The Effect of Drilling Mud Density on Penetration Rate

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Abstract - ***Drilling is an important part of the oil industry and penetration rate must be enhanced to ensure speedy completion of drilling operation. Weight on bit, Rotary speed, drill bit type, formation characteristics and mud properties are the basic factors that affect the penetration rate of a bit. The focus of this work is on density which is a rheological property of the drilling fluid. Data obtained from eight wells were analyzed to ascertain the effects of Mud density on penetration rate.***

Water and Oil based Muds were used to drill these wells which were in Sandstone/Shale formations and Penetration rates were plotted against the mud weight. From a field in Alaska, another set of data were obtained to illustrate the effect of Plastic viscosity and Methylene Blue Test (MBT) on the penetration rate. For the Water based mud, the average densities of 10.5, 11.5 and 8.9 ppg. produced average penetration rates of 25 and 24 and 37 ft/hr. respectively. Similarly, the average penetration rates of 28, 35 and 50ft/hr. were obtained by the Oil based mud densities of 11.3, 11.1 and 8.6 ppg. respectively. It can be deduced that the rate of penetration was reduced by the increase in Mud density. In order to drill effectively and efficiently, the right drilling mud density should be formulated. A substantial amount of time and drilling cost can be saved in drilling cost analysis when drilling conditions are suitable to facilitate fast penetration rates and good hydrostatic pressures.

Key Words: *Drilling mud, Rate of Penetration, Water based Mud, Oil based Mud, Density*

1. INTRODUCTION

In producing crude oil from a reservoir, located thousands of feet in the earth's crust, a production conduit needs to be created and later completed to form a hole between the reservoir and the surface. The success of drilling at fast rate and getting fast rate of penetration does not depend solely on the capability of the state-of-the art drilling equipment, but also found to depend among other things on the type and weight of drilling mud used [1]. During drilling activities, drilling mud is usually used to prolong bits life, minimize fluid loss, control well pressure and lots more. Drilling mud should be able to impose sufficient hydrostatic pressure, normally in the range of 250psi to 450psi higher than the formation pressure. Failure to produce the expected hydrostatic pressure will initiate the influx of formation fluid - a phenomenon known as kick, which may lead to blowout. Generally, blowout will only occur if well kick could not be controlled/killed in a relatively short period [2][3]. It is very important to recognize and understand the factors which effect penetration rate and drilling efficiency such as, Bit type, Circulating System Hydraulics, Bit weight and Drilling fluid type and properties [4]. The advantages of oil-base mud to water-base mud become more pronounced when drilling deeper formations [5]. In modern drilling practices it is necessary to identify operations that could make drilling cost reduction possible. [6].

Mud weight which is defined as the density of drilling mud (mass divided by volume), expressed in pounds per gallon (ppg or Ib/gal), pounds per cubic feet (lb/ft^3) or kilograms per cubic meter (kg/m^3) has been identified as one of the factors that impact drilling rate [7]. While the drilling mud is essential for all its numerous functions, however, it plays a very important role in the Rate of penetration (ROP) in rotary drilling. It has long been known that drilling mud weight affects ROP, this fact was established early in drilling literatures and confirmed by numerous laboratory studies. However, several early studies focused directly on mud properties with standard mud weight of 9–10 ppg. But in recent times, mud weight has been raised to as much as 14.5 ppg giving it an excess of close to 5 ppg. It is true that mud weight controls hydrostatic pressure (HP) in a well bore and prevents unwanted fluid flow into the well, it is also true that the weight of the mud prevents collapse of the casing and the open hole, but excessive mud weight will cause the weight of the drilling mud to go higher above the pressure gradient of the formation, this in turn impacts penetration rate (PR). Fast PR is the target in every drilling activity and if achieved can reduce the well drilling cost. Thus the selection of mud weight is a challenge one faces during drilling operations [8][9]. Penetration rate is decreased by increasing plastic viscosity, solid content and mud weight [10].

Field data are usually collected and analyzed to identify the characteristics of a drilling fluid that enhance the rate of Penetration and to quantify the impact of particular fluid properties on the Penetration rate during oilfield development. This information is used to evaluate the economics of a drilling fluid treatment program in order to deliver optimal drilling performance and minimum drilling cost rather than minimum fluid cost. Bit hydraulics can be improved through rheological modification without adjusting flow rate or nozzle size. For the properties of the fluid, there is an inverse proportionality between the penetration rate and plastic viscosity, true vertical depth, equivalent bentonite content, laminar flow behavior index, and fluid viscosity at the bit and direct proportionality with Reynolds number at the bit [11]. Drilling rate is not directly dependent on the type or amount of solids in the fluid but on the impact of those solids on the fluid properties, particularly on the viscosity of the fluid as it flows through the bit nozzles. This conclusion indicates that the drilling rate should be directly correlative to fluid properties which reflect the viscosity of the fluid at bit shear rate conditions, such as the plastic viscosity [12].

1.1 Mud Density and Solid Content

The mud density is considered in relation to the HP imposed on the hole. At a given depth, larger the mud density results in larger pressure. When this pressure in the hole bottom is examined, in the face of the formation pressure acting on opposite direction to it, the net effect is called Differential Pressure, that is the difference between the HP and the Formation Pore Pressure. It is this Differential Pressure that affects drilling rate when mud density is considered. High Differential Pressure opposes cuttings removal thus causing regrinding of drill cuttings and retardation of Penetration Rate. It also leads to the strengthening of the rock and causes Chip- Hold – Down [13]. Mud weight is calculated by sum of weights over sum of volumes. It is increased by adding solid materials and decreased by adding water, oil or aerating the fluid [14][15].

Many mud properties vary with its solids content. Though solids slow down drilling rate the prevailing drilling conditions necessitates addition of Bentonite and weighting materials like Barite, Ilmenite etc. to increase mud density and ensure mud's stability in transporting cuttings to the surface. Solids are controlled by installing solids removal equipment at the rig and also adding Polymer materials like Sodium Carboxyl-Methylene Cellulose (CMC) to minimize Bentonite requirement in the mud and make for increased drilling rate [16].

1.2 Objective of the Study

The objective of this study is to identify the effect the weight of drilling mud has on the ROP in rotary drilling. It seeks to investigate what could impede drilling rate and also take a linear approach to determining the economic effects of this variable on the drilling operation.

2. Effect of Weighting Materials on Penetration Rate

Over the years, combined approach to solutions and methods of enhancing drilling fluid in order to increase the Rate of Penetration is being used in the industry with mixed successes. The success of increased ROP has been comfortably achieved through the type of drill bits used but mud properties tend to have great impact on the level in which Penetration Rate would have ordinarily been accomplished [17]. Works performed by several investigators have shown that many bit and fluid components affect PR. More importantly, Darley and Gray [18], in their work using Ilmenite as weighting material to check the effect of weighting material type on ROP showed that while there is less penetration using Barite which produced high mud density, higher penetration was achieved with Ilmenite which was attributed to its moderate mud weight.

In drilling activities, it is important to note that the most indispensable feature of drilling fluid is to remove and transport cuttings to the surface but its ability to accommodate weighting materials is of paramount importance as this stabilizes the well bore [19]. The lighter the mud weight, the faster the penetration rate as all other variables are kept constant [20]. According to them, less dense mud has the tendency to move faster (higher velocity) than heavier mud weight thereby cleaning the hole and allowing new contact point for the bit and fluids. Rheological properties of fluid (Viscosity, Yield point and Gel strength) have less effect on ROP than mud density [21][22]. With less solids content, mud are lighter and move with great velocity; this velocity can push cuttings to the surface in shorter time, thereby ensuring faster PR which was achieved using Ilmenite [2]. According to them, the significant advantage that could be realized from the utilization of lower solids content mud is increase in ROP.

In the fundamental work of EcKel, [23][24] as noted by Bourgoyne et al.,[25] Eckel used Reynolds number to relate bit hydraulics, fluid rheology and ROP under "The Full range of Reynolds numbers". He identified mud density as key factor that affects the flow pattern of these fluids under normal operating conditions. The field reports by Beck et al., [11] showed that the Rate of Penetration increased by lowering mud density and consequently raising Reynolds number and that conventional hydraulics were essentially the same. They further stated that even though the hydraulics house power at the bit remains constant there is a change in PR observed in the field. This change was attributed to change in mud density. Hemphill and Clark [26] demonstrated how the type of bit and mud chemistry affect penetration rates in their work on PDC-Bit Selection and Mud Chemistry effects on Drilling Rates.

Another set of Data was obtained from a field in Alaska to illustrate the properties of drilling mud as it relates with the Rate of Penetration. See Table 5. It was found that PV (Plastic viscosity) and MBT (Methylene Blue Test) both provide suitable correlations to drilling speed and were used to provide basic relationships between rate of penetration and the drilling fluid. The plastic viscosity, by convention was calculated from the Fann Viscometer data as:

$$PV = R_{600} - R_{300} \qquad (1)$$

And the MBT was taken directly from the mud checks. It should be noted that the MBT provides a suitable measurement of the increase in drill solids in the mud, as there were no incremental bentonite additions to the fluid. The clear relationship between plastic viscosity and penetration rate and MBT and penetration rate are shown in Figures 3 and 4 respectively. Thus the basic premise that drilling speed should correlate to solids-related rheological properties is proven. These relationships provide an immediate basis for a fluid treatment program designed to optimize drilling cost.

Product additions during the drilling phase of the well should be made after considering the effects of individual products on fluid plastic viscosity. Fluid-loss additives like PACs, bentonite and Iignites are particularly harmful to PV values, and their use should be minimized or at least not introduced until as late in the well as practically possible without compromising wellbore integrity. The bentonite-free KCl fluids used in the field re-entry sidetrack has been successfully recycled without loss of penetration-rate performance from the fluid. This fact is evident in Figures 3 and 4, shown by the performance of "conditioned" muds. In two attempts to condition recycled fluids to specific plastic viscosity and MBT values, it was demonstrated that the key to fluid performance is in the specific properties generated, not basic mud type (i.e. new vs. recycled muds.) On the initial attempt to condition a recycled fluid, fluid properties fell short of those desired. Plastic viscosity and MBT values were higher than desired, and the fluid performed as if it were simply a used fluid. On the second attempt, plastic viscosity and MBT were conditioned to suitable values, and the corresponding fluid performed as if it were newly built. Thus, maintenance of specific fluid properties is the key to rate of penetration performance. When synthetic diamond insert bits were used, maximum penetration rates were observed for the minimum solids system [27].

3.1 Methodology

The information for this study was collected from the drilling data of eight wells that were drilled in the Niger Delta of Nigeria. Some of these wells were drilled in the same field. In-situ data were also collected from wells drilled in the same region with close relation to the ones collected previously. In all, data from fifteen wells were collected but only those drilled with water and oil base muds are presented. Along with the data obtained for the drilling study, a comparison of the drilling fluid system was also done to determine their effects on the overall drilling operation. The different formations encountered during the drilling operations were also studied and the varying effects highlighted.

The bit types used on these wells were the same Poly Crystalline Diamond (PCD) bits. Plastic viscosity, Viscosity and Yield point were all constant. The Pump flow rate was varied within the range of $\pm$ 2 gpm which made it approximately constant, Weight on Bit (WOB) was kept constant throughout the drilling operations of the intervals selected and Rotary Rounds per Minute (RPM) was maintained at constant rate. Solids and sand content varied based on weight of fluid and weighting material type used. Variation of mud weight was mainly at the depths of 4500ft down to 10,000ft and this interval is studied to determine the effects of mud weight on the rate of penetration. Attention was given to the weight of the mud in relation to the penetration rate. Different mud densities were studied carefully to determine their effects on the ROP. Data from two other different wells [well 5 and 8] where the mud density was approximately the same with increment of just $\pm$ 0.1ppg was analyzed and used as the bench mark to determine the extent in which high mud density impacted ROP.

3.2 Mud System

Two types of drilling fluid were used in the drilling of these wells – water and oil base muds containing 50,000 ppm to 75,000 ppm chlorides. Fluid loss of the mud was controlled with modified lignite, and Pre-hydrated Bentonite was added for viscosity control. The weighting material used was Barite and the properties of these muds are described in Tables 1 and 2.

Table -1: Mud Properties for the Water Base Mud

Well No.	1	2	3	4	5
V, secs	68-80	65-79	68-80	65-70	73-80
PV, cp	13-15	12-14	13-15	13-14	13-15
Gel, lbf/100ft	20-21	20-21	20-21	19-21	19-20
Solids, % by vol.	10-14.8	10.5-16.5	10-16	12.5-13	10-13.5
Sands, % by vol.	0.1-0.25	0.3-0.35	0.2-0.25	0.2-0.25	0.2-0.25
Mud weight, ppg	8.6-12.5	9.7-11.7	10.5-12.5	11-12	8.9-9.0
Chlorides, ppm	63,000–75,000	60000–65000	6000–75000	6000–70000	6000–63000
YP, lbf/100ft^2	18-20	17 - 19	18 -21	18 -19	18-20

Table -2: Mud Properties for the Oil Base Mud

Well No.	6	7	8
Viscosity,secs	65-75	70-80	65-70
Pv, cp	25-40	30-35	30-35
Gel 16f/100ft^2	21-22	2021	20-21
Solids,% by vol.	13-14	13-14	13-14.2
Sand, % by vol.	25-40	20-30	20-20
Mud wt, ppg	10.5-12.5	10.5-12.2	8.0-9.0
Chlorides, ppm	52,000-60000	50000-55000	50000-60000

4.1 Results and Discussions

The results obtained from the analysis of the data of the drilling activities performed using varying mud densities to check the effects of Mud Weight on Penetration Rate are shown in Figures 1 and 2. The different mud weights were varied for both water and oil base muds and the remaining fluid variables were kept constant. Generally, one difficulty in relating ROP to one or more mud properties is interrelationships among those properties. However, this challenge was fixed and mud density separately examined while other properties were kept constant.

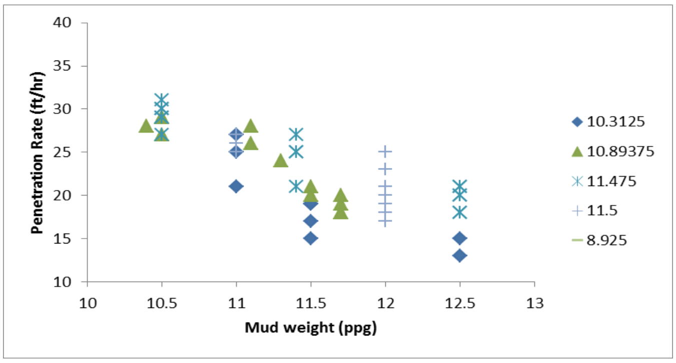

Fig. -1: Penetration Rate vs. mud weight -water based mud

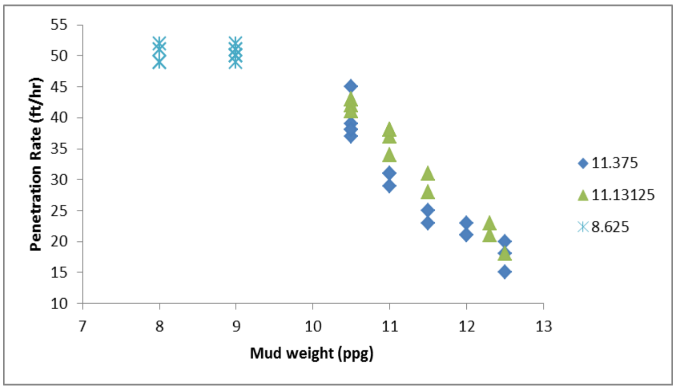

Fig. -2: Penetration Rate vs. mud weight -oil based mud

In Figure 1 the result of using Water base mud with density ranging from 8.9 ppg to 11.8 ppg was shown. Table 1 is the properties of the water based mud. From the result it is observed that for average mud weight of 9.7ppg, while the mud density increased, Penetration Rate reduced – inverse proportionality. The steep slope indicated that the Penetration Rate reduction was significant, as mud density varied. Fluid viscosity and other mud and drilling parameter had little or no effect on the overall performance of the mud and drilling activity. The interval drilled was mainly sand stone, WOB, and bit type had no effects as they were all constant. The result obtained from the work of Donald and Greg [28], shows that mud density impeded Penetration Rate as this can be observed from the fact that the footage drilled using a particular mud density was different from that obtained with another mud weight even though the same formation was drilled and other fluid parameters and drilling variables were kept within range.

The analysis of well data obtained from a sandstone formation drilled with average mud weight of 10.3ppg and 25lbs WOB is also shown in Figure 1. It is observed from the result that variation in mud density had similar effects on penetration rate as that obtained with average mud weight of 9.7 ppg. 4297 ft of hole was drilled for 155 hours with average mud weight of 10.3 ppg. From the result, it can be seen that the reduction in penetration clearly shows that increase in mud weight affected PR. ROP clearly changed (from 33ft/hr to 18 ft/hr) when compared to what was obtained initially and the last recorded. This clearly agrees with the work of Rabia [1] where he stated that while drilling fluid tends to create clearance for bits rotation, its weight however constitutes a menace to the full capacity of bits operation and hence reduced ROP due to high mud density. The result of average mud densities of 11.5ppg and 11.8 ppg is also shown in this Figure. It is observed that the increase in mud density affected penetration rate to a large extent. The two wells were drilled with a constant WOB (25 lbs) and Rotary RPM was uniform for the individual wells.

Even a slight variation in mud weight can have a significant shift in Penetration rate. This means that slight shift in mud density has great influence in the rate at which penetration can go. Overall, it was observed that as fluid properties remained constant and drilling parameters unchanged, penetration rate varied because of the variation in mud weights. The last water base mud has an average mud weight of 8.9 ppg which has a peculiar feature. The slope of the plot is gentle and the penetration rate reduced from 39 ft/hr to 33ft/hr within the mud weight change. The well was drilled with a constant WOB (25lbs) and uniform Rotary rounds per minute (40 RPM). The particular interval analyzed has little variation in mud density and consequently, the penetration rate was not affected significantly by the mud density. This could be attributed to the uniformity of the fluid and drilling variables. Although there is a $\pm$ 5 ft/hr in Penetration Rate, this may be due to lithological variations.

From all these results which follow the same trend, the lighter the mud weight, the faster the penetration rate when other variables are kept constant. This conclusively, means that when mud weight remains constant penetration rate will not change significantly. Figure 2 and Table 2 represent wells 6 to 8 drilling and oil base mud data and like the previous wells, all other data were constant. It is noted that from the result, the oil base mud followed same pattern as the water base mud. Penetration Rates were significantly reduced as the mud density increased. This shows that with low Solids content, muds are lighter and move with great velocity, which can push cuttings to the surface in short time and hence create faster ROP.

While oil base mud can provide reasonable PR in most situations; they have provided notoriously slow rates in most wells where the Solid content is high and maximum PR is obtained for minimum solids system. No sharp decline in PR was seen, but however, there was a reduction in PR which can be attributed to increased Solids content which is a function of high mud density. This was equally observed in well number 7. The result of the effects of Mud weight on ROP using oil base mud of average density 9.0 ppg shows no variation in Penetration Rate as the mud density remained constant. The mud properties and other drilling parameters were kept constant.

The near straight plots obtained indicate that the mud density was not changed and the penetration rate remained almost constant. From the data, it is observed that WOB was 25 lbs and pump pressure was 453 $\pm$ 2 gpm. This result and that of the water base mud of average mud weight of 8.9 ppg is a clear indication that when drilling fluid and drilling parameters are kept constant, we will record a uniform penetration rate. Taking a difference between these results, one can readily say that the water base mud weight of 8.9 and the oil base mud weight of 8.6 ppg, where the mud weight was not varied produced an almost clear uniform Penetration Rate. This indicates that uniform Mud weight will produce uniform Penetration Rate if all other drilling parameters and formation strength remains constant. The same pattern of penetration was obtained from both oil and water base muds but oil base mud would have produced better penetration rate if formations where they were used were the same (Sandstone/Shale).

With the low (steady) mud weight used in drilling well 5, the penetration rate was between 33-39 ft/hr. Similarly, in the well 9 drilled with oil base mud, a constant mud density (9.0ppg) recorded an average of 50 ft/hr footage, while mud with density of 11.0 ppg drilled an average of 30ft/hr. This implies that at every hour drilled with over-weighed mud, 20 feet is lost.

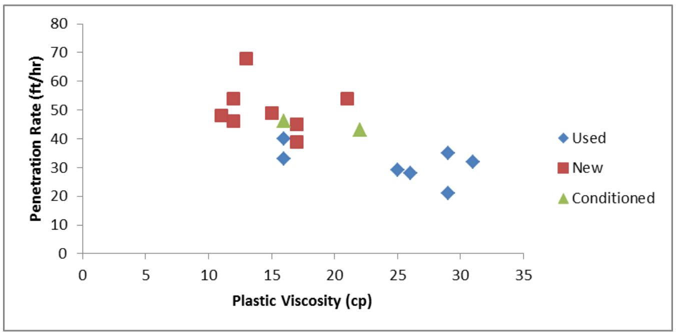

Fig.-3: Penetration Rate vs. Plastic viscosity for sandstone/ shale formation

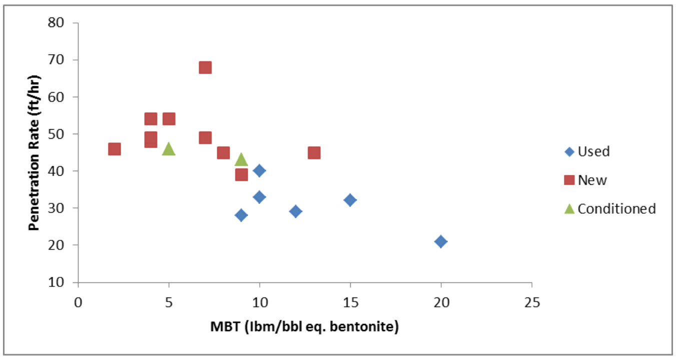

Fig.-4: Relationship between Penetration Rate and MBT

4.1 CONCLUSIONS

Field data analyzed indicated that significant increase in Penetration Rate can be obtained by the appropriate choice of mud density. The properties for each of the wells did not appear to be the deciding factor. The most deciding factor that enhanced Penetration rates was the low Mud density which is done by keeping other parameters of the fluid constant. However, maintaining a uniform mud density showed that Penetration Rate remained relatively constant as drilling progressed.

Selecting the correct mud weight for drilling the individual sections constitutes a key factor to realizing effective drilling and avoiding borehole problems. Too low mud weight may result in collapse and fill problems, while too high mud weight may result in mud losses or pipe sticking. Practice has also shown that excessive variations in mud weight may lead to borehole failure, thus a more constant mud weight programme should be targeted. Care should be taken in the choice of mud weight to avoid pipe sticking and lost circulation during drilling operation. Consequently, while weighing the options of borehole problems, the mud density should equally be considered as a tool which can if not properly managed increase the drilling cost.

NOMENCLATURE

CMC	-	Carboxyl Methylene Cellulose
Cp	-	Centipoise
CHDP`	-	Chip Hold Down Pressure
D	-	Depth
FV	-	Fluid Viscosity
HP	-	Hydrostatic Pressure
Gal	-	Gallon
gpm	-	Gallon per minute
lbf	-	Pound force
lbs	-	Pounds
MBT	-	Methylene Blue Test, Ibm/bbl bentonite
PAC	-	Polyamionic Cellulose
PCD	-	Poly Crystalline Diamond
Ppm	-	Parts per million
Ppg	-	Pounds per gallon
PR	-	Penetration Rate
PV	-	Plastic Viscosity
ROP	-	Rate of Penetration
Rpm	-	Rounds per minute
Sec.	-	Seconds
Vol.	-	Volume
WOB	-	Weight on Bit
YP	-	Yield Point
ρm	-	Mud density

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