Automation of works on a bench to choose the optimal parameters of devices in case of pulsed non-stationary flooding of hydrocarbon reservoirs

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Abstract. The bench was developed in the Laboratory of Hydraulic Devices at the Department of Oil Field Machines and Equipment, which allows creating conditions close to the bottomhole conditions of any well. Laboratory-experimental studies conducted at the bench included two stages: a) study of output parameters and the corresponding selection of optimal design parameters of the developed devices; b) study of the influence of pressure and frequency of fluid pulses on the penetration of working fluid in sand samples.

1. Introduction
The issues related to the development of the wave impact technology on the bottomhole zone of wells and formation may be successfully solved only with an objective understanding of the mechanism of action taking into account the real conditions of the process, as well as with the scientifically based choice of the developed structures of pressure wave emitters for their effective use in processing. When solving these problems, it becomes necessary to create a universal laboratory bench, which makes it possible to study the influence of liquid fluctuation parameters on the characteristics of rock samples of the hydrocarbon deposit and to select the optimal ratio of design parameters of the developed devices.

2. Materials and methods
The proposed bench was developed in the Laboratory of Hydraulic Devices at the Department of Oil Field Machines and Equipment of the Branch of the University in the City of Oktyabrsky of Ufa State Petroleum Technological University, which allows creating conditions close to the bottomhole conditions of any well. It includes a test chamber with a holder, manifold lines, and a system of shut-off control devices, a set of instrumentation and a piston pump [1-3]. The bench, the schematic diagram of which is shown in Figure 1, consists of a column 1 installed on foundation 2 with shock-absorbing gasket 3 using anchor bolts 4 and a flange nipple 5. In turn, a flexible hose 6 is connected to a flange nipple by flange connection, which is connected to double-acting piston two-cylinder pump 9 mGy 7. Column 1 has two outlets: the first one 8 for discharge of injection fluid and the second one 9 for connection of holder 10.
Fig. 1. Schematic diagram of a laboratory unit

High-pressure gate valve 11 is installed at the output of the first outlet. To measure the necessary parameters during laboratory tests, the bench design provides for the following instrumentation: pressure gauges at the inlet of the working fluid 12 and in the annulus 13, pressure strain transducers 14, which use the direct inclusion of strain gauges according to the bridge diagram, with communication channels 15. Strain transducers D16 are connected to vibration measuring equipment VI-6TN, which is designed to measure the outputs of the strain gauge and report directly to one of the galvanometers of the multichannel loop light beam oscilloscope N 041Y.4.2 through amplifier 17.

Using a light beam oscilloscope, decisions were quickly made to adjust and debug the measuring path. To present a more visible picture of the amplitude of pressure fluctuation and its regulation, the bench includes the oscilloscope S1-49 18, which receives signals from the beam oscilloscope. The vibration of the bench itself was measured using a DU-5S sensor 19. The flow rate of the working fluid was measured by a volumetric method in the calibrated vessel 20, from where, after measurement, the fluid was supplied to the receiving tank 21. The ground pressure is generated in the holder by means of a manual oil pump 22, and leakage of working fluid from each chamber of the holder was measured by the measuring tank 23.

The technical characteristics of the developed bench design are given in Table 1.

Laboratory-experimental studies conducted at the bench included two stages: a) study of output parameters and the corresponding selection of optimal design parameters of the developed devices; b) study of the influence of pressure and frequency of fluid pulses on the penetration of working fluid in sand samples.
Table 1. Technical characteristics of the bench

| Parameter                                               | Numerical value |
|---------------------------------------------------------|-----------------|
| Maximum allowable pressure in the column, MPa          | 20              |
| Diameter of flanged adapter, mm                         | 50              |
| Diameter of fluid outlet from the chamber, mm           | 60              |
| Measuring range of fluid oscillation frequency, Hz      | 5–3000          |
| Connection thread of flanged adapter as per GOST 633-80| NKT 60          |
| Overall dimensions of the test column, mm:              |                 |
| - height                                               | 1065            |
| - outer diameter                                       | 180             |
| - internal diameter                                    | 164             |
| Overall dimensions of the holder, mm:                   |                 |
| - outer diameter                                       | 122             |
| - length                                               | 349             |
| Column weight, kg                                       | 82              |

When studying the work of the developed vibrators on the bench, the following technique is used. The vibrator is placed into a test column 1, which is fastened by a thread NKT60 GOST 633-80 to a flange nipple 5. A pump 7 supplies the working fluid through a gate valve 26 and a flexible hose 6 to the vibrator. Since the flow rate of the pump has a strictly fixed value (with the known diameter of the cylinder sleeves, the stroke length of the piston and the number of double strokes of the piston), the required fluid flow rate for the vibrator is obtained by bypassing a portion of the fluid through the gate valve 25 into the measuring vessel 20. Thus, the flow rate of the working fluid entering the vibrator is determined by:

\[
Q_V = Q_{t,p} \cdot \eta_{vol} - Q_{meas},
\]

where \(Q_{t,p}\) – theoretical pump capacity; \(\eta_{vol}\) – volumetric pump efficiency; \(Q_{meas}\) – capacity measured in tank 20.

After measuring the fluid flow rate in the container 20, the gate valve 24 is opened and the containers 20 and 21 are connected with each other. The flow rate of the fluid passing through the vibrator is controlled by a gate valve 25. The pressure of the working fluid before the vibrator and in the annular space is fixed by readings of pressure gauges 12 and 13, respectively. The change in the differential pressure actuated in the vibrator is achieved by a gate valve 11, from where the working fluid enters the receiving vessel 21. The fluid pulses generated by the vibrators both in the delivery line and in the test column are measured by strain gauges 14, the signals from which are transmitted through the pulse amplifier 17 to the beam oscilloscope 16. Beam deviation is directly proportional to the measured amplitude of pressure change (at appropriate calibration of strain gauges by reference pressure gauge at static pressure using measuring press) at sensor connection point, and signal is recorded on photo paper. To compare the obtained results it is necessary to measure fluctuations of the fluid pressure created by the pump. The measurements are performed by a sensor 14 in delivery line with open flange nipple 5 (without installation of the vibrator).

The laboratory-experimental works at the second stage of the study are carried out in two directions [4, 5]. In the first direction, fluid leaks through samples are studied at different mode parameters. The procedure is as follows. The holder, the diagram of which is shown in Figure 2, has three chambers for installing the tested samples, and all chambers are interchangeable. The tested samples are installed in holders, which are previously placed in a rubber casing. Using the vibrator installed in the test chamber 1 (Fig. 1), the necessary values of the frequency and amplitude of the fluid pressure fluctuation are created, which are recorded on the photo paper. The value of fluid pressure up to the tested sample is adjusted by a gate valve 11 (Fig. 1) and its values are fixed by the readings of a pressure gauge 13. Behind the rubber casing of the analyzed sample the ground pressure in the housing 4 is created by means of a manual oil pump, and the value of fluid leaks through the analyzed
sample is measured by the volumetric method by means of its withdrawal from the holder through the outlet 9. The studies are carried out alternately for one, two and three analyzed samples. The resulting values are represented as graphical dependencies.

![Diagram of holder](image)

**Fig. 2.** Holder: 1 – test column; 2 – thrust flange; 3 – sealing collar; 4 – housing; 5 – test sample; 6 – rubber casing; 7 – intermediate flange; 8 – outlet for connection with oil manual pump; 9 – outlets for fluid measurement and installation of strain gauges; 10 – channels for communication of internal cavity of housings; 11 – end flange

3. Results and Discussion

In the second direction of laboratory studies, the absorption value of pressure fluctuation amplitude is determined. To this end, pressure strain gauges are installed in the outlets 9, the signals from which are recorded by the beam oscilloscope on the photo paper. The required values of the mode parameters (frequency and amplitude of pressure fluctuation, pressure to the tested sample, ground pressure) are created in the same sequence.

The studies are carried out alternately for three samples, and the strain gauges are installed after each tested sample.

Laboratory-experimental studies of the mechanism of change of fluid pulsed parameters on rock samples and processing of obtained results.

Sand of the following particle size distribution was used as a model of porous medium: sand diameter in the range of 0.21-0.42 mm [6, 7]. For the preparation of samples, a shape was used, the internal dimensions of which were as follows: diameter – 24 mm; length – 40 mm. The sand was prescreened, washed with distilled water, and pressed in a press with a final force of 1200 H. The studies were carried out using three pressure values in the test chamber $p=1.0; 1.5; 2.0$ MPa, at each pressure value in the test chamber the following external pressure values were created for the samples $p_e=0.5; 1.4; 2.3$ MPa. The oscillation frequency of the fluid was created using vibrators, the value of which for all experiments was the same: 200, 400, 600, 800, 1000, 1200 Hz, and the error was not more than $\pm 5\%$. The obtained laboratory results are presented in Tables 2, 3 and 4.

| Fluid oscillation frequency, $f$, Hz | $p_1$ | $p_2$ | $p_3$ | $p_1$ | $p_2$ | $p_3$ | $p_1$ | $p_2$ | $p_3$ | $p_1$ | $p_2$ | $p_3$ |
|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 200                                 | 0.0323 | 0.0312 | 0.0310 | 0.0376 | 0.0378 | 0.0381 | 0.0373 | 0.0376 | 0.0381 | 0.0373 | 0.0376 | 0.0381 |
| 400                                 | 0.0434 | 0.0421 | 0.0413 | 0.0396 | 0.0398 | 0.0400 | 0.0393 | 0.0396 | 0.0400 | 0.0393 | 0.0396 | 0.0400 |
| 600                                 | 0.0562 | 0.0522 | 0.0502 | 0.0548 | 0.0550 | 0.0553 | 0.0542 | 0.0545 | 0.0552 | 0.0543 | 0.0545 | 0.0552 |
| 800                                 | 0.0687 | 0.0603 | 0.0596 | 0.0672 | 0.0675 | 0.0677 | 0.0665 | 0.0668 | 0.0676 | 0.0667 | 0.0669 | 0.0677 |
| 1000                                | 0.0623 | 0.0613 | 0.0584 | 0.0661 | 0.0664 | 0.0666 | 0.0653 | 0.0656 | 0.0664 | 0.0655 | 0.0658 | 0.0666 |
| 1200                                | 0.0618 | 0.0592 | 0.0580 | 0.0663 | 0.0666 | 0.0669 | 0.0651 | 0.0654 | 0.0663 | 0.0656 | 0.0659 | 0.0668 |
| 1400                                | 0.0611 | 0.0598 | 0.0563 | 0.0654 | 0.0657 | 0.0659 | 0.0632 | 0.0635 | 0.0653 | 0.0636 | 0.0639 | 0.0651 |
| 1600                                | 0.0602 | 0.0576 | 0.0560 | 0.0658 | 0.0661 | 0.0664 | 0.0633 | 0.0636 | 0.0655 | 0.0638 | 0.0641 | 0.0654 |
Based on the experimental data, a regression analysis was carried out, on the basis of which the qualitative ratios between factorial and effective signs were identified.

For all three cases, a matrix of the full factor experiment was compiled. The regression equations represented the dependence \( q = \varphi(f, P, P_r) \) in linear form. The dependence of regression coefficients was checked using the Student’s t-test and in all three cases the combination of \( fP \) and \( fPP \) factors does not affect the performance characteristic. The hypothesis of the adequacy of the proposed models was tested using the F-Fisher test [8, 9]. The regression equations are as follows:

\[
q_1 = (-0.000324 + 0.00000983 \cdot f + 0.0271 \cdot P + 0.0301 \cdot P_r - 0.0125 \cdot P \cdot P_r) \cdot 10^{-4};
\]
\[
q_2 = (0.08213 + 0.000021 \cdot f + 0.09038 \cdot P + 0.09735 \cdot P_r - 0.0447 \cdot P \cdot P_r) \cdot 10^{-5};
\]
\[
q_3 = (0.78906 + 0.000028 \cdot f + 0.09696 \cdot P + 0.10895 \cdot P_r - 0.0489 \cdot P \cdot P_r) \cdot 10^{-6};
\]

Experimental and calculated graphical dependencies \( q = \varphi(f) \) (at \( P = 1 \) MPa and \( P_r = 0.5 \) MPa) are shown in Figures 3, 4, 5. The analysis of obtained results revealed that as the frequency of fluid oscillation increases, the amount of fluid passing through the sample of porous medium increases, with the largest value \( q \) reaching in the frequency range of 600-1000 Hz. As for the value of pressures,
namely their effect on $q$, the conducted laboratory studies confirm the theoretical results of most authors.

Fig. 3. Diagram of the dependence of fluid leaks through one sample of porous medium on the frequency of fluid oscillations at $P = 1$ MPa and $P_r = 0.5$ MPa: 1 – design; 2 – experimental

Fig. 4. Diagram of the dependence of fluid leaks through two samples of porous medium on the frequency of fluid oscillations at $P = 1$ MPa and $P_r = 0.5$ MPa: 1 – design; 2 – experimental

Fig. 5. Diagram of the dependence of fluid leaks through three samples of porous medium on the frequency of fluid oscillations at $P = 1$ MPa and $P_r = 0.5$ MPa: 1 – design; 2 – experimental

In the second stage of laboratory tests, the preparation and composition of porous medium samples were the same as for the first case [10]. The amplitude of the change in fluid pressure was recorded after each sample. The experiments were carried out at a fluid pressure of 2.0 MPa, fluid oscillation frequency of 1000 Hz, and a sample pressure value of 1.0; 2.0; 3.0 MPa.
The results are shown in Figures 6, 7, 8. Based on the detailed consideration of the change in the amplitude of the pressure fluctuation, the following conclusions may be drawn. As the penetration depth of the vibrations increases, the absorption of the amplitude of the pressure fluctuation corresponds to a linear decrease, and as the ground pressure increases, the linear change in absorption is distorted.

Fig. 6. Change of the amplitude of pressure fluctuation for various values of external pressure upon samples of the porous medium at $P_f = 1.0$ MPa

Fig. 7. Change of the amplitude of pressure fluctuation for various values of external pressure upon samples of the porous medium at $P_f = 2.0$ MPa

Fig. 8. Change of the amplitude of pressure fluctuation for various values of external pressure upon samples of the porous medium at $P_f = 3.0$ MPa

Figures 9, 10, 11 show the results of change of pressure oscillation amplitude at different values of fluid oscillation frequency (at $P = 20$ MPa, $P_f = 1.5$ MPa). The obtained data, after comparison, allows making the following conclusion. The lowest absorption is characteristic of the oscillation frequency in the range of 0-1000 Hz, which confirms assumptions with an error of ±10%.

Fig. 9. Change of pressure fluctuation amplitude at different values of fluid oscillation frequency after 1 sample (P=2.0 MPa, $P_f = 1.5$ MPa)

Fig. 10. Change of pressure fluctuation amplitude at different values of fluid oscillation frequency
after 2 samples (P=2.0 MPa, $P_r=1.5$ MPa)

Fig. 11. Change of pressure fluctuation amplitude at different values of fluid oscillation frequency after 3 samples (P=2.0 MPa, $P_r=1.5$ MPa)

4. Conclusion

The laboratory and experimental studies conducted at the bench included two stages: a) study of output parameters and the corresponding selection of optimal design parameters of the developed devices; b) study of the influence of pressure and frequency of fluid pulses on the penetration of working fluid in sand samples.

When studying the work of the developed pulse devices for non-stationary pulse flooding on the bench, a technique is used that allows creating conditions as close as possible to real borehole conditions.

The second stage of laboratory and experimental studies included two directions. In the first direction, fluid leaks through samples are studied at different mode parameters. The procedure is as follows. The holder, the diagram of which is shown in Figure 2, has three chambers for installing the tested samples, and all chambers are interchangeable. In the second direction of laboratory studies the absorption of pressure fluctuation amplitude is determined.

References

[1] Zaynagalina L Z On the determination of design and geometric parameters of a upper bit slurry grinder IOP Conference Series: Materials Science and Engineering. 2020. C. 012094. DOI:10.1088/1757-899X/905/1/012094

[2] Zaynagalina L Z Dynamics of the oscillatory system of the near-bit slurry grinder IOP Conference Series: Materials Science and Engineering. 2020. C. 012092. DOI:10.1088/1757-899X/905/1/012092

[3] Zaynagalina L Z On the development of an experimental design and field test of an upper bit tool IOP Conference Series: Materials Science and Engineering. 2020. C. 012093. DOI:10.1088/1757-899X/905/1/012093

[4] Kuleshova L S, Kadyrov R R, Mukhametshin V V, and Akhmetov R T 2019 Auxiliary equipment for downhole fittings of injection wells and water supply lines used to improve their performance in winter IOP Conference Series: Materials Science and Engineering (MEACS 2018 – International Conference on Mechanical Engineering, Automation and Control Systems) 560(1) 012071 1-6 DOI: 10.1088/1757-899X/560/1/012071

[5] Haoran Zh, Yongtu L and Xingyuan Zh 2017 Sensitivity analysis and optimal operation control for large-scale waterflooding pipeline network of oilfield Journal of petroleum science and engineering 154 pp. 38-48

[6] Sun W and Mun-Hong H 2017 Forecasting and uncertainty quantification for naturally fractured reservoirs using a new data-space inversion procedure European Assoc Geoscientists & Engineers Computational geosciences 15th Conference on the Mathematics of Oil Recovery (ECMOR) (Amsterdam, Netherlands) 21(5-6) pp.1443-1458

[7] Khabibullin M Ya Managing the processes accompanying fluid motion inside oil field converging-diverging pipes Journal of Physics: Conference Series. International Conference "Information Technologies in Business and Industry". 2019. C. 042012. DOI: 10.1088/1742-6596/1333/4/042012
[8] Khabibullin M Ya Managing the reliability of the tubing string in impulse non-stationary flooding *Journal of Physics: Conference Series. International Conference “Information Technologies in Business and Industry” - 4 - Mechatronics, Robotics and Electrical Drives*. 2019. C. 052012. DOI:10.1088/1742-6596/1333/5/052012

[9] Polyakov V N, Chizhov A P, Kotenev Yu A and Mukhametshin V Sh 2019 Results of System Drilling Techniques and Completion of Oil and Gas Wells *IOP Conference Series: Earth and Environmental Science (IPDME 2019 – International Workshop on Innovations and Prospects of Development of Mining Machinery and Electrical Engineering)* 378(1) 012119 pp.1–7 DOI: 10.1088/1755-1315/378/1/012119

[10] Malyarenko A M, Bogdan V A, Kotenev Yu A, Mukhametshin V Sh, and Umetbaev V G 2019 Wettability and formation conditions of reservoirs *IOP Conference Series: Earth and Environmental Science (IPDME 2019 – International Workshop on Innovations and Prospects of Development of Mining Machinery and Electrical Engineering)* 378(1) 012040 1–6 DOI: 10.1088/1755-1315/378/1/012040

[11] Galimullin M L, Khabibullin M Ya Experience with sucker-rod plunger pumps and the latest technology for repair of such pumps *Chemical and Petroleum Engineering*. 2020. vol. 55. № 11-12. pp.896-901. DOI: 10.1007/s10556-020-00710-1

[12] Kadyrov R R, Mukhametshin V V, Galiullina I F, Kuleshova L S, and Safiullina A R 2020 Prospects of applying formation water and heavy brines derived therefrom in oil production and national economy *IOP Conference Series: Materials Science and Engineering (ISEES 2020 – 3rd International Symposium on Engineering and Earth Sciences)* 905(1) 1-6 DOI: 10.1088/1757-899X/905/1/012081