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Friction Reduction by using of Multi-Walled Carbon Nanotubes in Water Based Mud

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Abstract

The growing demands of drilling fluids for long extended-reach wells require innovative solutions to tackle torque and drag issues in the wellbore. Nanotechnology is a promising advancement that is already being applied in other sectors to reduce friction coefficients in hydraulic hose lubrication fluids. Beyond their other roles, drilling fluids also act as lubricants within the wellbore. It is widely recognized that oil-based muds (OBM) provide superior lubrication efficiency compared to water-based muds (WBM). Consequently, there is increasing research interest in the effective application of nanoparticles in drilling fluids, especially in WBM, to lessen the mechanical friction between the drill string and casing. This study conducted tribological tests to explore whether friction reduction occurs with MWCNT at concentrations of 0.125, 0.250, 0.500, 0.750, and 1.250 g. Various particle concentrations in the fluid were examined to see if lubrication efficiency could be optimized for a specific particle concentration. The study's experimental phase employed a pin-on-disk apparatus alongside a modular compact rheometer (MCR), facilitating tribology and viscosity assessments. The tribology tests assess the friction factor between metals, which is affected by the fluid's lubrication properties. Meanwhile, the rheology equipment determines the fluid's viscosity across a range of temperatures, following the established guidelines of the Fann viscometer. Despite having an international procedural manual, the results from the pin-on-disk apparatus are considered dependable. A key observation highlights the interplay between temperature and nanoparticles within the fluids. Results from the pin-on-disk apparatus demonstrate that nanoparticles significantly lower the friction factor.

Keywords: *Multi-Walled carbon nanotubes; Water based drilling mud; Rheological properties.*

1. Introduction

Nanotechnology is currently being adopted in the oil and gas industry to improve existing processes [1]. However, the use of nanoparticles for reservoir stimulation is limited to rare cases due to the high cost of this technology. Another promising oil and gas field application may lie in the drilling process. Adding nanoparticles to drilling fluids could decrease the mechanical friction between the drill string and the casing. The demand for "smart drilling fluids" is on the rise, offering various advantages from colloidally suspended fluids [2]. One significant benefit is the potential to lower the overall quantity of larger particle components. The extensive surface area of smaller particles allows for a reduced concentration stemming from the high surface volume of nanoparticles. The same functions conventional drilling fluids provide can be achieved with fewer particles. A lower total particle concentration also lessens the holding effect of the drilling fluid [3].

Nanoparticles in drilling fluids have the potential to act as lubrication additives. This project aims to conduct experiments that assess the friction reduction process [4]. Oil-based mud (OBM) is the preferred drilling fluid for minimizing friction due to its superior lubrication properties compared to water-based mud (WBM) [5]. This benefit stems from oil's nonpolar characteristics, which facilitate particle movements without attractive or repulsive forces between them. In contrast, WBM is an ionic fluid, inherently charged, which limits its lubrication efficiency, making water a less optimal lubricant despite its lower environmental impact. Thus, it becomes crucial to explore and improve the lubrication capabilities of WBM using nanoparticles. The study will also explore how temperature influences the properties of fluids containing nanoparticles, especially under elevated temperatures [6]

The MCR apparatus serves as a testing device for tribology and rheology evaluations. A different measurement cell can be attached to the apparatus for each specific application. Furthermore, the internationally standardized pin-on-disk apparatus offers only a limited selection of tests [7]. This study outlines the experimental setup for both tribology measurement tools. The MCR apparatus will be employed before the pin-on-disk apparatus to assess possible temperature effects on nanoparticle behavior within the fluid and establish optimal particle concentrations [8]. Following these findings, a series of pin-on-disk tests will be executed. This approach will help determine whether the MCR apparatus is suitable for measurements, corroborated by the findings from the pin-on-disk tests.

Tribology is the study of frictional behavior between different elements [9]. Friction arises when surfaces come into close contact, leading to interactions between their particles, which generate a drag force. The level of friction can vary based on the material's abrasiveness, asperity, and shape [10]. Every interaction of materials creates friction, and the hardness of different materials affects their surface structures, linking tribology directly to wear. Factors such as material selection, friction levels, and the nature of material movement influence the interactions of material surfaces [11]. As friction increases, so does material wear in direct correlation. Wear is characterized as the loss of material resulting from any form of induced friction. The friction encountered between two surfaces is referred to as external or mechanical friction, while internal friction occurs among the material's own particles. This report focuses on the mechanical friction behavior of two materials [12].

The fluid's composition dictates its tribological characteristics, greatly affecting its performance as a lubricant. The key influencing factors are outlined below. The tribological characteristics rely on the following:– the size of the particles; – the shape of the particles;– the concentration of the particles; – the particle solidness; – the forces acting on the materials; – the material properties like abrasiveness (asperity); – the time frame of the material contacts and – the base fluid e.g. water or oil.

Minimizing friction is crucial in drilling long-deviated wells [13]. Water-based fluids (WBFs) typically exhibit a coefficient of friction (COF) exceeding 0.1, whereas oil-based fluids (OBFs) usually have a COF below 0.1. The ideal drilling fluid should aim for the lowest COF to reduce wear on the drilling string. This minimized wear can also apply to the existing casing, which is significant because casing degradation can alter tri-axial burst and bi-axial collapse limits. Damage to the casing creates serious risks since it can hinder the capacity to handle high circulating pressures, particularly during a kick. Research by [14] found that drilling fluids enhanced with 0.5 wt% nanoparticles (NPs) can remarkably decrease the lubricating coefficient by as much as 93.4%. Furthermore, [15] reported that the friction factor of the mud cake diminishes as the concentration of silica NPs rises. A study by [16] on NPs in drilling fluids suggests that incorporating NPs may effectively address loss circulation and differential sticking problems by reducing friction. Additionally, [17] examined NPs and determined that the fluid is optimal for drilling extended lateral sections due to its lowered friction. Finally, [18] discovered that NPs used in surfactant-based fluids improve horizontal and directional drilling by forming a thin, impermeable filter cake, while simultaneously reducing friction and keeping solid content low.

In field trials, using boron nanoparticles (NPs) can extend the life of drill bits by 75% compared to graphene NPs [19]. This improvement can be attributed to the high surface-to-volume ratio of the nano-sized particles, their superior lubricating properties over bulk materials, and the interaction of these particles with the hydrophobic and hydrophilic characteristics of the drilling tools, all of which significantly reduce friction at the drill bit [20].

Other types of nanoparticles (NPs) evaluated for improving lubricity and minimizing torque and drag include Pal, graphene, and boron. Research indicated a 34% decrease in torque with one drilling fluid sample containing 7.4 wt% NPs. Another study utilized a sample with 5 wt% graphene NPs, realizing an 80% reduction in torque at 200°F and as much as a 50% cut in torque at 350°F. In a field trial, drilling mud with graphene NPs at 3 wt% concentration tripled the rate of penetration (ROP) and remained stable at high temperatures, reaching up to 349°F. During this trial, the coefficient of friction (COF) fell from 0.21 to 0.08, comparable to synthetic-based muds, with a 44% reduction in torque and a stable equivalent circulating density (ECD).

2. Material and method

2.1. Drilling fluid additives

The materials for tests primarily supplied by M-I Swaco. The apparent density of bentonite when quarried and piled under natural moisture conditions falls between 1.5 and 1.8 g/cm³. For milled bentonite products, the apparent density fluctuates depending on the fineness of the milling process, ranging from 0.7 to 0.9 g/cm³. The trade name is POLYPAC UL, and it belongs to the chemical class of Polyanionic cellulose polymers, which are recognized for their outstanding thickening properties and capacity to form stable viscoelastic gels. POLYPAC UL is primarily used as an additive in oil well drilling fluids, where it plays a critical role in ensuring wellbore stability. PAC is a trade name for a product known as M-I PAC*, which is utilized primarily for fluid loss control in various drilling applications. Carbopol, a specialized chemical compound, is marketed under the product name SAFE-CARB. It serves multiple functions in various applications, primarily as a weighting agent in drilling fluids. SAFE-CARB is particularly effective as a lost circulation material, helping to prevent the loss of drilling fluids into porous formations. Additionally, it acts as a bridging material, facilitating the sealing of fractures and enhancing the stability of the borehole.

2.2. Synthesis of MWCNTs

The multi-walled carbon nanotubes (MWCNT), which were synthesized at the Nanotechnology Center within the Egyptian Petroleum Research Institute. One notable characteristic of MWCNTs is their hydrophobic nature, which presents challenges when attempting to disperse them in aqueous environments. To overcome this limitation and improve their compatibility with water, we implemented a chemical modification strategy involving the introduction of functional groups onto the surface of the nanotubes. This was achieved through a process of acid treatment, specifically utilizing nitric acid in a concentration of 69%.

The treatment procedure was as follows: we began by taking one gram of MWCNTs and subjecting it to boiling and refluxing with 40 mL of nitric acid for a duration of four hours. This step was crucial as it allowed the nitric acid to effectively react with the surface of the MWCNTs, leading to the introduction of carboxyl groups (–COOH) that enhance their hydrophilicity. After the refluxing period, the reaction mixture was carefully diluted with deionized water to neutralize excess acid. The resulting suspension was then subjected to a filtration process to separate the modified MWCNTs from the aqueous phase. To ensure that all traces of acidity were removed, the filtered MWCNTs were rinsed multiple times with deionized water until the washings no longer showed any acidic properties, which was confirmed through pH testing.

Following the washing steps, the cleaned MWCNTs were collected and placed in an oven to dry for a full twelve-hour period. This drying process was essential to eliminate any residual moisture that may have been present after rinsing. The final product of this modification process is a multi-walled carbon nanotube that is now functionalized with carboxyl groups, henceforth referred to as MWCNT-COOH.

MWCNTs were produced at 720°C with $CaCO_3$ serving as the catalyst. The pH of the suspension was maintained at 7.0. The mixture was then heated and dried overnight at 120°C to create MWCNTs.

2.3. Water-based drilling mud (WBDM)

WBDM is the most widely used drilling mud in the petroleum industry. Water serves as the continuous phase, establishing the initial rheological properties of the drilling mud. In this study, a WBDF system was initially prepared using fresh water and Na-bentonite (6 w/v %) with a particle size of less than 75 µm, in accordance with API 13A guidelines. The pH of the fluid was adjusted with sodium hydroxide (NaOH) to maintain it within the range of 9.5 to 10. After the mud was prepared, it was mixed for a total of 30 minutes, serving as an arbitration specimen. Subsequently, the same drilling mud was prepared, and various amounts of MWCNTs (0.125, 0.250, 0.500, 0.750, and 1.25 g) were added. The mixture was continuously stirred for 3 minutes and then aged for 16 hours at an average temperature of 25°C. The formulations of traditional WBDM and WBDM enhanced with MWCNTs are presented in Table 1.

Table 1. Formulations of conventional and MWCNTs added WBDM.

Materials	Base	Base + 0.125 g MWCNT	Base + 0.250 g MWCNT	Base + 0.500 g MWCNT	Base + 0.750 g MWCNT	Base + 1.250 g MWCNT
Water [g]	350	350	350	350	350	350
Polypac [g]	1	1	1	1	1	1
Pac [g]	0.5	0.5	0.5	0.5	0.5	0.5
Soda ash [g]	4	4	4	4	4	4
Bentonite [g]	10	10	10	10	10	10
Barite [g]	150	150	150	150	150	150
Carbopol [g]	0.08	0.08	0.08	0.08	0.08	0.08
MWCNT-COOH [g]	0	0.125	0.25	0.5	0.75	1.25

The primary tribological measurement tools are provided by the Tribology Lab at the Egyptian Petroleum Research Institute. For this project, the available equipment includes a pin-on-disk device designed for experiments following ASTM International Standard G99 and DIN 50324. The MCR 302, illustrated in Figure 1 and produced by Anton Paar, offers various modification options that facilitate the analysis of the rheological and tribological characteristics of nanoparticles in drilling fluids. One option allows for traditional viscosity measurements. Additionally, a modification set known as the Tribology System (T-PTD 200) supports tribological testing using the ball-on-three-plates setup principle.

Figure 1. Modular compact rheometer (MCR).

The MCR - Tribometer Measurement Cell allows for assessing the friction and lubrication properties of fluids through tribology tests. Important adjustable factors include normal force, rotational speed, temperature, and the distance from the apex of the steel ball to the base of the testing setup. The sliding speed is directly proportional to the system's rotational speed. The software accommodates various standard measurement tasks, including the Stribeck curve and a static friction test, where torque increases uniformly. Typically, experiments are conducted at room temperature and normal atmospheric pressure. Additionally, the MCR automatically identifies the installed measurement cell application in the apparatus.

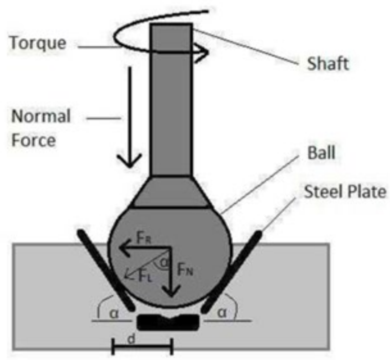

Figure 2. Friction measurement schematic of the MCR 302.

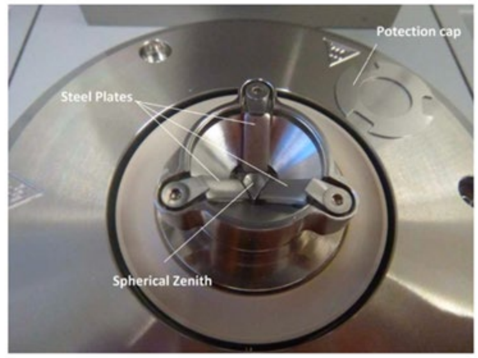

Figure 3. Three steel plates in the friction apparatus of the MCR.

The tribology measurement principle utilizes the ball-on-three-plates concept, as shown in Figure 2. This schematic illustrates a ball attached to a shaft, applying a specific downward normal force onto the steel plates. The contact points between the ball and plates rely on the deflection angle α of the steel plates, which also determines the distance d between the apex of the ball and the contact point. When the steel ball and shaft are lowered, the experiment commences, and the shaft spins about its axis. Additionally, the gap between the steel ball and the base of the sample holder is adjustable, typically between 0 mm and 5 mm, though it can be set wider. For each test, new steel plates and a fresh steel ball are installed in the apparatus.

Figure 3 shows the three sample plates securely attached to the sample holder. The sample holder, in turn, is affixed to the MCR apparatus to avoid any unintended movements that might disrupt and compromise the measurements. Furthermore, the sample ball is pressed into a shaft to prevent the ball from rotating.

For every friction test, it’s crucial that the testing material is clean and has not interacted with anything besides the testing fluid. One precaution is wearing gloves to prevent equipment contamination. The tribology test using the MCR instrument computes the friction coefficient through specific formulas. By knowing the defined normal force FN of the rotating steel ball and measuring the deflection angle α, the sample-specific normal load FL can be calculated (equation 1). In conjunction with the calculated friction force FR, which relies on the momentum M, the radius r of the steel ball, and the deflection angle α (equation 2), the necessary friction factor μ can be derived (equation 3). The MCR device can exert a maximum normal load of 50 N, corresponding to a friction force of 70 N [10]. For every friction test, it’s essential that the testing material is free from contamination and only interacts with the testing fluid. Wearing gloves is a key measure to safeguard the equipment from contamination.

The tribology test performed with the MCR instrument measures the friction coefficient using specific equations. By determining the normal force FN from the rotating steel ball and recording the deflection angle α, we can calculate the normal load FL relevant to the sample (equation 1). Alongside the calculated friction force FR—which depends on the momentum M, the radius r of the steel ball, and the deflection angle α (equation 2)—we can derive the necessary friction factor μ (equation 3). The MCR device can apply a maximum normal load of 50 N, corresponding to a friction force of 70 N.

Normal load

The force acting perpendicular to the ball and the three sample plates is called the normal force. This normal force can differ in various experiments; it can either be predetermined as a constant value or adjusted gradually throughout the experiment series.

$$F_L = \frac{F_N}{\cos\alpha} \quad (1)$$

Friction force

The variation in momentum determines friction force. In each experiment, the radius r and deflection angle α are kept constant, as the steel ball's size is uniform across all tests. The height from the steel ball's peak to the basin's bottom remains unchanged. The material sample holder must also be consistent in shape and thickness for every steel plate.

$$F_R = \frac{M}{r.\sin\alpha} \quad (2)$$

Friction factor

The friction factor is equal to the friction force divided by the friction load and is, therefore, a dimensionless number used in fluid mechanics. It expresses the quality and efficiency of a lubricant. The lower the friction factor, the better the lubrication, and vice versa for high friction factors.

$$\mu = \frac{F_R}{F_L} \quad (3)$$

Sliding speed and sliding distance

To understand a Stribeck curve, you need to know the specific sliding speed vs or sliding distance ss. The graph illustrates how friction behavior evolves over time and with distance. Equations 4 and 5 explain how the deflection angle φ, the radius r of the steel ball, and its rotation n affect these two parameters. The sliding speed relies on the steel ball's rotation and, therefore, on the momentum. When the momentum fluctuates slightly, the sliding speed changes accordingly.

$$v_s = \frac{2\pi}{60}.n.r.sin\alpha \quad (4)$$

The sliding distance expresses the contact duration of two materials. This length usually results in a sample-specific mass loss, which can be analyzed by the wear groove formed.

$$s_s = \varphi.r.sin\alpha \quad (5)$$

The measurement cell includes a built-in heating chamber, enabling the sample temperature to range from -40°C to 200°C. This capability ensures an experimental environment that remains unaffected by the room temperature. The heating and cooling system necessitates a cooling mechanism to avert overheating of the apparatus overheating.

3. Results and discussion

3.1. Effect of MWCNT-COOH on frictional properties

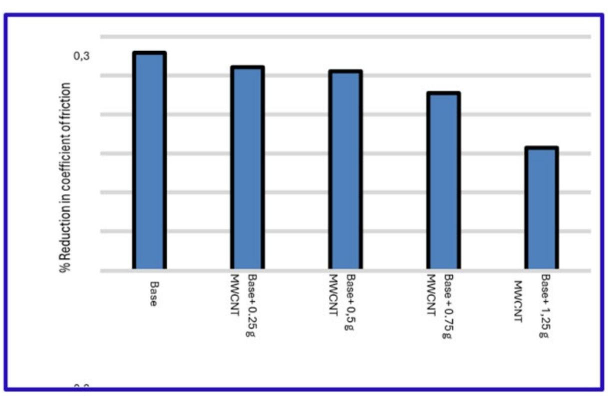

Figure 4. Coefficient of friction for the different drilling fluids.

This section presents the results from the frictional test conducted using the CSM tribometer. The data gathered offers insights into the lubricating properties of various drilling fluids. To confirm the reliability of the tribometer data, multiple measurements were performed. Figure 4 displays the average values for the different drilling fluids, revealing that the Base + 1.25 g MWCNT formulation exhibited the lowest friction coefficient. Additionally, tribometer readings showed a decline across all fluids treated with MWCNT.

Observations indicate that incorporating all nanoparticle suspensions improves system lubricity by lowering the coefficient of friction. This reduction is non-linear, typically showing that smaller amounts provide the most notable enhancement. Specifically, when assessing the impact of multi-walled carbon nanotubes on lubricity, 0.75 g and 1.25 g levels produce the most considerable benefits. Findings reveal that further increasing the nanoparticle suspension quantity beyond these levels leads to elevated coefficients of friction.

Figure 5 presents the coefficient of friction changes in percentage. The reduction in friction is close to a linear trend line when the concentration of nanoparticles increases. The coefficient of friction decreased by 6.7% for Base + 0.25 g MWCNT, 8.5% for Base + 0.5 g MWCNT, 18.5% for Base + 0.75 g MWCNT, and 43.6% for Base + 1.25 g MWCNT.

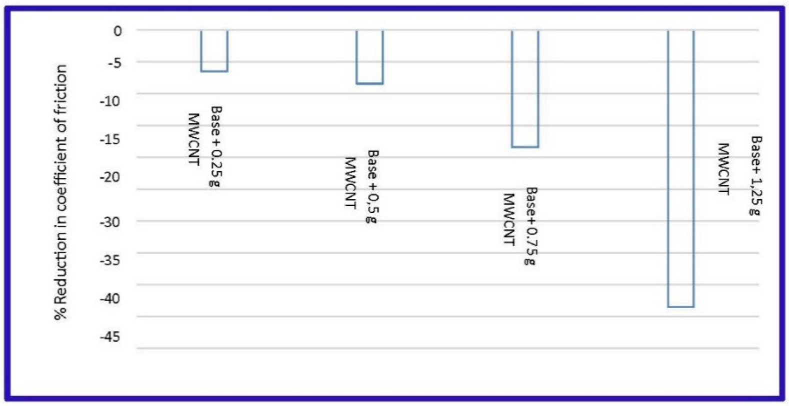

Figure 5. Percent change for coefficient of friction.

In Figure 5, we see that multi-walled carbon nanotubes have a minimal impact on the coefficient of friction, showing a maximum reduction of only 13.7%. Nevertheless, the coefficient of friction for the reference fluid itself decreased from 0.249 to 0.187 over the course of 48 days. Previous findings suggest that both the reference fluid's properties and those of the MWCNT-COOH system evolve over time. Figure 5 also illustrates the coefficient of friction for the reference fluid mixed with 0.07 g of multi-walled carbon nanotubes after 6 days, which reveals a percentage change of -36.8%. It appears that a clearer distinction between the coefficients of friction for both the MWCNT-COOH systems and the reference fluid will emerge after a brief storage period.

Figures 6 and 7 display the friction coefficients obtained from tribometer tests of multi-walled carbon nanotubes (MWCNT).

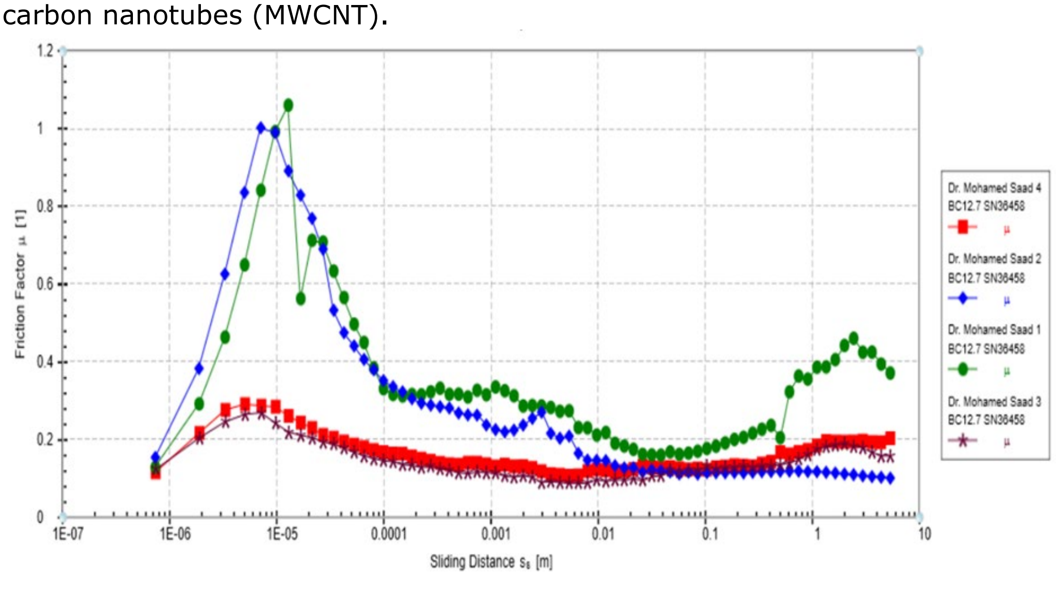

Figure 6. The friction factor versus sliding distance.

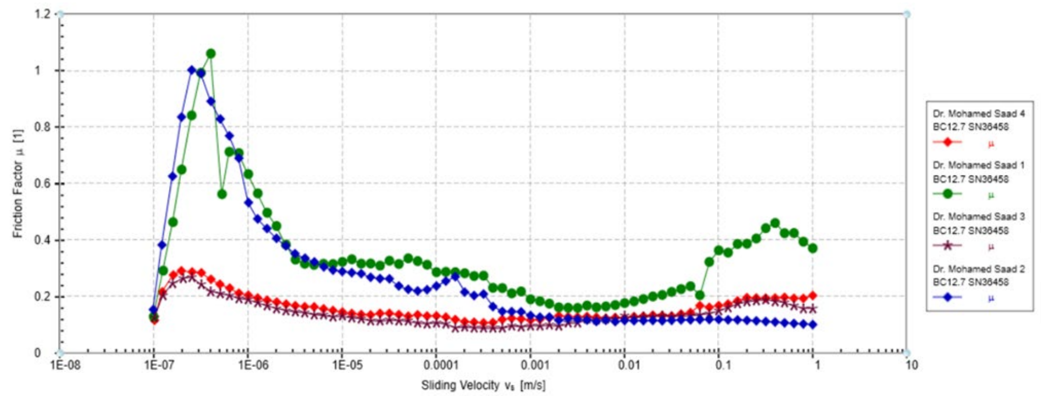

Figure 7. The friction factor versus sliding velocity.

Figures 8, 10, 12, 14, 16, and 18 present a detailed analysis of the relationship between the friction factor and sliding distance for various composite mixtures, namely the Base material and its modified versions: Base + 0.25 MWCNT, Base + 0.5 MWCNT, Base + 0.75 MWCNT, and Base + 1.25 MWCNT. As the concentration of multi-walled carbon nanotubes (MWCNT) increases in these mixtures, a distinct trend emerges—a progressive decrease in sliding distance.

This decrease signifies a marked improvement in the tribological performance of the material. The enhanced concentrations of MWCNT play a critical role in reducing friction and resistance during sliding movements, which allows for smoother transitions and improved overall efficiency. Enhanced wear resistance and lower energy consumption during operation are additional benefits associated with the increased MWCNT content.

This reduction in sliding distance indicates a substantial improvement in the tribological properties of the material. The presence of higher MWCNT concentrations effectively lowers friction and resistance during the sliding process, resulting in a smoother, more efficient movement. Enhanced wear resistance is another critical advantage observed, contributing to prolonged material lifespan and lower maintenance costs in practical applications. The incorporation of MWCNTs not only enhances performance but also potentially leads to reduced energy consumption in various operational contexts.

These trends are further illustrated in Figures 9, 11, 13, 15, and 17, which provide valuable insights into the sliding velocity at different concentrations of MWCNTs. The data clearly show that as the concentration of MWCNTs rises, not only does the sliding distance decrease, indicating less overall friction, but there is also a corresponding increase in sliding velocity. This relationship illustrates the positive effects of MWCNT reinforcement on material dynamics, confirming that higher MWCNT content leads to both lower resistance and faster movement.

Ultimately, these findings showcase how the introduction of MWCNTs significantly transforms the mechanical properties of the Base material, resulting in tangible improvements in performance metrics. The complex interplay between sliding distance, velocity, and friction factor underlines the exceptional potential of MWCNTs in advancing composite material technology. This research paves the way for innovative applications across various industries, offering new opportunities for optimizing material performance and efficiency in engineering and manufacturing processes.

Overall, these findings illuminate how the integration of MWCNTs into the Base material not only transforms its mechanical properties but also significantly enhances its performance characteristics across various applications. The multifaceted relationship between sliding distance, velocity, and friction factor emphasizes the remarkable potential of MWCNTs in advancing material technology, paving the way for novel innovations in manufacturing and engineering disciplines.

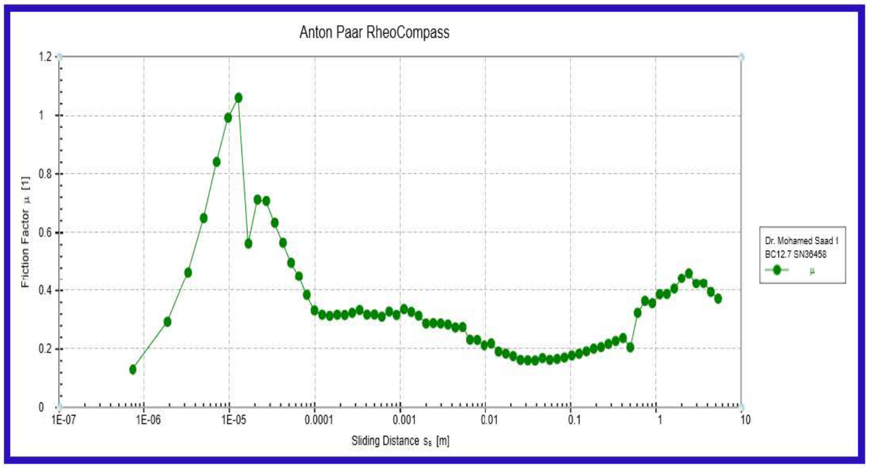

Figure 8. The friction factor versus sliding distance for base.

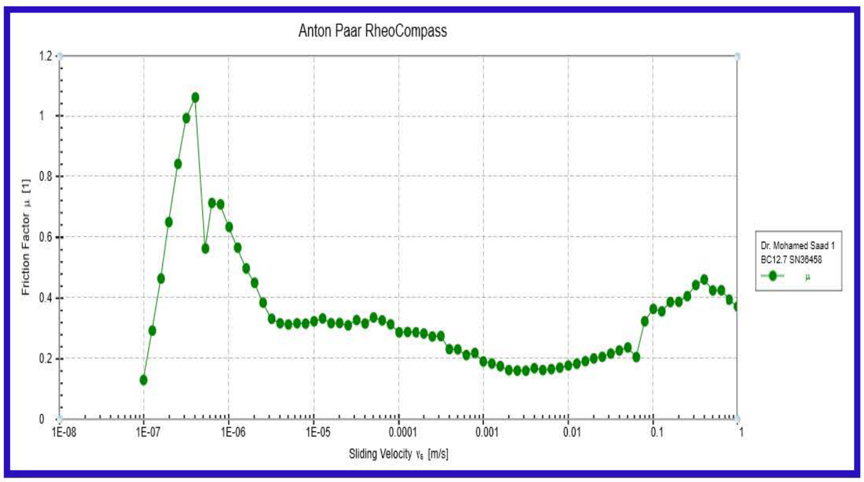

Figure 9. The friction factor versus sliding velocity for base.

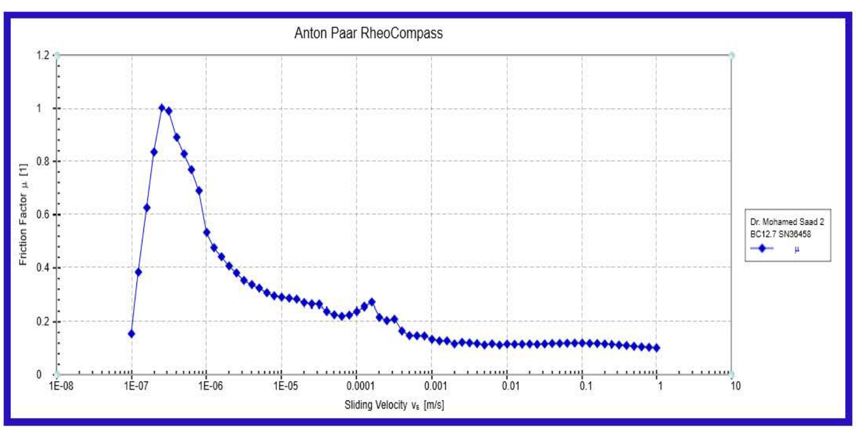

Figure 10. The friction factor versus sliding velocity for base +0.25 MWCNT.

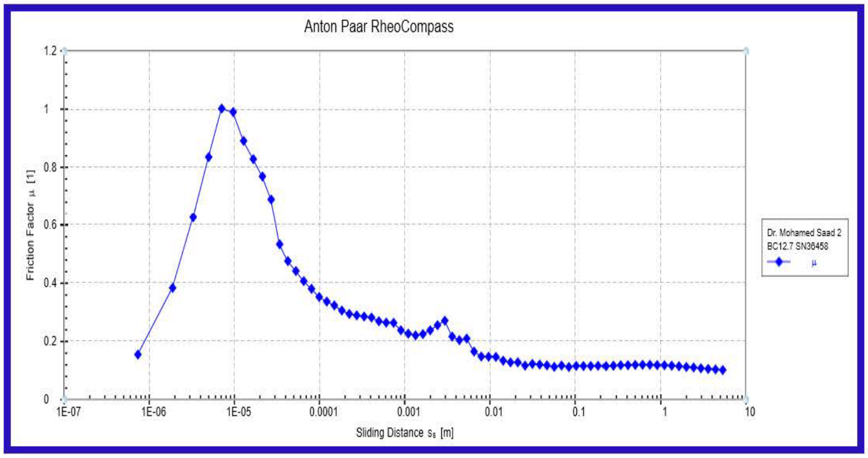

Figure 11. The friction factor versus sliding distance for base +0.25 MWCNT.

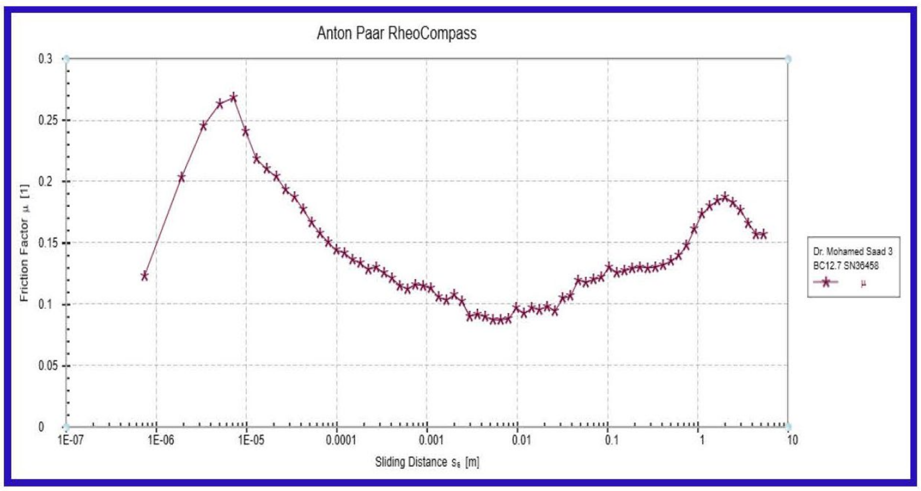

Figure 12. The friction factor versus sliding velocity for base + 0.5 MWCNT.

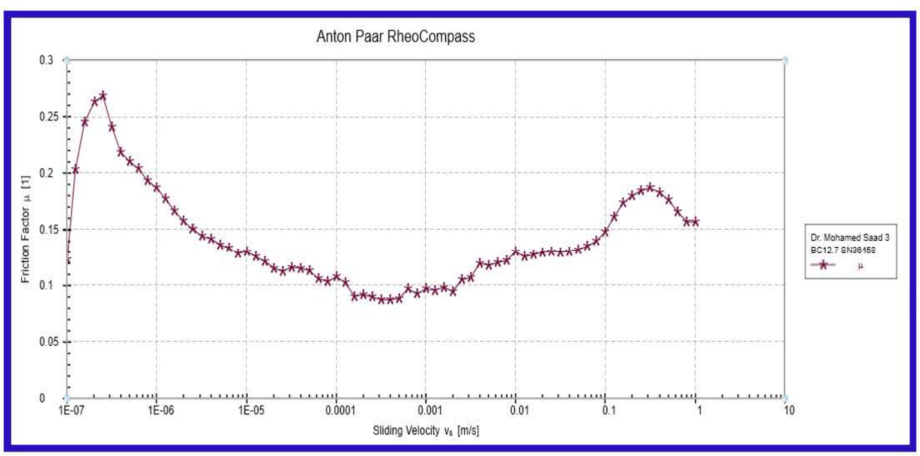

Figure 13. The friction factor versus sliding distance for base + 0.75 MWCN.

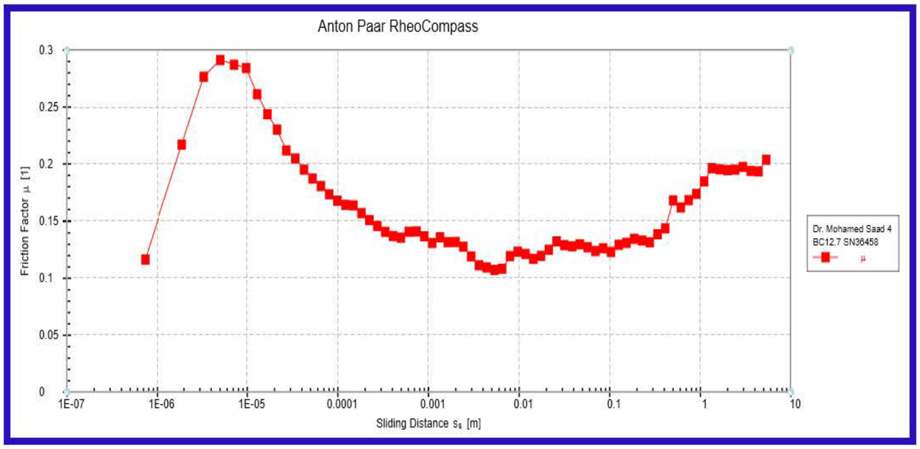

Figure 14. The friction factor versus sliding velocity for base + 0.75 MWCN.

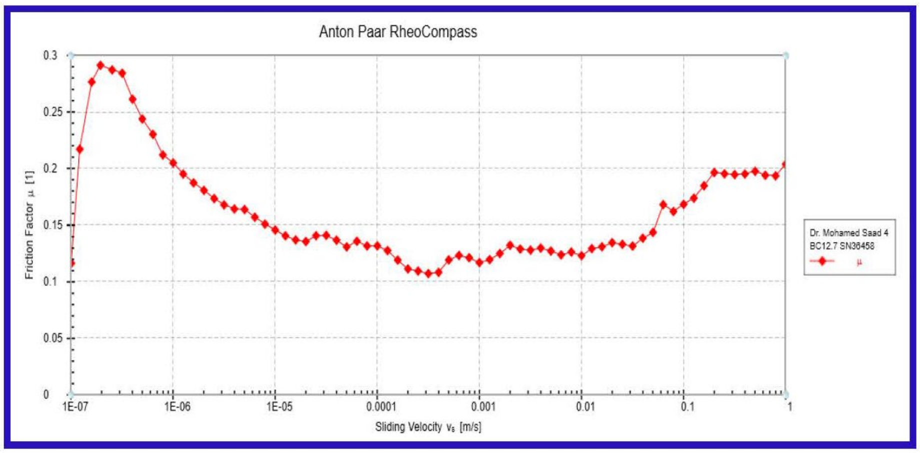

Figure 15. The friction factor versus sliding distance for base + 1.25 MWCN.

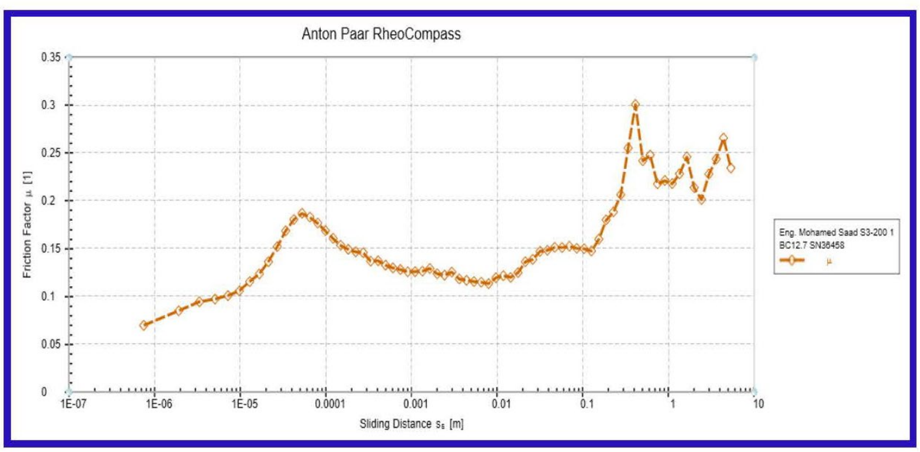

Figure 16. The friction factor versus sliding velocity for base + 1.25 MWCN.

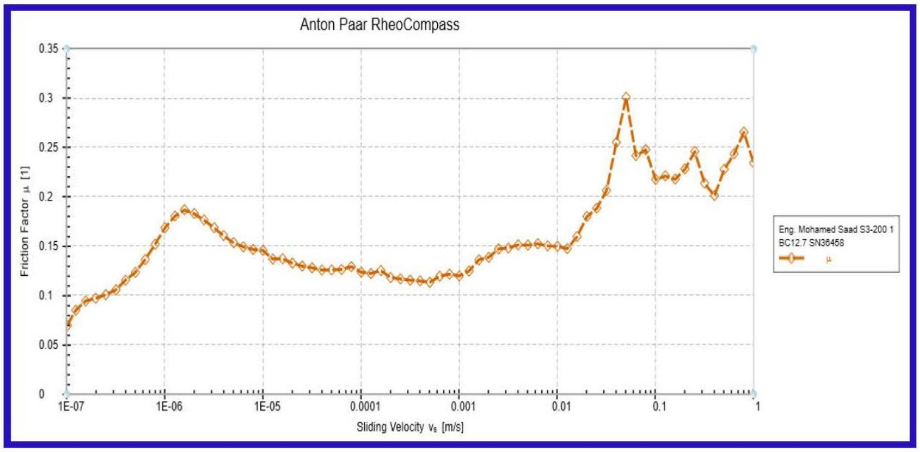

Figure 17. The friction factor versus sliding velocity for base + 1.25 MWCN.

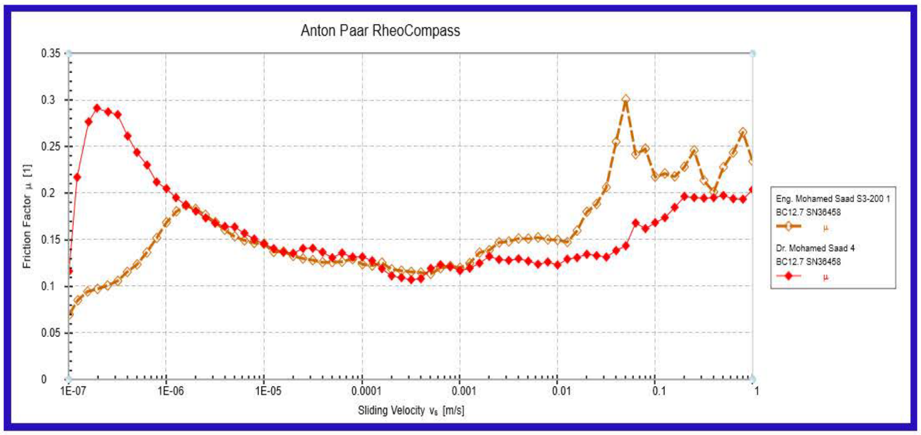

Figure 18. The friction factor versus sliding distance for base + 0.75 MWCN and base + 1.25 MWCNT.

In summary, the findings from these analyses demonstrate how the inclusion of MWCNTs significantly alters the mechanical properties of the Base material, leading to substantial enhancements in performance. This interplay between sliding distance, velocity, and friction factor highlights the potential of MWCNTs to improve the efficacy and efficiency of composite materials in real-world applications, opening new avenues for innovation and development in the field of material science.

4. Conclusion

There is a coupling effect between temperature and nanoparticles. With increasing temperature, friction reduction can be reduced to a certain amount. However, this effect depends on the nanoparticle material used and its physical characteristics at this small scale. Friction factor and wear are directly linked, with increasing friction coefficient increases material wear. The interaction between nanoparticles and polymers does not seem as significant as assumed. However, further tests are needed to make this conclusion more concrete. Nanoparticles, when used as additives in drilling fluids, enhance the lubrication process by providing efficient lubrication improvements. The efficiency of lubrication is influenced by particle concentration.

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