PERM JOURNAL OF PETROLEUM AND MINING ENGINEERING
ВЕСТНИК ПНИПУ. ГЕОЛОГИЯ. НЕФТЕГАЗОВОЕ И ГОРНОЕ ДЕЛО
ISSN 2224-9923
Volume / Том 18 №2 2018
http://vestnik.pstu.ru/geo/

УДК 622.276-224.7:534

Article / Статья



# EVALUATION OF THE WAVE EFFECT EFFECTIVENESS IN CARBONATE RESERVOIRS WITH HIGH VISCOSITY OIL

**Vladimir V. Poplygin, Marian Wiercigroch[1]**

Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)
[1]University of Aberdeen (Centre for Applied Dynamics Research, King's College, AB24 3UE, Aberdeen, United Kingdom of Great Britain and Northern Ireland)

# ОЦЕНКА ЭФФЕКТИВНОСТИ ПРИМЕНЕНИЯ ВОЛНОВОГО ВОЗДЕЙСТВИЯ В КАРБОНАТНЫХ КОЛЛЕКТОРАХ С ВЫСОКОЙ ВЯЗКОСТЬЮ НЕФТИ*

**В.В. Поплыгин, М. Уирсигроч[1]**

Пермский национальный исследовательский политехнический университет (614990, Россия, г. Пермь, Комсомольский пр., 29)
[1]Абердинский университет (Центр исследования прикладной динамики, Королевский колледж, AB24 3UE, Абердин, Соединённое Королевство Великобритании и Северной Ирландии)

Received / Получена: 09.07.2018. Accepted / Принята: 24.10.2018. Published / Опубликована: 30.11.2018

*Key words:*
oil production, water cut, wave effect, fracture-porous reservoir, permeability, hydrodynamic modeling, oil recovery factor, unsteady flooding.

Development of fracture-porous reservoirs can be followed by breakthroughs of water injected into reservoirs through the system of cracks to production wells. This process can reduce the coverage of reservoir by sweeping, which will ultimately lead to a decrease in oil recovery factor. In order to perform a more effective fractured-porous reservoir flooding it is possible to use various methods associated with the injection of gel and sediment-forming agents, the use of wave technologies etc. The paper considers the formation with high-viscosity oil and fractured-porous reservoir. It is observed that water cut increase faster than oil recovery. The authors of the paper propose to use the wave effect associated with the stops of both injection and production wells. Shut-off and shut-in time of each well should be selected based on the parameters of the bottomhole zone. The specific value of the end time of the interaction of blocks and fractures when the pressure changes at the points of the reservoir can be roughly estimated from the beginning of the straight section of the pressure build-up curve in the fracture-porous reservoir. For the selected formation reservoir time of the end of the interaction between fractures and blocks with pressure changes was determined. Various options for implementation were proposed. Process impact modelling was performed using the Tempest More software package. According to the results of the simulation, it can be noted that the wave phenomenon is effective in terms of water cut reduction. Neverthelles, there are losses in oil production with long periods of shut-off of the wells. It should be noted that the time of interaction between fractures and blocks substantially depends on the permeability of the bottomhole zone; the higher the permeability the lower the time. It was also found that a variable frequency wave results in a greater effect.

*Ключевые слова:*
добыча нефти, обводненность, волновое воздействие, трещинно-поровый коллектор, проницаемость, гидродинамическое моделирование, коэффициент извлечения нефти, нестационарное заводнение.

При разработке трещинно-поровых коллекторов возможны прорывы нагнетаемой в пласты воды через систему трещин к добывающим скважинам. Данный процесс может снизить охват пласта воздействием системы разработки, что в итоге приведет к снижению коэффициента нефтеизвлечения. Для более полного охвата пласта воздействием на трещинно-поровом коллекторе возможно использование различных методов, связанных с закачкой геле- и осадкообразующих агентов, применением волновых технологий и др. В работе рассмотрена залежь с высоковязкой нефтью и трещинно-поровым коллектором. По объекту наблюдается опережение роста обводненности над выработкой запасов нефти. Авторы работы предлагают использовать волновое воздействие, связанное с остановками как нагнетательных, так и добывающих скважин. Время остановки и работы каждой скважины следует выбирать исходя из параметров призабойной зоны. Конкретное значение времени окончания взаимодействия блоков и трещин при изменении давления в точках пласта можно грубо оценить по началу прямолинейной части кривой восстановления давления в трещинно-поровом коллекторе. Для выбранного участка залежи определены времена окончания взаимодействия между трещинами и блоками при изменении давления, предложены различные варианты реализации. Моделирование процесса воздействия выполнено в программном комплексе Tempest More. По результатам моделирования можно отметить, что с точки зрения снижения обводненности волновое воздействие эффективно, но при длительных остановках добывающих скважин происходят потери добычи нефти. Следует отметить, что время взаимодействия между трещинами и блоками существенно зависит от проницаемости призабойной зоны, и с ее увеличением это время снижается. Также в работе установлено, что больший эффект при воздействии получен при использовании волны переменной частоты.

**Vladimir V. Poplygin** (Author ID in Scopus – 36574114000) – Associate Professor at the Department of Oil and Gas Technologies (tel.: +007 342 219 82 38, e-mail: poplygin@bk.ru). The contact person for correspondence.
**Marian Wiercigroch** (Author ID in Scopus – 56229012200) – Professor of the School of Engineering (tel.: +007 342 219 82 38, e-mail: poplygin@bk.ru).

**Поплыгин Владимир Валерьевич** – доцент кафедры нефтегазовых технологий (тел.: +007 342 219 82 38, e-mail: poplygin@bk.ru). Контактное лицо для переписки.
**Уирсигроч Мариан** – профессор Инженерной школы (тел.: +007 342 219 82 38, e-mail: poplygin@bk.ru).

* The study was carried out with the financial support of the Government of the Perm region in the framework of the research project No. С-26/786 dated 21 December 2017.

Исследование выполнено при финансовой поддержке Правительства Пермского края в рамках научного проекта № С-26/786 от 21.12.2017 г.

## Introduction

In the situations involving high number of sand beds, significant variations in stringers' permeability and presence of a fracture network, the water injected into the formations may burst through certain stringers or a fracture system to the producing wells [1, 2]. This process may limit the formation coverage by the development system, ultimately reducing oil recovery ratio [3-5]. Such deposit characteristics are most often encountered in carbonate reservoirs. In order to cover the formation with the stimulation, it is possible to use various methods related to the injection of gelling and sediment-forming agents [6-13], application of wave technologies [14-19, etc. Wave stimulation of the deposits may be achieved with the following methods [20-23]:

1) Cyclical flooding by significant change of the water injection rates (reduction or termination of injection) for a certain period of time with further renewal;

2) Change of filtration flows' direction by redistribution of water injection and fluid drainage across different deposit areas;

3) Focal flooding by additional water injection in the areas with a weak response to the previously deployed flooding system;

4) Forced fluid withdrawal from wells or groups of wells in highly flooded deposit areas, etc.

The above methods are usually used when oil production from a deposit starts declining.

A good effect from hydrodynamic stimulation methods is achieved in carbonate reservoirs [20] because they are mainly represented by fractured-porous reservoirs. More than a half of oil produced in Perm region is found in carbonate reservoirs [24].

There are various methods for determining the optimal time of injection and well shutdown to create a wave of pressure redistribution [25-29]. This paper considers the option of comprehensive cyclical stimulation of the production target through both injection and producing wells.

## Wave stimulation design

Wave stimulation of deposits is achieved through a wave of pressure redistribution. The speed of formation pressure redistribution will depend to a material extent on its filtration characteristics, which are expressed through the value of the permeability ratio. In Perm region, effective oil-saturated thicknesses usually don't exceed 10 m, and log-based permeability of more than 60 % of the reservoirs does not exceed 0.1 µm. In such conditions even low-viscosity oil may have a significant impact on the filtration in the formation [30]. The information set out in specialized publications [31-32] show that the use of comprehensive wave stimulation (on producing and injection wells) causes the flow of oil to the flooded channels, which is directly reflected in the hydrodynamic research results and allows increasing the coverage of a non-homogenous reservoir with the stimulation.

The processing of recovery curves indicates that a detrimental change in the characteristics of the wellbore area (WBA) leads to the slowdown of bottom hole pressure recovery in the shutdown well, which can be explained by the reduction of the area influenced by the well and the slowdown of fluid flow to the wellbore (Fig. 1) [33].

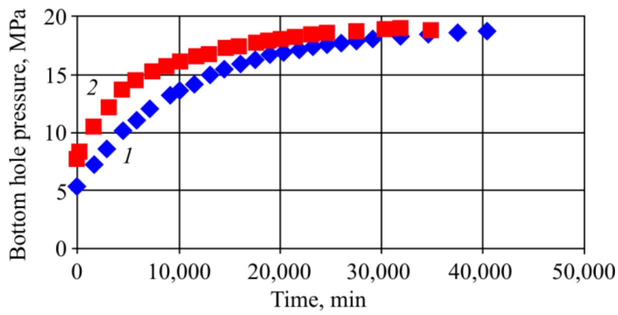


Fig. 1. Pressure recovery in the well 772 of Tournaisian target: *1* – $k_{WBA}$ = 0.0197 µm$^2$; *2* – $k_{WBA}$ = 0.0544 µm$^2$

In case of a change of pressure in the wellbore during the period of positive pressure impulses, the opening of formation fractures increases [34] and a fading filtration wave is formed. This wave may be presented as a harmonic fluctuation. With the lapse of time, certain drawdown pressure values will be established at each point of the formation as a result of redistribution of drawdown pressure at each point of the formation. Upon the creation of a pressure wave in several wells, each wave will evoke the exchange of fluids between blocks and fractures proportionate to the drawdown pressure at each given point. Whereas the wave is a harmonic motion, then during one half-period the fluid will flow through the blocks to the fractures and during another – from fractures to the blocks. Upon the creation in wellbores of pressure waves with different correctly selected frequencies, it is possible to create the resultant oscillations with maximum possible drawdown pressures in different points of the formation. The magnitude and frequency of the wave shall be selected based on the state of the wellbore areas. In [35] it is shown that with long time intervals the pressures in the blocks and fractures almost align and any cross-flows are terminated. The same paper suggests the determination of the closing time of interaction between blocks and fractures, when the well pressure recovery curve becomes straight in logarithmic coordinates. Based on hydrodynamic modelling in [36], it is noted that the best technological effect from well shutdown and activation in terms of water cut reduction is possible in case of work/downtime ratio of one to three.

Taking into account the above, we are going to evaluate the possibility of using short-term well shutdowns to create filtration wells and improve the effectiveness of deposit development on Tournaisian carbonate target with highly viscous oil in Perm region (Fig. 2).

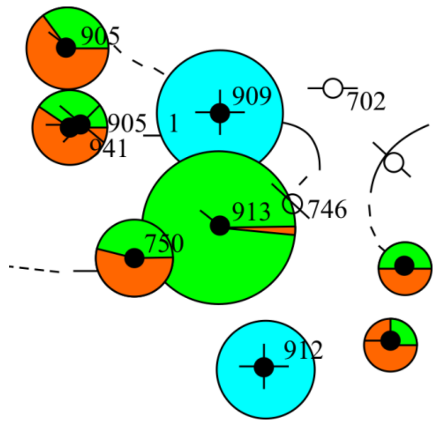


Fig. 2. A section of the deposit identified for evaluating the possibility of using filtration waves

Key deposit parameters are set out in Table 1. The target is characterized by lower values of permeability, low gas content of formation oil, high oil density and high number of sand beds.

Table 1

Geological and physical parameters of Tournaisian formation

| | Beryozovskoye oilfield |
|---|---|
| Average net oil thickness, m | 5.3 |
| Porosity, % | 15 |
| Permeability according to logging, μm$^2$ | 0.035 |
| Sand content ratio, unit fractions | 0.38 |
| Average number of permeable intervals, unit fractions | 3.56 |
| Oil viscosity in reservoir conditions, mPa·s | 87.08 |
| Oil density in reservoir conditions, tonnes/m$^3$ | 0.914 |
| Bubble point pressure, MPa | 8.9 |
| Gas content, m$^3$/tonne | 6.6 |
| Water viscosity in reservoir conditions, mPa·s | 1.44 |
| Water density in reservoir conditions, tonnes/m$^3$ | 1.179 |

The water cut of producing wells in the deposit section varies from 26 to 98 %, while oil output varies in the range of 1.1-8.1 tonnes/day.

The closing time of interaction between blocks and fractures ($T_C$) in case of a change of pressure in formation points may be roughly indicated by the start of the flat part of the pressure recovery curve of a fractured-porous reservoir (Fig. 3).

The following time values ($T_C$) were obtained for the wells located in the area: 747 – 95 hrs; 750 – 119 hrs; 905 – 46 hrs; 909 – 132 hrs; 912 – 83 hrs; 913 – 25 hrs; 926 – 105 hrs; 941 – 63 hrs.

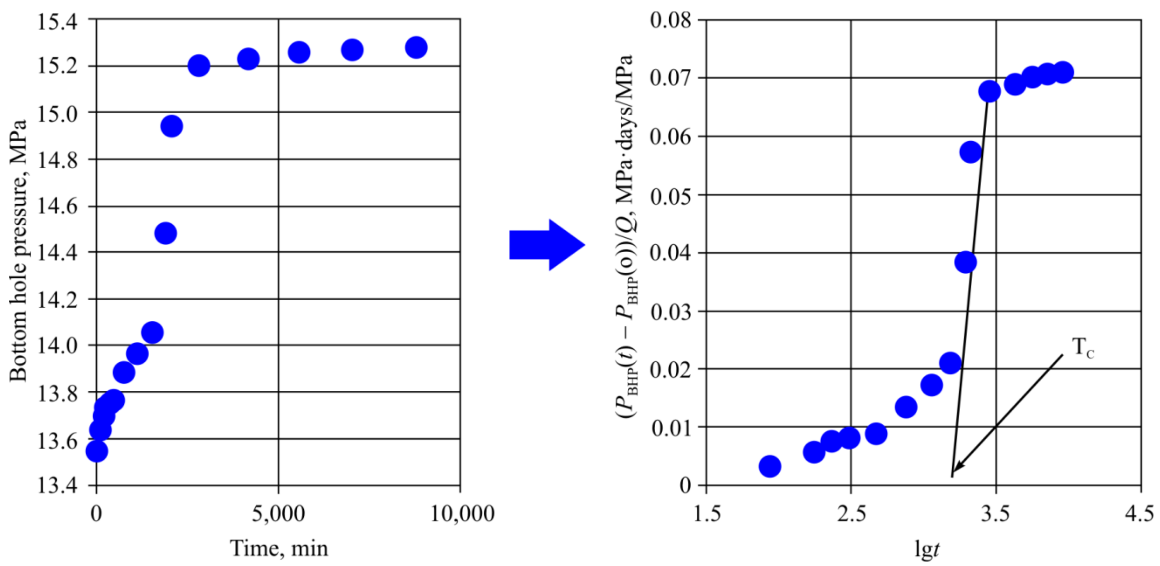


Fig. 3. The estimated closing time of interaction between blocks and fractures for Well 913. $P_{BHP}(t)$ and $P_{BHP}(o)$ – borehole pressure at time $t$ after a well shutdown and at the moment of shutdown, respectively

Table 2

Results of hydrodynamic modelling of wave stimulation during the first year

| Option | Time of well work/downtime, hrs | Accumulated fluid production, thousands of $m^3$ | Accumulated oil production, thousands of tons | Water cut, % |
|---|---|---|---|---|
| Basic | Wells operation in the current mode | 426.72 | 162.839 | 0.83 |
| 1 | 25/25* | 430.833 | 163.798 | 0.80 |
| 2 | 25/25 | 430.343 | 163.435 | 0.80 |
| 3 | 84/84 | 430.253 | 163.268 | 0.80 |
| 4 | 132/132 | 424.172 | 162.413 | 0.83 |
| 5 | Individual $T_C$ | 430.451 | 163.663 | 0.81 |

Note: * – only injection wells.

## Hydrodynamic modelling of wave stimulation

The software complex Tempest More has modelled the following options for creating a filtration wave: option 1 – periodic operation of only injection wells of the area; options 2-4 – setting the same operation and downtime mode for all the wells in the area at a constant level (option 2 – minimal time (25 hrs); option 3 – average time (84 hrs); option 4 – maximum time (132 hrs), option 5 – setting an individual operation and downtime mode for each well ($T_C$).

The results of hydrodynamic modelling are set out in Table 2.

The modelling has shown that practically all the options involve the growth of accumulated oil production as compared to the basic value, at the same time stagnation and slight reduction of water cut is observed. A negative technological effect was achieved as a result of long shutdown of producing and injection wells. The highest technological effect was observed only in case of periodic operation of only injection wells (cyclical water cut according to option 1) (Fig. 4).

The total oil output of the wells in the area as at the end of the first year of the modelling period amounted to 13.8 $m^3$/day in the basic option, and in other options – to 31-35 $m^3$/day; this means that the effect from cyclical stimulation even during a year will yield a lengthy positive impulse for the deposit development. In case of comprehensive stimulation the highest effect is achieved by different frequency operation of the wells, when the time of well operation and shutdown is selected individually based on the wellbore areas' parameters.

Studies [37-40] conclude that in case of comprehensive wave motion the effectiveness of the technology declines with time with same frequency. In connection with the evaluation of modelling results it should be noted that the rate of incremental oil production slows down and, therefore, it is necessary to correct the motion parameters in order to maintain high technological indicators.

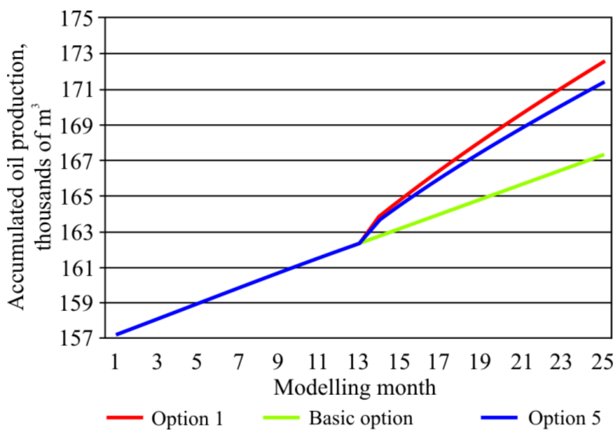


Fig. 4. Results of Modelling

## Conclusions

The provided materials allow drawing the following conclusions:

1. Wave technologies may be an effective method of enhancing the metrics of oil deposits development.

2. When planning comprehensive stimulation (on the producing and injection wells), it is necessary to choose the operation and downtime of each well based on their wellbore areas' characteristics.

3. It is necessary to change the operation and downtime of the wells to support high technological metrics of wave motion.

## References


1. Hou J., Luo M., Zhu D. Foam-EOR method in fractured-vuggy carbonate reservoirs: Mechanism analysis and injection parameter study. *Journal of Petroleum Science and Engineering*, 2018, vol.164, pp.546-558. DOI: 10.1016/j.petrol.2018.01.057

2. Min H., Chen L., Wang L., Zhang L., Chen J. Characteristics and mechanism of water production for fractured vuggy carbonate reservoirs, Halahatang Oilfield. *Journal of Southwest Petroleum University*, 2017, vol.39, iss.1, p.114-123. DOI: 10.1016/j.jngse.2017.02.022

3. Liu C., Li K., Tian X., Zhao G., Chen Y., Mahlalela B.M. Experimental studies on production performance of oil reservoirs with bottom water. *Journal of Petroleum Science and Engineering*, 2019, vol.172, pp.527-537. DOI: 10.1016/j.petrol.2018.09.052

4. Glover P.W.J., Lorinczi P., Al-Zainaldin S., Al-Ramadan H., Daniel G., Sinan S. Advanced fractal modelling of heterogeneous and anisotropic reservoirs. *SPWLA 59th Annual Logging Symposium*, 2018, 2-6 June. London.

5. Liu P., Mu Z., Wang W., Liu P., Hao M., Liu J. A new combined solution model to predict water cut in water flooding hydrocarbon reservoirs. *International Journal of Hydrogen Energy*, 2017, vol.42, iss.29, pp.18685-18690. DOI: 10.1016/j.ijhydene.2017.04.166.

6. Gladkikh E.A., Khizhnyak G.P. Rezultaty issledovaniy vodoizolyatsionnogo sostava na kernovoy modeli sloisto-neodnorodnogo plasta [Results of research of waterproofing composition on a core model of a layered heterogeneous formation]. *Oil industry*, 2017, no.11, pp.118-121. DOI: 10.24887/0028-2448-2017-11-118-121

7. Stroganov M.A. Tekhnologii vyravnivaniya profilya priemistosti nagnetatelnykh skvazhin s primeneniem kremniyorganicheskikh tamponazhnykh materialov gruppy AKOR [Technology of conformance control of injectivity profile of wells using silicone plugging materials of AKOR group]. *Neft. Gaz. Innovatsii*, 2016, no.4, pp.69-73.

8. Abilkhairov D.T., Almukhametova E.M., Vladimirov I.V. Rezultaty vnedreniya tekhnologii vyravnivaniya profilya priemistosti s primeneniem gellana v kachestve tamponiruyushchego agenta [Results of applying new technology injectivity profile alignment of gellan as agent plugging]. *Neftegazovoe delo*, 2017, vol.15, no.1, pp.65-69. DOI: http://dx.doi.org/10.17122/ngdelo-2017-1-65-69

9. Khasanov I.M. Rezultaty primeneniya tekhnologiy po vyravnivaniyu profiley priemistosti (VPP) nagnetatelnykh skvazhin na mestorozhdeniyakh AO "Vareganneftegaz" [Results of application of the technologies for conformance control of injectivity profiles of wells on the fields of Varioganneftegaz JSC]. *Neft. Gaz. Innovatsii*, 2015, no.7, pp.28-33.

10. Yushkov I.R., Tsvetkov G.A. Itensifikatsiya dobychi vysokovyazkoy nefti Opalikhinskogo mestorozhdeniya [Intensification of highly-viscous oil recovery at the Opalikhinskoe field]. *Vestnik Permskogo universiteta. Geologiya*, 2017, vol.16, no.1, pp.84-90, DOI: 10.17072/psu.geol.16.1.84

11. Cavallaro A.N., Martinez M.E.G., Ostera H., Panarello H., Cordero R.R. Oilfield reservoir souring during waterflooding: A case study with low sulphate concentration in formation and injection water. *Proceedings SPE International Symposium on Oilfield Chemistry2005*, no. SPE 92959, pp.131-142. DOI: 10.2118/92959-MS

12. Wassmuth F.R., Arnold W., Green K., Cameron N. Polymer flood application to improve heavy oil recovery at East Bodo. *Journal of Canadian Petroleum Technology*, 2009, 48(2), pp.55-61. DOI: 10.2118/09-02-55

13. Hou J., Li Z.-Q., Cao X.-L., Song, X.-W. Integrating genetic algorithm and support vector machine for polymer flooding production performance prediction. *Journal of Petroleum Science and Engineering*, 2009, vol.68, iss.1-2, pp.29-39. DOI: 10.1016/j.petrol.2009.05.017

14. Paliy A.O., Rayanov R.R. Prichiny neuspeshnosti nestatsionarnogo zavodneniya pri razrabotke nizkopronitsaemykh kollektorov nefti [The reasons for the failure of unsteady flooding in the development of low-permeability oil reservoirs]. *Neft, gaz i biznes*, 2013, no.6, pp.38-42.

15. Tarakanova O.E., Galiullin M.M., Dubovetskaya N.V. Nestatsionarnoe zavodnenie kak sposob povysheniya effektivnosti realizovannoy sistemy podderzhaniya plastovogo davleniya [Non-stationary water injection as a way of waterflood system performing]. *Neftyanoe khozyaystvo*, 2013, no.11, pp.49-53.

16. Shulev Yu.V., Vinokhodov m.a., Kryanev D.Yu., Petrakov A.M., Shilova A.I., Zhukov R.Yu. Primenenie metodov uvelicheniya nefteotdachi i adresnykh obrabotok skvazhin na mestorozhdeniyakh OAO "Slavneft-Megionneftegaz" [Application of enhanced oil recovery methods and targeted well treatments at the fields of Slavneft-Megionneftegaz OJSC]. *Neftyanoe khozyaystvo*, 2012, no. 1, pp.64-66.

17. Vaganov L.A., Telegin I.G. Vliyanie ostanovok nagnetatelnykh skvazhin na razrabotku obekta YuS1 mestorozhdeniya "Gribnoe" [Impact of shut-off of injection wells on the development of the facility for the $YuS_1$ field "Gribnoe"]. *Izvestiya vysshikh uchebnykh zavedeniy. Neft i gaz*, 2011, no.4, pp.66-71.

18. Vaganov L.A., Telegin I.G. Analiz effektivnosti nestatsionarnogo zavodneniya yurskikh otlozheniy Kogalymskogo rayona [Analysis of Jurassic deposits non-stationary waterflooding efficiency]. *Izvestiya vysshikh uchebnykh zavedeniy. Neft i gaz*, 2011, no.6, pp.62-68.

19. Kruglov Ya.A. O primenenii nestatsionarnogo zavodneniya na obvodnennykh neftyanykh mestorozhdeniyakh [On the use of non-stationary waterflooding in flooded oil fields]. *Vestnik Severo-Kavkazskogo gosudarstvennogo tekhnicheskogo universiteta*, 2012, no.3 (32), pp.85-87.

20. Amelin I.D., Surguchev M.L., Davydov A.V. Prognoz razrabotki neftyanykh zalezhey na pozdney stadii [Late stage oil development forecast]. Moscow, Nedra, 1994, 308 p.

21. Shchipanov, A.A., Surguchev, L.M., Jakobsen, S.R. Improved oil recovery by cyclic injection and production. *Society of Petroleum Engineers – SPE Russian Oil and*

*Gas Technical Conference and Exhibition*, 2008, 2, pp.901-911. DOI: 10.2118/116873-MS

22. Mai A., Kantzas, A. Improved heavy oil recovery by low rate waterflooding. *Society of Petroleum Engineers – International Thermal Operations and Heavy Oil Symposium*, *ITOHOS 2008* "Heavy Oil: Integrating the Pieces", 2008, 2, pp.727-738. DOI: 10.2118/117648-MS

23. Guan W., Wu S., Jiang Y., Liang J. 3D physical model of steam injection in high water-cut reservoir. *Shiyou Xuebao/Acta Petrolei Sinica*, 2009, vol.30, iss.3, pp.404-408.

24. Poplygin V.V., Beloglazova E.A., Ivanova A.S. Analysis of acid treatments in complex geological and technological conditions. *Perm Journal of Petroleum and Mining Engineering*, 2014, vol.13, no.10, pp.83-90. DOI: 10.15593/2224-9923/2014.10.8

25. Chumakov G.N. Probabilistic estimate of effectiveness of the method of cyclic bed fluid injection. *Perm Journal of Petroleum and Mining Engineering*, 2014, vol.13, no.13, pp.49-58. DOI: 10.15593/2224-9923/2014.13.5

26. Khabibullin M.Ya., Suleymanov R.I., Zaynagalina L.Z., Petrov V.A. Varianty impulsnogo nestatsionarnogo zavodneniya v blokovykh sistemakh razrabotki [Options of pulse non-stationary water flooding in block systems of development]. *Izvestiya vysshikh uchebnykh zavedeniy. Neft i gaz*, 2017, no.5, pp.99-103.

27. Vladimirov I.V., Almukhametova E.M., Umetbaev V.G. Teoreticheskoe issledovanie vliyaniya posloynoy pronitsaemostnoy neodnorodnosti produktivnogo plasta na effektivnost nestatsionarnogo zavodneniya [Theoretical study of the effect of stratified permeability heterogeneity of the reservoir on the efficiency of non-stationary waterflooding]. *Problemy sbora, podgotovki i transporta nefti i nefteproduktov*, 2015, no.2(100), pp.33-45. DOI: 10.17122/ntj-oil-2015-2-33-45

28. Vladimirov I.V., Pichugin O.N., Veliev E.M. Tekhnologiya nestatsionarnogo vozdeystviya, predusmatrivayushchaya periodicheskuyu rabotu dobyvayushchikh i nagnetatelnykh skvazhin v protivofaze [Technology of a formation non-stationary simulation that envisages periodic operation of producing and injection wells in in the antiphase]. *Neftepromyslovoe delo*, 2015, no.11, pp.56-59.

29. Huang X., Ling Y. Water injection optimization using historical production and seismic data. *Proceedings – SPE Annual Technical Conference and Exhibition*, *SPE Annual Technical Conference and Exhibition*, 24-27 September, San Antonio, 4, pp.2202-2209. DOI: 10.2118/102499-MS

30. Nazarova L.N. Vliyanie sootnosheniya parametrov, opredelyayushchikh gidroprovodnost plasta, na velichinu raschetnogo koeffitsienta izvlecheniya nefti [Influence of parameters ratio that defines the formation flow capacity on the value of the calculated oil recovery factor]. *Oilfield engineering*, 2014, no.10, pp.20-23.

31. Vladimirov I.V., Almukhametova E.M., Varisova R.R. Analiz vliyaniya nestatsionarnogo zavodneniya na rezultaty gidrodinamicheskikh issledovaniy skvazhin [Analysis of non-stationary water-flooding on the results of wells' hydrodynamic research]. *Oilfield engineering*, 2016, no.10, pp. 55-57.

32. Vladimirov I.V., Almukhametova E.M., Varisova R.R., Abutalipova E.M., Avrenyuk A.N. Analiz vliyaniya nestatsionarnogo zavodneniya na rezultaty gidrodinamicheskikh issledovaniy skvazhin [Analysis of non-stationary water-flooding on the results of wells' hydrodynamic research]. *Territoriya Neftegaz*, 2016, no.9, pp.68-71.

33. Feng Q., Wang S., Gao G., Li C. A new approach to thief zone identification based on interference test. *Journal of Petroleum Science and Engineering*, 2010, vol.75, iss.1-2, pp.13-18. DOI: 10.1016/j.petrol.2010.10.005

34. Mamedova M.A. Issledovanie parametrov prizaboynoy zony treshchinnykh plastov pri neustanovivshemsya rezhime [Investigation of parameters of the bottomhole zone of fractured formations at unsteady state]. *Bulatovskie chteniya*, 2018, vol.2, no.1, pp.252-254.

35. Molokovich Yu.M. Neravnovesnaya filtratsiya i ee primenenie v neftepromyslovoy praktike [Nonequilibrium flow and its application in oilfield practice]. Moscow, Izhevsk, RkHD, Institut kompyuternykh issledovaniy, 2006, 214 p.

36. Tsiklis I.M., Moiseeva E.F. Issledovanie vliyaniya prodolzhitelnosti perioda prostoya/raboty nagnetatelnykh skvazhin na effektivnost primeneniya nestatsionarnogo zavodneniya v neftyanykh zalezhakh v usloviyakh chas [The study of the effect of time of stopping/operating period of injection wells on the effectiveness of non-stationary flooding in partially degassed deposits]. *Bulatovskie chteniya*, 2017, vol.2, pp.296-301.

37. Vladimirov I.V., Pichugin O.N., Gorshkov A.V. Opyt primeneniya tekhnologiy nestatsionarnogo zavodneniya na zalezhakh vysokovyazkoy nefti mestorozhdeniya Severnye Buzachi [Experience of application of non-stationary flooding technology at high-viscous deposits of North Buzachi oil field]. *Oilfield engineering*, 2013, no.11, pp46-52.

38. Sanchez-Rivera D., Mohanty K., Balhoff M. Reservoir simulation and optimization of Huff-and-Puff operations in the Bakken Shale. *Fuel*, 2015, vol.147, pp.82-94. DOI: 10.1016/j.fuel.2014.12.062

39. Wen H., Sun N., Liu Y. Index system evaluating water flooding development effect of oilfield at ultra-high water cut stage. *Journal of Petroleum Exploration and Production Technology*, 2017, vol.7, iss.1, pp.111-123. DOI: 10.1007/s13202-016-0249-3.

40. Khokhlov V.I., Galimov Sh.S., Kotenyev Yu.A., Sultanov Sh.Kh., Mukhametshin V.V. Effektivnost nestatsionarnogo zavodneniya v protsesse izmeneniya gorno-geologicheskikh usloviy ekspluatatsii produktivnykh plastov [Non-stationary water-flooding efficiency in the process of mining-geological conditions change of productive formations operation]. *Geologiya, geofizika i razrabotka neftyanykh i gazovykh mestorozhdeniy*, 2018, no.1, pp.54-58.

## Библиографический список


1. Hou J., Luo M., Zhu D. Foam-EOR method in fractured-vuggy carbonate reservoirs: Mechanism analysis and injection parameter study // Journal of Petroleum Science and Engineering. – 2018. – Vol. 164. – P. 546–558. DOI: 10.1016/j.petrol.2018.01.057

2. Min H., Chen L., Wang L., Zhang L., Chen J. Characteristics and mechanism of water production for fractured vuggy carbonate reservoirs, Halahatang Oilfield // Journal of Southwest Petroleum University. 2017. – Vol. 39, iss. 1, – P. 114–123. DOI: 10.1016/j.jngse.2017.02.022

3. Liu C., Li K., Tian X., Zhao G., Chen Y., Mahlalela B.M. Experimental studies on production performance of oil reservoirs with bottom water // Journal of Petroleum Science and Engineering. – 2019. – Vol. 172. – P. 527–537. DOI: 10.1016/j.petrol.2018.09.052

4. Glover P.W.J., Lorinczi P., Al-Zainaldin S., Al-Ramadan H., Daniel G., Sinan S. Advanced fractal modelling of heterogeneous and anisotropic reservoirs // SPWLA 59th Annual Logging Symposium, 2-6 June. – London, 2018.

5. Liu P., Mu Z., Wang W., Liu P., Hao M., Liu J. A new combined solution model to predict water cut in water flooding hydrocarbon reservoirs // International Journal of Hydrogen Energy. – 2017. – Vol. 42, iss. 29. – P. 18685–18690. DOI: 10.1016/j.ijhydene.2017.04.166

6. Гладких Е.А., Хижняк Г.П. Результаты исследований водоизоляционного состава на керновой модели слоисто-неоднородного пласта // Нефтяное хозяйство. – 2017. – № 11. – С. 118–121. DOI: 10.24887/0028-2448-2017-11-118-121

7. Строганов М.А. Технологии выравнивания профиля приемистости нагнетательных скважин с применением кремнийорганических тампонажных материалов группы АКОР // Нефть. Газ. Инновации. – 2016. – № 4. – С. 69–73.

8. Абилхаиров Д.Т., Альмухаметова Э.М., Владимиров И.В. Результаты внедрения технологии выравнивания профиля приемистости с применением геллана в качестве тампонирующего агента // Нефтегазовое дело. – 2017. – Т. 15, № 1. – С. 65–69. DOI: http://dx.doi.org/10.17122/ngdelo-2017-1-65-69

9. Хасанов И.М. Результаты применения технологий по выравниванию профилей приемистости (ВПП) нагнетательных скважин на месторождениях АО «Варьеганнефтегаз» // Нефть. Газ. Инновации. – 2015. – № 7. – С. 28–33.

10. Юшков И.Р., Цветков Г.А. Итенсификация добычи высоковязкой нефти Опалихинского месторождения // Вестник Пермского университета. Геология. – 2017. – Т. 16, № 1. – С. 84–90. DOI: 10.17072/psu.geol.16.1.84

11. Oilfield reservoir souring during waterflooding: A case study with low sulphate concentration in formation and injection waters / A.N. Cavallaro, M.E.G. Martinez, H. Ostera, H. Panarello, R.R. Cordero // Proceedings – SPE International Symposium on Oilfield Chemistry 2005, SPE 92959. – P. 131–142. DOI: 10.2118/92959-MS

12. Polymer flood application to improve heavy oil recovery at East Bodo / F.R. Wassmuth, W. Arnold, K. Green, N. Cameron // Journal of Canadian Petroleum Technology. – 2009. – 48 (2). – P. 55–61. DOI: 10.2118/09-02-55

13. Hou J., Li Z.-Q., Cao X.-L., Song, X.-W. Integrating genetic algorithm and support vector machine for polymer flooding production performance prediction // Journal of Petroleum Science and Engineering. – 2009. – Vol. 68, iss. 1–2. – P. 29–39. DOI: 10.1016/j.petrol.2009.05.017

14. Палий А.О., Раянов Р.Р. Причины неуспешности нестационарного заводнения при разработке низкопроницаемых коллекторов нефти // Нефть, газ и бизнес. – 2013. – № 6. – С. 38–42.

15. Тараканова О.Э., Галиуллин М.М., Дубовецкая Н.В. Нестационарное заводнение как способ повышения эффективности реализованной системы поддержания пластового давления // Нефтяное хозяйство. – 2013. – № 11. – С. 49–53.

16. Применение методов увеличения нефтеотдачи и адресных обработок скважин на месторождениях ОАО «Славнефть-Мегионнефтегаз» / Ю.В. Шульев, М.А. Виноходов, Д.Ю. Крянев, А.М. Петраков, А.И. Шилова, Р.Ю. Жуков // Нефтяное хозяйство. – 2012. – № 1. – С. 64–66.

17. Ваганов Л.А., Телегин И.Г. Влияние остановок нагнетательных скважин на разработку объекта ЮС1 месторождения «Грибное» // Известия высших учебных заведений. Нефть и газ. – 2011. – № 4. – С. 66–71.

18. Ваганов Л.А., Телегин И.Г. Анализ эффективности нестационарного заводнения юрских отложений Когалымского района // Известия высших учебных заведений. Нефть и газ. – 2011. – № 6. – С. 62–68.

19. Круглов Я.А. О применении нестационарного заводнения на обводненных нефтяных месторождениях // Вестник Северо-Кавказского государственного технического университета. – 2012. – № 3 (32). – С. 85–87.

20. Амелин И.Д., Сургучев М.Л., Давыдов А.В. Прогноз разработки нефтяных залежей на поздней стадии. – М.: Недра, 1994. – 308 с.

21. Shchipanov A.A., Surguchev L.M., Jakobsen S.R. Improved oil recovery by cyclic injection and production // Society of Petroleum Engineers – SPE Russian Oil and Gas Technical Conference and Exhibition. – 2008. – 2. – P. 901–911. DOI: 10.2118/116873-MS

22. Mai A., Kantzas A. Improved heavy oil recovery by low rate waterflooding // Society of Petroleum Engineers – International Thermal Operations and Heavy Oil Symposium, «Heavy Oil: Integrating the Pieces». – 2008. – 2. – P. 727–738. DOI: 10.2118/117648-MS

23. Guan W., Wu S., Jiang, Y., Liang J. 3D physical model of steam injection in high water-cut reservoir // Shiyou Xuebao / Acta Petrolei Sinica. – 2009. – Vol. 30, iss. 3. – P. 404–408.

24. Поплыгин В.В., Белоглазова Е.А., Иванова А.С. Анализ результатов проведения кислотных обработок в сложных геолого-технологических условиях // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2014. – Т. 13, № 10. – С. 83–90. DOI: 10.15593/2224-9923/2014.10.8

25. Чумаков Г.Н. Вероятностная оценка эффективности применения метода циклической закачки жидкости в пласт // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2014. – Т. 13, № 13. – С. 49–58. DOI: 10.15593/2224-9923/2014.13.5

26. Варианты импульсного нестационарного заводнения в блоковых системах разработки / М.Я. Хабибуллин, Р.И. Сулейманов, Л.З. Зайнагалина, В.А. Петров // Известия высших учебных заведений. Нефть и газ. – 2017. – № 5. – С. 99–103.

27. Владимиров И.В., Альмухаметова Э.М., Уметбаев В.Г. Теоретическое исследование влияния послойной проницаемостной неоднородности продуктивного пласта на эффективность нестационарного заводнения // Проблемы сбора, подготовки и транспорта нефти и нефтепродуктов. – 2015. – № 2 (100). – С. 33–45. DOI: 10.17122/ntj-oil-2015-2-33-45

28. Владимиров И.В., Пичугин О.Н., Велиев Э.М. Технология нестационарного воздействия, предусматривающая периодическую работу добывающих и нагнетательных скважин в противофазе // Нефтепромысловое дело. – 2015. – № 11. – С. 56–59.

29. Huang X., Ling Y. Water injection optimization using historical production and seismic data // Proceedings – SPE Annual Technical Conference and Exhibition, SPE Annual Technical Conference and Exhibition, 24–27 September, San Antonio. – 4. – P. 2202–2209. DOI: 10.2118/102499-MS

30. Назарова Л.Н. влияние соотношения параметров, определяющих гидропроводность пласта, на величину расчетного коэффициента извлечения нефти // Нефтепромысловое дело. – 2014. – № 10. – С. 20–23.

31. Владимиров И.В., Альмухаметова Э.М., Варисова Р.Р. Анализ влияния нестационарного заводнения на результаты гидродинамических исследований скважин // Нефтепромысловое дело. – 2016. – № 10. – С. 55–57.

32. Анализ влияния нестационарного заводнения на результаты гидродинамических исследований скважин / И.В. Владимиров, Э.М. Альмухаметова, Р.Р. Варисова, Е.М. Абуталипова, А.Н. Авренюк // Территория Нефтегаз. – 2016. – № 9. – С. 68–71.

33. Feng Q., Wang S., Gao G., Li C. A new approach to thief zone identification based on interference test // Journal of Petroleum Science and Engineering. – 2010. – Vol. 75, iss. 1–2. – P. 13–18. DOI: 10.1016/j.petrol.2010.10.005

34. Мамедова М.А. Исследование параметров призабойной зоны трещинных пластов при неустановившемся режиме // Булатовские чтения. – 2018. – Т. 2, № 1. – С. 252–254.

35. Молокович Ю.М. Неравновесная фильтрация и ее применение в нефтепромысловой практике. М. – Ижевск: РХД, Институт компьютерных исследований, 2006. – 214 с.

36. Циклис И.М., Моисеева Е.Ф. Исследование влияния продолжительности периода простоя/работы нагнетательных скважин на эффективность применения нестационарного заводнения в нефтяных залежах в условиях частичного разгазирования // Булатовские чтения. – 2017. – Т. 2. – С. 296–301.

37. Владимиров И.В., Пичугин О.Н., Горшков А.В. Опыт применения технологий нестационарного заводнения на залежах высоковязкой нефти месторождения Северные Бузачи // Нефтепромысловое дело. – 2013. – № 11. – С. 46–52.

38. Sanchez-Rivera D., Mohanty K., Balhoff M. Reservoir simulation and optimization of Huff-and-Puff operations in the Bakken Shale // Fuel. – 2015. – Vol. 147. – P. 82–94. DOI: 10.1016/j.fuel.2014.12.062

39. Wen H., Sun N., Liu Y. Index system evaluating water flooding development effect of oilfield at ultra-high water cut stage // Journal of Petroleum Exploration and Production Technology. – 2017. – Vol. 7, iss. 1. – P. 111–123. DOI: 10.1007/s13202-016-0249-3

40. Эффективность нестационарного заводнения в процессе изменения горно-геологических условий эксплуатации продуктивных пластов / В.И. Хохлов, Ш.С. Галимов, Ю.А. Котенев, Ш.Х. Султанов, В.В. Мухаметшин // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2018. – № 1. – С. 54–58.

Please cite this article in English as:
Poplygin V.V., Wiercigroch M. Evaluation of the wave effect effectiveness in carbonate reservoirs with high viscosity oil. *Perm Journal of Petroleum and Mining Engineering*, 2018, vol.18, no.2, pp.149-156. DOI: 10.15593/2224-9923/2018.4.5

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Поплыгин В.В., Уирсигроч М. Оценка эффективности применения волнового воздействия в карбонатных коллекторах с высокой вязкостью нефти // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2018. – Т.18, №2. – С.149–156. DOI: 10.15593/2224-9923/2018.4.5