Introduction

Hydraulic fracturing is an impact on the productive reservoir by pumping a fluid into it under high pressure. In addition to increasing the productivity of the field, the results of this method are used to determine some important characteristics of the developed reservoirs using the pressure curves of fracturing, such as the pressure of the fracture closure, rock permeability and the initial pore pressure in the formation. Furthermore, the hydraulic fracturing is considered as the main way to determine the minimal tectonic stress of the reservoir (Koning et al., 1985), which is one of the necessary parameters for geomechanical models of oil or gas fields.

Most of the currently used methods for determining the reservoir permeability require additional procedures in the field for an extended period of time (Asalkhuzina et al., 2016). In the case of low-permeable reservoir developments, this procedure may have significant financial costs. So, it becomes reasonable to search methods of mini hydraulic fracturing data analysis, which will reveal the necessary characteristics of the reservoir without affecting the field development process.

The main goal of the presented work is to analyze the pressure curves obtained in laboratory experiments on mini hydraulic fracturing. The exact aims are to determine the fracture closure pressure and to compare it with the known minimal stress applied to the laboratory sample; to calculate the permeability of the model sample and also to compare it with real permeability that is known from the laboratory measurements.

Experimental setup

A special experimental setup was assembled for modelling the processes associated with fracturing (Trimonova et al., 2017) (Figure 1). The fracture was created by pumping viscous fluid through the preliminary created cased borehole with perforations at a constant rate. The pressure change in the borehole is recorded through the whole experiment. Because the fracture was not fixed by proppant, these experiments were more similar to the mini hydraulic fracturing process. The setup consists of two steel covers and a ring between them to form a chamber for pouring specially prepared material that simulates the formation in which the fracture occurs and propagates. The diameter of the working chamber is 43 cm and the height is 6.6 cm.

![Figure 1](image)

**Figure 1** Scheme of the experimental setup, where $\sigma_1$ and $\sigma_2$ are horizontal loads applied to the model sample and $\sigma_3$ is vertical load applied to the model sample.

The setup is arranged in such a way that three-axis loads can be applied to the studied sample by pumping fluid or gas under a certain pressure through the special upper and side thin cameras.

The hydraulic fracturing experiment conducts in several stages. Initially, a mixture of gypsum and cement is prepared to create a model sample. This material was chosen according to similarity criteria...
(Trimonova et al., 2017), which were deduced with the help of preliminary measurements of both the elastic modulus of the material and the filtration characteristics, including the permeability that was equal to 2 mD. The next stage is pouring the mixture into the setup. After the solidification of the modeling material, it is saturated with the fluid of lower viscosity then that used for fracturing. Then, the fracturing fluid is pumped into the central borehole. An example of the curve of the pressure versus time recorded during this experiment is shown in Figure 2a.

The method

Initially, the G-function technique was used for analyzing the pressure-time dependence (Nolte, 1979), which allows to determine the time of the fracture closure, and, accordingly, the pressure of the fracture closure. This technique analyzes experimental data by plotting the following dependencies: the pressure versus the G-function, the first derivative of the pressure versus G-function and semi-logarithmic derivative of the pressure versus G-function. The specific mutual behavior of these curves helps to determine the time and the pressure of the fracture closure.

The dependence of the pressure on the G-function in this technique is derived from the continuity equation. The G-function equation has the following form (1):

$$G(t,t_0) = \frac{16}{3\pi} \left[ \left( 1 + \frac{t-t_0}{t_0} \right)^{3/2} - \left( \frac{t-t_0}{t_0} \right)^{3/2} \right] - 1,$$

where $t_0$ - the injection shut-in time; $t$ - current time.

The second stage of the obtained pressure curves analyzing was the application of the method for the permeability determination (Nolte et al., 1997). This method examines a formation in which the fracture has already closed and the radial flow regime of the fluid has been established. At the same time, it is considered that possible minimal leaks from closed crack are negligibly small. Thus, the dependence of the pressure on time has the form (2):

$$p_w = p_i + \frac{q\mu}{4\pi k h} \ln \left( 1 + \frac{16t_c}{\pi^2(t-t_c)} \right),$$

where $p_w$ - the pressure in the well; $p_i$ - the initial pressure in the model sample; $t$ - current time; $t_c$ - time of the fracture closure; $q$ - the rate of rapture fluid injection into the formation; $\mu$ - the viscosity of the rapture fluid; $k$ - the permeability of the model sample; $h$ - the height of the model sample.

The expression obtained above is simplified by introducing a new dimensionless time function $F(t,t_c)$. The equation is written in the form (3):

$$p_w - p_i = \frac{q\mu}{4\pi k h} F(t,t_c),$$

From the obtained linear dependence of the pressure in the well in the model sample on the dimensionless function time, the permeability is expressed.

Data Analysis

Results of the six experiments were analysed. Here is an example of the analysis of one of these experiments. In the analysed experiment, a minimal vertical load of 0.9 MPa was applied to the model sample, while horizontal loads were 1.5 MPa.

After conducting the hydraulic fracturing experiment, the pressure-time dependence was obtained (Figure 2a).
Before processing, the pressure-time dependence curve was smoothed. Then the G-function technique was applied to it (Figure 2b). The analysis was carried out from the moment the injection was stopped until the end of the recording. During this period, it was considered that leaks into the formation from the fracture occur at a constant rate.

According to the G-function technique, the semi-logarithmic derivative of pressure in the initial period of time behaves like a straight line passing through the origin. The time of the fracture closure is determined at the moment of deviation of this curve from such typical behaviour. According to Castillo (Castillo, 1987), additional verification of the result is performed by the behaviour of the first derivative – it must have the form of a straight horizontal line at this time interval.

As a result, the value of the time of the fracture closure was obtained, which is equal to 210 seconds. This value corresponds to the pressure of the fracture closure that is equal to 1.1 MPa. The estimated value differs from the minimal vertical stress corresponding to the vertical load applied to the sample under experimental conditions.

After that, the permeability of the model sample was also calculated. The obtained value was equal to 56 mD, which exceeds the known value of the experimental sample permeability equal to 2 mD.

**Results**

Here are the results of the analysis of all six conducted experiments (Table 1).

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Time of the fracture closure, sec</th>
<th>Pressure of the fracture closure, MPa</th>
<th>Minimal stress on the sample, MPa</th>
<th>Permeability, mD</th>
</tr>
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<td>1</td>
<td>308.7</td>
<td>4.9</td>
<td>0.6</td>
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<td>2</td>
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<td>5.5</td>
<td>0.6</td>
<td>14</td>
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<td>3</td>
<td>209.9</td>
<td>1.1</td>
<td>0.9</td>
<td>56</td>
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<tr>
<td>4</td>
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<td>4.8</td>
<td>0.8</td>
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<td>5</td>
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<td>0.3</td>
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<td>6</td>
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<td>3.8</td>
<td>0.5</td>
<td>13</td>
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</tbody>
</table>

**Table 1 Results of processing the curves obtained during series of laboratory experiments.**

It should be noted, that there are large differences between the values of the minimal stress and the pressure of the fracture closure obtained experimentally and theoretically. That discrepancies in the
values may be explained by the possible presence of back-stress, that was caused by the filtration of the fluid from the fracture to the reservoir. Also, the differences in values could probably arise due to some possible plastic effects in the model sample, because preliminary experiments on a gypsum sample showed that this material exhibits plastic properties under load.

The fact, that the experimentally and theoretically calculated permeability values are significantly differed, may be explained by not completely closed fracture in the model sample.

Conclusions

As a result of the work, data from a laboratory mini hydraulic fracturing experiment was analysed and the values of fracture closure pressure and permeability of the model sample were obtained.

The calculated theoretically values were compared with experimentally obtained values, and significant deviations in theoretical calculations were found.

Difference in the values of the minimal stress applied to the sample and the pressure of the fracture closure found using the G-function technique casts doubt on the theory where the pressure of the fracture closure is equal to the minimal tectonic stress of the developed oil or gas field.

The differences in the experimentally and theoretically calculated permeability values are most likely caused by the fact that the fracture was not completely closed. It leads to the conclusion that the neglect of an open fracture significantly affects the establishment of the flow regime and calculation of the value of permeability, the most important characteristic of the developed field.

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References


