used as PCM. The 2871, 2900 cm^{-1} C-H stretching peak and the 1400, 700 cm^{-1} peaks of the nonadecane were observed as characteristic n-alkane peaks. Figure 4.4 (b) shows the FTIR peaks of TDI and nanocapsules. Peaks around 2200 cm^{-1} , 1500 cm^{-1} are characteristic peaks belonging to the isonate groups (-NCO) of TDI. The peaks around 2200 and 1500 cm^{-1} in the spectra of the empty capsule are the unreacted isonate groups of TDI. The 814, 1106, 123, and 1537 cm^{-1} seen in the results of the empty capsule are characteristic peaks of PCM-free nanocapsules. These peaks at 3306 cm^{-1} N-H stretching and 1537 cm^{-1} N-H bending vibrations indicate the formation of the urethane bond. In Figures 1 a and 1 b, the peaks at 1645 cm^{-1} belong to the carbonyl (-CO) group of polyurethane (PU), and the peaks around 1100 cm^{-1} belong to the ester

group (C=O=C) of PU. Thus, it is seen that the shell structure of the capsules is polyurethane.



a) FTIR peaks of nonadecane and FDM nanocapsules

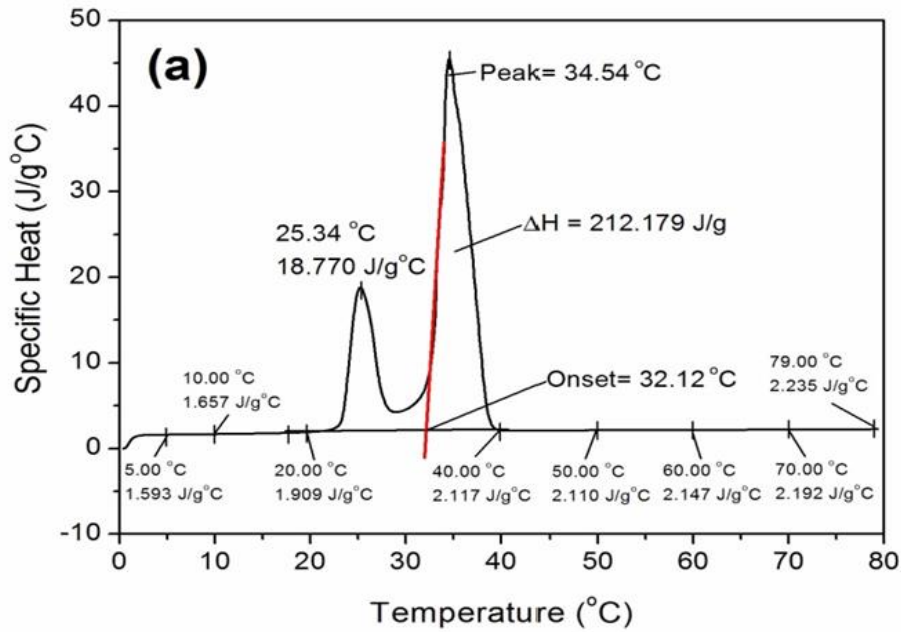


b) FTIR peaks of TDI and empty nanocapsules

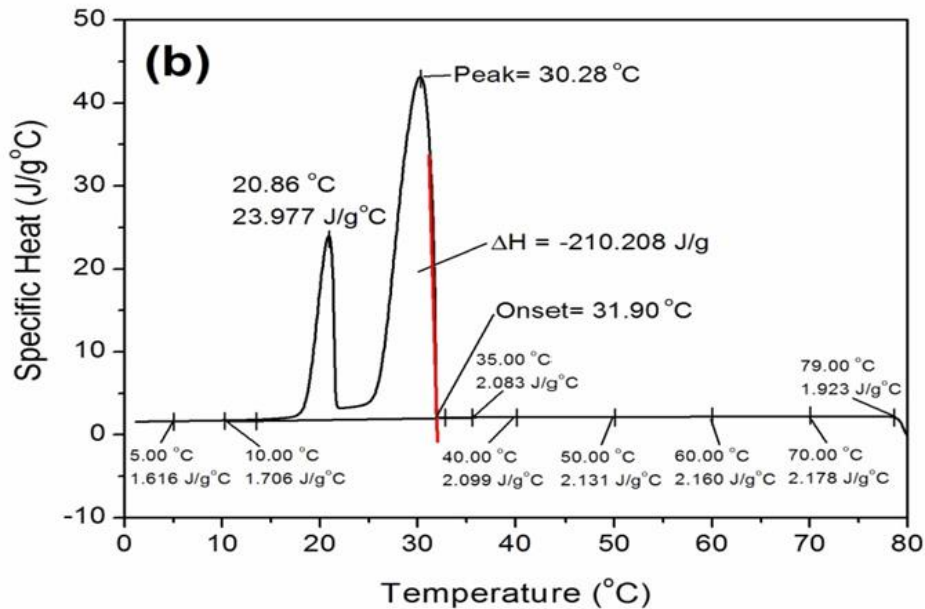
Figure 4.4 FTIR analysis of nanocapsules

The thermal properties of PCM (nonadecane) and PCM-containing nanocapsules, such as phase change temperatures (melting-solidification temperatures) and latent heats, were determined using DSC. Figures 4.4 and 4.5 show the DSC curves of nanocapsules that are pure nonadecane and nanocapsules that contain nonadecane while they are being heated and cooled. The curves have two endothermic and two exothermic peaks. The small peaks on the left side of the curves show the peaks of solid-solid phase transitions, and the main peaks show the peaks of solid-liquid or liquid-solid phase transitions. The melting and freezing temperatures were 30.28 and 34.54 °C for nonadecane and 28.93 and 33.8 °C for nanocapsules containing PCM, respectively. The

small variations in the melting temperature of the encapsulated nonadecane were due to the limitations of the crystallization behavior of the nonadecane inside the polyurethane shell (inside the capsule). The latent heats of melting and solidification were 212.18 and 210.21 J/g for n-nonadecane and 92.85 and 91.86 J/g for PU/nonadecane.



a) Isıtma



b) soğutma

Figure 4.5 DSC curves of nanocapsules

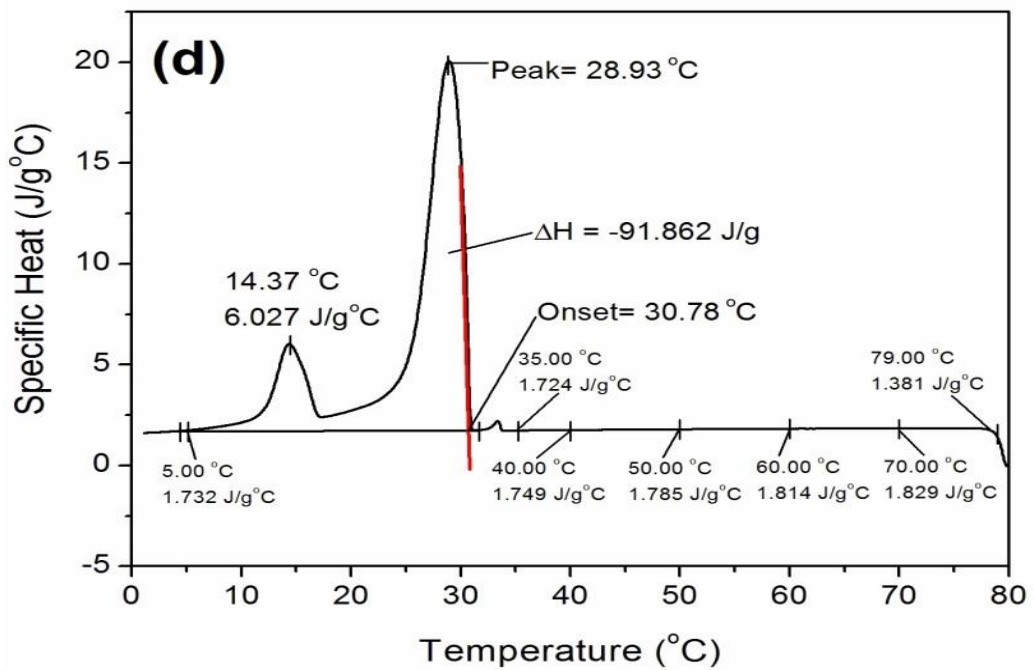
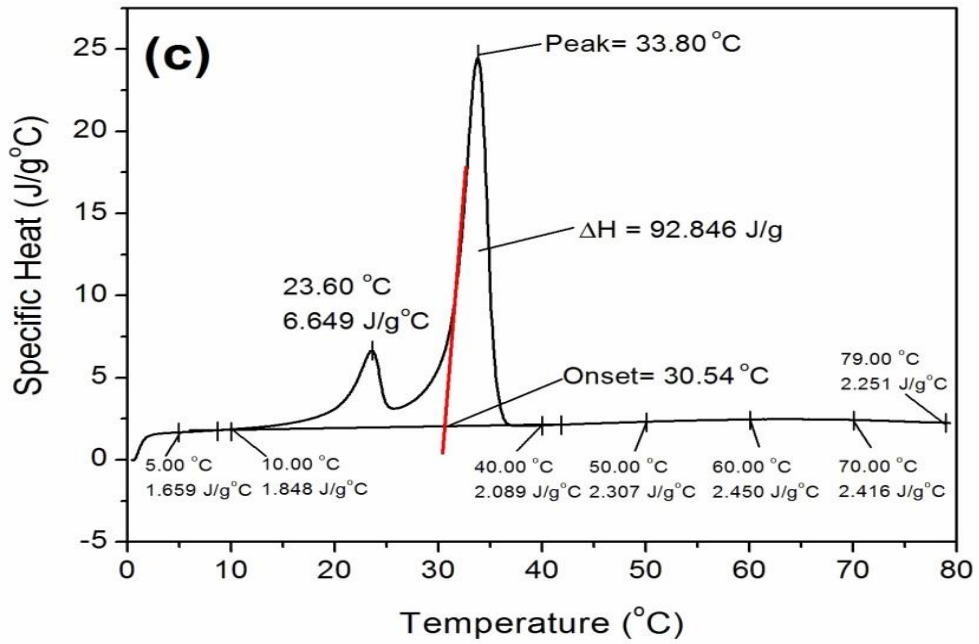


Figure 4.5 DSC curves of nanocapsules (continued)

The PCM content of the nanocapsules was determined by using equation 4.1.

$$\% n - nonadekan(W) = \frac{\Delta H_{NFDM}}{\Delta H_{FDM}} \times 100 \quad (4.1)$$

In the equation, ΔH_{NFDM} = PCM latent heat of melting of nanocapsules containing PCM is J/g^{-1} , ΔH_{FDM} = latent heat of melting of n-nonadecane is J/g^{-1} . With the help of the equation, it was determined that 47.7% of the PCM used could be encapsulated.

4.2 Preperation of Nanofluids

As mentioned earlier, the nanofluids were prepared using the two-step nanofluidic method. One of the methods used to determine the stability of the nanofluids is photography. Figures 4.6, 4.7, and 4.8 show photographs of the nanofluids.

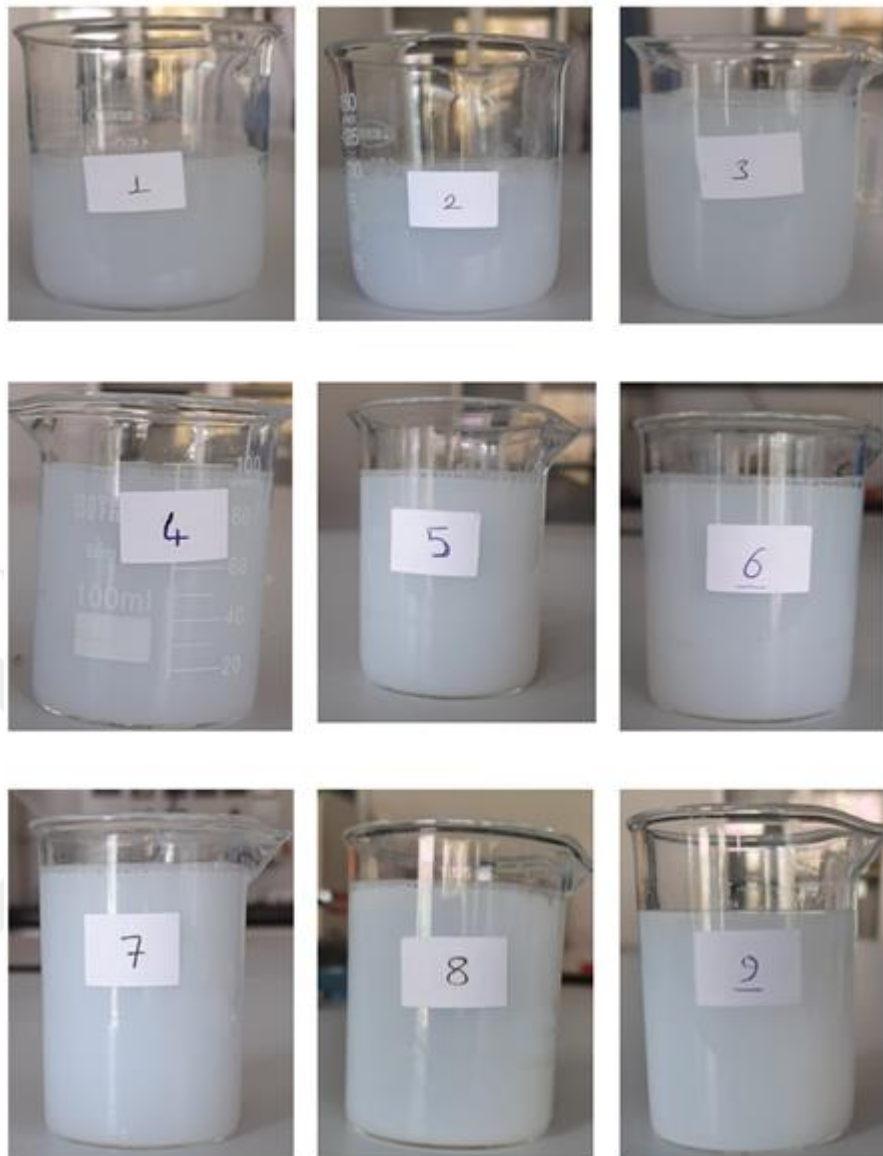


Figure 4.6 Aluminum-oxide/water nanofluids samples



Figure 4.7 Polyurethane nanocapsules/water nanofluid



Figure 4.8 Hybrid nanofluids samples

The density in the suspension images goes up as the solid ratio goes up in the three nanofluids made with Al_2O_3 , PU nanocapsules, and Al_2O_3 -PU hybrid nanoparticles. The use of surfactants in nanofluids is an important factor that increases stability. As the amount of surfactant increased, nanofluids with denser images were obtained.

4.3 Thermal Conductivity

Figure 4.9 shows the thermal conductivity values of Al₂O₃/water nanofluids. S1, S2, and S3 represent the amounts of surfactant (tergitol) used. S1 is 0.05 g, S2 is 0.1 g, and S3 is 0.15 g. As the solid ratio increased, the thermal conductivity values also increased. It is also observed that the thermal conductivity values increased as the amount of surfactant increased. Since the surfactant keeps the particles in the suspension stable, increasing the amount of surfactant increases the thermal conductivity values by increasing stability. In addition, due to the high thermal conductivity of metal nanoparticles, the thermal conductivity values of the nanofluids prepared with Al₂O₃ were higher than the thermal conductivity value of pure water at the same temperature (0.610 W/m.K.), as expected.

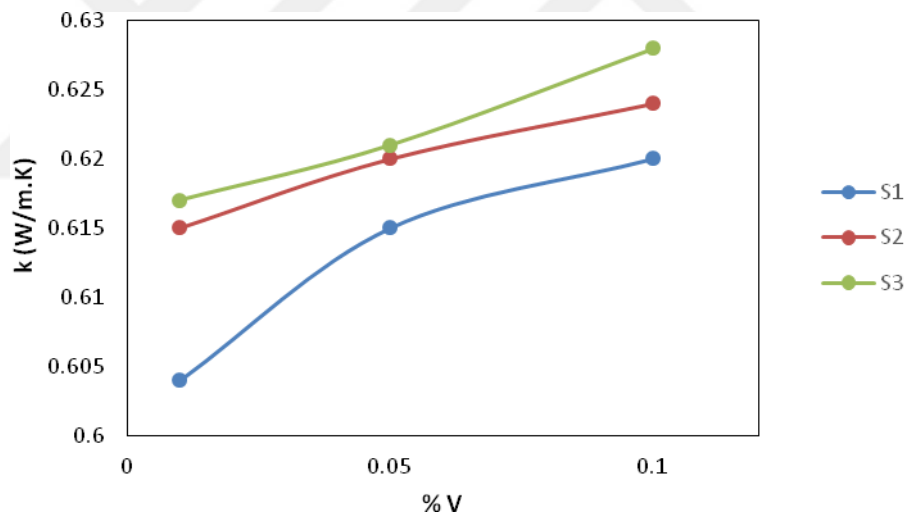


Figure 4.9 Thermal conductivity of Al₂O₃/Water nanofluids

The thermal conductivity values of PU nanocapsules/water nanofluids are shown in the graph in Figure 4.10. Polyurethane is a material with a lower thermal conductivity value than pure water. Therefore, the thermal conductivity values of the nanofluids prepared with polyurethane capsules remained below the thermal conductivity value of pure water. The thermal conductivity values of the nanofluids increased as the solid content increased. While the highest thermal conductivity values were obtained at the highest

amount of surfactant, higher thermal conductivity values were obtained at the amount of S2 (0.10 g) surfactant than at the amount of S1 (0.05 g) surfactant. This shows that the amount of surfactant does not have a very high effect on the stability of polyurethane nanocapsules/water nanofluids.

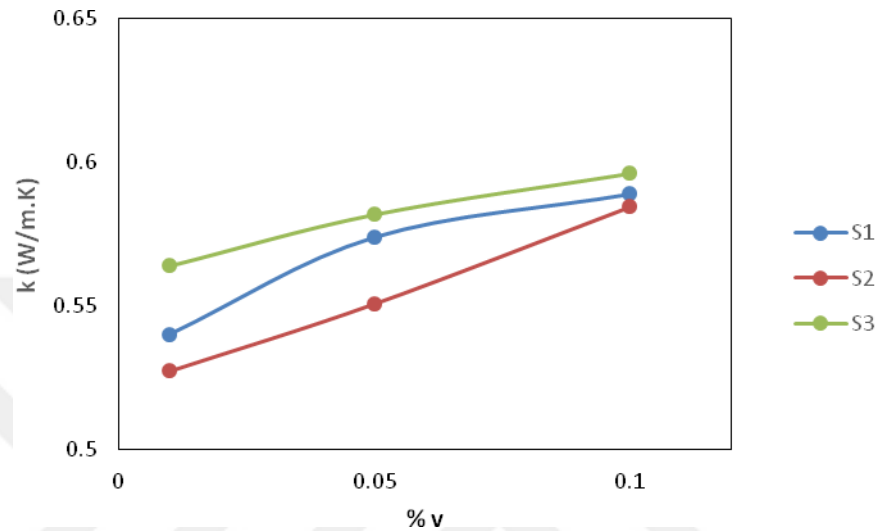


Figure 4.10 Thermal conductivity of PU nanocapsules/Water nanofluids

Figure 4.11 shows the thermal conductivities of hybrid nanofluids. In hybrid nanofluids, 50% of the volumetric solid ratio is Al_2O_3 and 50% is PU nanocapsules. The thermal conductivity values of all nanofluids in hybrid nanofluids were higher than the thermal conductivity values of pure water. Thermal conductivity values increased with increasing solid ratios. However, there are not very high increases between the volumetric ratios. Due to the low thermal conductivity of polyurethane, low thermal conductivity values were obtained in hybrid nanofluids.

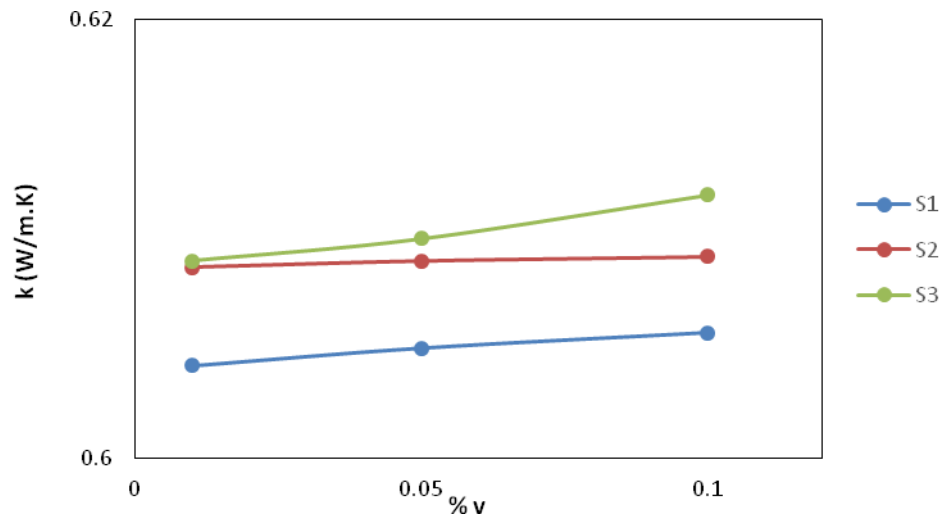


Figure 4.11 Thermal conductivity of Hybrid nanofluids

4.4 Viscosity

Like thermal conductivity, viscosity is also an important parameter that gives an idea about stability in nanofluids. Figure 4.12 shows the viscosity values of $\text{Al}_2\text{O}_3/\text{water}$ nanofluids. The viscosity of the surfactant used (tergitol) is higher than that of pure water. In addition, the solids added to the nanofluids cause the viscosity of the fluids to increase. The viscosity values obtained for all three solid ratios were higher than the viscosity value of pure water. The viscosity values also increased with the increase in the amount of surfactant. While increasing the solid ratios was expected to increase the viscosity values, the viscosity values of $\text{Al}_2\text{O}_3/\text{water}$ nanofluids decreased. This indicates that nanoparticles settle more with an increase in the solid ratio.

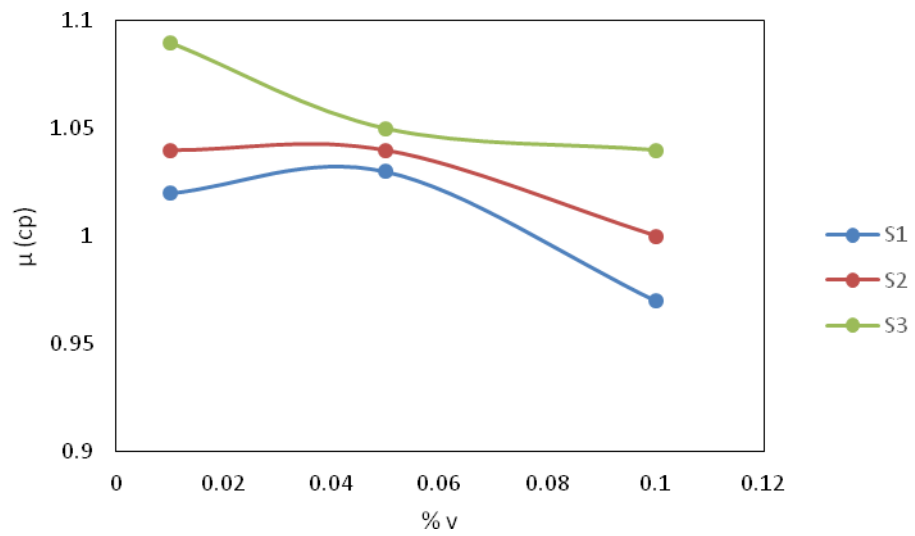


Figure 4.12 Viscosity of Al₂O₃/Water nanofluids

Figure 4.13 shows the viscosity values of PU nanocapsules/water nanofluids. It is seen that the viscosity values increase as expected with the increase in the solid ratio and surfactant amount. Suspended nanoparticles and surfactant increased the viscosity of the base fluid to which they were added.

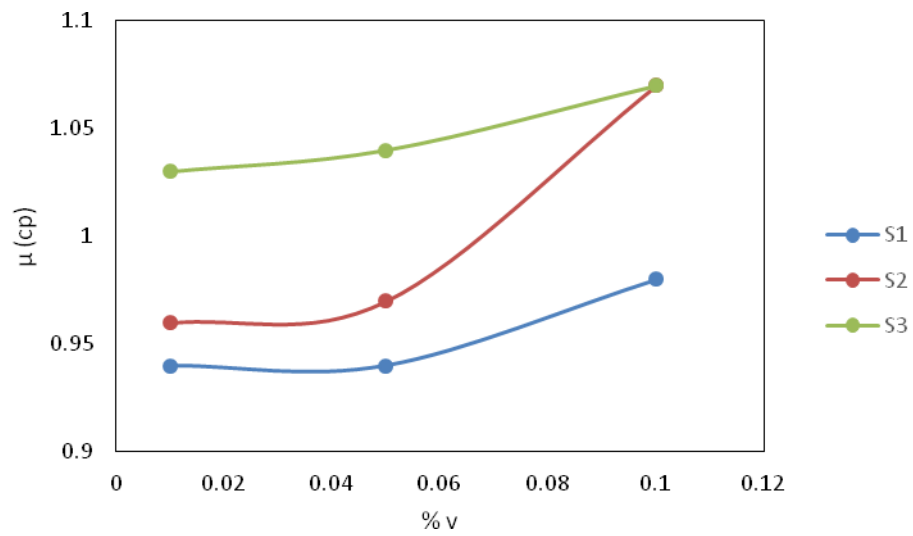


Figure 4.13 Viscosity of PU nanocapsules/Water nanofluids

Figure 4.14 shows the viscosity values of nanofluids containing Al_2O_3 and Pu nanocapsules as solids. The viscosity values increased with the increase in the amount of surfactant. In addition, the increase in the amount of solid increased the viscosity values.

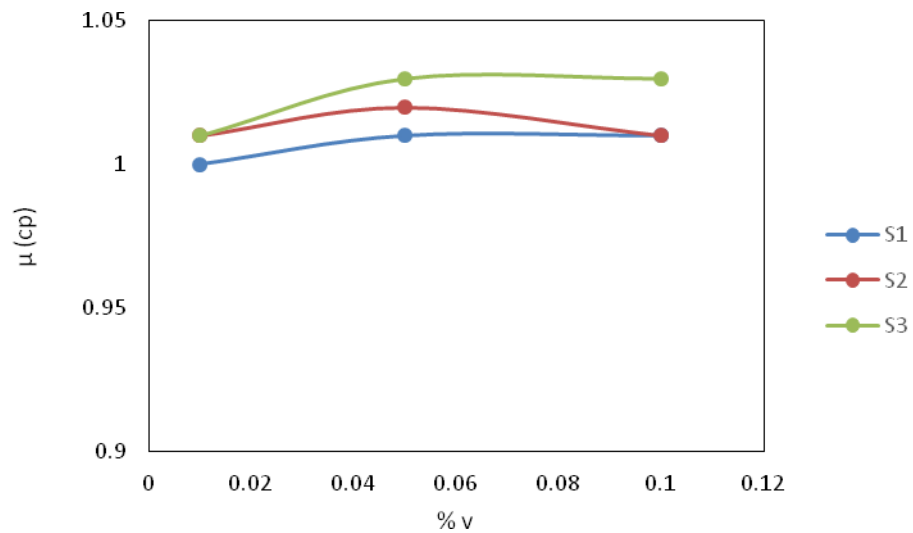


Figure 4.14 Viscosity of Hybrid nanofluids

5. CONCLUSIONS AND RECOMMENDATION

In this study, in which 27 samples of Al_2O_3 /water, polyurethane, and hybrid (Al_2O_3 /polyurethane) nanofluids were prepared and the physical properties of these nanofluids were determined, the following results were obtained:

- The thermal conductivity of nanofluids increased with an increasing surfactant volumetric ratio.
- An increasing amount of surfactant allowed the nanofluids to remain suspended.
- Increasing the volumetric ratio of solids resulted in an increase in thermal conductivity.
- Viscosity values increased as the surfactant volumetric ratio and solid amount increased.
- As the amount of solid is increased, denser image nanofluids are obtained.
- As the surfactant volumetric ratio of the nanofluids increases, more intensely imaged nanofluids are obtained.

The work involved in preparing nanofluids and determining their physical characteristics is substantial. A variety of different methods described in the scientific literature have produced long-lasting, stable nanofluids.

To obtain highly stable nanofluids by using different surfactant amounts, various surfactants, and a longer time of ultrasonication, there are methods to increase the stability of nanofluids.

It is possible to determine how many days the nanofluids can remain stable, which will determine the best nanofluid to be used in an application.

REFERENCES

- Allahyar, H. R., Hormozi, F. and ZareNezhad, B. 2016. Experimental investigation on the thermal performance of a coiled heat exchanger using a new hybrid nanofluid. *Experimental thermal and fluid science*, 76: 324-329.
- Babar, H., Sajid, M. U. and Ali, H. M. 2019. Viscosity of hybrid nanofluids: a critical review. *Thermal Science*, 23(3): 1713-1754.
- Batchelor, G. K. 1977. The effect of Brownian motion on the bulk stress in a suspension of spherical particles. *Journal of fluid mechanics*, 83(1): 97-117.
- Brinkman, H. C. 1952. The viscosity of concentrated suspensions and solutions. *The Journal of chemical physics*, 20(4): 571-571.
- Bumataria, R. K., Chavda, N. K. and Panchal, H. 2019. Current research aspects in mono and hybrid nanofluid based heat pipe technologies. *Heliyon*, 5(5): e01627.
- Buongiorno, J., Hu, L. W., Kim, S. J., Hannink, R., Truong, B. A. O. and Forrest, E. 2008. Nanofluids for enhanced economics and safety of nuclear reactors: an evaluation of the potential features, issues, and research gaps. *Nuclear Technology*, 162(1): 80-91.
- Buzea, C., Pacheco, I. I. and Robbie, K. 2007. Nanomaterials and nanoparticles: sources and toxicity. *Biointerphases*, 2(4): MR17-MR71.
- Ch, P. B. and Cho, Y. I. 1998. Experimental Heat Transfer: A Journal of, Thermal Energy Transport, Storage, and Conversion Hydrodynamic Generation and Heat Transfer Study of Dispersed Fluids with Sumicron Metallic Oxide. *Therm. Energy*, 11(2): 151-70.
- Chandravadhana, A., NandaKumar, V. and Venkatramanan, K. 2020. Mono and hybrid nanofluid based heat sink technologies-a review. In *Journal of Physics: Conanofluidence Series*. IOP Publishing, 1644(1): 012048.
- Choi, S. U. and Eastman, J. A. 1995. Enhancing thermal conductivity of fluids with nanoparticles (No. ANL/MSD/CP-84938, CONANOFLUID-951135-29). Argonne National Lab.(ANL): Argonne, IL (United States), 7: 89.
- Davis, R. H. 1986. The effective thermal conductivity of a composite material with spherical inclusions. *International Journal of Thermophysics*, 7(3): 609-620.

- De Groot, J. J., Kestin, J. and Sookiazian, H. 1974. Instrument to measure the thermal conductivity of gases. *Physica*, 75(3): 454-482.
- Demirbas, M. F. 2006. Thermal energy storage and phase change materials: an overview. *Energy Sources, Part B: Economics, Planning, and Policy*, 1(1): 85-95.
- Eastman, J. A., Choi, S. U. S., Li, S., Yu, W. and Thompson, L. J. 2001. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Applied physics letters*, 78(6): 718-720.
- Eastman, J. A., Choi, U. S., Li, S., Thompson, L. J. and Lee, S. 1996. Enhanced thermal conductivity through the development of nanofluids. *MRS Online Proceedings Library (OPL)*: 457, 3.
- Einstein, A. 1906. A new determination of molecular dimensions. *Ann. Phys.*, 19, 289-306.
- Ferlier, L. 2019. Collective Wisdom in the Digital Age: Digitizing Early Modern Collections at the Royal Society. In *Collective Wisdom: Collecting in the Early Modern Academy*, 4: 289-307.
- Frankel, N. A. and Acrivos, A. 1967. On the viscosity of a concentrated suspension of solid spheres. *Chemical Engineering Science*, 22(6): 847-853.
- Ganvir, R. B., Walke, P. V. and Kriplani, V. M. 2017. Heat transfer characteristics in nanofluid—a review. *Renewable and sustainable energy reviews*, 75, 451-460.
- Godson, L., Raja, B., Lal, D. M. and Wongwises, S. E. A. 2010. Enhancement of heat transfer using nanofluids—an overview. *Renewable and sustainable energy reviews*, 14(2): 629-641.
- Guth, E. and Simha, R. 1936. Untersuchungen über die Viskosität von Suspensionen und Lösungen. 3. Über die Viskosität von Kugelsuspensionen: Zur Berechnung des Wandeanofluidlusses und der Wechselwirkung bei der Viskosität, sowie bei rotierenden Kugeln. *Kolloid-Zeitschrift*, 74, 266-275.
- Hamilton, R. L. and Crosser, O. K. 1962. Thermal conductivity of heterogeneous two-component systems. *Industrial and Engineering chemistry fundamentals*, 1(3): 187-191.
- Harish, S., Ishikawa, K., Einarsson, E., Aikawa, S., Inoue, T., Zhao, P. and Maruyama, S. 2012. Temperature dependent thermal conductivity increase of aqueous

- nanofluid with single walled carbon nanotube inclusion. *Materials Express*, 2(3): 213-223.
- Haruta, M., Kobayashi, T., Sano, H. and Yamada, N. 1987. Novel gold catalysts for the oxidation of carbon monoxide at a temperature far below 0 °C. *Chemistry Letters*, 16(2): 405-408.
- Hong, T. K., Yang, H. S. and Choi, C. J. 2005. Study of the enhanced thermal conductivity of Fe nanofluids. *Journal of Applied Physics*, 97(6): 064311.
- Hussein, A. K. 2015. Applications of nanotechnology in renewable energies—A comprehensive overview and understanding. *Renewable and Sustainable Energy Reviews*, 42, 460-476.
- Hwang, Y. J., Lee, J. K., Lee, C. H., Jung, Y. M., Cheong, S. I., Lee, C. G. and Jang, S. P. 2007. Stability and thermal conductivity characteristics of nanofluids. *Thermochimica Acta*, 455(1-2): 70-74.
- Ilyas, S. U., Pendyala, R., Narahari, M. and Susin, L. 2017. Stability, rheology and thermal analysis of functionalized alumina-thermal oil-based nanofluids for advanced cooling systems. *Energy conversion and management*, 142, 215-229.
- Innovation, S. and Ziche, P. 2005. 1. Innovations: The 'New' Philosophy of Nature and its Ambiguous Relation to its Past Ostwald claimed that his Lectures on the Philosophy of Nature from 1901 (the lectures were published in 1902), 2 together with his journal *Annalen der Naturphilosophie* (founded in the same year), 3 marked a new epoch in the. *Wilhelm Ostwald at the Crossroads Between Chemistry, Philosophy and Media Culture*, 1(2): 29.
- Jeffrey, D. J. 1973. Conduction through a random suspension of spheres. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, 335(1602): 355-367.
- Jin, R., Cao, Y., Mirkin, C. A., Kelly, K. L., Schatz, G. C. and Zheng, J. G. 2001. Photoinduced conversion of silver nanospheres to nanoprisms. *science*, 294(5548): 1901-1903.
- Kim, S. H., Choi, S. R. and Kim, D. 2007. Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation, 9: 54.
- Kleinstreuer, C. and Feng, Y. 2011. Experimental and theoretical studies of nanofluid thermal conductivity enhancement: a review. *Nanoscale research letters*, 6, 1-13.

- Kleinstreuer, C. and Feng, Y. 2011. Experimental and theoretical studies of nanofluid thermal conductivity enhancement: a review. *Nanoscale research letters*, 6, 1-13.
- Krieger, I. M. and Dougherty, T. J. 1959. A mechanism for non-Newtonian flow in suspensions of rigid spheres. *Transactions of the Society of Rheology*, 3(1): 137-152.
- Kwak, K. and Kim, C. 2005. Viscosity and thermal conductivity of copper oxide nanofluid dispersed in ethylene glycol. *Korea-Australia Rheology Journal*, 17(2): 35-40.
- Lee, S., Choi, S. S., Li, S. A. and Eastman, J. A. 1999. Measuring thermal conductivity of fluids containing oxide nanoparticles. *Journal of Applied Physics*, 4(1): 87.
- Lewis, N. S. and Nocera, D. G. 2006. Powering the planet: Chemical challenges in solar energy utilization. *Proceedings of the National Academy of Sciences*, 103(43): 15729-15735.
- Li, C. H. and Peterson, G. P. 2006. Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids). *Journal of Applied Physics*, 99(8): 084314.
- Li, Y., Tung, S., Schneider, E. and Xi, S. 2009. A review on development of nanofluid preparation and characterization. *Powder technology*, 196(2): 89-101.
- Matsuda, H., Ebata, A., Teramae, K. and Hishinuma, N. 1993. Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles dispersion of Al₂O₃, SiO₂ and TiO₂ ultra-fine particles. *Netsu Bussei*, 4: 227-233.
- Maxwell, J. C. 1873. *A treatise on electricity and magnetism*. Oxford: Clarendon Press, 1(4): 76.
- Missana, T. and Adell, A. 2000. On the applicability of DLVO theory to the prediction of clay colloids stability. *Journal of Colloid and Interface Science*, 230(1): 150-156.
- Mostafa, A. M. and Yahia, A. 2017. Physico-chemical kinetics of structural build-up of neat cement-based suspensions. *Cement and Concrete Research*, 97: 11-27.
- Mukherjee, S. and Paria, S. 2013. Preparation and stability of nanofluids-a review. *IOSR Journal of Mechanical and civil engineering*, 9(2): 63-69.

- Murshed, S. M. S., Leong, K. C. and Yang, C. 2008. Investigations of thermal conductivity and viscosity of nanofluids. *International journal of thermal sciences*, 47(5): 560-568.
- Nagasaka, Y. and Nagashima, A. 1981. Absolute measurement of the thermal conductivity of electrically conducting liquids by the transient hot-wire method. *Journal of Physics E: Scientific Instruments*, 14(12): 1435.
- Nikkam, N. 2014. Engineering nanofluids for heat transfer applications. PhD. Thesis, KTH Royal Institute of Technology University, 61 page, Sweden.
- Oyeleke, O. O., Ohunakin, O. S., Adelekan, D. S., Atiba, O. E., Nkiko, M. O. and Jatinder, G. 2021. Recent Advancements in the Development of Nanofluid Technology in Heat Transfer Applications. In *IOP Conanofluidence Series: Materials Science and Engineering*. IOP Publishing, 1107(1): 12209.
- Pang, C. and Kang, Y. T. 2012. Stability and thermal conductivity characteristics of nanofluids (H₂O/CH₃OH+ NaCl+ Al₂O₃ nanoparticles) for CO₂ absorption application. *Journal of Applied Physics*, 7(3): 86.
- Parametthanuwat, T., Bhuwakietkumjohn, N., Rittidech, S. and Ding, Y. 2015. Experimental investigation on thermal properties of silver nanofluids. *International Journal of Heat and Fluid Flow*, 56: 80-90.
- Patel, H. E., Das, S. K., Sundararajan, T., Sreekumaran Nair, A., George, B. and Pradeep, T. 2003. Thermal conductivities of naked and monolayer protected metal nanoparticle based nanofluids: Manifestation of anomalous enhancement and chemical effects. *Applied physics letters*, 83(14): 2931-2933.
- Phuoc, T. X., Soong, Y. and Chyu, M. K. 2007. Synthesis of Ag-deionized water nanofluids using multi-beam laser ablation in liquids. *Optics and Lasers in Engineering*, 45(12): 1099-1106.
- Poole, C. P. 2003. frank J. Owens. Introduction to nanotechnology, *Journal of Applied Physics*, 8: 77.
- Popa, I., Gillies, G., Papastavrou, G. and Borkovec, M. 2010. Attractive and repulsive electrostatic forces between positively charged latex particles in the presence of anionic linear polyelectrolytes. *The Journal of Physical Chemistry B*, 114(9): 3170-3177.

- Prasher, R., Bhattacharya, P. and Phelan, P. E. 2005. Thermal conductivity of nanoscale colloidal solutions (nanofluids). *Physical review letters*, 94(2): 025901.
- Rivas-Cruz, F., Hernandez-Martinez, E. G., Portillo-Velez, R. D. J. and Rejón-García, L. 2022. Nanotechnology applications in ground heat exchanger pipes: A review. *Applied Sciences*, 12(8): 3794.
- Sajid, M. U. and Ali, H. M. 2018. Thermal conductivity of hybrid nanofluids: a critical review. *International Journal of Heat and Mass Transfer*, 126: 211-234.
- Salunkhe, P. B. and Shembekar, P. S. 2012. A review on effect of phase change material encapsulation on the thermal performance of a system. *Renewable and sustainable energy reviews*, 16(8): 5603-5616.
- Santucci, A., Verdini, L. and Verdini, P. G. (1986). Data-acquisition system for measurement of thermal diffusivity and propagation properties of thermal waves by a non-steady-state method. *Review of scientific instruments*, 57(8): 1627-1632.
- Sarkar, J., Ghosh, P. and Adil, A. 2015. A review on hybrid nanofluids: recent research, development and applications. *Renewable and Sustainable Energy Reviews*, 43: 164-177.
- Selvam, C., Raja, R. S., Lal, D. M. and Harish, S. 2017. Overall heat transfer coefficient improvement of an automobile radiator with graphene based suspensions. *International Journal of Heat and Mass Transfer*, 115, 580-588.
- Shanthi, R., Anandan, S. S. and Ramalingam, V. 2012. Heat transfer enhancement using nanofluids: An overview. *Thermal Science*, 16(2): 423-444.
- Thuiller, W., Albert, C., Araújo, M. B., Berry, P. M., Cabeza, M., Guisan, A. and Zimmermann, N. E. 2008. Predicting global change impacts on plant species' distributions: future challenges. *Perspectives in plant ecology, evolution and systematics*, 9(3-4): 137-152.
- Vekas, L., Bica, D. and Avdeev, M. V. 2007. Magnetic nanoparticles and concentrated magnetic nanofluids: Synthesis, properties and some applications. *China particuology*, 5(1-2): 43-49.
- Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. and Bairlein, F. 2002. Ecological responses to recent climate change. *Nature*, 416(6879): 389-395.

- Wan, M., Yadav, R. R., Yadav, K. L. and Yadaw, S. B. 2012. Synthesis and experimental investigation on thermal conductivity of nanofluids containing functionalized Polyaniline nanofibers. *Experimental Thermal and Fluid Science*, 41: 158-164.
- Wang, X. Q. and Mujumdar, A. S. 2008. A review on nanofluids-part II: experiments and applications. *Brazilian Journal of Chemical Engineering*, 25: 631-648.
- Xing, M., Yu, J. and Wang, R. 2016. Experimental investigation and modelling on the thermal conductivity of CNTs based nanofluids. *International Journal of Thermal Sciences*, 104: 404-411.
- Xu, B., Li, P. and Chan, C. 2015. Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: a review to recent developments. *Applied Energy*, 160, 286-307.
- Xuan, Y. and Li, Q. 2000. Heat transfer enhancement of nanofluids. *International Journal of heat and fluid flow*, 21(1): 58-64.
- Xuan, Y. and Li, Q. 2000. Heat transfer enhancement of nanofluids. *International Journal of heat and fluid flow*, 21(1): 58-64.
- You, S. M., Kim, J. H. and Kim, K. H. 2003. Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer. *Applied physics letters*, 83(16): 3374-3376.
- Yu, W. and Xie, H. 2012. A review on nanofluids: preparation, stability mechanisms, and applications. *Journal of nanomaterials*, 2: 1-17.
- Zhang, Y. 2013. *Nanotechnology Science and Technology Series Nova Science Publishers, Inc. New York*, 8: 98.
- Zhu, H., Zhang, C., Liu, S., Tang, Y. and Yin, Y. 2006. Effects of nanoparticle clustering and alignment on thermal conductivities of Fe₃O₄ aqueous nanofluids. *Applied Physics Letters*, 89(2): 023123.

CURRICULUM VITAE

Personal Information

Name and Surname : Ali Rahmah Ali ALBURGHEEF

Education

MSc Çankırı Karatekin University
Graduate School of Natural and Applied Sciences 2020-2023
Department of Chemical Engineering

Undergraduate Baghdad University
Faculty of Engineering 1992-1996
Department of Chemical Engineering