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Experimental Investigation of Hybrid Nanofluids Influence on Engine Oil Rheology and Associated Pumping Power Requirements

Davvod firouzi, Mohammad Abbaszadeh, Abbas Kamaloo*

3 km, Daneshgah Boulevard, Minab, Hormozgan, Iran, Minab National Skilling University

Abstract

This study examines the rheological properties of Fe_3O_4-MWCNTs/Oil (SAE40) nanofluid, focusing on its behavior at temperatures ranging from 25°C to 50°C. Stable suspensions with solid volume fractions from 0.05% to 1.6% were prepared by dispersing Fe_3O_4-MWCNTs (80:20% vol.) in SAE40 oil. Viscosity measurements were performed across shear rates from 666.5 s^{-1} to 9331 s^{-1}. The results confirmed that the nanofluid exhibits Newtonian behavior across all concentrations and temperatures. A notable increase in dynamic viscosity was observed with higher solid volume fractions, while viscosity decreased with rising temperature. The maximum viscosity enhancement achieved was 46%. Based on experimental data, a precise correlation was proposed to predict dynamic viscosity. Sensitivity analysis indicated that viscosity is more sensitive to changes in solid volume fraction than temperature. Additionally, the effect of nanofluids on pumping power required for oil flow was investigated, confirming their potential for thermal engineering applications.

Keywords: Hybrid Nanofluids; Viscosity of hybrid nanofluid; Nanoparticles; Nanotechnology in Lubrication; Fluid Dynamics

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Introduction

The term *nano* originates from the Greek word meaning “dwarf” or “small.” In modern science, it refers to an extremely small scale—approximately 100 nanometers, which is about the width of just three to four atoms. To put this into perspective, a nanometer is roughly one-thousandth the diameter of a human hair [1].

Nanotechnology, in its literal sense, means “technology at the nanoscale.” It enables the design, fabrication, and development of novel materials, devices, and systems at dimensions on the order of one billionth of a meter, achieved through atom-by-atom and molecule-by-molecule manipulation and rearrangement. This involves controlling matter at the atomic and molecular level over a length scale of 1 to 100 nanometers, thereby creating structures that often display unique properties and functionalities arising from their reduced size and quantum effects.

It is important to note that *nanoscience* and *nanotechnology* are distinct concepts. Nanoscience is the study of phenomena and material properties at the atomic and molecular scale—properties that often differ significantly from those at larger dimensions—whereas nanotechnology refers to the deliberate design, characterization, production, and application of structures, devices, and systems by controlling their nanoscale geometry and dimensions.

Corresponding Author:st_a_kamaloo@azad.ac.ir
Tel:+989123491829

Transitioning from microparticles to nanoparticles can lead to dramatic changes in behavior and performance. Rather than being a completely new discipline, nanotechnology represents a revolutionary approach to existing sciences and engineering domains. Its ultimate goal is to construct materials and components atom-by-atom and molecule-by-molecule on the nanometric scale.

Among the various branches of nanotechnology, nanofluids—fluid suspensions containing ultrafine nanoparticles—have emerged as promising candidates for enhanced heat transfer applications. Their superior performance compared to conventional fluids stems from the large surface area and high thermal conductivity of dispersed nanoparticles, coupled with improved stability and reduced weight [2].

However, nanofluids also face challenges that have hindered their large-scale adoption in thermal systems, even after two decades of research. A major drawback, especially with nano-silica-based fluids, lies in their physical and chemical instability, manifested in phenomena such as particle agglomeration and sedimentation on heat-transfer surfaces. These issues can diminish thermal performance and, in some cases, negate the benefits of using nanofluids altogether.

The properties of nanofluids depend on both the type of base fluid (organic or inorganic) and the nature of the suspended nanoparticles. Unlike conventional two-phase mixtures containing micro- or millimeter-sized particles, nanofluids exhibit unique heat transfer behavior due to their nanoscale dispersion. The introduction of ultrafine particles changes the thermal conductivity and convective characteristics of the host liquid, offering significant potential for performance enhancement [4,5].

One of the most widely reported benefits of nanofluids is a marked increase in thermal conductivity, even at very low particle concentrations. This effect often occurs without disrupting the Newtonian behavior of the fluid, which is advantageous for pumping and system design.

Depending on their formulation, nanofluids have found potential or demonstrated applications in a wide range of sectors, including:

- **Heat Exchangers:** Increased thermal efficiency, energy savings, and improved fluid heat transfer properties, with reduced pump power consumption.
- **Heating and Air Conditioning Systems:** Enhanced energy performance, system downsizing, and improved spatial efficiency in buildings.
- **Lubrication:** Higher load-carrying capacity, reduced wear in components such as bearings and gears, and extended machinery lifespan.
- **Transportation Industry:** Downsizing of engines, pumps, and radiators, reduced operating costs, and minimized environmental impact.
- **Nuclear Reactors:** Increased critical heat flux, improved accident safety, and enhanced reactor cooling efficiency.
- **Brake Systems:** Better heat dissipation and improved operational safety.
- **Aerospace and Aviation:** Weight and space savings in thermal systems, critical for spacecraft and aerospace vehicles.

A key advantage of nanofluids in heat transfer systems is their ability to deliver significant performance gains without proportionally increasing energy consumption. For example, doubling the heat transfer rate in a conventional system might require increasing pump power by a factor of ten. However, by increasing the thermal conductivity of the working fluid—through nanoparticle addition—by just threefold, it is possible to achieve the same heat transfer improvement without added pumping energy. This translates to lower operating costs, reduced system size and weight, and overall improved economic feasibility [7,8].

In summary, nanofluids offer considerable promise for enhancing heat transfer efficiency, downsizing thermal systems, and reducing operational energy demands. Nevertheless, addressing their stability and long-term performance challenges remains essential for full-scale industrial adoption.

Nano fluids and Their Thermal Properties

Nano fluids, engineered colloidal suspensions of nanoparticles in a base fluid, have garnered significant attention in recent years due to their enhanced thermophysical properties compared to their base fluids. The dispersion of nanoparticles, typically in the nanometer range (1-100 nm), can dramatically alter properties such as thermal conductivity, viscosity, and heat transfer coefficients. This section will delve into the fundamental principles governing the thermal behavior of Nano fluids, exploring the various mechanisms contributing to their improved performance.

The potential applications of Nano fluids span a wide array of fields, including solar energy systems, electronic cooling, and industrial heat exchangers. Their ability to efficiently transport heat makes them promising candidates for next-generation heat transfer fluids.

The thermal conductivity of a fluid is a critical parameter that dictates its ability to transfer heat. For Nano fluids, the enhancement in thermal conductivity is often attributed to several mechanisms:

- **Brownian motion:** The random movement of nanoparticles within the base fluid can lead to increased energy transfer through collisions.
- **Particle-to-Particle Conduction:** Direct contact between nanoparticles can facilitate heat transfer.
- **Layered Nanoparticle Effect:** The formation of adsorbed molecules or layers around nanoparticles can create high thermal conductivity paths.
- **Ballistic Phonon Transport:** In some cases, phonon transport through nanoparticles can be more efficient than in the bulk fluid.

The base fluid plays a crucial role in the overall performance of a Nano fluid. Common base fluids include water, ethylene glycol, and various oils. The selection of the base fluid depends on the intended application and operating conditions.

The concentration of nanoparticles, known as the volume fraction, is another key factor influencing the thermophysical properties of Nano fluids. Generally, increasing the volume fraction leads to an enhancement in thermal conductivity, but this effect can be non-linear and is often accompanied by an increase in viscosity.

Scientific Commentary:
The interplay between nanoparticle size, shape, material, concentration, and the base fluid properties is complex. Understanding these relationships is paramount for designing Nano fluids with optimized thermal performance for specific applications. While significant

progress has been made, challenges remain in achieving stable Nano fluid dispersions and predicting their long-term behavior under various operational stresses.

Nano fluids represent a fascinating application of nanotechnology in the realm of fluid mechanics and heat transfer. They are defined as suspensions of nanoparticles, typically with at least one dimension in the range of 1 to 100 nm, within a base fluid. These nanofluids offer demonstrably superior thermal conductivity compared to conventional heat transfer fluids, such as water, ethylene glycol, or oils. The nanoscale size of the dispersed particles is central to their enhanced properties. This small size improves stability against sedimentation, meaning the nanoparticles remain suspended for longer periods without settling out. Furthermore, it dramatically increases the surface area available for heat exchange per unit volume of the fluid. Critically, this enhancement in thermal performance can often be achieved while maintaining lower overall weight compared to suspensions of larger particles. Even at relatively low concentrations of nanoparticles, nanofluids can significantly enhance the thermal conductivity of the base fluid without fundamentally altering its Newtonian behavior.

However, despite their promising properties, the widespread practical application of nanofluids still faces significant challenges. The most notable among these is the issue of physical and chemical stability of the suspension. Problems such as particle aggregation (where nanoparticles clump together) or deposition onto heat transfer surfaces can lead to a reduction in heat transfer performance. In some severe cases, these stability issues can completely hinder their adoption in sensitive industrial systems.

Nanofluids can be formulated with an extremely wide variety of base fluids (which can be either organic or inorganic) and different types of nanoparticles.

This vast combinatoric possibility results in unique combinations of thermophysical properties, allowing for tailored solutions for specific

applications. When compared to traditional suspensions of micro- or millimeter-scale particles, nanofluids provide several key advantages:

• Increased thermal conductivity: This is the most significant and widely recognized benefit, enabling more efficient heat transfer.

• Enhanced heat transfer coefficients: This means more heat can be
transferred per unit area and per degree temperature difference, leading to more compact and efficient systems.

The potential for smaller, lighter, and more efficient heat exchangers: By•
improving the heat transfer capabilities of the fluid, the size of the heat transfer equipment can be reduced, leading to weight savings and improved overall system efficiency.

These remarkable properties make nanofluids exceptionally promising for a diverse range of applications, including but not limited to:

• Heat exchangers: Nanofluids can significantly improve the efficiency of heat exchangers and reduce the pumping power required to circulate the fluid, leading to energy savings and more compact designs.

• HVAC systems: Their enhanced thermal performance can contribute to greater energy efficiency and allow for the design of smaller, space-saving heating, ventilation, and air conditioning units.

• Lubricants: When used as additives in lubricants, nanofluids can reduce friction and wear, thereby increasing the lifetime of mechanical parts in engines and machinery.

• Automotive industry: Applications include the development of more compact engines and radiators, leading to lower emissions and improved fuel efficiency.

• Nuclear reactors: Nanofluids hold potential for enhancing safety margins and improving the removal of accident heat due to their superior thermal properties.

• Aerospace systems: Their ability to reduce weight and enhance thermal control makes them attractive for various aerospace applications.

From an energy perspective, the advantages of using nanofluids are particularly compelling. They can provide the same level of improvement in heat transfer performance as significantly higher pumping power when using conventional fluids. Crucially, this enhanced performance is achieved without the corresponding penalty of increased energy consumption for pumping. This Fundamental characteristic makes Nano fluids highly attractive for both achieving significant energy savings and enabling substantial system size reduction in a wide array of thermal management applications.

Multi-Walled Carbon Nanotubes (MWCNTs)

Multi-walled carbon nanotubes consist of several concentric single-walled nanotubes nested within one another. These tubes are arranged coaxially, where each wall is essentially a rolled graphene sheet.

The distance between the walls is approximately 0.34 nm, similar to the spacing between graphene layers in graphite. Due to the weak van der Waals forces between these layers, the outer walls can slide relative to the inner ones. Compared to single-walled carbon nanotubes, MWCNTs exhibit greater structural robustness, are less prone to defect propagation, and can maintain mechanical integrity even with partial layer damage.

Advantages:

- Higher resistance to mechanical damage.
- More durable under chemical and thermal stress.
- Easier to produce in industrial quantities compared to single-walled varieties.

Applications:

MWCNTs are widely used in reinforcing composite materials, enhancing electrical conductivity, improving thermal conductivity, and as support structures for catalysts. In Nano fluid applications, their high aspect ratio and excellent conductivity make them ideal for boosting the overall heat transfer performance.

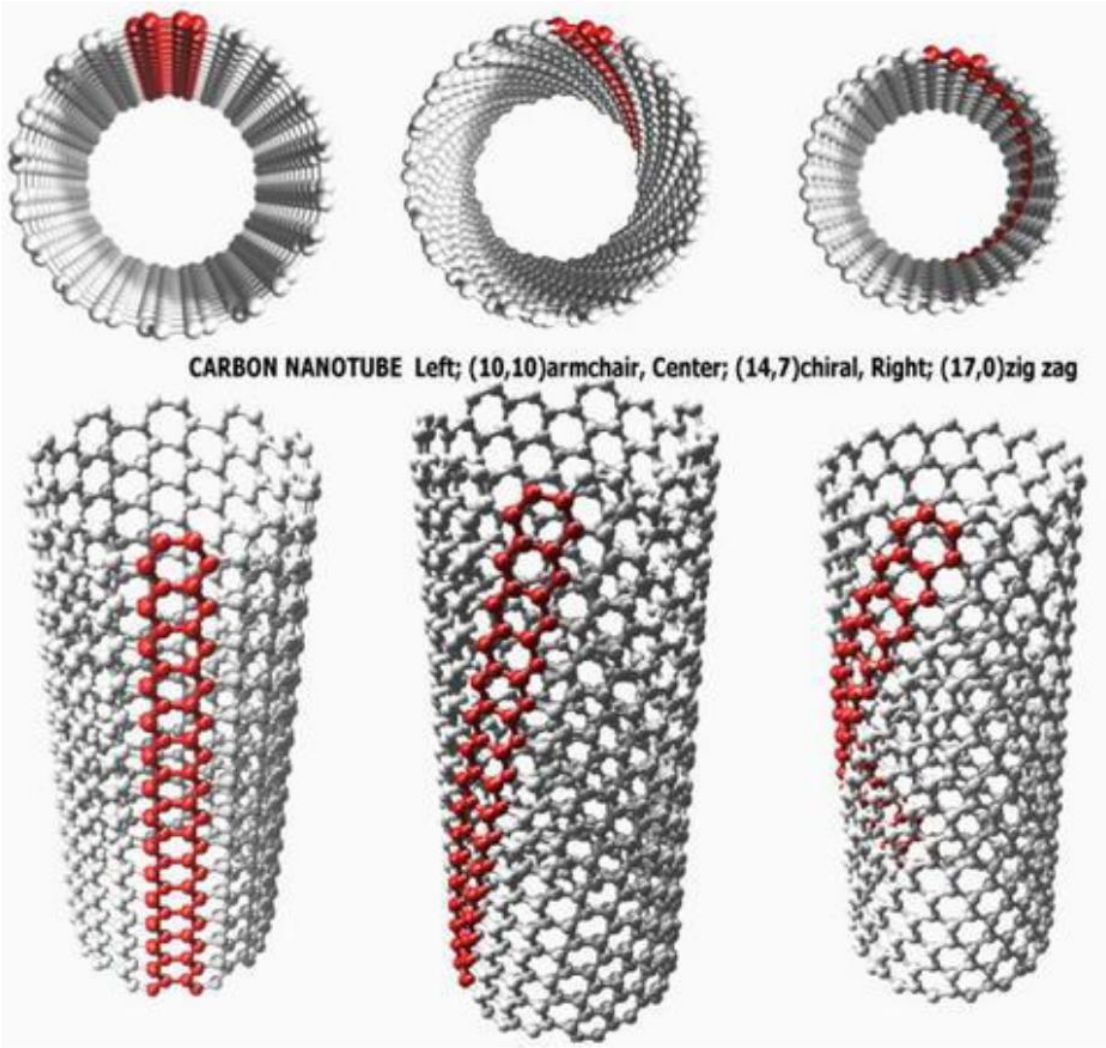

Fig.1 Structural representation of single-walled and multi-walled carbon nanotubes, showing concentric graphene layers in MWCNTs and their relative alignment. (Adapted from Şen et al., 2014)

Multi-walled carbon nanotubes consist of several concentric graphene cylinders nested within each other. Despite their structural complexity, the weak van der Waals forces between adjacent layers allow the outer shells to slide over the inner shells without breaking the entire structure.

This feature makes MWCNTs significantly more durable and resistant to fracture compared to single-walled nanotubes. Additionally, due to these interlayer properties, their potential applications in nanofluid technology are even greater.

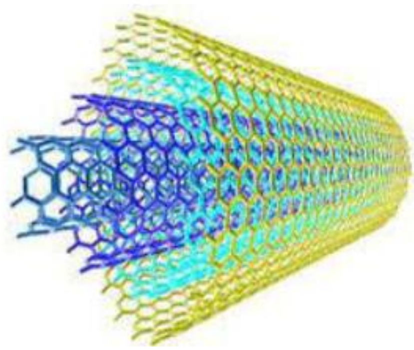

Figure 2: Schematic of a multi-walled carbon nanotube structure.

Materials and Methods

Base Oil and Hybrid Nanoparticles

The base lubricant oil employed in this study was characterized by its defined hydrocarbon composition, viscosity grade, and density, conforming to ASTM D445 and D1298 standards. Hybrid nanoparticles were synthesized via a controlled chemical co-precipitation route, ensuring precise stoichiometric composition. Transmission electron microscopy (TEM) revealed predominantly spherical morphologies with a mean particle diameter below 50 nm. Surface functionalization using silane coupling agents was implemented to enhance dispersibility and chemical stability within the oil matrix. Thermal conductivity was quantified through the transient hot-wire technique (ASTM D7896).

Sample Preparation

specifications of Materials for Preparing the Nanofluid in This Experiment

To prepare the experimental nanofluid, the following materials were used:

SAE40 base oil with specifications listed in **Table 1** was used as the base fluid

Table 1 – Specifications of SAE40 engine oil [57]

Property	Value
Kinematic viscosity at 100°C (cSt)	15.5
Density at 15°C (kg/m³)	885
Viscosity index	128
Flash point (°C)	242
Pour point (°C)	-12

Multi-walled carbon nanotubes (MWCNTs) and iron oxide nanoparticles, with specifications listed in **Table 2**, were used for the preparation of the nanofluid.

Table (2) – Specifications of MWCNTs and iron oxide nanoparticles [58]

Property	MWCNTs	Iron oxide (Fe_2O_3) nanoparticles
Purity (%)	97	99.8
Color	Black	Brown
Outer diameter (nm)	15–20	20–30
Inner diameter (nm)	5–15	–
Length (mm)	10–30	–
Thermal conductivity (W/m·K)	3500	150
Density (g/cm³)	1.35–1.40	5.24
Specific surface area (m²/g)	>110	150–250

Nanofluid formulations were prepared by gravimetrically measuring nanoparticle masses with a microbalance of ±0.1 mg accuracy. The nanoparticles were incrementally introduced into the base oil under gentle stirring, followed by addition of a non-ionic surfactant (0.5 wt %) to suppress agglomeration. Preliminary pre-mixing was conducted prior to high-energy dispersion.

$$\varphi = \frac{(w/\rho)Fe3O4 + (w/\rho)MWCNTs}{(w/\rho)Fe3O4 + (w/\rho)MWCNTs + (w/\rho)SAE40} \times 100 \quad (1)$$

It is also possible to determine the required amount of iron oxide nanoparticles and multi-walled carbon nanotubes (MWCNTs) for different volume fractions using Equation (1), which relates the volume fraction (φ) to density (ρ) and weight (W):

(w/ρ)Fe3O4+(w/ρ)MWCNTs+(w/ρ)SAE40=600ml

φ=ρFe3O4W+ρMWCNTW+ρSAE40WρFe3O4W+ρMWCNTW×100

$$0.5 =$$

$$[(w/\rho)Fe3O4/600ml$$

$$] \times 100 \Rightarrow (w/\rho)Fe3O4 = 0.75ml = 0.75cm3$$

$$\Rightarrow \begin{cases} wFe3O4 = 2.9175\ g \\ wMWCNTs = 0.525\ g \end{cases}$$

Viscosity Measurement

A viscometer is a device used to measure viscosity. When a solid object is immersed in a liquid inside a viscometer, there is always a relative motion between the solid object and the liquid (the measuring medium). This motion is either generated by moving the measuring object within the fluid or by moving the fluid itself relative to the object. The resistance force generated by the fluid against this motion is proportional to the magnitude of the viscosity.

In this work, to measure the viscosity of nanofluid samples, a rotational-type viscometer (as shown in Figure 3-4) was utilized.

Viscosity

Viscosity is the resistance of a fluid to the flow of one layer past another. The ratio of the applied shear stress to the resulting rate of deformation is called viscosity. Using Newton's second law of motion (F=maF = maF=ma), the relevant studies of viscosity are categorized accordingly.

Viscosity Measurement

Viscometers are devices for measuring the viscosity of liquids. Viscosity can be considered from two aspects:

- **Dynamic** viscosity (μ\muμ)
- **Kinematic** viscosity (ν\nuν)

Rotational Viscometer with a Coaxial Cylinder

In this type of viscometer (Figure 3-1), a cylinder called the bob is placed inside another cylinder called the cup. The fluid is contained in the space between these two cylinders. By rotating one of the cylinders at a known angular velocity (TTT) and measuring the torque (τ\tauτ) acting on the other cylinder, the shear rate and shear stress can be determined.

Thus, by knowing the relationship between shear rate and angular velocity—while noting that the velocity varies across different points in the fluid layer—the velocity at the wall of the cylinder can be related directly to the tangential velocity (vvv) near the inner cylinder wall.

From this relationship, the connection between shear rate (γ\gammaγ) and velocity is obtained, and for viscometers operating at different speeds, the relationship between torque and shear rate is given as:

$$\eta = \frac{\tau}{\gamma}$$

Rotational viscometers with cylinders are classified based on the gap between the two cylinders into two general categories:

1. **Narrow-gap viscometers** — In these, the gap is small relative to the cylinder's radius and height, so curvature effects are negligible. The relationship between torque and angular velocity is straightforward.
2. **Wide-gap viscometers** — In many materials, especially those containing solid particles or mixtures, because the distance between the surfaces is relatively large, curvature effects cannot be ignored, and the calculations require correction factors to account for the geometry between the two cylinders. These devices are designed accordingly.

This indicates that to determine the relationships for this type of viscometer, it must be assumed that the velocity remains constant at various points within the gap between the rotating and stationary cylinders, and that the tangential velocity of the rotating cylinder's surface varies linearly with radius.

Since it is difficult to achieve the above conditions in practice, viscometers using this method are more suitable for low-viscosity fluids.

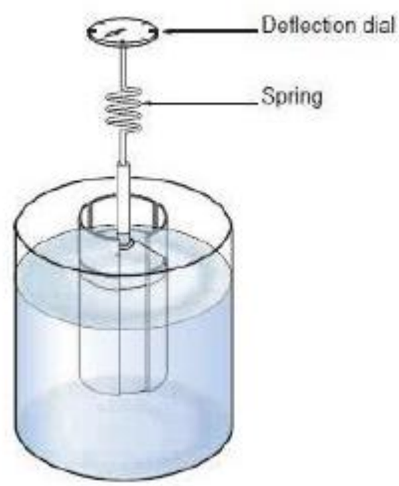

Figure ٣: Rotational viscometer with a movable spindle [7]

Experimental Procedure

First, to conduct experiments on the nanofluid, the nanofluid must be stabilized and homogenized. For accurate testing, the nanofluid must maintain stability and uniformity; therefore, the prepared nanofluid should be stable for an extended period with no visible sedimentation or agglomeration.

As a result, stabilizing and homogenizing the prepared nanofluid samples is among the most important steps in the experimental process. In this test, the stabilization of the nanofluid was carried out in several steps to prevent sedimentation.

Initially, MWCNT–Fe_3O_4 nanoparticles were weighed according to Table 3-5 to achieve volume fractions of 0.5%, 1%, 1.5%, and 2.5% by adding them to SAE 40 base oil. The mixture was then stirred with a magnetic stirrer at 2000 rpm for 24 hours.

Next, the mixture was subjected to ultrasonic homogenization (90 W power, 15 minutes duration).

Afterward, to ensure the structural integrity of the nanoparticles, their morphology in the dried nanoparticle powder obtained after sonication was analyzed using field emission scanning electron microscopy (FESEM). The diameter and wall structure of the MWCNTs were verified, as shown in Figure 4

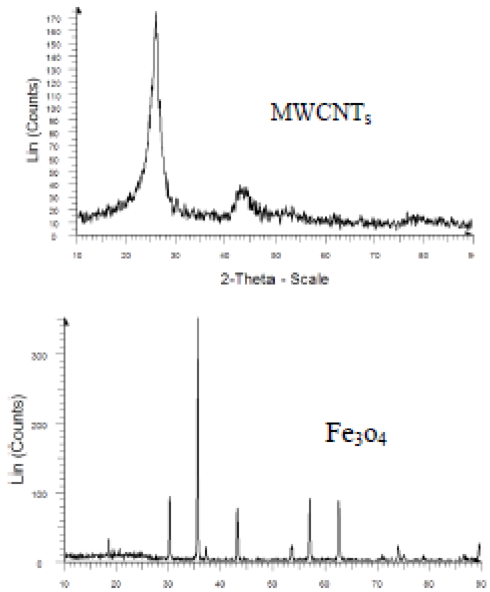

Fig 4. XRD

Fig 5. nanofluid mixture

Additionally, XRD analysis was performed on the nanoparticles, and the results are presented in Figure 4. Similarly, Figure 4 shows the XRD results for the MWCNTs, and Figure 3-5 shows the spectra for Fe_3O_4 nanoparticles. The XRD analysis confirmed the purity and elemental composition of the MWCNT and Fe_3O_4 nanoparticles. These analyses also showed that the primary factor affecting the internal tube arrangement is the base fluid, and the results for the nanofluid mixture are displayed in Figure 5.

Result and Discussion

Viscosity is a measure of a fluid's resistance to flow. In fact, it is the value obtained by dividing the shear stress by the shear rate. If the relationship between shear stress and shear rate is linear, then the fluid is considered Newtonian, meaning that the viscosity remains constant at different shear rates. In that case, the fluid is Newtonian. Considering Figures 6 and 7, this point can be observed.

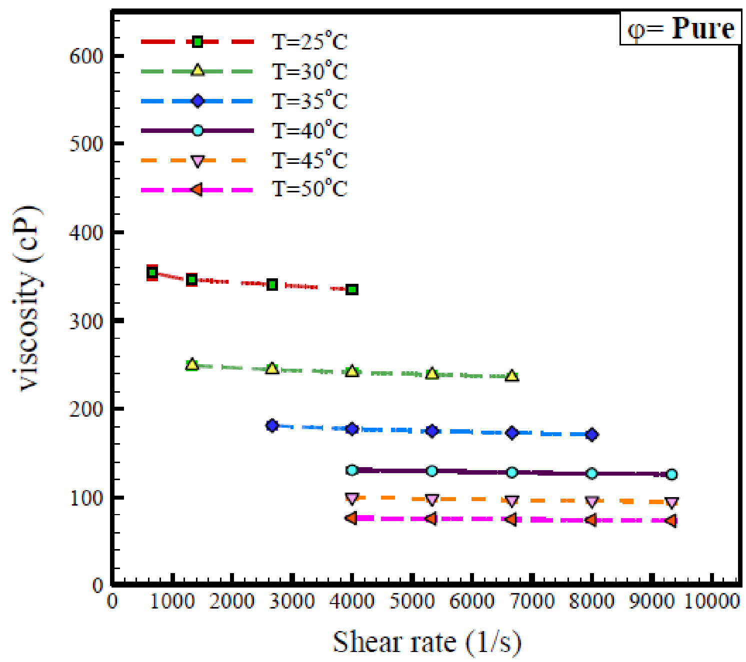

Fig.6 Relationship Between Shear Rate and Base Fluid Viscosity at Different Temperatures

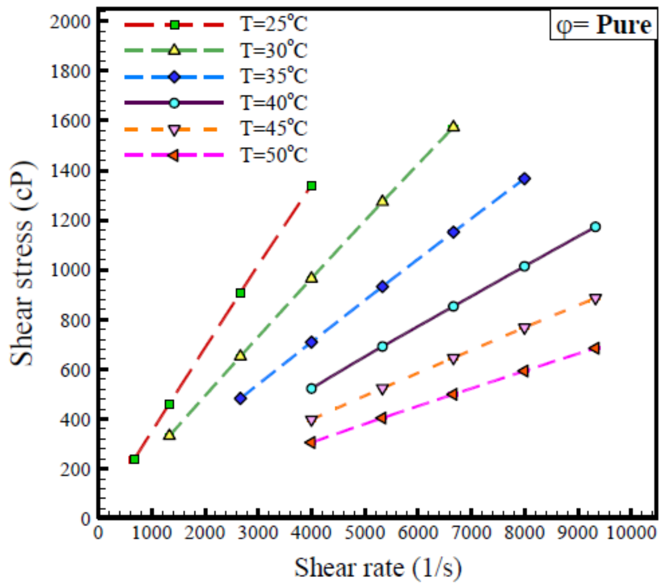

Fig.7 Relationship Between Shear Rate and Base Fluid Viscosity at Different Temperatures

As can be seen in Figures 6 and 7 and Table (3), with increasing shear rate, the viscosity remains constant, and/or the increase in shear stress is proportional to the increase in shear rate (shear stress is proportional to shear rate), which indicates that the base fluid exhibits Newtonian behavior.

Temp (°C)	Shear Rate		Viscosity		Shear Stress (dyne/cm²)
	(RPM)	(1/s)	CP	Poise	
25	50	66.5	442.4	4.424	291.91
	100	1333	442.2	4.422	587.55
	200	2666	442.4	4.424	1181.14
	300	3999	442.4	4.424	1690.97

Table (3) — Amount of Nanofluid Viscosity with a Volume Fraction of 0.5% at Different Rotational Speeds and Corresponding Shear Stresses

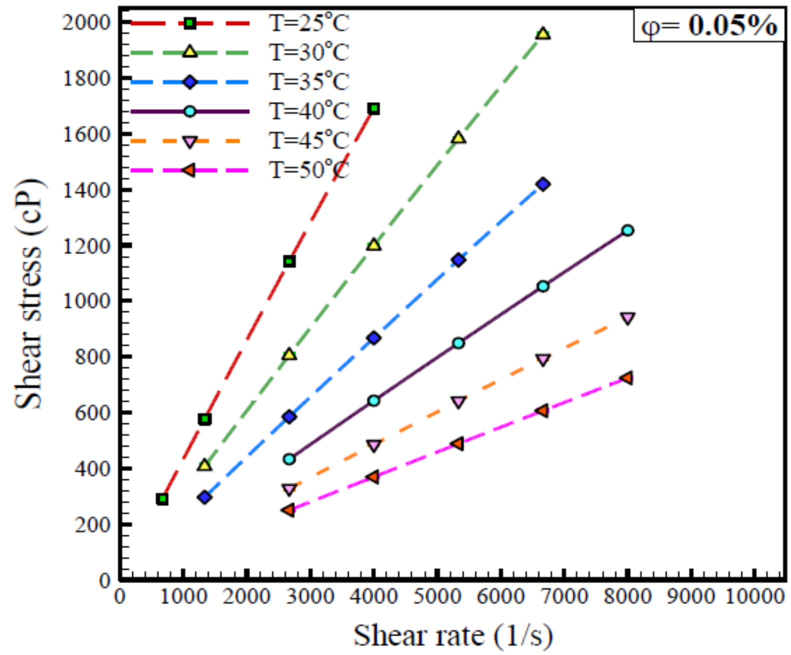

Figure (8) — Relationship Between Nanofluid Shear Rate and Shear Stress at Different Temperatures and a Volume Fraction of 0.5%

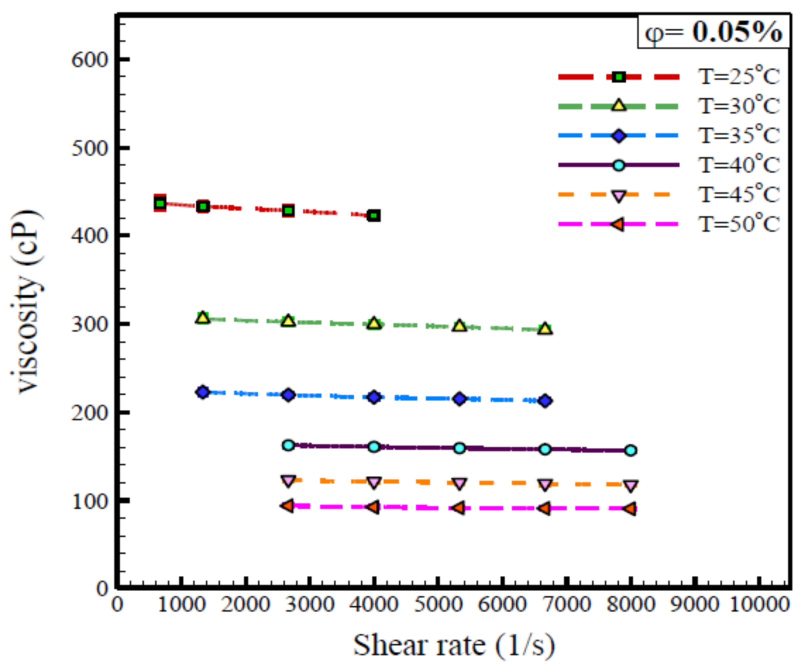

Figure (9) — Relationship Between Shear Rate and Apparent Viscosity of Nanofluid at Different Temperatures and a Volume Fraction of 0.5%

As shown in Figures 8 and 9 and Table (4), with an increase in shear rate, viscosity remains constant and/or the shear stress increases proportionally with the shear rate. This proportional relationship (shear stress vs. shear rate) indicates that the nanofluid with a 0.5% volume fraction exhibits Newtonian behavior.

In the next step, by adding 0.1% nanoparticles, the behavior of the resulting nanofluid at different temperatures and rotational speeds is examined. The results obtained from the measurements at 25°C are presented in Table (5). Similarly, Figures (10) and (11) show the shear stress and viscosity values of the nanofluid at various temperatures.

Temp (°C)	Shear Rate		Viscosity		Shear Stress
	(RPM)	(1/s)	CP	Poise	(dyne/cm²)
25	50	66.5	442.4	4.424	291.91
	100	1333	442.2	4.422	587.55
	200	2666	442.4	4.424	1181.14
	300	3999	442.4	4.424	1690.97

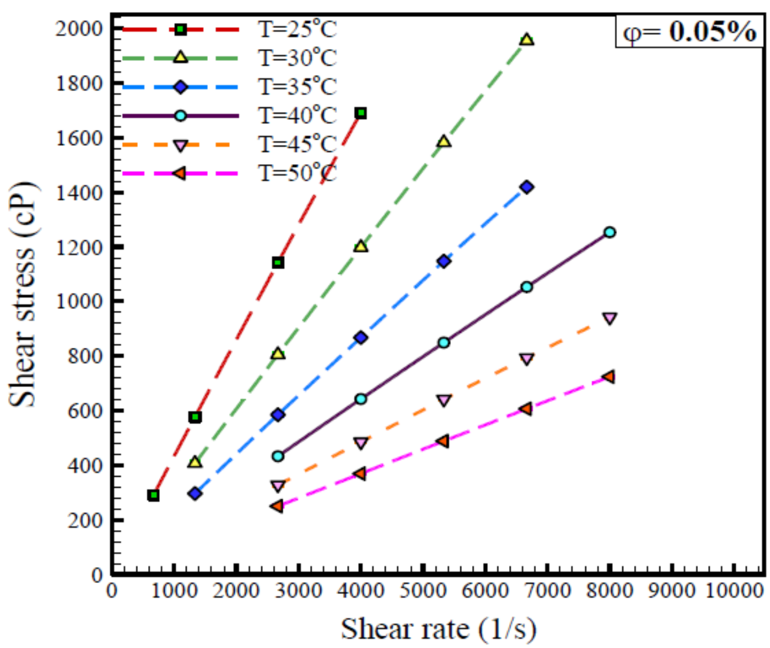

Figure (10) — Relationship Between Shear Rate and Shear Stress of Nanofluid at Different Temperatures and a Volume Fraction of 0.5%

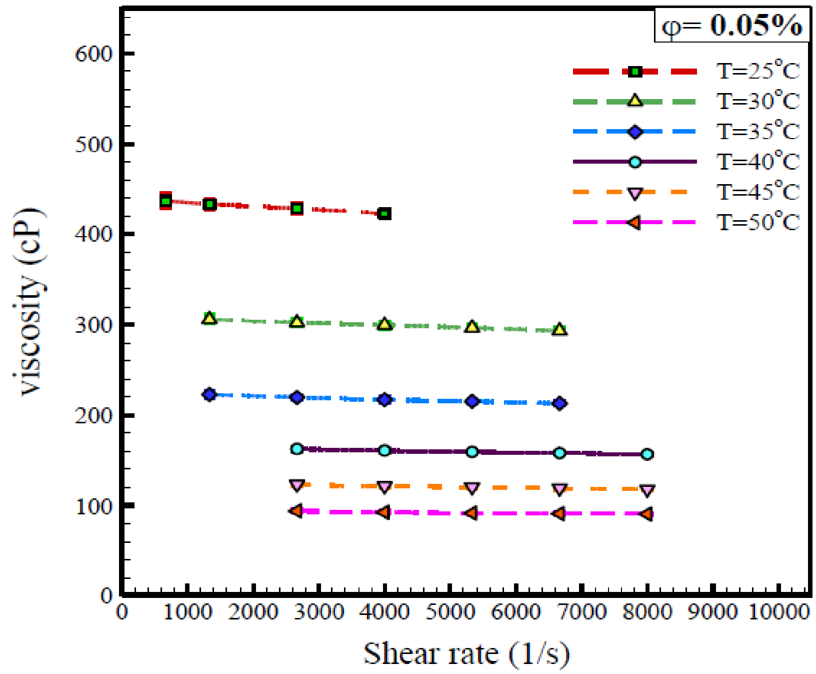

Figure (11).Relationship Between Shear Rate and Apparent Viscosity of Nanofluid at Different Temperatures and a Volume Fraction of 0.5%

Effect of Nanoparticle Volume Fraction on Nanofluid Viscosity

In Figure (12), it can be observed that with an increase in the nanoparticle volume fraction at a certain temperature, the viscosity of the **Nanofluid** increases. Considering Figure (12) at 25 °C, the base fluid viscosity is 344.15, and the increase is due to adding nanoparticles and nanotubes until reaching At a volume fraction of 0.5%, the viscosity of the nanosil increases to 430.2 cP at 25 °C, and at volume fractions of 0.8% and 1.6%, the viscosity of the nanosil increases to 527.5 cP, 520.5 cP, and 582.0 cP, respectively.

Similarly, at 50 °C and at similar volume fractions, the viscosity of the nanosil can be evaluated. It can be observed that at 50 °C and volume fractions of 0.8% and 1.6%, the viscosity of the nanosil increases to 181.8 cP and 183.2 cP, respectively, while the viscosity of the base fluid at the same temperature is 179.4 cP.

Finally, based on the obtained data, it can be concluded that with increasing volume fraction, the viscosity of the nano fluid increases.

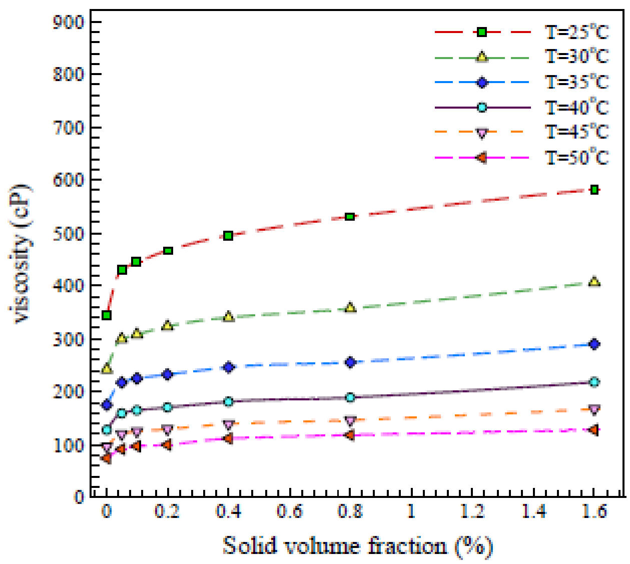

Figure (12) — Variations of Viscosity with Volume Fraction at Different Temperatures

Result:

Viscosity is one of the most important parameters in nanofluids. This is because adding nanoparticles to a base fluid increases the viscosity, which in turn reduces flow rate in a system and increases pressure drop. Indeed, if the inlet and outlet dimensions of a fluid transfer system are fixed, the higher viscosity will lead to increased energy demand by the pump or compressor. Therefore, when a nanofluid is intended for use in rotating and moving systems, its viscosity must be as low as possible.

In reality, nanofluids with high practical potential are those capable of increasing heat transfer while also reducing friction at the contact surfaces.

The goals of the present research are:

1. To synthesize a nanofluid with a base oil that has greater thermal stability and lower viscosity.
2. To measure the viscosity of the nanofluid for evaluating its thermal applications.
3. To investigate the effect of nanoparticle addition on the torque of an engine.

In this study, the base fluid used was SAE40 motor oil. The nanoparticles comprised spherical iron oxide and multi-walled carbon nanotubes.

To examine the viscosity of the SAE40 oil, the oil was first poured into small glass containers with screw caps. The SAE40 oil viscosity was then measured at temperatures of 25, 30, 40, 50, 60, 70, and 80°C using a Brookfield rotational viscometer with coaxial cylinders (Model DV-III Ultra, USA).

It can be said that increasing the temperature, or precisely controlling the heating of the nanofluid, does not reduce viscosity on its own; rather, as the temperature rises, the kinetic energy of the molecules increases, the bonds between molecules weaken, and the fluidity of the nanofluid increases, showing less resistance to flow. Another factor affecting viscosity is the change in volume fraction. Increasing the volume fraction raises viscosity at all temperatures. As the volume fraction increases under constant shear rate, viscosity also increases, indicating that viscosity has a direct dependency on nanoparticle type.

It should be noted that the chosen temperature range is due to the fact that, within this interval, the amount of viscosity directly depends on the volume fraction, and the results obtained are more accurate for assessing the relationship between viscosity and volume fraction

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