Exploring the Impact of Multiwall Carbon Nanotubes on Enhancing Water-Based Mud Performance

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Abstract

Drilling fluids are critical components in hydrocarbon and geothermal well construction, particularly in extreme downhole environments such as deep reservoirs and high-temperature geothermal systems. Key challenges in designing water-based drilling muds (WBDM) for these applications include effective thermal management, maintenance of rheological stability, and enhancement of thermal conductivity under high-temperature, high-pressure (HTHP) conditions. Recent advances in nanotechnology suggest that nanoscale additives, such as uniformly dispersed carbon nanotubes (CNTs), can significantly improve the thermorheological performance of drilling fluids compared to conventional formulations. However, stabilizing critical fluid properties—including viscosity, filtration efficiency, mud cake integrity, and gel strength—remains a persistent challenge in WBDM optimization. This study evaluates the efficacy of multi-walled carbon nanotubes (MWCNTs), synthesized via chemical vapor deposition (CVD), as performance-enhancing additives in WBDM. MWCNTs were integrated into a standard bentonite-based mud system at concentrations of 0.125, 0.250, 0.500, 0.750, and 1.250 g per 350 mL. The rheological properties (plastic viscosity, yield point, gel strength) and filtration characteristics (API fluid loss, mud cake thickness) of the nanofluid-enhanced muds were systematically assessed under API 13B-1 recommended practices. Comparative analysis revealed a concentration-dependent improvement in performance, with the 1.250 g MWCNT formulation exhibiting optimal results: a 38% reduction in fluid loss, a 22% increase in yield point, and enhanced thermal stability at 120°C. These findings underscore the potential of MWCNTs as high-performance additives for HTHP drilling applications, offering a pathway to improve wellbore stability and operational efficiency in challenging subsurface environments.

Introduction

Drilling fluids, or "drilling muds," serve as indispensable engineering tools in hydrocarbon and geothermal well construction. Their primary functions include transporting cuttings to the surface, cooling and lubricating the drill string, stabilizing wellbores through hydrostatic pressure control, and forming low-permeability filter cakes to minimize fluid invasion into formations (Bourgoyne et al. 1991). Among the three primary categories—water-based (WBM), oil-based (OBM), and air-based fluids—WBMs dominate global usage due to their cost-effectiveness and environmental compliance (Amanullah et al. 2011).

Conventional WBMs comprise bentonite clays, viscosifiers (e.g., xanthan gum), fluid-loss additives (e.g., starch), and alkaline regulators. However, their performance in high-pressure, high-temperature (HPHT)

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environments remain constrained by thermal degradation of polymers, inadequate lubricity, and poor shale inhibition, necessitating advanced formulations for extreme drilling applications.

Nanotechnology has emerged as a transformative paradigm for enhancing WBM performance. Nanoparticles, with their high surface area-to-volume ratios (<100 nm), enable precise control over rheological, thermal, and filtration properties through mechanisms such as pore-throat bridging, interfacial tension modulation, and polymer-nanoparticle synergistic effects (Alvi et al. 2018). Multi-walled carbon nanotubes (MWCNTs) exhibit exceptional mechanical strength (~1 TPa tensile modulus) and thermal conductivity (~3,000 W/m·K), making them ideal candidates for HPHT drilling fluid optimization (Xing et al. 2015). Studies demonstrate that MWCNT-enhanced WBMs achieve superior thermal stability, reduced friction coefficients (approaching OBM performance), and enhanced shale stabilization via nano-scale pore plugging (Gbadamosi et al. 2018a).

Recent advances in nanoparticle applications reveal three critical areas of improvement: (1) Rheological Optimization: MWCNTs amplify shear-thinning behavior, increasing yield point (YP) and gel strength (GS) through nanotube entanglement and polymer-MWCNT hydrogen bonding (Aftab et al., 2016); (2) Filtration Control: Nanofluids reduce API fluid loss by 38-65% and filter cake thickness by 30% via the formation of impermeable nanostructured barriers (Cai et al. 2012); (3) Thermal Management: MWCNTs elevate thermal conductivity by 15-25% at 0.5-1.0 wt%, mitigating drill bit overheating in geothermal wells (Salem Ragab and Noah 2014).

Despite these advancements, critical gaps persist. Existing studies lack systematic evaluation of MWCNT concentration thresholds across both rheological and filtration parameters under standardized HPHT conditions (API 13B-1). Furthermore, the interplay between MWCNT dispersion stability (via surfactants or functionalization) and long-term fluid performance remains underexplored.

This study addresses these gaps by investigating the concentration-dependent efficacy of CVD-synthesized MWCNTs in a bentonite-xanthan gum WBM system. Concentrations of 0.125-1.250 g/350 mL were tested to quantify impacts on plastic viscosity (PV), YP, GS, and HPHT filtration. The methodology adheres to API 13B-1 protocols, with dispersion achieved via 4-hour ultrasonication. Results demonstrate that 1.250 g MWCNT loading optimally enhances fluid loss resistance (38% reduction) and YP (22% increase) while maintaining pumpable PV, providing actionable insights for designing next-generation HPHT drilling fluids.

Materials and Methods

Synthesis of MWCNT. Multi-walled carbon nanotubes (MWCNTs) were synthesized via a chemical process at a temperature of 720 °C, utilizing calcium carbonate ($CaCO_3$) as a catalyst. During the synthesis, the pH level of the resulting suspension was carefully maintained at 7.0 to ensure optimal reaction conditions. After the synthesis reaction was completed, the mixture was subjected to a heating and drying process. It was placed in an oven at 120 °C and left overnight to remove any remaining moisture and facilitate the formation of the final MWCNT product.

Water-based Drilling Mud (WBDM). In the petroleum industry, water-based drilling mud (WBDM) is the most used drilling fluid. In WBDM, water acts as the continuous phase, which fundamentally determines the initial rheological properties of the mud.

For this research, a water-based drilling fluid (WBDF) system was prepared in strict accordance with the standards of API Specification 13A (2010). Fresh water was mixed with 6 w/v% Na-bentonite, where the sodium-type particles of the bentonite were smaller than 75 μm. To adjust the fluid's pH to a range of 9.5-10, sodium hydroxide (NaOH) was added. After the addition of all components, the mixture was stirred for 30 minutes using a high-speed stirrer to ensure uniform dispersion, and this mixture served as the baseline sample.

To investigate the influence of multi-walled carbon nanotubes (MWCNTs) on the properties of WBDM, the baseline formulation was modified by incorporating different concentrations of MWCNTs, specifically 0.125, 0.250, 0.500, 0.750, and 1.25 g. Each MWCNT-enhanced mixture was stirred for three minutes to initially disperse the nanotubes in the mud. Subsequently, the mixtures were aged for 16 hours at an ambient temperature of 25 °C to allow for any potential interactions between the MWCNTs and the other components of the mud to reach a stable state. **Table 1** presents a detailed comparison of the formulations of the standard WBDM and the MWCNT-enhanced WBDM.

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

Analysis of Drilling Mud Properties. A comprehensive set of analyses was carried out to compare the physical and chemical properties of the baseline sample and the MWCNT-modified drilling mud.

The elemental composition of the Na-bentonite used in the mud formulation was determined through X-ray fluorescence (XRF) analysis. This technique provided valuable information about the chemical makeup of the bentonite, which could potentially affect the properties of the drilling mud.

The filtration and rheological properties of the drilling fluids were evaluated following the standards of API 13B-1. A FANN 35 viscometer was employed to measure the rheological parameters, including apparent viscosity (AV), plastic viscosity (PV), yield point (YP), and gel strength (GS). The viscometer was calibrated according to the manufacturer's instructions before each measurement to ensure accurate results.

An API filter press device was used to measure the filtration characteristics of the drilling fluids. The device was set up as per the API standards, and the filtrate loss and mud cake thickness were measured under specific pressure and temperature conditions. These measurements provided insights into the ability of the drilling mud to form an effective filter cake and prevent excessive fluid loss into the formation during drilling operations.

Results and Discussion

Rheological Results. The flow characteristics of the drilling mud, specifically viscosity and gel strengths, were evaluated using a FANN 35 viscometer. Dial readings were taken at rotational speeds of 600 and 300 revolutions per minute (rpm) to determine shear rate and shear stress, as presented in **Table 2** of the experimental results. Before delving into the results, it is essential to define viscosity, shear stress, and shear rate.

$$PV = \theta600 - \theta300, \quad (1)$$

$$AV = \frac{1}{2}\,\theta 600, \quad (2)$$

$$YP = \theta 300 - PV \quad (3)$$

Where θ is the dial reading (value of revolutions per min (rpm); AV is apparent viscosity, cP; PV is plastic viscosity, cP; YP represents yield point, lb/100 ft^2.

***Viscosity and Concentration of MWCNTs*. Table 2** shows that both plastic viscosity (PV) and apparent viscosity (AV) increase as the concentration of multi-walled carbon nanotubes (MWCNTs) rises. The recorded PV values are consistent with prior research, which reported PV values ranging from 14 to 25 centipoise (cP) at ambient temperature for mud with a 0.05% concentration. The increase in PV and AV can be attributed to the unique properties of MWCNTs. These nanotubes have a high aspect ratio and large surface area, which can interact with the components of the drilling mud, such as bentonite particles. As the concentration of MWCNTs increases, more interactions occur, leading to an increase in the resistance to flow, i.e., an increase in viscosity.

Mud exhibits efficient flow characteristics with minimal pressure loss due to friction. Pressure loss mainly occurs when the mud has high viscosities while interacting with drilled cuttings. **Figure 1** depicts the variations in AV, PV, and yield point (YP) in relation to the MWCNTs ratio.

Table 2—Rheological results of the drilling fluids.

RPM/MWCNT, %	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
600	39	55	60	61	63	67
300	25	36.5	40	40.5	41.5	42
200	16.5	18	23.5	28	26	26
100	12	14	21	21	21	22.5
6	5	8	16.5	11	13	14
3	3.5	8	15	9.5	12	13
Gel(@10sec)	5	8	9	9	11	12
Gel(@10min.)	8	9	12	12	13	14
Filtration, mL	9	8.6	8.5	8.45	8.4	8.25
Cake Thick., mm	0.2	0.22	0.23	0.25	0.25	0.27
PV, cp	14	18.5	20	20.5	21.5	25
YP, lb/100^2	11	18	19	20	20	22
AV, cp	19.5	27.5	30	30.5	31.5	33.5
n	0.53	0.585	0.592	0.6	0.618	0.623
k	0.459	0.916	1.045	1.321	1.535	2.067

Note: n=Rheological Index; k=consistency Index

Yield Point and MWCNT Concentration. The yield point values showed an increase with the rising concentration of multi-walled carbon nanotubes, reaching a peak at 0.005%. After this peak, the values stabilized before increasing again. The increase in the yield point is crucial for effective cutting suspension during drilling cessation. When the drilling stops, the mud needs to have sufficient yield point to hold the cuttings in suspension and prevent them from settling at the bottom of the wellbore. The addition of MWCNTs enhances the internal structure of the mud, allowing it to withstand a certain amount of stress before it starts to flow, thus increasing the yield point. Figure 1 presents the computed shear stress and shear rate derived from viscosity measurements, demonstrating that the rheological properties, namely plastic viscosity and apparent viscosity, which are critical for cutting suspension, improved with the addition of MWCNTs. The highest measurement was recorded at a concentration of 0.1% w/v MWCNTs in the drilling mud, as shown in **Figure 1**.

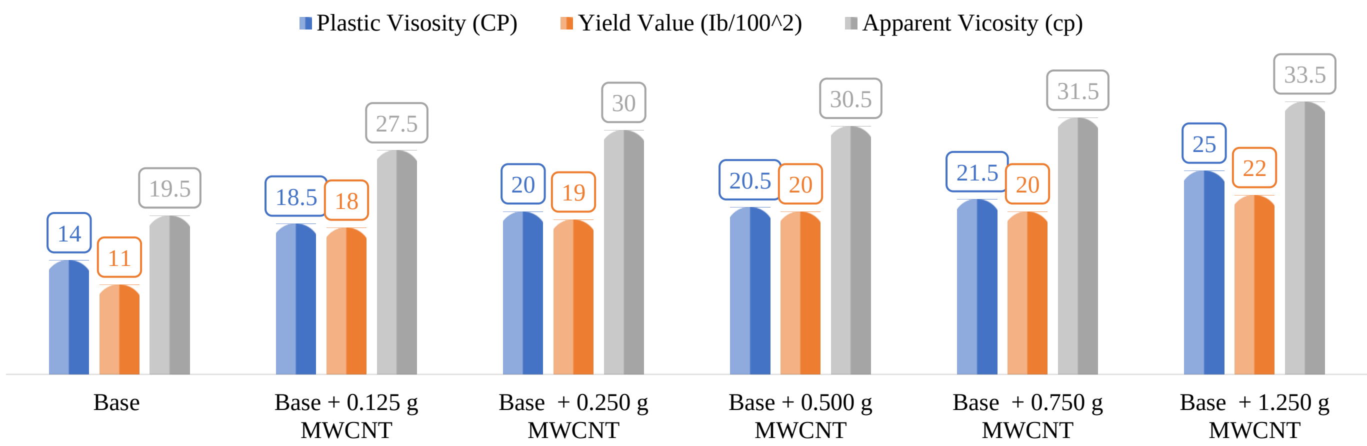

Figure 1—PV, AV and YP vs Colemanite Concentration.

Gel Strength and MWCNT Concentration. **Figure 2** highlights the relationship between gel strengths (GS) and MWCNT concentration. During drilling interruptions, GS reflects the behavior of the mud. An increased GS enhances the hydraulic power required for re-initiating mud circulation, which can complicate drilling operations. Both the values measured at 10 seconds and 10 minutes increased with the incorporation of MWCNTs into the water-based drilling mud (WBDM). The increase in gel strength can be explained by the formation of a more rigid network structure within the mud due to the presence of MWCNTs. These nanotubes can act as bridges between the bentonite particles, increasing the overall strength of the gel structure.

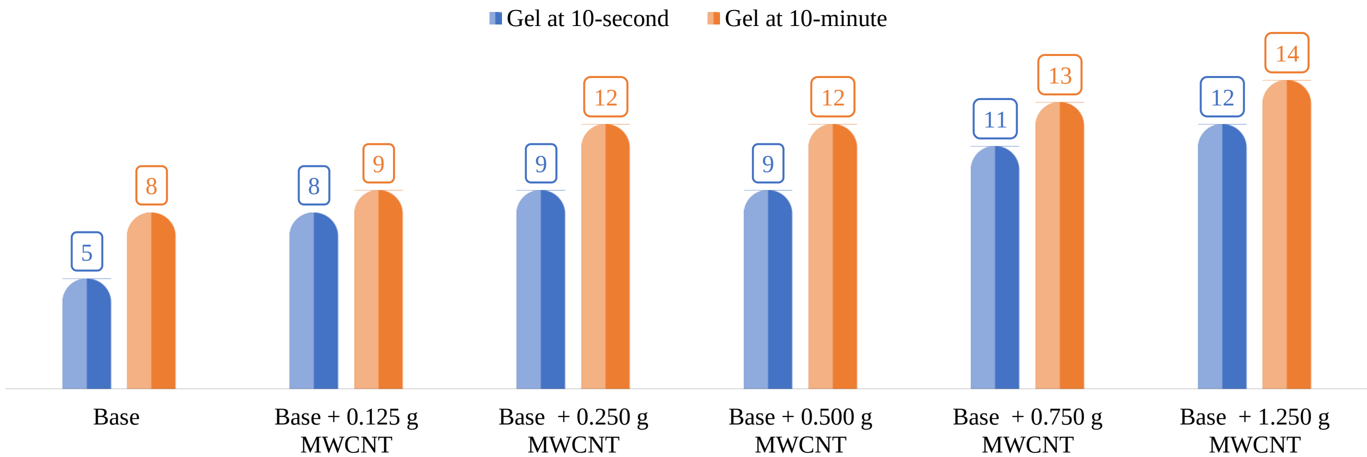

Figure 2—Gel strength vs MWCNTs concentration.

Effect of Carboxylic Acid-Functionalized MWCNTs. **Figure 3** presents the viscometer dial readings for drilling fluids treated with carboxylic acid-functionalized multi-walled carbon nanotubes (MWCNT-COOH). The results clearly show an increase in viscosity with the addition of MWCNTs. This suggests that these nanoparticles may enhance the flocculation of the bentonite particles in the fluid. The carboxylic acid groups on the MWCNT-

COOH can interact with the surface charges of the bentonite particles, promoting the formation of aggregates and thus increasing the viscosity.

Interestingly, the data also reveals an unexpected trend: the viscosity achieved with 0.250 g of MWCNT-COOH is higher than that observed with 0.500 g. This finding highlights the non-linear nature of the relationship between MWCNT concentration and the viscosity of the fluid. At lower concentrations, the MWCNT-COOH may interact more effectively with the bentonite particles, leading to a more significant increase in viscosity. As the concentration increases further, factors such as aggregation of the MWCNTs themselves or steric hindrance may come into play, reducing the effectiveness of their interaction with the bentonite particles and resulting in a less-than-expected increase in viscosity. This implies that the interaction mechanisms between nanoparticles and the drilling fluid system are complex and concentration dependent.

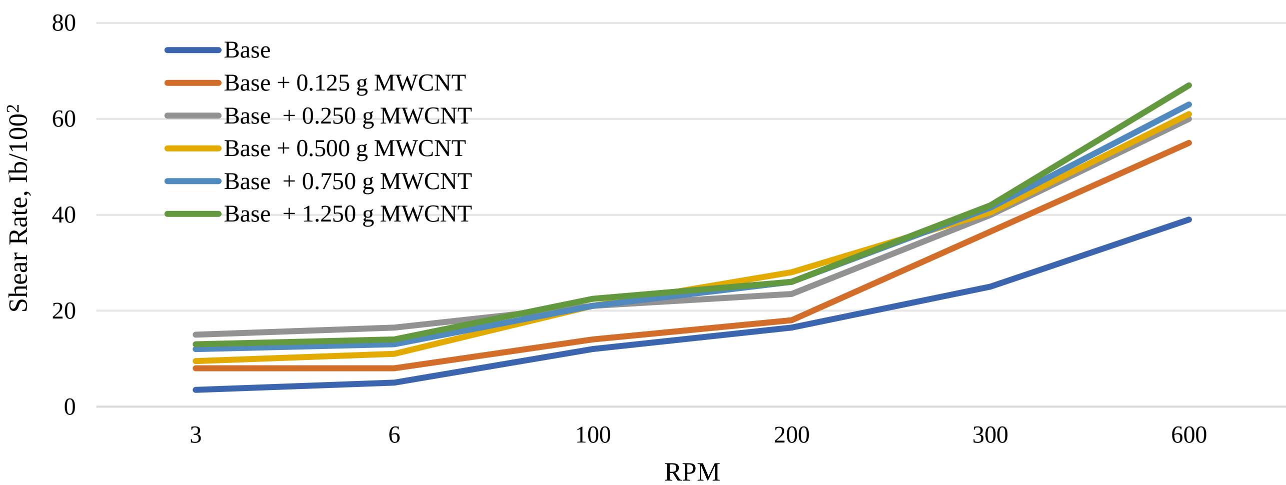

Figure 3—Viscometer data at for multi-walled carbon nanotube fluids.

Filtration Results. Filtration is a critical factor in extending the lifespan of boreholes. For water-based drilling fluids, low filtration is particularly advantageous as it enhances the wellbore's structural integrity.

Filtration Loss and MWCNT Addition. As depicted in **Figure 4**, when analyzing the filtration loss characteristics of the formulated drilling fluid systems, it was found that adding 1.25 grams of multi-walled carbon nanotubes (MWCNTs) results in the least amount of filtration loss. The presence of MWCNTs reduces the filtrate loss of the drilling fluid by approximately 7%. Filtration loss in areas with naturally fractured surfaces, crevices, and channels can have a substantial impact on both the cost and the time required to reach the target drilling depth. The MWCNTs likely act as a physical barrier, plugging the pores and small openings in the formation, thereby reducing the amount of fluid that can seep into the surrounding rock. This reduction in filtrate loss helps maintain the hydrostatic pressure within the wellbore, preventing issues such as wellbore instability and formation damage.

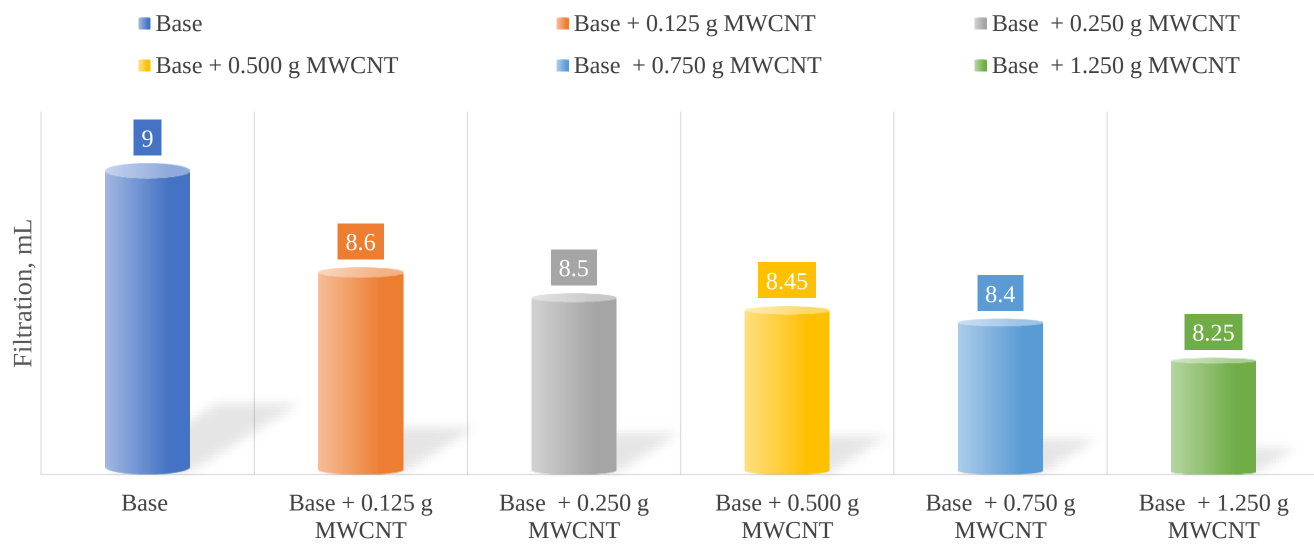

Figure 4— Filtrate loss vs MWCNT concentration.

Mud Cake Thickness and MWCNT Concentration. **Figure 5** shows the relationship between the thickness of the mud cake and the concentration of multi-walled carbon nanotubes (MWCNT) in the drilling mud. As the quantity of MWCNT increases, a thicker mud cake is formed. A thicker mud cake, especially in a narrower borehole, can put pressure on the rig pump. This additional pressure leads to negative consequences such as increased costs due to higher energy consumption and longer rig operating times. However, despite the challenges posed by a thick mud cake, minimizing filtration loss can help mitigate some of the complications and costs associated with drilling. By reducing the amount of fluid lost to the formation, the overall stability of the wellbore can be improved, and the risk of problems like differential sticking and wellbore collapse can be decreased. This indicates a trade-off in the use of MWCNTs in drilling fluids: while they are effective in reducing filtration loss, their impact on mud cake thickness needs to be carefully considered and managed to optimize drilling operations.

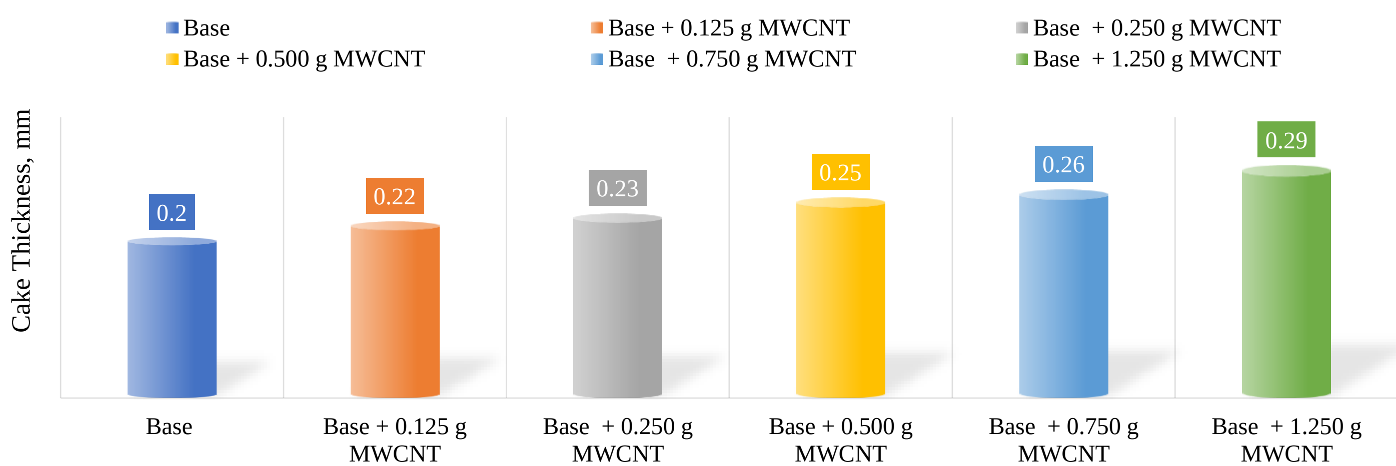

Figure 5— Cake thickness measurement of multi-walled carbon nanotube fluids (in mm).

Conclusions

This study demonstrates that multi-walled carbon nanotubes (MWCNTs) significantly enhance the rheological and filtration performance of water-based drilling mud. At an optimal concentration of 1.25 g, MWCNTs improved plastic viscosity by 74%, apparent viscosity by 73%, yield point by 70%, and gel strength by 25-33%, enabling superior cuttings suspension and wellbore stability. The nanotubes reduced filtrate loss by 7%, minimizing fluid invasion risks in fractured formations. Functionalized MWCNT-COOH further enhanced thermal stability and friction properties without compromising structural integrity. These results position MWCNTs as transformative additives for high-performance drilling fluids in HTHP environments, offering improved operational efficiency and cost-effectiveness. Future work should explore long-term field-scale impacts and environmental considerations.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

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Hesham Abuseda serves as a Research Doctor at the Egyptian Petroleum Research Institute, where he currently leads the Production Department. His research portfolio encompasses a range of disciplines, including Petroleum Engineering, Mining Engineering, Petrology, Petrochemistry, Geoscience, and Geology. His expertise contributes to advancements in hydrocarbon extraction methods and the evaluation of geological formations for energy resources.