Type of contribution:
Editorial
▶ Research Paper
Case Study
Review Paper
Scientific Data
Report of Tech. Application

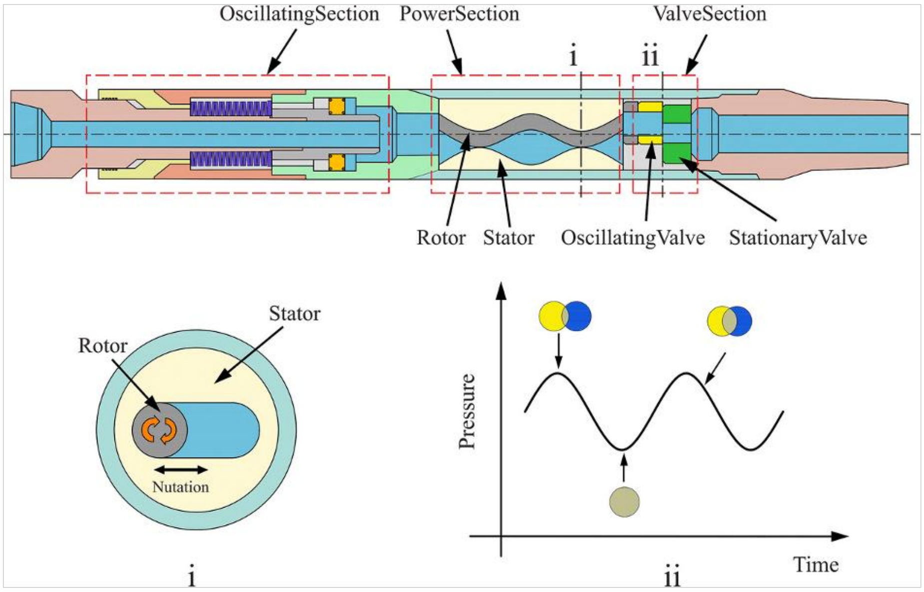
mesi e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 5, No. 1 (2025) pp 62-70
https://doi.org/10.31603/mesi.11381

Effect of friction reducing devices on wellbore formation

Rini Setiati[1]*, Samuel Melvern L P Samosir[1], Muh. Taufiq Fathaddin[1], Priagung Rakhmanto[1], Oknovia Susanti[2], Widia Yanti[3]

[1] Magister of Petroleum Engineering, Faculty of Earth and Energy Technology, Universitas Trisakti, Jakarta 11440, **Indonesia**
[2] Department of Mechanical Engineering, Faculty of Engineering Universitas Andalas, Padang 25163, **Indonesia**
[3] Environment, Development, and Sustainability - Faculty of Graduate School, Chulalongkorn University, 320231, **Thailand**
✉ rinisetiati@trisakti.ac.id



Highlights:

- Friction Reduction Tool (FRT) generated axial oscillation to reduce friction between drill string and wellbore so the weight transfer to the drill bit will be optimum and reduce stick & slip.
- The output of FRT is to reduce Stick-slip & weight transfer issue so the Rate of Penetration (ROP) and Mechanical Specific Energy (MSE) can be increase.
- It turns out that increasing the penetration rate in achieving the drilling target can be achieved optimally by using the Friction Reduction Tool (FRT) so that the drill bit can easily penetrate the formation during drilling operations without damaging the formation reservoir.

Article info
Submitted: 2024-05-15
Revised: 2025-03-09
Accepted: 2025-03-09

Publisher
Universitas Muhammadiyah Magelang

Abstract
Friction is one of the unavoidable factors during drilling. If not properly managed, it can significantly reduce the rate of penetration (ROP), especially in horizontal wells. This research aims to examine the effectiveness of the Friction Reduction Tool (FRT) in managing friction without causing damage to the formation. The FRT is designed to reduce friction between the drill string and the wellbore by minimizing contact. However, its performance is often influenced by two main factors: formation characteristics and drilling parameters. This study analyzes Well X-4, which was drilled without FRT, and Well X-5, which was drilled with FRT from a depth of 2837 m (MD). The analysis focuses on the tool's impact on stick-slip issues, ROP, and mechanical specific energy (MSE). The results indicate that the use of FRT reduced stick-slip levels and MSE, enabling the drill bit to penetrate the formation more easily. Additionally, activating the FRT from the start increased the penetration rate by 18% compared to drilling without it. These findings suggest that the FRT effectively enhances the drilling rate while preserving the formation integrity.

Keywords: Friction reduction tool; Stick-slip; Rate of penetration; Mechanical specific energy

1. Introduction

The difficulty in reaching the predetermined depth is part of the problems often encountered in oil well drilling. This has led to optimizing parameters such as increasing Weight on Bit (WOB) to increase RPM with subsequent improvement in Rate of Penetration (ROP). However, there is still difficulty in increasing the penetration rate and achieving drilling targets. This is observed from the analysis of previous research results that some of the indications of problems are incomplete weight transfer to the drill bit, resulting in a slowdown in penetration rate, and the most extreme is the issue of downhole stick-slip. Drilling performance was reported to have become inefficient due to the stick-slip vibration effect [1]. Some previous studies that discuss Friction reduction Tools include systematic engineering strategies, which result in safe and perfect recovery from stuck pipe scenarios by utilizing friction reduction tools [2]. In general, there are two types of downhole tools used to generate benign vibrations in the drill string and/or bottom hole assembly (BHA) to reduce friction: axial oscillating tools (AOT) and lateral vibratory tools (LVT). Axial oscillating tools provide much more effective friction reduction, which improves drilling performance in horizontal wells [3]. To overcome the problems associated with effective weight transition on the drill bit (WOB) during long-distance horizontal shale gas well drilling, hydro-oscillators are increasingly being used both in China and abroad to reduce drill string resistance and increase the rate of penetration (ROP) for horizontal section drilling, which can greatly reduce the cost of drilling horizontal shale gas wells. The effects of installation location, maximum vibration force, and vibration frequency of the hydro-oscillator on drag reduction are simulated, and comparison and analysis have been carried out using field data, with the calculation results providing a theoretical basis for field application of the hydro-oscillator and optimization of structural parameters [4].

The situation is assumed to be the reason for the failure that reduces penetration rates, increases drilling time, and also contributes to increased drilling costs. This is possible because the occurrence of stick-slip vibration issues can be detected through a sudden decrease in ROP values and an increase in WOB values during drilling process. The problem has the capacity to significantly disrupt drilling process because of the slow penetration rate and high downhole issues. The wells used in this research were drilled through Bottom Hole Assembly (BHA) using the Rotary Steerable System (RSS) with PDC-type drill bit. The RSS used is often associated with stick-slip issues which can reduce the efficiency of drill string applied for drilling. Moreover, incomplete weight transfer to drill bit is another issue identified to be causing problems in the wells. WOB was added to optimize the penetration rate but the intervention rather caused further reduction as well as a very high torque with the possibility of endangering the whole drilling process.

The efforts to address the problems led to the suggestion of additional tools for drill string. This is necessary because friction is part of the factors that can hinder drilling in the oil and gas industry by causing torque and drag. Torque is normally generated from the top drive or rotary table movement while drag is the load from BHA. The issues associated with these concepts need to be addressed in order to properly deliver weight transfer to the bit and increase ROP [5]. This is due to the fact extreme torque and drag (T&D) has the ability to reduce ROP in addition to stick-slip problems and cause BHA damage, leading to higher costs of drilling. Stick-slip can be determined through a reduction in ROP and an increase in WOB during drilling [6]. However, it is possible to reduce the problems identified through both mechanical and chemical methods. The mechanical aspect focuses on using vibration to reduce T&D without any damage to the formation [7]. Moreover, previous research titled "Faster ROP in Hard Chalk: Proving a New Hypothesis for Drilling Dynamics" showed that the application of Anti Stick-slip Tools provided significant results in drilling efficiency and cost savings [8].

The results from the research showed that the tools could reduce friction from all directions, overcome vibration in hard layers, ensure aggressive drill bit application while maintaining low WOB values, and allow drill bit to be used longer and faster. Research has also been conducted to identify and recognize the types of vibration that occur during drilling process. The three types identified include the torsional, axial, or bit bouncing phenomenon, and lateral vibration [9]. It was observed that stick-slip vibration was mostly found in oil well drilling with the torsional type reported when the bit rotation completely stopped (stick) and a phase where the bit reached the rotational speed up to twice the normal speed (slip) [10].

Torsional vibration, also known as stick-slip, occurs when the rapid rotation of drill bit and drill string causes stiffness, weaknesses, and dynamic friction interaction. In some wells, torque fluctuations are not severe and do not reach full stick-slip every time which stops the bit completely in a torsional cycle. Meanwhile, the vibration can become severe when there are high torque loads in hard rock with aggressive bits. It is also important to state that the bits do not only stop but also have the potential to get stuck or fail to rotate. In such cases, the penetration rate can be reduced with the interval length becoming shorter, potentially damaging drill bit or drilling equipment [11].

There are several developments of Friction Reduction Tools that have been tried to be applied in the drilling process. Jidong oil well, experiencing the problem of friction torque and casing wear during the construction process in drilling, designed a lower friction torque and protective sleeve that lowered the anti-friction torque tool [12]. Horizontal well drilling faces more technical challenges, including high friction force, poor weight transfer, and complex bottomhole conditions, etc. These problems often lead to low drilling efficiency, reduced extended reach capacity, poor tool surface control, and significantly increased costs [13].

2. Methods

This research was conducted using 2 wells, X-4 and X-5, as the samples to be compared and evaluated using mechanical methods. Moreover, Friction Reduction Tool (FRT) was applied to reduce friction between drill string and casing or borehole with subsequent effect on stick-slip, ROP, mechanical specific energy (MSE), BHA, as well as torque and drag.

ROP is the speed at which drill bit penetrates the rock being drilled and is usually influenced by several factors, including rock characteristics, the combination of WOB and rotary speed (RPM), the bit, drilling fluid or mud, and drilling hydraulics [15]. The other influential factors include Mud Weight (MW), flow rate, and the type of bit used. Moreover, stick-slip or torsional vibration can slow down drilling operations and increase drilling costs [16]. MSE is also defined as the energy required to break the rock volume during drilling and is considered an important factor in evaluating drilling efficiency [17]. There is normally a rotation force known as torque in the mechanical process between drill string and the formation or casing [18], [19]. Meanwhile, drag is the axial force generated based on the contact between the moving drill string and the formation or casing. The two phenomena can occur due to side forces generated between the borehole and all drill string elements as well as the friction associated with the movement of drill string. As previously stated, torque originates from the motion generated by the top drive or rotary table while drag is associated with the weight of drill string [7]. It is important to state that extreme torque and drag (T&D) can be detrimental to drilling operations and equipment. Several technologies have been developed to address T&D issues [20] such as the application of relevant tools to reduce friction under wellbore during drilling process. This is in the form of FRT which is divided into 2 components, including Shock Tool (ST) and Friction Tool (FT) as presented in **Figure 1**, to assist in reducing downhole friction during drilling operations.

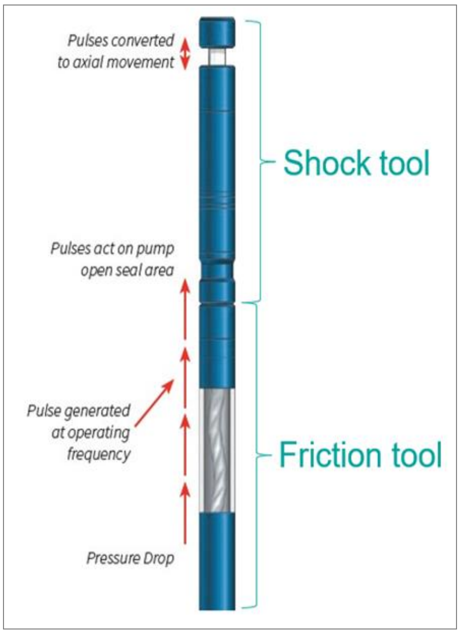


Figure 1. The schematic of material preparation

FRT uses strong axial motion to reduce friction between drill hole and drill string to increase weight transfer to drill bit, improve ROP, and reduce stick-slip. It is also important to state that the tool has 2 components, the Rotor and the Stator, similar to those in a drill motor, commonly referred to as the power section in **Figure 2**. The power section normally rotates according to the flow rate and generates impulses to ST above FT. Meanwhile, ST can be used in conjunction with FRT and Conventional Drilling BHA due to the capacity to generate vibrations needed to break static friction in order to minimize the contact between drill string and casing or formation.

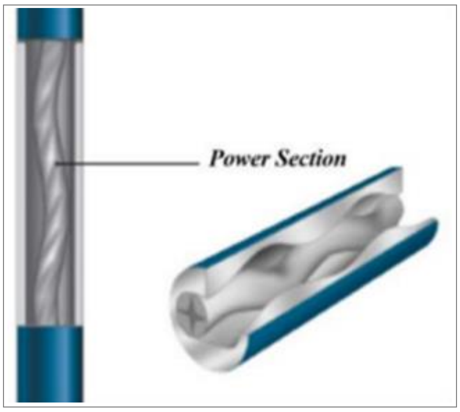


Figure 2. Power section [14]

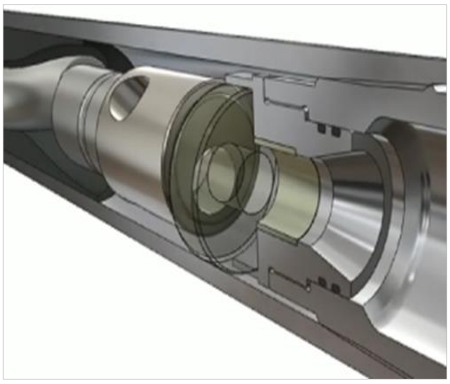


Figure 3. Oscillating valve assembly and stationary valve assembly [21]

There is a valve called Oscillating Valve Assembly (OVA) at the end of FT which faces another known to be Stationary Valve Assembly (SVA) as presented in **Figure 3**. The mechanism of the power section causes a movement between OVA and SVA, leading to pressure pulses delivered to ST to perform the axial movement required to generate vibrations and break static friction [21].

The dynamic excitation tool consists of three main components which are the power, the valve, and the oscillation sections as presented in **Figure 4**. The power section is a positive displacement motor (PDM) with a 1:2 ratio rotor inside the stator, the valve section consists of OVA and SVA, and the oscillation section is ST which has a spring-loaded mandrel axially. As mud is pumped through the power section, the rotor is progressively moved and rotated in the stator, generating a nearly linear sweep motion of OVA. The oscillation of OVA causes cyclical restriction of the flow path by passing through SVA in order to produce the desired pressure pulses in the string as shown in i and ii. Moreover, the mandrel normally extends when internal pressure is applied to the open area of the pump on ST.

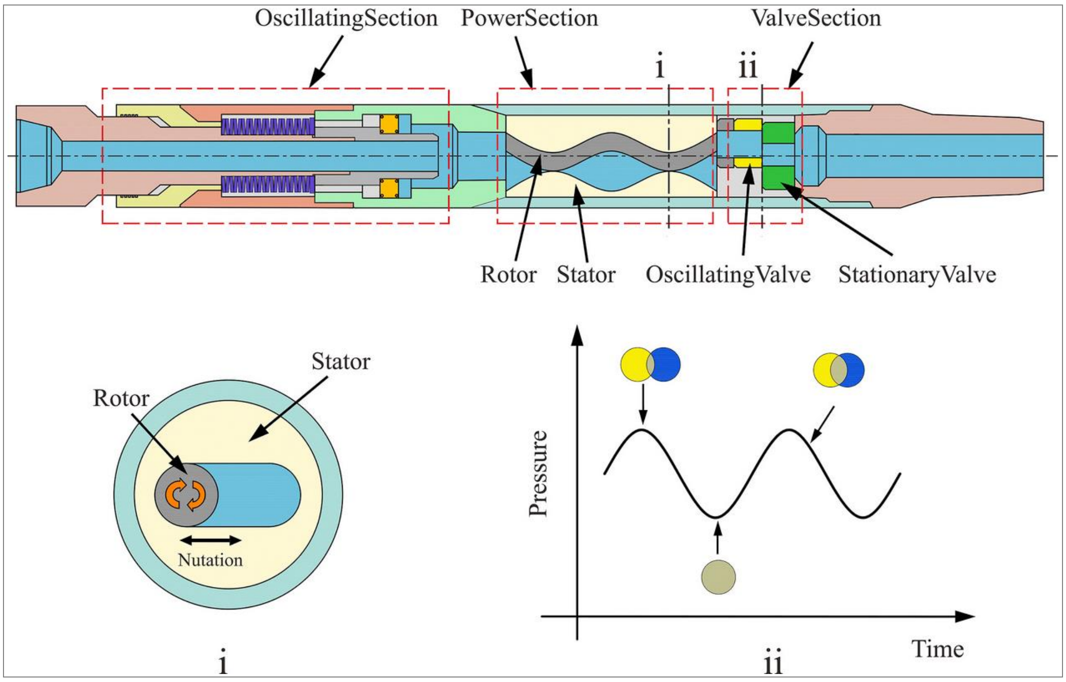


Figure 4. Axial oscillation generator tool (AGT) [13]

The mandrel returns to its original position after the pressure is released. It is also important to state that the cyclic axial oscillation of ST keeps the string continuously moving, breaking static friction with the wellbore while increasing weight transfer to the drill bit and reducing reactive torque in the borehole [13], [22], [23]. The software was required to model or design the placement of FRT as well as to simulate torque and drag during the drilling process. This led to the adoption of Vibrascope with the assistance of Excel due to the ability to accurately place FRT with a significant effect on the simulation results of torque and drag [24], [25]. Furthermore, software also assisted in simulating the speed value (RPM) of drill string which was required for critical speed analysis to avoid torsional, axial, and lateral vibrations.

Several supporting data on BHA design (OD, ID, Length, and Mass), Hole Size, Weight on bit, MW, Well Trajectory (Depth, Inclination, and Azimuth), Friction factor open hole and casing hole, Previous casing depth, and RPM were required in the software as the input to determine output such as torque and drag values for a specific well. Moreover, the output data were plotted on a chart in Excel to visualize the changes before and after using this tool, show specific depths to determine the achievement of the target from the beginning to the desired depth, and identify the potential torque and drag considered to be good. The graph also showed the placement of FRT to determine the optimal point to provide the most significant reduction.

3. Results and Discussion

This research focused on evaluating 2 wells, including X-4 without FRT during drilling and X-5 that activated FRT starting from 2837 m (MD). Moreover, the 4 parameters analyzed were ROP, stick-slip, MSE, and torque.

3.1. Results

The results showed that ROP of X-4 was higher than X-5 from 1500 to 2837 m (MD) because FRT was not activated. After FRT was activated from 2837 to 4133 m (MD), ROP of well X-5 became higher as shown in **Figure 4** and this reduced drilling time and costs. **Figure 5** was used to compare X-4 and X-5 before and after the introduction of FRT. The results showed that X-4, indicated by the gray color, was drilled starting from a depth of 1503 m (MD) to 4133 m (MD). The penetration rate from 1503-2837 m (MD) was found to be 68 m/hr and the value reduced to 30.6 m/hr at 2837-4133 m (MD) while the average was recorded to be 44.13 m/hr.

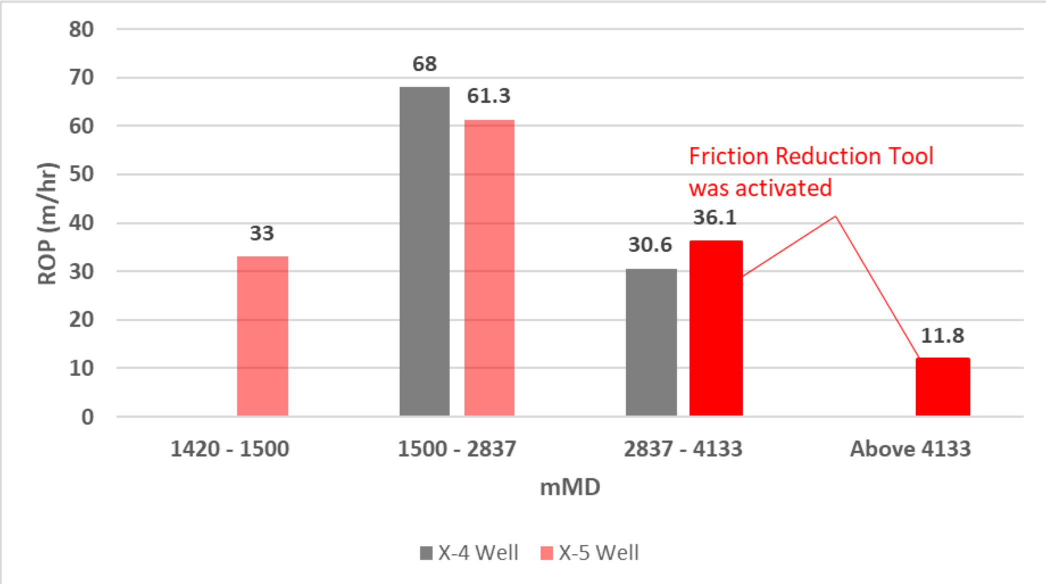


Figure 5. ROP of X-4 vs X-5

X-5 was represented by the light pink color before FRT activation and the red color after FRT. It was observed that drilling was initiated at a depth of 1420 m (MD) to 4201 m (MD) with an interval of 2781 m (MD) was 151 meters deeper than X-4. The penetration rate recorded at 1503-2837 m (MD) was 61.3 m/hr and the value also reduced to 36.1 m/hr for 2837-4133 m (MD) until drilling target was reached when it changed to 11.8 m/hr.

Wells X-4 and X-5 are in the same formation, namely a formation consisting of Sand Stone, Clay Stone and Coal. The drilling carried out also uses the same fluid, namely the SOBM mud type with a difference in mud weight of 1.38 SG (for X-4) and 1.4 SG (for X-5).

The bit details used in wells X-4 and X-5 are the same, namely PDC 616 (6 blades, 16 mm cutters) both of them use the same type of bit. Weight on Bit (WOB) on a well without FRT is 13.9 klbf, while for the use of FRT, the WOB used is 13.1 klbf. The trajectory of the X-4 well without FRT has an inclination in: 32.20 deg and an inclination out: 9.89 deg. While the X-5 well with FRT has an inclination in: 9.51 deg and an inclination out: 7.26 deg. Meanwhile, the pumping rate used is 1800-2650 lpm for well X-4 and 1800-2500 lpm for well X-5. The comparison of the two wells showed that the application of FRT from the start increased the penetration rate. This was evident in the depth range of 2837-4133 m (MD) where the well with the tool had an 18% higher penetration rate and increase. Moreover, FRT further reduced stick-slip from 114 c/min to 79 c/min and 41 c/min as presented in the following **Figure 6**. The trend showed that FRT worked effectively as observed from the ability to reduce stick-slip and increase ROP.

The comparison of stick-slip values for X-4 and X-5 in **Figure 6** showed that the value for X-4, represented by the gray color, increased by 12% from the depth range of 1500-2837 m (MD) to 2837-4133 m (MD). However, the value was smaller compared to X-5 but continued to increase as drilling became deeper. The results further showed that X-5 had stick-slip value of 101 c/min at the beginning of drilling and later increased to 114 c/min before FRT was introduced. Meanwhile, the introduction of the tool reduced the value by 44% and later by 93% when drilling reached a deeper target of 4248 m (MD). This relatively high stick-slip value was associated with the potential increase in the percentage of claystone encountered at a deeper depth. The inclusion of FRT also reduced MSE value for X-5 compared to X-4, as presented in **Figure 7**. The observation showed that drill bit was not sufficiently hard to penetrate the formation and the weight transfer was delivered effectively.

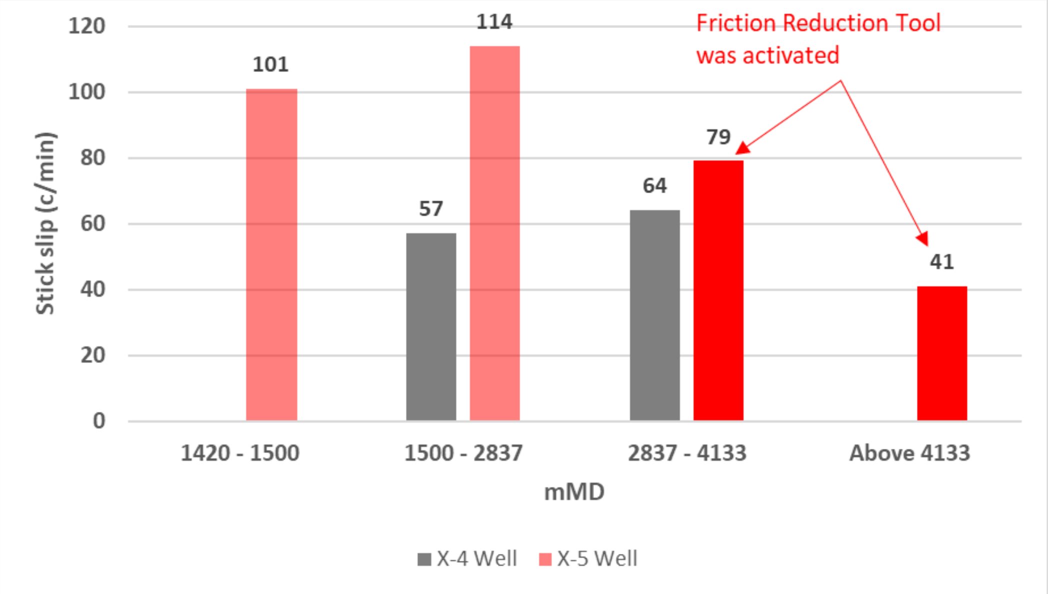


Figure 6. Stick-slip of X-4 vs X-5

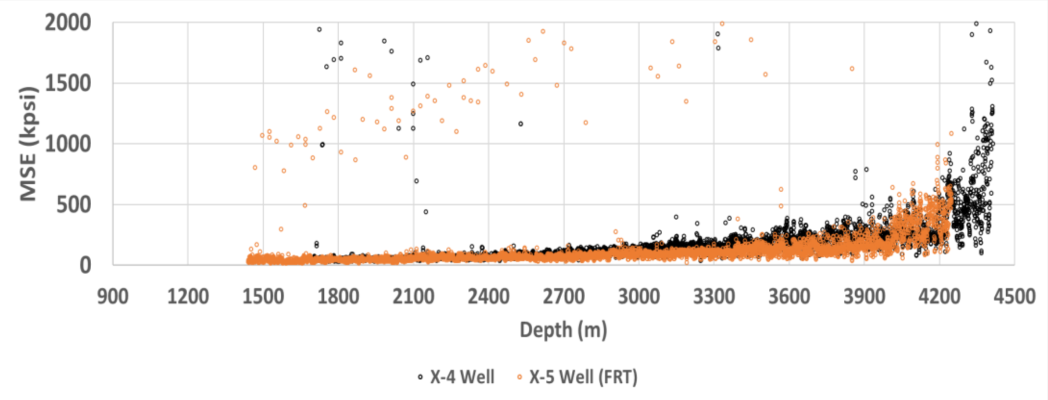


Figure 7. MSE of well X-4 vs well X-5

The X-4 well has a drilling target at a depth of 4412 m (MD) using a push the bit RSS drill string. This well is a well that does not activate the Friction Reduction Tool until it reaches the drilling target and gets an ROP of 44.13 m/hr. Starting from a depth of 3000 m (MD) the ROP value decreases gradually and this is indicated due to a problem below the well, namely stick-slip. The X-5 well has a drilling target at a depth of 4248mMD using a push the bit RSS drill string. At the beginning of the section to a depth of 2873mMD, the Friction Reduction Tool is not activated because the stick-slip level is still relatively low and the ROP value is 58.54 m/hr with a WOB of 11.9 T. After a depth of 2873mMD the stick-slip level increases and finally this tool is activated so that it can get a stable ROP value and a decrease in the stick-slip value.

During the drilling, the guidelines when meet stick & slip is reduce the WOB and increase the RPM but the effect is decreasing the ROP. Another method is pick-up the string (off-bottom) and waiting a few minutes to release the stick & slip but it will increase the drilling time. During the drilling using FRT, no need to adjust the parameters like the guidelines because these tools can help to mitigate the stick & slip so it can be more manageable and the output are reduce the drilling time and save the BHA from damage cause the stick slip. It will reduce the drilling cost and Damage Beyond Repair (DBR).

Mechanical Specific Energy (MSE) value of X-5 was found to be lower than X-4 after the introduction of FRT, as presented in **Figure 7**. The activation of the tool at a depth of 2873 m (MD) slightly increased MSE but was 40% lower than the value for X-4. The higher MSE value in X-4 showed that drill bit required more effort to break the formation to be penetrated. Moreover, torque is part of the factors influencing MSE value, and the changes observed for X-4 and X-5 are presented in **Figure 8**. The results showed that torque increased for both wells but X-4 had higher values than X-5 without FRT. The value for X-5 was observed to have reduced and became constant after the activation of FRT. The increasing torque in X-4 showed that drill bit required more work to penetrate the formation. Furthermore, the vibration effects of FRT did not damage the formation or cause fractures but only minimized the contact between drill string and wellbore.

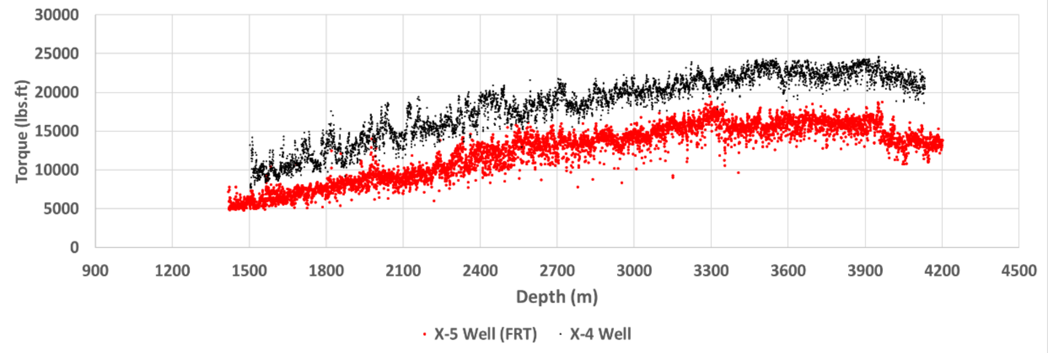


Figure 8. Torque of well X-4 vs well X-5

3.2. Discussion

X-4 was the well drilled without using the FRT tool. The ROP was initially high at 68 m/hr but gradually declined to 30.6 m/hr, despite increasing the weight on bit (WOB). The MSE value rose by approximately 40% toward the end of drilling, suggesting that the applied WOB was not fully transferred to the drill bit due to inefficient energy transfer. Frequent stick-slip events were observed, which disrupted drilling performance, although the target depth was eventually reached.

In contrast, well X-5 had FRT activated at 2873 m (MD). Although ROP also declined from 61.3 m/hr to 11.8 m/hr, the reduction was not as drastic as in X-4. The MSE increase was milder, especially after FRT activation, indicating improved drilling efficiency. Notably, at similar depths, X-5 showed an 18% higher ROP compared to X-4. Stick-slip levels in X-5 were high before FRT activation but decreased significantly afterward, while in X-4, stick-slip increased at greater depths. Torque rose in both wells, but became more stable in X-5 after FRT was engaged, further supporting the tool’s effectiveness.

Overall, the application of FRT helped reduce stick-slip and enhance ROP without requiring significant parameter adjustments. Normally, stick-slip is mitigated by lowering WOB and increasing RPM, which often reduces ROP. With FRT, operators can maintain or even push parameters to achieve higher ROP while minimizing vibration and mechanical risks. This not only improves drilling performance but also contributes to better tool longevity and operational cost efficiency.

4. Conclusion

In conclusion, reducing stick-slip has a significant impact on improving the Rate of Penetration (ROP), allowing drilling targets to be achieved more efficiently through the application of the FRT tool. This was evidenced by an 18% increase in ROP and a reduction in torque in the well where FRT was applied. Drilling parameters in the FRT well were also lower than those in the offset well (average WOB: 13.1 klbf vs. 13.9 klbf). These changes indicate that the drill bit was able to penetrate the formation more easily, as resistance from stick-slip was effectively minimized without causing environmental harm. The use of FRT not only improves ROP and reduces stick-slip, but also protects the Bottom Hole Assembly (BHA), extending its service life and contributing to overall drilling cost efficiency in the future.

Acknowledgements

The authors are grateful to the Master of Petroleum Engineering Study Program, FTKE, Trisakti University, for the support provided in conducting this research.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding – Trisakti University.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

References

[1] A. Zakuan, A. Junaida, B. Subroto, H. Hermawan, A. Fatakh, and A. Halim, "Stick Slip Mitigation Plan to Improve Drilling," in *SPE Asia Pacific Oil and Gas Conference and Exhibition*, SPE, Sep. 2011. doi: 10.2118/141988-MS.

[2] P. Silva *et al.*, "Case Study: Innovative Applications of Friction Reduction Tools to Solve Drilling Problems in Tough Environment Multilateral Wells," in *Gas and Oil Technology Showcase and Conference*, SPE, May 2024. doi: 10.2118/219241-MS.

[3] R. Gee, C. Hanley, R. Hussain, L. Canuel, and J. Martinez, "Axial Oscillation Tools vs. Lateral Vibration Tools for Friction Reduction – What's the Best Way to Shake the Pipe?," in *SPE/IADC Drilling Conference and Exhibition*, SPE, Mar. 2015. doi: 10.2118/173024-MS.

[4] J. Fu, Z. Ren, J. Bai, F. Qin, and B. Li, "The friction-reducing principle and application of the drill string with a hydro-oscillator," *Journal of Petroleum Science and Engineering*, vol. 165, pp. 453–461, Jun. 2018, doi: 10.1016/j.petrol.2018.01.076.

[5] L. Augusto Horta Nogueira and R. Silva Capaz, "Biofuels in Brazil: Evolution, achievements and perspectives on food security," *Global Food Security*, vol. 2, no. 2, pp. 117–125, 2013, doi: 10.1016/j.gfs.2013.04.001.

[6] E. W. Robnett, J. A. Hood, G. Heisig, and J. D. Macpherson, "Analysis of the Stick-Slip Phenomenon Using Downhole Drillstring Rotation Data," in *SPE/IADC Drilling Conference*, SPE, Mar. 1999. doi: 10.2118/52821-MS.

[7] K. Bai, H. Fan, H. Zhang, F. Zhou, and X. Tao, "Real Time Torque and Drag Analysis by Combining of Physical Model and Machine Learning Method," in *Proceedings of the 10th Unconventional Resources Technology Conference*, Tulsa, OK, USA: American Association of Petroleum Geologists, 2022. doi: 10.15530/urtec-2022-3723045.

[8] E. Akutsu *et al.*, "Faster ROP in Hard Chalk: Proving a New Hypothesis for Drilling Dynamics," in *SPE/IADC Drilling Conference and Exhibition*, SPE, Mar. 2015. doi: 10.2118/173068-MS.

[9] B. Saldivar, I. Boussaada, H. Mounier, S. Mondié, and S. I. Niculescu, "An Overview on the Modeling of Oilwell Drilling Vibrations," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 5169–5174, 2014, doi: 10.3182/20140824-6-ZA-1003.00478.

[10] G. Ramakrishnan, "Quenching of Self-Excited Vibrations in Multi Degree-of-Freedom Systems: Application to Stick-Slip Mitigation in Drilling," in *SPE/IADC International Drilling Conference and Exhibition*, SPE, Mar. 2019. doi: 10.2118/194115-MS.

[11] J. R. Bailey, G. S. Payette, and L. Wang, "Improved Methods to Understand and Mitigate Stick-Slip Torsional Vibrations," in *IADC/SPE Drilling Conference and Exhibition*, SPE, Mar. 2018. doi: 10.2118/189673-MS.

[12] Y. Li, X. Xu, X. Wu, Y. Zhou, and J. Pan, "Development and Application of Friction and Torque Reduction Tools for Extended Reach Well," in *Proceedings of the International Field Exploration and Development Conference 2023*, 2024, pp. 771–779. doi: 10.1007/978-981-97-0256-5_64.

[13] L. Tang, S. Zhang, X. Zhang, L. Ma, and B. Pu, "A review of axial vibration tool development and application for friction-reduction in extended reach wells," *Journal of Petroleum Science and Engineering*, vol. 199, p. 108348, Apr. 2021, doi: 10.1016/j.petrol.2021.108348.

[14] National Oilwell Varco, *Agitator TM Systems Handbook*. 2016.

[15] R. Baker, *A Primer Of Oilwell Drilling*. 2001.

[16] W. Liu, F. Yang, X. Zhu, and X. Chen, "Stick-slip vibration behaviors of BHA and its control method in highly-deviated wells," *Alexandria Engineering Journal*, vol. 61, no. 12, pp. 9757–9767, Dec. 2022, doi: 10.1016/j.aej.2022.01.039.

[17] F. Dupriest *et al.*, "Standardization of Mechanical Specific Energy Equations and Nomenclature," in *IADC/SPE International Drilling Conference and Exhibition*, SPE, Mar. 2022. doi: 10.2118/208777-MS.

[18] U. J. F. Aarsnes and R. J. Shor, "Stick-slip and Torsional Friction Factors in Inclined Wellbores," *MATEC Web of Conferences*, vol. 148, p. 16002, Feb. 2018, doi: 10.1051/matecconf/201814816002.

[19] B. C. Purnomo and N. Widodo, "Torque and Power Characteristics of Single Piston LPG-Fueled Engines on Variations of Ignition Timing," *Automotive Experiences*, vol. 2, no. 1, pp. 22–27, 2019, [Online]. Available: http://journal.ummgl.ac.id/index.php/AutomotiveExperiences/article/view/2632

[20] X. Zhu *et al.*, "New Analysis Theory and Method for Drag and Torque Based on Full-Hole System Dynamics in Highly Deviated Well," *Mathematical Problems in Engineering*, vol. 2015, pp. 1–13, 2015, doi: 10.1155/2015/535830.

[21] R. Mudhoffar, J. M. Lumbantobing, and P. Bayuartha, "Analysis of friction reduction system during drilling operation at high inclination well on field X," *Society of Petroleum Engineers - SPE/IATMI Asia Pacific Oil and Gas Conference and Exhibition 2019, APOG 2019*, 2019, doi: 10.2118/196410-ms.

[22] Y. Chen, C. He, X. Zhou, and H. Yu, "Analysis of factors affecting drilling friction and investigation of the friction reduction tool in horizontal wells in Sichuan," *Advances in Mechanical Engineering*, vol. 11, no. 7, p. 168781401986296, Jul. 2019, doi: 10.1177/1687814019862963.

[23] O. R. Adetunji, M. C. Ogbuokiri, O. U. Dairo, O. B. Olatunde, and I. K. Okediran, "The Effect of Excess Heat Utilization on the Production Cost of Cement," *Mechanical Engineering for Society and Industry*, vol. 1, no. 2, pp. 104–114, 2021.

[24] Y. Long, X. Wang, P. Wang, and F. Zhang, "A Method of Reducing Friction and Improving the Penetration Rate by Safely Vibrating the Drill-String at Surface," *Processes*, vol. 11, no. 4, p. 1242, Apr. 2023, doi: 10.3390/pr11041242.

[25] H. Yanxin, L. Liàng, L. Chāomǐn, and W. Bǎo, "Vibroscope," CN205843915U, 2016 [Online]. Available: https://patents.google.com/patent/CN205843915U/en