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Title:

Notching as a New Promising Well Intervention Technique to Control Hydraulic Fracturing in Horizontal Open Holes

Authors:

Gallyam Aidagulov[1,2], Eric Edelman[1], Dominic Brady[1]

Abstract:

Economic production of oil and gas from tight formations requires complex completions and stimulation treatments such as multistage hydraulic fracturing of horizontal wellbores. In case of tight and competent reservoirs when wells can be completed openhole – this can be done time- and cost-effectively using the assembly comprised of tubular, packers to isolate stages and sliding sleeve valves between them operated with drop ball mechanism. This stimulation technique can be improved further by reducing some of the risks associated with it. First, the length of the treated openhole section for each stage that can reach 1,000 ft. implies no control on the orientation and position of the initiated fracture. Also, rock strength and in-situ stresses can be sometimes so high that it makes the breakdown of the formation impossible without reaching the pressure limits of surface equipment and pumps.

Recently, a technique consisting of cutting notches in the wellbore wall was proposed as well intervention steps prior to fracturing operations. Each notch plays the role of a weak-point in the rock which develops high stress concentration at the tip and helps to initiate the fracture at pressures lower than in other parts of the treated section. This allows the initiation of the fracture in the transverse direction and at the exact position of the notch. Due to the initiation of the fracture in the transverse direction and the high stress concentration at the notch tip, the formation breakdown pressure can be significantly lowered.

We present new experimental studies of the notching technique along with the latest laboratory results of hydraulic fracturing block tests to demonstrate the benefits of notches. Circular notches were cut using the miniature laboratory analog of a high pressure jetting tool applied in the field. The reported tests repeatedly demonstrate the positive effect of the notch on the orientation of the initiated fracture and the decrease of the breakdown pressure. A reasonable fit between the observed pressure trends and theoretical modeled ones is also obtained and discussed.

Keywords:

Hydraulic fracture initiation, openhole, notch, laboratory block test, fracture breakdown pressure, high pressure jetting, multistage fracturing, well intervention.

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Introduction

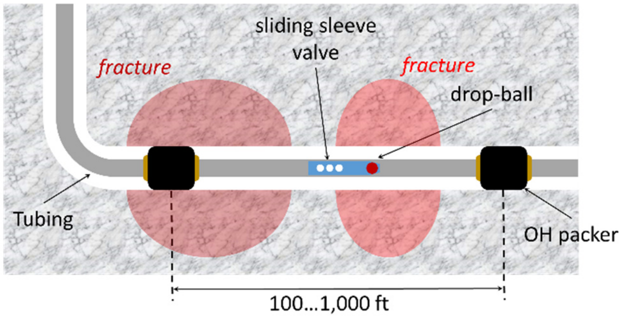

Fig. 1. Multistage hydraulic fracturing stimulation in horizontal openhole well. Undesired longitudinal fractures are highlighted with red color.

Economic production of oil and gas from tight formations requires complex completions and stimulation treatments such as multistage hydraulic fracturing of horizontal wellbores. In case of tight and competent reservoirs when wells can be completed openhole – this can be done time- and cost-effectively using the assembly comprised of tubular, openhole (OH) packers to isolate stages and sliding sleeve valves between them operated with drop ball mechanism (**Fig. 1;** Aviles et al. 2013). This stimulation technique can be improved further. First, the length of the treated openhole section for each stage that can reach 1,000 ft. (Al-Naimi et al. 2008) implies no control on the position of the initiated fracture, which will open at the weakest point or layer. Even if the wellbore is drilled along the minimal far-field stress direction, the hydraulic fracture may still initiate longitudinally due to the tensile hoop stresses developed near the wellbore (Daneshy 2009; Lecampion et al. 2013). In this case, any further re-orientation of the fracture into the preferred fracture plane – which is transverse to the borehole – will cause undesired fracture tortuosity. Another risk will be for the longitudinal fracture to break beyond the openhole packer isolating the treated zone (as schematically shown in Fig. 1 by one of undesired red fractures). Also, rock strength and in-situ stresses can be sometimes so high that it makes the breakdown of the formation impossible without reaching the pressure limits of surface equipment and pumps.

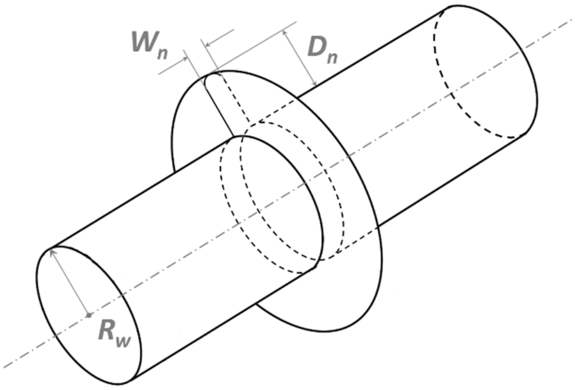

Fig. 2. Schematic drawing of the circular notch cut into the wellbore wall.

Recently, a technique consisting of cutting notches (**Fig. 2**) in the wellbore wall was proposed as well intervention steps prior to fracturing operations (Chang et al. 2014). This allows the initiation of the fracture in the transverse direction at the exact position of the notch and at lower breakdown pressure compared to unnotched open hole.

We present new experimental studies of the notching technique along with the latest laboratory results of hydraulic fracturing block tests to demonstrate the benefits of notches. Circular notches were cut using the miniature laboratory analog of a high pressure jetting coiled-tubing (CT) tool applied in the field (Bartko et al. 2016). The reported tests repeatedly demonstrate the positive effect of the notch on the orientation of the initiated fracture and the decrease of the breakdown pressure. A reasonable fit between the observed pressure trends and theoretically modeled ones is also obtained and discussed.

Circular notch: How does it work?

Each notch plays the role of a weak point in the rock which develops high stress concentration at the tip and helps to initiate the fracture at pressures lower than in other parts of the treated section.

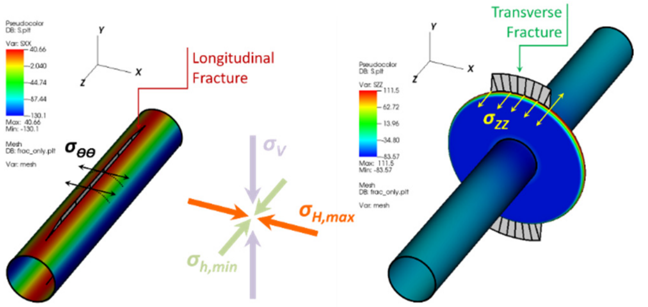

Fig. 3. Simulated tensile stress concentrations at the wellbore wall for the unnotched (left) and notched wellbores. Initiated hydraulic fractures are.

This is demonstrated in **Fig. 3** by numerical simulation of hydraulic fracture initiation from the unnotched and notched horizontal wellbores aligned with the minimal horizontal far-field stress $\sigma_{h,min}$, $\sigma_{h,min} < \sigma_{H,max} < \sigma_V$. The numerical model used here - was presented by the authors earlier (Aidagulov et al. 2015).

Without a notch only the hoop stress, $\sigma_{\theta\theta}$, becomes tensile at the wellbore wall as the wellbore pressure increases during the hydraulic fracturing treatment. This leads to the initiation of a longitudinal fracture. With a notch, the axial stress, σ_{ZZ}, concentrated at the notch tip initiates transverse fracture. As notch gets deeper, axial stress increases raising the chances for transverse fracture to initiate at lower pressure. Due to the initiation of the fracture in the transverse direction and the high stress concentration at the notch tip, the formation breakdown pressure can be significantly lowered.

Laboratory investigation

The effect of circular notch on initiation of hydraulic fractures has been studied in the laboratory by performing hydraulic fracturing block tests. Tests were done inside the true triaxial stress frame installed in Schlumberger Research Center in Dhahran (**Fig. 4**).

Fig. 4. True triaxial stress frame used to perform hydraulic fracturing block tests.

In hydraulic fracturing block test rock samples in a form of rectangular block are utilized. Each sample has a borehole drilled in the center of the block. Sample is loaded inside the stress frame which is able to apply and maintain stresses at the sample in 3 directions independently to simulate complex in-situ stress conditions. In the lab setup the applied stresses are marked according to their directions: East-West (EW), North-South (NS) and Top-Bottom (TB) as shown in **Fig. 5**. Then viscous fracturing fluid is injected to the wellbore raising the borehole pressure followed by initiation and growth of hydraulic fracture. The current experimental setup also allowed us to collect the acoustic emission data during the test which helped to reconstruct the details of fracture initiation and growth process (Edelman et al. 2016).

For the purposes of the current study, only upper part of the borehole has 6-in. casing tube cemented with epoxy and leaving the 12-in. openhole section in the center of the block. Stress applied in TB direction along the borehole represents the minimal far-field stress. Depending on the test, up to one circular notch is cut to the borehole wall in the center of the openhole section. Below are some specific details for the block tests:

- Rock type: Indiana limestone, permeability range of 1-10 mD;
- Test type: dry (non-saturated)
- Block size: 18 x 18 x 24 in.
- Borehole:
  - diameter: 1.25 in.
  - completion: 12-in. long openhole section (OH) in the center of the block
- Notch: 1 x circular notch in the OH center
- Fracturing fluid: silicone oil
  - viscosity: 1E6 cP
- Fluid injection rate: 30 ml/min.

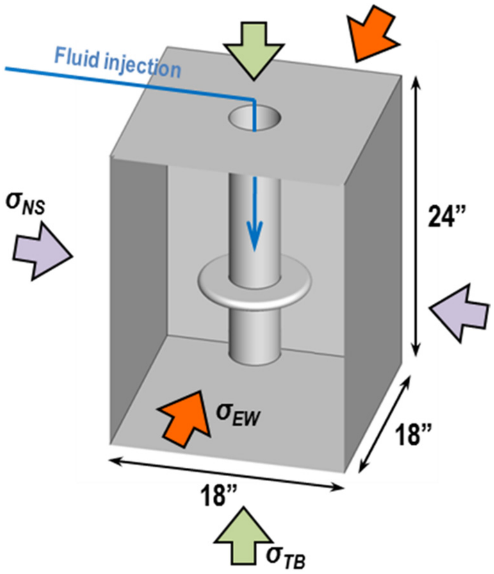

Fig. 5. Hydraulic fracturing block test. Stresses applied independently at the block in 3 directions are shown with arrows. There is a circular notch cut in the middle of the open section of the borehole.

Values of the applied stresses were the same through all the tests performed and are listed in **Table 1**.

Lab notation	**Field analog**	**Value**
σ_{TB}	Horizontal minimal, $\sigma_{h,min}$	2,250 psi
σ_{EW}	Horizontal maximum, $\sigma_{H,max}$	3,000 psi
σ_{NS}	Vertical, σ_{V}	3,500 psi

Table 1. Values of applied stresses used in experimental program.

Only depth of the notch was varied between the tests in order to demonstrate repeatedly the effect of notch and its depth on initiation of hydraulic fracture (orientation and breakdown pressure). This included baseline cases with unnotched open holes.

Laboratory Notching Tool

Special high pressure water jetting tool was implemented to cut notches in laboratory block samples. This is a miniature analog of the coiled tubing (CT) jetting tool that was applied to cut notches in the field (Bartko et al. 2016). The tool has rotating head, 27.93 mm in diameter, equipped with 3 jetting nozzles located within the same plane and phased 120°. Each nozzle has an orifice of 0.9 mm in diameter (**Fig. 6**).

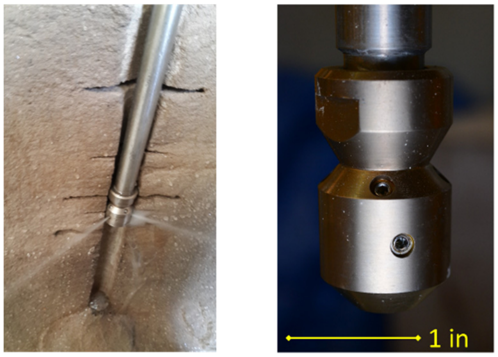

Fig. 6. Cutting circular notches in the lab. Left: jetting tool inside the borehole and the notches cut. Right: a close-up of rotating jetting head of the laboratory notching tool.

In the contrast to the field, where jetting operations are usually accomplished with abrasives, in the lab notches were cut by jetting with water only. To initiate rock cutting, one has to maintain the water jetting pressure above the certain threshold value (Momber 2004) which was found empirically during the separate tool characterization tests (Fig. 6, left). Combination of 6,000 psi jetting pressure and 30 L/min pumping rate was found optimal for the equipment available and was used to cut all the notches in the current work. This ensured maximum repeatability and control over the notch depth as a function of the jetting time. Under these conditions notches with depth up to 2 in. were achieved (**Fig. 7**) which corresponds to 1.6 wellbore diameters (WBD).

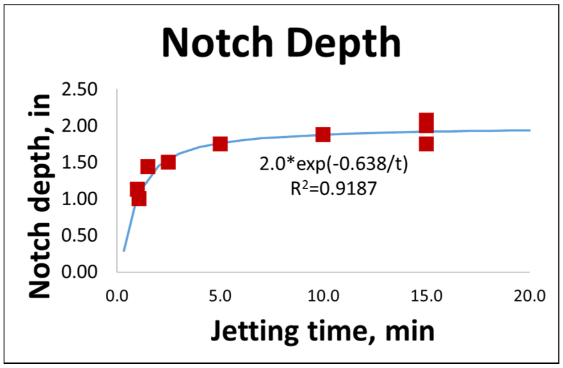

Fig. 7. Laboratory notching tool: depth of the notch cut as a function of jetting time.

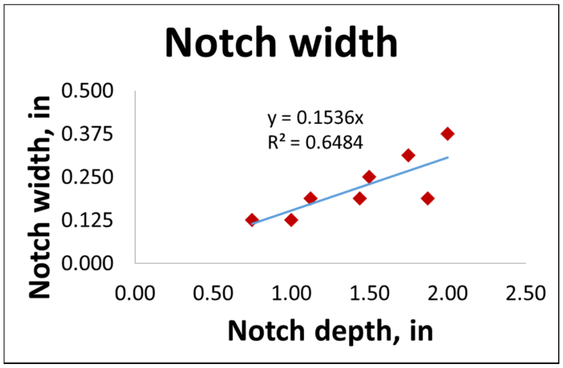

Fig. 8. Width and depth of the notches cut in the lab.

The depth of the notch cut was observed to grow very rapidly in the very beginning of the jetting operation. This means less control on the notch depth in cutting shallower notch compared to deeper ones. Also, as notch gets deeper (due to longer jetting time) it generally becomes wider as shown in **Fig. 8**, although the aspect ratio remained very high for all notches.

Effect of Notch on Hydraulic Fracture Initiation

A total of 6 block tests were performed with an objective to demonstrate repeatedly the effect of notch on initiation of hydraulic fracture from the open hole. This was done by performing the experiments keeping all the experimental parameters the same except the notch depth. Two block tests (tagged as Blolck2 and Block3) were performed with open boreholes without notches to establish a baseline. Those were followed by the tests for the boreholes having one circular notch in the center of the open section. Overall, notch depths of 1.2×WBD and 1.5×WBD were tested having each notch depth repeated twice: Block7 & 8 and Block4 & 6 respectively.

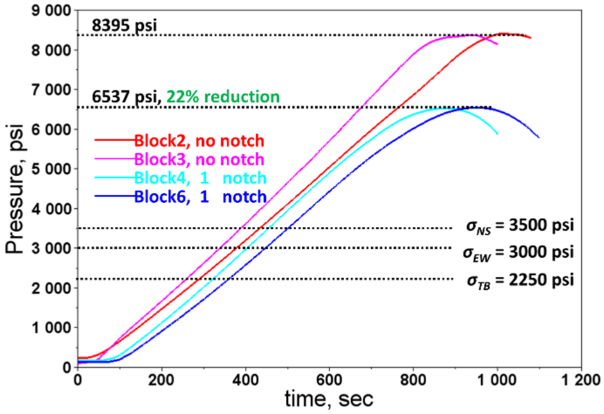

Fig. 9. Hydraulic fracturing block tests. Borehole pressure as a function of time.

The following conclusions can be drawn.

First, excellent repeatability has been observed. **Fig. 9** shows the plots of borehole pressure as a function of time for the selected test cases of borehole without notch (Block2 & 3) and 1.5×WBD deep notch (Block4 & 6). One can see that fracture breakdown pressures (maximum pressure values) coincide almost perfectly when test conditions were repeated.

Second, in the absence of the notch, a longitudinal fracture initiates at the open hole, despite the fact that the borehole is along the minimal stress direction. In this case, hydraulic fracture grows along the borehole till it reaches casing bottom or the end of the borehole. At those points where the mechanical advantage of the borehole is lost, the fracture starts to re-orient into the preferred fracture plane which is orthogonal to the borehole (**Fig. 10**). In all cases, when 1.2×WBD or 1.5×WBD deep notch was placed in the middle of the open section – fracture initiated at the notch in transverse direction as illustrated in **Fig. 11** by the post-test photos of Block4 and Block6 cut open. Initial notches can be seen there as circular cavities with a borehole as a center.

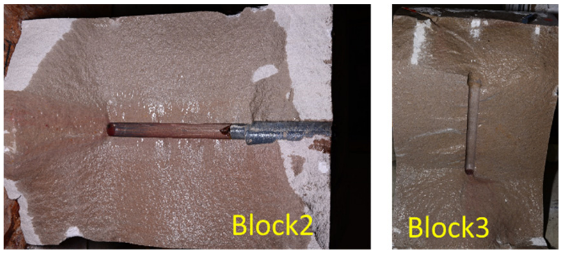

Fig. 10. Longitudinal fracture initiated along the borehole in the absence of the notch.

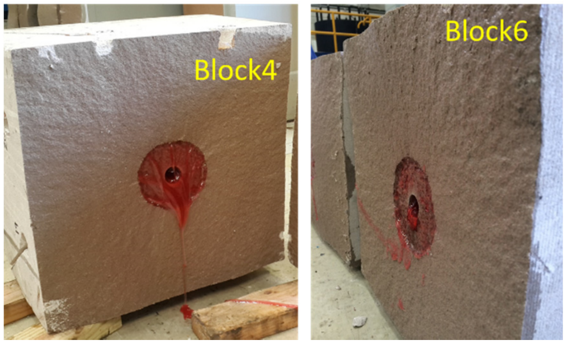

Fig. 11. Transverse fracture initiated at the notch orthogonally to the borehole.

The obtained result confirms one of the findings of the previous studies by Chang et al. (2014) shown that a notch depth of at least 1×WBD is required to initiate transverse fractures in the block tests. In the present work we continue those studies by utilizing the same applied stresses, fluid viscosity and injection rate but with the focus on the effect of the single notch and repeatability of the results. The latter was accomplished by repeating the experiment twice for the same parameters set which is rarely done in hydraulic fracturing block testing due to high complexity of each tests. Also, in the current work each experiment was performed on a larger block sample which exceeds by more than 4 times in volume the block used by Chang et al. (2014).

Probably, the most important result from the application point of view is in the reduction of fracture breakdown pressure caused by the notch. In Fig. 9 it is clearly seen that once the 1.5×WBD deep circular notch was cut in the center of the open hole, the breakdown pressure dropped by 22% compared to the, otherwise the same, un-notched borehole cases.

Theoretical Model Validation

Aidagulov et al. (2015) proposed the theoretical model for initiation of hydraulic fracture from the notched open hole. Below we use the obtained experimental data to validate it.

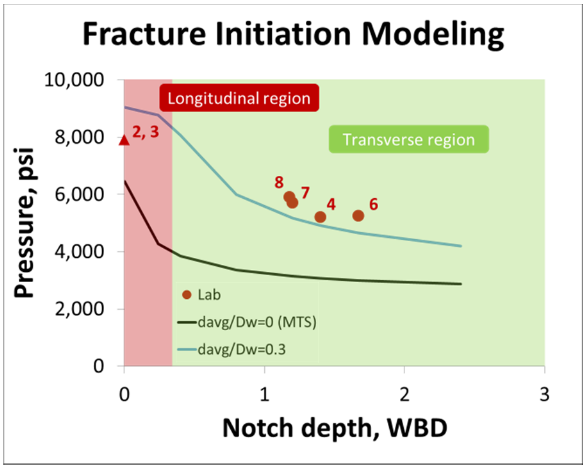

Fig. 12. Fracture initiation pressures observed in block tests as a function of the notch depth for transverse (circles) and longitudinal (triangles) fractures. Solid lines: simulation.

The theoretical model simulates the position and orientation of the incipient fracture as well as borehole pressure at which the fracture initiates – as a function of rock mechanical properties and in-situ stresses (Fig. 3). The fracture initiation pressure (FIP) corresponds to the borehole pressure at which the fracture in the rock appears and is different from the fracture breakdown pressure (FBP). In the contrast to FBP, FIP is difficult to measure directly and indirect measurement techniques are usually applied in block testing (Chang et al. 2014). In the current work FIP was taken as the point at which borehole pressure curve (Fig. 9) starts to delineate from the straight line. FIP values obtained for each block test were then plotted against the notch depth in **Fig. 12** with the corresponding test ID number printed next to the point. Here triangles and circles correspond to longitudinal and transverse fractures respectively.

Then the theoretical model was applied to simulate hydraulic fracture initiation observed in the tests. Numerical simulation was done for the following parameter values (one is referred to Aidagulov et al. (2015) for more details on the model):

- Fracture criterion: stress averaging maximum tensile stress criterion (SAMTS):
  - Stress averaging length, d_{avg} – was varied to fit the pressure data;
- Borehole diameter, D_w=1.25 in.
- U-shaped notch, fixed width, W_n=0.5 in.
- Notch depth, D_n – varied;
- Rock properties:
  - Young's modulus, YM=3E6 psi;
  - Poisson's ratio, PR=0.22;
  - Rock tensile strength, TS=950 psi; reasonable for Indiana limestone.

FIP values calculated with the model is plotted in Fig. 12 with the solid curves. Blue curve is obtained using the SAMTS criterion with the averaging length parameter value $d_{\mathrm{avg}}=0.3D_w=0.375$ in. chosen to provide the best fit to the observed FIP values. Black curve corresponds to the local maximum tensile stress (MTS) criterion which is a specific case of the SAMTS criterion for $d_{\text{avg}}=0$.

One can see that classical MTS criterion based solely on the tensile strength of the rock (which was picked reasonably for Indiana limestone) – is far below the FIP values observed in the block tests. Meanwhile, the non-local SAMTS model can be fitted to match reasonably well the observed pressure trends. Also, it captures the transition between the longitudinal and transverse fracture initiation which happens starting from the certain depth of the notch (red and green zones in Fig. 12).

Conclusions

We presented new experimental studies of the notching technique along with the latest laboratory results of hydraulic fracturing block tests to demonstrate the benefits of notches. Circular notches were cut using the specially implemented miniature laboratory analog of a high pressure jetting CT tool applied in the field. This new tool allows to cut circular notches with the depth up to 2 in. or 1.6×WBD in a well-controlled manner. The reported tests repeatedly demonstrated the positive effect of the notch on the orientation of the initiated fracture and the decrease of the breakdown pressure up to 22% for the experimental conditions under study. A reasonable fit between the observed fracture initiation pressure dependence on the notch depth and theoretical modeled one is also obtained.

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