American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-9, Issue-4, pp-125-132
www.ajer.org
Research Paper Open Access

Comparative Analysis of Drilling Rate of Penetration Models

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ABSTRACT
The rate of penetration models analyzed in this research covers the earliest models developed from 1958 to 2018. They include the Speer's, Graham & Muench, Maurer, Galle & Wood, Reed, Bourgoyne & Young, Reza & Alcocer, Warren, Parker, Osgouei, John, Iqbal and Thomas models. The comparative analysis adopted indicators such as method, years of development, technique, and period in history, effect on cost reduction, dimensional capacity, and objectives, drilling parameters, contribution to knowledge and what can be improved upon. The qualitative analysis was done in thematic format and also presented in tabular form. Findings revealed that earlier models utilized fewer parameters making them expensive and cannot produce the required level of effectiveness while the newer models are comprehensive with the best selection of drilling parameters making them efficient and cost effective.

KEYWORDS: *drilling rate of penetration model, comparison of drilling rate of penetration models, qualitative analysis of drilling rate of penetration models*

Date of Submission: 22-03-2020 Date of acceptance: 08-04-2020

I. INTRODUCTION

In recent years the increasing demand for energy research from the ground has forced operators to develop a subject of survey ensuring that well drilling is realized in a more efficient manner. For that reason oil and gas companies tend to find different methods with different consideration on drilling activities in order to reduce cost, increase performance and overcome possible difficulties. There is no doubt that energy sources are reducing day by day and the oilfield exploitation will be more difficult in the future. These entail that the future project should improve productivity and make well construction cost effective. New methods which improve drilling operations have been based in technological advantages that maximize the desired goals.

The basic principle for all operations is the relation between cost and time, which are two interdependent amounts. It is understood that when time expands, cost increases and vice versa. From the beginning of the 20th century, oil and gas companies have realized how important is to minimize drilling operation cost. As a result, all efforts aim to increase drilling speed in order to accelerate penetration rate (ROP) (Mensa-Wilmot, 2010). It is generally accepted that there are many factors referred to as performance qualifiers (PQ) which influence ROP. Some of them are more important, some other less and all together make the relationship complex, as they require the development of mathematical models in order to be determined. Consequently, only when all parameters affecting ROP are met to the greatest extent possible, they give the best combination of drilling operating conditions. Hence, during the drilling process the main objective is to conduct all the activities in the most economic way

It is remarkable that structure and properties formation is one of the most importantfactors on drilling process. There are controllable factors such as bit types, fluid properties, WOB, horsepower,hydraulics and rotary speed. While the driller follows the good drilling practice, hehas the opportunity to select and determine the factors using suitable models whichpredict the rate of penetration.

The scope of this study is to comparatively analyze all models that have been used for ROPpredictions during the drilling operation from the earliest method during the scientific period until today.

II. DRILLING PROCESS

A plant with several operating systems conducts the process of the drilling. Boiling for such services needs two major constituencies, according to Azar, in 2007: skilled workforce and hardware systems. In fact, the construction of holes includes components such as equipment and consumables such as bottles, asphalt, dirt, water and others. The staff comprises a number of drillers and a section of factory processes. For the optimum drilling operations, the drilling engineers may develop the mud-program, casing and cementing systems, hydraulics, drill bit programs, drilling string and well-control programs in choosing the type of plant. The Party is in charge of daily operations, with workers including the machine pusher and the boiler team like the derrick and motor employees, the boilers, the manufacturing plant, the roustabout, and so on. A power generation machine, the hoist system, the drainage method for the drilling fluid, the revolving device, the control system for well blowouts, the data acquisition and monitoring system for boiling.

III. DRILLING RATE OF PENETRATION MODELS

Speer's Method, 1958

Speer proposed a drilling rate penetration model in 1958 while analyzing a method for determining optimum drilling techniques. In a single diagram, he integrated five relationships to assess optimal drilling technologies from minimal field test results.

According to El-Nadi& Osman (1976), Speer determined a drilling equation which represents the combined effect of various parameters on penetration rate.

$$T_p = T_O + 0.9\, P_c$$

Constants were built from a less square study of empirical data for penetration rate equations. The calculations and concept maps help to assess the drilling capacity of various training courses. Drilling parameters in the speer system included depth and function of shape, penetration levels, bit-to-bit weight, rotary speed, pumping pressures, measurements of the mud pump, bit conditions (type, diameter, size of the pump), and fluid boiling properties.

Cunningham's Method, 1960

The levels of boiling of a close bit are proportional to the spinning velocity of the bit at atmospheric pressure for the wide range of RPM and WOB mentioned below.:

$$R = KW_aN$$

R = drilling rate (ft/hr);
W = weight on bit (klbf) ;
N = rotary speed ; and
K, a = constants of proportionality

Graham and Muench Method, 1959

In 1959, Graham and Munch proposed a formula for the penetration rate for boiling. There were constants describing the respective configurations occurring in the field in the mathematical ties suggested. With the aid of computations under any boiling conditions their analysis was able to suggest optimal weight at bit and rotor speed to reduce the overall boiling costs. The equation below represents the mathematical model proposed by Graham and Muench.

$$f_5 = e^{a_5 x_5} = \left\{\frac{\frac{w}{db} - \left(\frac{w}{d_b}\right)t}{4 - \left(\frac{w}{d_b}\right)t}\right\}^{a_5}$$

The diameter and weight feature of the bit is specified by "a5." The bit weight and bit diameter are known as directly affecting the rate of penetration above.

Maurer's Method, 1962

Based on the ideal principle of cleaning of rotary drilling, Maurer established a boil rate of penetration in 1962. Maurer developed penetration rate of bits of the roller-cone given the process of the rock cratering. The calculation was based on the state of "complete brushing" where all rock dust is deemed extracted between the impact of the tooth. A working relationship was established between drilling intensity, bit weight and string speed given that the hole was properly cleaned under conditions. The relationships acquired were also noted as depending on the extent of perforation. The intensity of the boiling equation as shown below.

$$\frac{dF}{dt} = K\left(\frac{N(W - W_0)^2}{D^2S^2}\right)$$

Where, $\frac{dF}{dt}$ = Rate of penetration (ft/hr);
K = Constant of proportionality;
N = Rotary Speed;
W = Weight on bit (klbf);
W_0 = Threshold weight on bit (klbf);

D = Bit diameter (inch); S = Rock strength (psi)

Galle & Woods' Method, 1963

In 1963 Galle and Woods introduced the best perforated weight and spinning speed pattern for rotary rock parts. The weight selection impact on bit WOB and RPM has been examined. You provided the best selection diagrams of the mixture of boiling parameters. They have shown that when utilizing their system, boxing costs are reduced.

We have also published an analysis showing a connection to only millled tooth bits developed for Soft Formations between dent wear rate and rotary rpm. Boiling prices, video, boiling hours and teeth conditions can be measured in their graphs and the slow bit is carried. Boiling costs were shown to be minimized with the variations of the prescribed boiling parameters. We displayed the calculation of boiling intensity as shown below in the equation according to weight on WOB and RPM bit.

$$\frac{dF}{dt} = C_{fd}\frac{W^k r}{a^p}$$

Where, C_{fd} is the formation drillability parameter;

a = 0.028125 h^2 + 6.0h + 1

k = 1.0

p = 0.5

$$r_{hard-formations} = \left[e^{\frac{-100}{N^2}}N^{-0.428} + 0.2N\left(1 - e^{\frac{-100}{N^2}}\right)\right] \text{.............................} \ 2.5$$

$$r_{soft-formations} = \left[e^{N^2}N^{-0.75} + 0.5N\left(1 - e^{\frac{-100}{N^2}}\right)\right] \text{.........................} \ 2.6$$

$$W = \frac{7.88WOB}{D_b}$$

Reed's Model, 1971

In 1971, as Reed decided to analyze a Monte Carlo solution to optimum boiling, he suggested a penetration rate model. In order to reorder and smooth tracks and to reduce the costs per foot in intermediate Monte Carlo measurements, the linear (with the least square technique) and curvilinear smoothing techniques are being established. Owing to the rigor and the exceptional facility of restriction inclusion, the approach established was useful.

Bourgoyne and Young's' Method, 1974

In 1974, Bourgoyne and Young introduced a concept for the penetration of boiling levels when the optimum boiling and irregular measurement of pressure using a multi-regression method. The process of boiling optimization is the largest approach for Bourgoyne and youngsters. This approach is therefore deemed the most suitable tool for maximizing drilling in real time.

Data of at least 25 wells were used to extract a1, a2, a8 constants. They finished with the finding that drilling expense can be minimized by about 10 percent using relatively simple equations for optimization. The following is a description of the equations.

Rate of penetration is expressed as:

$$\frac{dh}{dt} = Exp\left(a_1 + \sum_{j=2}^{8} a_j x_j\right)$$

Where;

$\frac{dh}{dt} = Rate\ of\ penetration$; h = Depth, ft; t = Time, hrs; $a_j = Constants;$

$$x_j = Drilling\ parameters$$

Reza and Alcocer Model, 1986

In 1986, a special computer simulation model for the well boiling was introduced for Reza and Alcocer. For the use of Buckingham Pi theorem, Reza and Alcocer have established a multidimensional, non-linear fluid, spatial, dimensionless drilling model. Buckingham Pi theorem is a theorem for dimension-less computation used for constructing equations. The formula consisted of three equations: penetration rate, slow rate and wear rate. Their research expressed the impact on three calculations of these variables: bit-to-bit weight, rotary velocity, bit diameter, bit-to-bit width, bit-to-bearing diameter, strength of fluid.They defined the rate of penetration in a non-linear, multivariable system as shown in the following equation.

$$\frac{F}{Nd_p} = C_1\left[\frac{Nd_p^2}{v}\right]^a \left[\frac{Nd_p^3}{Q}\right]^b \left[\frac{Ed_p}{W}\right]^c \left[\frac{\Delta pd_p}{W}\right]^d$$

Where, C_1, a, b, c, and d are unknown parameters.

Warren's Model, 1986

At the time of evaluating the efficiency of roller cone parts, Mr Warren suggested another formula for drilling penetration rate in 1986. Warren implemented a ROP model which covers both the original production of the chip and the cuttings. The penetration rate of which they are extracted is two words and only operates with the complete cleaning of the cavity. The first term specified the optimum weight-on-bit WOB impact limit, while the second term, on the other hand, envisaged penetration of the tooth into the shape. The equation for both steel tooth and bit form was found to match the experimental data.

$$ROP = \left[f_c \times \left(\frac{aCCS^2 d_b^2}{NW^2} + \frac{b}{RPM\ d_b}\right) + \frac{cd_b \gamma_f \mu}{F_{jm}}\right]$$

Adapted to the below:

$$ROP = \left(\frac{aS^2 d_b^3}{N^b W^2} + \frac{C}{Nd_b} + \frac{cd_b \gamma_f \mu}{F_{jm}}\right)^{-1}$$

Where:

ROP = Rate of penetration (m/h); a, b, c = Bit coefficients (dimensionless); CCS = Rock confined compressive strength (psi); db= Bit diameter (in); N = RPM = Bit revolutions (rev/min); W = WOB = Weight on bit (klbf); γf = Drilling fluid density (Ib/gal); † = Drilling fluid plastic viscosity (cp) ; fc = Chip-hold down function (dimensionless); Fjm = Modified jet impact force function (klbf)

Wojtanowicz and Kuru Method, 1990

In 1990, in the study of minimum cost well-boilering technique using dynamic programming Wojtanowicz and Kuru suggested a model for drill rate penetration. A modern technique for designing and monitoring the drilling cycle has been proposed by Wojtanowicz and Kuru; principle of single-bit control is paired with optimal multi-bit drilling scheme for a well. In contrast with traditional boiling optimization and standard field experience, the dynamic boiling approach has been measured for a considerable cost saving capacity of 25 and 60 percent respectively. For costly and long-lasting PDC bits the approach seemed to be the most cost effective by using their performance better and decreasing the number of bits required for the hole.

$$F_V = R_c A_c (\sin\theta' + \mu\cos\theta') + R_p A_w$$
$$F_h = R_c A_c (\sin\theta' - \mu\cos\theta') + \mu R_p A_w$$

Mechanical Specific Energy Method, 1992

In 1992, Pessier and Fear suggested a mechanically specific energy system for estimating the rate of penetration of boiling when quantifying common problems in boiling with mechanical and sliding energy coefficients.

The mechanical energy technique introduced by Teale in 1965 was improved by Pessier and Fear. They performed machine simulator experiments and laboratory tests for the quantification and creation of a power-balanced boiling model under hydro-stress conditions. They developed a mechanical energy equation. They found better detection methods for handling problems of bohring parts, which are quicker and more comfortable by constantly tracking the operation, (like WOB and ROP targeted evaluation).

The drilling energy equation is determined from the following equation, which is extracted by the mechanical energy extended on a little.:

$$SE = \frac{20WN}{Df} \times t$$

Where,

SE = Drilling specific energy (MJ/m3); W = Weight on bit (kg); N = Rotating speed (rpm); D = the hole diameter (mm); F = Footage (ft.); t = Rotating time (min)

Hareland and Rampersad Method, 1994

A model for estimating the drilling efficiency of drag bits was developed by Hareland and Rampersad in 1994. It was focused on mass reduction where the cutting rate is equal to the penetration rate in front of the cutters. In order to properly take spatial relation and rock failure criterion into consideration the results of the operating parameters were integrated, as shown below..

$$ROP = \frac{14.14\ W\ N\ \cos\alpha}{\sigma\ D\ \tan\theta} \frac{a}{N^b W^c}$$

Bonet Drilling Optimization Method, 1995

In 1995, Bonet, Cunha and Prado suggested a tool to measure the rate of penetration of bohring parameters thus modeling the optimisation of bohring as a new way of optimizing bohring parameters and increasing bohring performance. For the activity of a whole system of boiling from original to final range, Bonet, Cunha and Prado studied the costs for boiling in standardized configurations. The main aim of this project was to determine the best perforation parameters for each bit used during the perforation process, the amount of bits to use and the depth to adjust each bit. A computer program to ease system use has been created. The mathematical expression for the proposed drilling rate is presented below

$$\frac{dy}{dt} = \frac{K * (W - M) * N^{\gamma}}{(1 + C_2 H_t)}$$

w: bit weight, thousands pounds; m: bit weight extrapolated to zero range of drilling; ll: exponent voicing impact of rotary velocity on the rate of drilling; C2: constant; ht: height of the normalized tooth, flat, straight and maximum tooth.

Parkers Model, 2000

Technology created by Parker, Collins, Pelli and Brancato in 2000 to help pick roller bits and predict ideal bit-bit weight and speed rotation. The research was carried out using the Bourgoyne and Young approach on the basis of relevant field experience. The optimum weight and rotational velocity determined on the basis of minimum cost per foot. The program was created by Bourgoyne and Young.

$$\frac{df}{dt} = e\left(\sum_{j}^{8} -2a_j x_j\right)$$

Ozbayoglu and Omurlu Model, 2005

For the goal of reducing the boiling costs, Ozbayoglu and Omurlu built a model for boiling penetration rate in 2005 by optimizing the boiling parameters. In order to reduce the costs of drilling, Ozbayoglu and Omurlu suggested a model in which they optimized mathematically drill parameters. It was known to have a direct effect in terms of weight, rotational speeds, form of bit and wear, and hydraulic parts. An analytical cost boiling equation with a non-linear penetration rate was described. Drilling parameters of the current field data from the literature have been optimized by means of certain mathematical models using the given equation. They noticed that the expense of exploration was lowered up to four times.

Osgouei Model, 2007

The Osgouei model for directional and horizontal wells was created in 2007. Osgouei established an essential model for calculating the penetration rate for the Insert and PDC bits, which would provide a practical solution to this problem. Both inclined and horizontal wells this model is going to fit.

John's Model, 2012

John suggested in 2012 a model to measure the penetration level of drilling and establish customized decisions by viewing geographical and boiling data on remote wellsites in real time. In real time, We found out that the asset department and contractors using data for early decisions are generated with a paradigm shift. It has been shown that prompt decisions can be made with the best experience from around the globe after the relevant data has been transferred to and from the factory.

Iqbal Drilling Optimization, 2014

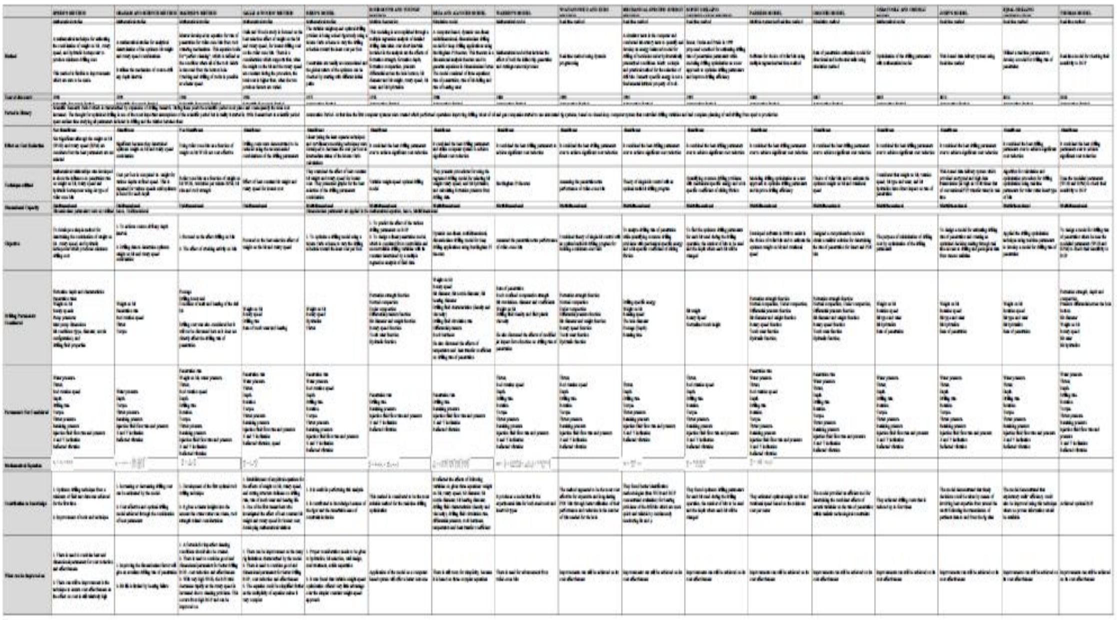
Iqbal provided the estimation and optimization algorithm for optimizing the drilling with real-time bits form roller cutter parameters. The technique consists of measures in which weight exponents have been measured at the specified penetration levels, the best string length and WOB parameters have been calculated using the correlation .

Thomas Model, 2018

In 2018 Thomas introduced a calculation of the rate of penetration of boiling by using the standard parameters (WOB and RPM). The model stresses parameters influencing ROPs such as formulation power, formation width, training compaction, differential pressure across the bottom of the hole, bit diameter and bit weight, rotational speed, bit wear, bit hydraulics. The boiler can regulate the Rotary speed (RPM Rotations by Minute) and bit weight (WOB) very easily among these parameters. Such parameters apply to ROP explicitly. Increased ROP results in more ROP. This is why these criteria were taken into account in this paper; to see to what degree they influence the ROP when a defined percentage is increased or declined.

IV. COMPARATIVE ANALYSIS OF THE MODELS

See Appendix 1 - Attached



V. DISCUSSION

To effectively develop an optimal control system for rotary drilling of oil wells, all the existing mathematical models for calculating the penetration rate would be analyzed critically.The comparative analysis of the drilling rate of penetration models is done with focus on their application in the petroleum industry, analyzing the parameters of their methods as well as their benefits and weaknesses. The development of all these suitable models took place in the first 20 years of research into drilling optimization, such as rotary drilling bits, fluid dynamics, casing installation; cement (Tansev, 2013). The earliest era is the period during which all methods and tools improved, hence it was named development period (Tansev, 2013). This is the period that precedes the development of Speer's model.

This is followed by the scientific era in which oil companies started to perceive the importance of research. Speer, Graham and Muench, Maurer and Galle and Wood models were developed in this period (Tansev, 2013). During these years the scientific period took place and consequently the total cost increased (Tansev, 2013). The thought for optimized drilling is one of the most important assumptions of the scientific period. Speer, Graham and Muench, Maurer and Galle and Wood spent lengthy time studying all parameters included in drilling and the relation between them.

This period was closely followed by an era known as automation period. A research by Reeds initiated this period. At that time the first computer systems were created which performed operations improving drilling (Tansev, 2013). Most of oil and gas companies started to use automated rig systems, based on closed-loop computer system that controlled drilling variables and had complete planning of well drilling from spud to production. Models by Bourgoyne and Young, Reza and Alcocer, Warren, Parker, Osgouei, John, Iqbal, Thomas were developed in this period.

The Graham and Muenh study in 1959 can be regarded as the first integrated model which approached and included the most important drilling factors (Maidlaand, 2010). More precisely this mathematical model evaluated the correlation between WOB and rotary speed, as well as the shelf life of bit (Maidlaand, 2010). In short, drilling rate was predicted combining depth, rotary speed and WOB (Maidlaand, 2010). Another research was carried out in 1963 by Galle and Woods in which they created special arranged graphs which indicated the best combination of drilling parameters. So far the most important model on which all modern studies have relied is the linear penetration model by Bourgoyne and Young (Maidlaand, 2010). This model uses multiple regression analysis in order to achieve the best selection of drilling parameters.

The Speer's, Graham & Muench, Maurer, Galle & Wood and Reed models are designed to achieve one dimensional drilling and cannot be utilized for dynamic drilling. Bourgoyne and Young, Reza and Alcocer, Warren, Parker, Osgouei, John, Iqbal, Thomas developed an inclusive system that can achieve multi-dimensional drilling which makes them suitable for dynamic drilling.

Reed method predicted the best combination of factors, such as weight on the bit and rotary speed, taking into consideration two different cases, when all other variables were constant and when they were fluctuated. This method reached the same result as Galle and Wood method, but is considered more accurate because it has resolved the Monte Carlo Scheme. It should also be mentioned that this method presented effective advantages in connection with field application

VI. CONCLUSION

Viewing all the rate of penetration methods and comparing their strengths can help in deciding which model works best for a particular drilling operation with the aim of reducing cost. The works researched spanned from 1958 to 2018 cutting across the scientific research period and the automation period. the major comparison areas included method, year of discovery, period in history, effect on cost reduction, technique utilized, dimensional capacity, objective, drilling parameters considered, parameters not considered, mathematical equation, contribution to knowledge and what can be improved on.

Early models focused on modeling a number of parameters which influence the boiling rate while the other variables were assumed or retained. A complete and comprehensive simulation was subsequently given with most of the parameters that influence penetration levels. Optimization models have already been developed that are able to optimize the parameters influencing the penetration rate in real time.

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Prof. Adeboye Olatunbosun,etal." Comparative Analysis of Drilling Rate of Penetration Models.” *American Journal of Engineering Research (AJER)*, vol. 9(04), 2020, pp. 125-132.