Simulation of proppant flowback from hydraulic fractures

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Abstract. Hydraulic fracturing has become one of the main and most effective methods of intensifying oil production. A method of bench-scale study with the use of modern measuring equipment, automation of experimental variable measurements according to specified algorithms ensuring high-level works was developed in order to obtain reliable data on proppant migration in a fracture. The laboratory facility makes it possible to determine the speed of proppant flowback from a fracture, proppant permeability depending on layer elevation. The tests show the nature of permeability change as the pressure increases. The conditions under which the height of a filling layer varies depending on pressure were identified. The test bench greatly facilitates and accelerates the experiments. The use of modern information and measurement systems makes it possible to significantly increase the volume of received information and improve its quality. The use of experimental results obtained through hydraulic fracturing will allow for additional increase in hydrocarbon production.

1. Introduction
Hydraulic fracturing (HF) is currently the most efficient well intervention (WI) ensuring multiple increase of oil production and development efficiency improvement of low-permeable reservoirs [1-3]. The expanded application of HF has led to an increase in consumables, including proppants, which are the main components in the technological complex of this method [4-5].

Today in Russia there are many types of proppants. They have different properties. Quite often proppant manufacturers when demonstrating the advantages of proppant try to hide the disadvantages of their products, and oil and service companies having no necessary equipment to test proppants cannot assess the purchased product in a timely manner [6]. Incorrect choice of proppant can lead to problems when fixing the HF fractures.

A method of bench-scale study with the use of modern measuring equipment, automation of experimental variable measurements according to specified algorithms ensuring high-level works was developed in order to obtain reliable data on proppant migration in a fracture. A test bench was developed to study the proppant migration from hydraulic fractures.

This laboratory facility makes it possible to determine the speed of proppant flowback from a fracture, proppant permeability depending on layer elevation. Proppants were tested using modern equipment:
- optical microscopy systems;
- electronic analytical balance;
- bench unit to measure hydrodynamic characteristics of proppants;
- filter or testing sieve.

The test bench greatly facilitates and accelerates the experiments. The use of modern information and measurement systems makes it possible to significantly increase the volume of received information and improve its quality.

During experimental studies according to the proposed method, a fracture filler is first selected. Depending on the study objectives, sand, various types of proppants and other fillers may be used.

2. Materials and methods

The proppant conductivity system was designed to obtain data that allow assessing the efficiency of proppant during HF. In this unit, the experiment was conducted at various pressures and temperatures that model formation conditions. Permeability of proppant is determined at different flow rates and pressure drops [7].

Figure 1 shows the layout of proppant conductivity test unit.

A conductivity cell (Figure 2, 3) – the cell is made of metal. The cell is designed for compression pressures of up to 80 MPa. Two parts of a rock are placed in the cell, the space between which models a fracture. The cell design allows pressure monitoring during fluid filtration through proppant fracture.

The core used in the test represents a 0.5 cm sandstone tile treated to the cell size. The elasticity modulus of a test piece was about 25,000 MPa and permeability of about 0.25 μm²*10⁻³. The rock is insulated with high temperature seals.

Pressure is provided by a small press. The press ensures the compression pressure from 5 to 80 MPa. The load increases at 0.5 MPa per minute, which can be seen with a pressure gauge mounted in a hydraulic line. The use of the press also allows for proppant destruction experiments.

The supply is ensured by a hydraulic booster and a reservoir. Cell inlets and outlets are equipped with mesh filters.

The width of samples is determined by micrometers. The average value is used for calculations. The obtained width is included into the computer and used in the calculation of experimental findings.
Throughout the test, the liquid flow is weighed using an electronic balance. Using the density of the sample, the flow rate is calculated. All data from the balance are recorded.

The temperature of the cells was controlled by the liquid flow through the heated proppant column. To avoid heat losses, all equipment is isolated.

During the experiment, it is necessary to measure the pressure parameters – differential pressure along the length of the measurement unit and compression pressure. The pressure drop in the cells is measured using a water column of known height to set the required interval. The zero mark is checked before each data read, and the interval is checked periodically.

![Figure 2. Filter cell configuration](image)

**Figure 2.** Filter cell configuration

![Figure 3. Conductivity cell](image)

**Figure 3.** Conductivity cell

The schematic diagram of the bench is shown in Figure 4.

The unit consists of a body 1 (a bench itself) made in the form of a cylinder 2, in an axial channel 3 of which there are two pistons 4, with a gap 5, in which wedging layer – proppant – is located. Gap 5 simulates a rock fracture. Cylinder body 2 has transverse slots isolated by branch pipes 6 with swivel nuts 7. Filter 8 is installed in an outlet branch pipe 6 for collection of released proppant particles. Axial
channel 3 of cylinder 2 is covered from above and from below by caps 9 in which adjusting screws 10 are installed. A binding unit and a power drive of the bench are shown in Figure 5.

Figure 4. Test bench design

Figure 5. Binding unit and power drive
To ensure the supply of the working fluid under pressure (at preset flow rate) into a gap 5, the power hydraulic cylinder 11 is designed, which represents a chamber 12. The chamber 12 is closed hermetically from above and from below by caps 13 in which chokes 14, 15, 16 are installed. The axial channel of chamber 12 accommodates a power piston 17 with a rod 18. The choke 14 is connected through a hose 19 with high pressure source representing inert gas bottle.

A three-way valve 20 is installed on a gas high pressure line. The choke 15 is connected through a valve 21, a flow regulator 22 and a valve 23 with an inlet branch pipe 6 of a bench 1. The outlet 6 of a bench 1 is connected through high-pressure tube to a reservoir 24 through a valve 25. The outlet 26 of the reservoir 24 is connected via high-pressure tube 27 to a choke 16 on a lower cap 13.

Unit operation

When valves 25 and 23 are closed, pistons 4 are installed into reservoir 24 in cylinder 2, in gap 5, between which a proppant layer of certain fraction is placed. The power piston 17 in power hydraulic cylinder 11 is in extreme upper position. With closed gate 21 a cavity 12 of power cylinder 11 is filled with working liquid by opening of gates a and b. The extreme top position of a rod 18 is controlled. Valves b and c are closed.

Valves 21 and 23 are opened with the formation of hydraulic connection of gap 6 between pistons 4 in bench 1. Valve 20 is opened from the source of high pressure of gas, with supply of the power cylinder 11 to the axial channel 12, as well as with the action on the area of power piston 17.

The movement of power piston 17 is controlled along rod 18. The flow of the working fluid through the tube with valve 21 gets through inlet branch pipe 6 of bench 1 and moves in gap 6 between pistons 4 affecting the proppant particles. Besides, proppant particles not attached in the gap migrate to the outlet branch pipe 6, where they are caught by a filter 8. After extrusion of the working fluid portion from power hydraulic cylinder 11, rod 18 is in extreme lower position. Closing a three-way valve 20 with inert gas, high pressure source is cut off and gas is released from the axial channel 12 of the power hydraulic cylinder 11 above the power piston 17. At the same time valves 23 and 25 on bench 1 are closed. The working fluid is supplied from reservoir 24 at open valves b and c, simultaneously filling axial channel 12 of power hydraulic cylinder 11 and moving power piston 17 upwards thus controlling the output of the rod 18. The cover 7 is disconnected on the outlet branch pipe 6 with removal of the filter 8 and estimation of the amount of removed proppant. The flow rate of the working fluid is ensured through the gap 6 between pistons 4, and estimation of flow rate is carried out after measurement of the gap 5 and counting the filtration area. The flow rate of the working fluid is also carried out by measuring the time of movement of the power piston 17, together with the rod 18, with recalculation of flow speed parameters in the gap 6. After installation of pistons (4) in the bench 1, the preparatory works are carried out for the next test cycle. The operation can be carried out with different fractional composition of proppant particles, simulating different flow rates in the gap 6, and estimating the results associated with proppant particles deposited in the filter 8.

By changing the flow rate of the inert gas it is possible to simulate the different flow rates of the working fluid through the gap 6 between the pistons 4. Test and measuring tools of the bench shall provide measurements of pressure, temperature, supply and head of the pump.

Since the studies are based on a closed cycle of circulation of the working fluid, it gradually heats up and its viscosity decreases. Fracture parameters are measured by the measuring system in continuous mode at a temperature varying over time.

3. Research results

Russian oil workers use proppants of four fractions to secure the HF fracture, of which two are the main fractions: 16/20, 12/18 and two auxiliary fractions: 16/30 and 20/40. The choice of the desired size of proppant grains is determined by a whole set of factors. The larger the granules, the more permeable the proppant package in the fracture. However, the use of a large fraction proppant has additional problems when it is transported along the fracture [8]. This study examined the proppant of fraction 16/20. For the first tests 5 samples (a), (b), (c), (d), (e) are presented on the unit. In terms of
their bulk density, proppants (b), (c), (d), (e) are considered light proppants because they have low bulk weight (less than 1.6 kg/m$^3$). Proppants (a) are medium-density.

The test results are shown in Table 1.

| Indicator                                      | A     | b     | C     | d     | e     |
|------------------------------------------------|-------|-------|-------|-------|-------|
| Crushing resistance (mass fraction of crushed granules), %, under pressure, MPa: |       |       |       |       |       |
| 7                                              | 1.5   | 11    | 5.5   | 4     | 5     |
| 14                                             | 2.5   | 15.5  | 7.5   | 5.5   | 8.5   |
| 28                                             | 7     | 25    | 17    | 11    | 15.5  |
| 42                                             | 12    | 31    | 30    | 18    | 19    |
| 49                                             | 16.5  | 38    | 37.5  | 27    | 23    |
| Filter residue, %:                             |       |       |       |       |       |
| No. 1 (4.5 mm)                                 | 6     | 4     | 2.5   | 3.5   | 0.5   |
| No. 2 (5 mm)                                   | 9     | 6     | 4     | 5     | 2     |
| No. 3 (5.5 mm)                                 | 14    | 11    | 7     | 9     | 6     |
| No. 4 (6.0 mm)                                 | 20    | 24    | 15    | 19    | 10    |
| No. 5 (6.5 mm)                                 | 26    | 26    | 19    | 23    | 15    |
| No. 6 (7.0 mm)                                 | 30    | 32    | 25    | 28    | 18    |
| No. 7 (7.5 mm)                                 | 44    | 39    | 31    | 31    | 21    |
| Sphericity                                     | 0.9   | 0.9   | 0.9   | 1     | 0.9   |
| Circularity                                    | 0.8   | 0.9   | 0.9   | 0.9   | 0.9   |
| Packing density, g/cm$^3$                       | 1.8   | 1.55  | 1.4   | 1.5   | 1.3   |

The measurements of hydrodynamic characteristics of proppants – permeability, layer width depending on pressure are shown in Figures 6, 7. The experiment showed that proppant (a) had the best permeability of the package, then in descending order (b), (c), (d) and (e) (Figure 6). The permeability of proppant (e) was very low at high pressure. The reduction in the height of the proppant layer (Figure 7) shows the fraction of broken particles, i.e. the ability to withstand loads. The permeability and conductivity of the package is reduced due to the height of the proppant layer and the reduction in the number of filter pores. According to Figure 7, it can be noted that a larger number of granules were broken down with pressure increase (decrease of the layer height), thereby significantly reducing permeability and conductivity of the proppant package [9].

![Figure 6. Permeability of proppant pack depending on pressure](image-url)
4. Conclusion
1. Light proppants do not always meet consumers’ expectations. The studies showed that a decrease in the weight of light proppants (b), (c), (d), (e) used for HF leads to a significant decrease in the permeability of their packaging compared to the medium-strength proppant (a).
2. As the fracture closing pressure increases, the permeability and conductivity of the proppant pack decreases. The main peculiarity if the general change in conductivity as the pressure increases.
3. The developed test bench was introduced into the training process at the Institute of Oil and Gas of the North Caucasus Federal University to test various types of proppants.

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