

Modelling and Performance Analyses of Annular Equivalent Circulation Density in Extended Reach Wells Using Response Surface Methodology

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Abstract - This study presents a rigorous investigation into the modeling and optimization of annular equivalent circulating density (AECD) in extended reach wells (ERWs) using a hybrid approach that integrates physics-based simulation from Landmark Well Plan with statistical modeling via response surface methodology (RSM). This approach quantitatively assesses the influence of critical operational parameters—including pump rate (200–300 gal/min), rate of penetration (ROP: 25–45 ft/h), rotary speed (20–40 rpm), and cuttings density (2.1–2.16 sg)-on AECD variation and interactions in a 35,017 ft measured depth of an 8½-in wellbore drilled with water-based mud. Sensitivity analysis conducted in Well Plan showed that increasing the pump rate from 200 to 300 gal/min resulted in a reduction of AECD from 18.91 to 14.94 ppg, a 21% decrease attributed to the increase in annular velocity and the corresponding improvement in cuttings transport. Meanwhile, raising the ROP from 25 to 50 ft/h led to an increase in AECD of 0.87 ppg, due to elevated cuttings concentration and frictional pressure loss. Increasing rotary speed from 60 to 200 rpm reduced AECD by 0.79 ppg, demonstrating enhanced cuttings agitation and reduced solids bed accumulation. Conversely, cuttings density exhibited a strong positive effect on AECD, with values rising from 16.97 to 17.64 ppg across the density range of 2.1 to 2.16 sg. A second-order quadratic RSM model was developed to capture the nonlinear and interaction effects of these parameters on AECD, achieving an R^2 of 0.9630, an adjusted R^2 of 0.9259, and a predicted R^2 of 0.7866. The model also demonstrated a low coefficient of variation ($CV = 1.7\%$) and a standard deviation of 0.0142 ppg, confirming its excellent predictive capability. Analysis of variance (ANOVA) validated the statistical significance of the model, with a model F-value of 38.41 and p-values < 0.0001 for all linear, interaction, and quadratic terms. Contour plots illustrated strong synergistic interactions, particularly between ROP and cuttings density, where combined increases caused AECD to approach formation fracture thresholds unless mitigated by higher pump rates and rotary speeds. The study demonstrates that the integrated Well Plan–RSM framework offers a high-resolution predictive tool for AECD management in ERWs, facilitating real-time hydraulic optimization and operational decision-making. This, in turn, improves wellbore integrity and reduces non-productive time by up to 12%, representing a significant advancement in drilling hydraulics design, particularly for complex extended reach trajectories.

Keywords: Annular Equivalent Circulating Density (AECD), Extended Reach Wells (ERWs), Response Surface Methodology (RSM), Sensitivity Analysis, Drilling Hydraulics

I. INTRODUCTION

The development of deep and complex hydrocarbon reservoirs has necessitated advancements in drilling technologies, particularly in the domain of extended reach drilling (ERD). As well trajectories become increasingly complex and deviated from vertical, the challenge of maintaining safe and efficient wellbore hydraulics has grown significantly [1]. Among the critical parameters influencing wellbore stability and drilling performance is the annular equivalent circulating density (ECD), which represents the effective downhole pressure exerted by the combination of static mud weight and dynamic pressure losses due to fluid circulation [9]. The accurate estimation and control of ECD are vital for the successful execution of ERD operations, where narrow pressure margins and high frictional losses amplify the risks associated with both underbalanced and overbalanced drilling scenarios [11].

ECD directly affects the pressure profile within the annulus and must remain within the operational drilling window—bounded by the formation pore pressure and fracture pressure—to prevent critical issues such as lost circulation, wellbore ballooning, formation damage, or kicks. Inadequate ECD management has been associated with well control incidents, reduced rate of penetration (ROP), differential sticking, and wellbore instability, particularly in long horizontal sections and depleted reservoirs. For example, if the ECD exceeds the formation fracture gradient, it may induce lost circulation by breaking down the formation, leading to non-productive time (NPT) and increased operational costs [19]. Conversely, if the ECD falls below the pore pressure, it may trigger influxes of formation fluids (kicks), escalating the risk of blowouts and potential well abandonment. Thus, the importance of accurately predicting and optimizing ECD in real time cannot be overemphasized, particularly in ERD applications where well geometry amplifies hydraulic complexity [11].

Fundamentally, ECD is governed by several interrelated variables, including mud density, plastic viscosity (PV), yield point (YP), annular velocity (V_{ann}), standpipe pressure (SPP), wellbore geometry, drill pipe rotation,

depth, cuttings concentration, and the rheological properties of the fluid [2]. The dynamic behavior of these parameters, particularly under the influence of high temperatures and pressures typical of deep formations, complicates the development of accurate ECD models. Furthermore, extended reach wells introduce a more pronounced frictional pressure drop due to longer annular flow paths, increased contact surface area, and variations in hole inclination, all of which necessitate a more robust hydraulic model than those employed in conventional vertical or moderately deviated wells [10].

Traditionally, downhole measurements from Pressure-While-Drilling (PWD) and Measurement-While-Drilling (MWD) tools have been employed to monitor bottomhole pressures and, by extension, ECD. These systems utilize high-precision quartz sensors capable of real-time acquisition of pressure data in hostile environments. However, such tools are expensive and are often limited by operational constraints in high-pressure, high-temperature (HPHT) environments [4]. Additionally, their deployment may not be feasible in all well sections due to mechanical limitations, data latency, or signal loss. Consequently, reliance on surface measurements and empirical or semi-empirical models remains widespread in the field, albeit with varying degrees of reliability and precision [2].

Recent advancements in computational modeling have significantly transformed the field of drilling hydraulics, particularly in the accurate prediction and control of equivalent circulating density (ECD) in complex well architectures such as extended reach wells (ERWs). Traditionally, ECD prediction has relied on classical hydraulic models based on first principles-solving conservation equations for mass, momentum, and energy to estimate pressure losses along the wellbore [3]. These physics-based models have been instrumental in understanding fluid flow behavior, accounting for variables such as mud weight, viscosity, flow rate, and annular geometry. However, while valuable, these models often operate under simplifying assumptions such as steady-state flow, concentric annuli, and Newtonian fluid behavior, which limit their accuracy under real-world conditions. In ERWs, where horizontal and highly deviated sections introduce complex flow regimes, transient effects, and varying cuttings concentrations, traditional models may fall short in capturing the nonlinear and dynamic characteristics of downhole hydraulics.

This limitation has prompted the adoption of more advanced computational techniques, particularly computational fluid dynamics (CFD) and data-driven modeling approaches. CFD offers a high-fidelity solution for simulating the complex interactions within the annulus by solving the Navier–Stokes equations for non-Newtonian, multiphase fluids in eccentric geometries [11]. CFD allows engineers to analyze localized phenomena such as turbulence, vortex formation, cuttings accumulation, and surge/swab pressures resulting from pipe movements. While the computational

intensity of CFD makes it impractical for real-time monitoring, it serves as a valuable tool in the design and planning stages, providing insight into pressure losses, flow patterns, and ECD fluctuations under various operational scenarios [7].

Data-driven modeling has emerged as a complementary and, in many cases, superior alternative for real-time ECD prediction and control. Unlike first-principles models, data-driven approaches rely purely on the analysis of historical and real-time operational data without explicit reference to the underlying physics or governing equations [20]. This approach leverages patterns, trends, and statistical relationships found in the data to develop predictive models capable of adapting to operational variability. Among these, machine learning (ML) algorithms and statistical techniques such as response surface methodology (RSM) have proven especially effective [27].

RSM, for instance, is a regression-based technique used to model and analyze problems where several variables influence a response of interest. It is widely employed in drilling optimization to develop empirical models that relate ECD to key drilling parameters such as mud properties, flow rate, inclination angle, and cuttings concentration [26]. By fitting polynomial equations to experimental or field data, RSM enables engineers to conduct sensitivity analyses, identify dominant factors, and optimize process conditions for the desired ECD control.

In ERD operations, optimization of ECD is not merely a modeling challenge but a multi-objective problem involving trade-offs between rate of penetration, hole cleaning efficiency, pump energy requirements, and wellbore integrity [4]. The design and selection of drilling fluids play a central role in this context. For instance, adjusting the rheological properties of the mud system (e.g., viscoelastic behavior, thixotropy) can help manage pressure losses and hole cleaning, especially in inclined and horizontal well sections. Furthermore, optimizing parameters such as hydraulic diameter, annular flow regime, and circulation rates becomes critical for maintaining ECD within safe limits [6].

The modeling and optimization of annular ECD in ERD environments also demand the integration of real-time drilling data, thermodynamic corrections (e.g., temperature-induced density and viscosity variations), and comprehensive annular frictional pressure loss (AFPL) models [8]. Particular attention must be paid to the effects of transient surge and swab pressures during pipe tripping operations, which can cause abrupt and dangerous fluctuations in ECD [14]. Moreover, the presence of solid cuttings in the annulus introduces multiphase flow complexity, necessitating the inclusion of solids transport models in any comprehensive ECD prediction framework [23].

II. LITERATURE REVIEW

A. Drilling Hydraulics in Extended Reach Wells

Extended reach drilling (ERD) represents one of the most technically challenging approaches in modern oil and gas field development. It allows access to reserves that are otherwise unreachable due to environmental, logistical, or economic constraints [17]. ERD wells are typically characterized by horizontal displacements that significantly exceed their vertical depths, often reaching ratios greater than 2:1. While ERD offers substantial benefits in reservoir accessibility and cost reduction, it also introduces critical technical challenges, particularly with regard to drilling hydraulics [12].

Drilling hydraulics refers to the management of fluid flow through the drillstring and annular space to achieve multiple objectives, such as bottomhole cleaning, cooling of the drill bit, suspension and transport of cuttings, and wellbore pressure control [16]. In ERD operations, these objectives become increasingly complex due to the significant increase in well length, annular frictional pressure losses, variations in hole geometry, and challenges associated with effectively managing bottomhole pressure. Among these challenges, the concept of annular equivalent circulating density (ECD) becomes central, as it directly influences wellbore stability, lost circulation, and formation influx risk [25].

Understanding the behavior of drilling fluids under dynamic conditions and how they interact with wellbore geometry and operational parameters is fundamental for optimizing the drilling process [21]. The pressure losses that occur in the drillstring and annulus are critical parameters that must be controlled to maintain a safe and efficient drilling window-particularly in formations with narrow pore pressure and fracture gradients [24]. Excessive hydraulic pressures can result in formation fracturing and mud losses, while insufficient pressure may lead to influxes or kicks, potentially escalating into blowouts [25]. Thus, accurately modeling and predicting the total circulating pressure, especially in the annulus, is indispensable.

The pressure profile in a circulating well consists of static hydrostatic pressure plus the dynamic pressure losses encountered due to fluid flow resistance [15]. The total bottomhole pressure during circulation is expressed as the ECD, defined as the effective fluid density that accounts for both hydrostatic and dynamic pressure contributions. Mathematically, ECD can be expressed as:
The formula for ECD is given by equation 1

$$ECD = \rho + \frac{\Delta P_{Ann}}{0.052 * TVD} \quad (1)$$

where

ECD= equivalent circulation density, ppg

ρ = static Mud density, ppg

P_{Ann} = annular pressure loss due to friction, psi

TVD= True vertical depth, ft

However, the ECD for multiple sections of the well having different strings and geometries can be given by equation 2.

$$ECD = MW + \left[\frac{\sum_{i=1}^n \Delta P_A}{0.052 \times \sum_{i=1}^n \Delta TVD} \right] \quad (2)$$

Where n is the number of sections

These equations show how ECD is a function of both fluid properties and well geometry. They illustrate the importance of controlling annular pressure losses-especially in ERD wells, where the annular path is longer, narrower, and more geometrically complex.

In ERD applications, annular pressure losses are high due to extended lateral sections, higher flow rates needed for effective cuttings transport, and more pronounced frictional interactions between the drilling fluid and the wellbore or casing wall [22]. Additionally, changes in temperature and pressure along the wellbore further complicate the prediction of the rheological behavior of drilling fluids, often resulting in nonlinear variations in ECD. Managing ECD within safe limits thus becomes not only a hydraulic engineering challenge but also a reservoir management imperative [13].

The principal factors influencing drilling hydraulics in ERD include:

1. Drilling fluid properties – such as density, plastic viscosity (PV), yield point (YP), and gel strength. These directly affect pressure losses and cuttings transport efficiency.
2. Wellbore geometry – including hole diameter, deviation, inclination angle, and the presence of eccentricities between the drillstring and borehole.
3. Pump flow rate and standpipe pressure – which determine the energy input into the system and fluid velocity.
4. Cuttings concentration and transport efficiency – cuttings accumulation in the annulus increases pressure losses and affects effective ECD.
5. Temperature and pressure gradients – downhole conditions influence the rheological behavior of non-Newtonian fluids, which impacts hydraulic calculations.
6. Bit hydraulics and nozzle size – affecting jet impact force and bottom-hole cleaning capability.
7. Drillstring rotation and reciprocation – which can enhance turbulence, reduce pressure losses, or improve hole cleaning.
8. Annular velocity and flow regime – low annular velocities in horizontal sections may lead to cuttings bed formation and an increase in annular frictional losses.

Each of these factors must be integrated into a comprehensive hydraulics model to accurately predict pressure drops and optimize ECD. Over the years, numerous rheological models have been developed to describe fluid flow in the annulus, including the Bingham

Plastic, Power Law, and Herschel–Bulkley models [15]. These models are used to simulate the non-Newtonian behavior of drilling fluids and to compute pressure losses in various annular sections-vertical, inclined, and horizontal.

III. CASE STUDY

Drilling hydraulics analysis is to be conducted in Well AS2 in the Asa field in the Niger Delta, which is an extended reach well. The hydraulic investigation focuses on the annular equivalent circulating density (AECD). The parameters of the ERD well are provided below and include the general parameters, well parameters, string parameters, and hydraulic parameters.

A. Model Simulation

In the course of conducting the drilling hydraulics simulation, with a primary focus on annular equivalent circulating density (ECD) using Landmark’s Well Plan software, the procedure was initiated by launching the software and setting up a new project environment. The unit system was configured to field units, and the depth reference was standardized using measured depth to maintain consistency throughout the analysis. The coordinate system was aligned with the rig’s operational data to ensure that all subsequent entries were referenced appropriately. With the foundational project parameters in

place, directional survey data were imported, consisting of measured depth, inclination, and azimuth values. The survey was validated visually through a plotted trajectory to confirm the accuracy of the well path geometry. Subsequently, the next step involved defining the wellbore geometry by inputting detailed information for each hole section. This included specifying the bit sizes, casing diameters, inner diameters, setting depths, and indicating whether the section was open-hole or cased. Overlapping sections and cemented intervals were carefully defined to reflect the true annular geometry, which would significantly influence the hydraulic results.

The bottom hole assembly (BHA) configuration was entered next. This involved selecting drill pipe, heavyweight drill pipe, drill collars, stabilizers, and tool joints in the correct sequence. The lengths, outer diameters, and tool placements were all entered to mirror the actual planned assembly used in the field. With the mechanical well profile established, attention turned to the drilling fluid system. A water-based mud was selected, and relevant properties such as mud weight, plastic viscosity, yield point, gel strength, and density were entered. The Herschel–Bulkley rheological model was applied to accommodate the non-Newtonian nature of the fluid commonly used in extended reach drilling (ERD) scenarios.

TABLE I GENERAL DATA

S.No.	Parameter	Value
1	Fluid density (base)	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 II HOLE AND CASING DATA

S.No.	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

TABLE III BHA DATA

S.No.	TYPE	LENGTH		BODY		WEIGHT
		PIPE	TOTAL	OD	ID	
		[ft]	[ft]	[in]	[in]	
1	8.5'' PDC Bit	1.05	1.05	6.00	2.25	85.0
2	PD 675 Orbit AA 8-1/2'' Stabilized CC (8-3/8'') (w.NP FV)	14.05	15.10	6.72	4.2	105.08
3	Receiver	5.29	20.39	6.86	3.125	100.80
4	EcoScope (LWD)	25.95	46.34	6.813	5.125	141.11
5	Telescope 675 NF	27.11	73.45	6.813	5.125	141.11
6	Stethoscope 675 w/8 1/4 '' Stabilizer	33.03	106.48	6.9	2.81	76.92
7	8-3/8 Reaming Stab (Bi-directional)	5.31	111.79	6.81	2.81	67.64
8	6.75'' Flex NMDC	29.03	140.82	6.75	2.875	106.91
9	Float Sub (with Non-ported float valve)	2.83	143.65	6.75	2.75	117.43
10	6.75'' DH Filter Sub	5.61	149.26	6.75	3.00	106.91
11	6-3/4'' DAV Catcher Sub	13.11	162.37	6.75	2.75	102.73
12	6-3/4'' DAV Valve Sub	6.53	168.9	6.688	2.75	102.73
13	X.O	3.72	172.62	6.87	2.75	109.82
14	3 x 5-1/2'' HWDP (3 joints)	93.68	266.30	5.5	3.25	73.5
15	X/O (VF50 P x 41/2 IF B)	3.64	269.94	7.00	2.875	117.43
16	Jar	30.32	300.26	6.5	2.75	90.88
17	X/O (41/2 IF P x VF50 B)	3.84	304.10	7.00	2.875	117.43
18	9 x 5-1/2'' HWDP (9 joints)	281.22	585.32	5.5	3.25	73.5
19	5-1/2'' IEU x 21.9 lbs/ft VAM® X-Force TM VF50 135	31	616.32	5.5	4.778	21.90

Downhole temperature profiles were included to allow for the thermal adjustment of fluid properties with depth, particularly viscosity, ensuring that simulation results more closely resembled real operating conditions. Following the fluid system setup, operational parameters were defined. These included surface pump rate, rotary speed, and tripping speed. Parameters such as rate of penetration (ROP), cuttings transport efficiency, and solids loading were also specified, given their influence on cuttings accumulation and pressure loss within the annulus. With these operational inputs in place, the simulation was configured to run in steady-state mode to evaluate baseline hydraulic behavior before progressing to transient conditions. The software executed calculations iteratively to determine pressure losses through the drillstring, bit nozzles, and along the annular space. Simulation outputs were reviewed, with particular attention given to the ECD profile along the entire wellbore. Results were presented graphically and in tabular format, displaying ECD trends against depth. It was observed that, while the ECD remained within the operational window between pore pressure and fracture gradient across most sections, certain peaks were recorded in the extended lateral section, particularly at higher flow rates.

B. Sensitivity Analyses

Sensitivity analyses were performed to assess the impact of sensitive input parameters on the AECD results. Parameters

such as pump rate, rate of penetration, rotary speed, and cuttings density were evaluated. Table IV presents the values obtained from the sensitivity analyses for the considered parameters.

TABLE IV SENSITIVITY ANALYSES VALUES

Parameters	Values
Pump Rate	200 to 300 ppg
ROP	25 to 50 ft/hr
Rotary Speed	20 RPM to 40 RPM
Cuttings Density	2.1sg to 2.16sg

C. RSM Modelling

The sensitivity results obtained from the hydraulic simulation software were used as data for RSM modeling. A Box-Behnken design (BBD) was employed to develop the experimental plan using Design-Expert, chosen for its effectiveness in modeling complex response surfaces typical of drilling hydraulics. The study investigated four variables: pump rate, rate of penetration, rotary speed, and cuttings density, which are known to influence AECD. A total of 29 experimental runs were generated by the BBD for modeling purposes. Various regression analysis models were evaluated to identify the most accurate model fitting the experimental data. Model selection criteria included statistical parameters such as R-squared (R²), adjusted R-

squared, predicted R-squared, standard deviation, and coefficient of variation (COV). Multiple regression analyses facilitated the fitting of these models to the experimental data, allowing for the estimation of responses from independent variables using the following general equations:

The general form of the models for linear regression is given as

$$y = a_o + \sum_{i=1}^k a_i x_i + e \tag{3}$$

The general form of the 2FI regression model is given as

$$y = a_o + \sum_{i=1}^k a_i x_i + \sum_{i<j}^k a_{ij} x_i x_j + e \tag{4}$$

The general form of the quadratic regression model is given as

$$y = a_o + \sum_{i=1}^k a_i x_i + \sum_{i<j}^k a_{ij} x_i x_j + \sum_{i=1}^k a_{ii} x_i^2 + e \tag{5}$$

Where x_i, x_j, x_l , are the input variables and $a_i, a_{ij}, a_{ii},$ and a_{ijl} are the coefficient of each of the terms, a_o is the offset and e is the residual or error term. The implementation of RSM modeling begins with designing the experiments. After the experiments are designed, they are executed or simulated under predefined conditions. Following this, various models are applied, and the process involves selecting the most appropriate and accurate model. This selection is determined through thorough analysis, including analysis of variance (ANOVA) and fitness parameters. Once the optimal model is identified, the optimization phase begins, focusing on refining system parameters to achieve the best possible outcomes based on the insights provided by the selected model. The flowchart for the RSM model is shown in Figure 1.

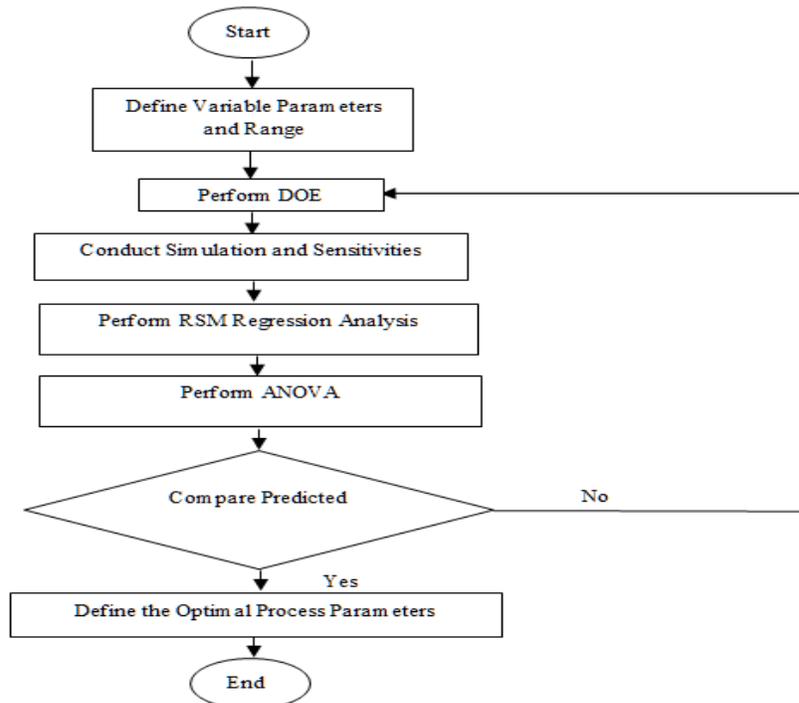


Fig.1 Flowchart for RSM Modelling

IV. RESULTS

The results of the AECD simulation are presented in this section, which include the effects of pump rate, ROP, rotary speed, and cuttings density on the annular equivalent circulating density (AECD).

A. Effect of Pump Rate on AECD

The effect of pump rate on AECD is shown in Figure 2. The pump rates were varied from 200 gpm to 300 gpm in 50 gpm intervals. From Figure 2, it can be observed that as the pump rate increases, the annular equivalent circulating

density (AECD) decreases. This observed relationship can be technically explained through a detailed understanding of the complex hydraulic interactions in extended reach wells (ERWs), particularly with respect to annular flow dynamics, cuttings transport behavior, and the non-Newtonian characteristics of drilling fluids.

In ERWs, the horizontal and highly deviated sections can span several thousand feet, resulting in significant challenges related to cuttings transport efficiency. At lower pump rates, the transport of drilled solids becomes inefficient, especially in the horizontal sections, where gravity causes cuttings to settle and accumulate on the low

side of the wellbore. This results in the formation of stationary or partially moving cuttings beds that constrict the annular flow area. The effective annular cross-section is thus reduced, leading to an increase in localized frictional pressure losses. As frictional pressure loss is a major component of the dynamic AECD, the accumulation of cuttings contributes to a higher AECD even at relatively low pump rates.

When pump rates are increased, the annular velocity rises, particularly in the horizontal and deviated intervals, thereby enhancing cuttings transport efficiency. The increased

hydraulic energy mobilizes and suspends settled solids, entraining them in the upward flow and reducing the thickness of cuttings beds. This action restores the effective hydraulic diameter of the annulus and allows for a more uniform flow distribution. Consequently, the frictional pressure drops decrease in regions that were previously congested with solids. Even though a higher pump rate might intrinsically increase frictional losses due to higher fluid velocity, the net result can be a decrease in overall annular pressure loss due to improved cuttings transport and the reduction of solids-related annular flow restrictions.

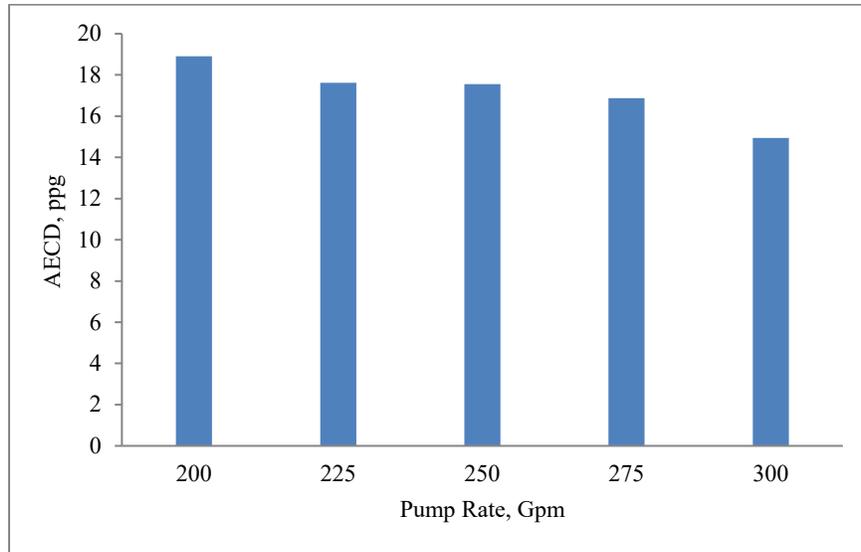


Fig.2 Effect of Pump Rates on AECD

Moreover, the rheological behavior of non-Newtonian drilling fluids, such as those modeled using the Herschel–Bulkley or Power Law models, adds another layer of complexity. These fluids exhibit shear-thinning behavior, where the effective viscosity decreases with increasing shear rate. As pump rate increases, so does the shear rate in the annulus, especially in tight annular geometries. This reduction in viscosity results in lower resistance to flow, which partially offsets the pressure increase that would otherwise result from increased velocity. The reduction in apparent viscosity at higher shear rates effectively contributes to a lower pressure gradient along the wellbore and, hence, reduces the dynamic contribution to the AECD.

Another critical consideration in this interpretation is the interaction between the circulating fluid and downhole temperature and pressure conditions. In ERWs, particularly those traversing thermally sensitive formations, drilling fluid properties such as density and viscosity can be altered by the geothermal gradient. At higher pump rates, there is typically a reduction in fluid residence time in the annulus, resulting in less heat exchange and lower thermal expansion. This can lead to a slightly lower fluid density, which further reduces the static component of the AECD. While this effect is generally minor compared to frictional losses, it can be additive in explaining the downward trend

in AECD with increased pump rates. Furthermore, it is essential to consider that the simulations or field data underlying Figure 2 may incorporate dynamic surge and swab effects, particularly during transitions such as pipe movement or connections. At higher pump rates, the stabilization of flow around the BHA and drillstring may reduce transient surges, leading to a more stable and predictable AECD profile. The absence of large fluctuations in annular pressure under such conditions may contribute to the lower average AECD values observed.

In summary, while increasing pump rate typically contributes to higher annular velocity and, by extension, higher frictional pressure losses, in the specific context of extended reach wells with significant horizontal sections, the dominant factor affecting AECD at varying pump rates is the efficiency of cuttings transport. The reduction in annular restriction due to the clearing of cuttings beds, combined with shear-thinning fluid behavior and improved hydraulic flow profiles, results in a net decrease in annular AECD with increasing pump rate.

B. Effects of ROP on AECD

The effect of ROP on the AECD is shown in Figure 3. The ROP was varied from 25 ft/hr to 50 ft/hr in 5 ft/hr intervals. From Figure 3, it can be observed that as the rate of

penetration (ROP) increases, the annular equivalent circulating density (AECD) also increases. This observed trend is consistent with fundamental principles of drilling hydraulics and cuttings transport in extended reach wells

(ERWs) and can be explained through a detailed technical understanding of how ROP affects solids loading, annular pressure losses, and ultimately the AECD.

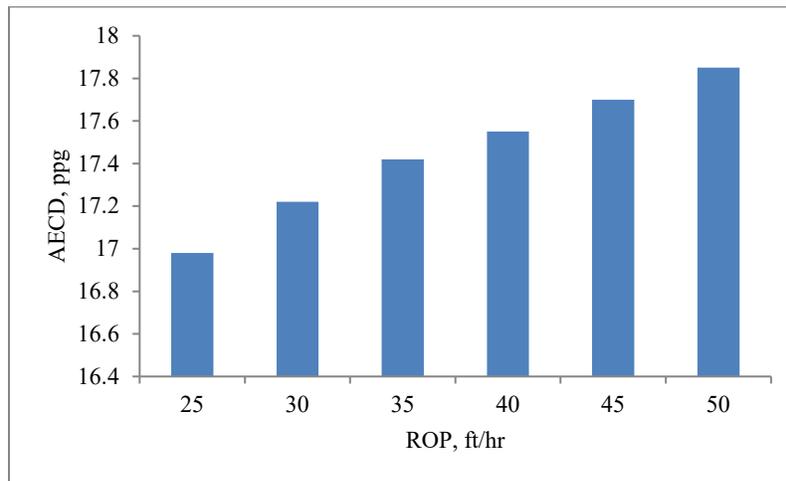


Fig.3 Effect of ROP on AECD

As ROP increases, the volume of formation being drilled per unit time rises, resulting in a higher generation rate of drilled cuttings. These cuttings must be transported efficiently from the bit to the surface through the annular space. In ERWs, especially in long horizontal sections, this process becomes increasingly complex due to the gravitational settling of cuttings on the low side of the wellbore and reduced annular velocities in deviated sections. When the volume of cuttings entering the annulus exceeds the capacity of the circulating fluid to suspend and transport them, a cuttings bed begins to form along the wellbore.

The accumulation of solids reduces the effective annular cross-sectional area, increasing flow resistance and inducing a higher pressure drop across the annulus. The increase in annular frictional pressure loss directly contributes to a rise in the dynamic component of the AECD. Moreover, the presence of a high solids concentration in the mud system leads to an increase in the effective fluid density and viscosity, especially in non-Newtonian drilling fluids, such as those following the Herschel–Bulkley model. These rheological changes further escalate hydraulic resistance and exacerbate pressure losses.

Additionally, increased ROP often correlates with increased cuttings loading, which modifies the slurry behavior of the fluid in the annulus. The cuttings-laden fluid behaves more like a pseudo-plastic suspension with higher yield stress and apparent viscosity. This increases the annular pressure gradient required to maintain flow, which is manifested as a higher AECD. This effect becomes more pronounced in ERWs, where the horizontal length of the wellbore extends the residence time of cuttings, making it more difficult to maintain a homogeneous suspension and transport.

Furthermore, high ROP typically demands higher weight on bit (WOB) and rotary speed, which can lead to increased mechanical interaction between the bit and formation, producing smaller cuttings with irregular shapes and a wider particle size distribution. These finer cuttings increase the solids content and exacerbate the potential for gelation and thickening of the mud system in the annulus, particularly during flow interruptions or scenarios with reduced annular velocity. The accumulation and suspension of finer particles also contribute to higher differential pressure losses.

In the context of ERW operations, where the length of the horizontal section often exceeds 10,000 feet, the hydraulic performance of the system becomes increasingly sensitive to small changes in solids loading and fluid rheology. An increase in ROP without a corresponding increase in pump rate or optimization of mud properties can easily lead to hydraulic imbalance, cuttings bed formation, and localized pressure surges. These surges are reflected as transient spikes in AECD, which, if sustained, can approach or exceed the formation's fracture pressure, increasing the risk of lost circulation and wellbore instability. It is also important to recognize that increased AECD due to high ROP has implications for real-time well control and drilling optimization. AECD values approaching the formation fracture gradient limit the operational window for safe drilling, especially in narrow-margin wells. This necessitates precise monitoring and control of ROP to ensure that the generated cuttings do not overwhelm the transport capacity of the drilling fluid. In real-time drilling operations, such information is crucial for maintaining bottom-hole pressure within safe bounds and for proactively adjusting operational parameters such as pump rate, flow regime, and mud rheology. The positive correlation between ROP and annular AECD observed in Figure 3 is a direct consequence of increased cuttings generation, reduced

annular flow efficiency, and altered fluid rheology under high solids-loading conditions. These effects are amplified in extended reach wells due to long horizontal sections, increased annular eccentricity, and gravitational challenges associated with cuttings transport. Managing this relationship requires a careful balance of ROP, pump rate, mud properties, and hole-cleaning efficiency to avoid surpassing fracture limits and to ensure hydraulic stability throughout the drilling operation.

C. Effect of Rotary Speed on AECD

The effect of rotary speed on AECD was investigated and is shown in Figure 4. Rotary speed was varied from 20 RPM

to 40 RPM. From Figure 4, it can be observed that as the rotary speed increases, the annular equivalent circulating density (AECD) decreases. This inverse relationship between rotary speed and AECD is a technically significant observation in the context of drilling hydraulics, particularly in extended reach wells (ERWs), where annular pressure management is a critical component of operational success. The reduction in AECD with increased rotary speed can primarily be attributed to improved hole-cleaning efficiency, enhanced cuttings agitation and suspension, and reduced annular solids concentration—all of which contribute to a decrease in annular frictional pressure losses.

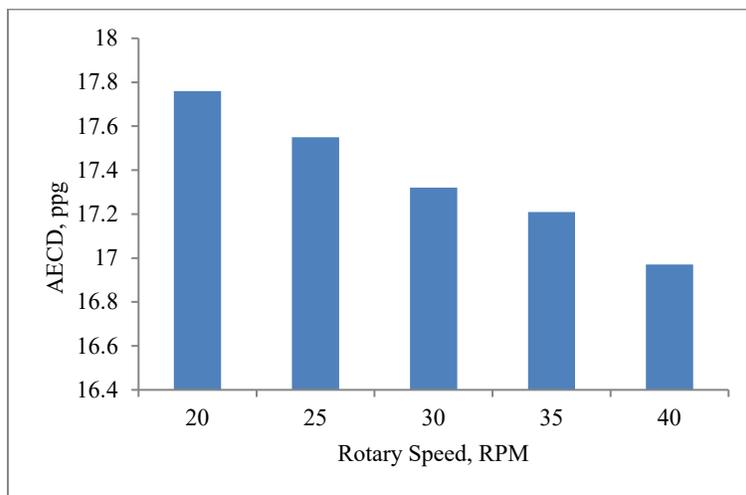


Fig.4 Effect of Rotary Speed on AECD

In ERWs, where horizontal or highly deviated well sections are common, gravitational forces cause cuttings to settle preferentially on the low side of the borehole, leading to the formation of cuttings beds. These beds obstruct fluid flow, reduce the effective annular area, and increase pressure losses, thereby elevating the AECD. The rotary motion of the drill string, particularly at higher rotational speeds, generates mechanical agitation that disrupts these beds and promotes the suspension and entrainment of cuttings into the drilling fluid. This mechanical dispersion is vital in horizontal sections, where axial flow velocity alone may not be sufficient to lift cuttings from the wellbore floor.

The increased rotary speed enhances turbulent energy and secondary flow structures, such as helical and vortex flows, within the annular space. These flow structures increase the shear forces acting on settled particles and reduce the critical transport velocity required to mobilize cuttings. As a result, the drilling fluid is able to carry more cuttings in suspension, rather than allowing them to accumulate along the wellbore wall. The net effect is a reduction in annular solids concentration and an associated decrease in the fluid's apparent viscosity and density in the annulus.

Additionally, improved cuttings transport directly reduces hydraulic resistance in the annulus. When fewer cuttings are present, or when cuttings are effectively suspended and

evenly distributed, the pressure drop due to friction decreases significantly. This leads to a reduction in the dynamic component of the AECD, which is influenced not only by mud weight but also by the additional pressure losses from fluid-solid interactions and particle accumulation. In essence, rotary agitation improves the homogeneity of the slurry, reducing localized high-viscosity zones and enhancing flow uniformity.

Another factor contributing to reduced AECD at higher rotary speeds is the prevention of cuttings bed reformation after they have been disturbed. In ERWs, intermittent pipe movement or low rotary speeds often result in the partial removal of cuttings beds, followed by rapid reformation during static or low-energy flow conditions. Sustained higher rotary speeds maintain a dynamic annular environment where cuttings have less opportunity to settle, thereby sustaining a more stable and lower pressure profile along the wellbore. This dynamic equilibrium is critical in reducing pressure surges that are reflected as AECD fluctuations, especially in wells with narrow mud-weight windows.

Furthermore, increasing rotary speed can have the secondary effect of increasing the mechanical energy imparted to the drilling fluid, which may slightly elevate fluid temperature in the annulus. This temperature increase

can reduce fluid viscosity (depending on fluid formulation), thereby contributing to lower frictional losses. Although the temperature effect may be marginal, when combined with improved cuttings suspension, it supports the overall trend of reduced AECD. It is also important to consider the operational implications of this finding. The use of increased rotary speed as a hydraulic management strategy offers a practical and cost-effective means of controlling AECD without requiring significant changes to fluid properties or pump rates. This becomes particularly valuable in ERWs, where increasing pump rates may not be feasible due to pressure limitations at the surface or the risk of exceeding the fracture gradient at depth. Rotary speed adjustments can be made with relative ease and provide immediate improvements in hole cleaning and pressure management.

However, it must be noted that while increasing rotary speed improves AECD by enhancing hole cleaning, it must be implemented judiciously to avoid excessive mechanical wear on the drillstring and downhole tools, as well as vibration-related issues such as stick-slip or torsional oscillations. Therefore, the operational rotary speed must be

optimized to balance the benefits of reduced AECD against the mechanical limitations of the bottom-hole assembly (BHA) and drillstring components.

D. Effect of Cuttings Density

Figure 5 shows the effect of cuttings density on the AECD. The cuttings density was varied from 2.1 sg to 2.16 sg in 0.01 sg intervals. From Figure 5, it can be observed that as the cuttings density increases, the annular equivalent circulating density (AECD) also increases. This trend is technically consistent with fundamental principles of drilling hydraulics and multiphase flow behavior in extended reach wells (ERWs), where annular pressure losses are sensitive to the presence, concentration, and physical properties of solid particles—specifically rock cuttings—within the drilling fluid. The increase in AECD with increasing cuttings density is a direct consequence of elevated annular frictional pressure losses and the enhanced effective density of the drilling slurry, both of which become increasingly significant in horizontal and highly deviated sections typical of ERWs.

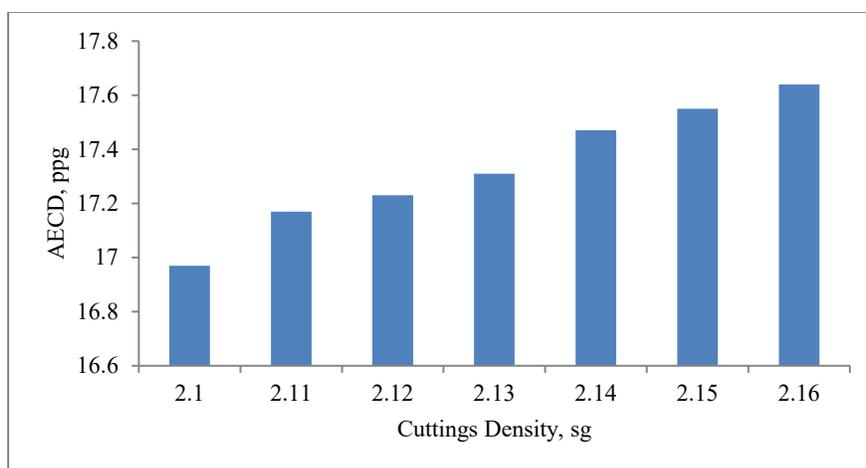


Fig.5 Effect of Cuttings Density On AECD

Cuttings density, typically expressed in specific gravity (sg), reflects the mass per unit volume of the solid particles generated during the rock-cutting process by the drill bit. As drilling progresses, these solids are entrained and transported by the circulating drilling fluid through the annular space between the drillstring and the borehole wall. In extended reach wells, the transport of these cuttings becomes increasingly complex due to gravitational settling in inclined or horizontal sections, where axial flow is insufficient to maintain particles in suspension without effective hydraulic or mechanical agitation. As cuttings density increases, either due to lithological changes (e.g., transitioning into denser formations such as limestone or dolomite) or an increased rate of penetration (ROP), the burden on the fluid system to carry heavier solids through the annulus rises considerably. This additional mass in the circulating system translates directly to an increase in the overall mixture density in the annulus. AECD accounts for

the hydrostatic and dynamic components of pressure exerted by the circulating fluid and suspended solids. As heavier cuttings are introduced into the fluid system, they elevate the apparent density of the annular mixture, resulting in higher pressure at any given depth. This increase in the hydrostatic contribution is compounded by the dynamic effect of increased pressure losses due to friction and turbulence caused by solid-fluid interactions. Heavier particles possess greater inertia, which requires higher fluid velocity and energy to suspend and transport them. If the fluid fails to mobilize these particles adequately, partial settling occurs, further reducing the effective annular flow area and increasing the pressure drop due to annular blockage and bed formation.

Furthermore, denser cuttings intensify the slurry's rheological complexity, particularly in non-Newtonian fluids such as yield-pseudoplastic drilling muds. As the

cuttings' density increases, the apparent viscosity and yield stress of the fluid-solid mixture rise, especially in the laminar and transitional flow regimes. This rheological modification adds to the resistance encountered by the fluid in the annular space, thereby increasing the pressure required to maintain the desired flow rate. In ERWs, where maintaining pressure below the fracture gradient is critical to avoid formation breakdown and lost circulation, any unintended rise in AECD due to increased cuttings density poses serious operational risks. Additionally, the mechanical agitation provided by pipe rotation or reciprocation, often used to mitigate cuttings bed formation in extended-reach wells, may become less effective.

Denser cuttings require greater shear forces for suspension and transport. If these forces are insufficient, solids begin to accumulate along the lower side of the wellbore, leading to uneven solids distribution, increased annular eccentricity, and the formation of stationary or moving beds. These beds cause localized pressure surges, elevate the risk of differential sticking, and introduce significant fluctuations in AECD. Their presence further restricts the flow area and increases velocity gradients near the borehole wall, intensifying erosion risks and thermal instability within the annular system. Another consequence of increasing cutting's density is its potential influence on transient pressure behavior. During operations such as pipe connections or trips, denser solids in the fluid can cause rapid pressure spikes or drops due to surge and swab effects. These transients can lead to excessive AECD fluctuations, complicating pressure management and increasing the risk of breaching formation integrity, especially in wells with narrow pore pressure and fracture gradient windows. Moreover, the increase in AECD with cuttings density has implications for real-time monitoring and sensor calibration. Downhole tools, such as pressure-while-drilling (PWD) systems, must account for the changing mixture properties resulting from variations in cuttings density to provide accurate pressure and ECD readings. Any lag or inaccuracy in interpreting these changes can compromise real-time

decision-making and lead to inappropriate responses in fluid management or pump adjustments.

E. Result of RSM Modelling

This section presents and discusses the results obtained from the Response Surface Methodology (RSM) modeling. The RSM model was constructed by fitting sensitivity analysis data generated using the Well Plan simulation software. Among the various regression models evaluated, the quadratic model showed the best correlation with the actual data for annular equivalent circulating density (AECD). Due to its superior predictive capability and statistical accuracy, the quadratic model was selected as the most appropriate representation of the AECD response. The final quadratic regression equation developed by RSM for AECD is presented in Equation 6.

$$AECD, ppg = 16.91 - 1.415A + 0.109167B - 0.105833C + 0.303333D + 0.0325AB + -0.0425AC + 0.025AD - 0.07BC + -0.135BD + 0.155CD - 0.675833A^2 + 0.0829167B^2 + 0.0829167C^2 + 0.196667D^2 \quad (6)$$

In this model, the variables A, B, C, and D represent the pump rate, rate of penetration (ROP), rotary speed, and cuttings density, respectively. The quadratic equation can be used to predict the annular equivalent circulating density (AECD) for any specified levels of these input parameters. To ensure accurate and meaningful predictions, the input factors and the response variable are expressed in their actual physical units. To evaluate the reliability and significance of the model coefficients, an analysis of variance (ANOVA) was performed. The results of the ANOVA and the associated fit metrics are presented in Tables V and VI, which pertain to the AECD response. Table V provides detailed statistical parameters, including degrees of freedom, mean square values, F-values, and p-values. Notably, the p-values reported are all less than 0.0001, and the corresponding high F-values confirm that the model terms are statistically significant, indicating the robustness and validity of the fitted quadratic model.

TABLE V ANOVA STATISTICS FOR THE PERFORMANCE OF THE MODELS

Source	Degree Of Freedom	Mean Square	F-Value	P-Value
Model	14	2.11	26	<0.0001 Significant
Residual	14	0.0813		
Cor Total	28			

TABLE VI FIT SUMMARY STATISTICS FOR THE MODEL

Fit Parameter	Value
R ²	0.9630
Adjusted R ²	0.9259
Predicted R ²	0.7866
Adeq Precision	16.7585
Std dev	0.2851
C.V. %	1.7

The summary statistics corresponding to the ANOVA, which include key model performance indicators such as the coefficient of determination (R^2), adjusted R^2 , predicted R^2 , adequate precision, standard deviation, and the coefficient

of variation (C.V.), are presented in Table VI. These metrics collectively provide a comprehensive evaluation of the model's predictive capability, goodness of fit, and overall reliability

TABLE VII ACTUAL AND PREDICTED RESULTS AECD

Run	Pump Rate, ppg	ROP, ft/hr	Rotary Speed, RPM	Cuttings Density, sg	Actual AECD, ppg	Predicted AECD, ppg
1	250	35	30	2.125	16.91	16.91
2	250	45	30	2.1	16.96	17.13
3	250	35	20	2.15	17.6	17.44
4	250	45	40	2.125	16.91	17.01
5	200	35	30	2.15	17.72	18.12
6	250	35	20	2.1	16.99	17.15
7	300	35	40	2.125	14.94	14.75
8	200	45	30	2.125	17.72	17.81
9	200	35	30	2.1	17.82	17.57
10	250	25	20	2.125	16.95	17
11	250	35	40	2.15	17.78	17.54
12	200	25	30	2.125	17.83	17.66
13	200	35	40	2.125	17.85	17.67
14	250	25	30	2.15	17.76	17.52
15	300	45	30	2.125	14.95	15.04
16	250	45	20	2.125	17.64	17.36
17	300	35	30	2.1	14.94	14.69
18	250	35	30	2.125	16.91	16.91
19	250	35	30	2.125	16.91	16.91
20	250	35	40	2.1	16.55	16.63
21	200	35	20	2.125	17.68	17.8
22	300	25	30	2.125	14.93	14.76
23	250	25	40	2.125	16.5	16.93
24	250	25	30	2.1	16.54	16.64
25	250	45	30	2.15	17.64	17.47
26	250	35	30	2.125	16.91	16.91
27	300	35	30	2.15	14.94	15.34
28	300	35	20	2.125	14.94	15.05
29	250	35	30	2.125	16.91	16.91

Table VII shows the predicted values generated by the RSM models for each input variable, alongside the actual output data. It emphasizes the strong correlation observed between the experimental results and the predictions made by the RSM models.

Figure 7 shows the actual vs. predicted response for the quadratic regression model. Figure 7 depicts parity plots illustrating the relationship between the actual and predicted AECD. These plots demonstrate that the actual and predicted output responses closely align along the 45-degree line, indicating strong regression and agreement between the two datasets. Thus, there is an acceptable level of

agreement between the actual data (simulated sensitivity dataset) and the predicted responses from the RSM model.

1. Interaction Response of Parameters Using 3D Plots and Contour Plots: Figure 7 presents contour plots derived from the RSM model, illustrating the interactive effects of the independent variables on the annular equivalent circulating density (AECD). These graphical representations provide a clear visualization of how variations in the input parameters affect the response, offering valuable insights into the nature and strength of their interactions.

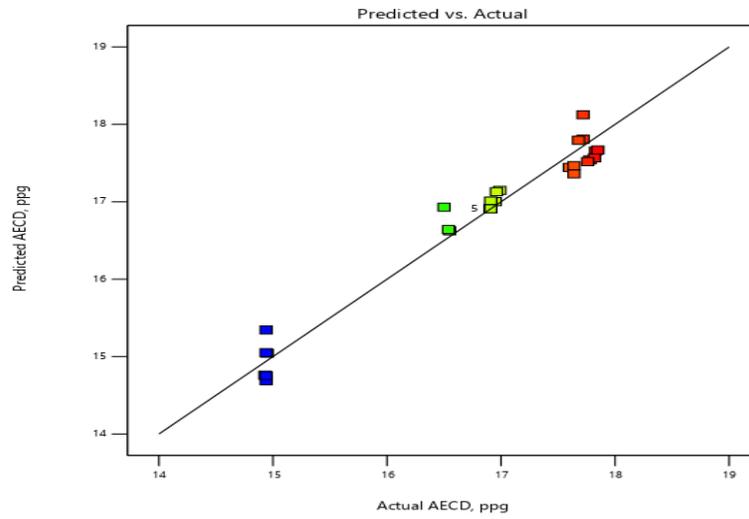


Fig.6 Parity Plot of Actual Vs Predicted Values AECD

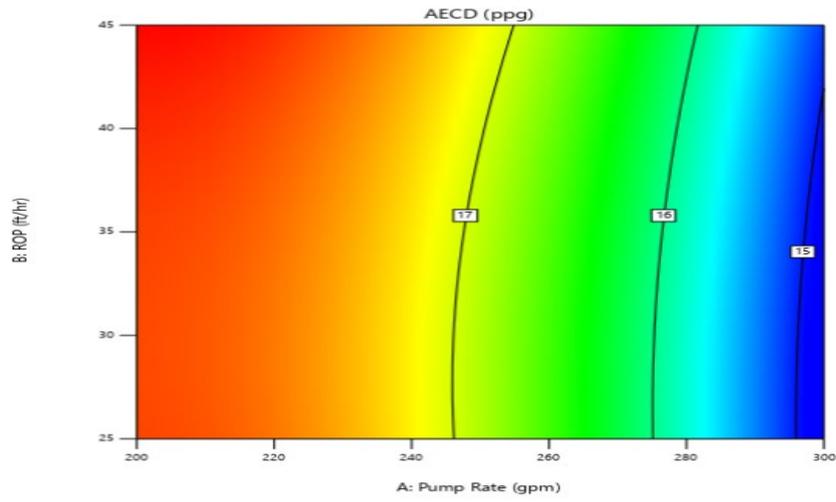


Fig.7a Contour Plots for AECD from RSM

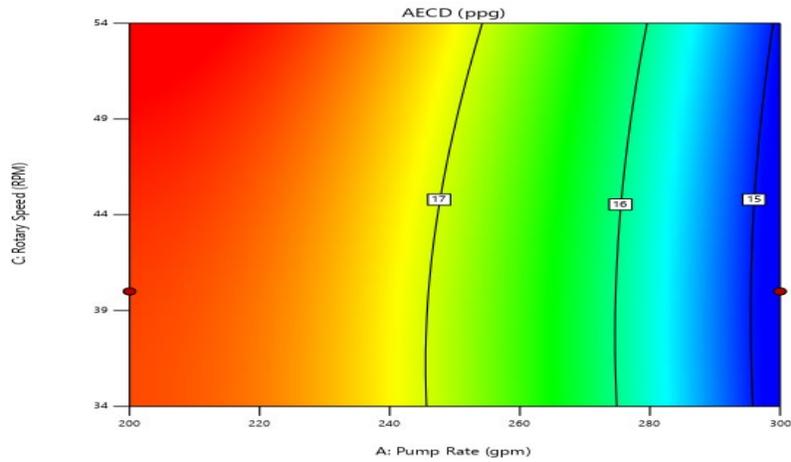


Fig.7b Contour Plots for AECD from RSM

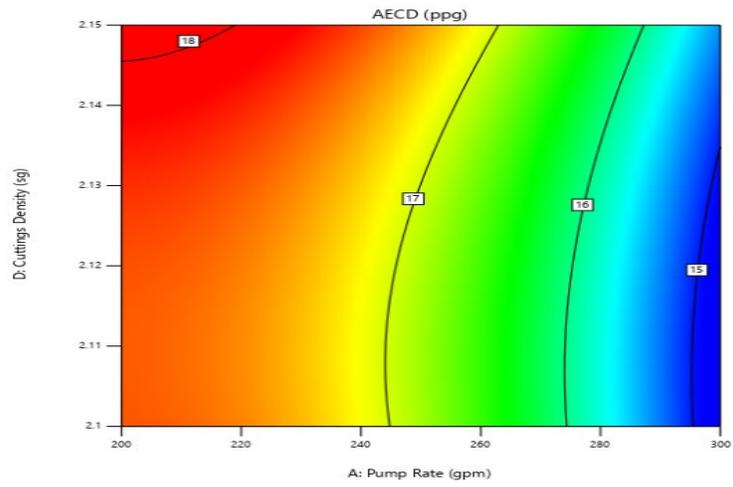


Fig.7c Contour Plots for AECD from RSM

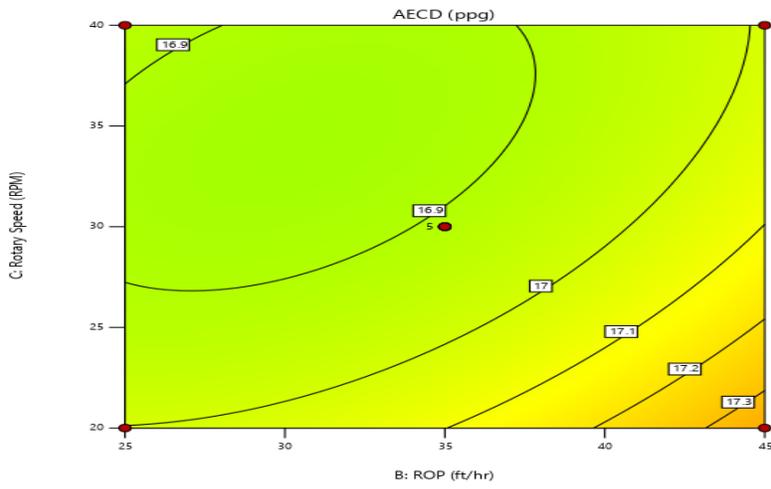


Fig.7d Contour Plots for AECD from RSM

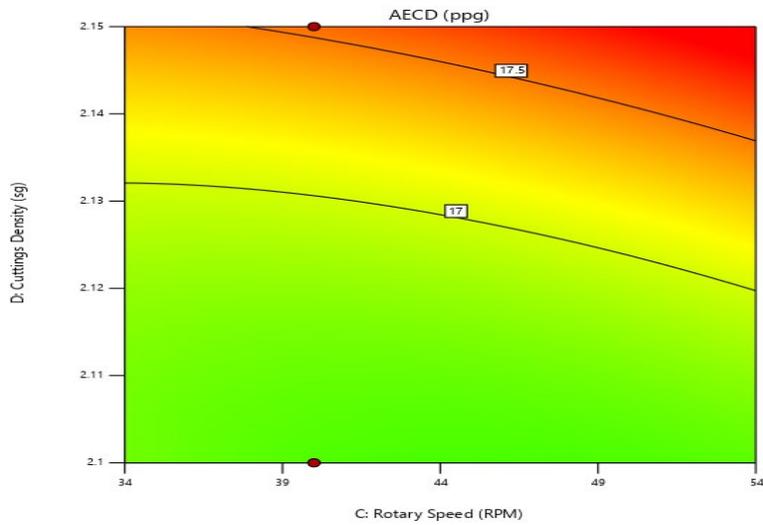


Fig.7e Contour Plots for AECD from RSM

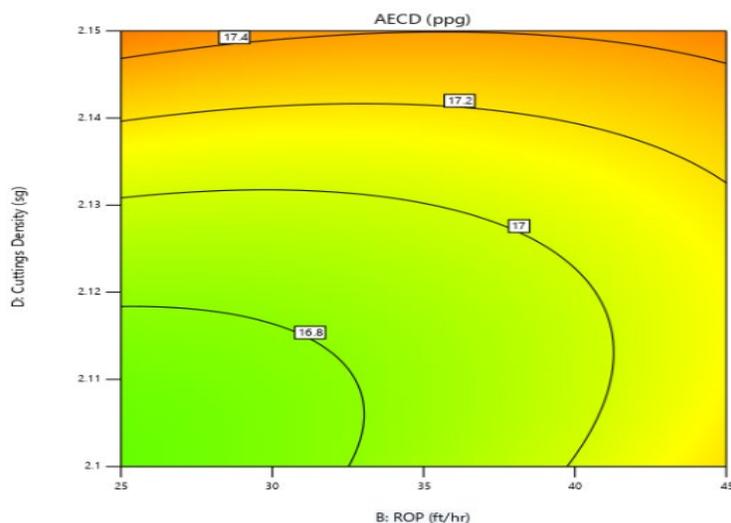


Fig.7f Contour Plots for AECD from RSM

Figures 7a through 7f present the contour plots generated from the Response Surface Methodology (RSM) analysis, which are instrumental in examining the interactive effects between pairs of independent drilling parameters on the annular equivalent circulating density (AECD). These contour plots help visualize how two variables simultaneously influence the response, allowing for better interpretation of their combined effects and interaction dynamics during drilling operations.

In Figure 7a, the interaction between pump rate and rate of penetration (ROP) is depicted. The plot shows that increasing the pump rate results in a reduction of AECD, particularly at lower ROP values. This is attributed to the enhanced annular velocity from higher pump rates, which improves cuttings transport and reduces pressure losses. However, when the pump rate is held constant, an increase in ROP leads to a rise in AECD. This is expected, as higher ROP introduces more cuttings into the annular space, increasing the solids concentration and, consequently, the effective density and frictional losses, which raise AECD.

Figure 7b illustrates the interaction between pump rate and rotary speed. It is observed that higher pump rates contribute to lower AECD values, especially at increased rotary speeds. This synergistic effect indicates that both parameters help improve hole-cleaning efficiency. Higher rotary speeds aid in agitating the cuttings bed and promoting particle suspension, while increased pump rates further enhance cuttings transport. Together, they reduce annular blockage and friction, resulting in a decrease in AECD. This implies an inverse relationship between both pump rate and rotary speed with AECD.

In Figure 7c, the interaction between pump rate and cuttings density is shown. At lower cuttings densities, increasing the pump rate results in a noticeable decrease in AECD, reflecting improved hydraulic efficiency. However, as the cuttings density increases and the pump rate is held constant, AECD rises due to the heavier solids content in

the annulus. This condition leads to increased hydrostatic pressure and frictional losses, especially when the transport capacity of the fluid becomes insufficient to handle the heavier solids effectively.

Figure 7d shows the combined influence of ROP and rotary speed on AECD. The plot indicates that increasing ROP causes AECD to rise, particularly when rotary speed is low. This is due to the generation of more cuttings that are not adequately agitated or lifted by the reduced mechanical action, causing cuttings accumulation and pressure build-up. However, when ROP is held constant, increasing rotary speed results in a decrease in AECD. This reduction is attributed to improved mixing and mobilization of cuttings from the wellbore, which reduces annular friction and the pressure required to circulate the fluid.

Figure 7e explores the interaction between ROP and cuttings density. It is evident from the contour that at higher ROP values, AECD increases significantly with an increase in cuttings density. This reflects the combined impact of more solids being generated (due to high ROP) and their inherently higher density, which together elevate the mixture's effective density and annular pressure losses, thereby increasing AECD. This interaction is critical in extended-reach wells, where cuttings transport efficiency becomes more challenging in longer lateral sections.

Finally, figure 7f illustrates the interaction between rotary speed and cuttings density. It is observed that at higher cuttings densities, increasing the rotary speed leads to an increase in AECD. Unlike the expected behavior, where higher rotary speed improves cuttings transport, the presence of very dense cuttings appears to dominate the interaction, resulting in an increased overall annular fluid density despite improved agitation. In such scenarios, the benefit of rotary-induced suspension may not be sufficient to offset the pressure burden caused by heavier solids, leading to an overall increase in AECD.

V. CONCLUSION

A comprehensive modeling and analysis of drilling hydraulics, focused on annular equivalent circulating density (AECD) in extended-reach wells (ERWs), has been successfully conducted, integrating simulation data from WellPlan and statistical modeling through response surface methodology (RSM). This study provides an in-depth evaluation of the interdependent effects of critical drilling parameters—namely, pumps rate, rate of penetration (ROP), rotary speed, and cuttings density—on AECD behavior under ERW conditions. Simulation results from WellPlan revealed that increasing pump rates consistently reduced AECD, a consequence of enhanced annular velocity and improved cuttings transport capacity, which mitigates solids accumulation and subsequent frictional pressure losses.

In contrast, increased ROP and higher cuttings density were shown to increase AECD due to greater cuttings generation and solid loading, intensifying annular pressure losses. Rotary speed exhibited an inverse relationship with AECD, as increased rotational agitation facilitated better suspension and removal of cuttings, thereby decreasing hydraulic resistance. However, interactive effects among parameters demonstrated non-linear behaviors, indicating that their combined influence on AECD cannot be adequately captured using simple linear models. To quantify these interactions and improve prediction accuracy, a quadratic RSM model was developed and validated using sensitivity data derived from WellPlan simulations. The regression model demonstrated strong statistical performance, with R^2 , adjusted R^2 , and predicted R^2 values of 0.9630, 0.9259, and 0.7866, respectively. The minimal disparity between adjusted and predicted R^2 indicates high model reliability and minimal overfitting. A low coefficient of variation (1.7%) and standard deviation further affirm the consistency and robustness of the model outputs. ANOVA results confirmed the statistical significance of all independent variables and their interactions, with high F-values and p-values well below the 0.05 threshold. Visualizations from the contour plots reinforced the predictive insights of the model, illustrating the individual and interactive effects of drilling parameters on AECD. These plots provided a diagnostic platform for understanding how operational changes influence AECD and for identifying optimal parameter ranges that maintain AECD within the safe hydraulic window, thereby preventing formation breakdown, wellbore instability, and lost circulation risks. This study demonstrates that the integration of physics-based hydraulic simulations and data-driven modeling constitutes a powerful approach for AECD analysis in ERWs. Such a hybrid framework not only enhances predictive accuracy but also supports proactive drilling fluid and parameter management. The methodology enables real-time optimization and contributes significantly to the design of safer and more efficient extended-reach drilling operations, ultimately reducing non-productive time and enhancing overall wellbore integrity.

Declaration of Conflicting Interests

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REFERENCES

- [1] A. Alsaihati, S. Elkatatny, and A. Abdulraheem, "Real-time prediction of equivalent circulation density for horizontal wells using intelligent machines," *ACS Omega*, vol. 6, no. 1, pp. 934–942, 2020.
- [2] M. Al-Rubaii, M. Al-Shargabi, B. Aldahlawi, D. Al-Shehri, and K. M. Minaev, "A developed robust model and artificial intelligence techniques to predict drilling fluid density and equivalent circulation density in real time," *Sensors*, vol. 23, no. 14, p. 6594, 2023.
- [3] K. Alasgarov, *Analysis of Equivalent Circulation Density Management in Drilling Operations*, M.S. thesis, Khazar Univ., Azerbaijan, 2017.
- [4] K. Z. Abdelgawad, M. Elzenary, S. Elkatatny, M. Mahmoud, A. Abdulraheem, and S. Patil, "New approach to evaluate the equivalent circulating density (ECD) using artificial intelligence techniques," *J. Pet. Explor. Prod. Technol.*, vol. 9, pp. 1569–1578, 2019.
- [5] M. A. Alum and F. Egbon, "Semi-analytical models on the effect of drilling fluid properties on rate of penetration (ROP)," in *SPE Nigeria Annual International Conference and Exhibition*, pp. SPE-150806, 2011.
- [6] H. H. Alkinani, A. T. Al-Hameedi, S. Dunn-Norman, M. A. Al-Alwani, R. A. Mutar, and W. H. Al-Bazzaz, "Data-driven neural network model to predict equivalent circulation density ECD," in *SPE Gas & Oil Technology Showcase and Conference*, pp. D021S010R001, 2019.
- [7] F. Badrouchi, V. Rasouli, and N. Badrouchi, "Impact of hole cleaning and drilling performance on the equivalent circulating density," *J. Pet. Sci. Eng.*, vol. 211, p. 110150, 2022.
- [8] N. Bolivar, J. Young, S. Dear, J. Massam, and T. Reid, "Field result of equivalent-circulating-density reduction with a low-rheology fluid," in *SPE/IADC Drilling Conference and Exhibition*, pp. SPE-105487, 2007.
- [9] K. Bybee, "Equivalent-circulating-density fluctuation in extended-reach drilling," *J. Pet. Technol.*, vol. 61, no. 2, pp. 64–67, 2009.
- [10] V. Dokhani, Y. Ma, and M. Yu, "Determination of equivalent circulating density of drilling fluids in deepwater drilling," *J. Nat. Gas Sci. Eng.*, vol. 34, pp. 1096–1105, 2016.
- [11] X. L. Guo, Z. M. Wang, and Z. H. Long, "Study on three-layer unsteady model of cuttings transport for extended-reach well," *J. Pet. Sci. Eng.*, vol. 73, no. 1–2, pp. 171–180, 2010.
- [12] W. Huang and D. Gao, "Analysis of drilling difficulty of extended-reach wells based on drilling limit theory," *Petrol. Sci.*, vol. 19, pp. 1099–1109, 2022, doi: 10.1016/j.petsci.2021.12.030.
- [13] K. C. Igwilo, E. E. Okoro, P. N. Ohia, P. Nwanro, and N. C. Izuwa, "A new approach to wellbore stability models using diagnostic iterative design: Case study-Niger Delta," *Petrol. Coal*, vol. 62, no. 2, 2020.
- [14] K. C. Igwilo, E. E. Okoro, A. A. Nwude, A. O. Mamudu, and C. Y. Onuh, "A review on gas well optimization using production performance models-A case study of horizontal well," *Open J. Yangtze Oil Gas*, vol. 3, no. 1, pp. 57–67, 2018.
- [15] K. C. Igwilo, Y. Yikarebogha, J. U. Obibuikwe, and N. Uwaezuoke, "Investigation of hydraulics performance of periwinkle shell powder for HPHT cementing operations in the Niger Delta," *Petrol. Coal*, vol. 66, no. 3, 2024.

- [16] X. Li, D. Gao, Y. Zhou, and H. Zhang, "Study on open-hole extended-reach limit model analysis for horizontal drilling in shales," *J. Nat. Gas Sci. Eng.*, vol. 34, pp. 520–533, 2016.
- [17] X. Li, D. Gao, and X. Chen, "A comprehensive prediction model of hydraulic extended-reach limit considering the allowable range of drilling fluid flow rate in horizontal drilling," *Sci. Rep.*, vol. 7, no. 1, p. 3083, 2017.
- [18] H. Miao, Z. Qiu, V. Dokhani, Y. Ma, and D. Zhang, "Numerical modeling of transient cuttings transport in deviated wellbores," *Geoenergy Sci. Eng.*, vol. 227, p. 211875, 2023.
- [19] S. Naganawa and K. Okatsu, "Fluctuation of equivalent circulating density in extended reach drilling with repeated formation and erosion of cuttings bed," in *IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, pp. SPE-115149, 2008.
- [20] M. S. Nobandegani, M. R. S. Birjandi, T. Darbandi, M. M. Khalilipour, F. Shahraki, and D. Mohebbi-Kalhari, "An industrial steam methane reformer optimization using response surface methodology," *J. Nat. Gas Sci. Eng.*, vol. 36, pp. 540–549, 2016.
- [21] K. O. Omomo, A. E. Esiri, and H. C. Olisakwe, "Hydraulic modeling and real-time optimization of drilling fluids: A future perspective," 2024, doi: [10.58175/gjret.2024.2.2.0030](https://doi.org/10.58175/gjret.2024.2.2.0030).
- [22] S. W. Petrie and R. Doll, "Benefits of using continuous circulation systems in ERD wells to manage ECD, bottom hole pressure and hole cleaning," in *SPE/IADC Middle East Drilling Technology Conference and Exhibition*, pp. D031S015R002, SPE-2021.
- [23] T. Robinson, D. Gomes, M. H. MeorHashim, M. H. Yusoff, M. F. Arriffin, A. Mohamad, and E. Othman, "Real-time estimation of downhole equivalent circulating density ECD using machine learning and applications," in *SPE/IADC Drilling Conference and Exhibition*, pp. D022S008R001, SPE-2022.
- [24] N. Uwaezuoke, K. C. Igwilo, E. E. Okoro, S. Adenubi, and J. U. Obibuike, "Improved model for equivalent circulating density and improved annular pressure drop estimation: Drilling approach," *Petrol. Coal*, vol. 64, no. 1, 2022.
- [25] J. Xiang, J. Wang, W. Lou, X. Wang, C. Zhao, and F. Zhang, "Quantitative analysis and modeling of transient cuttings transport impact on drill string mechanics in extended reach drilling," *Processes*, vol. 13, no. 1, p. 35, 2024.
- [26] D. D. Yusuf, E. J. Upahi, and H. O. Yusuf, "Multi-response optimization of planting process of a seed ridge planter using response surface methodology (RSM)," *Arid Zone J. Eng. Technol. Environ.*, vol. 19, no. 4, pp. 897–910, 2023.
- [27] M. Yusuf, A. S. Farooqi, M. A. Alam, L. K. Keong, K. Hellgardt, and B. Abdullah, "Response surface optimization of syngas production from greenhouse gases via DRM over high-performance Ni–W catalyst," *Int. J. Hydrogen Energy*, vol. 47, no. 72, pp. 31058–31071, 2022.