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Synergizing Controlled Annular Mud Level Technique and Drilling Fluid Performance to Optimize the Casing Design Program

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Abstract

Controlled Annular Mud Level (CAML), is a Managed Pressure Drilling technology used to drill deep and ultra-deep offshore wells, which is often encountered by narrow and challenging operating windows. This technique uses a submersible pump to change the liquid level in the riser to precisely control the bottom-hole pressure during drilling operations. The flexibility in changing the liquid level in the riser allows the use of higher density drilling fluids as well as higher pump rates.

In this paper, a sensitivity analysis is carried out to study the possibility of synergizing the CAML drilling technique and drilling fluid performance to optimize casing design program. Drilling fluid density, fluid's rheological properties, sagging potential, lost circulation, and hole-cleaning are the main variables investigated.

The results show that if sag prevention properties and fluid rheological parameters are controlled, changing the liquid level in the riser in conjunction with using higher density drilling fluids will enable to drill deep and challenging offshore wells. In addition, the number of casing strings can be reduced considerably by using this synergistic approach.

A case study is performed in this paper for an offshore well in Black Sea to validate this approach. The validation reveals that if the synergistic approach is applied, the number of casing strings is reduced by around 26% in comparison to casing design in conventional drilling. The paper also proposes a best practice guideline of how to synergize the CAML drilling technique and drilling fluid performance to optimize the casing design program.

Introduction and Literature Review

In recent years, the fast advance in technology has allowed a continuous expansion of oil and gas frontiers. Just few years ago, part of the reservoirs being explored today were considered unreachable either due to high cost of the required drilling technology, or simply due to the lack of technology. One of the greatest expansion can be seen on offshore exploration, where seawater levels have gone from 3,000 ft to 10,000 ft with total measured depths of up to 30,000 ft. The large reservoirs and high production rates found offshore justify the high cost associated with these explorations. The cost of an offshore well is now approximately in the range of hundreds millions of dollars (Sugden et al. 2014; Godhavn et al. 2014).

There are several challenges to be overcame when drilling offshore wells. One of the most common challenges is drilling in narrow operating windows. Narrow operating windows are a tight difference between pore pressure and fracture pressure. An offshore well often requires high number of casings strings, more material, extra operational time and logistics, and higher chances of Non Productive Time (NPT). For a high cost well to be profitable, high production rates are required. To achieve the necessities of production rates, a minimum production tubing and production casing size needs to be available. The increased number of casings strings limits the maximum production casing size of the well, which significantly affect the project economics. Therefore reducing number of casings strings and NPT time is key to the profitability of the project.

Controlled Annular Mud Level is a Dual Gradient Drilling (DGD) technology item. Controlled Annular Mud Level drilling uses a subsea mud lift pump module set at mid-riser level and a mud return line to circulate the mud back to the rig. This allows to vary the fluid level in the riser, above the subsea mud lift pump location (Ziegler et al. 2013). By changing the relative pumping rates between the rig pump and the subsea mud lift pump, the fluid level inside the riser will change. The change in fluid level affects directly the hydrostatic pressure, which has great impact on the annular pressure profile. The variation of fluid level improves Bottom Hole Pressure (BHP) control. The fluid level can be changed to compensate for Equivalent Circulating Density (ECD), and use heavier fluid in order to mimic the operating window pressure profile. The improved BHP control allows to compensate for any unexpected variation in the formation pressure. The faster detection of the kick/lost circulation event improves the drilling safety, and allow to reduce NPT (Ziegler 2014). The use of two fluids with different gradient in Controlled Annular Mud Level drilling is another advantage. For example, drilling with air on upper part of the riser allows the potential use of a heavier fluid on bottom. The heavier fluid results in an annular pressure profile that tends to stay inside the operating window for longer sections. The kick tolerance is also improved by the use of heavier fluid. Therefore the number of casings will be reduced, which leads to improvements in casing design. (Schubert et al. 1999)

In order to optimize the Controlled Annular Mud Level drilling in terms of reduced number of casings strings, it is important to design a high density fluid with low ECD. In certain conditions, such as drilling naturally fractured sands, the concern of riser collapse should be considered in terms of designing a fluid that minimize/reduces the risk of lost circulation events. The design must not neglect the key requirements of the drilling fluid as defined by Bourgoyne et al. (1991) and Hoover et al. (2009), namely hole cleaning, primary well control, borehole stability and clays inhibition, etc. In order to attend these requirements, the drilling fluid must contain viscosifiers, filtration control, and weighting materials. Weighting material, the material added to the fluid system to increase its density, is usually in suspension. The most common weighting material is the conventional API barite. According to many studies, higher concentration of API barite increases the potential of barite settling. Barite settling, also known as Barite Sag, can lead to bed formation and fluctuation in the fluid density, which affects bottom hole pressure and can lead to kick or lost circulation. Barite Sag is more common on inclined and horizontal sections than in vertical. Nguyen et al. (2014) found that annular velocity has the most contribution in reducing the dynamic potential of Barite Sag and set a minimum annular velocity of 150ft/min to avoid Barite Sag. To avoid Barite Sag during long static periods, it is necessary to have a fluid design with increased gel strength. Another possibility to avoid Barite Sag is the use of Micronized Barite, which has a reduced size particle that minimizes the risk of Barite Sag. Sharma et al. (2015) revealed, that micronized barite is able to mitigate barite sag in a well shut for 13 days. It was also utilized to reduce fluid's rheological properties, reducing ECD and improving drilling in a narrow operating window. (Hanson et al. 1990; Nguyen et al. 2009; Nguyen et al. 2014; Bern et al. 1996).

This paper will discuss the potential synergy of Controlled Annular Mud Level drilling with drilling fluid performance to optimize casing design program. The effects of fluid's rheological properties, fluid density, and annular velocity on the casing design in Controlled Annular Mud Level drilling is investigated. The application of micronized barite fluids in Controlled Annular Mud Level drilling is also discussed.

Results and Discussion

General Casing Design

It is very important in casing design to reduce the number of casing strings and reduce the total length of the casings. The number of casings strings greatly depends on three important factors, namely operating window, kick tolerance, and the flowing bottomhole pressure or equivalent circulating density (ECD). The pore and fracture formation pressures are mainly functions of well depth and formation properties. It is common in designing and completing an oil or gas well, that the pore and fracture pressure gradient curves are assumed to be fixed. In other words, the operating window is not controllable when designing a particular well. The kick tolerance is the maximum amount of formation gas entering the wellbore at which the well is shut-in and the kick is circulated out safely without damaging the casing shoe. The kick tolerance depends mainly on the kick intensity, i.e. the difference between the maximum anticipated pore pressure and bottomhole pressure. Static bottomhole pressure is the only factor that can affect the kick tolerance. ECD is the summation of the fluid density and the equivalent density (ED) of the frictional pressure in the annulus. ECD can be controlled by changing the hydrostatic pressure, circulation flow rate, and drilling fluid's rheological properties. Generally speaking, the minimum number of casing strings can be achieved by controlling the hydrostatic pressure, circulation flow rate and drilling fluid's rheological properties.

In conventional drilling, controlling the hydrostatic pressure can be done by changing the fluid density. However, in Controlled Annular Mud Level drilling, the hydrostatic pressure can be controlled by the fluid level in the riser in addition to the fluid density. The static bottomhole pressure in the Controlled Annular Mud Level drilling is calculated as follows:

$$ED = \rho_m \frac{TVD-REL}{TVD} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ρ_m is the drilling fluid density in ppg; TVD is the total true vertical depth in ft; and REL is the riser empty level in ft.

One of the objectives in casing design is to keep the flowing bottomhole pressure as close as possible to the static bottomhole pressure. If this objective is achieved, then the casing seat can is set at a shallower depth, resulting in a less total length of casing strings. Also, Eq. 1 indicates that increasing the riser empty level results in reducing the hydrostatic pressure causing a lower equivalent density. This reduction in equivalent density can be compensated by using either higher fluid density or higher circulation rate. In other words, by controlling the fluid density or/and the circulation rate, the ECD in Controlled Annular Mud Level drilling can be kept similar as the equivalent density in conventional drilling at which the riser empty level equals to zero.

Casing Design in Conventional Drilling

Figure 1 shows an example of how to obtain the number of casing strings in casing design with conventional drilling when using a conventional barite drilling fluid. The well, located in black sea, has the target depth of 18,143 ft (5,500 m), and a water depth of 8,202 ft (2,500 m). The equivalent densities of the pore and fracture formation pressures are shown in Fig. 1 (Rocha, 2001) Note that the safety margins of 0.3 and 0.5 were included to the pore and fracture pressure curves shown in Fig. 1, respectively. The annular velocity of 3.0 ft/s (0.914 m/s) is applied for all the simulations runs. The drilling fluid used has a yield point (τ_y) of 18 lbf/100ft^2, and Bingham plastic viscosity (μ_p) of 18 cp. The frictional pressure loss in the annuli between each casing and the hole is calculated. The ECDs in each casing were then computed and shown in Fig. 1. The number of casing strings attained using casing design conventional drilling is five with a total length of 28,543 ft (8,700 m).

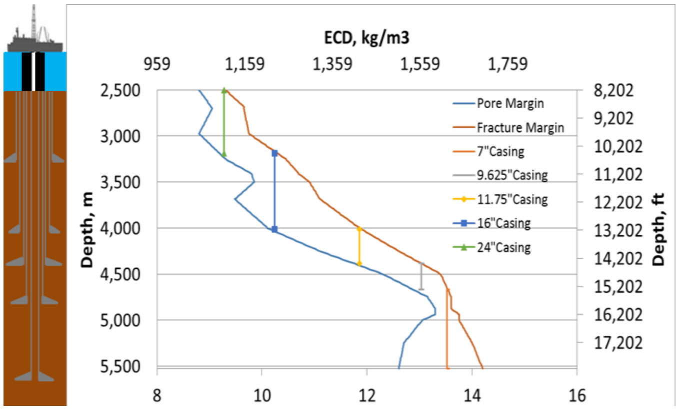

Figure 1: Casing setting depth in conventional drilling with conventional barite drilling fluids

Micronized barite drilling fluid has proven to have a minimal sag potential and offer a lower ECD when comparing it with the conventional barite drilling fluid (Sharma et al. 2015). Let's consider a micronized barite drilling fluid, which has τ_y = 8 lbf/100ft^2 and μ_p = 20 cp. Because of the lower yield point of the micronized barite comparing to the conventional API barite, the frictional pressure loss is less leading to a reduction in ECD. Note that this comparison is carried out by keeping the fluid densities and annular velocities in all of the simulations the same. Another advantage of using micronized barite fluid is that the annular velocity can be kept at a low value to reduce the ECD. As long as the value of annular velocity is maintained to have an efficient hole cleaning, sag is not a concern with micronized barite fluids (Sharma et al. 2015). Figure 2 shows the casing setting depth when using micronized barite drilling fluid. Comparing Fig. 1 and Fig. 2 reveals that the number of casing strings when using the different fluids is the same but different in setting depth. When using the micronized barite, the casing depths of each casing can be set shallower and hence helping to reduce the total length of the casings from 28,543 ft to 26,250 ft. This reduction is about 8% of the total casing length.

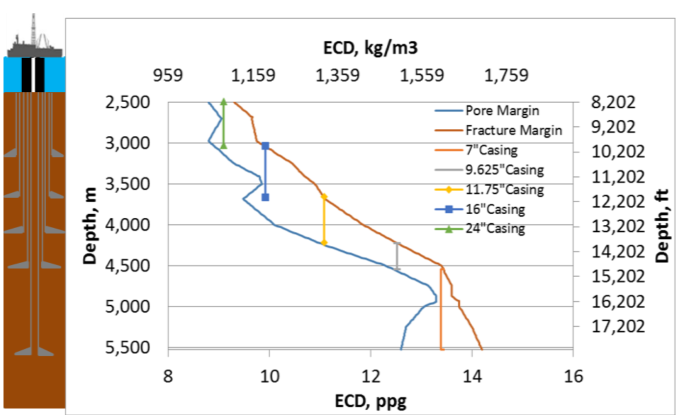

Figure 2: Casing setting depth in conventional drilling with micronized barite drilling fluids

Casing Design in CAML Drilling

Figure 3 shows the behavior of equivalent density calculated by using Eq. (1) when changing the riser empty level. In these simulations, a constant fluid density of 15 ppg was used. If the riser empty level equals to zero then the equivalent density is a vertical line as shown in Fig. 3. As the riser empty level gets higher, the static bottomhole pressure decreases. The equivalent density is no longer a vertical line; instead it is curved because of the zero equivalent density in the riser empty level. In general, when the riser empty level is higher, the static bottomhole pressure (or equivalent density) is less and the equivalent density -curves shift to the left. Therefore, a heavier drilling fluid and a higher circulation rate can be used in Controlled Annular Mud Level drilling to have a similar circulating bottomhole pressure.

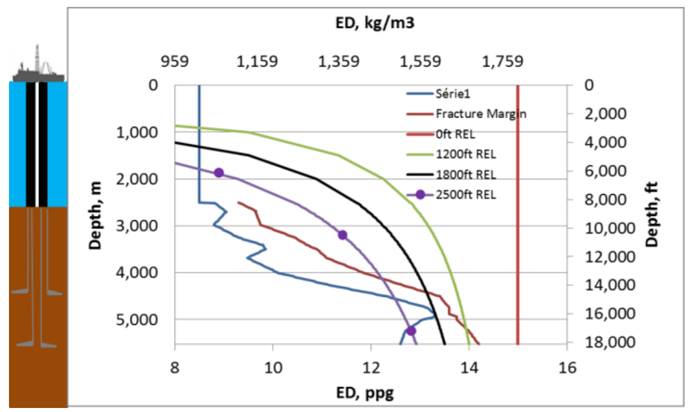

Figure 3: CAML drilling with heavier drilling fluid

Figure 4 shows the casing setting depth when using Controlled Annular Mud Level drilling in conjunction with the use of heavier drilling fluids. In this simulation, a riser empty level of 2,100 ft (640 m) and the annular velocity of 3 ft/s (0.914 m/s) were chosen. The fluid density used for the deepest casing was 15.3 ppg which is 2 ppg more than that in conventional drilling (REL = 0). However, with the value of REL of 2,100 ft, the ECD at 18,000 ft (5,500 m) is 13.8 ppg. In addition, as mentioned in the previous discussion, the ECD profile in the Controlled Annular Mud Level drilling is not a vertical line, but it is curved. Because of these reasons, when applying the graphical casing design method, a total number of casing strings reduces from five to three casings. Controlled Annular Mud Level drilling with heavier density fluid reduced the total length of casings from 26,250 ft to 21,095 ft. This reduction is about 26% when comparing to the casing design in conventional drilling.

All the simulations carried out so far are for the case of 2,100 ft of REL. One of the most critical concerns when operating risers in offshore drilling is the critical-riser collapse pressure. According to Ziegler (2012 and 2014), the common critical collapse pressure for most of the risers is in the range of 860-1,300 psi (REL of 2000-3000 ft). When changing the riser empty level values from 2,100 to 3,000 ft, the fluid density was allowed to increase from 15.3 to 16.2 ppg to keep the bottomhole pressure inside the operating window. The simulation runs show that the number of casing strings remains the same and the casing setting depth are similar to that in Controlled Annular Mud Level drilling for the case of 2,100-ft of REL. In summary, it can be concluded that, the number of casing strings of three is the minimum/optimum value for this well with REL range of 2,000-3,000 ft and fluid density in last casing ranges from 15.3-16.2 ppg.

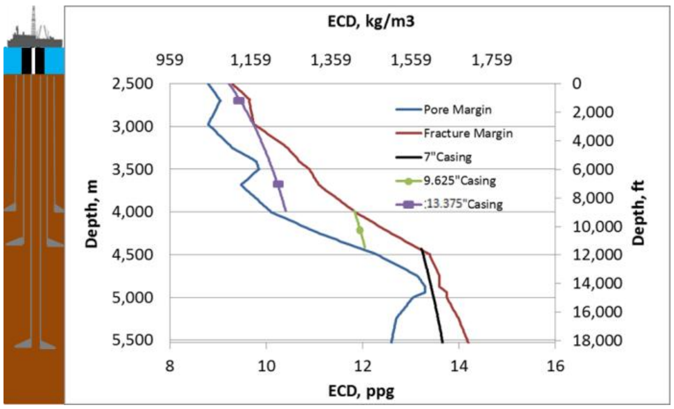

Figure 4: Casing Setting Depth in CAML Drilling

Effect of Fluid Properties and Annular Velocity in CAML Drilling

It is well known that using weighting materials may affect the viscosity of drilling fluids. In this analysis it is assumed that drilling is performed with a fluid satisfying the Bingham viscosity model. If the values of yield point or plastic viscosity are too high due to the high fluid density, the ECD can be high resulting in a poor performance of Controlled Annular Mud Level drilling. Therefore, it is important to know the limitations of yield point, plastic viscosity and annular velocity to obtain an optimal casing design.

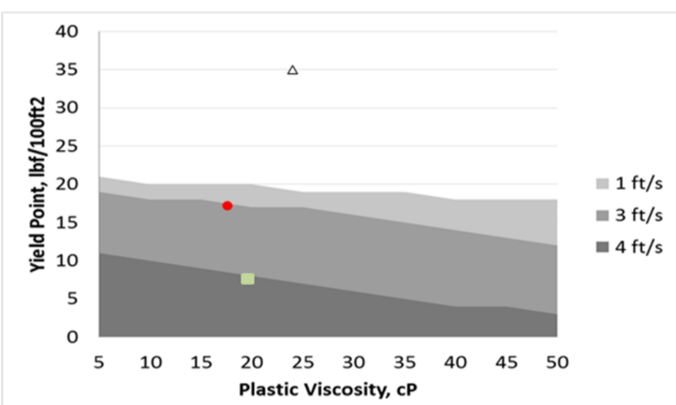

Figure 5: Fluid and Annular Velocity Design for Optimized CAML Drilling (REL of 2,100ft; Casing Amount of 3)

The sensitivity analysis was carried out by varying the values of yield point, plastic viscosity and annular velocity in such a way that the number of casing strings remains an optimum value of three. The ranges of yield point, plastic viscosity, and annular velocity were chosen as follows: 0-40 lbf/100ft^2, 5-50 cp, and 1-4 ft/s, respectively. These ranges are the most common ones in drilling operations (Van Oort et al. 1996, Siffeman et al., 1997, and Sharma et al., 2015). The results as illustrated in Figs. 5 and 6 show the limit lines for different combinations of plastic viscosity, yield point and annular velocity that can be used and keep the minimum number of casing strings of three. Figure 5 also shows three data points representing three different fluids for three applications. The lowest yield point fluid application is for micronized barite fluid when using Controlled Annular Mud Level Drilling. This fluid has a yield point of 8 lbf/100 ft^2 and plastic viscosity of 20 cp. Figure 5 shows that if the annular velocity is varied from 1 to 4 ft/s, the number of casing strings is still an optimum value of three. The other two applications are interpreted similarly. Note that the only difference between Figs. 5 and 6 is the values of the riser empty level. The values of the riser empty level in Figs. 5 and 6 are 2,100 ft and 3,000 ft, respectively. Comparing the results in Figs. 5 and 6 reveals that the higher the values of the riser empty level, the wider the range of fluid rheological properties and the annular velocity will be.

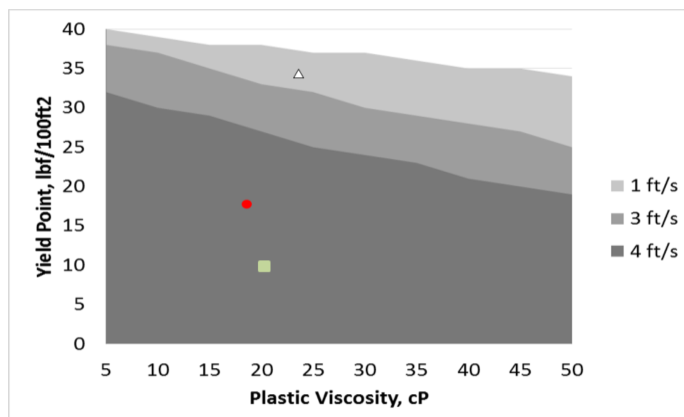

Figure 6: Fluid and Annular Velocity Design for Optimized CAML Drilling (REL of 3,000ft; Casing Amount of 3)

Concluding Remarks

In this paper, an approach of synergizing drilling fluid performance and Controlled Annular Mud Level drilling to optimize the casing program is introduced. The sensitivity analysis was carried out by changing key variables, including fluid's rheological properties, fluid density, and annular velocity to optimize the casing design. The benefits of the new approach can be summarized as follows:

- Offers wider ranges of yield point, plastic viscosity, fluid density, and annular velocity for optimal casing design.
- Reduces the number of casing strings and the total casing length
- Mitigate sag and lost circulation problems.

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Nomenclature

BH = *Bingham Fluid*
BHP = *Bottomhole Pressure*
CAML = *Controlled Annular Mud Level*
DGD = *Dual Gradient Drilling*
ECD = *Equivalent Circulating Density*
ED = *Equivalent Density*
NPT = *Non Productive Time*
REL = *Riser Empty Level*
TVD = *True Vertical Depth*

Units

ppg = *pound per gallon*
ft = *feet*
cp = *centipoise*
m = *meter*
psi = *pounds per square inch*
kg = *kilogram*
s = *second*
lbf = *pound force*

Greek Letters

τ_y = *Yield Point*
μ_p = *Plastic Viscosity*
ρ = *Fluid Density*

Subscripts

$_m$ = *Mud*

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