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INJECTION OF HIGH-SULFUR GAS FOR RESERVOIR PRESSURE MAINTENANCE AT OIL AND GAS CONDENSATE FIELDS OF THE REPUBLIC OF KAZAKHSTAN

Abstract. The paper addresses the technological and geological–physical aspects of injecting high-sulfur associated gas into productive formations of oil and gas condensate fields in order to maintain reservoir pressure, utilize acid gases, and improve the efficiency of reservoir development. The prerequisites for the large-scale implementation of this technology at the major fields of the Republic of Kazakhstan—Karachaganak, Tengiz, and Kashagan—are analyzed, including the shortage of sour gas processing capacities, restrictions on pollutant emissions, and the need to increase hydrocarbon recovery factors.

The key industrial safety, environmental, and techno-economic factors determining the selection of gas injection as a priority reservoir stimulation and pressure maintenance agent are identified, along with the requirements for well integrity, casing string stability, and corrosion resistance of equipment when operating in aggressive environments.

Using the Karachaganak field as an example, the application of the cycling process is considered as a practical method for increasing liquid hydrocarbon recovery from gas condensate reservoirs, reducing in-reservoir condensate losses, and stabilizing the reservoir energy state.

It is shown that high-sulfur gas injection is an important element of the reservoir pressure maintenance system and rational subsurface management; however, it requires further optimization of injection regimes, taking into account geological heterogeneity of reservoirs, porosity–permeability characteristics of rocks, phase behavior of fluids, and long-term risks associated with possible gas migration and technogenic impacts on the reservoir system.

Keywords. Reservoir pressure maintenance; gas injection; high-sulfur gas; cycling process; oil and gas condensate fields; hydrogen sulfide; Republic of Kazakhstan.

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ҚАЗАҚСТАН РЕСПУБЛИКАСЫНДАҒЫ МҰНАЙ-ГАЗКОНДЕНСАТ КЕН ОРЫНДАРЫНДА ҚАБАТ ҚЫСЫМЫН ҰСТАП ТҰРУ ҮШІН ЖОҒАРЫ КҮКІРТТІ ГАЗДЫ АЙДАУ

Аңдатпа. Мақалада мұнай-газконденсат кен орындарының өнімді қабаттарына жоғары күкіртті ілеспе газды қабат қысымын ұстап тұру, қышқыл газдарды кәдеге жарату және кен орындарын игерудің тиімділігін арттыру мақсатында айдау технологиялық және геологиялық-физикалық тұрғыдан қарастырылған. Қазақстан Республикасының ең ірі кен орындарында — Қарашығанақ, Теңіз және Қашаған кен орындарында — осы технологияны кеңінен енгізудің алғышарттары талданған, соның ішінде күкіртті газды өңдеу қуаттарының жеткіліксіздігі, ластаушы заттар шығарындыларына қойылатын шектеулер және көмірсутектерді алу коэффициентін арттыру қажеттілігі көрсетілген.

Газды қабатқа әсер етудің басым агенті ретінде таңдауды айқындайтын негізгі өнеркәсіптік қауіпсіздік, экологиялық және технико-экономикалық факторлар, сондай-ақ агрессивті орта жағдайында жұмыс істегенде ұңғымалардың герметикалығы, шегендеу колонналарының тұрақтылығы және жабдықтардың коррозияға төзімділігіне қойылатын талаптар атап өтілген.

Қарашығанақ кен орны мысалында газконденсатты залеждерде сұйық көмірсутектерді алу коэффициентін арттырудың, қабатта конденсаттың жоғалуын азайтудың және залеждің энергетикалық жай-күйін тұрақтандырудың практикалық әдісі ретінде сайклинг-процесті қолдану қарастырылған.

Жоғары күкіртті газды айдау қабат қысымын ұстап тұру және жер қойнауын ұтымды пайдалану жүйесінің маңызды элементі екені көрсетілген, алайда коллекторлардың геологиялық біртексіздігін, жыныстардың фильтрациялық-сыйымдылық қасиеттерін, флюидтердің фазалық мінез-құлқын және газдың ықтимал миграциясымен, қабат жүйесіне техногендік әсермен байланысты ұзақ мерзімді тәуекелдерді ескере отырып, айдау режимдерін одан әрі оңтайландыруды талап етеді.

Кілт сөздер. қабат қысымын ұстап тұру; газ айдау; жоғары күкіртті газ; сайклинг-процесс; мұнай-газконденсат кен орындары; күкіртсутек; Қазақстан Республикасы.

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ЗАКАЧКА ВЫСОКОСЕРНИСТОГО ГАЗА ДЛЯ ПОДДЕРЖАНИЯ ПЛАСТОВОГО ДАВЛЕНИЯ НА НЕФТЕГАЗОКОНДЕНСАТНЫХ МЕСТОРОЖДЕНИЯХ РЕСПУБЛИКИ КАЗАХСТАН

Аннотация. В статье рассмотрены технологические и геолого-физические аспекты закачки высокосернистого попутного газа в продуктивные пласты

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нефтегазоконденсатных месторождений с целью поддержания пластового давления, утилизации кислых газов и повышения эффективности разработки залежей. Проанализированы предпосылки широкого внедрения данной технологии на крупнейших месторождениях Республики Казахстан — Карачаганакском, Тенгизском и Кашаганском, включая дефицит мощностей по переработке сернистого газа, ограничения по выбросам загрязняющих веществ и необходимость повышения коэффициента извлечения углеводородов.

Отмечены основные промышленно-безопасные, экологические и технико-экономические факторы, определяющие выбор закачки газа в качестве приоритетного агента воздействия на пласт, а также требования к герметичности скважин, устойчивости обсадных колонн и коррозионной стойкости оборудования при работе в агрессивных средах.

На примере Карачаганакского месторождения рассмотрено применение сайклинг-процесса как практического метода увеличения коэффициента извлечения жидких углеводородов в газоконденсатных залежах, снижения потерь конденсата в пласте и стабилизации энергетического состояния залежи.

Показано, что закачка высокосернистого газа является важным элементом системы поддержания пластового давления и рационального недропользования, однако требует дальнейшей оптимизации режимов закачки с учетом геологической неоднородности коллекторов, фильтрационно-емкостных свойств пород, фазового поведения флюидов и долгосрочных рисков, связанных с возможной миграцией газа и техногенным воздействием на пластовую систему.

Ключевые слова. Поддержание пластового давления; закачка газа; высокосернистый газ; сайклинг-процесс; нефтегазоконденсатные месторождения; сероводород; Республика Казахстан.

Introduction. The development of deep oil and gas condensate fields in the Republic of Kazakhstan, characterized by high hydrogen sulfide content and complex fractured–porous reservoir structures, is accompanied by intensive reservoir pressure decline and rapid depletion of natural reservoir energy [2,3,9,15].

Among the largest and most technologically complex assets are the Karachaganak, Tengiz, and Kashagan fields, distinguished by substantial hydrocarbon reserves, high initial reservoir pressures, and increased aggressiveness of formation fluids [15–18]. Maintaining the energy state of reservoirs is a necessary condition for sustaining stable production levels of oil, gas, and condensate, increasing hydrocarbon recovery factors, and ensuring efficient long-term development of the resource potential of these fields [1,4,5,6].

Development projects for these fields envisage the application of reservoir pressure maintenance systems based on the reinjection of associated and formation gas, which is also considered a technological solution for the utilization of hydrogen sulfide–containing gases and for reducing environmental loads [10; 12; 17; 18; 20]. At the same time, the effectiveness of gas injection in terms of improving ultimate oil recovery and gas condensate recovery remains debatable and is largely determined by geological heterogeneity of reservoirs, fracture systems, porosity–permeability properties of rocks, and specific features of the phase behavior of formation fluids under changing thermobaric conditions [7,8,9,13].

In this context, a relevant scientific and practical task is a comprehensive analysis of the efficiency of high-sulfur gas injection at various stages of field development, taking into account domestic and international experience, as well as substantiation of optimal injection regimes ensuring technological, industrial, and environmental safety [10,14,19].

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Research Materials. The study is based on open and generalized information sources reflecting the current state and experience in applying associated gas reinjection technologies at the largest oil and gas fields of the Republic of Kazakhstan [1,2,3,4,5,6,7,8,9,12,13,14,15]. The materials used include:

- published scientific articles and review papers by domestic and international authors on reservoir pressure maintenance and gas reinjection;
- proceedings of conferences, symposia, and industry forums on the development of oil and gas condensate fields;
- generalized data from monographs, textbooks, and reference publications on hydrocarbon field development;
- data presented in open analytical reports and presentation materials of operators of major oil and gas projects in Kazakhstan;
- regulatory and technical documents and industry guidelines governing gas injection technologies and industrial safety requirements for handling high-sulfur associated gas.

The materials are of a review and informational nature and do not contain primary field or experimental data.

Research Methods. The study employs general scientific theoretical and analytical methods aimed at systematizing and generalizing existing information without conducting original experimental or computational work [1,2,5,6,9,13].

- analysis and synthesis to identify key factors determining the effectiveness of associated gas injection and to form an integrated view of technological and economic aspects of the method;
- comparative analysis to compare different approaches to reservoir pressure maintenance (gas injection, water flooding, combined methods) at the level of concepts and practical experience reported in the literature;
- systematization and classification to structure information by application areas (pressure maintenance, cycling process, associated gas utilization, industrial safety issues);
- logical generalization to formulate conclusions on the advantages, limitations, and prospects of gas reinjection at oil and gas condensate fields;
- review and analytical method for critical consideration and interpretation of existing scientific and industrial approaches without verification based on original calculations or modeling.

Research Limitations. This study is of a review and analytical nature and does not involve field observations, laboratory experiments, or reservoir simulation. The conclusions are based on the interpretation and generalization of data presented in open sources and reflect the current state of the problem in the scientific and technical literature.

Results and Discussion. The analysis of the practice of associated gas reinjection at the largest oil and gas fields of the Republic of Kazakhstan reveals a number of key results and patterns characterizing its technological, economic, and environmental efficiency [12,15,16,17,18]. First of all, associated gas injection has become an integral element of the development strategy of the country's largest oil and gas projects.

The historical experience of the Karachaganak field, as well as the subsequent implementation of similar solutions at the Tengiz and Kashagan fields, demonstrates the high adaptability of this technology to the conditions of large oil and gas condensate accumulations. In practice, gas reinjection has evolved from an experimental or auxiliary measure into a core technological solution for fields with a high gas–oil ratio.

From an economic and resource perspective, the selection of gas as a reservoir pressure maintenance agent represents a justified alternative to conventional water flooding. Due to water scarcity and the high cost of constructing water treatment and injection facilities, water-

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based reservoir pressure maintenance in Kazakhstan is expensive [4,6,9]. Therefore, the use of associated gas, which is already produced together with oil, is a more economically viable option, as it does not require the construction of additional water supply systems and improves the overall project economics.

An additional factor strengthening the feasibility of gas reinjection is the limitation of commercial utilization of associated gas [10,14,19,20]. The high content of hydrogen sulfide and other acid components complicates gas processing and commercial use, while low domestic gas prices reduce the investment attractiveness of gas processing facilities. Under these conditions, gas injection into the reservoir serves not only as a reservoir pressure maintenance method but also as an effective associated gas utilization tool that minimizes flaring volumes and related environmental impacts.

The analysis of technological aspects of gas injection indicates that this method stabilizes the reservoir energy state and contributes to maintaining production indicators at relatively stable levels. At the same time, limitations in oil displacement efficiency are identified due to the specific features of gas flow in fractured–porous reservoirs. Preferential gas flow through high-permeability channels reduces sweep efficiency of the matrix part of the reservoir and may lead to premature gas breakthroughs in producing wells [5,6,13]. This limits the contribution of gas reinjection to direct oil recovery enhancement, especially under conditions of high reservoir heterogeneity.

Issues of industrial safety and reliability of field equipment deserve special attention. Injection of high-sulfur gas is associated with increased corrosion loads on field infrastructure elements, which creates additional technological risks. Operational practice shows that without the use of corrosion-resistant materials, inhibitor protection, and equipment condition monitoring systems, the reliability of gas injection systems is significantly reduced. Thus, the technological effectiveness of gas reinjection is directly related to the level of engineering support and the quality of industrial safety systems.

A special place in the analysis is occupied by the experience of implementing the cycling process at the Karachaganak oil and gas condensate field [7,8,16]. The results obtained show that the reinjection of dehydrated gas allows maintaining reservoir pressure at a safe level at which liquid hydrocarbons do not condense out of the gas phase in the reservoir. This prevents condensate losses in the subsurface and promotes more complete recovery of valuable components to the surface, providing an additional effect in the form of increased condensate recovery factor, reduced hydrocarbon losses, and decreased flaring volumes. Under gas condensate reservoir conditions, the cycling process demonstrates a more pronounced technological and economic effect compared to conventional gas injection primarily aimed at pressure maintenance.

Overall, the results of the analysis indicate that reinjection of high-sulfur associated gas is an effective tool for stabilizing the development of the largest fields in Kazakhstan; however, its potential for enhancing oil recovery in fractured–porous reservoirs remains limited.

Prospects for further improving the efficiency of this technology are associated with the improvement of injector well placement systems, the application of reservoir simulation to optimize injection schemes, and the introduction of intelligent reservoir management systems that allow timely response to changes in filtration and phase behavior conditions in the reservoir.

Conclusions. The results presented allow general conclusions to be drawn regarding the role and effectiveness of associated gas reinjection in reservoir development at the largest oil and gas condensate fields of the Republic of Kazakhstan [1,2,3,4,5,6,7,8,9,12,13,14,15,16,17, 18]. The systematization of historical implementation experience, analysis of economic and resource prerequisites, and consideration of technological limitations and practical cases made

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it possible to comprehensively assess the potential of gas injection as a reservoir pressure maintenance tool and as a means of improving development efficiency.

Key conclusions:

1. The technology of associated gas reinjection into reservoirs has become a well-established element of the development strategy for the largest oil and gas fields in the Republic of Kazakhstan. The experience of the Karachaganak, Tengiz, and Kashagan fields demonstrates a high degree of adaptability of this technology to the conditions of large oil and gas condensate accumulations with high gas–oil ratios.

2. The choice of gas as a reservoir pressure maintenance agent in Kazakhstan is economically and resource-efficient. Limited water resources and the high capital intensity of water injection infrastructure make gas injection a competitive alternative to traditional pressure maintenance methods.

3. A significant driver for the widespread implementation of gas reinjection is the limited commercial utilization of associated gas due to its high hydrogen sulfide content and the low economic attractiveness of gas processing projects under current pricing conditions. Thus, gas injection performs a dual technological and environmental function.

4. While stabilizing reservoir pressure and production levels, gas reinjection in fractured–porous reservoirs has limited potential for enhancing oil recovery due to uneven sweep efficiency and the tendency of gas to preferentially flow through high-permeability channels.

5. The efficiency and reliability of gas injection technology largely depend on the level of industrial safety and technical equipment of field facilities. Injection of high-sulfur gas requires the use of corrosion-resistant materials, inhibitor protection systems, and continuous monitoring of equipment condition.

6. The implementation of the cycling process at the Karachaganak field demonstrates that under gas condensate reservoir conditions, gas reinjection provides an additional technological effect by preventing in-reservoir condensation of liquid hydrocarbons and increasing the condensate recovery factor, thereby expanding the functional role of gas injection beyond simple pressure maintenance.

7. Promising directions for improving the efficiency of gas reinjection have been identified, including the development and application of reservoir (hydrodynamic) simulation, optimization of injection well placement, and the implementation of intelligent reservoir management systems that ensure more uniform sweep of the reservoir and reduce the risks of premature gas breakthrough.

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