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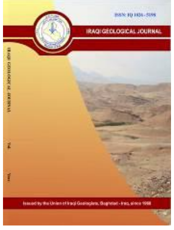

Assessing Acid Fracturing for Low-Permeability Carbonate Formation to Improve Oil Production

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Abstract

This study investigates the application of hydraulic acid fracturing to enhance oil production in the Mishrif Formation of the Al-Fakkah oilfield due to declining flow rates and wellhead pressures resulting from asphaltene deposition and inadequate permeability. Implementing acid fracturing, an established technique for low-permeability carbonate reserves, was essential due to the inadequacy of prior solvent cleaning and acidizing efforts. The document outlines the protocols established prior to and following the treatment, emphasizing the importance of careful oversight to guarantee safety and efficacy. In the MiniFrac treatment, 150 barrels of #30 cross-linked gel were injected at 25 barrels per minute, followed by an overflush with 30# linear gel. Laboratory tests confirmed the fluid's stability. The simulation results suggest that the average fracture conductivity is 285 millidarcy feet, with an effective etched fracture length of 109 m, an acid height of 41 m, and a mean etched width of 0.195 inches. The peak injection rate was maintained at 25 barrels per minute, and the peak surface treating pressure reached 9,190 psi. Post-fracturing thermal responses were monitored using High Precision Temperature logs, which confirmed significant enhancements in the productivity of the Mishrif Formation. This comprehensive approach addresses the challenges posed by low permeability and optimizes the hydraulic fracturing process, thereby enhancing hydrocarbon recovery in the region.

Keywords: Improved productivity; Hydraulic acid fracturing; Mishrif Formation; Al-Fakkah oil field

1. Introduction

Hydraulic fracturing is a well-stimulation technique that has evolved over the past seventy years to enhance production from low-permeability reservoirs and source rocks. The first deliberate hydraulic fracturing took place in 1947 at the Klepper No. 1 well in Kansas, USA (Menouar et al., 2018; Bazan, 2019), and it has since become a globally prevalent stimulation method. Before 2000, vertical wells typically required a single fracture for stimulation (Castillo, 1987; Meyer and Bazan, 2011; Zhu et al., 2015). Researchers performed nearly one million fracture treatments between 1950 and 2000. However, the number of wells with severe deviations has increased significantly since 2000, resulting in increased fracture treatments per well from one or two to more than 200 (Bazan, 2019), with global estimates now ranging between five and six million procedures.

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Countries like China and Argentina are adopting similar strategies to extract hydrocarbons from formations with extremely low permeability (Nolte, 1979; Meyer and Bazan, 2011; Vivian Yuen-Lee, 2013; Hashim et al., 2023). The hydraulic fracturing process consists of four stages: pumping a pad fluid, injecting slurry, displacing slurry with proppant, and stopping pumping to allow for formation closure (Cinco-Ley and Samaniego-V., 1981; Yuen-Lee et al., 2013; Guo et al., 2014; Hurtado et al., 2020; Almahdawi et al., 2023). The industry has explored innovative techniques at each stage, including variations in pad volumes and displacement methods (Rassenfoss, 2013; Zhu et al., 2015; Aljawad et al., 2020; Isah et al., 2021; Zhou et al., 2021). Acidizing techniques, including wellbore acidizing for cleaning and matrix acidizing for treatment beyond the wellbore, play complementary roles in well stimulation (Bauer et al., 2013; Ali and Ziauddin, 2020; Alameedy, 2022). Acid fracturing targets limestone and dolomite formations, initiating fractures through fluid injection that exceeds the minimum horizontal stress (Al Rbeawi et al., 2018; Kadhim et al., 2020). Whether or not acid fracturing works depends on fracture conductivity and penetration. Because carbonate formations are less permeable, fractures tend to be narrow (McLeod, 1984; Guo et al., 2007; Ghommem et al., 2015; Chacon and Pournik, 2022; Alameedy et al., 2023a; Shirley et al., 2017; Ibrahim et al., 2020; Alameedy et al., 2022b).

The oil well in southern Iraq was originally designed to exploit the Asmari and Mishrif Formations as a vertical oil producer (Al-Baldawi, 2023; Hashim, 2023). Nevertheless, the production rate diminished swiftly due to downhole impediments from asphaltene accumulations. Notwithstanding efforts to clean and acidize the well, it persisted in its decline, achieving a production rate of 730 bbl/d with a water cut fluctuating between 5% and 22%. By mid-2018, the well-necessitated gas lift for production and additional treatments failed to reinstate natural flow. This study presents a novel approach to hydraulic acid fracturing designed to enhance the productivity index of the Mishrif Formation. It consolidates insights from all project segments, offering detailed information on each operational phase while addressing health, safety, and environmental (HSE) concerns. The treatment is motivated by a significant decline in flow rate and wellhead pressure due to inadequate formation permeability and asphaltene deposition, which have hindered sustainable production. Since acidizing and solvent cleaning have not worked in the past, a new kind of stimulation is required. Acid fracturing is a well-known method for treating low-permeability limestone reservoirs, and this article explains how it works and what to do before and after the treatment.

Fractures in the Mishrif Formation are oriented in a northwest-southeast direction because the Mishrif Formation is a carbonate rock with a dominant NE-SW compressive stress direction. In ultra-low permeability carbonate reservoirs, these fractures are essential for improving permeability, improving fluid flow and ultimately leading to increased hydrocarbon recovery. For the most part, the Formation is made up of limestones, which are well-known for the intricate pore structures and varying permeability characteristics that they possess. The lithological variation is a factor that contributes to the quality of the reservoir and affects the distribution of fluids and the storage capacity. Intergranular, moldic, and vuggy pores are among the many types in the Mishrif Formation. These pores are necessary for the storage of hydrocarbons. However, the overall permeability of the matrix is extremely low, which necessitates the presence of fractures to improve the fluid flow level and the reservoir's productivity (Mohammad et al., 2024).

In the process of hydrocarbon recovery, the Mishrif Formation, which is distinguished by carbonate reservoirs with extremely low permeability, is an essential component. Additionally, fractures significantly increase the formation's effective permeability, although matrix permeabilities are typically around 0.071 md. Fractures, which act as primary conduits for fluid flow, are a significant contributor to the main permeability contribution in these reservoirs. Fracture development blocks have the potential to have an average permeability of 123.6 md, which makes them indispensable for improving oil recovery and optimizing acid fracturing operations. When it comes to the Mishrif Formation, a solid understanding of the fracture distribution and characteristics is necessary for effective reservoir management (Hasoon and Farman, 2024).

2. Materials and Methods

2.1. Hydraulic Acid Fracturing Operations Sequence

Acid fracturing is a sophisticated field operation necessitating meticulous oversight to guarantee safety, production efficiency, and comprehensive documentation of pressures, materials, and expenses. Treatment execution involves the direct oversight of the fracturing procedure, emphasizing pressure analysis, consumable performance, quality assurance/quality control (QA/QC) protocols, and equipment efficacy(Bazan, 2019). Operational efficiency emphasizes the effective execution and cost management of the support processes, materials, and personnel necessary for a successful hydraulic fracturing program. Fig. 1 illustrates the interplay between operational efficiency, treatment implementation, and stimulation design. The stimulation design dictates the necessary equipment, fluids, proppant, chemicals, and rig configurations to achieve fracture geometry goals and economic criteria. Treatment execution involves direct oversight within the control van, emphasizing pressure analysis, consumable performance, and quality assurance/quality control protocols. Operational efficiency emphasizes the effective execution and cost management of the support processes, materials, and personnel necessary for a successful hydraulic fracturing program. Comprehensive planning and targeted project management can mitigate or resolve the majority of operational challenges and logistical complications in effectively executing hydraulic and acid fracturing.

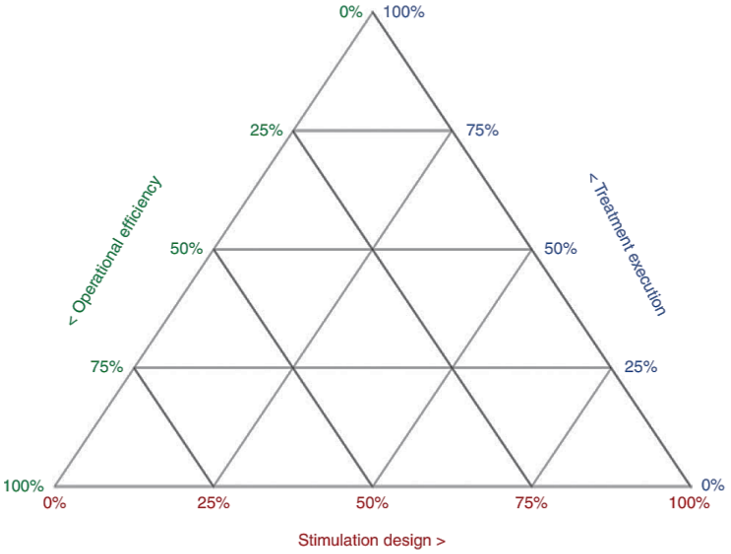

Fig.1. Ternary diagram of field execution and implementation (Bazan, 2019)

Contemporary hydraulic fracturing methods in North America, characterized by multiwell, multistage horizontal completions of unconventional reservoirs, pose distinct challenges for field execution and quality assurance/quality control in shale fracturing. Unconventional resource treatments necessitate a shift, demanding reduced focus on traditional quality control and pre-job testing practices (treatment execution) while prioritizing enhanced efficiency in well-completion execution and project management.

A cohort of senior engineers and middle management may have exclusively engaged with unconventional wells, possessing a perspective more aligned with project execution and operational efficacy than technical specialization. Prioritizing cost and efficiency exclusively does not enhance well performance; however, an inflexible commitment to fracturing-design theory, disregarding cost and efficiency, is imprudent and threatens project economics.

We have categorized and presented an operational flow diagram for hydraulic acid fracturing in Fig. 2. This sequence encompasses several essential steps to guarantee the efficacy and safety of the fracturing process. The operations begin with pre-fracturing logging procedures, which include the Radial Bond Log (RBT) and High Precision Temperature (HPT) log, conducted through the casing to assess the well's condition and establish baseline data.

Subsequent to these preliminary logs, the acid fracturing string is inserted into the borehole, accompanied by a sequence of preparatory procedures, such as solvent cleaning and flowback operations. The primary hydraulic acid fracturing procedure is subsequently conducted, followed by post-fracturing logging to assess the treatment's efficacy. These activities encompass supplementary HPT logs and Spectral Noise Logs (SNL) to observe temperature fluctuations and fluid dynamics within the formation.

The sequence culminates with optional pressure build-up tests to further evaluate the well's performance and guarantee stable production. Every stage in this sequence is carefully orchestrated and implemented to maximize the fracturing process and improve the well's output.

The Hydraulic Acid Fracturing treatment protocol starts by performing a Cement Bond Log using the Radial Bond Tool (RBT) to evaluate the strength of the cement bond within the casing. Subsequently, a High Precision Temperature (HPT) log is conducted into the casing to detect any deviations in temperature and evidence of fluid flow. Subsequently, the acid fracturing string is advanced into the wellbore.

Subsequently, the coiled tubing unit is established to carry out a solvent-cleaning operation, eliminating debris, and the well is forced back to cleanse it. The fluid saturations are determined by conducting a saturation evaluation using the Sigma log model. Subsequently, the fracturing equipment is commissioned, primed, and subjected to pressure testing while ensuring meticulous mixing and quality control of chemicals.

An initial analysis of the formation is conducted, followed by a step rate test to ascertain the variations in fracture gradients and the treatments for mini-fractures. An evaluation of the effectiveness of the mini-frac treatments is carried out by conducting a High Precision Temperature log through the tubing. The collected data is examined, and modifications to the primary fracturing design are implemented as necessary while maintaining diligent quality control of chemical mixing.

Next, the primary hydraulic acid fracturing treatment is carried out. Subsequently, the fracturing equipment is dismantled, and the wireline installation is established. A High Precision Temperature and Spectral Noise Log (SNL) is performed on the tubing following fracturing. This log records the shut-in HPT main down pass at a 5 m/min rate from 3945 to 4065 m. Subsequently, the wireline unit is disassembled.

The coiled tubing unit is reassembled, the gas lift is started, and the well is operated by returning the fluid back through the coiled tubing and flowback equipment. Under flowing conditions at a rate of 5 m/min, a High Precision Temperature log is recorded within the 3945 to 4065 m range. Continuous monitoring and recording of the flowing pressure for at least 24 hours is conducted to guarantee consistent production before closing the well. Optionally, a build-up pressure test is performed and documented for around 96 hours. Ultimately, the wireline unit is dismantled, the well is terminated, and the acid fracturing string is extracted from the well cavity.

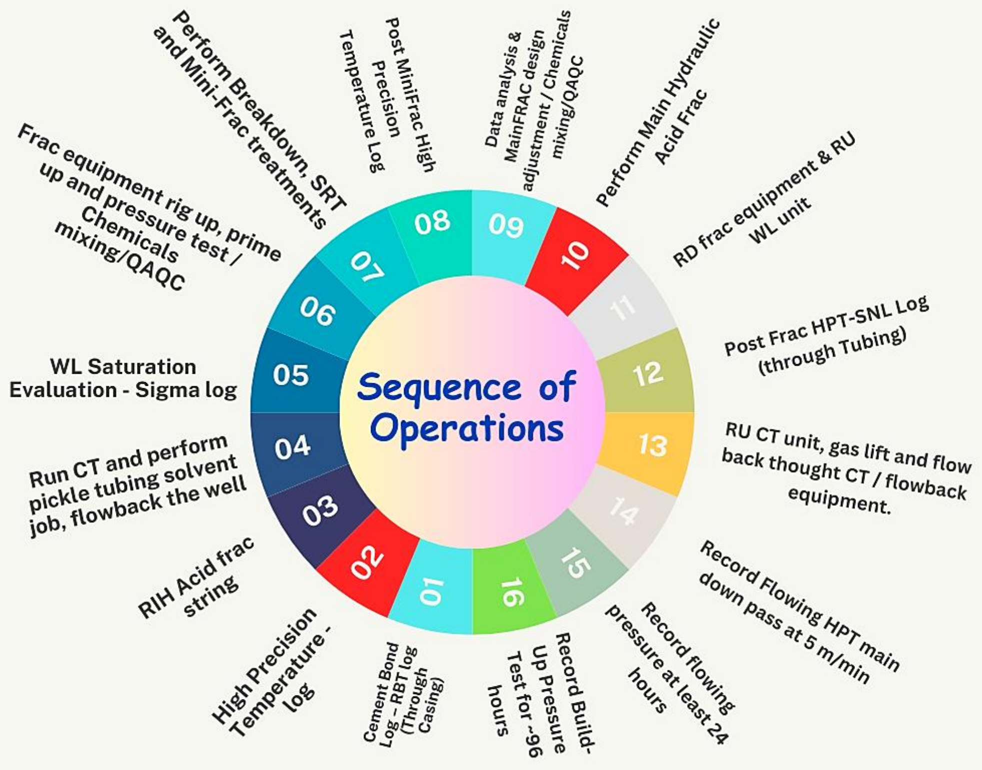

Fig.2. Flow diagram for hydraulic acid fracturing

2.2. Wireline Operations

The planned wireline logging surveys preceding and succeeding the acid fracturing operation are detailed here. Initially, a Radial Bond Log (RBT) will be conducted across the casing prior to the MiniFrac; the RBT log will be documented across the free pipe segment from 2870 to 2800 m, a repeated section logged from 4210 to 4110 m, and the principal RBT Cement Bond Log recorded from total depth (4210 m) to 3500 m. After that, a High Precision Temperature (HPT) log will be run across the casing pre-MiniFrac; the main down pass will be recorded at 5 m per minute from 3945 to 4065 m, and then a repeat up pass at the same speed and interval. Through the casing pre-MiniFrac, a Saturation Evaluation using the Sigma log will also be performed with both main and repeat Sigma up passes noted at 5 m per minute from 4125 to 3945 m.

With these steps repeated after six hours, post-MiniFrac, a High Precision Temperature (HPT) log will be recorded via the tubing, including the main down pass at 5 m per minute from 3945 to 4065 and a repeat up pass at the same speed and interval. Following the primary hydraulic acid fracturing, a High Precision Temperature and Spectral Noise Log (HPT-SNL) will be recorded through the tubing, including a shut-in HPT main down pass at 5 m per minute from 3945 to 4065 m, a repeat HPT up pass, and subsequently flowback operations. Spectral Noise Log (SNL) stations will record the flowing HPT main down pass from 3945 to 4065 m at 5 m per minute from 3945 to 4065 m.

The High-Resolution Pressure tool will be parked at 3985 m (7 m above the perforation), the flowing pressure recorded for at least 24 hours at a stable producing status before shut-in, and a Build-Up Pressure Test conducted for almost 96 hours, optionally through the tubing.

2.3. Baseline HPT Temperature Log

Conducting a Baseline High Precision Temperature (HPT) temperature log under static conditions for 12 hours before the MiniFrac operation is an essential pre-processing step for this well. This process entails performing a primary HPT temperature calibration followed by a subsequent calibration to guarantee precision. The main objective of this baseline logging is to document the high surface temperature (HPT) profile prior to the acid fracturing treatment.

The operational parameters for HPT temperature logging involve sampling the temperature log within the 3945 to 4065 m range and subsequently measuring the tension log. Furthermore, this set of initial data will serve as a benchmark for assessing the efficiency of the following acid fracturing treatment.

2.4. The SIGMA Logging Tool

The Pulse Decay Neutron (PDN) - SIGMA log process commences with the assembly of the PDN Tool String in accordance with the proposed tool string assembly sketch. Sufficient sinker bar weights, a Casing Collar Locator (CCL), a Gamma Ray (GR) tool, and the Pulse Decay Neutron Tool are all included in this assembly. It is imperative to confirm that all tools have been inspected before deployment, with the tool checks observed at the well site. The operation commences with acquiring a zero reading and the subsequent running in a hole (RIH) with the PDN-SIGMA tool string at a moderate pace until it reaches 150 m from the Kelly Bushing (mKB). The tool's functionality is verified at this depth, and a station is documented. Subsequently, the tool string is maintained at a standard rate of 40 m per minute until it reaches 4125 m mKB. The provided open hole (OH) reference log is employed to perform depth correlation. The primary SIGMA up pass is recorded at 5 m per min from 4125 to 3945 m mKB, followed by a repeat SIGMA up pass at the same speed and interval to guarantee data accuracy and reliability. This comprehensive procedure ensures the integrity and precision of the PDN-SIGMA logging operation.

The current formation oil/water contact (OWC) is accurately identified by running the reservoir saturation sigma tool in this well under shut-in conditions prior to the acid fracturing operation. The procedure entails the execution of a primary SIGMA up pass, followed by a subsequent SIGMA up pass to guarantee the reliability of the data.

3. Results

With a water cut of zero percent, the current studied well, which was finished in April 2013, was initially producing oil at a rate of 1500 bbl/day. On the other hand, the well's output decreased rapidly, and by October 2013, it had stopped producing natural flow. Downhole obstructions brought on by asphaltene buildup made it impossible to carry out a static pressure test in March 2014. Due to these obstructions, the test was unsuccessful. Over 600 grams of sludge that contained 37.11 % asphaltene were successfully extracted from a depth of 953 m by a rigless operation when it was carried out in August 2014. During June 2016, solvent cleaning and acidizing were carried out, which led to an increase in production of 1669 bbl/day, a reduction in water content of 0.2%, and a wellhead pressure of 37 kg/cm^3. However, by January 2017, production had dropped to 706 bbl/day, with a 3% reduction in water consumption. An additional perforation, solvent cleaning, and acidizing operation was carried out in February 2017, resulting in an increase in production to 1189 bbl/day with a water reduction of 4%. The well's production rate dropped to 730 bbl/day by the middle of 2018, and the water cut was between 5 and 22 %. This occurred despite the efforts that were made.

The MiniFrac treatment entails injecting a PAD volume of 150 barrels of #30 cross-linked gel into the formation at a steady rate of 25 barrels per minute, succeeded by an overflush of 5 barrels with 30# linear gel. Essential parameters to be assessed during this process encompass closure pressure, fluid efficiency, formation leak-off characteristics for the 30# crosslinked gel, net pressure trend, and any non-ideal phenomena, including fracture complexity or the occurrence of natural fractures (NF).

Common Acid (HCl 15%) is utilized as a reactive fluid for perforation cleaning and facilitating breakdown. X-linked gel (GB-30) is a viscous, non-reactive fluid used to create and propagate hydraulic fractures.

The primary acid systems, comprising HGA 25% and Emulsified Acid Systems (EAS), are gelled and emulsified reactive systems engineered to optimize acid-etched conductive fractures and attain maximum acid penetration. A VES Acid Diverter (CDA 15%) is employed to regulate excessive leak-off and guarantee comprehensive coverage of the designated formation interval. Closure Fracture Acid (HCL 15%) is a reactive fluid characterized by a significant leak-off rate, facilitating fracture closure and radial etching near the wellbore.

All fluids and additives have been validated through laboratory tests, encompassing gel and acid systems, stability, and compatibility with hydrocarbons at reservoir temperature. The tests are conducted at the OiLSERV stimulation laboratory in Basra utilizing chemical samples from the batches designated for the fracturing treatment. This thorough methodology guarantees the efficacy and safety of the fracturing procedure, thereby augmenting the productivity of the Mishrif Formation.

The Young's modulus, a measurement of the rock's stiffness, distinguishes the Mishrif Formation, which is located in the carbonate rock category. Between 0.2 and 0.4 is the range that its Poisson's ratio, which is a measure that describes the relationship between axial and lateral strain, can find itself in. When the Poisson's ratio is lower, it indicates less lateral expansion is associated with applying vertical stress, which is beneficial for forming fractures. In acid fracturing, the mechanical properties of the formation are also extremely important parameters. The values of its compressive strength range from 30 to 150 MPa, which is typical for carbonate reservoirs. Its compressive strength is particularly high. It is common for its tensile strength to be lower than its compressive strength, typically falling somewhere between 10 and 20 percent of its compressive strength. When it comes to acid fracturing, the brittleness of the rock is necessary for success because it tends to fracture more easily when subjected to stress. The Mishrif Formation can become more brittle due to natural fractures, making it easier for fractures to propagate when acid treatments are undertaken.

A Hydraulic Acid Fracturing treatment has been precisely formulated utilizing Frac Gel, Emulsified Acid, and Hybrid Gelled Acid to improve the productivity index of the Mishrif Formation. A summary of the fluid that was utilized in the stimulation job for this well can be found in Table 1.

Table 1. Fluid types and volumes used in acid job frac

Operation	Fluid type	Volume (bbl)
MiniFrac	cross-linked gel	150
	linear gel	225
MainFrac	Common Acid HCL 15%	150
	Emulsified Acid EAS	700
	VES Acid CDA 15%	675
	Gelled Acid: HGA 25%	700

The simulation results as shown in Fig. 3 demonstrate an effective etched fracture length of 109 m and an effective acid height of 41 m. The mean etched width is determined to be 0.195 inches, accompanied by an average fracture conductivity of 285 millidarcy-feet (md-ft). The ratio of Fracture Conductivity to Half Length and Average Permeability (FCD) is established at 0.04. The initial data originate from simulation outcomes, and the definitive geometry will be enhanced following modifications to the job design volumes. This modification will consider the outcomes from the MiniFrac and Temperature Log Frac Height measurements, guaranteeing an optimized and efficient fracturing treatment.

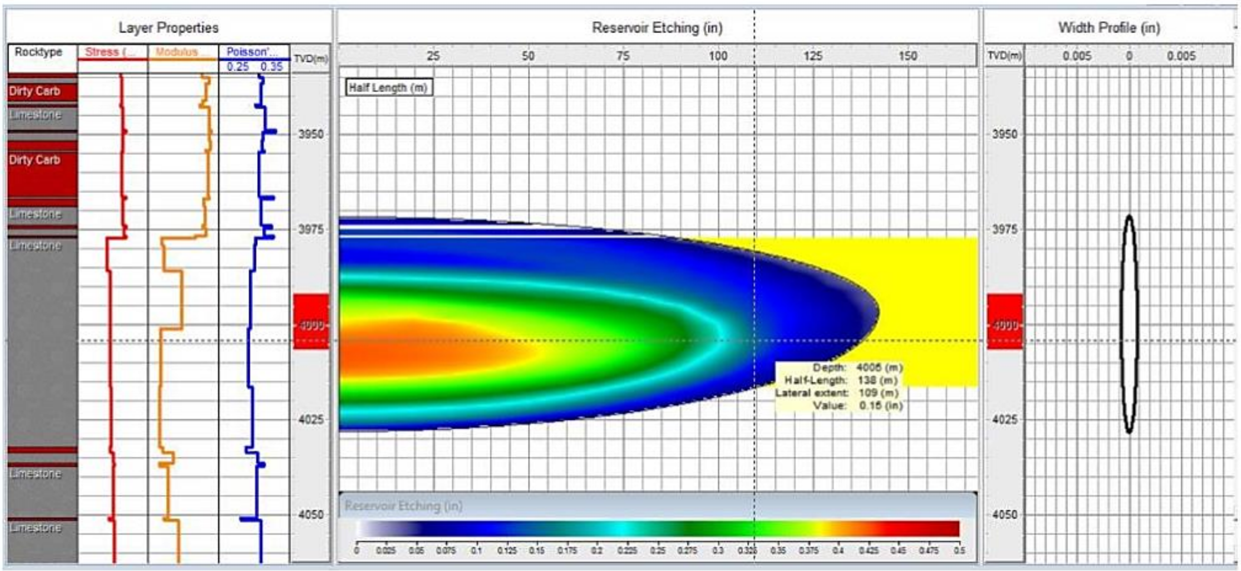

Fig.3. Frac geometry at the depth of 4006 m

The hydraulic acid fracturing treatment simulation outcomes reveal several critical parameters, as illustrated in Fig. 4 . The peak surface treating pressure attained was 9,190 psi, whereas the mean surface treating pressure was 6,246 psi. The maximum downhole treating pressure was recorded at 9,599 psi, while the average downhole treating pressure was 9,543 psi. The peak injection rate attained was 25 barrels per minute (bpm). A hydraulic horsepower (HHP) 5,631 was necessary to meet these conditions. These results offer essential insights into the operational parameters and efficacy of the fracturing treatment, facilitating further optimization and ensuring the desired outcomes in augmenting the productivity of the Mishrif Formation.

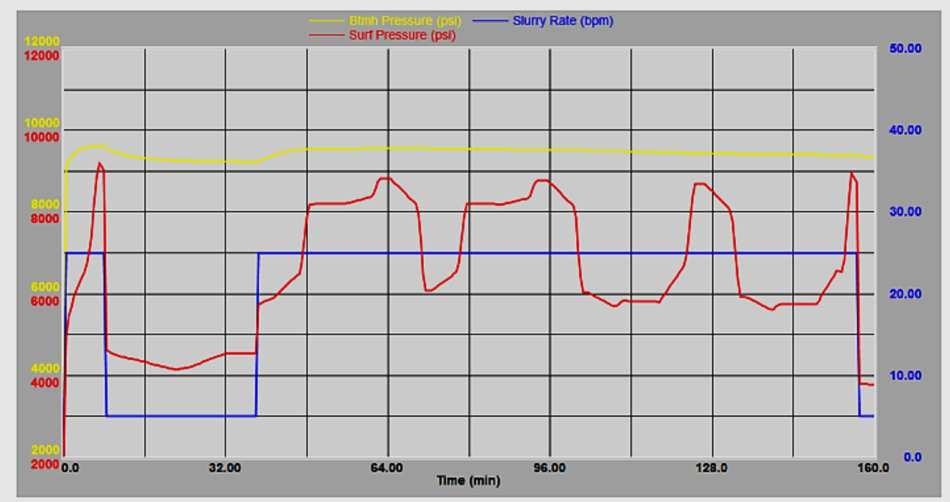

Fig.4. Surface and bottom hole pressure with slurry rate plot

High Precision Temperature (HPT) logs are run following Main Acid Fracturing to track the thermal response of the well and evaluate the success of the fracturing operation. Immediately following the main acid fracturing operation, the first down pass is executed at five m per minute. This first log offers a basic temperature profile following treatment. One hour following the first pass, the second down pass is carried out at the same speed to record any instantaneous thermal changes. Complementing three hours after the first pass, the third down pass keeps an eye on the temperature change inside the well. At last, six hours following the first pass, the fourth down pass generates a complete temporal temperature profile. Understanding the thermal behavior of the formation and the distribution of the fracturing fluids depends on these sequential logs, hence supporting the evaluation of the success of the fracturing treatment. Fig. 5 illustrates the Post Main Frac Temperature Survey conducted on June 2, 2019. The third track from the right in the figure compares baseline (pre mini-frac) and post mini-frac temperatures. The black curve denotes the baseline temperature, whereas the red curve reflects the initial down pass executed immediately following the mini-frac job. The green curve denotes the second pass, executed one hour subsequent to the first; the pink curve illustrates the third pass, undertaken three hours after the initial pass; and the blue curve depicts the fourth pass, performed six hours following the first pass.

The post mini-frac temperature survey validates the cooling impact of the mini-frac fluid throughout the entire flushed zone, extending from 3993 to 4046 m, excluding the segment between 4004 and 4009 m. The peak cooling effect occurs between 4010 and 4030 m, signifying considerable fluid dynamics and thermal exchange in this formation segment. This comprehensive temperature profiling is crucial for comprehending the thermal dynamics and efficacy of the mini-fracturing treatment.

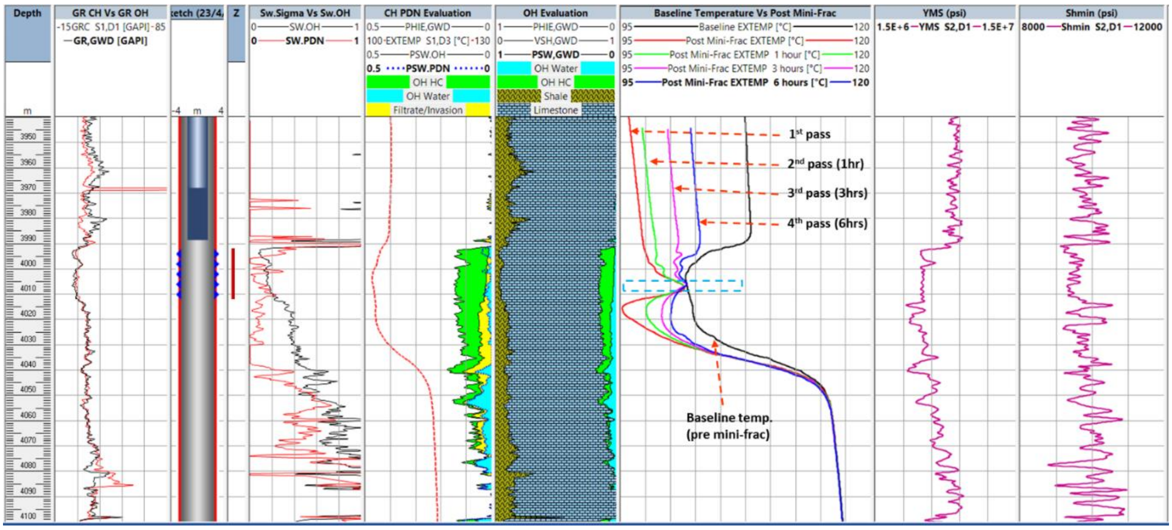

Fig.5. Post Main Frac Temperature Survey conducted on June 2

Fig. 6 displays the post-main frac temperature survey, the job done after the 6 days for the last survey. From the right-hand side in the figure, the third track shows a comparison between the baseline (pre-frac) and post Main Frac temperatures. The red curve corresponds to the first down pass carried out right after the main breaking action; the black curve shows the baseline temperature. The green curve indicates the second pass; the pink curve shows the third pass, carried out three hours after the first pass; the blue curve shows the fourth pass, carried out six hours after the first pass.

The post-Main Frac temperature survey indicates notable cooling effects spanning the Frac height's interval from 3992 to 4035 m. The temperature stays cooler than the baseline below 4034 m but rises rapidly to converge with it, implying that some of the injected fluid was displaced downward into the interval between 4035 and 4055 m during the main fracturing operation. Following the SNL-DMPT run under flowing conditions will help one to ascertain the exact active Frac height.

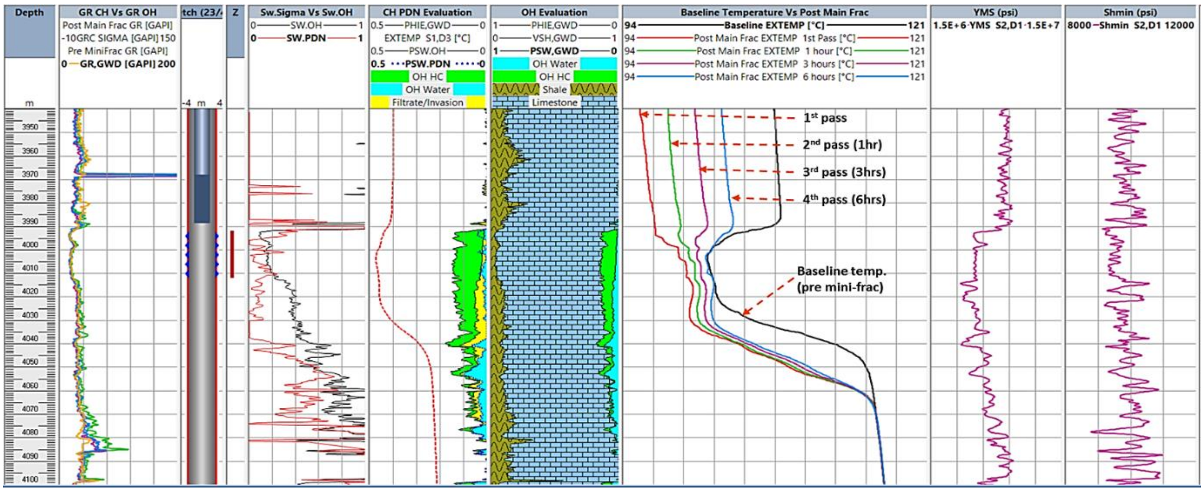

Fig.6. Post Main Frac Temperature Survey conducted on June 8

4. Conclusions

In the MiniFrac treatment, 150 barrels of #30 cross-linked gel were injected at a rate of 25 barrels per minute, and the gel was subsequently overflushed with 30# linear gel. Key parameters were evaluated, including fluid efficiency, fracture complexity, and closure pressure. To optimize acid-etched fractures, the MainFrac treatment employed a variety of fluids, such as Common Acid (HCl 15%) for perforation cleaning, X-Linked Gel (GB-30) for fracture propagation, and primary acid systems (HGA 25% and Emulsified Acid Systems). The stability and compatibility of these fluids were confirmed through laboratory tests. The simulation results suggest that the average fracture conductivity is 285 millidarcy feet, with an effective etched fracture length of 109 m, an acid height of 41 m, and a mean etched width of 0.195 inches. The peak surface treating pressure was 9,190 psi, and the peak injection rate was 25 barrels per minute. These were the operational parameters. In order to guarantee an optimized and efficient treatment, High Precision Temperature logs were implemented post-fracturing to monitor the thermal response.

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