ISSN 2712-8008
Volume / Том 25 №1 2025
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.276
Article / Статья

Determination of the Optimal Injection Ratio of Fluids in Water-Gas Influence

Nikolai V. Leushin, Alexander P. Shevelev, Alexander Y. Gilmanov

Tyumen State University (6 Volodarskogo st., Tyumen, 625003, Russian)

Определение оптимального соотношения закачки флюидов при водогазовом воздействии

Н.В. Леушин, А.П. Шевелев, А.Я. Гильманов

Тюменский государственный университет (Российская Федерация, 625003, г. Тюмень, ул. Володарского, 6)

Received / Получена: 01.12.2024. Accepted / Принята: 05.12.2024. Published / Опубликована: 24.02.2025

Keywords:
Water-gas stimulation, water-gas mixture, gas-oil contact, horizontal well, gas factor, associated petroleum gas, reservoir pressure maintenance, near-wellbore zone, enhanced oil recovery, oil recovery coefficient, hydrocarbons, compositional model, pilot industrial operations, modeling, correlation.

Hard-to-recover reserves are icreasing in size every year, and the classical development of fields with such reserves is not so effective, therefore the application of enhanced oil recovery methods is relevant. Such method of enhanced oil recovery as water-gas stimulation will be presented in this paper.
There are two types of water-gas simulation: alternating water and gas injection and simultaneous injection. Alternating water and gas injection is focused in this work. The process involves the sequential injection of gas followed by water.
This method is widely implemented, and experience in conducting such operations has already been accumulated. The goal was to identify scenarios that could cover the realistically possible conditions for the application of water-gas stimulation and to find the optimally effective ratio of water and gas injection. The parameters for ranking included reservoir permeability, reservoir compartmentalization, the development system with various well designs and spacing between wells, as well as various volumes of injected agents (water, gas).
Multivariate calculations were carried out on a sectoral hydrodynamic model (E300). Since experiments on miscibility conditions were not conducted, it was assumed that oil displacement during water-gas influence occurred without gas mixing with oil.
Based on the processing of the entire dataset (more than 10,000 calculations), a database of development systems with various input geological and physical characteristics was formed and dependencies for cumulative oil production at different volumes of water and gas injection were obtained.
The effect of water-gas stimulation is noticeable with reservoir permeability greater than 20 mD. The effective water and gas injection ratio should ensure that the liquid withdrawal compensation is above 100%, both for water and gas injection.

Ключевые слова:
водогазовое воздействие, водогазовая смесь, газонефтяной контакт, горизонтальная скважина, газовый фактор, попутный нефтяной газ, поддержание пластового давления, призабойная зона пласта, повышение нефтеотдачи пласта, коэффициент извлечения нефти, углеводород, композиционная модель, опытно-промышленные работы, моделирование, корреляция.

Трудноизвлекаемые запасы растут с каждым годом, и классическая разработка месторождений с такими запасами не так эффективна, поэтому применение методов увеличения нефтеотдачи актуально. В работе будет представлен метод увеличения нефтеотдачи как водогазовое воздействие.
Классифицируют два вида водогазового воздействия: попеременная закачка воды и газа и совместная. В исследовании рассматривается попеременная закачка воды и газа. Сам процесс представляет собой порционную закачку сначала газа, затем воды.
Данный метод обширно внедряется и уже накоплен опыт проведения таких мероприятий, целью было сформировать такие сценарии, чтобы в наибольшей степени охватить реально возможные условия применения водогазового воздействия и найти при этом оптимальное соотношение закачки воды и газа. Под параметры ранжирования были взяты проницаемость коллектора, расчлененность пласта, система разработки с различными конструкциями скважин и расстоянием между скважинами, а также различные объемы закачиваемого агента (вода, газ).
Многовариантные расчеты проводились на секторной гидродинамической модели (E300). Так как опыты на условие смесимости не проводились, считалось, что вытеснение нефти при водогазовом воздействии происходило без смешения газа и нефти.
По результатам обработки всего массива данных (более 10 000 расчетов) была сформирована база систем разработок с различными входными геолого-физическим характеристиками, где получены зависимости накопленной добычи нефти при различных объемах закачки воды и газа.
Эффект применения водогазового воздействия заметен при проницаемости коллектора более 20 мД. Эффективное соотношение закачки воды и газа – это компенсация отборов жидкости, которая должна быть выше 100 % как при закачке воды, так и закачке газа.

© **Nikolai V. Leushin** – PhD student at the Department of Modeling Physical Processes and Systems (tel.: +007 912 492 93 38, e-mail: leushinnikval@mail.ru). The contact person for correspondence.
© **Alexander P. Shevelev** (Author ID in Scopus: 37013734300, ORCID: 0000-0003-0017-4871) – Doctor in Physics and Mathematics, Professor at the Department of Modeling Physical Processes and Systems (tel.: +007 912 991 90 14, e-mail: a.p.shevelev@utmn.ru).
© **Alexander Y. Gilmanov** (Author ID in Scopus: 57205429154, ORCID: 0000-0002-7115-1629) – PhD in Physics and Mathematics, Associate Professor at the Department of Modeling Physical Processes and Systems (tel.: +007 904 496 18 41, e-mail: a.y.gilmanov@utmn.ru).

© **Леушин Николай Валентинович** – аспирант кафедры моделирования физических процессов и систем (тел.: +007 912 492 93 38, e-mail: leushinnikval@mail.ru). Контактное лицо для переписки.
© **Шевелев Александр Павлович** – доктор физико-математических наук, профессор кафедры моделирования физических процессов и систем (тел.: +007 912 991 90 14, e-mail: a.p.shevelev@utmn.ru).
© **Гильманов Александр Янович** – кандидат физико-математических наук, доцент кафедры моделирования физических процессов и систем (тел.: +007 904 496 18 41, e-mail: a.y.gilmanov@utmn.ru).

Please cite this article in English as:
Leushin N.V., Shevelev A.P., Gilmanov A.Y. Determination of the Optimal Injection Ratio of Fluids in Water-Gas Influence. *Perm Journal of Petroleum and Mining Engineering*, 2025, vol.25, no.1, pp. 47-51. DOI: 10.15593/2712-8008/2025.1.6

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Леушин, Н.В. Определение оптимального соотношения закачки флюидов при водогазовом воздействии / Н.В. Леушин, А.П. Шевелев, А.Я. Гильманов // Недропользование. – 2025. – Т.25, №1. – С. 47–51. DOI: 10.15593/2712-8008/2025.1.6

Introduction

The relevance of this topic is due to the growing share of hard-to-recover reserves, which makes water-gas stimulation of formations (WGS) a promising tool for achieving economic benefits through enhanced oil recovery.

The technology of water-gas stimulation is becoming attractive for implementation, and the number of measures taken is growing. The greatest application of this technology was found at the Samotlor field. The effect obtained from this measure is unique: the amount of additional oil produced at this field was greater than oil production at other fields [1–8].

This type of geological and technical intervention - water-gas stimulation - was carried out at such fields as Samotlor, Bitkovskoye, Ilishevskoye, Alekseevskoye and had positive results [9–18].

At the Samotlorskoye field WGI made it possible to increase oil production and reduce water cut at the pilot development area. As a result of these measures the oil recovery factor was increased by more than 5 %.

At the Bitkovskoye field this technology increased the oil recovery factor by 16 %. This result was achieved by increasing reservoir pressure (the decline trend changed), thereby increasing the oil flow rate and stabilising the gas factor. Additional production from water-gas stimulation amounted to 750 thousand tonnes of oil.

The application of WGI at the Ileshevskoye field (1999) gave a positive result. The effect of the measures was recorded in the form of increased oil production, reduced water and associated gas production.

At the Alekseevskoye field WGI has been carried out since 2005. By mixing produced water and associated gas the mixture was injected into the well. The effect of this measure made it possible to increase the oil recovery factor by 40 % (from 0.170 fractions of unit to 0.240 fractions of unit).

The effect of this technology was also obtained at other fields. For example, at the Vakhovskoye field about 5 thousand tonnes of additional produced oil were obtained due to water-gas simulation.

How much to pump? What is the volume of gas and water injection? And under what geological conditions water-gas injection will show itself better? And what is the injection mode? These questions will be answered in the course of this work.

Criteria and Approaches

Water-gas stimulation is the economically expensive activity. It requires specialists with extensive experience and equipment to ensure reliability and safety of such hydrodynamic modelling (HDM).

To select the conditions for performing WGS the analysis of A.I. Vashurkin and M.S. Svishchev study was used. The criteria are presented in Fig. 1.

The generated variants were calculated on a hydrodynamic model. The model of E300 type [19–37] satisfies all the conditions for taking into account the movement of three phases (Fig. 2). With its help it is possible to consider how a hydrocarbon fluid displaces gas of different component composition.

Obtaining plausible calculations is achieved by using a sector model which satisfies the applicability criteria for conducting WGS (Table).

Different degrees of uncertainty are found in all areas. Hydrocarbon extraction is no exception, and uncertainties can be found in both surface and subsurface infrastructure (Fig. 3).

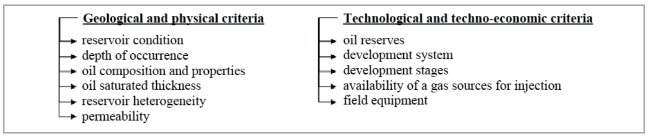

Fig. 1. WGS site selection criteria

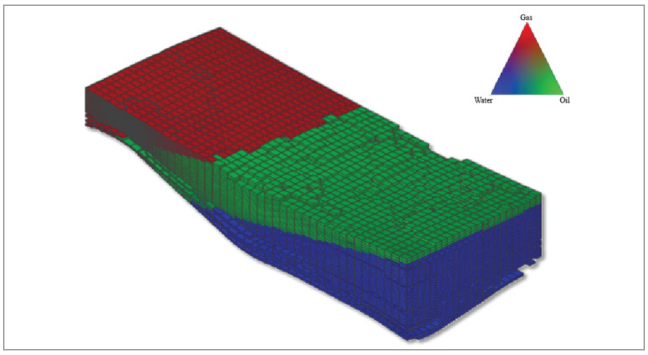

Fig. 2. Sectoral WGS for carrying out multivariate calculations

Parameters of the sector hydrodynamic model

Parameter	Value
Initial oil saturation, %	85
Initial water saturation, %	15
$p_{in.res}$, MPa	13.1
P_{sat}, MPa	13.1
$K_{porosity}$, %	15
$K_{compressibility}$, Mpa^{-1}	10^{-4}
$K_{permibility}$, mD	355
Gas content, m^3/t	75

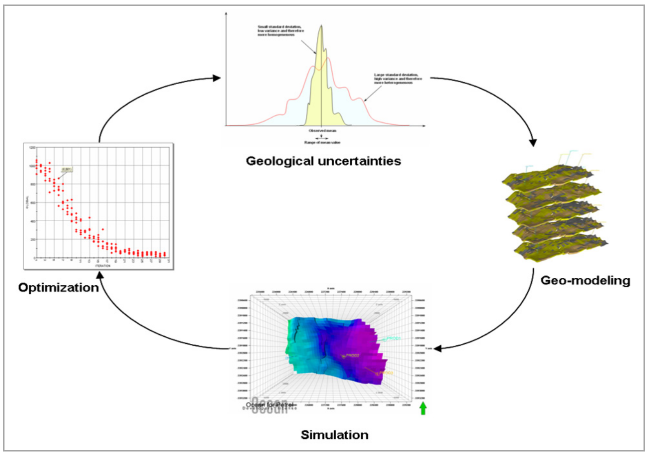

Fig. 3. Methodology for systematic uncertainties analysis

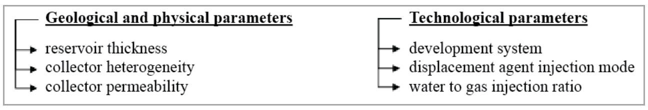

Fig. 4. Parameters for variations

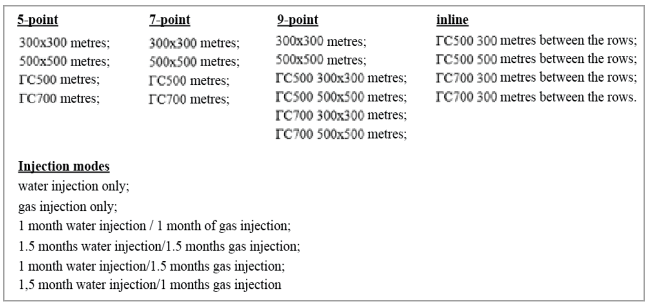

Fig. 5. List of well grids and injection modes

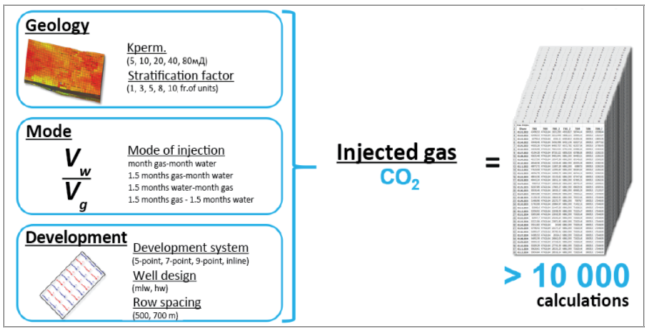

Fig. 6. Scope of data for the study

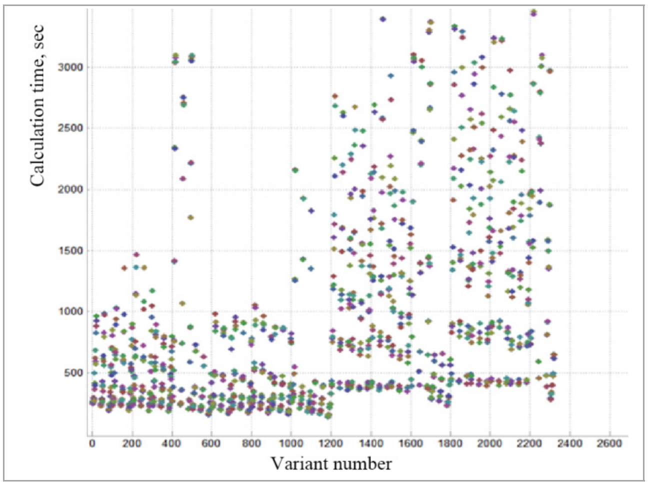

Fig. 7. Fragment of dependency of calculation time duration from variant number

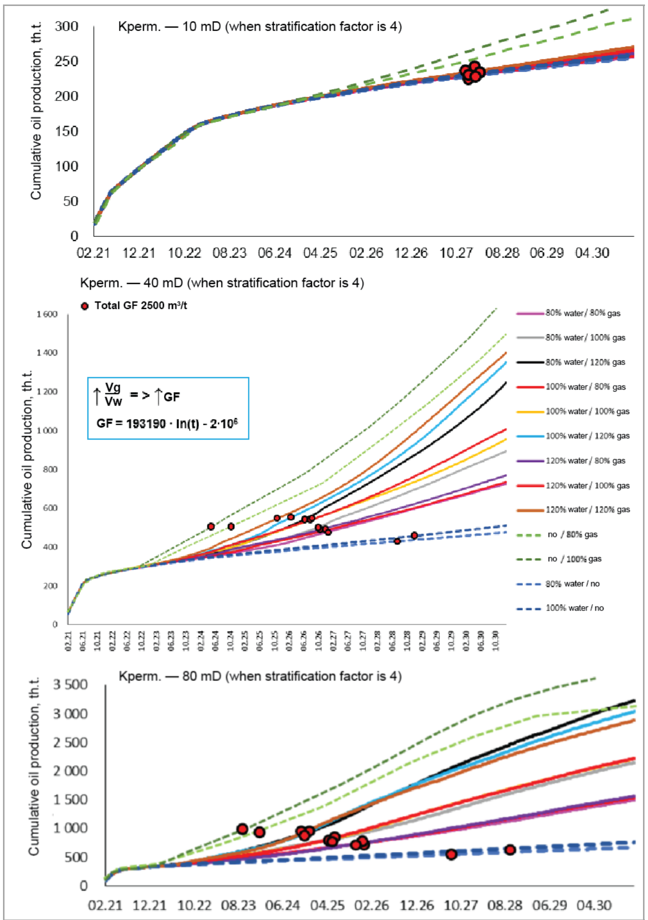

Fig. 8. Distribution of cumulative oil production depending on the ratio of injection volumes of agents (water and gas)

For risk mitigation the solution which covers most of the possible combinations of the criteria enumeration is used. The main geological-physical and technological parameters [38–45], affecting the conditions of applicability of the technology, will be varied in the work (Fig. 4).

The variation of parameters using arithmetic was set in a hydrodynamic simulator. To change the thickness of the formation and pore volume, the change in active cells due to the introduction of a non-reservoir was used. Reservoir heterogeneity and permeability were selected by the analysis of the actual experience of the technology (values for reservoir heterogeneity – 1, 4, 8, for permeability – 5, 10, 20, 40, 80 mD).

The approach to field development is individual, so creating scenarios with technological parameters was time-consuming.

Different well designs, their location in relation to each other and so on do not give a clear understanding of the impact of gas and water injection. Therefore, in order to cover a large volume, the most common models of well spacing (18 variants) were formed to make calculations on hydrodynamic simulator. Six injection modes were also considered (Fig. 5).

The total generated data set is more than 10.000 calculations (Fig. 6).

Each calculation took different time: from 3 min to 1 h. The duration of the calculation depended on the number and design of wells and injection mode (Fig. 7).

Results

The results were analysed on the example of a five-point development system with 500 m long horizontal wells under different water and gas injection modes, permeability of the reservoir and its compartmentalization. To assess the effect of water-gas influence, the indicator of cumulative oil production over time was taken. The gas factor (GF > 2500 m^3/t) is the criterion affecting the success of the variant. Due to high GF values, there are complications in the operation of downhole pumping equipment, as well as infrastructure limitations.

The results of the calculations are presented in Fig. 8.

Discussion

The analyses of all varying parameters show that at reservoir permeability less than 10 mD the effect of WGS is insignificant and not very sensitive to different variations of gas and water injection modes, while the displacing agent of gas injection is more effective, both at 80 % and 100 % compensation of withdrawals. This is associated with the fact that gas (CO_2) has greater mobility. When mixed with the oil phase it reduces its viscosity and capillary forces holding back residual oil.

However, with increasing permeability (>20 mD) the gas factor becomes a limiting factor in the efficiency of the measure. At the same time the gas factor correlates with the injected volume of gas and water. The more gas is injected into the reservoir the earlier the gas factor limit values are reached. Further efficiency of the WGS technology depends on the economic component.

Conclusion

The effect of water-gas stimulation is noticeable at permeability of the reservoir more than 20 mD. The effective ratio of water injection to gas injection is the compensation of fluid withdrawals and should be higher than 100 % for both water and gas injection.

Based on the results of processing the entire data set (more than 10,000 calculations) it has been formed a database of development systems with different input geological and physical characteristics. According to this database applicability criteria at which the water-gas impact is successful have been determined.

A correlation between the achievement of ultimate gas factor (GF > 2500 m^3/t), the ratio of injected fluid and geological and physical characteristics of reservoir has been found.

By studying all scenarios, the optimum fluid injection ratio was identified depending on different well designs, development systems, and geological and physical characteristics.

References

1. Zatsepin V.V., Maksutov R.A. Osnovnye voprosy primeneniia i klassifikatsii tekhnologii vodogazovogo vozdeistviia [Key issues of application and classification of water-gas impact technologies]. *Neftepromyslovoe delo*, 2008, no.12, pp. 16-21.
2. Maksutov R.A., Zatsepin V.V. Klassifikatsiia tekhnologii vodogazovogo vozdeistviia [Classification of water-gas impact technologies]. *Tekhnologii TEK*, 2007, no. 1, pp. 42-45.
3. Ruzin, L.M., Moroziuk O.A. Metody povysheniia nefteotdachi plastov (teoriia i praktika) [Methods of enhancing oil recovery (theory and practice)]. Ukhta, 2014, 127 p.
4. Drozdov A.N., Egorov Iu.A., Telkov V.P. et al. Tekhnologiia i tekhnika vodogazovogo vozdeistviia na neftianye plasty. Chast' 2. Issledovanie dovytesneniia modeli nefti vodogazovymi smesiami posle zavodneniia [Technology and technique of water-gas impact on oil reservoirs. Part 2. Study of additional displacement of oil model by water-gas mixtures after flooding]. *Territoriia Neftegaz*, 2006, no. 3, pp. 48-51.
5. Kazakov K.V., Bravichev K.A. Tekhnologiia intensifikatsii vodogazovogo vozdeistviia na nizkopronitsaemykh kollektorakh [Technology of intensification of water-gas impact on low-permeability reservoirs]. *Vestnik TsKR Rosnedra*, 2014, no. 6, pp. 46-51.
6. RD 39R-05753520-1125-94. Rukovodstvo po primeneniiu tekhnologii vodogazovogo vozdeistviia na neftianye plasty [RD 39R-05753520-1125-94. Guide to the application of water-gas stimulation technology on oil reservoirs]. Tomsk: TomskNIPIneft', 1994, 82 p.
7. RD 39-9-151-79. Rukovodstvo po proektirovaniiu i primeneniiu metoda zavodneniia s gazovodianymi smesiami [RD 39-9-151-79. Guide to design and application of the flooding method with gas-water mixtures]. Tiumen': SibNIINP, 1979, 141 p.
8. Lysenko V.D. Problemy razrabotki zalezhi nefti pri gazovom zavodnenii i chereduiushcheisia zakachke vody i gaza [Problems of oil reservoir development with gas flooding and alternating water and gas injection]. *Neftepromyslovoe delo*, 2007, no. 2, pp. 4-15.
9. Zatsepin V.V. Opyt promyshlennoi realizatsii tekhnologii vodogazovogo vozdeistvii s zakachkoi vodogazovoi smesi v plast [Experience of industrial implementation of water-gas interaction technology with injection of water-gas mixture into the formation]. *Neftepromyslovoe delo*, 2007, no. 1, pp. 10-13.
10. Egorov Iu.A. Gazovye metody - novaia tekhnologiia uvelicheniia nefteotdachi plastov [Gas methods - a new technology for increasing oil recovery]. *Neftepromyslovoe delo*, 2009, no. 11, pp. 24-27.
11. Zaiakin K.A. et al. Analiz mezhdunarodnogo opyta zakachki uglekislogo gaza v razlichnykh geologo-tekhnologicheskikh usloviiakh razrabotki neftianykh mestorozhdenii [Analysis of International Experience of Carbon Dioxide Injection in Various Geological and Technological Conditions of Oil Field Development]. *Nedropol'zovanie*, 2023, vol. 23, no. 2, pp. 71-76. DOI: 10.15593/2712-8008/2023.2.3
12. Trofimov A.S. et al. Analiz realizatsii vodogazovogo vozdeistviia na neftianye plasty pervoocherednogo opytnogo uchastka Samotlorskogo mestorozhdeniia [Analysis of the implementation of water-gas impact on oil reservoirs of the primary experimental site of the Samotlor field]. *Perspektivy primeneniia gazovykh metodov povysheniia nefteotdachi plastov. Sbornik nauchnykh trudov*. Moscow: VNII, 1989, pp. 60-64.
13. Efremov E.P. et al. Vodogazovoe vozdeistvie na opytnom uchastke Samotlorskogo mestorozhdeniia [Water-gas interaction at the experimental site of the Samotlor field]. *Neftianoe khoziaistvo*, 1986, no. 12, pp. 36-40.
14. Ivanishin V.S., Karnaushevskaia Zh.I., Liskevich E.I. Ob effektivnosti sozdaniia gazovodianoi repressii na Bitkovskom mestorozhdenii [On the effectiveness of creating a gas-water repression at the Bitkovskoye field]. *Neftianoe khoziaistvo*, 1975, no. 2, pp. 35-38.
15. Muslimov R.Kh. et al. Proekt realizatsii vodogazovogo vozdeistviia na Alekseevskom mestorozhdenii [Project for the implementation of water-gas impact at the Alekseevskoye field]. *Neftepromyslovoe delo*, 2004, no. 6, pp. 23-31.
16. Zakirov S.N., Indrupskii I.M., Levochkin V.V. et al. Vodogazovoe vozdeistvie na Novogodnem mestorozhdenii [Water-gas impact at the Novogodnee field]. *Neftianoe khoziaistvo*, 2006, no. 12, pp. 40-43.
17. Muslimov R.Kh. Planirovanie dopolnitel'noi dobychi i otsenka effektivnosti metodov uvelicheniia nefteotdachi plastov [Planning additional production and evaluating the effectiveness of enhanced oil recovery methods]. Kazan': Kazanskii gosudarstvennyi universitet, 1999, 280 p.
18. Khizhniak G.P., Amirov A.M. et al. Effektivnost' primeneniia vodogazovykh smesei dlia povysheniia nefteotdachi i pereraspredeleniia fil'tratsionnykh potokov [Efficiency of application of water-gas mixtures used to increase oil recovery and rearrange fluid flow]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2016, vol. 15, no. 18, pp. 42-52. DOI: 10.15593/2224-9923/2016.18.5
19. Pospelova T.A., Kobiashev A.V., Guzhikov P.A., Vasil'ev A.S. et al. Dizain vodogazovogo vozdeistviia: puti dostizheniia smeshivaemosti, instrumenty i metody analiza, otsenka effektivnosti [Wag Design: Miscibility Challenge, Tools and Techniques for Analysis, Efficiency Assessment]. *Society of Petroleum Engineers*, 2019, 16 p. DOI: 10.2118/196758-MS
20. Valeev A.S., Shevelev A.P. Planirovanie parametrov vodogazovogo vozdeistviia [Design of WAG Parameters]. *SPE Russian Petroleum Technology Conference, Moscow, Russia, October 2017*, 2017, 11 p. DOI: 10.2118/187843-MS
21. Goncharova O.R., Kozlov S.V. Povyshenie effektivnosti razrabotki gazoneftianykh (neftegazovykh) zalezhei na osnove podbora optimal'nykh proektnykh reshenii dlia mestorozhdenii Permskogo kraia [Improvement of the effectiveness of gas-oil (oil-gas) reservoirs engineering by selecting rational design for Perm Region fields]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2020, vol. 20, no. 1, pp. 88-100. DOI: 10.15593/2224-9923/2020.1.8
22. Liskevich E.I. Eksperimental'nye issledovaniia protsessa kombinirovannogo vytesneniia nefti vodoi i gazom [Experimental studies of the process of combined displacement of oil by water and gas]. Ph D. Thesis. Ivano-Frankovsk, 1974, 151 p.
23. Kriuchkov V.I., Ibatullin R.R., Romanov G.V., Sakhabutdinov R.Z. Vodogazovoe vozdeistvie na plast na osnove poputnogo gaza kak al'ternativa zavodneniiu [Water-gas stimulation of the formation based on associated gas as an alternative to flooding]. *Interval*, 2002, no. 6, pp. 46-50.
24. Rublev A.B., Fedorov K.M., Shevelev A.P. Modelirovanie raboty zalezhi s primeneniem metoda material'nogo balansa [Modeling of deposit operation using the material balance method]. *Neft' i gaz*, 2011, no. 5, 33 p.
25. Cho J., Min B., Kwon S., Park G., Lee K.S. Compositional modeling with formation damage to investigate the effects of CO_2-CH_4 water alternating gas (WAG) on performance of coupled enhanced oil recovery and geological carbon storage. *Journal of Petroleum Science and Engineering*, 2021, no. 205, 108795 p. DOI: 10.1016/j.petrol.2021.108795
26. Kobiashev A.V., Piatkov A.A., Zakharenko V.A. et al. Otsenka minimal'nogo davleniia smesimosti i minimal'nogo urovnia obogashcheniia pri vytesnenii nefti poputnym neftianym gazom dlia uslovii mestorozhdenii Vostochnoi Sibiri [Estimating minimum miscibility pressure and minimum oil swelling when displaced by associated petroleum gas for the conditions of an East Siberian field]. *Ekspozitsiia neft' gaz*, 2021, no. 4, P. 35-38. DOI: 10.24412/2076-6785-2021-4-35-38
27. Li Z., Lei Z., Shen W., Martyushev D.A., Hu X. A Comprehensive Review of the Oil Flow Mechanism and Numerical Simulations in Shale Oil Reservoirs. *Energies*, 2023, no. 16 (8), 3516 p. DOI: 10.3390/en16083516
28. Fedorov K.M., Pospelova T.A., Kobiashev A.V., Vasil'ev A.S., Zakharenko V.A. et al. Proektirovanie smeshivaiushchegosia vodogazovogo vozdeistviia s uchetom obogashcheniia gaza na promysle [Miscible water-alternating-gas design with in-field gas enrichment]. *Gazovaia promyshlennost'*, 2019, no. 12 (794), pp. 46-52.
29. Gusev S.V. et al. Regulirovanie vodogazovogo vozdeistviia na plast [Regulation of water-gas impact on the formation]. *Neftianoe khoziaistvo*, 1990, no. 6, 146 p.
30. Kriuchkov V.I. [et al. Vodogazovoe vozdeistvie na plast na osnove poputnogo gaza kak al'ternativa zavodneniiu [Water-gas stimulation of the formation based on associated gas as an alternative to flooding]. *Interval*, 2002, no. 6, pp. 46-50.
31. Wang Q., Shen J., Lorinczi P. Oil production performance and reservoir damage distribution of miscible CO_2 soaking-alternating-gas (CO_2-SAG) flooding in low permeability heterogeneous sandstone reservoirs. *Journal of Petroleum Science and Engineering*, 2021, no. 204, 108741 p. DOI: 10.1016/j.petrol.2021.108741
32. Ping G., Zhonglin W., Guangtian T., Kailei Y., Bin L., Yukai L., Maolin Z. Case Analysis on Hydrocarbon Alternative Gas Miscible Flooding in PuBei Oil Field. *SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, September 2003*. DOI: 10.2118/80487-MS
33. Kokorev V.I. Razrabotka tekhnologii bor'by s gidratami pri osushchestvlenii vodogazovogo vozdeistviia [Development of technology of hydrates elimination during water-gas impact]. *Neftepromyslovoe delo*. 2010, no. 2, pp. 42-47.
34. Christensen J.R., Stenby E.H., Skauge A. Review of WAG Field Experience. *SPE Reservoir Evaluation & Engineering*, 2001, no. 2, pp. 97-106. DOI: 10.2118/71203-PA
35. Killough J.E. Reservoir Simulation with History-Dependent Saturation Functions. *Society of Petroleum Engineers Journal*, 1976, no. 16 (01), pp. 37-48. DOI: 10.2118/5106-PA
36. Shahverdi H., Sohrabi M. Modelling of Cyclic Hysteresis of Three-Phase Relative Permeability during WaterAlternating-Gas (WAG) Injection. *SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 2013*. DOI: 10.2118/166526-MS
37. Carlson F.M. Simulation of Relative Permeability Hysteresis to the Non-wetting Phase *SPE Annual Technical Conference and Exhibition*, 1981, 10157 p.
38. Petrakov A.M., Egorov Iu.A., Nenartovich T.L. O dostovernosti eksperimental'nogo opredeleniia koeffitsientov vytesneniia nefti metodami gazovogo i vodogazovogo vozdeistviia [On the reliability of the experimental determination of oil displacement coefficients by gas and water-gas stimulation methods]. *Neftianoe khoziaistvo*, 2011, no. 9, pp. 100-102.
39. Guo B.-E., Xiao N., Martyushev D., Zhao Z. Deep learning-based pore network generation: Numerical insights into pore geometry effects on microstructural fluid flow behaviors of unconventional resources. *Energy*, 2024, no. 294, 130990 p. DOI: 10.1016/j.energy.2024.130990
40. Shafiei M., Kazemzadeh Y., Martyushev D.A., Dai Z., Riazi M. Effect of chemicals on the phase and viscosity behavior of water in oil emulsions. *Scientific Reports*, 2023, no. 13, 4100 p. DOI: 10.1038/s41598-023-31379-0
41. Galkin V.I., Martyushev D.A., Ponomareva I.N., Chernykh I.A. Developing features of the near-bottomhole zones in productive formations at fields with high gas saturation of formation oil. *Journal of Mining Institute*, 2021, vol. 249, pp. 386-392. DOI: 10.31897/PMI.2021.3.7
42. Moradpour N., Pourafshary P., Zivar D. Moradpour N. Experimental analysis of hybrid low salinity water alternating gas injection and the underlying mechanisms in carbonates. *Journal of Petroleum Science and Engineering*, 2021, no. 202, 108562 p. DOI: 10.1016/j.petrol.2021.108562

43. Wang L., Li Z., Lu T., Lai F. Experimental verification of the effects of three metal oxide nanoparticles on mass transfer at gas-liquid interface. *Journal of Petroleum Science and Engineering*, 2022, no. 211, 110122 p. DOI: 10.1016/j.petrol.2022.110122
44. Holmgren C.R., Morse R.A. Effect of Free Gas Saturation on Oil Recovery by Water Flooding. *SPE*, 1951, vol. 192, pp. 135-140. DOI: 10.2118/951135-G
45. Mishchenko I.T. Raschety pri dobyche nefti i gaza [Calculations in oil and gas production]. Moscow, 2008, 295 p.

Библиографический список

1. Зацепин, В.В. Основные вопросы применения и классификации технологий водогазового воздействия / В.В. Зацепин, Р.А. Максутов // Нефтепромысловое дело. – 2008. – № 12. – С. 16–21.
2. Максутов, Р.А. Классификация технологий водогазового воздействия / Р.А. Максутов, В.В. Зацепин // Технологии ТЭК. – 2007. – № 1. – С. 42–45.
3. Рузин, Л.М. Методы повышения нефтеотдачи пластов (теория и практика): учеб. пособие / Л.М. Рузин, О.А. Морозюк. – Ухта, 2014. – С. 127.
4. Технология и техника водогазового воздействия на нефтяные пласты. Часть 2. Исследование довытеснения модели нефти водогазовыми смесями после заводнения / А.Н. Дроздов, Ю.А. Егоров, В.П. Телков [и др.] // Территория Нефтегаз. – 2006. – № 3. – С. 48–51.
5. Казаков, К.В. Технология интенсификации водогазового воздействия на низкопроницаемых коллекторах / К.В. Казаков, К.А. Бравичев // Вестник ЦКР Роснедра. – 2014. – № 6. – С. 46–51.
6. РД 39Р-05753520-1125-94. Руководство по применению технологии водогазового воздействия на нефтяные пласты. – Томск: ТомскНИПИнефть, 1994. – 82 с.
7. РД 39-9-151-79. Руководство по проектированию и применению метода заводнения с газоводяными смесями. – Тюмень: СибНИИНП, 1979. – С. 141.
8. Лысенко, В.Д. Проблемы разработки залежи нефти при газовом заводнении и чередующейся закачке воды и газа / В.Д. Лысенко // Нефтепромысловое дело. – 2007. – № 2. – С. 4–15.
9. Зацепин, В.В. Опыт промышленной реализации технологии водогазового воздействии с закачкой водогазовой смеси в пласт / В.В. Зацепин // Нефтепромысловое дело. – 2007. – № 1. – С. 10–13.
10. Егоров, Ю.А. Газовые методы – новая технология увеличения нефтеотдачи пластов / Ю.А. Егоров // Нефтепромысловое дело. – 2009. – № 11. – С. 24–27.
11. Анализ международного опыта закачки углекислого газа в различных геолого-технологических условиях разработки нефтяных месторождений / К.А. Заякин [и др.] // Недропользование. – 2023. – Т. 23, № 2. – С. 71–76. DOI: 10.15593/2712-8008/2023.2.3
12. Анализ реализации водогазового воздействия на нефтяные пласты первоочередного опытного участка Самотлорского месторождения / А.С. Трофимов [и др.] // Перспективы применения газовых методов повышения нефтеотдачи пластов: сб. науч. тр. – М.: ВНИИ, 1989. – С. 60–64.
13. Водогазовое воздействие на опытном участке Самотлорского месторождения / Е.П. Ефремов [и др.] // Нефтяное хозяйство. – 1986. – № 12. – С. 36–40.
14. Иванишин, В.С. Об эффективности создания газоводяной репрессии на Битковском месторождении / В.С. Иванишин, Ж.И. Карнаушевская, Е.И. Лискевич // Нефтяное хозяйство. – 1975. – № 2. – С. 35–38.
15. Проект реализации водогазового воздействия на Алексеевском месторождении / Р.Х. Муслимов [и др.] // Нефтепромысловое дело. – 2004. – № 6. – С. 23–31.
16. Водогазовое воздействие на Новогоднем месторождении / С.Н. Закиров, И.М. Индрупский, В.В. Левочкин [и др.] // Нефтяное хозяйство. – 2006. – № 12. – С. 40–43.
17. Муслимов, Р.Х. Планирование дополнительной добычи и оценка эффективности методов увеличения нефтеотдачи пластов / Р.Х. Муслимов. – Казань: Изд-во КГУ, 1999. – С. 280.
18. Эффективность применения водогазовых смесей для повышения нефтеотдачи и перераспределения фильтрационных потоков / Г.П. Хижняк, А.М. Амиров [и др.] // Вестник ПНИПУ. Геология. Нефтегазовое и горное дело. – 2016. – Т. 15, № 18. – С. 42–52. DOI: 10.15593/2224-9923/2016.18.5
19. Дизайн водогазового воздействия: пути достижения смешиваемости, инструменты и методы анализа, оценка эффективности / Т.А. Поспелова, А.В. Кобяшев, П.А. Гужиков, А.С. Васильев [и др.] // Society of Petroleum Engineers. – 2019. – 16 с. DOI: 10.2118/196758-MS
20. Валеев, А.С. Планирование параметров водогазового воздействия / А.С. Валеев, А.П. Шевелев // Society of Petroleum Engineers. – 2017. – 11 с. DOI: 10.2118/187843-MS
21. Гончарова, О.Р. Повышение эффективности разработки газонефтяных (нефтегазовых) залежей на основе подбора оптимальных проектных решений для месторождений пермского края / О.Р. Гончарова, С.В. Козлов // Вестник ПНИПУ. Геология. Нефтегазовое и горное дело. – 2020. – Т. 20, № 1. – С. 88–100. DOI: 10.15593/2224-9923/2020.1.8
22. Лискевич, Е.И. Экспериментальные исследования процесса комбинированного вытеснения нефти водой и газом : дис. канд. техн. наук : 05.15.06 / Евгений Иванович Лискевич. – Ивано-Франковск, 1974. – 151 с..
23. Водогазовое воздействие на пласт на основе попутного газа как альтернатива заводнению / В.И. Крючков, Р.Р. Ибатуллин, Г.В. Романов, Р.З. Сахабутдинов // Интервал. – 2002. – № 6. – С. 46–50.
24. Рублев, А.Б. Моделирование работы залежи с применением метода материального баланса / А.Б. Рублев, К.М. Федоров, А.П. Шевелев // Нефть и газ. – 2011. – № 5. – С. 33.
25. Compositional modeling with formation damage to investigate the effects of CO_2–CH_4 water alternating gas (WAG) on performance of coupled enhanced oil recovery and geological carbon storage / J. Cho, B. Min, S. Kwon, G. Park, K.S. Lee // Journal of Petroleum Science and Engineering. – 2021. – No. 205. – P. 108795. DOI: 10.1016/j.petrol.2021.108795
26. Оценка минимального давления смесимости и минимального уровня обогащения при вытеснении нефти попутным нефтяным газом для условий месторождений Восточной Сибири / А.В. Кобяшев, А.А. Пятков, В.А. Захаренко [и др.] // Экспозиция нефть газ. – 2021. – № 83. – С. 35. DOI: 10.24412/2076-6785-2021-4-35-38
27. A Comprehensive Review of the Oil Flow Mechanism and Numerical Simulations in Shale Oil Reservoirs / Z. Li, Z. Lei, W. Shen, D.A. Martyushev, X. Hu // Energies. – 2023. – No. 16 (8). – P. 3516. DOI: 10.3390/en16083516
28. Проектирование смешивающегося водогазового воздействия с учетом обогащения газа на промысле / К.М. Федоров, Т.А. Поспелова, А.В. Кобяшев, А.С. Васильев, В.А. Захаренко [и др.] // Газовая промышленность. – 2019. – № 12 (794). – С. 46–52.
29. Регулирование водогазового воздействия на пласт / С.В. Гусев [и др.] // Нефтяное хозяйство. – 1990. – № 6. – С. 146.
30. Водогазовое воздействие на пласт на основе попутного газа как альтернатива заводнению / Крючков В.И. [и др.] // Интервал. – 2002. – № 6. – С. 46–50.
31. Wang, Q. Oil production performance and reservoir damage distribution of miscible CO_2 soaking-alternating-gas (CO2-SAG) flooding in low permeability heterogeneous sandstone reservoirs / Q. Wang, J. Shen, P. Lorinczi // Journal of Petroleum Science and Engineering – 2021. – No. 204. – P. 108741. DOI: 10.1016/j.petrol.2021.108741
32. Case analysis on hydrocarbon alternative gas miscible flooding in PuBei oil field / G. Ping, W. Zhonglin, T. Guangtian, Y. Kailei, L. Bin, L. Yukai, Z. Maolin // SPE 80487. DOI: 10.2118/80487-MS
33. Кокорев, В.И. Разработка технологии борьбы с гидратами при осуществлении водогазового воздействия / В.И. Кокорев // Нефтепромысловое дело. – 2010. – № 2. – С. 42–47.
34. Christensen, J.R. Review of WAG Field Experience / J.R. Christensen, E.H. Stenby, A. Skauge // SPE. – 2001. – No. 2. – P. 97–106. DOI: 10.2118/71203-PA
35. Killough, J.E. Reservoir Simulation with History-Dependent Saturation Functions / J.E. Killough // SPE. – 1976. – No. 16 (01). – P. 37–48. DOI: 10.2118/5106-PA
36. Shahverdi, H. Modelling of Cyclic Hysteresis of Three-Phase Relative Permeability during WaterAlternating-Gas (WAG) Injection / H. Shahverdi, M. Sohrabi // SPE. – 2013. – No. 7. – P. 5232–5253. DOI: 10.2118/166526-MS
37. Carlson, F.M. Simulation of Relative Permeability Hysteresis to the Non-wetting Phase / F.M. Carlson // SPE Annual Technical Conference and Exhibition. – 1981. – P. 10157.
38. Петраков, А.М. О достоверности экспериментального определения коэффициентов вытеснения нефти методами газового и водогазового воздействия / А.М. Петраков, Ю.А. Егоров, Т.Л. Ненартович // Нефтяное хозяйство. – 2011. – № 9. – С. 100–102.
39. Deep learning-based pore network generation: Numerical insights into pore geometry effects on microstructural fluid flow behaviors of unconventional resources / B.-E. Guo, N. Xiao, D. Martyushev, Z. Zhao // Energy. – 2024. – No. 294. – P. 130990. DOI: 10.1016/j.energy.2024.130990
40. Effect of chemicals on the phase and viscosity behavior of water in oil emulsions / M. Shafiei, Y. Kazemzadeh, D.A. Martyushev, Z. Dai, M. Riazi // Scientific Reports. – 2023. – No. 13. – P. 4100. DOI: 10.1038/s41598-023-31379-0
41. Developing features of the near-bottomhole zones in productive formations at fields with high gas saturation of formation oil / V.I. Galkin, D.A. Martyushev, I.N. Ponomareva, I.A. Chernykh // Journal of Mining Institute. – 2021. – Vol. 249. – P. 386–392. DOI: 10.31897/PMI.2021.3.7
42. Moradpour, N. Experimental analysis of hybrid low salinity water alternating gas injection and the underlying mechanisms in carbonates / N. Moradpour, P. Pourafshary, D. Zivar. // Journal of Petroleum Science and Engineering. – 2021. – No. 202. – P. 108562. DOI: 10.1016/j.petrol.2021.108562
43. Experimental verification of the effects of three metal oxide nanoparticles on mass transfer at gas-liquid interface // L. Wang, Z. Li, T. Lu, F. Lai // Journal of Petroleum Science and Engineering. – 2022. – No. 211. – P. 110122. DOI: 10.1016/j.petrol.2022.110122
44. Holmgren, C.R. Effect of Free Gas Saturation on Oil Recovery by Water Flooding / C.R. Holmgren, R.A. Morse // SPE. – 1951. – Vol. 192. – P. 135–140. DOI: 10.2118/951135-G
45. Мищенко, И.Т. Расчеты при добыче нефти и газа / И.Т. Мищенко. – М., 2008. – 295 с.

Funding. The study had no sponsorship.
Conflict of interest. The authors declare no conflict of interest.
The authors' contribution is equivalent.