In-well vibration effect on cement stone impermeability

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Abstract. Impermeability tests are carried out on cement stone under the influence of operating downhole vibration exciter. It is found that cement stone preserves its porofractured structure under the static force impact. Under the local vibration effects within 10 h, the initial structure of microfractures becomes dynamic but the relative reduction in the proof-test pressure increases 2–3 times. The ingress of water is absent in cement stone, which means the absence of risk of behind-the-casing flow of fluid and water under the action of in-well vibrations.

1. Introduction
One of the problems that the petroleum industry is faced with worldwide is the low oil recovery factor which ranges as 0.3–0.4 in most operating fields. Hydrocarbons are mostly occluded inside pores and fractures in reservoirs. Conventional technologies of oil recovery based on reservoir pressure maintenance by injection of water into oil reservoirs are incapable to extract residual hydrocarbons [1].

Aimed to increase oil recovery factor, various methods of enhanced oil recovery are introduced in practice of oil-field development. The variety of enhanced oil recovery techniques is governed by complex physical and chemical processes running in oil reservoirs, as well as by geological features of different oil fields. The prevailing methods of enhanced oil recovery include [2–6]:

— chemical methods based on injection of chemical agents or water with surface-active substances into reservoirs;
— thermal methods based on displacement of oil using heat-carrying agents, or its subjection of reservoirs to intrastratal heat-generating oxidizing reactions;
— physical methods including fracking and vibro-wave effects.

The method of vibro-wave treatment of oil reservoirs seems to be more preferable among the listed techniques as it is applicable both individually and in combination with other methods of enhanced oil recovery, which improves their efficiency. The energy efficiency of vibration impact can be increased by placing exciter of elastic vibrations at the occurrence depth of pay zone, which calls for upgrading or innovative engineering of downhole vibration exciters [1, 2, 7].

This study aimed to test impermeability of cement stone under the action of vibrations generated by an experimental model of downhole exciter. The study has been undertaken to continue R&D project on engineering of a downhole exciter of electromagnetic pulses and vibrations using an electromagnetic shock unit (ESU) and a hydraulic shock unit (HSU). The technical feasibility of such machine and the lab-scale test data of its pilot prototype can be found in [8, 9].
2. Experimental setup and testing results
The downhole vibration exciter (Figure 1) is composed of HSU 1 connected with hydraulic pump 2 at the bottom and with ESU 3 at the top. The exciter is placed in a hole using tubing support 4 with lengthwise drawn cable connected to power and control unit 5. When actuated, hydraulic pump 2 fills HSU rubber 1 with pressure fluid. Cell 1 expands and force plungers 6 until they butt against production string 7. When a certain pressure is gained in HSU 1, hydraulic pump 2 is cut off, oil-dilled HSU cell 1 is shut and ESU 3 is actuated. Hammer piston 8 is lifted by magnetic field of top coil 9 to the upper dead spot, then is boosted by gravity and magnetic field of bottom coil 10 and hits plunger 11. Plunger 11 penetrates oil-filled HSU cell 1 and creates pressure surge which is transferred to the production string and to rock mass.

![Fig. 1. Arrangement of downhole electromagnetic pulse and vibration exciter.](image)

Production string 7 represents a column of steel casing pipes with cement stone filled in the annulus between the casing and walls of a borehole drilling in enclosing rock mass. One of the target functions of cement stone is disconnection of oil pool and water-bearing strata to eliminate leaks of hydrocarbons back and forth. To this effect, cement stone is to be impermeable and should prevent behind-the-casing flow. The downhole process flows, including vibration effects, should proceed with keeping integrity and impermeability of cement stone unaffected.

The test bench designed for the experimental study is shown in Figure 2. It represents a frame on a concrete bed, with a fragment of casing pipe 1 and centering mounted on the frame. HSU 3 is placed inside pipe 1, and ESU 4 is arranged on a special framing above HSU 3. The annulus between casing pipe 1 and centering 2 is filled with cement slurry (grade PTST I-150). Before filling the slurry, tube 5 is led to the outer surface of the casing pipe so that tube 5—pipe 1 contact point is spaced from the upper and lower ends of casing pipe 1 at 250 mm. Tube 5, via reservoir 6 with screw valve 7, is connected to plunger pump 8 (not shown in Figure 2). Hydraulic pressure is controlled using manometer 9.

The integrity criterion of cement stone in the tests was the stone impermeability. Pump 8 is meant to feed water via tube 5 to casing string 1. The water pressure drop with time is recorded (this operation is similar to pipe pressure testing). Hereinafter, we call the process of holding stone under water pressure for
20 m as the pressure testing and the pressure of water fed via tube 5 as the proof-test pressure. The ratio of the pressure drop for 20 min to the initial proof-test pressure in percent is called as the relative reduction in the proof-test pressure.

![Laboratory installation for cement stone impermeability tests.](image3)

**Figure 2.** Laboratory installation for cement stone impermeability tests.

It is known that the standard for the pressure gradient for cement stone to keep impermeability is 2.5 MPa per 1 m of cement lining. In the experimental installation described above, the minimum height of a damageable test area in cement stone is 0.25 m; therefore, the proof-test pressure is 0.625 MPa.

An operating vibration exciter exerts continuous static and periodic dynamic impact on a production string. For this reason, we implemented two series of tests: static and dynamic. The static tests were aimed to estimate relative reduction in the proof-test pressure as function of oil pressure in HSU; the dynamic test were intended to estimate the same proof-test pressure reduction as function of operating time of the vibration exciter. The pressure tests a–g implemented in time order in the static mode are described in Table 1.

**Table 1. Static pressure testing conditions**

| Pressure testing | a    | b    | c    | d    | e    | f    | g    |
|------------------|------|------|------|------|------|------|------|
| Load on cement stone | no load | loaded | loaded | unloaded | loaded | loaded | unloaded |
| Pressure in HSU, MPa | 0    | 5    | 10   | 0    | 15   | 20   | 0    |

From the static test data, we plotted two curves in Figure 3: curve 1—experiments a, b, c, e and f—impermeability of stone under the action of static horizontal thrust by HSU; curve 2—experiments a, d and g—impermeability of cement stone prior to application of HSU thrust and after its termination.
Figure 3. Relative reduction in proof-test pressure versus pressure in HSU.

The test results show that:
— after hardening, cement stone preserves the initial structure of microfractures and pores which govern a relative reduction in the proof-test pressure by 21%;
— an increase in the HSU pressure in the range of 0–20 MPa scales down the relative reduction in the proof-test pressure from 21 to 12% (curve 1). This is explained by the increased compressive load in cement stone and by closure of microfractures in it;
— after removal of load from cement stone, the relative reduction in the proof-test pressure is equal to the initial value (curve 2). This means that static loading of cement stone proceeds without growth of microfractures.

For the dynamic tests, we installed ESU 4 above HSU on the experimental installation (Figure 2). Oil is injected in HSU under pressure of 15 MPa, then ESU is actuated (blow energy $E_{\text{blow}} = 150–160 \text{ J}$; blow frequency $f = 3 \text{ Hz}$) at the time span of 10 h between the pressure tests. The averaged data on the relative reduction in the proof-test pressure were used to plot the curve in Figure 4.

Figure 4. Relative reduction in proof-test pressure versus operating time of vibration exciter.

During early hours of operation of the vibration exciter (10 h in Figure 4), a new and dynamic structure of microfractures is induced in cemented stone. This process is accompanied by higher relative reduction in the proof-test pressure, from 20 to 50%. When transient processes cease, a stable dynamic structure of microfractures sets in cement stone, and the relative reduction in the proof-test pressure ranges as 50–60%. It is critical that pressure water inrushes on exposed surfaces are absent. This means that the dynamic structure of microfractures covers a local zone in cement stone. The height of this zone is approximately equal to the length of contact between the load-applying element and the casing pipe (266 mm).

3. Conclusions
Cement slurry after it has been filled and completely hardened has a fractured-and-porous structure which is the cause of reduction in the final proof-test pressure by 20–25% as compared with its initial value. The
influence of the vibration exciter on the production string by the static thrust keeps the initial structure of pores and microfractures unchanged in cement stone. The pulsed vibration effects due to the downhole electromagnetic pulse generator induces the local dynamic structure of microfractures in the zone of the mechanical contact between the generator and the casing pipe, and the relative reduction in the proof-test pressure is 50–60%. The ingress of pressure water on exposed surface of cement stone is absent.

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