UDC 622.245.5

Improving the efficiency of terrigenous oil-saturated reservoir development by the system of oriented selective slotted channels

Sergei E. CHERNYSHOV [1]✉, **Vera A. REPINA**[1], **Nikolai I. KRYSIN** [1], **David Iain MacPherson MACDONALD** [2]
[1] *Perm National Research Polytechnic University, Perm, Russia*
[2] *University of Aberdeen, Aberdeen, Scotland, United Kingdom*

How to cite this article: Chernyshov.S.E., Repina V.A., Krysin N.I., MacDonald David Iain MacPherson. Improving the efficiency of terrigenous oil-saturated reservoir development by the system of oriented selective slotted channels. Journal of Mining Institute. 2020. Vol. 246, p. 660-666. DOI: 10.31897/PMI.2020.6.8

Abstract. A comparative assessment of variation in the flow rate of oil production wells was performed taking into account increasing of perforated area of the productive part of the rocks, as well as recover of reservoir rocks permeability due to their unloading by creating slotted channels with the method of oriented slotted hydro-sandblast perforation. Different orientation directions and slotting intervals were analyzed, taking into account water encroachment of individual interlayers and azimuth direction of the majority of remaining reserves in separate blocks of the examined formation.

In order to estimate development efficiency of terrigenous oil-saturated porous-type reservoirs by means of oriented slotted hydro-sandblast perforation, calculations were performed on a full-scale geological and hydrodynamic model of an oil field in the Perm Region. The object of modeling was a Visean terrigenous productive formation.

The modeling of implementing oriented slotted hydro-sandblast perforation was carried out on a 3D filtration model for fourteen marginal wells, located in the zone with excessive density of remaining recoverable reserves and heterogeneous reserve recovery along the section. An optimal layout of slotted channels along the depth of the productive part of the well section was developed. Selective formation of 24 slotted channels was carried out considering the intervals of increased oil saturation. Comparative analysis of estimated flow rate of the wells was performed for cumulative perforation of the examined productive formation and the developed method of slotted perforation. As a result of modeling, an increase in the oil average flow rate of 2.25 t/day was obtained. With oriented slotted hydro-sandblast perforation, incremental cumulative production for two years of prediction calculations per one well reached 0.5 thousand t.

Key words: production well; oriented slotted hydro-sandblast perforation; selective perforation; modeling of the productive formation; perforation technology; permeability recovering

Acknowledgement. This work was financially supported by the Ministry of Education and Science of the Perm Region during the implementation of project MIG-21 (Agreement No.C-26/785 from 21.12.2017)

Introduction. Providing conditions for recovering initial permeability of reservoir rocks allows to maximize flow rates of oil production wells and to improve development efficiency of an individual formation.

Equipment (Fig.1) and technology of oriented slotted hydro-sandblast perforation (OSHSP) allow to perform effective perforation of productive formations in the given direction, taking into account stress-strain state of the rocks and direction of remaining hydrocarbon reserves, as well as to reduce water cut of well production due to selective reservoir perforation and to increase well productivity [5, 6].

An apparent advantage of implementing oriented slotted perforation of productive formations is not only in unloading of the near-wellbore zone from the effective stresses [2]. Designed equipment and technological fluids allow to create a reliable reservoir-to-well hydrodynamic connectivity

Fig.1. Electronic model of hydro-sandblast perforator and orientation block for implementing OSHSP

without impairing reservoir properties of the productive formation, which enables to decrease stress-strain state of the rocks in the bottom-hole area and provides an opportunity to prepare the well for performing directed hydraulic fracturing in the future.

The first argument in favor of this technology is relatively low pressure and ensuring the safety of well casing. OSHSP technology suggests implementation of two regimes under operating pressures around 20 and 30 MPa. It should be noted that these are operating pressures of the units, whereas pressure loads on the casing do not exceed 10 MPa and remain local, which enables to ensuring the safety of well casing. According to calculations, under 10 MPa pressure in the perforation interval, the loads transmitted to the cement stone are not more than 0.65-1.72 MPa, which does not exceed bending strength of the cement stone, made from developed recipes of cement slurries (9-12 MPa after 4-7 days of curing).

The second important positive effect of the considered technology is effective stress unloading of reservoir rocks in the near-wellbore zone. The calculations assumed the characteristics of terrigenous porous-type reservoir of the Shershnevsky oil field: terrigenous reservoir, true vertical depth of 1,577 m, net oil pay of 3.6 m, porosity of 0.15, initial formation pressure of 15.0 MPa [2]. Estimation of elastic and strength properties was carried out using well log data (gamma ray, acoustic and density logging, cross-dipole full-wave acoustic logging), as well as correlation dependencies, obtained in core sample tests.

The possibility of rock failure was estimated by the presence of conventional zones of plastic deformations (according to N.S.Bulychev) [4], for which purpose the Mohr – Coulomb failure criterion was calculated:

$$\sigma_1 - p = UCS + (\sigma_3 - p)\frac{1+\sin\varphi}{1-\sin\varphi}, \tag{1}$$

where σ_1, σ_3 are the principal stresses; UCS is the uniaxial compression strength; φ is the angle of internal friction; p is the formation (pore) pressure.

Unloading of the rock mass was estimated by variation of average effective pressure $\Delta\sigma$. Unloading zones were limited by the value of $\Delta\sigma$, equal to 20 % of the initial stress level. It was assumed that if the variation of average effective pressure were smaller than this value, then its influence on rock permeability would be negligible:

$$\Delta\sigma = \frac{(\sigma_1^{(1)} + \sigma_2^{(1)} + \sigma_3^{(1)}) - (\sigma_1^{(0)} + \sigma_2^{(0)} + \sigma_3^{(0)})}{3}, \tag{2}$$

where $\Delta\sigma$ is the variation of average effective pressure; σ_1, σ_2, σ_3 are the principal effective stresses.

Overall, four main design options of slotted channel arrangement were considered in order to estimate the unloading zone. Fig.2 presents a model for the design option, in which unloading produced the greatest effect.

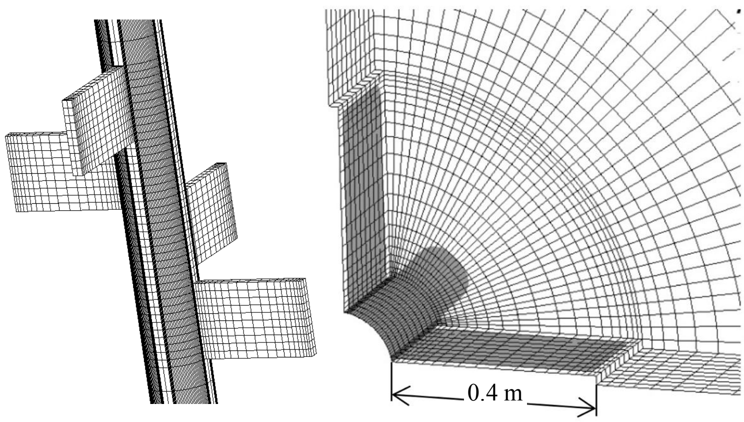

Fig.2. Computational model for the problem of slotted channel orientation and permeability improvement by SSS reduction

In order to assess the unloading effect from creating slotted channels, estimates of their influence on reservoir rock permeability were carried out using a dependency between permeability and confining effective pressure. For terrigenous reservoirs of the Shershnevsky oil field, it was identified that long-lasting action of an effective pressure exceeding natural pressure, led to a significant decrease in reservoir permeability. The rate of permeability reduction was higher for samples with greater initial permeability. For example, in the sample with initial permeability of 100 mD it decreased to 52 mD as a result of rising effective pressure [2].

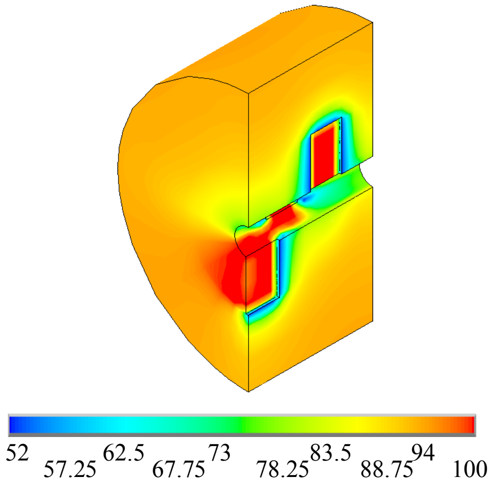

Fig.3. Permeability distribution under 5 MPa drawdown near the well with slotted perforation according to the computational model

Results of permeability estimation for terrigenous porous-type reservoirs after the formation of slotted channels are presented in Fig.3. It is expected that oil flow rate will increase by a factor of 3.5-7.3 due to effective stress unloading and extension of fluid filtration area.

Abroad a great number of research papers is devoted to different technologies of slotted hydromechanical and hydro-sandblast perforation of productive formations of oil and gas wells. For the most part, they discuss the advantages of this perforation method from the viewpoint of increasing reservoir rock permeability, well efficiency and safety of perforation work.

A.Chacon [7] demonstrated that the advantages of this method were clearly characterized by a significant increase in gas flow rates. In the works of M.Sharma [8], results of modeling were compared to experimental results of abrasive particle content and permeability in the zone of perforation holes. A good agreement of laboratory and field test results was observed.

M.A.Rahman [11] identified that permeability of an open well decreased by 30-75 % due to shaped charge perforating. Y.Zhang et al. [10] highlighted three main advantages of sandblast perforation method, which in addition to preserving the well casing, increased the efficiency of oil wells due to formation of slotted perforation holes, which in their turn allowed to reduce stress concentration in the direct proximity to the wellbore, as well as to overcome a contaminated area in the near-wellbore zone of productive formations.

The works of J.Yu and H.Li [12] specified that initial permeability and peak strength of sandstone varied depending on the effective stresses and the osmotic pressure under hydro-mechanical stimulation. It was established that a local compaction band formed under three-axial loading. Variation of permeability was determined by collapsing microfractures and compaction of the rock matrix, shattered after the elasto-plastic stage of deformation.

Advanced software and availability of relevant geological and hydrodynamic models of oil and gas fields enable to improve the efficiency of perforation technology by using results of fundamental research.

In paper [9] authors modeled the process of slotted channel formation, which included two regimes – cutting of the casing string and hydro-sandblast impact on the rock and slots creation. It was pointed out that, compared to cumulative perforation, the hole in the casing wall and the slotted channel in the cement were much larger for slotted hydro-abrasive perforation method. Besides, cumulative perforation led to formation of impermeable surface of created channels. In order to examine this phenomenon in greater detail, 3D numerical modeling was carried out [13], and the obtained model offered a general picture of stress distribution and fracture zone in the near-wellbore area of productive formations.

Methodology. One of the main tools for making justified strategic and tactical decisions in the development of hydrocarbon fields is the modeling of oil and gas recovery processes. Increase in the efficiency of oil and gas field development is associated with improving both the equipment and the technologies of reservoir development. Undoubtedly, any technology of reservoir stimulation must be justified through mathematical calculations before its practical implementation. Oil producing companies solve such problems using a software package *Tempest More* by ROXAR. This simulator is widely used for hydrodynamic model construction in the design of field development systems. Over the course of its existence a considerable experience of its application has been accumulated; moreover, a large number of additional tools have been incorporated into the simulator.

The functioning of hydrodynamic simulator involves solving a set of non-linear equations, based on the following relations: law of mass and energy conservation, law of mass transfer, equation of state.

Solving a set of differential equations allows to define the state of the model in each separate block at a given time point. These equations are fundamental and constitute the material balance equation [1]. Design solutions in oil and gas field development are justified using 3D geological and hydrodynamic models of multi-phase filtration [3].

In *Tempest More*, the estimation of well flow rates is carried out by applying Dupuis law and the law of mass conservation. Hydrodynamic modeling is performed on block models that contain data on static and dynamic properties. Modeling of oil recovery in a well from the block model requires information on well profile, recovery constraints, bottomhole pressure, as well as data on perforation interval. In this case, oriented slotted perforation is imitated by means of a key word BRANCH, which models additional branching of side channels from the well. By regulating geometrical dimensions and arrangement of branches, it is possible to reach considerable similarity with oriented perforation. Further it is identified, which calculation parameters of the model get affected and in what manner.

Well flow rate in the model depends on drawdown, formation and bottomhole pressures, fluid mobility and well-to-reservoir connectivity. Regardless of well geometry, well flow rates are connected to pressures by the following relation:

$$q_{il} = \lambda_{il} WI_l (p_l - p_{bh}), \tag{3}$$

where q_{il} is the flow rate of i^{th} component from the block l, exposed by the well; λ_{il} is the mobility of i^{th} component in the block l; WI_l is the well-to-reservoir connectivity in the block l; p_l is the pressure in the block l, adjusted to the depth datum of bottomhole pressure; p_{bh} is the bottomhole pressure in the well.

Well-to-reservoir connectivity is described by the formula:

$$WI_l = \frac{\theta k_l h_l f_l}{\ln r_{ol} / r_w + S_l}, \tag{4}$$

where θ is the coefficient, which considers wellbore location in the block, it can take the values of $\pi/2$, π and 2π for wells, located in the corner, at the boundary or in the center of the rectangular grid block, respectively; k_l equals $\sqrt{k_1 k_2}$ for the block l; k_1 and k_2 are the permeabilities in directions, orthogonal to the well direction; h_l is the perforation interval in the block l; f_l is the perforation factor in the block l; r_{ol} is the equivalent radius of the block l; r_w is the well radius; S_l is the skin factor in the block l.

After identifying model parameters and their interconnection, it can be inferred that, when the key word BRANCH is used to model oriented perforation, in each exposed block there will primarily be an increase in the perforation density. Formation of small oriented channels leads to expansion of the filtration area and reduction of filtration resistance in the given direction. As a result, developed azimuthal heterogeneity in the bottomhole zone area creates channels, which determine the principal direction of fluid filtration.

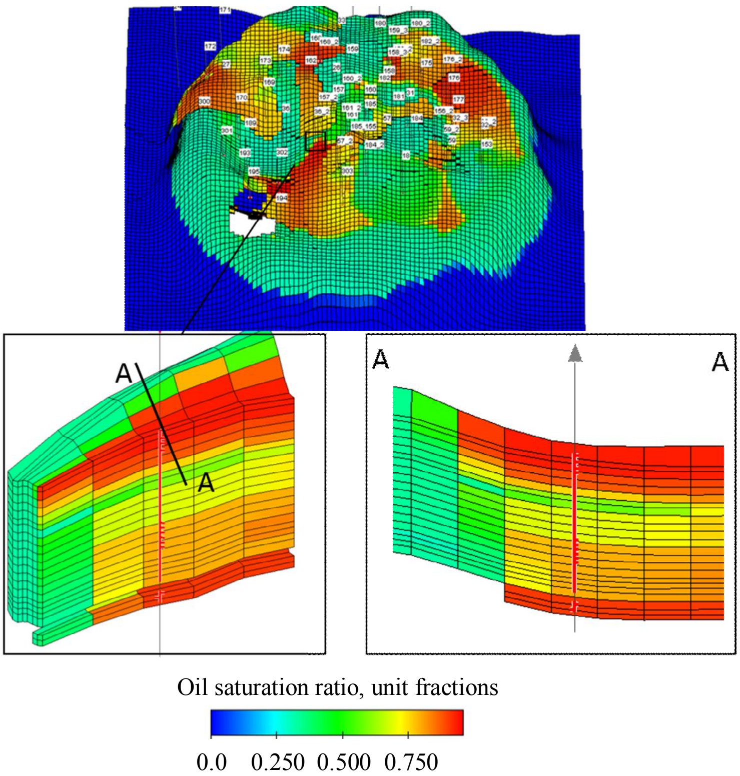

Fig.4. Distribution of current oil saturation in the 3D hydrodynamic model and direction of slotted channel formation

Modeling of the unloading effect from creating additional slotted channels was carried out by means of improving bottomhole zone properties of the well, and in particular by increasing the well-to-reservoir connectivity factor, according to formula (4).

In accordance with the proposed methodology of OSHSP implementation, the filtration area increased due to additional filtration sections of the productive formation.

Discussion. In order to assess the efficiency of implementing oriented slotted hydro-sandblast perforation as a method of productive formations completion – among other things, on earlier perforated wells – a full-scale hydrodynamic model of Visean terrigenous sediments of the Chashkinsky oil field was used. Terrigenous reservoirs of this field are porous, the average value of porosity coefficient reaches 0.15, permeability coefficient equals 50 mD. Currently the field is at the third stage of development. According to filed data, 50 % of the production well stock operates at oil flow rates below 5 t/day. In 2001 two production wells of the field were subject to slotted hydro-sandblast perforation, the average incremental flow rate after these measures reached 2.8 t/day per well.

In order to model OSHSP technology, wells located in the zone with excessive density of remaining recoverable reserves (RRR) and heterogeneous reserve recovery along the section were selected. A more detailed examination of calculation results was carried out using the example of well 1, which operated at the Chashkinsky field at the oil flow rate of 2-5 t/day and currently is out of production. Judging from the 3D cube of current oil saturation, it was decided to orient the slots towards its maximum value along the examined formation (Fig.4). The modeling of additional perforation drain channels in the given direction was carried out in the hydrodynamic simulator *Tempest More* by ROXAR.

Using a full-scale model of the productive formation, two design options were considered – with shaped charge perforating and with OSHSP implementation. In the second option, 24 additional slots were created during well perforation. Direction of the slots was set towards maximum oil saturation of the formation. Slots were arranged along the well section in the following pattern (Fig.4): 8 slots were located over the interval of 2.2 m in the upper part of permeable formation in the zone of increased oil saturation; 12 slots – over 2.8 m in the middle of oil saturated interval; 4 slots – over 0.7 m of the section in the lower part of the formation. Comparison of flow rates and cumulative oil production for well 1, before and after selective perforation modeling, is displayed in Fig.5.

As a result of OSHSP modeling using a 3D filtration model for well 1, an increase in the oil flow rate of 2.25 t/day was obtained, incremental production for two years of forecast calculations reached 0.5 thousand t.

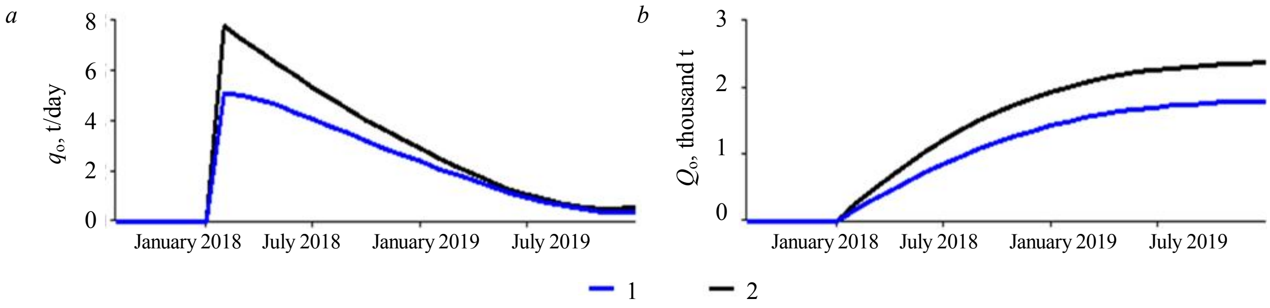

Рис.5. Parameters of well operation before and after OSHSP implementation: *a* is the oil flow rate; *b* is the cumulative oil production

1 is the shaped charge perforating; 2 is the OSHSP technology

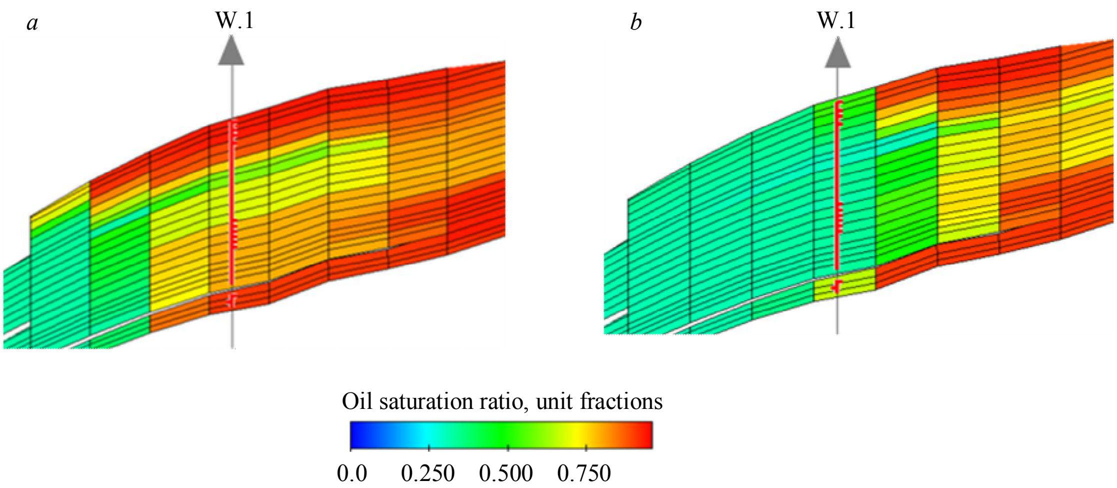

Fig.6. Well 1 section, illustrated by the 3D volume of oil saturation before (*a*) and after (*b*) OSHSP implementation

Fig.6 demonstrates the distribution of residual oil saturation ratio in the well section, two years after the implementation. Reservoir rocks perforation by system of oriented slots provided a more complete and uniform recovery of reserves along the well section.

According to results of estimations, performed for 14 marginal wells at the examined field, for a two-year period the average value of incremental oil flow rate reached 2.63 t/day per one well.

Conclusions. OSHSP implementation on a full-scale 3D hydrodynamic model confirms the positive effect of the proposed measures, aimed at increasing marginal well efficiency.

The considered technology allows to perform selective oriented non-damaging perforation of oil saturated formations with marginal wells in order to reduce water cut of well production and to increase efficiency of well operation. Obtained estimation results demonstrate the effectiveness of OSHSP technology under conditions of the examined field – for terrigenous porous-type reservoirs with occurrence depth of 1,500-2,300 m and permeability of 50-100 mD.

Presently the majority of oil fields in the Perm Region are at their final stage of development. Well operation at this stage is characterized by a low value of oil flow rate and high percentage of water cut in the product. Heterogeneous distribution of remaining recoverable reserves (RRR) across the area and along the section of the formation is associated with geological heterogeneity of reservoir properties and imperfection of field development system. In order to maximize additional RRR extraction, economically feasible measures should be taken to enhance oil recovery.

OSHSP technology allows to extract remaining reserves, including those in marginal well regions. Availability of flowmetric data of the well increases the effect of OSHSP implementation. Using of 3D hydrodynamic models enables to select the most suitable wells for OSHSP operations. In the absence of flowmetric data, a hydrodynamic model of the formation can be used to estimate porosity and permeability properties of the reservoir and to direct perforation channels away from the injection front in order to reduce current water cut of the wells, which will provide a better effect from the implementation.

REFERENCES

1. Aziz Kh., Settari E. Mathematical Modeling of Formation Systems. Moscow – Izhevsk: Institut kompyuternykh issledovanii, 2004, p. 416 (in Russian).

2. Ashikhmin S.G., Chernyshov S.E., Kashnikov Yu.A.1, Macdonald D.I.M. Geomechanical Analysis of the Influence of Orientation and Placement of Jet Slots on Terrigenous Reservoir Permeability. *Oil Industry*. 2018. N 6, p. 132-135. DOI: 10.24887/0028-2448-2018-6-132-135 (in Russian).

3. Zakirov E.S. Three-Dimensional Multi-Phase Problems of Forecast, Analysis and Regulation of Oil and Gas Field Development. Moscow: Graal, 2001, p. 303 (in Russian).

4. Kashnikov Yu.A., Ashikhmin S.G. Rock Mechanics in the Development of Hydrocarbon Fields. Moscow: Gornaya kniga, 2019, p. 491 (in Russian).

5. Chernyshov S.E., Ryabokon E.P., Turbakov M.S., Krysin N.I. Patent N 2645059 RF. The Method of Slotted Hydro-Sandblast Perforation. Publ. 15.02.2018. Bul. N 5 (in Russian).

6. Krysin N.I., Riabokon E.P.,Turbakov M.S.,Chernyshov S.E.1, Shcherbakov A.A. Improvement of Devices of Abrasive Jet Perforation in Oil Wells. *Oil Industry*. 2016. N 8, p.129-131 (in Russian).

7. Chacon A., Fadul J.C.J., Noguera J. Novel abrasive perforating with acid soluble material and subsequent hydrajet assisted stimulation provides outstanding results in carbonate gas well. Society of Petroleum Engineers. Presented at the SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition, 22-23 March 2016, Houston, Texas, USA. SPE-179083-MS. DOI: 10.2118/179083-MS

8. Sharma M.M. Nature of the compacted zone around perforation tunnels // Society of Petroleum Engineers. Presented at the SPE International Symposium on Formation Damage Control, 23-24 February 2000, Lafayette, Louisiana. SPE-58720-MS. DOI:10.2118/58720-MS

9. Huang Z., Niu J., Li G., Yuan X., Liu Y. Surface Experiment of Abrasive Water Jet Perforation. *Petroleum Science and Technology*. 2008. Vol. 26. Iss. 6, p. 726-733. DOI: 10.1080/10916460701208454

10. Zhang Y., Li G.-S., W Xiong., Huang Z., Niu J.-L. Stimulation mechanism of oil well using high-pressure water jet deep-penetrating perforation technique. *Journal of the University of Petroleum China*. 2004. Vol. 28. Iss. 2, p. 38-41.

11. Rahman M.A., Mustafiz S., Koksal M., Islam M.R. Quantifying the skin factor for estimating the completion efficiency of perforation tunnels in petroleum wells. *Journal of Petroleum Science and Engineering*. 2007. Vol. 58. Iss. 1-2, p. 99-110. DOI: 10.1016/j.petrol.2006.11.012

12. Yu J., Li H., Chen X., Cai Y., Wu N., Mu K. Triaxial experimental study of associated permeability-deformation of sandstone under hydro-mechanical coupling. *Chinese Journal of Rock Mechanics and Engineering*. 2013. Vol. 32. Iss. 6, p. 1203-1213.

13. Wang J.-A., Park H.D. Fluid permeability of sedimentary rocks in a complete stress-strain process. *Engineering Geology*. 2002. Vol. 63. Iss. 3-4, p. 291-300. DOI: 10.1016/S0013-7952(01)00088-6

***Autors*: Sergei E. Chernyshov,** *Candidate of Engineering Sciences*, *Associate Professor*, *nirgnf@bk.ru* (*Perm National Research Polytechnic University*, *Perm*, *Russia*), **Vera A. Repina,** *Senior Lecturer*, *silajcheva.v@yandex.ru* (*Perm National Research Polytechnic University*, *Perm*, *Russia*), **Nikolai I. Krysin,** *Doctor of Engineering Sciences*, *Professor*, *krysin_niko@mail.ru* (*Perm National Research Polytechnic University*, *Perm*, *Russia*), **David Iain MacPherson MacDonald,** *Professor*, *d.macdonald@abdn.ac.uk* (*University of Aberdeen*, *Aberdeen*, *Scotland, United Kingdom*).

The paper was received on 13 May, 2020.
The paper was accepted for publication on 15 July, 2020.