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Hydraulic Behaviour of Annular Pressure Loss and Circulating Pressure in Extended Reach Wells: A Simulation-Based Study

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***Abstract**: This study presents a comprehensive simulation analysis of the behavior of annular hydraulic systems in Extended Reach Wells (ERWs) using the Wellplan software package, with particular emphasis on annular pressure loss and the effects of circulating pressure under various drilling parameters. Because the fluid dynamics in ERWs are highly complex due to the long lateral sections of the wellbore, the simulation analysis investigated the hydraulic system's sensitivity to changes in mud weight, pump rate, rate of penetration (ROP), and cuttings density. The results show that annular pressure loss is inversely proportional to mud weight. Increasing the mud weight from 10 ppg to 10.8 ppg reduces the pressure loss from 2135.2 psi to 2117.08 psi. This indicates a lower average velocity through the system due to the damping effects of the fluid mass. However, the circulating pressure increases from 7285.08 psi to 7693.85 psi because of the linear increase in mud weight. The effect of pump rate exhibits non-monotonic behavior. Specifically, annular circulating pressure decreases from 7846.93 psi to 6201.6 psi as pump rate increases from 200 gal/min to 300 gal/min, but then the trend reverses when pump rate increases to 400 gal/min. This suggests the existence of a threshold beyond which the combined effects of inertia and frictional resistance become dominant. An increase in ROP from 20 ft/hr to 50 ft/hr produces only a marginal increase of 0.02% in annular pressure loss and a 0.15% increase in annular circulating pressure. In contrast, increasing cuttings density from 2.1 sg to 2.18 sg results in a slight decrease in pressure loss and a moderate 0.22% increase in circulating pressure, implying a secondary effect of cuttings-bed loading on overall pressure behavior. Overall, this study highlights the relative importance of mud weight and pump rate as the most critical controllable factors affecting downhole pressure profiles in ERWs.*

Keywords— Annular circulating pressure, Annular pressure loss, Extended Reach wells, Wellplan software, Hydraulics

1. INTRODUCTION

The development of extended reach drilling technologies has redefined the limits of access to the subsurface. Consequently, the ability to access hydrocarbon reservoirs at long horizontal offsets from the surface location has opened up numerous opportunities for the development of hydrocarbon reservoirs. These include offshore field development, marginal hydrocarbon reserves, as well as environmentally sensitive areas. Indeed, extended reach well development is highly advantageous for the aforementioned areas. On the other hand, the geometrical complexities of ERWs have redefined the importance of drilling hydraulics. Within the aforementioned realm of ERWs, annular circulating pressure as well as annular pressure losses have been redefined as significant output parameters. Indeed, the aforementioned output parameters have a direct bearing on the efficiency of the ERWs. Furthermore, ACP as well as APL have been found to be highly sensitive to various input variables. These include mud weight, pump rate, rate of penetration, rotary speed, as well as cuttings density. Indeed, the aforementioned input variables have a significant bearing on the hydraulic environment of the ERWs.

However, the drilling hydraulics in ERWs require a critical balance between keeping sufficient bottomhole pressure to prevent influxes into the well and keeping it low enough so that the formation is not fractured. ACP is "the summation of the pressures acting in the annulus caused by hydrostatic head, frictional loss, and dynamics." It is the governing factor in the balance between the above-mentioned pressures and is critical in keeping the pressure between the pore pressure and fracture pressure termed the "drilling margin." APL is "a measure of the opposition to the flow of the drilling fluid in the annulus." It is a significant factor in ACP since it is a major factor in frictional loss, which is a function of a variety of fluid and flow properties, especially in ERWs with high-angle or horizontal wells where cuttings transport is an issue [6].

Mud weight has a dual effect on the hydraulic regime. It is the major factor that determines the hydrostatic component of ACP and is very important when managing formation pressures. However, when the mud weight increases, the fluid becomes more dense, which causes the fluid's viscosity to increase as well. This increases the fluid resistance as the mud weight increases. This means that as the mud weight increases, the frictional drag that the fluid encounters becomes more substantial, which causes the APL to increase as well [10]. In addition to that, when the mud weight increases, the fluid becomes less effective at carrying cuttings, which causes an indirect effect on the fluid resistance as cuttings bed formation increases. This causes the fluid pressure to increase as well because of the cuttings bed formation. This shows that when designing ERWs, the effect of mud weight on fluid resistance needs to be considered properly [12].

On the other hand, the pump rate or flow rate is one of the major contributors to annular velocity. This has a major impact on cuttings transport as well as frictional pressure loss. When the pump rate increases, cuttings transport is improved as the fluid velocity increases, reducing the settlement of cuttings. However, there is a major disadvantage that comes with increased flow rates or pump rates. When the flow or pump rates increase, the frictional pressure loss increases as well because of the high flow rates or turbulent flow. The APL increases non-linearly with the pump rate, especially when the annulus is narrow and the flow is highly inclined. The major challenge with ERWs is that the horizontal section is long and the energy required to overcome the frictional barrier as well as gravity is high. When the pump rates increase to improve hole-cleaning capabilities, the APL increases to a point where the ACP approaches or exceeds fracture pressure, especially near the heel of the well [2].

Another level of complexity is the introduction of the concept of the rate of penetration (ROP). An increase in the ROP implies that the cuttings transported per unit time will increase. Consequently, the solids loading of the annular flow will increase. Failure to properly transport the cuttings will result in their accumulation along the low side of the wellbore, particularly in horizontal or near-horizontal wellbores. This will cause a reduction in the flow area as well as changes in the rheology of the cuttings-fluid mixture [5], [4]. Consequently, the apparent viscosity of the fluid will increase sharply. An increase in the ROP is desirable from the point of view of increasing the efficiency of the wellbore operations. An increase in the pump rate is therefore necessary to match the increased ROP to prevent hydraulic overload [12].

Although rotary speed is traditionally linked to the mechanical properties of the drilling process, such as the rotation of the drill bit, it is also connected to the hydraulic behavior. Indeed, the rotation of the pipe generates secondary flow patterns, creating turbulence in the annular flow, which interferes with the natural settling behavior of cuttings. This may be beneficial for the removal of cuttings beds, especially for hole cleaning [1]. Nevertheless, it generates dynamic fluctuations in the energy losses, especially for deviated wells where the flow is asymmetric. Indeed, at high rotary speeds, the turbulence may generate important energy losses, thus increasing the APL [11]. Moreover, the combination of the rotation of the pipe and the high viscosity of the mud may generate pulsating flow, which complicates the management of the real-time pressure [3].

Density and morphology of cuttings are not commonly considered factors in APL and ACP; however, they do play a vital role in their determination. Larger and heavier cuttings are more difficult to suspend and transport, especially in a laminar or transitional flow regime, which is common in low pump rates and high-angled sections [5]. As this occurs, it increases the overall resistance to flow, thus increasing APL and, in turn, ACP. Furthermore, because drilling fluids are non-Newtonian in nature, this increases their viscosity as more solids are introduced into the system, especially when they are in contact with bentonite and polymer fluids [8].

Other factors that could play a vital role in increasing APL and, in turn, ACP include wellbore geometry, especially annular clearance and wellbore inclination angles. As earlier explained, the shape and size of this annular space determine the cross-sectional area through which fluids flow, thus affecting their velocity [8]. In ERWs, where horizontal and high-inclination sections are dominant, this annular cross-section is not a perfect circle because of the eccentricity of the drill pipe [9]. This asymmetry gives rise to complex flow regimes such as stratified, slug, and laminar-turbulent flow, each having different characteristics in terms of pressure losses. Moreover, temperature and pressure changes along the wellbore cause fluid density and viscosity to change, impacting both hydrostatic and frictional components of ACP. In deeper wells, thermal thinning of the mud reduces viscosity, while pressure-induced gelation in some fluids increases viscosity, causing unexpected pressure anomalies [6].

From the above discussion, it is obvious that ACP and APL in ERWs are controlled by a complex array of factors, including those related to hydraulics, mechanics, and formation interactions. It is also obvious that conventional well models are not capable of capturing complexities related to horizontal wellbores, variable well inclinations, and variable drilling conditions. Accurate modeling and control of ACP and APL require advanced computing techniques, validated empirical correlations, and field data assimilation [7].

The objective of this research is to critically examine the effects of mud weights, pump rate, rate of penetration, rotary speed, cuttings density, etc., on annular circulating pressures and annular pressure losses while drilling ERWs. By critically analyzing the parameters through modeling, simulating, and where possible, validating the results, this research aims to contribute to the better understanding of the interaction of these parameters, thereby enhancing the knowledge of the effects of these parameters on wellbore hydraulic behavior. This research aims to develop a more effective analytical framework for the design, simulation, and implementation of wellbore hydraulic behavior, thereby enhancing the efficiency of the well construction process while drilling ERWs.

2. MATERIALS AND METHODS

2.1 Materials

Drilling hydraulics analyses is to be conducted in Well AS3 in Asa field in the Niger Delta, which is an extended reach well. The hydraulic investigation focuses on the annular pressure loss and the annular circulating pressures. The parameters of the ERD well are given below and include the general parameters, the well parameters, the string parameters and the hydraulic parameters.

Table 1: General Data

S/N	Parameter	Value
1	Mud weight	10.8 ppg
2	Block weight	90 kips
3	Block rating limit	1500 kips
4	Friction factors	0.25 OHFF/1.5CHFF
5	Total Well depth	35,017 ft
6	Section of Well under investigation	From 12,015 ft to 35,017 ft
7	Reservoir temperature	220°F
8	Geothermal gradient	1.74°F/100ft
9	Trip speed	60 ft/min
10	Slack-off weight (sliding)	20 kips
11	Maximum yield of Overpull	90%
12	Rheological model	Herschel-Bulkley

Table 2: Hole and Casing Data

S/N	Parameter	Value
1	Conductor Pipe	30 in OD, 28.5in ID, 234ppf, runs from surface to 400ft
2	Surface Casing	13-3/8 in OD, 12.415 in ID, 68ppf, runs from 400ft to 6102 ft
3	Intermediate Casing	9-5/8 in OD, 8.535 in ID, 53.5ppf, runs from 6102 ft to 12,150 ft
4	Hole Section	8-1/2 in Hole runs from 12,150 ft to 35,017 ft

2.2 Model Simulation

In order to carry out hydraulic simulations using Wellplan software for the evaluation of annular pressure losses and annular circulating pressures, it is important to follow a series of steps, which would ensure the accuracy of the results, especially for more complicated well designs such as Extended Reach Wells (ERWs). To start with, the Wellplan software is opened, after which a new well project is created. In the well project environment, the complete well trajectory is defined, including the vertical, horizontal, casing, and open hole sections. For ERW wells, the representation of the long horizontal section is critical, as it has major implications for the annular frictional pressure losses. Data such as hole diameter, casing OD, casing ID, well depth, measured depth, true vertical depth, etc., are fed into the trajectory and geometry sections.

Subsequent to this, the properties of the drilling fluid are defined. This includes the mud weight to be entered in pounds per gallon (ppg) or specific gravity (sg) units. This also encompasses the rheological properties of the drilling fluid, such as plastic viscosity, yield point, and the flow behavior index. For the purpose of sensitivity analysis of the mud weights, a number of simulation scenarios are defined. In these scenarios, the mud weights are varied over a given range while all other parameters are kept constant. For instance, the mud weights can be varied from a minimum of 10.0 to a maximum of 10.8 ppg. Subsequent to this, the pump rate is defined in terms of gallons per minute (gal/min). This parameter defines the volume rate of the drilling fluid being pumped through the system. For the purpose of analysis, different simulation scenarios are defined for the pump rates. These scenarios include a range of low to high values, such as between 200 to 400 gal/min. The effects of the changing values of the pump rates are observed. This includes the impact of the fluid velocities on the friction pressure loss and the resulting annular circulating pressure.

Next, the Rate of Penetration (ROP) is input into the model. The ROP will directly affect the generation of drilled cuttings. By varying the input of different ROP values, for example, 20, 35, and 50 feet per hour, the simulator will recalculate the cuttings loading. This will have an effect on the equivalent circulating density (ECD) and the pressure gradients. The rotary speed is another factor that is included in the simulation. Although the rotary speed is not a hydraulic parameter per se, in horizontal wells in ERWs, the cuttings transport may be affected indirectly by the rotary speed. The rotary speed is therefore varied to study the effects of cuttings transport on the annular pressures.

Cuttings Density is another input parameter to the simulator. This is particularly significant in ERWs. Cuttings transport is critical in ERWs to prevent cuttings accumulation. The cuttings density is input as specific gravity. The specific gravity of the cuttings is usually between 2.1 and 2.3. By varying the cuttings density input to the simulator, the effects of the cuttings on the pressure loss will be studied. Like in the previous parameters, only one variable is changed at a time.

After all the input parameters have been defined, the software runs the hydraulic model. The relevant outputs of interest, i.e., annular pressure loss and annular circulating pressure, are extracted from the results dashboard. Annular pressure loss represents the frictional pressure loss as the fluids flow through the annulus. On the other hand, annular circulating pressure is the total pressure at the bottom of the well during circulation. It is the sum of hydrostatic pressure, frictional pressure loss, and any surge pressures present.

All the simulation runs are recorded. The outputs of the simulation runs are compared. Graphs can be plotted to compare the outputs. For example, increasing the mud weight will increase the hydrostatic pressure. This will increase the annular circulating pressure. The annular pressure loss will either remain the same or decrease slightly due to the increased mud weight. Similarly, increasing the pump rates will increase or decrease the annular pressures depending on the flow regime.

2.3 Sensitivity Analyses

Sensitivity analyses were conducted to evaluate the influence of key input parameters on the Annular Equivalent Circulating Density (AECD). The parameters examined included pump rate, rate of penetration (ROP), rotary speed, and cuttings density. The results of the sensitivity assessments for each of these variables are presented in Table 3.

Table 3: Sensitivity Analyses values

Parameters	**Values**
Mud Weight	10.0 to 10.8 ppg
Pump Rate	225 to 400gal/min
ROP	20 to 50 ft/hr
Cuttings Density	2.1 sg to 2.18sg

3. RESULTS AND DISCUSSION

The results of the hydraulics simulation are presented in this section. The results for annular pressure losses are presented due to factors that impact it which are the mud weight, the pump rates, the ROP, and the cuttings density.

3.1 Effect of Mud Weight

The effect of mud weight on the annular pressure loss and the annular circulating density are presented in this section.

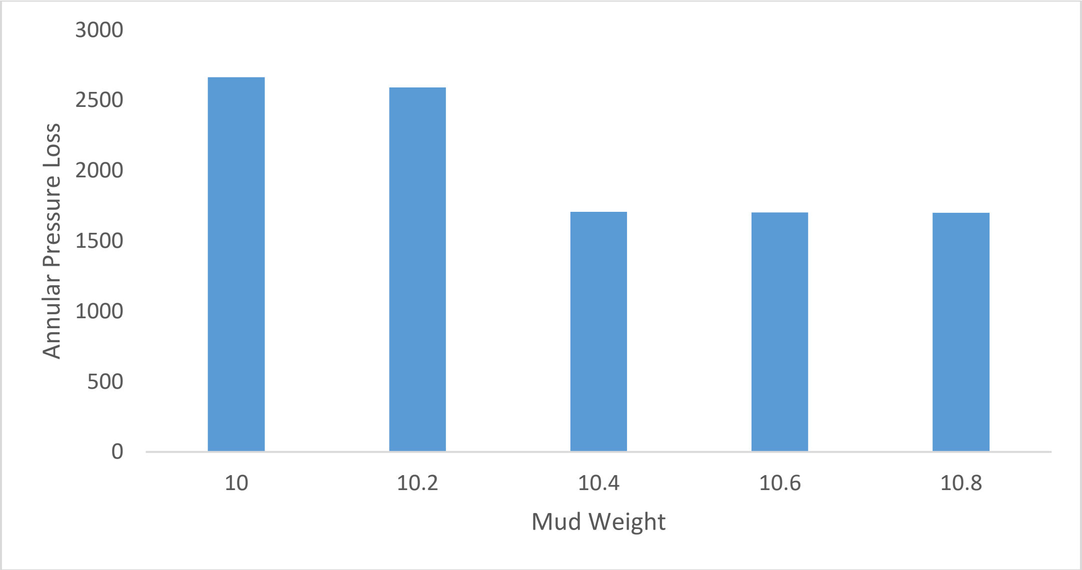

Figure 1: Effect of mud weight on annular pressure loss for ERWs

It is apparent from the results shown in Figure 1 and Figure 2 that an interesting hydraulic problem is observed in ERW well drilling. This is in relation to the effects of the mud weight on annular pressure loss as well as annular circulating pressures. The simulation results show that the annular circulating pressure increases as the mud weight is increased. On the other hand, the annular pressure loss is observed to decrease. A technical analysis of the various factors that contribute to the problem is necessary. This is in relation to the complex flow behavior in ERW wells characterized by large lateral offsets.

From the simulation results shown in Figure 1, it is apparent that the increase in the mud weight from 10.0 ppg to 10.8 ppg led to a decrease in the annular pressure loss from 2665 to 1699.42. This is a decrease of 965.58. This is approximately 32.2% of the original value, which is significant. The main reason for the decrease is the rheological characteristics of the drilling fluids. In this simulation, it is most probable that the increase in mud weight was accomplished by increasing the amount of solids or weightings without significantly affecting the plastic viscosity or yield point of the fluid. Therefore, although the density of the fluid increased, the amount of shear stress applied by the fluid to the walls of the annular space could have remained the same or even decreased due to the possibility of a dilution effect or laminar flow.

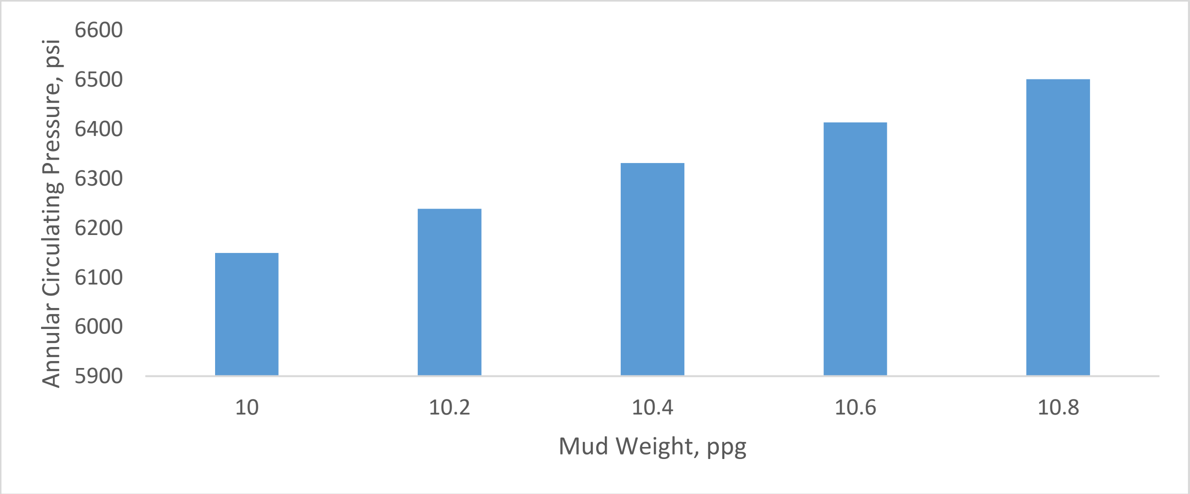

Figure 2: Effect of mud weight on annular circulating pressures for ERWs

In addition, it is worth noting that in extended reach wells, there are unique flow characteristics, especially because of their horizontal sections and their eccentric annular space. In this case, heavier fluids are likely to improve laminar stability by reducing turbulence, especially in moderate pumping rates and small Reynolds numbers. As a result, energy dissipation through shear stress on the walls is minimized, and this is seen in a decrease in annular pressure losses. In addition, heavier fluids are likely to improve cuttings transport efficiency in horizontal sections, thus ensuring minimal buildup of solids, which could otherwise increase mechanical losses.

From Figure 2 above, it is clear that annular circulating pressures are increased when the weight of the mud increases. For example, when the weight of the mud increases from 10.0 ppg to 10.8 ppg, the annular circulating pressures increase from 6148.99 to 6500.19, a difference of 351.2, which is a 5.7% increase. This increase is largely because of the increase in the hydrostatic component of pressures. Since the weight of the mud is directly proportional to the hydrostatic pressure, the density of the fluid would necessarily lead to an increase in the hydrostatic pressure exerted by the static column of the mud. In this particular problem, though there has been a slight reduction in the frictional component, i.e., the annular pressure loss, it is negligible compared to the rise in hydrostatic head due to the density of the fluid.

Annular Circulating Pressure is the sum of hydrostatic pressure, annular pressure losses, and the dynamic components due to acceleration and circulation. In this particular problem, the major factor that is affecting the ACP is the rise in hydrostatic head due to the density of the fluid. Since the hydrostatic component is a major contributor to the ACP, especially for deep wells or for ERWs with long depths, the ACP would still rise, though there is a slight fall in the annular losses. From the perspective of extended reach wells, the above result has significant operational consequences. Extended reach wells have significant horizontal sections that may extend for several kilometers. These sections have relatively shallow vertical depths in relation to measured depth. Consequently, the long horizontal length of extended reach wells demands proper management of equivalent circulating density to avoid exceeding fracture gradients. The increase in ACP with increasing mud weight implies that even slight changes in mud weight have significant effects on the total circulating pressure. These effects may cause overbalance problems. On the other hand, the decrease in APL implies that increasing mud weight may slightly improve the efficiency of flow in the annulus. This improvement in the annulus may result from better cuttings transport.

3.1.2 Effect of Pump Rates

The effects of pump rates on annular pressure loss and annular circulating pressures was investigated in figure 3 and figure 4 respectively. The pump rates were varied from 200 gal/min to 300 gal/min at 25 gal/min intervals.

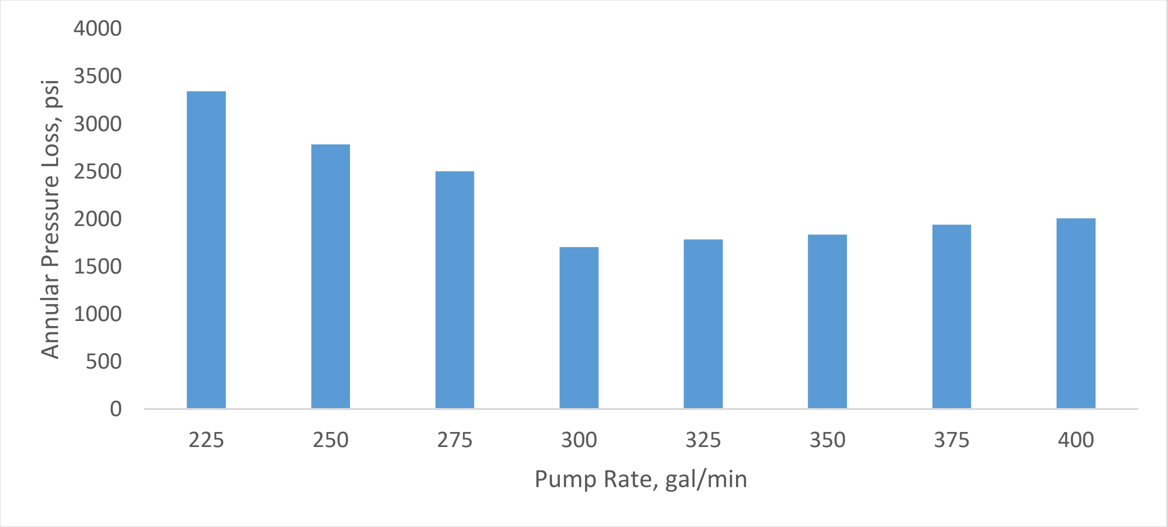

Figure 3: Effect of pump rates on the annular pressure loss for ERWs

The trends identified in Figures 3 and 4 with respect to the impact of changing pump rates on annular pressure loss and annular circulating pressures create a dynamic relationship between flow behavior and wellbore hydraulics with ERWs. The simulation results identify a non-monotonic trend whereby annular pressure loss and annular circulating pressure decrease with increasing pump rates from 225 gal/min to 300 gal/min and then increase with increasing pump rates from 300 gal/min to 400 gal/min. This non-monotonic trend needs to be technically explored based on fluid flow behavior and hydraulics within eccentric annuli and the complexities associated with ERWs.

In the initial phase from 225 gal/min to 300 gal/min, the annular pressure loss decreases, indicating improved hydraulics within the ERW during this pump rate range. The decrease in annular pressure loss during this phase may indicate that the flow behavior has changed from a turbulent or unstable flow pattern to a more stable or optimal flow pattern, which may be close to a fully developed laminar flow pattern or a more stable flow pattern within the annulus. The geometry of the ERW, especially the extended horizontal section, also contributes to an uneven distribution of the annular flow, often leading to a phenomenon of stratification with an increase in frictional resistance at a non-optimized flow rate. With a moderate increase in the pump rate, the system presumably exceeds the lower threshold to maintain an effective cuttings transport with a uniform velocity across the annulus, hence reducing the frictional forces.

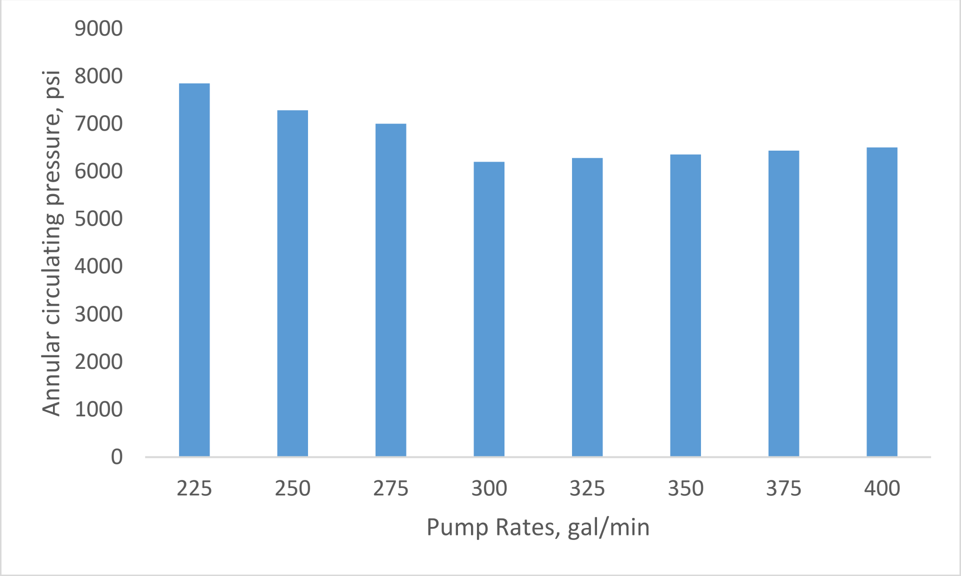

Figure 4: Effect of pump rates on the annular circulating pressures for ERWs

However, as the pump rate continues to rise from 300 gal/min to 400 gal/min, the annular pressure loss as well as the annular circulating pressures begin to rise. This represents the onset of a new energy flow regime that is likely characterized by increasing turbulence as well as Reynolds number effects, particularly in the more constricted or eccentric annulus characteristic of ERWs. The increase in pump rate will cause the velocity gradient to rise, resulting in increased frictional resistance along the wellbore wall as well as increased energy loss due to turbulence effects. In this flow regime, the increased cuttings transport as well as hydraulic sweep effects are balanced by the increasing need for pressure to drive the flow, as evidenced by the increasing annular pressure loss.

From the ERWS perspective, the above results demonstrate the need to properly optimize the pump rates. ERWs are particularly susceptible to hydraulic loading effects due to their significant measured depth as well as horizontal sections.

From the above results, it is evident that there is an optimal range of pump rates for which hydraulic performance is optimal in the sense that pressure loss is minimized while annular velocity is sufficiently high for efficient cleaning of the holes. Operating the pumps at rates lower than the optimal range may cause inefficient cleaning of the holes, resulting in cuttings accumulation in the horizontal section of the wellbore. This will increase the likelihood of pack-off and stuck pipe. On the other hand, running the pumps at rates higher than the optimal range will cause diminishing returns in addition to increased hydraulic load on the surface equipment. Moreover, the likelihood of exceeding the pressure margins in the formation will increase.

3.1.3 Effect of Rate of Penetration (ROP)

The effect of ROP on the annular pressure loss and the annular circulating pressures are investigated as presented in figure 5 and figure 6 respectively.

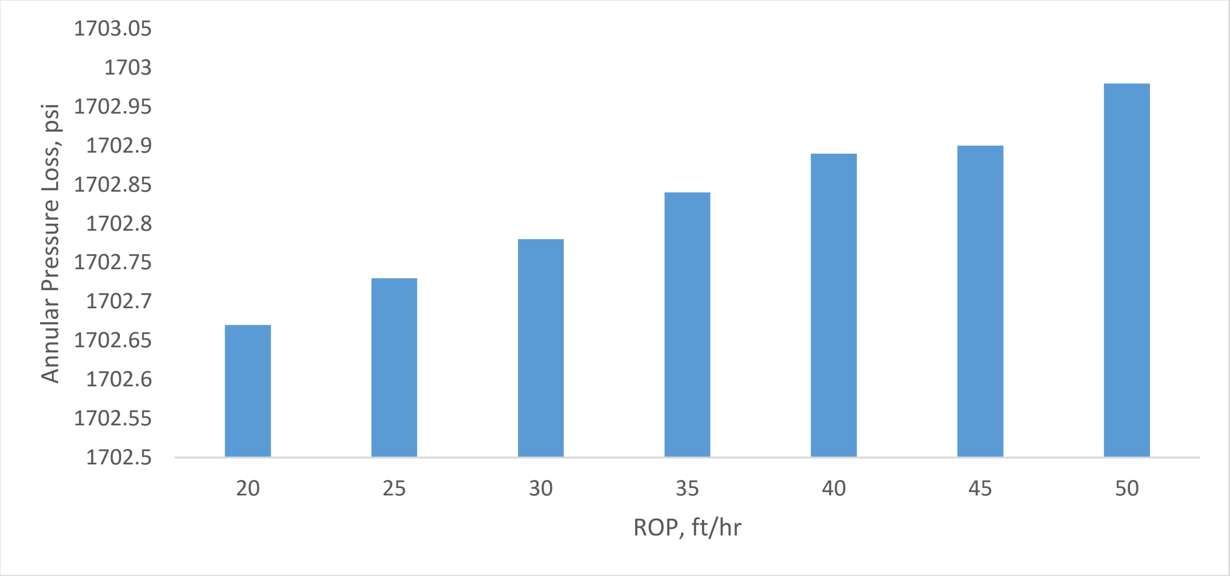

Figure 5: Effect of ROP on the annular pressure loss for ERWs

The results obtained from the evaluation of the effect of ROP on the annular pressure loss and the circulating pressures, as presented in Figures 5 and 6 for ERW, indicate a relatively stable hydraulic behavior with respect to the variations of the ROP. Specifically, as the ROP increases from 20 ft/hr to 50 ft/hr, the annular pressure loss increases by a minor amount from 1702.67 psi to 1702.98 psi, while the circulating pressure also increases from 6481.49 psi to 6491.00 psi.

In order to evaluate the impact of the ROP on the annular pressure loss and the circulating pressure quantitatively, the increase of the annular pressure loss amounts to an increase of merely 0.31 psi, while the total percentage increase amounts to an approximate value of 0.018%. Moreover, the increase of the circulating pressure amounts to an increase of 9.51 psi, while the total percentage increase amounts to an approximate value of 0.15%. These minor variations indicate that the effect of the ROP on the total hydraulic resistance and the circulating pressure is relatively minor with respect to the specific operating conditions of the system. These observations are based on the fundamental hydraulic behavior of cuttings transport.

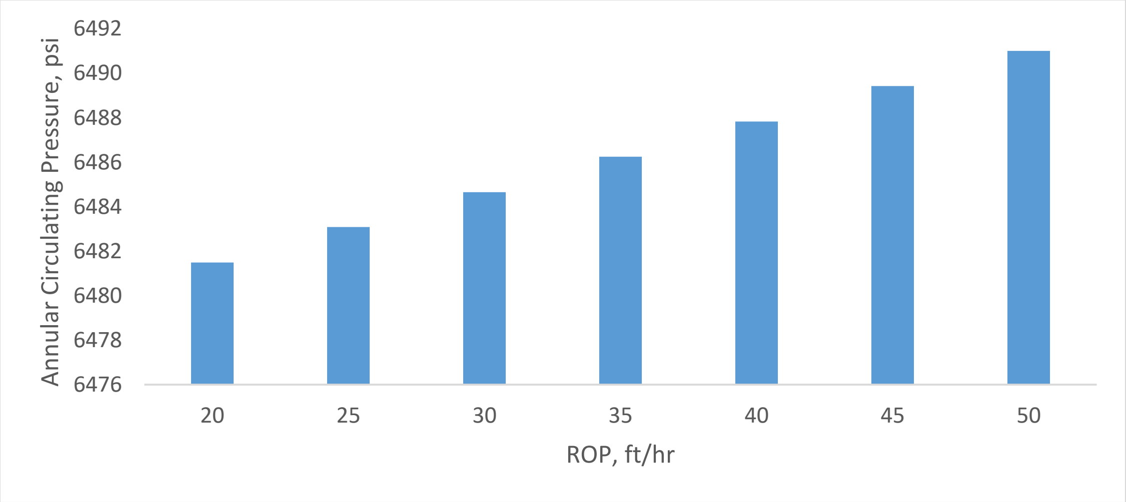

Figure 6: Effect of ROP on the annular circulating pressures for ERWs

In ERWs, the significant horizontal distance affects the flow distribution as well as the cuttings transport efficiency. With the increase in ROP values, the cuttings generation per time interval is increased. This may cause an increase in the concentration of cuttings in the annulus. Nevertheless, in the simulation above, the very small increase in pressure values indicates that the cuttings transport system is in a balanced state. This implies that the annular velocity as well as the rheological properties of the fluids are well optimized to prevent cuttings accumulation or increased cuttings transport resistance. This is in spite of the increased cuttings generation due to the increased ROP values.

The very small increase in annular pressure loss may have resulted from the slight increase in frictional resistance due to the increased concentration of cuttings in the drilling fluids. Nevertheless, the very small increase in annular pressure loss may have resulted from the ability of the fluids to carry the increased cuttings generation. Alternatively, the increase in cuttings concentration in the fluids may have little effect on the fluids' rheological properties. In addition, the long lateral section, which is a characteristic of ERWs, facilitates the dispersal of the cuttings along the flow path, thus minimizing the rise in pressure.

In the same way, the marginal rise in annular circulating pressure is due to a corresponding rise in the dynamic pressure The effect of cuttings density on the annular pressure loss and the annular circulating pressures are investigated as presented in figure 7 and figure 8 respectively.

component. Annular circulating pressure is a combination of hydrostatic head, annular pressure loss, and the dynamic component, which is a function of flow acceleration and the change in momentum. Thus, the marginal rise in annular circulating pressure may be attributed to a marginal change in the dynamic behavior of the fluid mixture. Since the rise in pressure is less than 10 psi for the corresponding rise of 30 ft/hr in the rate of penetration, it is clear that the system is well within the hydraulic limits and is not sensitive to the variation of the rate of penetration. For ERWs, where the hydraulic efficiency is critical due to the high frictional losses, the system’s lack of sensitivity to the rate of penetration is desirable. This implies that the operators have the flexibility to adjust the ROP within certain ranges without the possibility of major changes in pressure profile or the occurrence of high cuttings loading. However, it must be noted that while the pressure response is minimal, other non-hydraulic risks such as poor cleaning or high torque/drag can still be possible at high ROPs if the pumps rates and fluid properties are not concurrently optimized.

3.1.4 Effect of Cuttings Density

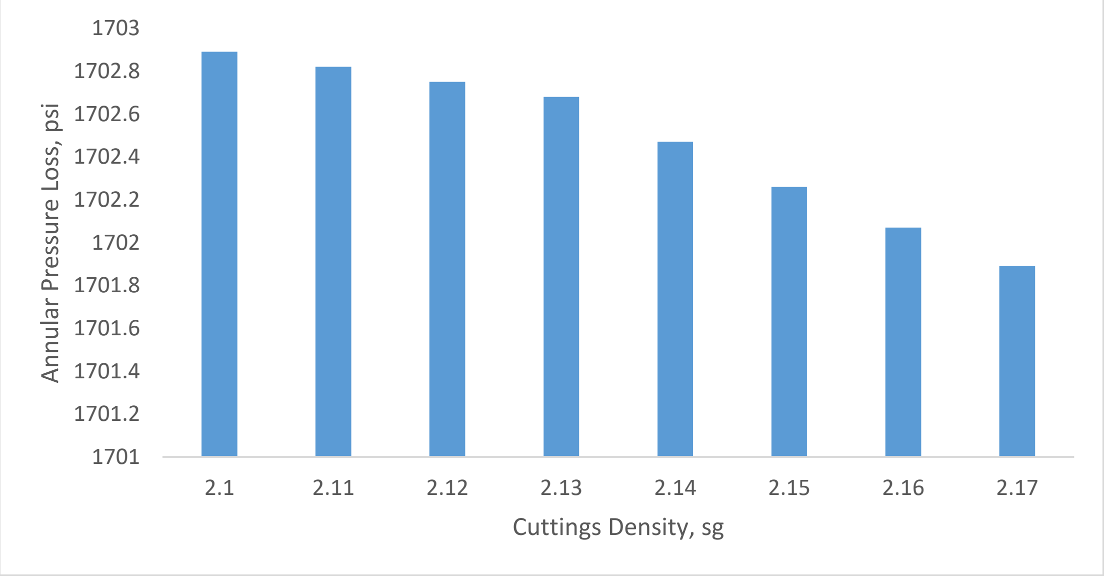

Figure 7: Effect of cuttings density on the annular pressure loss for ERWs

From the results provided in figures 7 and 8, which indicate the effect of cuttings density on annular pressure loss and annular circulating pressure, respectively, in an extended reach well (ERW), it is evident that the hydraulic behavior does not vary significantly due to the variation in cuttings densities. From figure 7, the variation in cuttings densities from 2.10 sg to 2.18 sg resulted in a slight and insignificant reduction in the annular pressure loss, which reduced from 1702.89 psi to 1701.72 psi, a net reduction of 1.17 psi and a percentage variation of 0.07%.

As can be seen from figure 8 above, the change in densities of the cuttings caused a slight and insignificant increase in the annular circulating pressure from 6487.83 psi to 6502.06 psi, a difference of 14.23 psi and 0.22% percentage variation. The seemingly contradictory but subtle trends of an almost flat decrease in annular pressure loss and an increase in annular circulating pressure can be explained by examining each component that contributes to the pressure profiles in the annulus. Annular pressure loss is mainly a function of the frictional resistance between the drilling fluid and the borehole or drill string wall. This frictional resistance is a function of fluid viscosity, fluid density, fluid velocity, and other parameters.

In the present case, the increase in the density of the cuttings, which could have resulted in the increase in the fluid density, did not result in a significant change in the frictional behavior. This could be an indication that the volume fraction of the cuttings in the fluid was well managed in the design of the fluid system. This meant that the increased weight of the cuttings had a nearly negligible impact on the pressure losses. This could be attributed to the fact that the cuttings were well suspended in the circulating fluid.

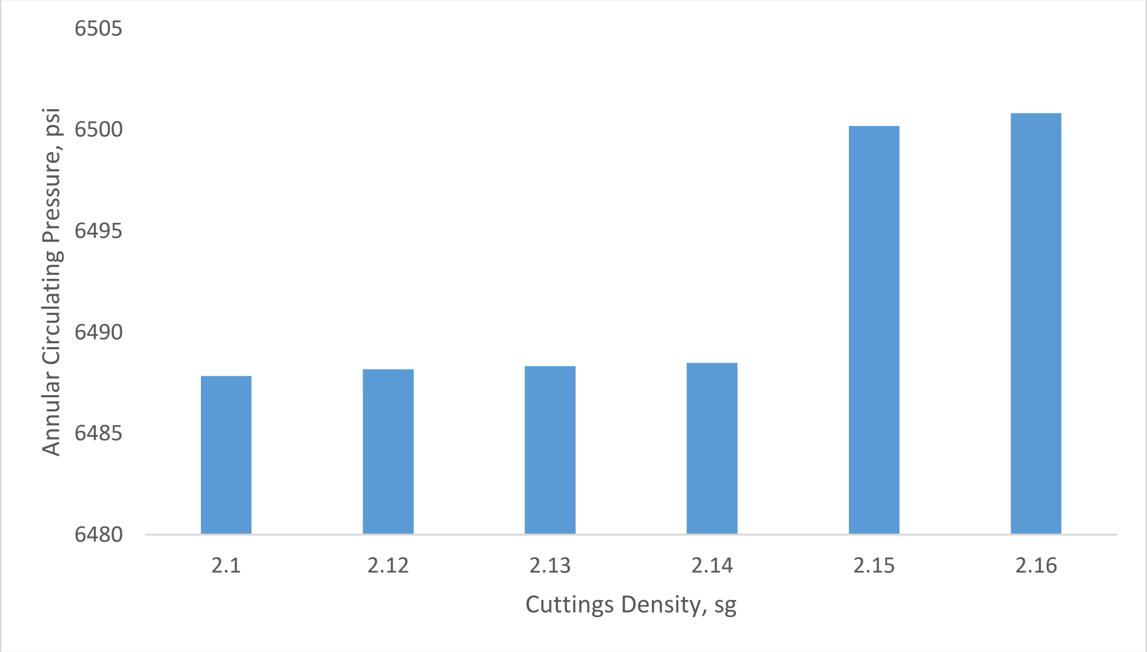

Figure 8: Effect of cuttings density on the annular circulating pressures

On the other hand, the slight increase noted in the annular circulating pressure can be explained by the cumulative effect of the marginal increase in fluid mixture density and the slight increase noted in the dynamic pressure components as a result of the increase in cuttings mass. The annular circulating pressure is made up of the hydrostatic pressure, the annular pressure loss, and the dynamic pressure as a result of the fluid flow. Although the frictional pressure loss was almost constant or slightly reduced, the hydrostatic pressure increased with the cuttings density because the mixture density was increasing in the annulus, though slightly. This explains the increase noted in the annular circulating pressure. The dynamic pressure may have also increased as a result of the additional inertia effect of the denser cuttings material, but given that the change was minimal, the effect was likely insignificant.

With reference to ER wells, where the horizontal displacement is long enough to be considerable and the hydraulic management complicated enough to be sensitive to such changes, even the smallest change in pressure behavior can be important. However, as can be deduced from the results, the well's hydraulic behavior appears to be insensitive to changes in the density of the cuttings within the range investigated. This could be a reflection of a well-managed cutting cleaning mechanism through sufficient velocities in the annulus and well-formulated mud properties that can accommodate the increased cutting weights without major effects on the pressure behavior. The long horizontal displacement could also be playing a role in the mitigation of the effects of the increased cutting density through a more gradual pressure redistribution.

Moreover, the lack of a considerable increase in pressure loss despite the increase in the mass of the cutting materials could be a reflection of a uniform distribution of the cutting materials rather than their accumulation at certain points in the wellbore. This would be particularly important in ER wells, where the problem of gravitational settling of the cutting materials is a major problem.

4. CONCLUSIONS

From the simulation results of the study, a thorough understanding of the behavior of annular pressure loss and annular circulating pressures in ERWs under different drilling conditions is achieved. The study revealed that out of all the parameters considered in the study, mud weight and pump rate have the highest impact on the annular hydraulic responses, while the effects of the rate of penetration and cuttings density are relatively smaller.

It is revealed from the study that increasing the mud weight will always result in a decrease in annular pressure loss due to the reduction in the velocity of the mud. On the other hand, the annular circulating pressures will increase proportionally due to the increased hydrostatic pressures. Similarly, the behavior of pump rates is found to have a nonlinear response. Increasing the pump rate moderately will result in a decrease in annular pressure loss as well as annular circulating pressures due to the increased efficiency of the pumps. On the contrary, increasing the pump rate will cause an increase in annular pressure loss as well as annular circulating pressures.

Conversely, increasing the penetration rate and cuttings density showed only insignificant changes in annular pressure loss and annular circulating pressure. This further confirms the hypothesis that the variables have limited hydraulic effects. It is evident from the above study that the ERW hydraulic system is more responsive to the properties of the fluids used in the system than to the generation rate of cuttings or the density of cuttings.

Overall, the study demonstrates the complex interdependency of annular hydraulics in ERWs. The long lateral sections of the ERW have increased the importance of the variables. The study confirms the importance of hydraulic modeling in ERWs to maintain wellbore pressure integrity. The trends of the variables established in the study provide a strong basis for optimizing the hydraulics of ERWs. The study confirms the importance of incorporating simulation-based techniques in well planning.

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