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Restoration of Rock Permeability Degraded by Well Killing Fluid Using Ultrasonic Vibrations: Experimental Studies

E.P. Riabokon, M.S. Turbakov, E.A. Gladkikh, E.V. Kozhevnikov, M.A. Guzev*
Perm National Research Polytechnic University, Perm, Russian Federation

The operation of oil production wells is accompanied by the invasion of well killing fluids into a near wellbore zone while well intervention which deteriorates rock permeability and decreases well oil rate. In order to restore the permeability of the rock in the near wellbore zone of the formation, it is proposed in this work to use ultrasonic alternating loading during well inflow stimulation. To study the effect of alternating loading on the permeability of rocks, a laboratory set-up is developed and filtration experiments are carried out. The rock studied was sandstone of medium permeability. The experimental studies included four stages: filtration of the killing fluid (calcium chloride solution) in the forward direction (simulating well killing); keeping the sample in conditions of pumped kill fluid; filtration of kerosene in the opposite direction (simulating an inflow stimulation) until the maximum possible restoration of permeability; filtration of kerosene in the reverse direction under ultrasonic alternating loading conditions for additional permeability restoration. It was revealed, that under conditions of ultrasonic alternating loading, the pore space of the rock, previously blocked by particles of the killing fluid, is unblocked and the permeability of the samples is restored. An analysis was made of the mechanism of blocking the pore space with the killing fluid and restoring the permeability of the rock.

Keywords: permeability, rock, ultrasonic vibrations, well killing fluid, pore space

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Introduction

Deterioration of the filtration characteristics of rocks in the near wellbore zone of formations is a widespread problem faced by production engineers. A decrease in permeability can occur due to technological loads during well operation (Poplygin et al., 2022), blocking of the pore space by precipitated paraffins and asphaltenes (Riabokon et al., 2023a; Riabokon et al., 2023b), as well as due to technological fluids used, for example, well killing fluids (Iscan et al., 2007). To restore the permeability of the near wellbore zone, deteriorated by well killing fluids, the method of increased drawdown (Salimi, Ghalambor, 2011), as well as treatment with various compositions are widely used (Amro, 2022). In addition to the classical methods of cleaning the rocks from killing fluid products, it is proposed to affect the rock with ultrasonic alternating loading (or vibrations).

To restore the permeability of rock in the near wellbore zone of formations, many authors are exploring an ultrasonic method for cleaning the pore space of rock from deposits of inorganic substances (salt), drilling fluid and well killing fluid, as well as polymers. For example, it was shown at the experimental installation for core flooding (Pu et al., 2011), that ultrasonic vibrations remove plugs of calcium carbonate at frequencies of 18-50 kHz. Using an experimental stand (Xu, Pu, 2013) with ultrasonic vibrations the authors restored the permeability of artificial rock samples sealed with inorganic substances ($CaCO_3$), paraffin deposits, drilling fluid, fine-grained substances, and polymers. Deposits of inorganic substances KCl and NaCl are also removed from samples under the influence of ultrasonic vibrations with a frequency of 22 kHz (Taheri-Shakib et al., 2018; Taheri-Shakib et al., 2017). The ultrasonic action destroys and removes drilling fluid and well completion fluid that has clogged the pore space (Shi et al., 2017). The value of restored permeability is significantly influenced by such parameters as frequency, specific power, duration of ultrasonic treatment and initial permeability of the core. Treatment at a frequency of 20 kHz, compared to frequencies of 18 kHz and 25 kHz, best restores the permeability of quartz and epoxy resin rock samples deteriorated by the injection of brine solutions (Khan et al., 2017). In (Poplygin et al., 2023), Zipf's law was used to assess the effectiveness of restoring rock permeability from the use of wave treatment of wells. In terms of field applications downhole tools have been developed (for example, in Mullakaev et al., 2009) that allow to unblock the pore space around production wells from deposits. It is shown (Dyblenko et al., 2008), that wave technologies are effective for completion the wells developing difficult to recover reserves. A large number of laboratory experiments were carried out (Dyblenko et al., 2008) on an experimental rig to study filtration phenomena. Using transparent plate models of a porous media, positive effects of increasing filtration characteristics when applying a field of elastic vibrations were obtained. In addition, on a bench installation for studying the processes of decolmatation of the bottom-hole formation zone in the field of elastic vibrations at different frequencies and amplitudes, the unblocking of the pore space of artificial cores from such mechanical particles as: corrosion products (rust microparticles), clay colmatants

* Corresponding author: Evgenii P. Riabokon
e-mail: riabokon@pstu.ru

(modeled by weakly swelling kaolinite in water) was studied. The authors found that the degree of permeability increment is proportional to the amplitudes of the oscillatory effect in areas of small amplitudes. As the level of oscillations increases, "saturation" occurs – a further increase in the amplitudes of pressure oscillations does not lead to a noticeable change in permeability. The oscillation frequency has a significant impact on the process of filtering suspended matter. There is a selective – the most optimal frequency range, in which the degree of permeability increment during the treatment process is maximum for any amplitude indicators. In (Kuznetsov et al., 2001), it is said that in the experiments carried out, the influence of elastic vibrations does not affect the permeability of zones blocked by colmatant.

Despite the results achieved in mentioned studies, in order to restore the permeability of rocks in the near wellbore zone degraded due to technological liquids (well killing fluids), it is eligible for experimental studies to simulate the conditions under which the fluid is filtered from the formation into the well. Such studies are usually carried out using standard laboratory rigs. However, to study the effect of ultrasonic vibrations on the permeability of rocks during fluid filtration, it is necessary to modify the standard laboratory rig and install an actuator and additional equipment.

The aim of the present paper is to study the effect of ultrasonic vibrations on the unblockage of the rock pore space blocked with brine crystals, which can be used in well conditions to help stimulation oil inflow after well intervention and well killing fluid invasion into a near wellbore zone. The major task of the study is to model the well conditions in which an ultrasonic actuator is installed inside the well in front of the pay zone and emits the vibrations towards the fluid flow that goes to the production well. In order to do that, a laboratory set-up was assembled that ensures fluid flow towards the ultrasonic vibrations emitted by a Langevin actuator.

In (Riabokon et al., 2023), the authors showed a laboratory set-up for studying the effect of ultrasonic vibrations on the filtration of paraffinic oil. The studies of the present paper were carried out on the same set-up of the department of Oil and Gas Technologies of Perm National Research Polytechnic University, which, in comparison with other studies, simulates well conditions in which the formation fluid and ultrasonic vibrations are directed towards each other causing rocks permeability to restore.

Materials and Methods

Materials

In the experimental study, sedimentary clastic rocks (sandstones) are used as a filtering porous medium; calcium chloride brine is used as a well killing fluid and a kerosene is used as a filtering formation fluid, described in the subsections below.

Description of rocks

The rock was extracted from a depth of 2 km during core drilling of production wells in an oil field in Perm region (Russia).

According to the results of petrographic analysis, the rock is a fine-medium-grained quartz sandstone. The clastic part of the sandstone is dominated by quartz; rock fragments (quartzites and single fragments of clayey rocks) and pelitized feldspars are less common. The cement is predominantly regenerative quartz with the formation of conformal structures. The kaolinite develops unevenly in the pores, poorly crystallized, with an admixture of hydromica (Fig. 1).

The void space of the rock is unevenly represented by intergranular isolated and partially open hollow pores, presumably of secondary origin (formed by the partial dissolution of part of the terrigenous fragments) of irregular shape, 0.08-0.5 mm in size.

According to the results of X-ray phase analysis, the bulk mineral composition of the rock is dominated by quartz, the minor minerals are potassium feldspar, and clay minerals include kaolinite. The characteristics of the samples are shown in Table 1.

Description of fluids

Kerosene was chosen as the filtered liquid (Fig. 2a). The kill fluid was selected from standard recommended solutions of calcium chloride $CaCl_2$ with a density of 1070 kg/m^3 and

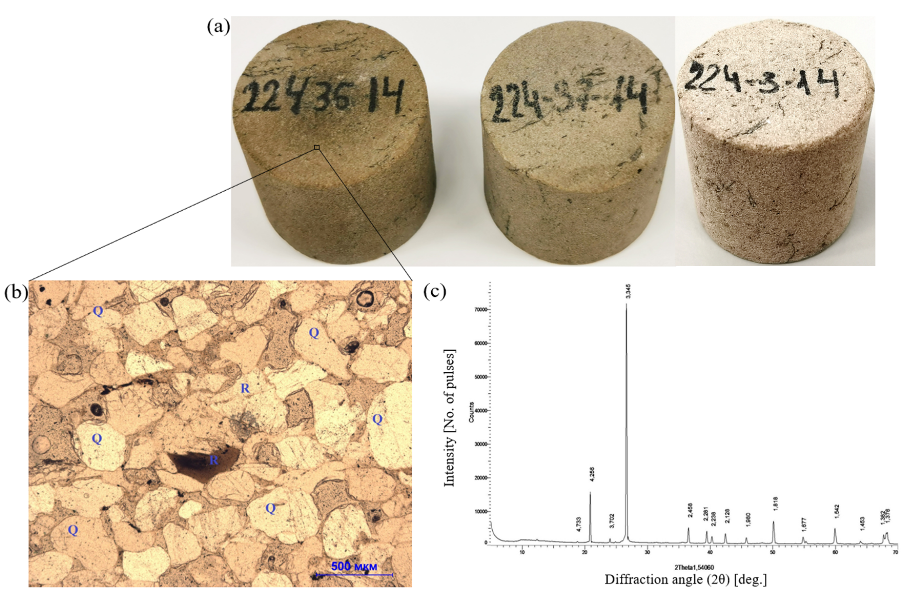

Fig. 1. Description of the studied rock: (a) photograph depicting the rock samples (plugs) for the study; (b) microphotograph of a fragment of a thin section of a sample, Q means quartz, R means rock fragments; (c) X-ray diffraction pattern of the sample

	Sample		
	224-36-14	224-37-14	224-3-14
Size			
- diameter, mm	30	30	30
- length, mm	30	30	30
Pore volume V, cm^3	3.71	3.71	3.81
Porosity ∅, %	17.1	17.2	17.6
Permeability on gas k	100.2	97.3	99.8
Mineral composition:			
- quartz		91.8 %	
- potassium feldspar		6.6 %	
- kaolinite		1.6 %	
Total minerals		100 %	

Table 1: Characteristics of the rock samples

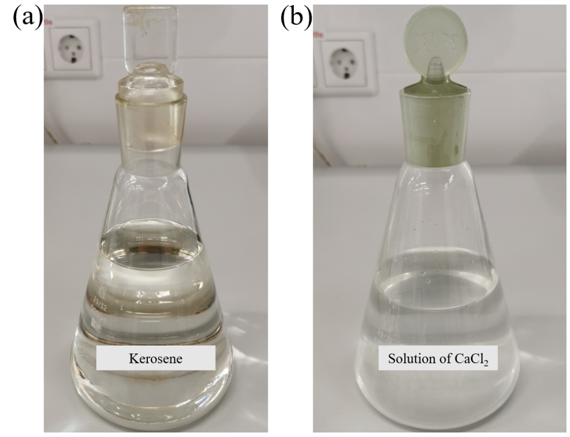

Fig. 2. Photographs depicting the liquids prepared for research: (a) kerosene; (b) well killing fluid brine

a salt content of 8.3% (Fig. 2b). In field conditions, the density is selected so as to correspond to the formation pressure and plus a margin to create repression on the formation (so that the killing fluid slightly enters the formation).

Methods

Description of the filtration rig

The studies are carried out on a laboratory rig, which is a modified Auto core Flooding System 300. The modification was made in the part of the liquid receiving chamber at the outlet of the core holder. For modernization, parts such as a sleeve, chamber and cover were manufactured. The sleeve is installed in the core holder and pressed against the rock sample. The hollow sleeve allows fluid flowing from the rock sample into the chamber. The chamber is a hollow cone-shaped part and is connected to a sleeve. The chamber has two pipes: the upper one for the outlet of the filtered liquid into the backpressure unit and then into the flow meter, and the lower one for emptying the chamber. The chamber is filled with liquid flowing out from the sample. The chamber has a sealing cap at the end. An elastic vibration emitter is screwed onto the cover. As a result of the reciprocating movement of the emitter elements, vibration is created on the chamber cover. The vibration of the cap is transmitted through the fluid filling the chamber, through the sleeve to the end of the rock sample, after which the vibrations are further propagated through the matrix and the fluid in the pore channels. Activation of ultrasonic vibrations leads to a change in the permeability of the rock. The modified design of the rig simulates the influx of fluid from the formation into the well, in which an elastic vibration generator is installed, sending vibrations into the near-well zone of the formation towards the filtered kerosene. A general view of the laboratory rig is shown in Fig. 3.

In experiments, a rock sample is in a state of uniform compression. Using a rubber cuff, a confining pressure is created in the core holder, simulating rock pressure equal to 6.9 MPa. Using pumps that supply liquid to the sample inlet, a pore pressure of 0.7–1.0 MPa is created, while the backpressure unit maintains the pressure at the sample outlet.

Stages of the study

To create the effect of deteriorated permeability, well killing fluid is pumped into the rock sample in the direction opposite to the filtration of formation fluid and left for several hours. In this way, well killing is modeled, in which the well killing fluid penetrates from the well into the rock of the near-well zone of the formation and blocks the pore space.

After creating a zone of deteriorated permeability, the sample is pumped with kerosene in the forward direction until the permeability stabilizes (Fig. 4). Stabilization of permeability corresponds to the displacement of the displaced volume of well killing fluid and its reaction products from the rock sample by kerosene. The fig. 4 shows that the permeability of sample 224-36-14 decreased by almost 68% from 100 mD to 32 mD. The permeability of sample 224-37-14 decreased by 75% from 100 mD to 25 mD. The permeability of sample 224-3-14 decreased by 77% from 140 mD to 32 mD. The most likely reason for the greater permeability deterioration is that the injected well killing fluid was left in

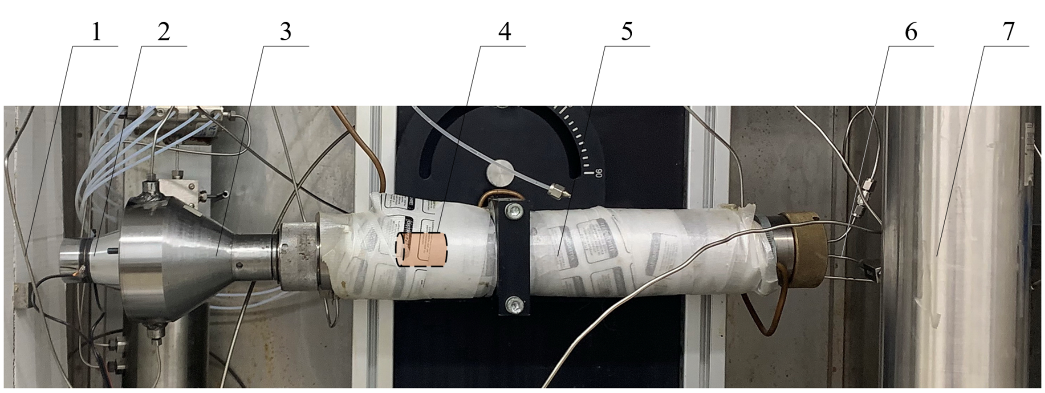

Fig. 3. A photograph depicting the laboratory setup for studying the filtration of well killing fluid and kerosene through rock: (1) line for removing liquid from the chamber; (2) ultrasonic vibration emitter; (3) chamber for receiving fluid from the core holder; (4) a rock sample mounted inside a core holder; (5) core holder; (6) liquid injection line; (7) reservoir with kerosene

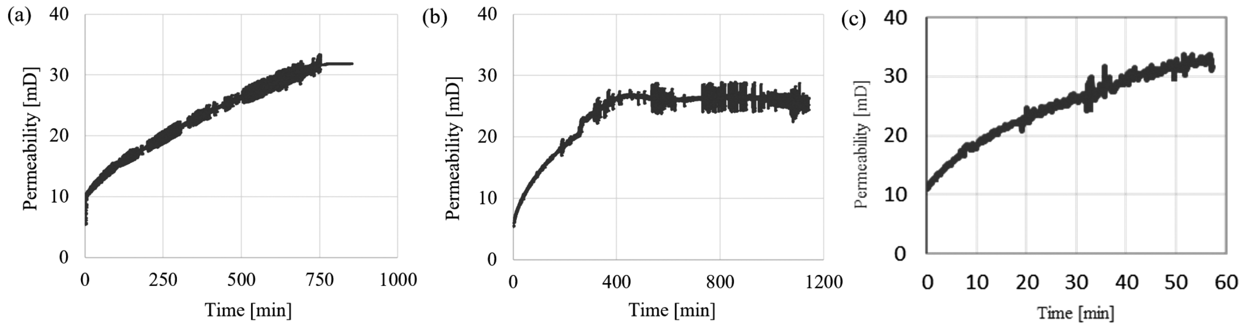

Fig. 4. Graphs of permeability recovery when the well killing fluid is displaced by kerosene from rock samples: (a) 224-36-14; (b) 224-37-14; (c) 224-3-14

the sample for 12 hours, which may have further blocked the pores in the sample by components of the solution.

To determine the permeability in laboratory conditions at a flooding rig, it is customary to use Darcy's law (Darcy, 1856), which defines it as the pore area in the cross section of a sample length l and area S, occupied by a liquid with a viscosity μ when filtering it at a flow rate Q when creating a pressure difference between the ends of the sample ΔP

$$k = \frac{Q \times \mu \times l}{S \times \Delta P} \quad \{D\}. \quad (1)$$

The parameters of activations in experiments are presented in Table 2. The influence mode is continuous.

Results and Discussion

As a result of the research, it was revealed that vibrations remove the rock blockage, while restoring its permeability. Treatment of sample 224-36-14 with vibration at different frequencies demonstrates the restoration of permeability from 32 mD to 42 mD (Fig. 5). It is possible to restore the deteriorated permeability by 31%, and the initial permeability can be restored by 10%. When processing sample 224-37-14, the permeability of the sample was restored from 27 mD to 41 mD (Fig. 6). It is possible to restore the degraded permeability by 52%, and the initial permeability can be restored by 14%. The permeability of sample 224-3-14 during treatment was restored from 32 mD to 50 mD (Fig. 7). Deteriorated permeability can be restored by 56%, original – by 13%. The results are summarized in Tables 3–4.

It is worth noting that despite the soaking of the well killing fluid in sample 224-37-14 and a stronger deterioration in its permeability, the impact of ultrasonic vibrations on it made it possible to more effectively restore permeability. The degree of restoration of the permeability of sample 224-36-14 is 2.5 times higher than that of sample 224-37-14.

From the point of view of substantiating the effect of ultrasonic vibrations, the following model can be proposed. When the well killing fluid is injected into sandstone samples, its particles are transported through permeable channels into the rock. Particles in the killing fluid originate when calcium chloride is added to the water and a hydrolysis reaction occurs to form hydrochloric acid and calcium hydroxide is formed; it is slightly soluble in water, especially with a pH above 7. When calcium chloride dissolves in water, heat is generated. It is not large in volume, but locally at the points of interaction of molecules this temperature is critical, so locally the conditions for the partial occurrence of this reaction can be met. Therefore, the reaction will take place, but only partially.

Calcium hydroxide is insoluble in water and its particles can be observed under a microscope. From Figure 8 it can be seen that the sizes of calcium hydroxide particles in the kill fluid are comparable to the sizes of the pore channels of the rock, which block the pores.

Further, when such particles enter a channel (pore), which has a constriction (mouth) comparable in size to the diameter of a brine particle, the latter is fixed in the channel, as a result of which other transported particles accumulate behind the first particle and completely block the channel (Fig. 9a). Blocking of channels leads to a decrease in the total flow area in the sample. As a result, in order to pump the same volume of liquid per unit time as before blocking the sample channels, it is necessary to create a greater pressure gradient between the ends of the sample. According to Darcy's law, an increase in the pressure gradient at a constant flow rate and the other parameters in formula (1) remaining unchanged requires an increase in permeability, this phenomenon is observed when pumping killing fluid into rock.

Despite the fact that when filtration is turned on in the opposite direction in order to displace brine particles that have entered the matrix, the permeability is not restored to the initial value. On the one hand, it can be assumed that the water contained in the calcium chloride solution leads to the swelling of clay particles (for example, montmorillonite) composing the rock sample. However, petrographic analysis (Table 1) showed that the rock contains no more than 2% of kaolinite clay, which is neutral to water. For the same reason, there are no changes in the wettability of the rock (Ghasemi, Shafiei, 2022). The most likely reason for the under-recovery of permeability seems to be mechanical movement of particles.

Sample	Frequency (kHz) and duration (min) of activation on stages							
	1	2	3	4	5	6	7	8
224-36-14	20/7	28/14	40/37	20/2				
224-37-14	20/20	20/5	28/13	28/8	40/8	20/3	28/3	
224-3-14	17/2	20/3	28/5	40/5	48/10	120/10	40/6	17/2

Table 2. Parameters of activations

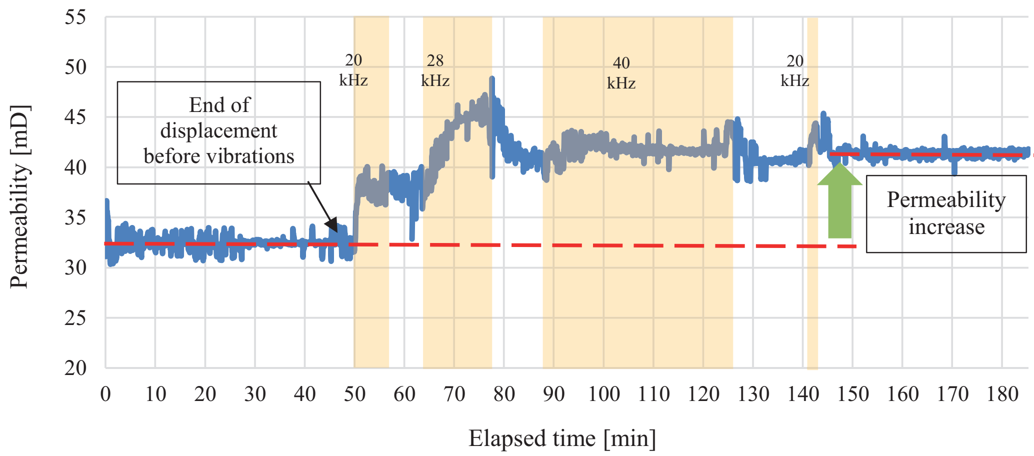

Fig. 5. Graph of changes in the permeability of sample 224-36-14 when ultrasonic vibration is activated. The periods of ultrasonic vibration activated are highlighted yellow

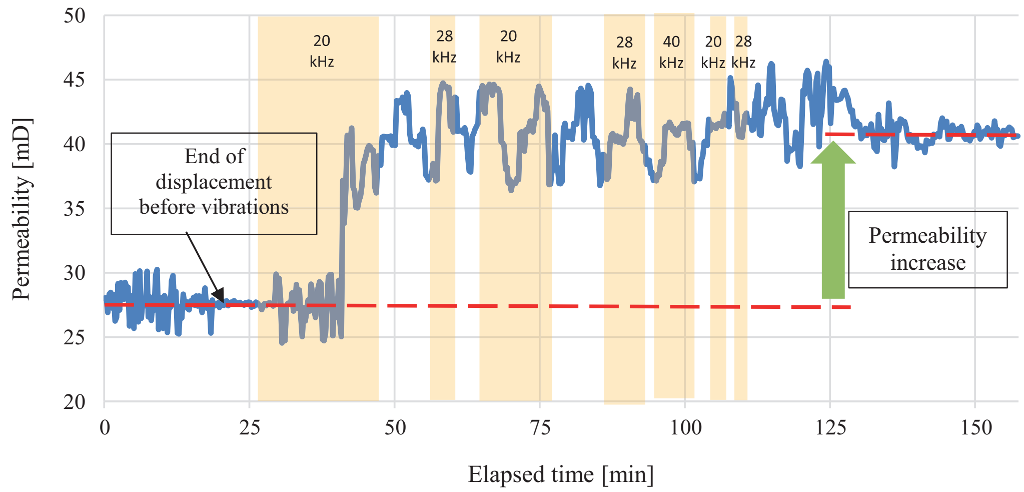

Fig. 6. Graph of changes in the permeability of sample 224-37-14 when ultrasonic vibration is activated. The periods of ultrasonic vibration activated are highlighted yellow

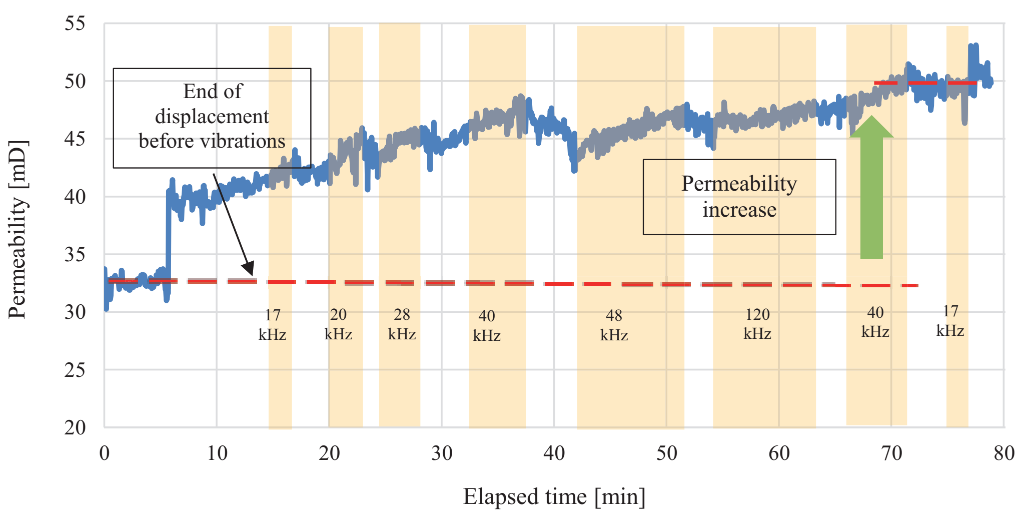

Fig. 7. Graph of changes in the permeability of sample 224-3-14 when ultrasonic vibration is activated. The periods of ultrasonic vibration activated are highlighted yellow

Frequency, kHz	Change in permeability of samples, mD		
	224-36-14	224-37-14	224-3-14
17	-	-	2
20	5	10	3.5
28	9.5	5.5	4.5
40	3	3.5	3
48	-	-	2
120	-	-	1

Table 3. Effects of different frequencies on the permeability of samples

Parameter	Sample		
	224-36-14	224-37-14	224-3-14
Permeability:			
- initial	100 mD	100 mD	140 mD
- deteriorated	32 mD	27 mD	32 mD
- restored	42 mD	41 mD	50 mD
Permeability restoration:			
- relatively deteriorated	31 %	52 %	56 %
- relative to the initial	10 %	14 %	13 %

Table 4. Results of the impact of vibrations on the permeability of samples

In particular, during reverse pumping liquid (kerosene) makes its way through the channels and part of the total amount of calcium hydroxide particles clogging the channels is removed from the sample through the same channels. However, firstly, not all particles are removed from the already fixed place (due to strong mechanical contact). Secondly, filtering through channels in the opposite direction, particles also encounter narrowings on their path and block them. A similar phenomenon of deterioration in permeability due to the migration of colloids is described in detail in (Kozhevnikov et al., 2022a, 2022b, 2023).

When elastic vibrations are activated, vibration of the matrix leads to displacement of calcium hydroxide particles and, as a result, their separation from the matrix. The displaced

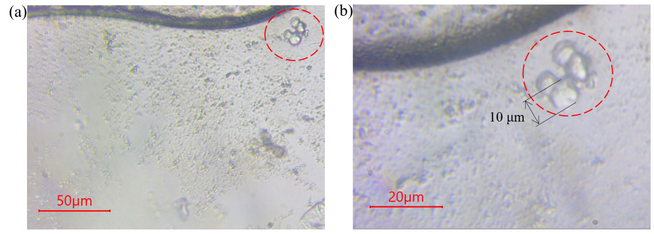

Fig. 8. Microphotographs depicting particles in the killing fluid: (a) 400x magnification; (b) 1000x magnification

particles instantly move through the channels along with the kerosene flow (Fig. 9b), as a result of which the permeability instantly increases, as shown in Figs. 5–7.

Conclusion

This work presents the experimental study of the influence of ultrasonic vibrations on the permeability of rock, the permeability of which is deteriorated by the well killing fluid. The study used a laboratory rig in which a Langevin emitter represents an element creating ultrasonic vibrations. Based on the results of the study, the following conclusions can be drawn:

(1) when killing fluid is pumped into the formation, the permeability of clastic rock decreases from 100 mD to 10 mD due to blocking of pore channels by particles of the killing fluid;

(2) ultrasonic vibrations lead to partial unblocking of the pore space of the rock and restoration of the average permeability relative to the initial one by 20% and relative to the deteriorated permeability by 62.5%;

(3) the most effective frequencies among the range of 17–120 kHz are the frequencies 20 kHz and 28 kHz that gave an average on three samples increase in permeability by 6.2 mD and 6.6 mD respectively.

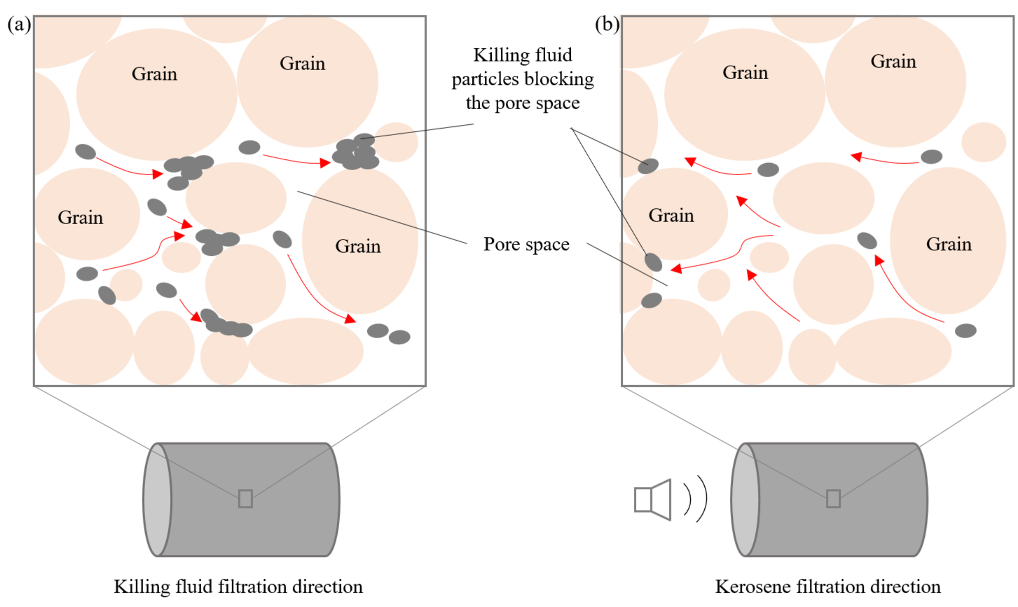

Fig. 9. Graphic model of blocking and unblocking of the pore space of the rock: (a) during infiltration of well killing fluid without ultrasonic vibration in the opposite direction (from the well to the formation); (b) when filtering kerosene in the forward direction (from the formation to the well) with ultrasonic vibrations

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References

Amro M.M. (2002). Laboratory Study and Field Matching of Matrix Acidizing of Petroleum Reservoir Rocks. *Journal of King Saud University – Engineering Sciences*, 14(1), pp. 119–135. https://doi.org/10.1016/S1018-3639(18)30748-7

Darcy H. (1856). Les Fontaines Publiques De La Ville De Dijon. Exposition Et Application Des Principes à Suivre Et Des Formules à Employer Dans Les Questions De Distribution D'eau: Ouvrage Terminé Par Un Appendice Relatif Aux Fournitures D'eau De Plusieurs Villes Au Filtrage Des Eaux Et à La Fabrication Des Tuyaux De Fonte, De Plomb, De Tole Et De Bitume. Paris: Dalmont, 647 p.

Dyblenko V.P., Kamalov R.N., Sharifulin R.I., Tufanov I.A. (2000). Increasing productivity and resuscitation of wells with the use of vibration-wave effects. Moscow: OOO "Nedra-Biznestsentr", 381 p. (In Russ.)

Dyblenko V.P., Tufanov I.A., Ochkovsky A.P., Lukyanov Yu.V., Imamov R.Z., Khakimov F.Sh., Khisamov R.S., Khurryamov A.M., Bayanov V.M. (2008). Complex of wave technologies for wells completion in case of field reserves difficult to recover. *Neftyanoe khozyaystvo = Oil Industry*, 11, 112–117. (In Russ.)

Ghasemi M., Shafiei A. (2022). Influence of brine compositions on wetting preference of montmorillonite in rock/brine/oil system: An in silico study. *Applied Surface Science*, 606, 154882. https://doi.org/10.1016/j.apsusc.2022.154882

Iscan A.G., Kok M.V., Bagci A.S. (2007). Permeability Reduction Due to Formation Damage by Drilling Fluids. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 29(9), pp. 851–859. https://doi.org/10.1080/00908310600713958

Khan N., Pu C., Li X., He Y., Zhang L., Jing C. (2017). Permeability recovery of damaged water sensitive core using ultrasonic waves. *Ultrasonics Sonochemistry*, 38, pp. 381–389. https://doi.org/10.1016/j.ultsonch.2017.03.034

Kozhevnikov E.V., Turbakov M.S., Gladkikh E.A., Riabokon E.P., Poplygin V.V., Guzev M.A., Qi C., Kunitskikh A.A. (2022). Colloid Migration as a Reason for Porous Sandstone Permeability Degradation during Coreflooding. *Energies*, 15, 2845. https://doi.org/10.3390/en15082845

Kozhevnikov E.V., Turbakov M.S., Riabokon E.P., Gladkikh E.A. (2023). Apparent Permeability Evolution Due to Colloid Migration Under Cyclic Confining Pressure: On the Example of Porous Limestone. *Transport in Porous Media*. https://doi.org/10.1007/s11242-023-01979-5

Kuznetsov O.L., Simkin E.M., Chilingar J. (2001). Physical foundations of vibration and acoustic influences on oil and gas formations. Moscow: Mir, 260 p. (In Russ.)

Mullakaev M.S., Abramov V.O., Pechkov A.A. (2009). Ultrasonic unit for restoring oil wells. *Chemical and Petroleum Engineering*, 45, 133–137. https://doi.org/10.1007/s10556-009-9160-9

Poplygin V., Qi C., Guzev M., Kozhevnikov E., Kunitskikh A., Riabokon E., Turbakov M. (2023). Assessment of the Elastic-Wave Well Treatment in Oil-Bearing Clastic and Carbonate Reservoirs. *FDMP-Fluid Dynamics & Materials Processing*, 19(6), pp. 1495–1505. http://dx.doi.org/10.32604/fdmp.2023.022335

Poplygin V.V, Riabokon E.P., Turbakov M.S., Kozhevnikov E.V., Guzev M.A., Jing H. (2022). Changes in rock permeability near-wellbore due to operational loads. *Materials Physics and Mechanics*, 48(2), pp. 175–183. https://doi.org/10.18149/MPM.4822022_3

Pu C., Shi D., Zhao S., Xu H., Shen H. (2011). Technology of removing near wellbore inorganic scale damage by high power ultrasonic treatment. *Petroleum Exploration and Development*, 38(2), pp. 243–248. https://doi.org/10.1016/S1876-3804(11)60030-X

Riabokon E., Gladkikh E., Turbakov M., Kozhevnikov E., Guzev M., Popov N., Kamenev P. (2023). Effects of ultrasonic oscillations on permeability of rocks during the paraffinic oil flow. *Géotechnique Letters*, 13(3), pp. 151–157. https://doi.org/10.1680/jgele.22.00137

Riabokon E., Gladkikh E., Turbakov M., Kozhevnikov E., Guzev M., Yin Q. (2023). The Effect of Ultrasonic Alternating Loads on Restoration of Permeability of Sedimentary Rocks during Crude Paraffinic Oil Flow. *Applied Sciences*, 13, 11821. https://doi.org/10.3390/app132111821

Salimi S., Ghalambor A. (2011). Experimental Study of Formation Damage during Underbalanced-Drilling in Naturally Fractured Formations. *Energies*, 4, pp. 1728–1747. https://doi.org/10.3390/en4101728

Shi X., Xu H., Yang L. (2017). Removal of formation damage induced by drilling and completion fluids with combination of ultrasonic and chemical technology. *Journal of Natural Gas Science and Engineering*, 37, pp. 471–478. https://doi.org/10.1016/j.jngse.2016.11.062

Taheri-Shakib J, Naderi H., Salimidelshad Y., Kazemzadeh E., Shekarifard A. (2018). Resolution limit in community detection. *Ultrasonics Sonochemistry*, 40A, 249–259. https://doi.org/10.1016/j.ultsonch.2017.06.019

Taheri-Shakib J., Naderi H., Salimidelshad Y., Teymouri A., Shekarifard A. (2017). Using ultrasonic as a new approach for elimination of inorganic scales (nacl): an experimental study. *Journal of Petroleum Exploration and Production Technology*, 8, pp. 553–564. https://doi.org/10.1007/s13202-017-0369-4

Turbakov M.S., Kozhevnikov E.V., Riabokon E.P., Gladkikh E.A., Poplygin V.V., Guzev M.A., Jing H. (2022). Permeability Evolution of Porous Sandstone in the Initial Period of Oil Production: Comparison of Well Test and Coreflooding Data. *Energies*, 15, 6137. https://doi.org/10.3390/en15176137

Xu H., Pu C. (2013). Removal of near-wellbore formation damage by ultrasonic stimulation. *Petroleum Science and Technology*, 31(6), pp. 563–571. https://doi.org/10.1080/10916466.2011.586959

About the Authors

Evgenii P. Riabokon – Researcher, Department of Oil and Gas Technologies, Perm National Research Polytechnic University

29, Komsomolskiy ave., Perm, 614990, Russian Federation
e-mail: riabokon@pstu.ru

Mikhail S. Turbakov – Cand. Sci. (Engineering), Associate Professor, Chief Researcher, Department of Oil and Gas Technologies, Perm National Research Polytechnic University

29, Komsomolskiy ave., Perm, 614990, Russian Federation
e-mail: msturbakov@gmail.com

Evgenii A. Gladkikh – Cand. Sci. (Engineering), Senior Researcher, Department of Oil and Gas Technologies, Perm National Research Polytechnic University

29, Komsomolskiy ave., Perm, 614990, Russian Federation
e-mail: gladkih.ea@mail.ru

Evgenii V. Kozhevnikov – Cand. Sci. (Engineering), Senior Researcher, Department of Oil and Gas Technologies, Perm National Research Polytechnic University

29, Komsomolskiy ave., Perm, 614990, Russian Federation
e-mail: kozhevnikov_evg@mail.ru

Mikhail A. Guzev – Dr. Sci. (Physics and Mathematics), Academician of the Russian Academy of Sciences, Chief Researcher, Department of Oil and Gas Technologies, Perm National Research Polytechnic University

29, Komsomolskiy ave., Perm, 614990, Russian Federation
e-mail: guzev@iam.dvo.ru

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Восстановление проницаемости горной породы, ухудшенной жидкостью глушения скважин, с помощью ультразвуковых колебаний: экспериментальные исследования

Е.П. Рябоконь[*], М.С. Турбаков, Е.А. Гладких, Е.В. Кожевников, М.А. Гузев

Пермский национальный исследовательский политехнический университет, Пермь, Россия

[*]Ответственный автор: Евгений Павлович Рябоконь, e-mail: riabokon@pstu.ru

В процессе эксплуатации скважин жидкости глушения ухудшают проницаемость пород в призабойной зоне пласта, что приводит к снижению дебита скважин. В работе экспериментально изучено влияние ультразвуковых колебаний на восстановление проницаемости осадочных пород на разработанном лабораторном стенде. В качестве фильтрующей пористой среды используются песчаники. Керосин используется в качестве фильтрующей жидкости. Раствор хлорида кальция используется в качестве жидкости для глушения скважин. Лабораторный эксперимент имитирует ухудшение проницаемости горной породы путем прокачки жидкости глушения через образцы горных пород. После создания зоны ухудшенной проницаемости образец горной породы промывается керосином в прямом направлении до стабилизации проницаемости. Затем выполняется фильтрация пластовой жидкости в прямом направлении в скважину, в которой установлен генератор ультразвуковых колебаний, посылающий колебания в прискважинную зону пласта в сторону фильтрующегося керосина. Фильтрация керосина осуществляется в условиях ультразвуковой вибрации. Выявлено, что в условиях ультразвуковых колебаний поровое пространство породы частично разблокируется, и проницаемость горных пород частично восстанавливается. Выполнен анализ механизма блокировки порового пространства жидкостью глушения скважин и восстановления проницаемости породы.

Ключевые слова: проницаемость, горная порода, ультразвуковые вибрации, жидкость глушения, поровое пространство

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References

Amro M.M. (2002). Laboratory Study and Field Matching of Matrix Acidizing of Petroleum Reservoir Rocks. *Journal of King Saud University – Engineering Sciences*, 14(1), pp. 119–135. https://doi.org/10.1016/S1018-3639(18)30748-7

Darcy H. (1856). Les Fontaines Publiques De La Ville De Dijon. Exposition Et Application Des Principes à Suivre Et Des Formules à Employer Dans Les Questions De Distribution D'eau: Ouvrage Terminé Par Un Appendice Relatif Aux Fournitures D'eau De Plusieurs Villes Au Filtrage Des Eaux Et à La Fabrication Des Tuyaux De Fonte, De Plomb, De Tole Et De Bitume. Paris: Dalmont, 647 p.

Dyblenko V.P., Kamalov R.N., Sharifulin R.I., Tufanov I.A. (2000). Increasing productivity and resuscitation of wells with the use of vibration-wave effects. Moscow: OOO "Nedra-Biznestsentr", 381 p. (In Russ.)

Dyblenko V.P., Tufanov I.A., Ochkovsky A.P., Lukyanov Yu.V., Imamov R.Z., Khakimov F.Sh., Khisamov R.S., Khurryamov A.M., Bayanov V.M. (2008). Complex of wave technologies for wells completion in case of field reserves difficult to recover. *Neftyanoe khozyaystvo = Oil Industry*, 11, 112–117. (In Russ.)

Ghasemi M., Shafiei A. (2022). Influence of brine compositions on wetting preference of montmorillonite in rock/brine/oil system: An in silico study. *Applied Surface Science*, 606, 154882. https://doi.org/10.1016/j.apsusc.2022.154882

Iscan A.G., Kok M.V., Bagci A.S. (2007). Permeability Reduction Due to Formation Damage by Drilling Fluids. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 29(9), pp. 851–859. https://doi.org/10.1080/00908310600713958

Khan N., Pu C., Li X., He Y., Zhang L., Jing C. (2017). Permeability recovery of damaged water sensitive core using ultrasonic waves. *Ultrasonics Sonochemistry*, 38, pp. 381–389. https://doi.org/10.1016/j.ultsonch.2017.03.034

Kozhevnikov E.V., Turbakov M.S., Gladkikh E.A., Riabokon E.P., Poplygin V.V., Guzev M.A., Qi C., Kunitskikh A.A. (2022). Colloid Migration as a Reason for Porous Sandstone Permeability Degradation during Coreflooding. *Energies*, 15, 2845. https://doi.org/10.3390/en15082845

Kozhevnikov E.V., Turbakov M.S., Riabokon E.P., Gladkikh E.A. (2023). Apparent Permeability Evolution Due to Colloid Migration Under Cyclic Confining Pressure: On the Example of Porous Limestone. *Transport in Porous Media*. https://doi.org/10.1007/s11242-023-01979-5

Kuznetsov O.L., Simkin E.M., Chilingar J. (2001). Physical foundations of vibration and acoustic influences on oil and gas formations. Moscow: Mir, 260 p. (In Russ.)

Mullakaev M.S., Abramov V.O., Pechkov A.A. (2009). Ultrasonic unit for restoring oil wells. *Chemical and Petroleum Engineering*, 45, 133–137. https://doi.org/10.1007/s10556-009-9160-9

Poplygin V., Qi C., Guzev M., Kozhevnikov E., Kunitskikh A., Riabokon E., Turbakov M. (2023). Assessment of the Elastic-Wave Well Treatment in Oil-Bearing Clastic and Carbonate Reservoirs. *FDMP-Fluid Dynamics & Materials Processing*, 19(6), pp. 1495–1505. http://dx.doi.org/10.32604/fdmp.2023.022335

Poplygin V.V, Riabokon E.P., Turbakov M.S., Kozhevnikov E.V., Guzev M.A., Jing H. (2022). Changes in rock permeability near-wellbore due to operational loads. *Materials Physics and Mechanics*, 48(2), pp. 175–183. https://doi.org/10.18149/MPM.4822022_3

Pu C., Shi D., Zhao S., Xu H., Shen H. (2011). Technology of removing near wellbore inorganic scale damage by high power ultrasonic treatment. *Petroleum Exploration and Development*, 38(2), pp. 243–248. https://doi.org/10.1016/S1876-3804(11)60030-X

Riabokon E., Gladkikh E., Turbakov M., Kozhevnikov E., Guzev M., Popov N., Kamenev P. (2023). Effects of ultrasonic oscillations on permeability of rocks during the paraffinic oil flow. *Géotechnique Letters*, 13(3), pp. 151–157. https://doi.org/10.1680/jgele.22.00137

Riabokon E., Gladkikh E., Turbakov M., Kozhevnikov E., Guzev M., Yin Q. (2023). The Effect of Ultrasonic Alternating Loads on Restoration of Permeability of Sedimentary Rocks during Crude Paraffinic Oil Flow. *Applied Sciences*, 13, 11821. https://doi.org/10.3390/app132111821

Salimi S., Ghalambor A. (2011). Experimental Study of Formation Damage during Underbalanced-Drilling in Naturally Fractured Formations. *Energies*, 4, pp. 1728–1747. https://doi.org/10.3390/en4101728

Shi X., Xu H., Yang L. (2017). Removal of formation damage induced by drilling and completion fluids with combination of ultrasonic and chemical technology. *Journal of Natural Gas Science and Engineering*, 37, pp. 471–478. https://doi.org/10.1016/j.jngse.2016.11.062

Taheri-Shakib J, Naderi H., Salimidelshad Y., Kazemzadeh E., Shekarifard A. (2018). Resolution limit in community detection. *Ultrasonics Sonochemistry*, 40A, 249–259. https://doi.org/10.1016/j.ultsonch.2017.06.019

Taheri-Shakib J., Naderi H., Salimidelshad Y., Teymouri A., Shekarifard A. (2017). Using ultrasonic as a new approach for elimination of inorganic scales (nacl): an experimental study. *Journal of Petroleum Exploration and Production Technology*, 8, pp. 553–564. https://doi.org/10.1007/s13202-017-0369-4

Turbakov M.S., Kozhevnikov E.V., Riabokon E.P., Gladkikh E.A., Poplygin V.V., Guzev M.A., Jing H. (2022). Permeability Evolution of Porous Sandstone in the Initial Period of Oil Production: Comparison of Well Test and Coreflooding Data. *Energies*, 15, 6137. https://doi.org/10.3390/en15176137

Xu H., Pu C. (2013). Removal of near-wellbore formation damage by ultrasonic stimulation. *Petroleum Science and Technology*, 31(6), pp. 563–571. https://doi.org/10.1080/10916466.2011.586959

About the Authors

Евгений Павлович Рябоконь – научный сотрудник кафедры нефтегазовых технологий, Пермский национальный исследовательский политехнический университет

Россия, 614990, Пермь, Комсомольский пр-т, д. 29
e-mail: riabokon@pstu.ru

Михаил Сергеевич Турбаков – канд. тех. наук, доцент, главный научный сотрудник кафедры нефтегазовых технологий, Пермский национальный исследовательский политехнический университет

Россия, 614990, Пермь, Комсомольский пр-т, д. 29
e-mail: msturbakov@gmail.com

Евгений Александрович Гладких – канд. тех. наук, старший научный сотрудник кафедры нефтегазовых технологий, Пермский национальный исследовательский политехнический университет

Россия, 614990, Пермь, Комсомольский пр-т, д. 29
e-mail: Gladkih.ea@mail.ru

Евгений Васильевич Кожевников – канд. тех. наук, старший научный сотрудник кафедры нефтегазовых технологий, Пермский национальный исследовательский политехнический университет

Россия, 614990, Пермь, Комсомольский пр-т, д. 29
e-mail: kozhevnikov_evg@mail.ru

Гузев Михаил Александрович – доктор физ.-мат. наук, академик РАН, главный научный сотрудник кафедры нефтегазовых технологий, Пермский национальный исследовательский политехнический университет

Россия, 614990, Пермь, Комсомольский пр-т, д. 29
e-mail: guzev@iam.dvo.ru

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