Modeling viscous fluid-induced fracture propagation in the compression field

IV Kolykhalov
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: ikolykhalov@mail.ru

Abstract. The paper describes the experimental studies into viscous fluid-induced fracture growth from the initially circular crack in the field of compression. The experimental relations between the induced fracture shape and viscosity and injection rate of pressure fluid are obtained. The influence of the pressure fluid properties on the induced fracture parameters is analyzed.

1. Introduction
Hydraulic fracturing is one of the highly efficient methods of enhanced hydrocarbon recovery from oil and gas wells and for stimulation of well injectivity. In this method, highly conductive fractures are induced in a reservoir to ensure oil/gas inflow to well bottom. Hydraulic fracturing allows enhanced well flow rate when conventional methods of oil and gas production are low effective [1]. Moreover, application of hydraulic fracturing enables mineral mining without mine construction, with hydrocarbon recovery from low-permeable and nonuniform reservoirs, production of high-viscous oil and coalbed methane drainage [2, 3]. Hydraulic fracturing is also widely used in assessment of natural tresses in rock mass [4].

Efficiency of hydraulic fracturing depends on many factors, such as spatial orientation, shape and size of induced fractures, producing characteristics of wells before hydraulic fracturing, characteristics of bottomhole formation zone, and reservoir properties (nonuniformity, volume of effective pay, geometry and physical layout of impermeable strata) [5]. The spatial orientation is the only factor that can be influenced. Creation of fractures of the required shape and size is necessary in multi-stage hydraulic fracturing of low-permeable and nonuniform reservoirs, and in production of low-viscous oil, in order that the induced fractures embrace the entire pay zone. Geometry of an induced fracture is considerably governed by difference of principal stresses, occurrence of closely spaced created and natural fractures, which can cause additional stress fields, as well as the properties and injection regime of pressure fluid [6]. The properties and injection regime of pressure fluid can play the dominant role in this case [7]. This study describes experimental modeling of nonrectilinear growth of a circular induced fracture under the action of viscous fluid in the field of uniaxial compression. The influence of viscosity and injection rate of pressure fluid on the geometry and symmetry of the induced fracture is of specific concern.

2. Experimental procedure
The hydraulic fracturing tests were carried out on a special uniaxial loading test bench. The test bench represents three metal plates with eight uniformly spread peep holes. Two plates are held rigidly parallel to each other by bolt pins, while the third plate in-between is movable (Figure 1).
Figure 1. Test bench: (a) scheme and (b) physical appearance; 1—sample made of organic glass; 2—peep holes, camera for recording projections of induced fracture shape on the plane of incipient crack; 3—dynamometer; 4— injection facility; 5—well; 6—incipient crack; 7—metal plates; 8—bolt pin.

Loading was performed using a screw and dynamometer DOSM ДОСМ-3-50. The test reservoir was simulated by cylinder blocks 260×260×110 mm in size made of polymethyl methacrylate (grade TOSN, State Standard GOST 17622-72). In the center of the block, a hole was drilled to simulate a well and was thread-joined with breakdown fluid feed system. The pressure fluid was water solution of glycerin CAS No 56-81-5 and tinting paste manufactured as per specifications TS 2332-014-76174671-2005. The fluid of the known viscosity was fed at the present flow rate. The fluid viscosity was measured using viscometers VPZH-4. The fluid pressure and the induced fracture shape were estimated during the tests.

The test specimen was a block with a hole drilled to a depth of 55 mm, and with an incipient cut with a radius of 6 mm. The cut was elongated to a radius of 12–14 mm using a plastic material. The elongation is required to prevent creation of a longitudinal fracture under the pressure fluid feed. Hydraulic fracturing was performed until the induced fracture reached the surface of the test block. The compression stress was $\sigma_z = 0.57$ MPa.

3. Results and discussion

Figure 2 shows the test specimens after the tests. The induced fractures look similarly, with wings oriented to different sides. When a test block is split along the hole, with two mutually perpendicular planes, it is possible to select such arrangement that wings of the fracture on one plane have the trajectories curved along the action of the maximum compression stress, while the trajectories on the other plane are rectilinear (dashed line in Figure 2). The comparison of the fracture shapes induced by fluids of different viscosity and injected at different rates shows that the fracture is asymmetrical relative to the dashed line in case of the fluid of lower viscosity. The area of the fracture above the dashed line is much larger than above the line in Figure 2a. This difference is smaller in Figure 2b.

In case of using the ideal pressure fluid, the induced fracture growth is unstable. The instability consists in small deflections from the circular shape of the initial crack, and these deflections undamp due to the influence of external factors, such as the nonuniformity of the medium, stresses around the fracture, and the fracture symmetry totally disappears. This phenomenon is observed in multi-stage hydraulic fracturing when the induced fractures create a nonuniform stress field. This instability is eliminated using a plastic material instead of the pressure fluid [8]. A viscous incompressible fluid has intermediate properties between an ideal fluid ($\mu_0 = 0$) and a plastic material, which is illustrated in Figure 2. The viscosity in the latter case in 11 times as high as in the former case, and the effect of stabilization (suppression of instability in the fracture growth process) is apparent. For example, the distances between the farthest point of the fracture front and the hole center on their projections from
the specimen surface are 96 and 50 mm in case of $\mu_0 = 70 \text{ MPa} \cdot \text{s}$ and are 71 and 57 mm in case of $\mu_0 = 670 \text{ MPa} \cdot \text{s}$.

![Figure 2](image)

**Figure 2.** Induced fractures in the test specimens: (a) $\mu_0 = 70 \text{ MPa} \cdot \text{s}, q_0 = 0.65 \cdot 10^{-6} \text{ m}^3/\text{s}$; (b) $\mu_0 = 670 \text{ MPa} \cdot \text{s}, q_0 = 0.75 \cdot 10^{-6} \text{ m}^3/\text{s}$.

For the comparison of the experimental results, we calculated numerically the growth of an axially symmetric fracture and a flat fracture [7] in the uniaxial compression field. The calculations used the programs developed by the displacement discontinuity method [9]. The problem of viscous fluid flow along the crack used the hypothesis from [1] that the effective normal stresses on the edges of the fracture were proportional to the normal displacements of these edges. This approximation in combination with the momentum equation yields a differential equation for pressure distribution in viscous fluid under injection along the fracture:

$$
\frac{\partial \Delta p_k(s,t)}{\partial s} - \frac{\partial \sigma_k(s,t)}{\partial s} = \frac{3\pi^2 \mu_0 q_0 E^3}{4^3 (1 - \nu^2)^3} \frac{1}{\Delta p_k^3(s,t) R_k^3(t)} 
$$

(axially symmetric problem),

$$
\frac{\partial \Delta p_k(s,t)}{\partial s} - \frac{\partial \sigma_k(s,t)}{\partial s} = \frac{3 \mu_0 q_0 E^3}{16 (1 - \nu^2)^3} \frac{1}{\Delta p_k^3(s,t) R_k^3(t)} 
$$

(plane problem),

where $\mu_0$ is the dynamic viscosity of fluid; $q_0$ is the fluid flow rate; $\sigma_k(s,t)$ is the sum of normal stresses generated on the fracture edges by external compression; $\Delta p_k(s,t)$ is the effective prop pressure inside the fracture; $s$ is the distance along the fracture length to the points of the maximum deflection. With these assumptions made, the computational resources are saved, and the accuracy of the description of the viscous fluid flow inside the fracture is affected insignificantly. The other parameters involved in the computation were: Young’s modulus and Poisson’s ratio of organic glass $E = 3.3 \cdot 10^9 \text{ MPa}$ and $\nu = 0.3$, the critical stress intensity factor $K_{lc} = 14 \text{ MPa} \cdot \text{s}$.

**Table 1.** Experiment and calculation data on growth of axially symmetric and flat induced fractures

| Description                          | $\mu_0 = 70 \text{ MPa} \cdot \text{s}, q_0 = 0.65 \cdot 10^{-6} \text{ m}^3/\text{s}$ | $\mu_0 = 670 \text{ MPa} \cdot \text{s}, q_0 = 0.75 \cdot 10^{-6} \text{ m}^3/\text{s}$ |
|--------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| $p(0,0)$, MPa                        | $\Delta^+_{\text{max}}(s)$, mm, $s = 50$ mm                                      | $\Delta^+_{\text{max}}(s)$, mm, $s = 57$ mm                                     |
| Experiment                           | 13.8                                                                              | 20.3                                                                             |
| Calculation for axially symmetric fracture | 13.56                                                                       | 19.74                                                                          |
|                                      | 33                                                                                 | 55                                                                               |
|                                      | $-39$                                                                              | $-43$                                                                            |
|                                      | 16.3                                                                               | 16.6                                                                             |
|                                      | $19$                                                                               | $17.5$                                                                           |
Calculation for flat fracture

| Calculation for flat fracture | 10.61 | 31.4 | −41.7 | 16.36 | 50.8 | −44.9 |

Table 1 gives the calculated values: $p(0,0)$ is the pressure in the hole at the moment of the fracture growth onset; $\Delta^\text{max}_+ \text{ and } \Delta^\text{max}_-$ are the maximum deflections of the fracture along the compression axis from the plane perpendicular to this axis and intersecting the incipient crack.

The comparison of the theory and test data shows that the axially symmetric fracture calculations describe more accurately the fracture growth in the uniaxial compression field at the early stage when the fracture is yet unturned along the action of the maximum stress. At the later stages of the induced fracture propagation, the flat fracture calculation offers the results which are the closest to the experimental data.

4. Conclusions
Curvilinear propagation of an initially circular induced fracture under the action of viscous fluid is experimentally examined in tests of organic glass specimens subjected to uniaxial compression along the fracture axis. It is found that the viscosity and injection rate of the pressure fluid has influence on the shape of the induced fractures: in case of higher viscous fluid, the induced fracture trajectories is less deviated from the rectilinear line and the fracture asymmetry relative to the well is weaker as against the ideal pressure fluid. The test data are compared with the computation results.

Acknowledgements
The study was supported by the Russian Foundation for Basic Research, Project No. 18-35-00295.

References
[1] Almukhametova EM, Vorsina NA and Syrtlanov OV 2013 Effective application of hydraulic fracturing in the Pokhovskoe oilfield Problems of Gathering, Treatment, Preparation and Transportation of Oil and Oil Products No 3 pp 23–29
[2] Klishin VI, Kurelnya MV and Pisarenko MV 2013 Improvement of technologies and methods of ground control in rock mass using hydraulic fracturing Mining Informational and Analytical Bulletin—MIAB Special Issue 6 pp 23–35
[3] Khalimov IU and Tursunova SU 2016 Improving the efficiency of in-situ leaching of uranium by hydraulic fracturing Mining Informational and Analytical Bulletin—MIAB No 11 pp 334–339
[4] Panov AV, Skulkin AA, Tsibizov LV and Rodin RI 2016 In situ stress evaluation by solving inverse problem based on hydrofracturing stress measurements Mining Informational and Analytical Bulletin—MIAB No 6 pp 381–388
[5] Cherny SG, Lapin VN, Esipov DV and Kuranakov DS 2016 Improving the efficiency of in-situ leaching of uranium by hydraulic fracturing Computational Continuum Mechanics Vol 8 No 2 pp 208–218
[6] Smetannikov OYu, Kashnikov YuA, Ashihmin SG and Shustov DV 2015 Numerical model of crack growth in hydraulic re-fracturing Journal of Mining Science Vol 52 No 4 pp 662–669
[7] Kolykhalov IV, Martynyuk PA and Sher EN 2016 Modeling fracture growth under multiple hydraulic fracturing using viscous fluid Journal of Mining Science Vol 52 No 4 pp 662–669
[8] Kolykhalov IV 2018 Physical modeling of axisymmetric hydrofracturing by plastic material injection in elastic medium IOP Conference Series: Earth and Environmental Science Vol 134
[9] Crouch SL and Starfield AM 1983 Boundary Element Methods in Solid Mechanics London: Allen and Unwin
[10] Linkov AM 2008 Numerical modeling of fluid flow and a hydraulically induced fracture propagation Journal of Mining Science Vol 44 No 1 pp 24–42