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Effect of Nano-Weighted Colloidal Particles on Mud Telemetry Velocity while Drilling Hydrocarbon Wells

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Abstract The use of barite to improve the properties of drilling fluids has its shortcomings, which then informed the quest for other viable alternatives such as nanoparticles. This study replaced micronized barite with nanoparticles (iron oxide and titanium oxide) with the aim of enhancing the mud pulse telemetry (MPT) signal quality dissipation. Because literature has shown that mud system dynamics and density are the major challenges during propagation of mud pulses during MWD of deep wells. Formulated oil-based drilling fluid samples which are multiphase and colloidal nature were adopted in this study. The influence of mud density on wave speed propagation through the oil-based mud systems was evaluated, and mud samples B1 and B2 which had the highest mud densities were seen to have the lowest corresponding wave speed (1.51 x 10^4 ft/sec) in the same drill pipe. It can be deduced from the results that drilling fluid density influences wave speed in the drill pipe; that is, wave speed and velocity decrease as drilling fluid density increases. The estimated drilling mud and dispersed particles bulk modulus, had no effect on the wave velocity inside the drill pipe; thus, the wave velocity remained unchanged at varying bulk modulus of the mud. The dispersed particles increased the wave velocity because, for a rigid solid, propagated by both transverse and longitudinal waves of same frequency, they happen to travel faster when propagated by longitudinal waves due to their longer wavelengths

Keywords Dispersed particle; Nanoparticles; MWD operation; Wave velocity; Drill pipe; Oil based mud system; Bulk modulus and density

1. Introduction

In the oil and gas industry, the Measurement while drilling (MWD) procedure is really vigorous, thus allowing for simultaneous real time information gathering within the wellbore. During drilling, MWD makes it easy to determine the trajectory/location of the drill bit and path/ route of a wellbore. The MPT device is built into the drill string, thus ensuring the transmission of real-time data even in directional and horizontal wells. The acquired data is transmitted to the surface and can be used for formation evaluation and geo-steering in real time. In all of these, there is a peculiar problem plaguing the MWD process, which essentially transmits data from downhole to the surface decoder [1]. The problem lies on the quality of the signal being transmitted. Signals from the MWD measurements have been known to attenuate with an increase in tool depth and the drilling mud properties. Hence, optimizing the performance of the tools and ensuring proper mud rheology is imperative [2].

Signal strength optimization requires knowledge of signal strength, tool modification, and type of drilling fluid, with the drilling fluid selection step being the primary line of action as regards this study. Mud type also affects signal amplitude and broadness; thus, extensive research is still required in this area [3]. Researchers, academicians and industry based research institutes are now discussing new techniques for detecting the effects of various sources of signal impairments and methods of reducing them; there are also patent quests and non-disclosure agreements being signed, especially when they are new technologies. However, one thing is common in the application of MWD techniques, which is the medium of transmission (drilling fluid) [4]. Factors that affect MPT data transmission in one drilling mud system will affect any hardware designed to transmit information through mud telemetry. Thus, further investigation into properties of drilling fluids that directly influence MPT data transfer should be encouraged, since it remains the most effective means of real time transmission of subsurface information during drilling [5].

As the wave signal is transmitted by the mud pulse telemetry system (MPT) via the drilling mud, the transmission energy is reduced, thus resulting in signal attenuation and dispersion. Changes in the drilling mud bulk modulus increases the susceptibility of the formation zone to operation-induced damages, which further affect the strength of the mud signal pulses and thus complicates the process [6]. Nano-based drilling mud reduces the level of differential sticking, as well as damage to the formation that occurs in the shale. Due to the high surface area to volume proportion and low concentration requirement contrasted with large-scale and small-scale material-based liquids, Nano-based liquid has been proposed as the choice fluid for drilling in very reactive and deeply folded shales that therefore adhere effectively to the bit, stabilizers, apparatus joint etc. which inhibit the decrease in rate of penetration (ROP). The use of nanoparticles as additives can also lead to an improvement in the properties of drilling muds thereby combating the difficulties arising within downhole conditions [7].

This study investigates the role of dispersed nanoparticle on signal impairments which affect the quantity and quality of mud pulse telemetry signal required to maximize real time data transmission. Signals from MWD instruments can be enhanced by replacing conventional oil-based fluids with an oil-based mud that has decreased low-end rheology (for example, barite, haematite and so on, with other weighting agent). Li et al. [5] highlighted mud system dynamics and density as the major challenges encountered during the propagation of MWD mud pulse for high temperature deep well drilling. But literature has highlighted the advantage of nanoparticles in such situations. It is for this purpose that this study attempts to replace micronized barite with nanoparticles (iron oxide and titanium oxide) with the aim of enhancing the MPT quality of signal dissipation. The formulated oil-based drilling fluid were both considered to be multiphase and colloidal in nature.

2. Materials and Methods

Formulation of Nano-Weighted Oil Based Mud System

Field applicable oil-based mud systems were formulated with barite as standard weighting agent, and the standard mud systems were infused with weighted Ferric oxide, and Titanium di-oxide nanoparticles. The main modification on the standard field applicable oil mud system in this study is the substitution of micronized barite with nanoparticles in order to investigate their effects on the drill pipe mud pressure pulse propagation and attenuation.

A total of six (6) oil based mud samples were formulated: Oil based mud (OBM) with barite of 70 g and 90 g as weighted standards (samples A1 and A2), OBM with Ferric oxide at 70 g and 90 g as weighting agent (samples B1 and B2), and OBM with Titanium di-oxide at 70 g and 90 g as field samples (samples C1 and C2). Table 1 shows other mud formulation additives used in this study.

Table 1: Specification of Models in stage

	Product Concentration Lab Barrel	
Product Name	*g*	*mL*
Synthetic Base Oil	-	212.96
Water	-	94.66
Primary Emulsifier	-	3.23
Secondary Emulsifier	-	2.15
Organophilic Clay	7	-
Rheology Modifier	-	0.53

Fluid Loss Agent	5	-
Lime	6	-
$CaCl_2$ (95%)	33.87	-

Nanoparticle Characterization

The Ferric oxide and Titanium di-oxide nanoparticles were purchased from chemical suppliers to the University Drilling Fluid Laboratory, and to ascertain the quality of the nanoparticles which were ≥ 94% pure, with a particle size ranging from 40 to 100nm; further analysis was undertaken. The nanoparticles composition was identified by a powder X-ray diffraction (Schimadzu 6000 model). The information in XRD analysis is provided by the interaction between X-rays and the sample material. X-rays have a characteristic radiation with peaks at different wavelengths, depending on the source material [8]. The wavelength of these peaks determines the extent to which it will penetrate, absorb, and scatter so as to ensure sufficient dispersion of the wavelength of the so-called radiation peak.

3. Mathematical Models for Mud Pulse Telemetry Evaluation

It is believed that the flow is laminar with density and viscosity independent of the angle of inclination around the drill-pipe [9]. But, mud-pulse velocity declines as mud system density increases. The objective of the oil and gas industry is to continue to support initiatives that will help develop technologies that will yield high data-transfer rates from the drill-bits that are both reliable and economically viable [10]. An understanding of fundamental principles of mud flow dynamics (MFD) will help provide an insight on how to deal with boundary constraints imposed on governing and constitutive equations for obtaining mud pulse velocity in drill pipes [11]. To accurately investigate the effects of mud property on mud pulse telemetry, the oil-based mud system must be seen as a multiphase fluid which contains solid particles alongside dissolved free gas and oil phase fluid; and all these affect the bulk fluid- modulus. Because according to Shi and Liu [12], the bulk modulus of a mud system is closely related to the mud pulse velocity. This study adopts equation (1) which is a continuity equation for one-dimensional unsteady flow in a pipe as proposed by Shi and Liu [12] for the estimation of mud pulse velocity in/around drill pipes (Figure 1). The equation was further modified to consider the multiphase nature of drilling mud system; it also considers the compressibility of the mud system in generating a suitable equation that applies to actual drilling mud systems.

$$\frac{1}{\rho}\frac{dp}{dt} + \propto^2 \frac{\partial v}{\partial x} = 0 \qquad (1)$$

Where,

$$V_t = V_l + V_g + V_s \qquad (2)$$

$$\rho = (1 - \beta_g - \beta_s)\rho_l + \beta_g\rho_g + \beta_s\rho_s \qquad (3)$$

And,

$$\beta_i = \frac{V_i}{V_t}, (i = g, s) \qquad (4)$$

$$\vartheta = \sqrt{\frac{K_l / \left((1-\beta_g-\beta_s)\rho_l + \beta_g\rho_g + \beta_s\rho_s\right)}{1 + \frac{K_l}{K_p} + \beta_g\left(\frac{K_l}{K_g} - 1\right) + \beta_s\left(\frac{K_l}{K_s} - 1\right)}} \qquad (5)$$

Literature have shown that oil-based mud systems do not only behave like multiphase fluid systems, but also like colloidal systems [13, 14]. Colloidal because, it contains finely divided solid materials which when dispersed in a fluid medium scatters a light beam and does not settle by gravity; the nanoparticle-mud system is an example. Based on these facts, equation (2) can be modified to get Equation (3).

$$\beta_i = \frac{V_i}{V_t}, (i = g, s, D) \qquad (6)$$

Where, g is for the possible dissolved gas, s for the dissolved solids, and p for the dispersed particles. Applying Equation (6) in (5), gives a modified equation used in examining the effect of dispersed nanoparticles on mud pulse velocity. The pressure wave velocity (m/s) is:

$$\vartheta = \sqrt{\frac{K_l / \left((1-\beta_g-\beta_s-\beta_D)\rho_l+\beta_g\rho_g+\beta_s\rho_s+\beta_D\rho_D\right)}{1+\frac{K_l}{K_p}+\beta_g\left(\frac{K_l}{K_g}-1\right)+\beta_s\left(\frac{K_l}{K_s}-1\right)+\beta_D\left(\frac{K_l}{K_D}-1\right)}} \quad (7)$$

Where, K_l is liquid bulk modulus (Pa), K_p is the drill pipe bulk modulus of elasticity (Pa), Kg is the free gas bulk modulus (Pa), K_S is the solid bulk modulus (Pa), K_D is the dispersed particle bulk modulus (Pa), β_g, β_S and β_D are the volume factor of the free gas, solid and dispersed particle contents, ρ_S, ρ_l, ρ_g and ρ_D are the density of the solid, liquid phase, gas phase and dispersed phase. The field and experimental data used for the calculations include K_l = 1.35 x 10^3 to 2.04 x 10^3 MPa, K_P = 2.1 x 10^3 MPa, K_g = 101 kPa, K_s = 1.62 x 10^3 MPa, K_D = 151 to 192 GPa and 209.1 to 218.1 GPa, ρ_l = 982.58, 1078.44, 1198.26, 1138.35, 1246.19, and 1342.06 kg/cu m, ρ_D = 4230 to 5240 kg/cu m, ρ_s = 2660 kg/cu m, and ρ_g = 2660 kg/cu m.

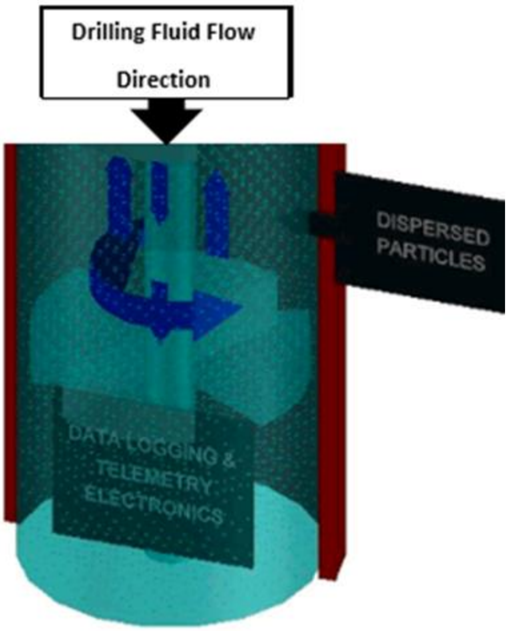

Figure 1: Cross Sectional Area of a Drill Pipe with Drilling Fluid Treated with Nanoparticles

4. Results & Discussion

Identification of the Nanoparticles used for Investigation

Tables 2 and 3 show the results of the XRD analysis for the nanoparticles used in preparing the OBM formulations. It indicates that the particles consist of y- and α- peaks of Ferric oxide and Titanium di-oxide. The diffractograms gave insight into the phase purity of the samples.

Table 2: XRD Data for Ferric Oxide

No.	Card	Chemical Formula	S	L	d	I	R
		Chemical Name (Mineral Name)		Dx	WT%	S.G.	
1	25-1402	Fe2O3	0.301	1.000(25/35)	0.811	-----	0.811
		Iron Oxide (Maghemite-\ITQ\RG, syn)		-----		-------	
2	29-1488	Al2Si2O5(OH)4	0.146	1.000(19/21)	0.805	-----	0.805
		Aluminum Silicate Hydroxide (Kaolinite-1\		-----		-------	
3	26-0911	(K,H3O)Al2Si3AlO10(OH)2	0.183	1.000(18/18)	0.803	-----	0.803
		Potassium Aluminum Silicate Hydroxide (Il		-----		-------	
4	19-0629	FeFe2O4	0.161	1.000(9/26)	0.803	-----	0.803
		Iron Oxide (Magnetite, syn)		-----		-------	

Table 3: XRD Data for Titanium Di-Oxide

No.	Card	Chemical Formula / Chemical Name (Mineral Name)	S	L / Dx	d / WT%	I / S.G.	R
1	21-1272	TiO2	0.352	0.778(7/39)	0.687	0.559	0.299
		Titanium Oxide (Anatase, syn)		-----		-------	
2	49-1057	K-Mg-Al-SiO2-H2O	0.300	0.750(9/22)	0.818	0.425	0.261
		Potassium Iron Magnesium Aluminum Silicate		-----		-------	
3	33-0664	Fe2O3	0.503	0.538(7/42)	0.723	0.628	0.244
		Iron Oxide (Hematite, syn)		-----		-------	
4	5-0586	CaCO3	0.500	0.765(13/42)	0.616	0.439	0.207
		Calcium Carbonate (Calcite, syn)		-----		-------	
5	21-1276	TiO2	0.078	0.444(4/38)	0.789	0.500	0.175
		Titanium Oxide (Rutile, syn)		-----		-------	

Formulated Oil Based Mud System Properties

In deep formation environments, where the temperature and pressure are prevalently high, the dynamics of mud and its density changes in the drill pipe are different from those of normal conditions [15]. Density has been identified from literature as one of the mud properties that affect propagation of mud pulse waves during MWD operations. Figure 2 shows the mud density of the six (6) formulated oil-based mud systems, and these data were used for further investigation in this study. All the mud system sample densities were within the API standard range. It was observed that at the two weighted masses (70 g and 90 g), Ferric oxide (samples B1 and B2) exhibited higher weights than those of the barite (samples A1 and A2) samples and followed by Titanium di-oxide (samples C1 and C2). Thus, Ferric oxide can be considered as a possible substitute for barite in the formulation of oil-based mud systems.

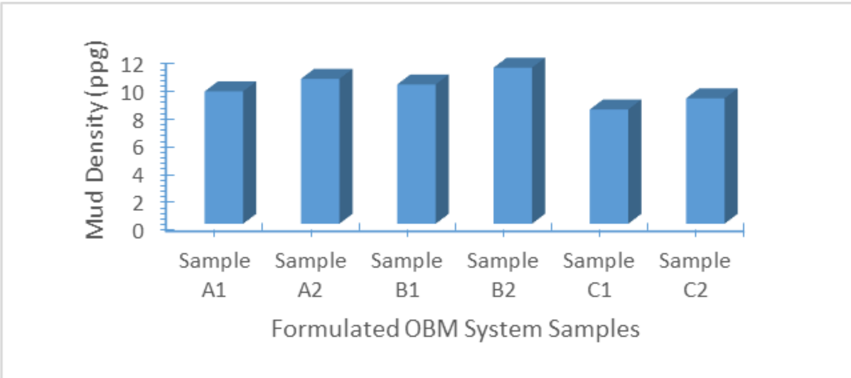

Figure 2. Density of the Formulated OBM System Samples

As the mud pulse telemetry system (MPT) wave signals are transmitted via the drilling mud, the energy of transmission reduces and hence attenuation and dispersion result. The influence of these mud densities on wave speed of the oil-based mud systems was evaluated using Equation (8), which is popularly known as the simplified Lamb- equation with consideration that the inner diameter and wall thickness of the drill pipe are constant. Thus, the wave speed of the mud systems inside the drill pipe were calculated using Equation (8).

$$c = \sqrt{\frac{1}{\rho\left(\frac{1}{\varepsilon_y}+\frac{1}{\varepsilon}\right)}} \qquad (8)$$

Where, ρ is the individual mud density of the formulated OBM, ε_V is the Young Modulus of Elasticity for the Drill Pipe (206.84 GPa), and ε is the Young Modulus of the OBM water-in-oil emulsion whose value is 2.3 GPa.

Figure 3 shows that high mud density directly reduces the wave speed in the drill pipe, because, mud samples B1 and B2 which had the highest mud density also had the lowest corresponding wave speed (1.51×10^4 ft/sec) in the same drill pipe. Also, mud samples C1 and C2 with lowest mud densities, had the highest wave speed in this study (1.67×10^4 ft/sec). As much as optimum density is required for successful drilling operation, care must be taken to ensure that the mud densities do not retard the wave speed during MWD operations. The density of a medium is one of the factors that affect the speed of mud telemetry, because density is the mass of a substance per volume. If a medium is denser per volume, it has more mass per volume, and as such it will transmit wave slower. Also, the speed of a mud telemetry depends on the density and bulk modulus.

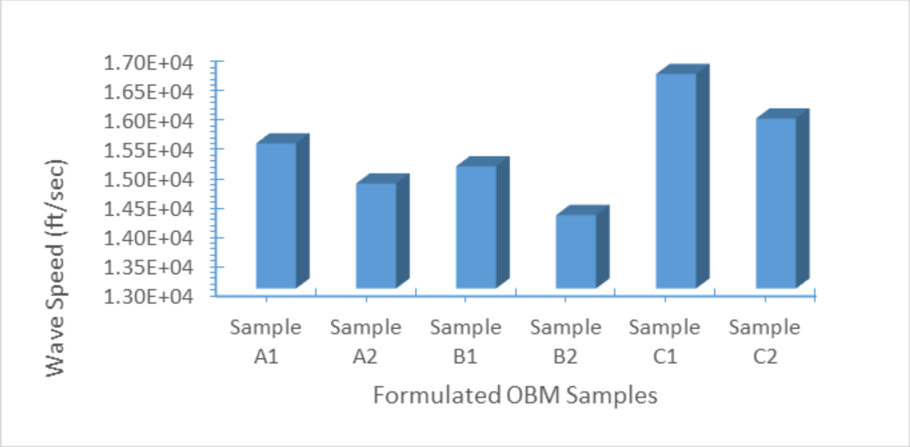

Figure 3: Effect of Mud Systems Density on Wave Speed in the Drill Pipe

When deploying MWD technology, the mud system inside the drill pipe is used as the wireless communication medium, thus the encoded signal can be distorted. It can be deduced from the results that drilling fluid density influences the mud-pulse velocity; that is, mud-pulse velocity decreases as drilling fluid density increases. For faster downhole to surface data transmission, high-speed real time data transmission is required to improve drilling efficiency. Depending on the severity of the mud channel conditions and signal distortions, to achieve maximum possible data rates, telemetry systems must be robust and flexible, both downhole and at the surface receivers [16].

Effect of dispersed Nanoparticles used as weighting agent on Pressure Wave Velocity

As MPT system signals propagate through the drilling mud along the borehole, signals are attenuated and dispersed. Literature has highlighted the sensitivity of mud pulse telemetry towards solids entrained in drilling fluids, though no detailed analysis is available for this behaviour and levels of significance observed [17, 18]. Till date, there is no known analysis on the effects of dispersed nanoparticles as mud flow property enhancers on the transmission behaviour of mud pressure pulses encountered during MWD operations. Drilling fluid as a colloidal system exhibits intermediate properties that span between suspensions and colloids but colloidal particles are small enough that they do not settle out; thus, the nanoparticles used as weighting agent in this study can be classified as colloidal particles. The particles in a colloid are large enough to scatter light, a phenomenon called the **Tyndall effect**, and as such can affect mud pulse telemetry [19]. Figure 4 shows the sand content analysis of the formulated OBM samples and the individual impacts of the weighting materials adopted. Sand content is the volume percentage of particles larger than 74 microns. The percentage sand content in this study increased as the volume of the weighting agents were increased. OBM samples C had the highest sand content as the weight volume was increased and this is followed by OBM samples B. OBM samples A had the lowest sand contents in this study.

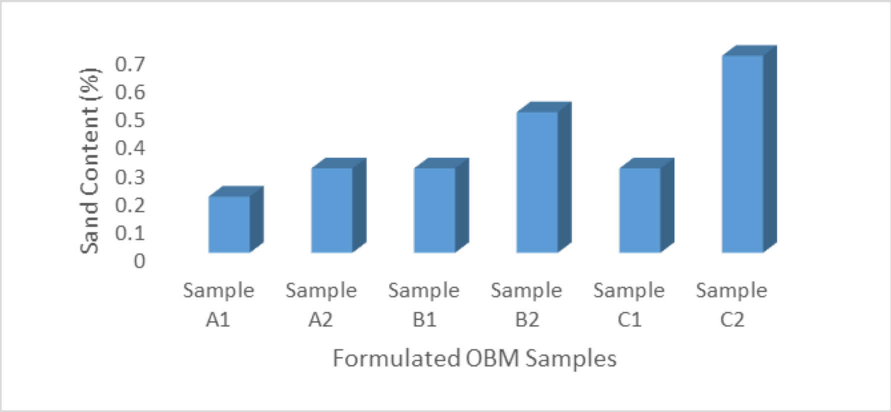

Figure 4: Impact of Weighting Agents weight-volume on percentage Sand Content of OBM

The basic principle of waves states that a wave does not move any mass in its direction of propagation but transfers energy. Because a wave only moves mass in the direction perpendicular to its direction of propagation. The propagation of wave in colloidal systems is represented by its velocity [20, 21]; thus, this section will be examining the effects of drilling fluid density, bulk modulus, dispersed particle bulk modulus and density on wave velocity inside the drill pipe during MWD. Velocity dispersion and attenuation in mud telemetry strongly depend on the properties of the drilling mud system used as medium.

Figures 5 and 6 show the effect of drilling fluid and dispersed particles bulk modulus respectively on wave velocity inside the drill pipe respectively, because, the measure of a fluid's resistance to compression of a hydraulic fluid if position, response time, and stability are critical. The results show that both the drilling fluid and dispersed particle bulk modulus have no significant effect on the wave velocity in the drill pipe; thus, the addition of the nanoparticle did not alter the physical properties of the formulated mud systems. Bulk modulus is a measure of resistance to compressibility of a fluid, and these plots show a constant value over the range of mud and disperse particle bulk modulus considered for the nanoparticles. From literature, it was only asserted that an increase in compressibility can affect the velocity of the wave inside a pipe; thus, the results are in agreement with this principle.

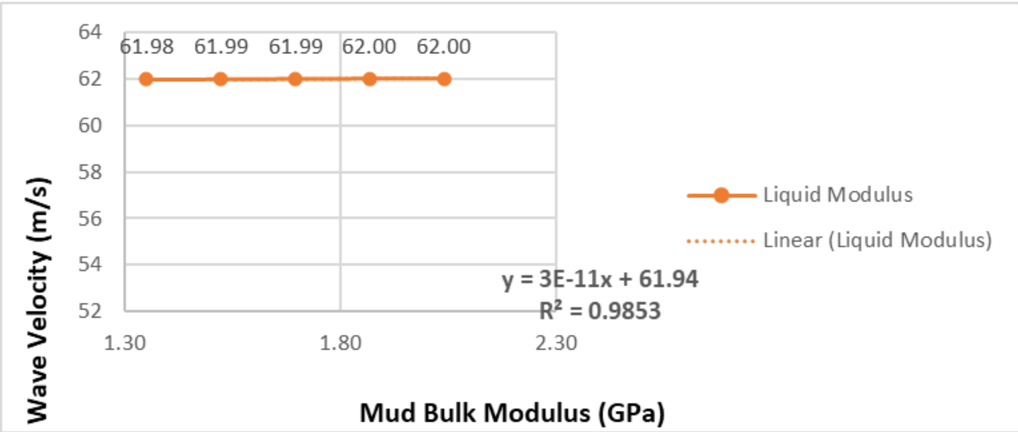

Figure 5: Effect of Drilling Fluid Bulk Modulus on Wave Velocity inside the Drill Pipe

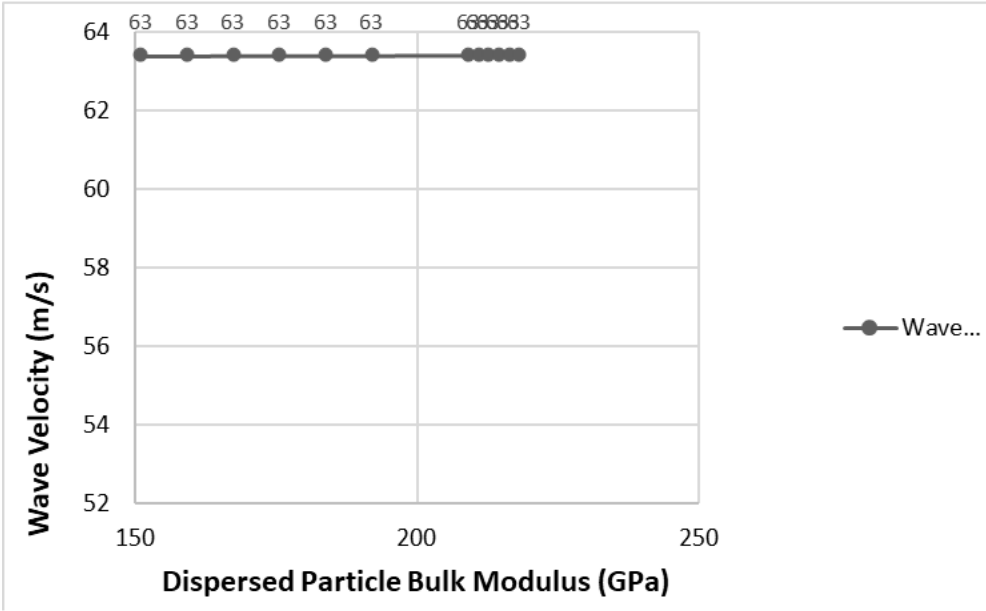

Figure 6: Effect of Dispersed Particles Bulk Modulus on Wave Velocity inside the Drill Pipe

It can be said that the performance requirements for hydraulic control systems are becoming more stringent. One of the functional properties of a fluid, which is often overlook, is its compressibility or, more often, bulk modulus [22]. Drilling fluid systems are fairly incompressible because a large pressure is required to produce a very small change in the liquid volume. But, Akkaya [23] in the study, "effect of bulk modulus on hydrostatic transmission systems performance", highlighted the need to consider bulk modulus as a variable parameter in developing realistic models. Bulk modulus is a fundamental and inherent property of liquids which expresses the change in density of the liquid as a function of external pressure applied to the liquid [24]. In this study, the results from drilling mud and dispersed particles bulk modulus numerical values, did not change the wave velocity inside the drill pipe; thus, the wave velocity remained unchanged. Dejtaradon et al. [25] and Okoro et al. [26] observed that the use of nanoparticles as additives improves the flow properties and density of drilling fluid systems. Figure 7 shows the effect of drilling fluid density on wave velocity inside the drill pipe. The results show that the density of the formulated drilling system affects the wave velocity in the drill pipe. Fluids with more mass per unit volume are heavier and require more energy to move them and thus, are sheared less easily.

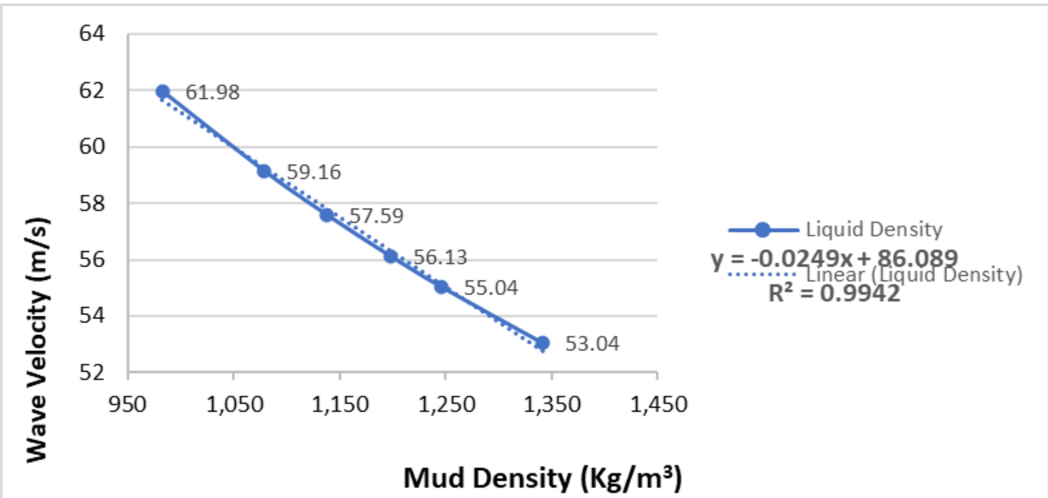

Figure 7: Effect of Formulated Mud Density on Wave Velocity inside the Drill Pipe

As the density of the formulated mud systems increases for samples A, C and B, the wave velocity decreases in that order also. Density is a thermodynamic property and is a function of pressure, temperature and composition.

The presence of weighting agents in the drilling fluid system allows the density of the drilling fluid to vary (increase) as a function of pressure. This was observed in this study with nanoparticles as weighting agents.
Li et al. [5] in their study highlighted the need to further investigate the effects of suspended solid particles on wave propagation and attenuation during MWD operations. This study investigated the dispersion effects of the nanoparticles used as weighting agent on wave velocity. Equations (5) and (7) were considered for this reason. Equation (5) did not capture the effects of dispersed particles on wave velocity, while Equation (7) considered this effect. Fig. 8 shows the simulation results of these two equations and it was observed that the dispersed particles have significant effects on the wave velocity. Dispersed particles are solids, and solids are rigid bodies with a certain shape and volume [27]. Atoms or molecules in a solid are very close to each other, and there is a great force of attraction between these molecules. Solids assume the flow patterns exhibited by the nature of the forces between carriers'/fluid molecules [28]. True solids are not incompressible, but they still require great strength to change their shapes. In some cases, intermolecular forces can organize solid molecules into a network of suspended solids. These suspended particles influence wave velocity, because the velocity of a wave is equal to the product of its wavelength and frequency and is independent of its intensity. If a point vibrates within a rigid solid, both transverse waves and longitudinal waves of the same frequency are sent out, and, because the longitudinal waves happen to have longer wavelengths, they will move faster. This principle validated by the illustration in Figure 8.

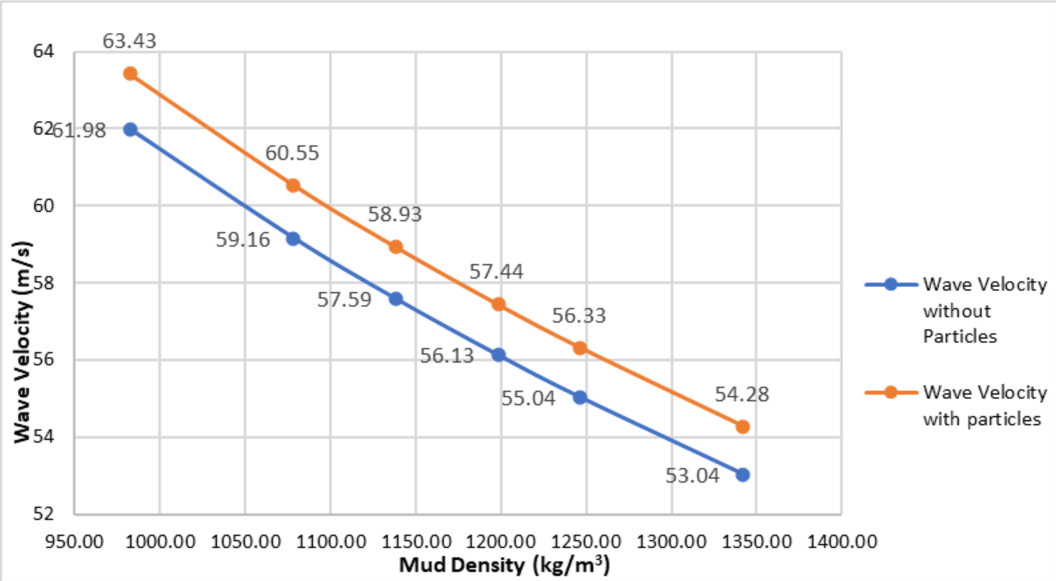

Figure 8: Effects of Dispersed Nanoparticles on Wave Velocity

The greater the density of a mud system, the slower the velocity of the mud telemetry. This observation is analogous to the fact that the frequency of a simple harmonic motion is inversely proportional to *m*, the mass of the oscillating dispersed nanoparticles [29]. Researchers have shown that mud pulse telemetry technologies have benefited the oil and gas exploration and drilling operations by providing low-cost, real-time data transmission during drilling operations [30]. In view of the difficulties associated with working with a mud pulse telemetry, this study proposed nanoparticle weighted drilling mud system as an attempt to improve the data transfer rate through communication channels (drill-pipe).

5. Conclusion

This study validates the effects of colloidal media formed from nano-weighted oil based mud on mud pulse velocity generated in a drilling pipe during measurement while drilling (MWD). The analysis of the adopted and modified models enabled the proper investigation of the formulated nano-weighted oil-based mud system properties, with further evaluation of the effect of dispersed nanoparticles that were used as the weighting agents on pressure wave velocity. The results revealed that the drilling fluid density influenced the drill pipe wave speed, and that the velocity decreased as the drilling fluid density increased. In other words, the wave speed and velocity decreased as the drilling fluid density increased. Also, the wave velocity remained unchanged with respect to bulk modulus since the drilling mud and dispersed particle bulk modulus' numerical values did not affect the drill pipe wave velocity. The findings support the relationship between basic parameters of the mass flow rate equation for flow dynamics. This study therefore established nanoparticle utilization as oil-based mud weighting agents for a robust fluid pulse signal transmission procedure in a mud pulse telemetry system (MPT) during measurement while drilling (MWD) as compared to a micronized barite system.

Declaration of Competing Interest

The authors of this study declare that they have no known competing personal relationships or financial interests that could have appeared to influence the work reported in this paper

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