Latin American Journal of Energy Research - Lajer
periodicos.ufes.br/lajer

Latin American Journal of Energy Research – Lajer (2021) v. 8, n. 1, pp. 59–66
https://doi.org/10.21712/lajer.2021.v8.n1.p59-66

Drilling optimization of petroleum wells: A data analysis of the drilling fluid flow-rate influence in ROP

Otimização de perfuração de poços de petróleo: Uma análise de dados da vazão de fluidos de perfuração no ROP

Lucas Sales Rodrigues de Oliveira[1,*], Andreas Nascimento[2,*], Diunay Zuliani Mantegazini[3], Nazem Nascimento[4]

[1] Program PRH-ANP/FINEP 53.1, Department of Engineering and Technology, *Universidade Federal do Espírito Santo – UFES*, Campus São Mateus, ES, Brazil
[2] Program PRH-ANP/FINEP 53.1, Department of Engineering and Technology, *Universidade Federal do Espírito Santo – UFES*, Campus São Mateus, ES, Brazil
[3] Graduate Program in Mechanical Engineering, *Universidade Estadual Paulista – UNESP*, Campus Guaratinguetá, SP, Brazil
[4] Visiting Researcher, Program PRH-ANP/FINEP 34.1, *Universidade Estadual Paulista – UNESP*, Campus Guaratinguetá, SP, Brazil
*Corresponding author, E-mail: andreas.nascimento@ufes.br and lucassalesrdo@gmail.com

Received: 01 June 2021| Accepted: 19 June 2021| Published online: 11 July 2021

Abstract: The petroleum industry is already demanding lowering exploration costs, which reflects in needs of reducing drilling operational costs, which can be achieved through implementation of more efficiency in operations. Researches have shown that scientist and companies are already experiencing different approaches aiming at boosting drillability. One method not well implemented is variation of flow-rate as a mechanical specific drilling parameter, given its complexity and relation to well integrity. This paper details the influence in flow-rate and related parameters in rate of penetration, showing how DHAP, ECD, Flow-rate and ROP are related to each other. It can be seen that by increasing a flow-rate, an increase in ROP is possible, but that flow-rate changes also influence the down-hole pressure and ECD, what imply in possible downhole differential pressure variation. The higher the down-hole differential pressure, the less will be the implied ROP. All these have influence on drilling efficiency.
Keywords: Drilling, fluid, data analysis, flow-rate, efficiency.

***Resumo**: A indústria de petróleo vem demandando reduções nos custos de exploração, o que reflete nas necessidades de se reduzir os custos operacionais de perfuração, e que pode ser atingido através da implementação de maior eficiência na operação. Pesquisas apontam que cientistas e companhias já estão experimentando diferentes abordagens visando incrementar a penetrabilidade da perfuração. Um método que não está bem implementado é a variação da vazão como um parâmetro mecânico específico de perfuração, dada sua complexidade e relação com a integridade do poço. Este artigo detalha a influência na vazão e parâmetros relacionados na taxa de penetração, apresentando como DHAP, ECD, vazão e ROP interagem uns com os outros. Pode-se ser observado que ao aumentar a vazão, um aumento em ROP é possível, mas que variações na vazão também influenciam a pressão de fundo de poço e ECD, implicando em possível variação do diferencial de pressão no fundo do poço. Um aumento do diferencial de pressão no fundo do poço, implica em um menor ROP. Todos esses fatores possuem influência na eficiência de perfuração.*
Palavras chave: Perfuração, fluido, análise de dados, vazão, eficiência.

1. Introduction

Petroleum and natural gas are strategic natural resources, composed by hydrocarbons (molecules of carbon and hydrogen) and are originated by a complex geological process. Among the factors for these fossil fuels generation are the presence of organic matter as the source for oil origination, deposition of rock sediments to the creation of the reservoir and source rock and high temperature and pressure conditions for organic matter maturation. In order to produce this resource, located below the surface (subsurface), it is necessary a combination of many efforts and process to reach and produce this natural resource.

Drilling is the first and most expensive stage in order to reach the oil reservoirs, being the process responsible for establishing pathway between the interest zone in the subsurface and the surface installations.

As a part of this stage, the Rate of Penetration (ROP) is an indicator of drilling progress as long as the drilled depth is increased and, for this, it has three important points for the best performance and drilling optimization which are the Weight on Bit (WOB), Rotations per Minute (RPM) and Mechanical Specific Energy (MSE). These three points have been the focus of many researches in order to increase drilling efficiency, gaining in operational time and financially to the industry.

However, the number of studies about the influence of drilling fluid flow-rate on ROP and MSE is not considerable when compared with the other parameters presented, and this is mainly due to the reduced variation limit imposed to this specific parameter while drilling, given by the formation pressures and well cleaning necessities that need to be closely followed.

The Mud Window Figure 1 is a graphic representing an information set necessary to the drilling operation, used as a reference to maintain the well integrity in terms of pressure while drilling. It presents the pore pressure as the inferior limit (fluid's formation pressure into the well) and fracture pressure needed to fracturing the well as the superior limit for the operation. According to it, the fluid properties (mainly density) and other flow parameters are defined, so that the pressure of the fluid may be maintained in the allowable range between the maximum and minimum values (Silva, 2015).

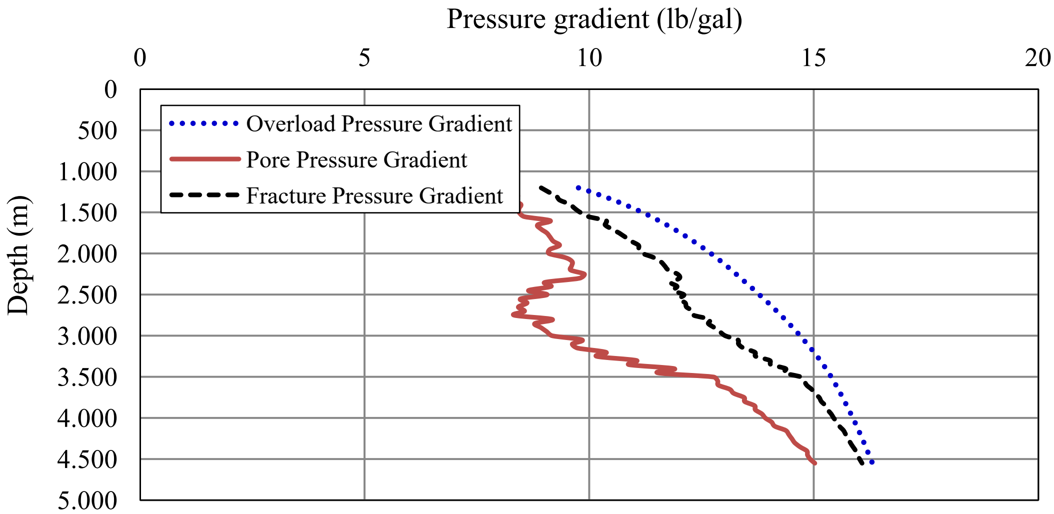

Figure 1. Mud Window (Source: Elaborated by author with Microsoft Excel 2016).

Insufficient well cleaning may lead to higher operational costs (Al-Rubaii, et al. 2020). According to Mohammadsalehi and Malekzadah (2012), to ensure a successfully well cleaning, the flow-rate while drilling must be higher than the sum of cuttings production rate (associated with the ROP) and the related slip velocity (speed the cuttings may slip, within the fluid, to the bottom hole direction).

Even with the limitations to the range of application of drilling fluid flow-rate variation, optimization of drilling has been demanded in the industry, as this has a high cost as a consequence of the quantity of factors and complexities involved, such as: geology of the formation, target location, presence of contaminants, applied technology, available equipment, experience and preference of the crew members, skilled drilling personnel, unexpected events, failures and safety (EIA, 2016).

According to Petrobras, in Brazil, the biggest challenge in terms of new oil and gas fields is the Pre-salt, a sequence of sedimentary rocks formed 100 million years ago during the separation of the American and African continent. After the deposition of organic matter, with the formation of the Atlantic Ocean, there was the deposition and formation of a salt layer approximately two thousand meters thick, which retained the accumulated organic matter and contributed for the hydrocarbon's generation. These are, nowadays, characterized as a complex deep carbonates' formation, the Pre-salt reservoir layer, located in depths that can be greater than 5,000 meters (Medina, 2012).

In this context, the objective of this paper is to verify and understand if the drilling fluid injection flow-rate variation is able to influence the rate of penetration and possible rooms in terms of optimization strategy, through a data analysis of real Pre-salt reservoir well data.

2. Literature review

The behavior of the drilling fluid in a given well being drilled and related parameters must be known for a coherent data interpretation. The analysis and discussions are focused on the following: flow-rate relation with ROP, Equivalent Circulating Density (ECD), Reynolds number, differential pressure and jet impact force.

2.1 Equivalent circulating density

As discussed earlier, the mud window is responsible for defining some fluid properties, and the main one of these is density, because of the impact it has on the down-hole pressure. However, this is not a static condition, but a dynamic one, given the drill-bit rotation, drill pipe rotation, and fluid circulation while drilling. A representation of these dynamic effects is the consideration of the Equivalent Circulating Density (ECD), which is defined by Ataga, Ogbonna, and Boniface (2012) as: "the sum of the hydrostatic pressure head of the fluid column, and the pressure loss in the annulus due to fluid flow. Eq. (1) by Hemphill, et al. (2007) presents the ECD.

$$ECD = ESD + \Delta P/0.052/TVD \quad (1)$$

Where ESD is the Equivalent Static Density, ΔP is the change in Pressure Drop and TVD is the True Vertical Depth. Thereby, the injection flow-rate variation contributes to the exercised pressure, which is limited by the mud window.

2.2 Reynolds number and differential pressure

The Reynolds number is a dimensionless parameter that, according no Rehm, et al. (2008), is used in the classification of fluid flow patterns in pipelines; lower values are associated to laminar flows and higher values to turbulent flows. The Eq. (2) presents the Reynolds number calculation.

$$N_{\Re} = \frac{\rho v d}{\mu} \quad (2)$$

Where $N_{\Re}$ is the Reynolds number, ρ is the fluid density, v is the average fluid velocity, d is the drill pipe internal diameter and μ is the absolute viscosity of the drilling fluid.

As can be seen by the relation of fluid velocity with the mentioned parameters, it's also possible to relate the flow-rate to it. In Nascimento (2016) research, experimental results from literature that derived of the ROP model by Bourgoyne Jr. and Young Jr. (1974) were explained, determining two relations for the ROP, given by Figure 2 and Figure 3, where the rate of penetration was higher for greater Reynolds numbers, decreasing by increase in differential pressures (pressure between the bottom hole and the formation), respectively.

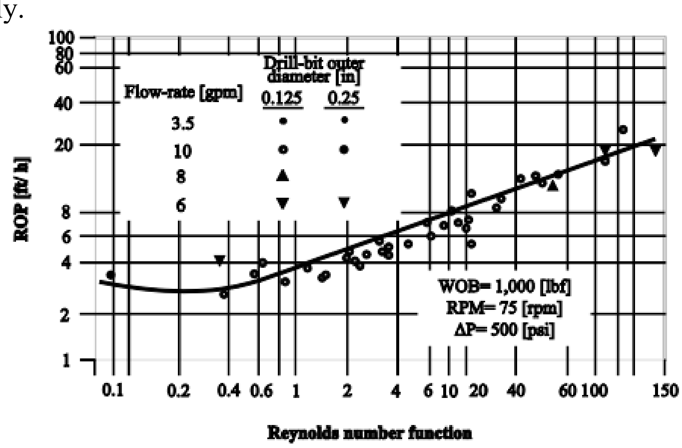

Figure 2. ROP versus Reynolds number (Source: Cunningham., 1959; Eckel, 1968, apud Nascimento, 2016).

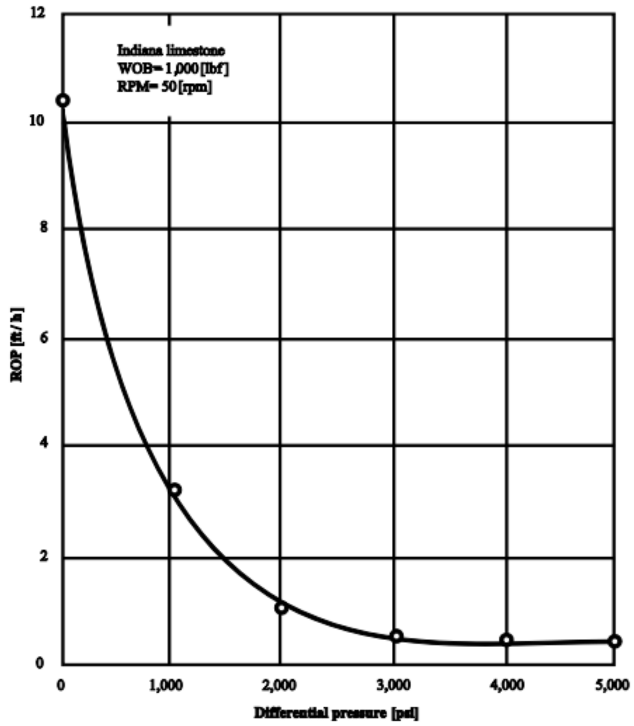

Figure 3. ROP versus Differential pressure (Source: Cunningham., 1959; Eckel, 1968, apud Nascimento, 2016).

2.3 Jet impact force

When the drilling fluid is injected in the well, passing through the nozzles from the drill-bit, a jet configuration can be observed, so that a force exercises impact weakening the formation, facilitating the drilling operation. The relation for the jet impact force, fluid velocity and flow-rate is obtained by Warren (1987, apud Nascimento, 2016), through an empirical formulation for jet dispersion in the bottom hole, presented by Eq.(3).

$$F_j = 0.000516\ \rho\ Q_{total} V \quad (3)$$

where F_j is the jet impact force used to characterize level of bit hydraulics (lbf), ρ is the fluid density, Q_{total} is the total nozzles flow-rate (gpm) and $V is the average velocity of jet nozzle (ft/s)$.

Figure 4 shows the influence of total jet impact force in ROP.

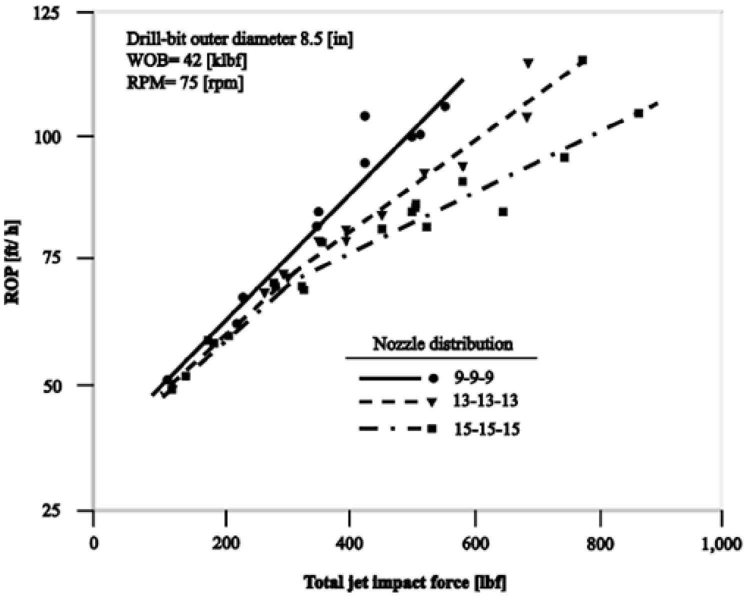

Figure 4. Influence of total jet impact force in the ROP (Source: Warren et al.,1984, apud Nascimento, 2016).

3. Methodology

For the data analysis, drilling data pack of a Brazilian pre-salt well from Nascimento (2016) was used, where information corresponds to a vertical drilling in carbonate reservoir lithology. The parameters presented were measured in the surface, relating 0.1524 m of depth steps. Table 1 presents the well data depth range and number of data points acquired.

The procedure for analyzing the data starts with a treatment, removing gaps and outliers that could prejudice the interpretations. For a visualization of the well profile, graphics relating the parameters to the drilled depths were plotted, and with the assistance of these, the parameters for analysis related to fluid flow-rate optimization were defined.

Two approaches to data analysis were proposed:

- Direct graphic method: the analysis is performed through a direct plot between the ROP and the fluid flow-rate. In the related graphs are also presented the trend line suited for the relation between the parameters, aiming at identifying the possible positive or negative relations;
- Indirect graphic method: It's done by plotting the total mud flow against the parameters related to its variation, which are known by the theoretical research and its behaviors are already expected to follow a defined trend (as per literature). These parameters, which are affected by the flow variation may be related to ROP in a different way than are presented by the direct graphic methods analysis, since the flow-rate, in some extension, can have both positive or negative influence on ROP, depending on many other related circumstances, however, the positive response is more likely to be expected.

Table 1. Well data information (Source: Nascimento, 2016).

Depth interval (m)	Well length (m)	Number of data points
5198.0592 to 5286.9084	88.8492	546

4. Results and discussion

Evaluating considers the following parameters for the presented analysis as the input data to graphics: ROP, TFLOW (total flow-rate of all active pumps), ECD and DHAP (downhole annulus pressure).

The expected relation they may have to the flow-rate for the defined parameters, by the literature review, are as following: increase in flow-rate is related to an increase in ECD, Reynolds number, and jet impact force, what may contribute to an ROP improvement. ECD increase, however, is responsible for the increase in the fluid column weight, and consequently, DHAP and differential pressure increase, leading to a lower ROP.

The first approach to the data presented is a direct graphic analysis method, where data has been plotted in a ROP versus TFLOW graphic, followed by a trend line for better visualization, Figure 5.

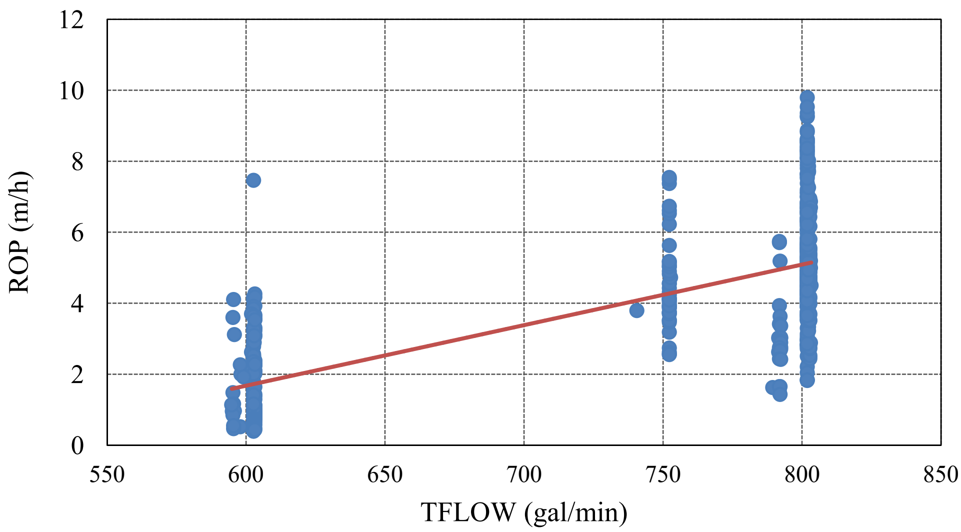

Figure 5. ROP versus TFLOW graphic (Source: Elaborated by author with Microsoft Excel 2016).

From this analysis, the data presents a direct relation with the increase in TFLOW associated to higher ROP values. From the graph presented, it is possible to infer the following: (a) an increase in flow-rate from 600 to 750 gpm, to a variation of ROP improving from 1.6 to 4.4 m/h; (b) and an increase in flow-rate of 750 to 800 gpm to a variation of 4.4 to 5.2 m/h in ROP. This can be expressed as an average variation of 0.018 m/h in ROP as from 1 gpm increase in TFLOW. For the second approach, three graphics were plotted, associating the following: (a) TFLOW with the ECD; (b) ECD with DHAP; (c) and DHAP with ROP.

Figure 6 presents the relation between TFLOW and ECD, where a 100 gpm increase in flow-rate corresponds to a variation of 0.1 lbm/gal (or ppg) in ECD.

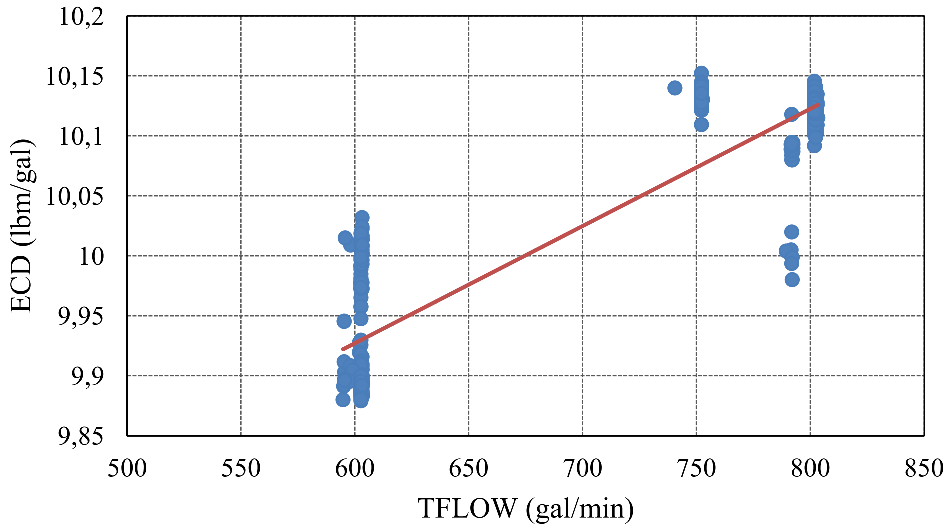

Figure 6. ECD x TFLOW graphic (Source: Elaborated by author with Microsoft Excel 2016).

Figure 7 presents the relation between DHAP and ECD, where a variation of 0.1 lbm/gal (or ppg) (ECD) corresponds to a variation of 50 psi (DHAP).

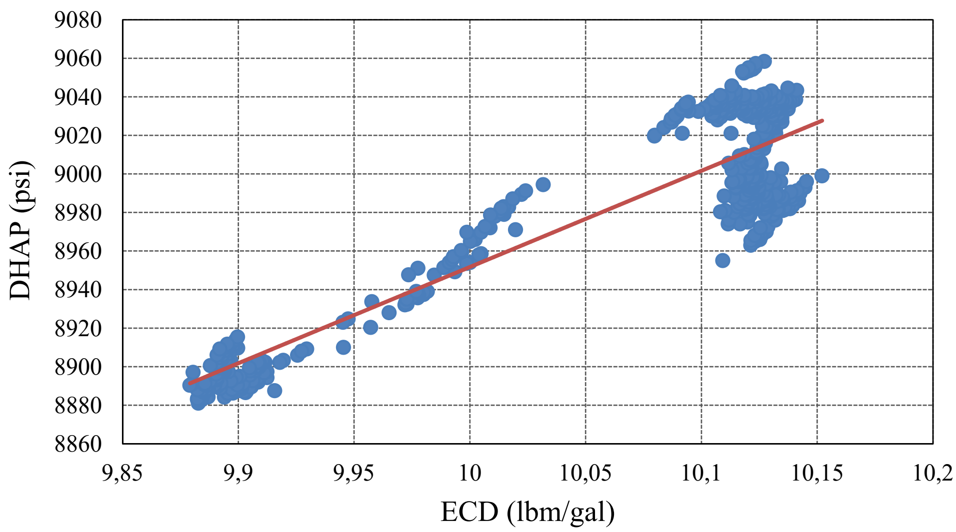

Figure 7. DHAP x ECD graphic (Source: Elaborated by author with Microsoft Excel 2016).

Figure 8 presents the relation between ROP and DHAP, however, it does not correspond with the literature expectation, where increasing in DHAP (i.e., potentially increasing the associated differential pressure between the formation and downhole pressures) should have a negative effect in ROP. For this specific case, it is not possible to answer in how far the increase in DHAP is representing an increase in differential pressure, since we do not have information about the variation of the pore pressure itself at this moment. Another reason is that, it can be that this variation in pressure is being cause by the increase in flow-rate, and that the jet impact force is prevail in relation to the eventual differential pressure increase.

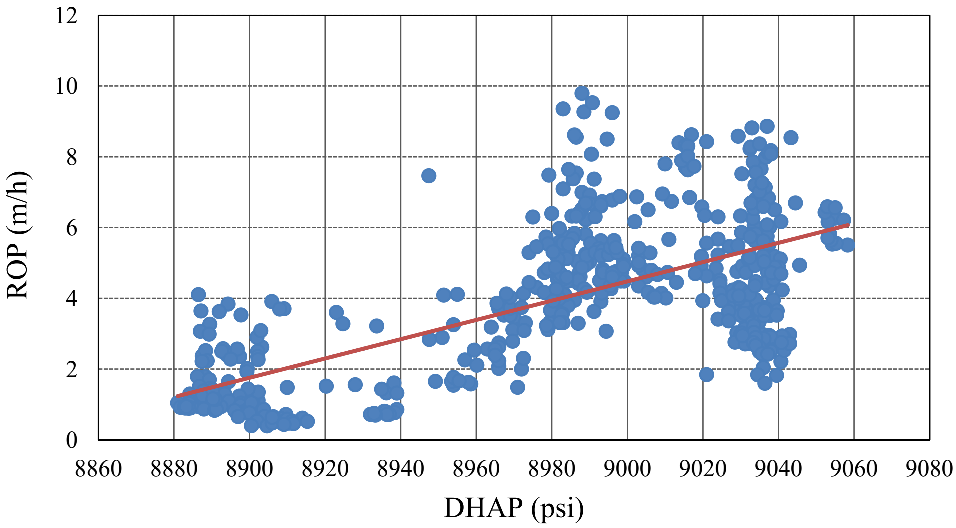

Figure 8. ROP x DHAP graphic (Source: Elaborated by author with Microsoft Excel 2016).

5. Conclusions

a) Direct and indirect graphic analysis presented shows an increase in ROP for higher flow-rate values.
b) Indirect graphic analysis was able to fulfill the theoretical relations presented for flow variation with ECD and DHAP.
c) For the given drilling depth data, the behavior expected for ROP with the DHAP didn't agreed with the literature, presenting the complexity involved in this process and fluid flow-rate influence that could be used in favor of increasing the rate of penetration for this section of the carbonate formations of Brazilian Pre-salt.
d) For further research, in terms of data analysis, it is recommended to have an increase of samples, wells and data set for better correlations.
e) Drilling fluid injection flow-rate control has proved to be associated with the drill-bit rate of penetration, and by this, it can be seen the possibility of better determining and applying these parameters changes for drilling efficiency improvement.

Acknowledgements

The authors of this presented research thanks the financial support of the *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* – ANP, the *Financiadora de Estudos e Projetos* – FINEP and the *Ministério da Ciência Tecnologia e Inovação* – MCTI, through the *Programa de Recursos Humanos da ANP para o Setor de Petróleo e Gás* - PRH-ANP/Finep 53.1. Thanks also given to the *Conselho Nacional de Desenvolvimento Científico e Tecnológico* - CNPq, and to the *Universidade Estadual Paulista* - UNESP (data availability).

Bibliographic references

Al-Rubaii, M. M. et al. (2020) 'Automated evaluation of hole cleaning efficiency while drilling improves rate of penetration', *International Petroleum Technology Conference 2020, IPTC 2020*. doi: 10.2523/iptc-19809-ms.

Ataga, E., Ogbonna, J. and Boniface, O. (2012) 'Accurate estimation of equivalent circulating density during high pressure high temperature (HPHT) drilling operations', *Society of Petroleum Engineers - 36th Nigeria Annual Int. Conf. and Exhibition 2012, NAICE 2012 - Future of Oil and Gas: Right Balance with the Environment and Sustainable Stakeholders' Participation*, 2, pp. 804–811. doi: 10.2118/162972-ms.

EIA (2016) 'Trends in U.S. oil and gas upstream costs', *US Energy Information Administration*, (March).

IADC (2014) 'Drilling Manual Drilling mechanics and performance', pp. 1–5. <https://www.iadc.org/wp-content/uploads/2015/08/preview-dp.pdf>.

Li, X. et al. (2017) 'Study on the drilling fluid flow rate allowable range in offshore drilling considering the extended-reach limit', *Society of Petroleum Engineers - SPE Abu Dhabi International Petroleum Exhibition and Conference 2017*, 2017-Janua. <http://doi.org/10.2118/188435-ms>.

Medina, P. (2012) *Uma abordagem da teoria dos jogos para ratear os benefícios oriundos da injeção de gás rico em co2 nos reservatórios do Pré-sal*. Dissertação de Mestrado, Planejamento Energético, UFRJ, Rio de Janeiro.

Mohammadsalehi, M. and Malekzadah, N. (2012) 'Application of new hole cleaning optimization method within all ranges of hole inclinations', *Society of Petroleum Engineers - International Petroleum Technology Conference 2012, IPTC 2012*, 1, pp. 68–75. <http://doi.org/10.2523/iptc-14154-ms>.

Nascimento, A. (2016) 'Mathematical Modeling for Drilling Optimization in Pre-salt Sections: a Focus on South Atlantic Ocean Operations'. Doctoral thesis, *Universidade Estadual Paulista (Unesp)*, Guaratinguetá, São Paulo. <https://repositorio.unesp.br/handle/11449/136182> (Accessed: 6 February 2021).

Petrobras (no date) *Pré-Sal*. [online]. <https://petrobras.com.br/pt/nossas-atividades/areas-de-atuacao/exploracao-e-producao-de-petroleo-e-gas/pre-sal/?gclid=Cj0KCQjw78yFBhCZARIsAOxgSx1uiiZH5KBUVkUzruEmw64jyUYb0eIgTm6oq2BPgZ3ZNSa_eQtiiZsaAkgoEALw_wcB> (Accessed: 5 April 2021).

Rehm, B. et al. (2008) 'Situational Problems in MPD', in *Managed Pressure Drilling*. Elsevier, pp. 39–80. <http://doi.org/10.1016/b978-1-933762-24-1.50008-5>.

Silva, D. S. da (2015) *Estudo de geopressões e assentamento de sapatas de revestimento*. Universidade Federal do Rio Grande do Norte.