Title:

Acoustic Analysis as Means for Detecting Early-Stage Hydraulic Fracture Initiation in Open and Notched Wellbores

Authors:

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Abstract:

Hydraulic fracturing has been used by the petroleum industry to access otherwise uneconomical hydrocarbon reservoirs by generating highly-conductive channels within tight-rock formations. In many instances tight formations require relatively high fracture initiation and breakdown pressures, and this work address this by placing mechanical weak points within the wellbore wall.

Large-scale hydraulic fracturing experiments were conducted on polyaxially stressed 24×18×18-in. samples of Indiana limestone to evaluate fracture growth behavior from both notched and un-notched open hole. Consolidating the acoustic emission data allowed the reconstruction of the hydraulic fracture initiation and growth processes, based on localizing the acoustic events and amplitudes from the 36 channel sensor array. These observations combined with the pressure, flow, displacement data and the post-test sample evaluation provide a comprehensive story of hydraulic fracture growth at a level of detail that cannot be obtained by downhole tools. This work enables a better understanding of fracture initiation, and how intervention can reduce breakdown pressure while minimizing near-wellbore fracture complexity.

Keywords:

Hydraulic fracture initiation, acoustic emission, openhole, notch, laboratory block test, fracture breakdown pressure, multistage fracturing, well intervention, microseismic.

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Introduction

Hydraulic fracturing has been used by the petroleum industry to access otherwise uneconomical hydrocarbon reservoirs by generating highly-conductive channels within tight-rock formations. This is illustrated in **Fig. 1** by schematic image of multiple hydraulic fractures created during the multistage stimulation treatment of the horizontal openhole wellbore which is nowadays a popular completion for tight and competent reservoir rock (Al-Naimi et al. 2008; Rahim et al. 2011).

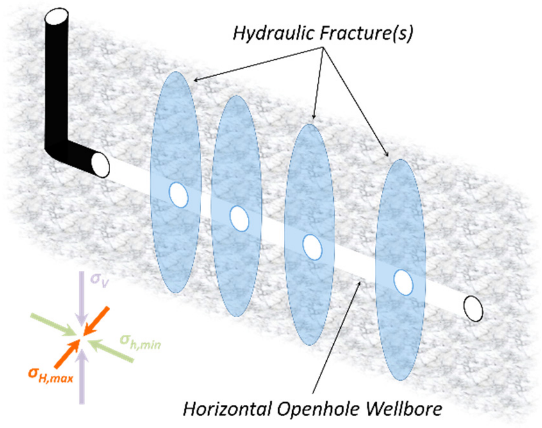


Fig. 1. Schematic image of the multistage hydraulic fracturing in horizontal openhole well.

Hydraulic fracturing in open holes comes with the several challenges. Having the wellbore oriented along the minimal far-field stress favors the transverse orientation of hydraulic fractures with respect to the wellbore which maximizes the reservoir contact area. However, this does not imply that hydraulic fractures initiate transversely at the wellbore, especially in the openhole case, due to tensile hoop stresses developed near the wellbore (Daneshy 2009; Lecampion et al. 2013). Fracture initiated longitudinally, as it re-orients into the preferred transverse direction will create undesired tortuosity near the wellbore. 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. Also, in many instances mechanically competent formations require relatively high fracture initiation and breakdown pressures, and this work considers the way to addresses this by placing notches as mechanical weak points within the wellbore wall (Chang et al. 2014; Aidagulov et al. 2016).

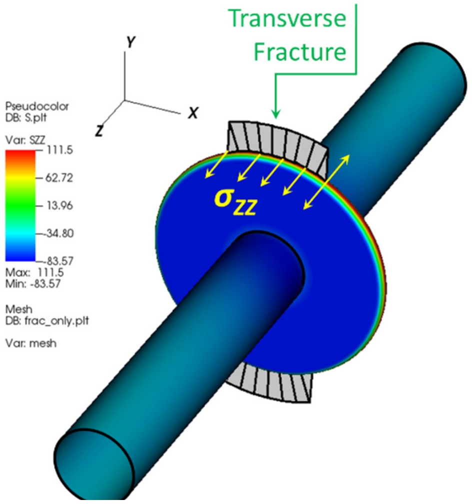


Fig. 2. Simulated axial tensile stress concentration at the notch tip which initiates transverse fracture.

Cutting a circular notch allows the initiation of the fracture in the transverse direction at the exact position of the notch and at lower breakdown pressure compared to un-notched open hole. This is demonstrated in **Fig. 2** by numerical simulation of hydraulic fracture initiation from the notched horizontal wellbore. There is a tensile axial stress concentration developed at the notch tip as borehole pressure increases during the fracturing treatment - which promotes initiation of transverse fracture at the notch location. The numerical model used here - was presented by the authors earlier (Aidagulov et al. 2015).

Large-scale hydraulic fracturing experiments were conducted on polyaxially stressed 24×18×18-in. samples of Indiana limestone to evaluate fracture growth behavior from both notched and un-notched open hole (Aidagulov et al. 2016). The present work focuses on the acoustic emission (AE) data acquired during those tests. We performed the analysis of AE data which allowed us to reconstruct the hydraulic fracture initiation and growth processes, based on localizing the acoustic events and amplitudes from the 36 channel sensor array. These observations combined with the pressure, flow, displacement data and the post-test sample evaluation provide a comprehensive story of hydraulic fracture growth at a level of detail that cannot be obtained by downhole tools. This work enables a better understanding of fracture initiation, and how intervention can reduce breakdown pressure while minimizing near-wellbore fracture complexity.

Hydraulic Fracturing Block Tests

Large-scale hydraulic fracturing experiments were conducted on polyaxially stressed 24×18×18-in. samples of Indiana limestone to evaluate fracture growth behavior from both notched and un-notched open hole (Aidagulov et al. 2016). These experiments were done inside the true triaxial stress frame installed in Schlumberger Research Center in Dhahran (**Fig. 3**). Below we summarize the key details about the conducted block tests for the sake of consistency.

Fig. 3. True triaxial stress frame used to perform hydraulic fracturing block tests.

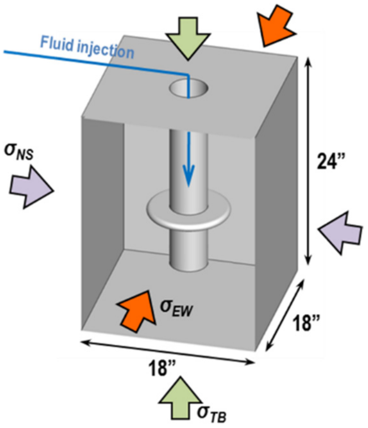


Fig. 4. Hydraulic fracturing block test. Stresses applied independently at the block in 3 directions are shown with arrows. There is a circular notch cut in the middle of the open section of the borehole.

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 true triaxial 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. 4**. 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.

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. **Table 1** summarizes the specific details for the block tests.

Rock type			Indiana limestone, 1-10 mD
Test type			Dry (non-saturated)
Block sample size, in × in × in			18 × 18 × 24
Borehole:			
		Diameter, in	1.25
		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, 1E6 cP
Fluid injection rate, mL/min			30
Applied stresses, psi:	**Lab notation**	**Field analog**	**Value**
	σ_{TB}	Horizontal minimal, $\sigma_{h,min}$	2,250
	σ_{EW}	Horizontal maximum, $\sigma_{H,max}$	3,000
	σ_{NS}	Vertical, σ_{V}	3,500

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 un-notched open holes.

Acoustic Monitoring of Fracture Initiation and Growth

Acoustic emission (AE) recorded during the hydraulic fracturing in laboratory has been successfully applied in the past to map initiation and growth of the induced fractures (Stanchits et al. 2014). In the present work AE data was acquired during each test using the array of 36 piezoelectric sensors glued to the surface of the block sample. Each sensor is to be embedded into the small pocket drilled in the rock to avoid its contact with the steel loading plate (**Fig. 5**). The waveforms from each sensor were precisely recorded using the acquisition system by Vallen Systeme GmbH. Localization of acoustic events hypocenters was performed post-test on the recorded data using the special software package by ASC.

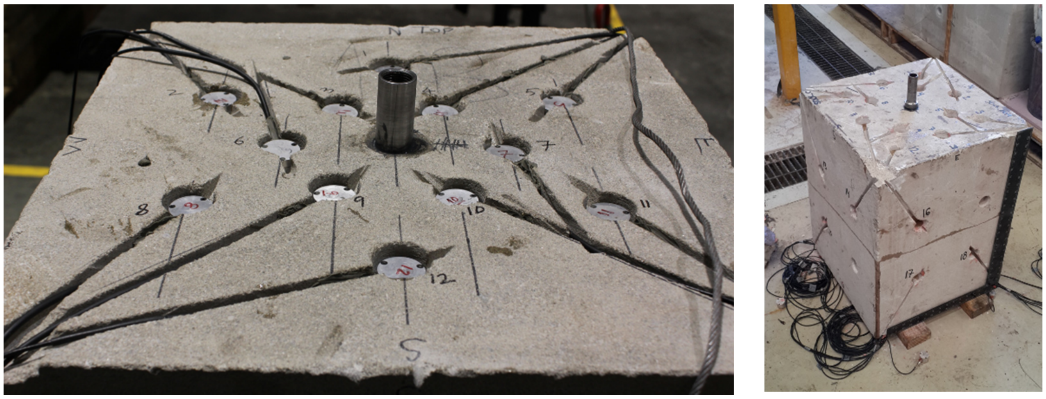


Fig. 5. Block samples with AE sensors installed.

Fracture Initiation Detection

Totally 6 block tests were performed with an objective to demonstrate repeatedly the effect of notch on initiation of hydraulic fracture from the open hole. In each data the following data was combined to provide a comprehensive story of hydraulic fracture growth (**Fig. 6**):

- Borehole pressure;
- Injected volume;
- Block face displacements;
- AE amplitude, rate, location.

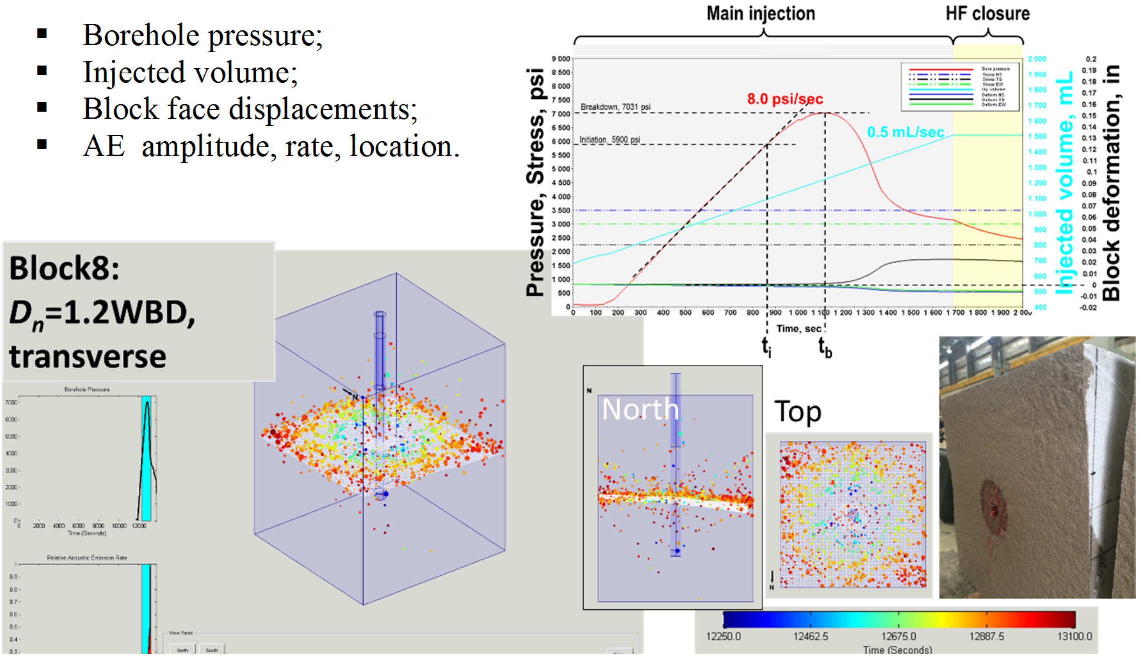


Fig. 6. Data collected in the block test: AE hypocenters localized, plotted in space and colored according to the time of the event; borehole pressure (solid red), injection rate (solid light blue), block deformation (solid black, blue, green), stresses applied to the block (dash-dot - blue, green, black). All is given by example of Block8 where transverse fracture initiated.

Block face displacements were measured by linear variable displacement transducers (LVDTs) connected to the block faces through the layers of steel loading plate, Teflon and plastic sheets served to relax any stress inhomogeneities, in case they appear at the contact with the rock. From the Fig. 6 one can see that the block deformation in TB direction (solid black curve) exceeded by far the deformations in EW (green) and NS (blue) directions in the course of injection. This was a clear indication of transverse fracture initiated during the test. However, reliable response of LVDT can not be detected till the very moment of fracture breakdown, t_b, when the borehole pressure attains its maximum. The actual initiation of hydraulic fracture (t_i) happened about 250 sec earlier when the pressure curve (solid red) started to delineate significantly from the straight line and indicated by sharp increase in AE rate was observed near the notch.

Fracture Growth

In **Fig. 7** one can see another example from the Block3 test where AE localizations were used to map the hydraulic fracture surface as it grown in time. This was the case when longitudinal fracture initiated from the un-notched open hole. Fracture surface appeared rather complex as fracture had to re-orient into the preferred fracture plane which is transverse to the wellbore. AE events hypocenters were plotted relative to the block with the color code from blue to red according to the time they occurred. Size of the bubble is related to the amplitude of the event in dB. The actual fracture surface was profiled post-test on the block cut open using the goniometer and shown in Fig. 7 as a white mesh. One can see that fracture surface obtained from the AE analysis matches well the actual surface profiled. AE analysis also indicated to the fracture branching at the bottom of the borehole which was not obvious to see only from the visual inspection of the block cut open.

Effect of Notch on Hydraulic Fracture Initiation

All the 6 block tests reported in the present work were performed with the AE data recorded and processed. This enabled a better understanding of fracture initiation process which is required for estimating the fracture initiation pressure (FIP). The conducted experiments shown clearly positive effect of the circular notch on decreasing the fracture breakdown pressure and minimizing near-wellbore fracture complexity.

In **Fig. 8** one can see the plots of borehole pressure recorded during the hydraulic fracturing experiments representing the cases of un-notched open hole (Block2 & 3) and single circular notch cut in the center of the open section to the depth of 1.5 wellbore diameter (WBD, Block4 & 6). The results of the repeated test conditions coincided remarkably demonstrating the 22% reduction in the fracture breakdown pressure (FBP) caused only by the notch placed in the wellbore.

Shallower notch depth of 1.2×WBD was also tried in the tests Block7 & 8. This notch depth also appeared to be sufficient to initiate transverse hydraulic fracture with FIP and FBP being a bit higher than in the case of 1.5×WBD deep notch but still significantly lower compared with the un-notched wellbore. This is shown in **Fig. 9** where FIP (marked with triangles) and FBP (marked with circles) are plotted as a function of notch depth having the un-notched wellbore corresponding to the zero depth notch. Pressure values are marked with color having green to represent transverse fracture and red – longitudinal fracture initiated. Up to 34% reduction in FIP caused by the notch has to be noted here.

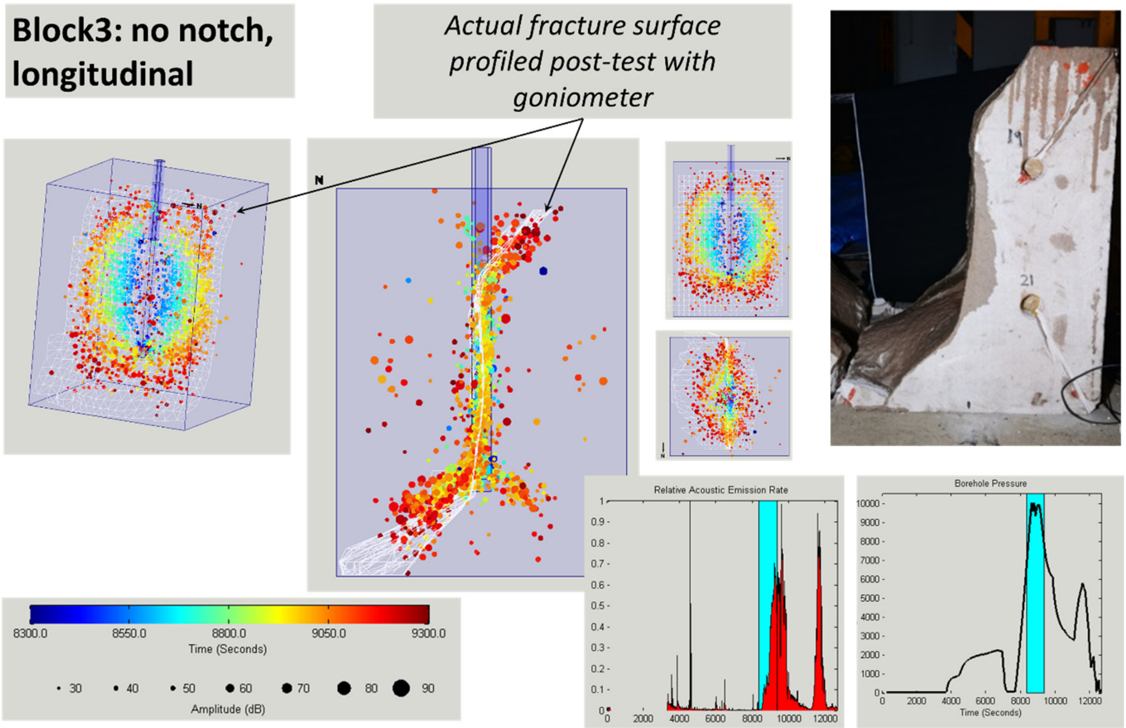
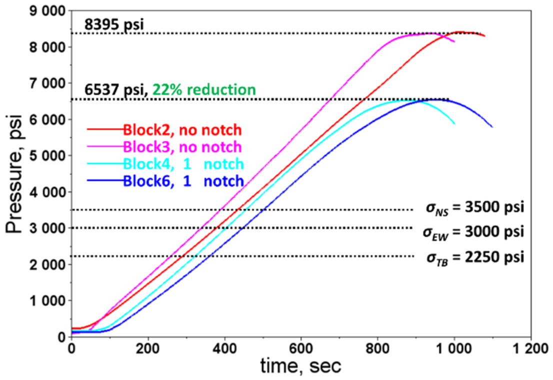


Fig. 7. AE data analysis performed for the test Block3 where longitudinal fracture initiated from the un-notched open hole. The localized AE events revealed the fracture surface as it grown with time with dots colored from blue to red accordingly to the time of the event. The fracture surface obtained from AE analysis matched well the actual surface observed on the block post-test.



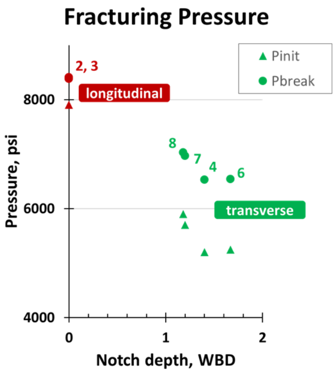


Fig. 8. Hydraulic fracturing block tests. Borehole pressure as a function of time. Breakdown pressure reduction by a notch is shown.

Fig. 9. Fracture initiation (Pinit) and fracture breakdown (Pbreak) pressures as a function of notch depth.

Conclusions

In the presented work it was demonstrated how the processing the acoustic emission data recorded during the hydraulic fracturing block testing experiments allowed the reconstruction of the hydraulic fracture initiation and growth processes which otherwise cannot be understood based solely on the post-test sample evaluation, pressure, flow and displacement data. Knowing a comprehensive story of hydraulic fracture growth was a great help in experimental studies of the effect of notch on initiation of hydraulic fractures from the openhole wellbores. Specifically, reduction up to 22% in fracture breakdown pressure while minimizing near-wellbore fracture complexity caused by notch was repeatedly demonstrated in the tests.

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References

Aidagulov, G., Alekseenko, O., Chang, F.F. et al. 2015. Model of Hydraulic Fracture Initiation from the Notched Open Hole, Presented at the SPE Saudi Arabia Section Annual Technical Symposium and Exhibition, Al-Khobar, Saudi Arabia, 21-23 April. SPE-178027-MS. http://dx.doi.org/10.2118/178027-MS.

Aidagulov, G., Edelman, E. and Brady, D. 2016. Notching as a New Promising Well Intervention Technique to Control Hydraulic Fracturing in Horizontal Open Holes. Presented at the 12th Middle East Geosciences Conference and Exhibition: Geo2016, Manama, Bahrain, 7-10 March.

Chang, F., Bartko. K., Dyer, S.et al. 2014. Multiple Fracture Initiation in Openhole without Mechanical Isolation: The First Step to Fulfill an Ambition. Presented at the SPE Hydraulic Fracture Technology Conference, The Woodlands, Texas, USA, 4-6 February. SPE-168638-MS. http://dx.doi.org/10.2118/168638-MS.

Daneshy, A. 2009. Horizontal-Well Fracturing: Why Is it So Different? *J Pet Technol* **61** (9): 28–35. SPE-0909-0028-JPT. http://dx.doi.org/10.2118/0909-0028-JPT.

Lecampion, B., Abbas, S. and Prioul, R. 2013. Competition between transverse and axial hydraulic fractures in a horizontal well. Presented at the SPE Hydraulic Fracturing Technology Conference, 4-6 February, Woodlands, TX, USA. SPE-163848-MS. http://dx.doi.org/10.2118/163848-MS.

Al-Naimi, K. M., Lee, B. O., Bartko, K. M., et al. 2008. Application of a Novel Open Hole Horizontal Well Completion in Saudi Arabia. Presented at the SPE Indian Oil and Gas Technical Conference and Exhibition, Mumbai, India, 4–6 March. SPE-113553-MS. http://dx.doi.org/10.2118/113553-MS.

Rahim, Z., Al-Kanaan, A., Johnston, B. et al. 2011. Success Criteria for Multistage Fracturing of Tight Gas in Saudi Arabia. Presented at the SPE/DGS Saudi Arabia Section Technical Symposium and Exhibition, Al-Khobar, Saudi Arabia, 15–18 May. SPE-149064-MS. http://dx.doi.org/10.2118/149064-MS.

Stanchits, S., Surdi, A., Gathogo, P. et al. 2014. Onset of Hydraulic Fracture Initiation Monitored by Acoustic Emission and Volumetric Deformation Measurements. *Rock Mech Rock Eng* **47**:1521–1532. http://dx.doi.org/10.1007/s00603-014-0584-y.