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Satbayev University

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НАЦИОНАЛЬНОЙ АКАДЕМИИ
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ADVANCED METHODS OF FRACTURE GEOMETRY ANALYSIS AND PARAMETERS SENSITIVITY STUDY

Abstract. This article highlights the Integrated Research study of production optimization using Multiphysics hydraulic fracturing simulator and advanced numerical matrix flow simulator. Current work is based on actual field study to understand one of the key challenges of the oilfield: what are the real geometry and characteristics of the hydraulic fractures, and how can we optimize them? Additional challenge for the project was a need to involve meaningful research component, meaning that software used in the project should be based on outstanding or new algorithms and workflows. In collaboration with Schlumberger Research Centers, the integrated Field-Software-Analytic workflow was developed to resolve challenges mentioned above. This workflow consisted of the following steps. First, for the first time in region, the Hydraulic-fracture-induced rock anisotropy survey was performed in fractured well using dipole acoustic tool. Then, Reservoir-centric Multiphysics fracturing simulator was employed to run digital sensitivity study of the fracture parameters. Finally, the hydrodynamic simulation using Intersect, with subsequent analysis, closed the loop. As a result of the applied workflow with the help of powerful Multiphysics model, it was revealed that the fracture effective length is overestimated by 40%, which significantly affects the fracturing projects profitability estimations. More than that, thanks to the advanced particle transport algorithm inside Multiphysics Fracturing Simulator, for the first time in region, the detailed proppant distribution inside hydraulic fractures were understood, and optimization recommendations were given. Example of this study clearly shows how integration of the latest digital Multiphysics solutions (Kinetix based on recognized reservoir-centric platform (Petrel can be combined with advanced surveys (induced anisotropy detection to yield a reasonable conclusion on hydraulic fracturing strategy.

Key words: Dipole Acoustic log, Hydraulic fracturing, Fracture geometry, Proppant distribution.

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ЖАРЫҚШАҚ ГЕОМЕТРИЯСЫН ТАЛДАУДЫҢ ЖӘНЕ ПАРАМЕТРЛЕРДІҢ СЕЗІМТАЛДЫҒЫН ЗЕРТТЕУДІҢ ОЗЫҚ ӘДІСТЕРІ

Аннотация. Бұл мақалада мультифизикалық фрекинг симуляторын және жетілдірілген сандық матрицалық ағынды имитаторды қолдана отырып, өндірісті оңтайландыруды кешенді зерттеу қамтылған. Ағымдағы жұмыс мұнай кен орнының негізгі мәселелерінің бірін түсінуге бағытталған нақты далалық зерттеулерге негізделген: гидравликалық үзілістердің нақты геометриясы мен сипаттамалары қандай және оларды қалай оңтайландыруға болады? Жобаның қосымша проблемасы маңызды зерттеу компонентін қосу қажеттілігі болды, яғни жобада қолданылатын бағдарламалық жасақтама көрнекті немесе жаңа алгоритмдер мен жұмыс процестеріне негізделуі керек. Schlumberger зерттеу орталықтарымен бірлесе отырып, жоғарыда аталған мәселелерді шешу үшін интеграцияланған бағдарламалық аналитикалық жұмыс процесі жасалды. Бұл жұмыс процесі келесі қадамдардан тұрды. Біріншіден, аймақта алғаш рет гидравликалық жарылудан туындаған тау жыныстарының анизотропиясын зерттеу дипольдік акустикалық құралды қолдана отырып, жарылған ұңғымада жүргізілді. Содан кейін жыртылу параметрлерінің сезімталдығына сандық зерттеу жүргізу үшін қабатқа бағытталған мультифизикалық сыну симуляторы қолданылды. Соңында, intersect көмегімен гидродинамикалық модельдеу, содан кейін талдау циклды аяқтады. Қолданылған жұмыс процесінің нәтижесінде қуатты мультифизикалық модельдің көмегімен үзілістің тиімді ұзындығы 40%-ға артқаны анықталды, бұл фрекинг жобаларының рентабельділігін бағалауға айтарлықтай әсер етеді. Сонымен қатар, мультифизикалық фрекинг симуляторындағы бөлшектерді тасымалдаудың жетілдірілген алгоритмінің арқасында аймақта алғаш рет фрекингтер ішіндегі проппанттың егжей-тегжейлі таралуы түсініліп, оңтайландыру бойынша ұсыныстар берілді. Бұл зерттеудің мысалы танылған коллекторға бағытталған платформаға (Petrel) негізделген ең жаңа цифрлық мультифизикалық шешімдердің (Kinetix) интеграциясы фрекинг стратегиясы туралы ақылға қонымды қорытынды жасау үшін кеңейтілген зерттеулермен (индукцияланған анизотропияны анықтау) қалай біріктірілетінін анық көрсетеді.

Түйін сөздер: Дипольді акустикалық каротаж, фрекинг, жарықшақ геометриясы, проппанттың таралуы.

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ПЕРЕДОВЫЕ МЕТОДЫ АНАЛИЗА ГЕОМЕТРИИ ТРЕЩИНЫ И ИССЛЕДОВАНИЯ ЧУВСТВИТЕЛЬНОСТИ ПАРАМЕТРОВ

Аннотация. В этой статье освещается комплексное исследование оптимизации добычи с использованием мультифизического симулятора гидроразрыва пласта и усовершенствованного численного матричного имитатора потока. Текущая работа основана на реальных полевых исследованиях, направленных на понимание одной из ключевых проблем нефтяного месторождения: какова реальная геометрия и характеристики гидравлических разрывов и как мы можем их оптимизировать? Дополнительной проблемой для проекта была необходимость включения значимого исследовательского компонента, что означало, что программное обеспечение, используемое в проекте, должно основываться на выдающихся или новых алгоритмах и рабочих процессах. В сотрудничестве с исследовательскими центрами Schlumberger был разработан интегрированный программный аналитический рабочий процесс для решения проблем, упомянутых выше. Этот рабочий процесс состоял из следующих шагов. Во-первых, впервые в регионе исследование анизотропии горных пород, вызванной гидравлическим разрывом, было выполнено в скважине с трещиноватостью с использованием дипольного акустического инструмента. Затем был использован мультифизический имитатор разрыва пласта, ориентированный на пласт, для проведения цифрового исследования чувствительности параметров разрыва. Наконец, гидродинамическое моделирование с использованием Intersect с последующим анализом замкнуло цикл. В результате примененного рабочего процесса с помощью мощной мультифизической модели было выявлено, что эффективная длина разрыва завышена на 40%, что существенно влияет на оценки рентабельности проектов гидроразрыва пласта. Более того, благодаря усовершенствованному алгоритму переноса частиц в мультифизическом симуляторе гидроразрыва пласта впервые в регионе было понято детальное распределение проппанта внутри гидроразрывов пласта и даны рекомендации по оптимизации. Пример этого исследования ясно показывает, как интеграция новейших цифровых мультифизических решений (Kinetix), основанных на признанной платформе, ориентированной на коллектор (Petrel), может сочетаться с расширенными исследованиями (обнаружение индуцированной анизотропии), чтобы дать разумный вывод о стратегии гидроразрыва пласта.

Ключевые слова: дипольный акустический каротаж, гидроразрыв пласта, геометрия трещины, распределение проппанта.

Introduction. Hydraulic fracturing technology makes it possible to extract previously inaccessible reserves of oil and natural gas. The success of hydraulic fracturing depends on a number of factors. First of all, the object for the implementation of the method must be selected taking into account its features, types of reservoirs, as well as the depth and intensity of development. The choice of technology depends on the conditions in which the well is located. When applied correctly, the efficiency of oil recovery in a treated well becomes much higher. The main root of the problem is understanding of actual fracture geometry (Webster et al., 2013) When modeling hydraulic fracturing (Lecampion et al., 2018), it is necessary to take into account several interrelated physical processes: the flow of a viscous fluid along the fracture, the elastic response of the fracture walls to fluid pressure, filtration fluid through the walls of the fracture into the reservoir, and the destruction of the rock to estimate influence of fracture geometry (Metelkin et al., 2017) on productivity and define the key reasons of the production decline (Miao et al., 2020). In this paper, we analyse Inorganic scales induced skin, Reservoir Pressure Depletion, and Fracture parameters degradation as three potential reasons of the production decline. There are two groups of challenges that triggered the need in this study from the practical point of view:

Reservoir parameters-related challenges.

Challenge to understand permeability-thickness in dynamic conditions (due to poor information about radial flow in low permeability reservoirs – (Y.L. Zhao et al., 2015)

Pressure depletion (this is reservoir between Unconv (Pavlyukov et al., 2020; Rezaei et al., 2017) and Conventional (Rezaei et al., 2017) range).

Lack of advanced modelling of fluid flow inside the fracture and proppant distribution within the fracture media (An Overview of Recent Advances in Hydraulic Fracturing Technology, n.d.; Cipolla et al., 2008)

Lack of understanding of in-situ stresses change during depletion (Zeng et al., 2019).

Challenges to understand the fracture evolution with time.

Fracture conductivity degradation (Miao et al., 2020).

Inroganic Scales inside the proppant pack of the fracture (Osiptsov, 2017).

Damage of the Frac face (ZHANG et al., 2020).

As a result of analytical and numerical (Multiphase hydraulic fracturing simulator) study, it was shown that the pressure in the fracture increases with increasing influence of the poroelasticity effect, and the fracture geometry remains almost unchanged. (Q. Zhao, 2019). Accounting for reverse stress in 3D simulation of hydraulic fractures was made in Multiphysics software (Stolyarov et al., 2019). The study showed that in the presence of inhomogeneities physical characteristics of the medium, the role of pore pressure increases, which qualitatively affects the direction of hydraulic fracture propagation and its geometric characteristics. In particular, if there are layers in the medium with substantially different permeability and the resulting inhomogeneity of the reverse stress, which prevents the propagation of a crack, there is an increase in either only the right or left wing of the crack. In the case when the influence of pore pressure is absent, this does not occur, and the fracture propagates in both directions. Therefore, stress shift is occurring during pressure depletion process (Rezaei et al., 2017) (Zeng et al., 2019).

Methodology. Advanced Methods of Fracture Geometry Analysis, and Fracture Parameters Sensitivity Study" is a second part of the Integrated laboratory, software and research study under the R&D scope. The Research and Scientific nature of this work is supported by the fact that Lagrangian -based Multiphysics hydraulic fracturing modelling software in combination with fracture height measurement techniques is a new approach to the production stimulation industry in Kazakhstan.

Design and Hypothesis: As the first step of the process, the design of the well A-210 for Hydraulic fracturing treatment was prepared. Below is the extraction from well model (Fig.1).

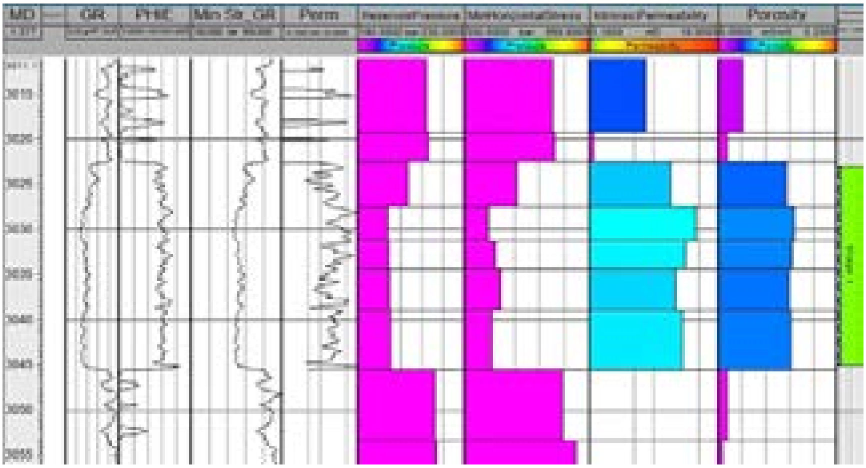


Figure 1. Extraction from well model

Based on the prepared well model, the main hypothesis to check was: Do we correctly predict the Fracture geometry, and if no – how to optimize it?

Diagnostic tests analysis using Bottomhole Pressure Gauge data: Diagnostic tests determine the in-situ parameters critical to optimum fracture treatment design. Assumed or inaccurate parameter values can result in reduced fracture penetration caused by pad fluid depletion and Increased treatment cost because of excessive pad volume. Diagnostic tests typically consist of the closure test and calibration test. Closure test determines closure pressure, which is the minimum in-situ rock stress. Accurate determination of closure pressure is important because all fracture analysis is referenced from it. Calibration testis an injection/shut-in/decline procedure with pad fluid, which is usually a viscous fluid pumped at proposed fracturing treatment rate. The well is then shut in and a pressure decline analysis is performed. The following data can be obtained during different stages of diagnostic tests analysis: Fracture extension pressure and rate, fracture closure pressure, fluid efficiency, leak off coefficient, dominant leak off mechanism; reservoir transient flow regimes, reservoir pressure, reservoir flow capacity (kh/m) or permeability.

For this particular study on well A-1, the Diagnostic testing was improved by

Introduction of the dynamic analysis (breakdown part of the injection tests and step-up/step-down part of the additional injection tests). The dynamic analysis helped to determine the following:

Breakdown pressure;

Fracture propagation pressure;

Friction analysis.

Use of downhole gauges to distinguish near-wellbore frictions and effects from the tubing effects and calibrate the tubing frictions data.

Use of temperature logging data after the calibration test to estimate the fracture initiation point and fracture height.

Calibration test opened the whole kh of the target sand layer, with average k lying in a range from 3 to 6 mD. The downhole gauge data are extremely important to determine after-closure transmissibility at the crosslinked stage, because the surface readings showed underestimated kh. From temperature log we obtained the fracture initiated, and most probably has the maximum width somewhere at 3030-3031 m. The reservoir model in fracture simulator was adjusted accordingly. Using fracture initiation point from temperature log, and step-like breakthrough signatures during injection test 2, the maximum reasonable number of zones with varying minimum-in-situ stress in target net pay can be 4 or 5. There is no practical need to finer layering of reservoir model in fracture simulators. The fracture top height is determined with satisfactory error +/- 2 meters; however, the fracture bottom determination is questionable (sonic tool helped to solve this – Fig. 2).

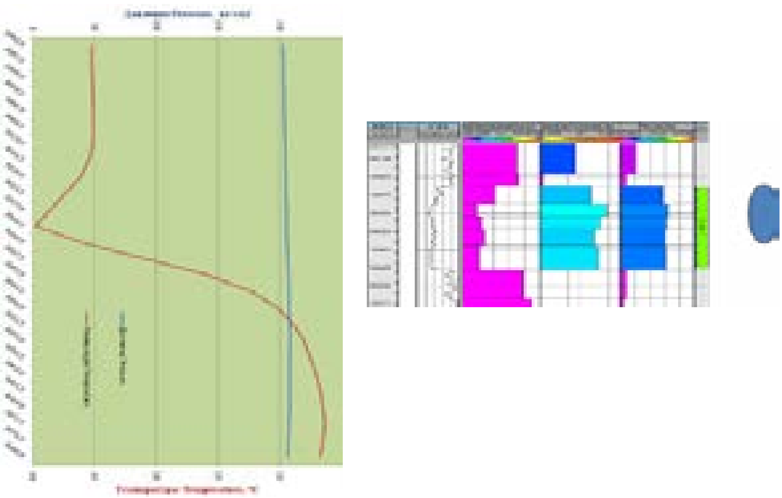


Figure 2. Fracture bottom determination is questionable

Dipole Acoustic Log Data Analysis: shear slowness was extracted from Dipole data using 5 receiver's multishot technique and the final results are good in the expected range of values

Definite presence of fracture was observed at depths 3016-3044 m: 3046-3060 – presence of wellbore diameter change (Fig. 3).

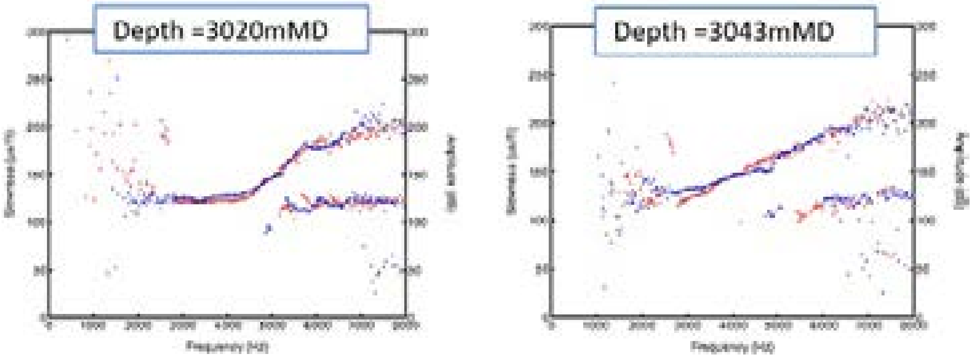
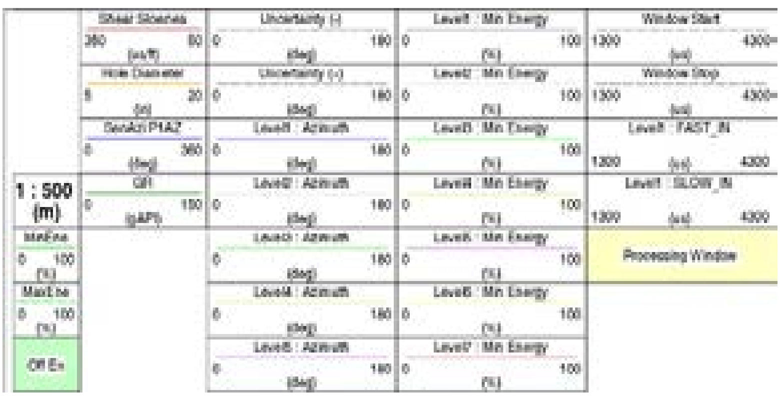


Figure 3. Definite presence of fracture was observed at depths 3016-3044 m

The fracture bottom may be masked by this fact (formation signal coherency becomes week and casing arrival appears to be visible), but presence of isotropic points at 3046 and 3055 may indicate that the fracture stopped at 3045, and the induced anisotropy signals below are caused by pumped fluid entry and work in washed out zone. Another important piece of information obtained from acoustic data is direction of the fracture plane. The deviation of the well is very low, so the precision of the fracture azimuth determination can be low. In general, the fracture azimuth is expected to be in WNW direction, in a range of 105 to 135 deg (refer to the log below, Fast Shear Azimuth red line) (Fig. 4). This fracture azimuth reflects the local maximum horizontal stress direction. The local maximum horizontal stress direction can be different in the vicinity of the geological faults. The minimum horizontal stress gradients observed during fracturing are indicating normal regime in this field, where normal faulting is expected. In this case, the maximum horizontal stress direction is aligned with the fault line. If the faulting lines are not aligned with the maximum horizontal stress direction given above, then either this maximum horizontal stress direction is a local feature, or the faulting history contains some strike-slip movement in the past.



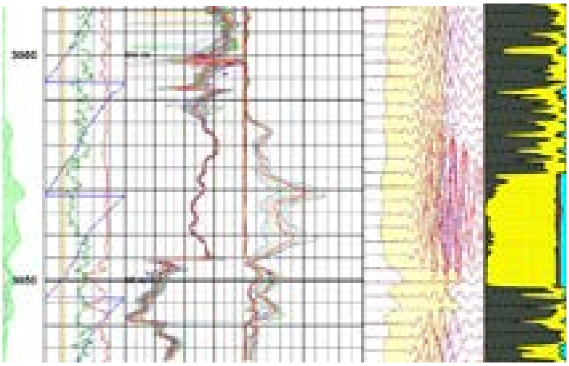


Figure 4. Fracture azimuth is expected to be in WNW direction, in a range of 105 to 135 deg (refer to the log, Fast Shear Azimuth red line)

Fracture Model Calibration: Using the data obtained from Mini-frac, temperature logs and Sonic tools, the Advanced Multiphysics software was used to recalibrate the fracture design. In the used Multiphysics method, transport equations describing the advection of proppants, fluids, and fibers via a conservative Lagrangian algorithm (particle-in-cell method) (Harlow 1964; Grigoryev et al. 2002). It has zero numerical diffusion and allows us to simulate slurry flow with no excessive smoothing. The velocity field for each component is calculated using a finite volume scheme on 2D grid in the x, y plane and closure relations for settling velocity and bridging. The particle-in-cell method gives an exact determination of fluid/proppant location and enables the capture of many important effects, thus combining advantages of both mesh and meshfree methods. These include materials degradation via tracking temperature and shear exposure; displacement of proppant in the near-wellbore area in case of overflush; correct simulation of tail-in/resin-coated proppant stages; and complex boundaries between fluids, proppants, and fibers. Algorithm allows for tracking exposure history for all fracturing materials and account for fluid and fiber degradation. Fluid degradation affects rheology according to a given experimental table.

Below is the fracture created during Calibration test, built on calibrated reservoir, before main job. (Fig. 5).

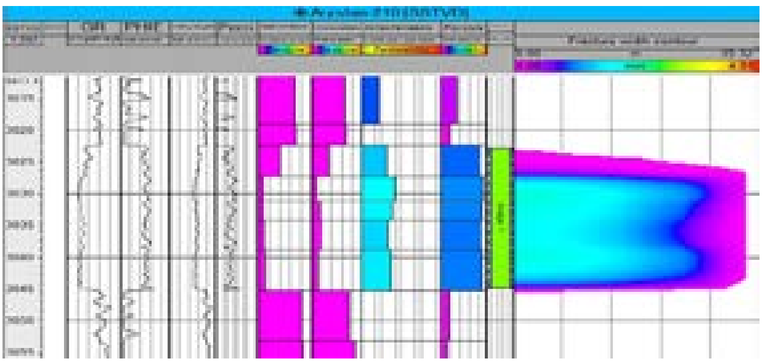


Figure 5. Fracture created during Calibration test, built on calibrated reservoir, before main job

Fracture Fluid Rheology Testing: For modelling of the actual job, the fluid rheology digital model was reconstructed. It is especially important, because the advanced fracturing software used in this study is equipped with Multiphysics fluid/proppant transportation algorithms, which are very representative, so the precision of fluid model becomes increasingly important in this case. The fluid rheology tests were performed on actual chemical and water samples from the field.

30# gel

pH	8.23 @ 24.8 degC
Viscosity @ 170 sec-1	54 cP
Viscosity @ 511 sec-1	27 cP

33# gel

pH	8.3 @ 24.4 degC
Viscosity @ 170 sec-1	60 cP
Viscosity @ 511 sec-1	34 cP

Sensitivity study on the Actual Fracture length Actual pumped job was simulated on the calibrated model. Two cases were checked in order to get a range of actual fracture length. P50: Less propped height due to any reason (slightly higher actual rate, less fracture width on top, more fracture toughness in vertical direction, and less in horizontal, etc.) P90: Height seen at acoustic data. The difference between two cases in propped length is not more than 5 meters (around 80 m for P90 vs 85 m for P50). Refer to figures below (Fig. 6).

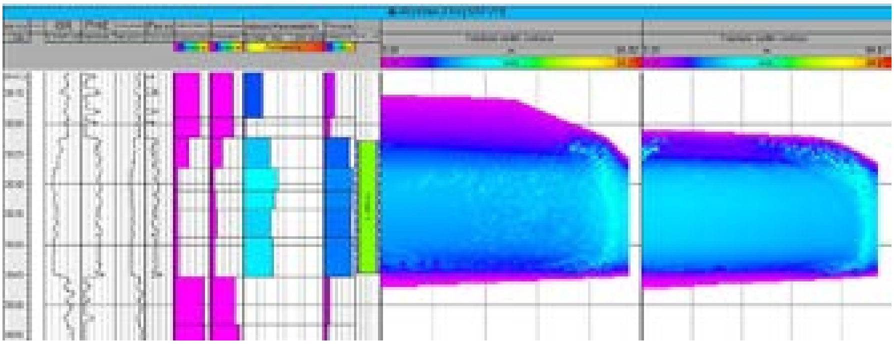


Figure 6. Calibrated fractures after Actual job: P90 (left) and P50 (right)

Refrac sensitivities: Modelling of the re-fracturing is a complex process, which can't be performed precisely because of the multiple factors: two different conditions of the reservoir itself, changed state of geomechanics components from the previous fractures, micro- and macro scale geometrical/completion/geology uncertainties. For this study, the following question was raised: when we perform frac, do we expect significant change of fracture plane direction, considering that crack during refracturing may be initiated in different depth than during initial fracturing.

Refrac modelling was performed in the following way:

The initial fracture was modeled on a less depleted zone.

The refracturing was modeled by giving 40% depletion, shifting the fracture initiation point 1-2 meters along the wellbore, increasing leakoff.

Planar3D modelling engine was used, to account for more complex processes.

Multiphysics simulator allowed stress shadowing effect (between two fractures) to be accounted for.

Job volumes were reduced, because the key parameters that we are interested in here is the initiation zone and several meters of the fracture propagation in a preferrable fracture plane.

Results. Results of refracturing simulations are shown below (Fig. 7). On the left – initial fracture, on the right – re-fracture. At the bottom – overlapped picture of both fractures, where yellow-orange-brown colors are reflecting refracture, and purple colors are initial fracture. Note, the cross-section is shown, the distance between two fractures from the top view is less than radius of the wellbore.

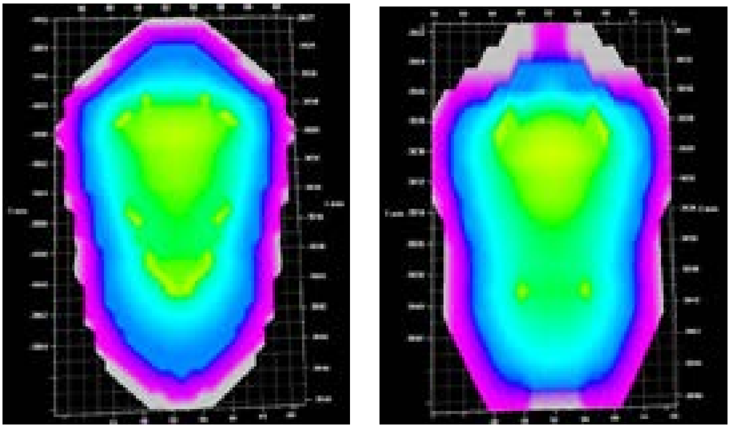


Figure 7. Results of refracturing simulations

It is noted in some publications in industry, e.g. SPE-106140 (picture below), that fracture reorientation may happen. In locally depleted zone. Thus, for refracturing candidates, it is recommended to observed the fracture efficiency. If fracture efficiency is close to that of during initial fracture, then probably fracture is created in new plane. However, if fracture efficiency is significantly lower, then, probably, the fracture is created along the initial fracture (Fig. 7).

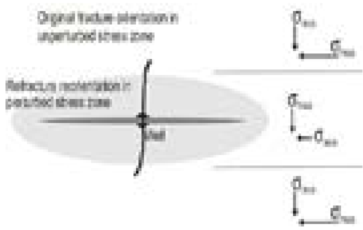


Figure 7. If fracture efficiency is significantly lower, then, probably, the fracture is created along the initial fracture

Conclusions and Recommendations. Fluids and Laboratory.

Consider decrease of gel loading of guar-based polymer by 5 pounds per thousand gallons, and increase of breaker delivered into the fracture (e.g. putting extra breaker into the flush) – to increase the Effective fracture length.

Consider performing Intermediate laboratory tests between the fracturing jobs in High-pressure – high temperature equipment, at least once every 5 jobs, or when new fluid is involved, and/or reservoir temperature changes by more than 10 ºC

Fracturing Treatment Strategy in depleting formation

As shown by production decline analysis, the key mechanism of the production decline for given fractured wells is the reservoir depletion.

Increase of pumping rate and proppant volume (from 45 t to 65 t) provides less than 10% of fracture half-length increase due to increased leak-off in depleted reservoir. Propped half-length gain per 1 ton of extra proppant is decreasing significantly once the job volume exceeds 60-70 tons. The significant portion of the effect from added propped half-length proppant is compensated by the added damage from the added polymer required to deliver extra proppant.

Consequently, main strategy to deal with depleting reservoir is to increase the effective fracture half-length via several options, the most remarkable are: (i) to minimize fluid volumes pumped into formation, use more aggressive PAD percentage, eliminate extra pumping stages like SRT, double injection test, because injection combined with SDT or SRT may be enough; (ii) use cleaner fluids, like the ones based on Cellulose or on the Viscoelastic Surfactants; (iii) use bigger proppants whenever possible, or more conductive proppant type

From the calibrated model, the following recommendations should be considered for lower permeability, higher fluid efficiency (>45%) wells like A-233, in order to increase the effective half-length:

Consider gradual replacement of some PAD volume from crosslinked to linear gel in the beginning of PAD stage. Start with replacement of 20% of X-linked PAD to linear gel, on first well, then try 30% on the next well. After each job analyses the net pressure gain. Stop increasing linear gel percentage if the net pressure gain becomes too aggressive.

Consider addition of 20/40 or 30/50 proppant in the initial stages of jobs if the fracture half-length exceeds 100 meters for wells with efficiency more than 45%. It may help to prop the near-tip region (10-20 m) of the fracture.

Consider channel fracturing technique, which can provide up to 50% effective fracture half-length increase (based on well A-210 estimation) for the same volume of proppant pumped in comparison with the conventional propped fracturing techniques; in addition, channel fracturing techniques will allow to optimize future costs by replacement of expensive proppant by the regular cheap sand.

There is a certain limit of profitability, which may happen at fluid efficiencies below 13%, and assuming clean revenue less than 30 USD/bbl, independently on measures taken to increase the fracture effective length.

Fracture and Reservoir understanding

Fracture height was successfully determined with acoustic methods. It was revealed that good calibration can provide frac height which is in satisfactory match with the actual fracture height. Acoustic methods showed higher precision than temperature logs.

WNW-NW is the max stress direction in the zone of well A-210.

Multiphysics advanced proppant transport modelling was applied for analysis of the internal fracture structure. It helped to reveal the effective half-length, and proppant distribution.

Fracture length was derived from the actual frac height. Maximum propped frac length is in range 90-95 m for well A-210, and 115 meters for well A-233; effective half-length is about 60% of this length.

Temperature logs helped to calibrated fracture height for well A-233 with good precision, because logs were recorded with higher frequency than on well A-210.

Reservoir pressure and kh/mu were determined (refer to technical details in report)

Fracture geometry development during injection test were defined: the strong PKN type in linear gels, with extent of height into the whole net pay at viscous stages, and further continuation of PKN-type growth.

Refracturing doesn't result in fracture propagation in different azimuth, or fracture plane twisting. Most probably, refracturing will happen in parallel to existing fracture, close to it.

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