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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT AND APPLICATION OF NEW TECHNOLOGIES FOR INTENSIFICATION OF OIL PRODUCTION, CONSIDERING THE PHASE STATE OF FORMATION FLUIDS

Specialty:	2526.01- "Technology of development of offshore fields"
Field of science:	Technical sciences
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The work was performed at the "Oil Gas Scientific Research Project Institut", SOCAR

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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and degree of development. At the current stage of oil and gas industry development, the majority of reservoirs are at the late stage of exploitation. During the exploitation of such reservoirs, complex phase transitions occur in the pore space as a result of changes in pressures and temperatures.

Gas-condensate reservoirs exhibit complex phase and flow behavior at pressures below the dew point pressure. For most gas-condensate reservoirs, the productivity of production wells typically declines due to the accumulation of retrograde condensate in the near-wellbore zone. Studying the filtration characteristics of gas-condensate mixtures in the subcritical region has significant scientific and practical importance. Effective and inexpensive methods for removing accumulated fluid at the bottomhole are essential to increase the productivity of gas and gas-condensate wells.

As a result of reducing bottomhole pressure in oil wells below the saturation pressure, gas evolves from the oil, creating a two-phase flow zone, which leads to changes in well productivity. A decrease in temperature in the near-wellbore area results in an increase in oil viscosity, intensifying the deposition process of asphaltene-resin-paraffin deposits. Additionally, decreases in reservoir and bottomhole pressures lead to the formation of sand plugs.

Existing methods of hydrocarbon production intensification often do not adequately account for the complexity of the processes occurring during fluid phase changes, which reduces the efficiency of the process. Although significant experimental and theoretical materials have been accumulated, there remain numerous questions requiring further research and systematic improvement of methods for oil recovery enhancement.

Therefore, the development and implementation of new technologies for oil recovery intensification, taking into account the phase state of reservoir fluids, constitute a highly significant and relevant task.

Aim and objectives of the research. The aim of the work is the development and application of new technologies for enhancing oil recovery, taking into account the phase state of reservoir fluids.

Main objectives of the research:

- Investigating the influence of subcritical nucleation on the flow of gas-condensate systems in porous media;
- Enhancing the efficiency of bottomhole fluid removal in gas wells;
- Developing a method for killing wells at bottomhole pressures below saturation pressure;
- Developing a wellhead device for shock-wave treatment of the near-wellbore zone;
- Preventing the formation of sand plugs in wells.

Research methods. The tasks set were addressed through theoretical, experimental, and field studies.

Main provisions submitted for defense:

- Mechanism of gas-condensate system flow in porous media based on the formation of stable subcritical condensate nuclei;
- Composition of solid surfactants for removing liquid from the bottomhole of inclined gas wells;
- Method for killing gas-producing wells at bottomhole pressures below saturation pressure;
- Design of a wellhead device for shock-wave treatment of the near-wellbore zone;
- Method for preventing the formation of sand plugs in wells by using metals with negative electrode potential.

Scientific novelty of the research:

1. A mechanism of gas-condensate system flow in porous media based on the formation of stable subcritical condensate nuclei is proposed;
2. A composition of solid surfactants has been developed for removing fluid from the bottomhole of inclined gas wells;
3. A method for killing gas-producing wells at bottomhole pressures below saturation pressure is proposed;
4. A design for a wellhead device for shock-wave treatment of the near-wellbore zone has been developed;
5. A method for preventing the formation of sand plugs in wells by using metals with negative electrode potential is proposed.

Practical significance of the research results.

The developed wellhead device for shock-wave treatment of the near-wellbore formation zone has been successfully tested on wells No. 2067 and No. 2013 of the "Neft Dashlary" field. Field tests of the proposed wellhead device resulted in increased oil production from these wells. In total, an additional 283 tons of oil were produced over an 8-month period.

Eurasian Patent No. 032854 dated 31.07.19 has been granted for the wellhead device for shock-wave treatment of the near-wellbore zone. Eurasian Patent No. 036356 dated 29.10.20 was obtained for the method of preventing sand plug formation in wells. Eurasian Patent No. 046618 dated 29.03.24 was granted for the method of killing a well.

Approbation of the work:

- Materials of the dissertation were presented and discussed at:

- II International Scientific and Practical Conference "Bulatov Readings" (March 31, 2018);

- III International Scientific and Practical Conference "Bulatov Readings" (March 31, 2019);

- International Scientific and Practical Conference "State and Prospects of Mature Field Exploitation," branch of JSC "Scientific Research Institute of Production and Drilling Technology of KazMunayGas" "KazNIPImunaigas," Aktau, May 16-17, 2019;

- IV International Scientific and Practical Conference "Bulatov Readings" (March 31, 2020).

Publications:

Based on dissertation materials, 13 works were published, including 6 articles, 4 conference materials, and 3 Eurasian patents.

Name of the institution where the dissertation work was carried out:

The research was performed at the Scientific Research and Design Institute "Neftegaz" SOCAR.

Structure and scope of work. The dissertation consists of an introduction, three chapters (Chapter 1 - 56 pages, Chapter 2 - 28 pages, Chapter 3 - 48 pages), comprising 209,280 characters, 8 figures, 15 graphs, 12 tables, a list of references including 128 items, and appendices.

BRIEF SUMMARY OF THE WORK

The introduction substantiates the relevance and development level of the dissertation, defines the goal and main research objectives, describes the research methods and scientific novelty, and indicates its practical significance.

The first chapter provides a literature review of existing methods for enhancing hydrocarbon production, taking into account their phase states.

As fields mature, productive reservoirs become waterflooded, well productivity declines, and reservoir pressures decrease, further complicating hydrocarbon production. To ensure profitability in exploiting such reservoirs, it is crucial to consider the phase states of reservoir fluids when enhancing oil recovery.

A gas-condensate system represents a hydrocarbon aerosol, a dispersed system with gas as the dispersion medium and liquid as the dispersed phase. The phase behavior of fluids significantly affects the filtration of hydrocarbon aerosols, particularly gas-condensate mixtures. Specifically, at pressures below the dew point pressure, liquid is released in the porous medium, causing a sharp decrease in gas-phase permeability and an associated reduction in gas flow.

Several studies have experimentally observed the existence of subcritical liquid clusters in vapors and aerosols. However, the stabilization mechanism of these subcritical liquid clusters and their influence on aerosol filtration in porous media remains practically unexplored.

Nonetheless, substantial experimental and theoretical data has been accumulated regarding gasified liquids (gas emulsions) in the subcritical region. It has been established that at pressures above saturation pressure, gasified liquids qualitatively alter rheology during steady-state filtration, increasing fluid flow rates by 2–3 times. During unsteady-state filtration, significant reductions in piezo-conductivity and increases in system compressibility occur. The following mechanism was proposed to explain these phenomena: during filtration of gasified liquids in the subcritical region, stable nuclei of the gas phase, sized approximately 1-100 nm, form on the surface of pore channels at a contact angle $\theta > 0\,^{\circ}$, creating a boundary layer that results in a slip effect and increased fluid flow rate as pressure approaches saturation pressure.

Thus, investigating the filtration characteristics of hydrocarbon aerosols, particularly gas-condensate mixtures in the subcritical region, is of substantial scientific and practical interest. The stabilization mechanism of subcritical condensate nuclei was examined, and experimental and theoretical studies of steady-state and unsteady-state filtration of gas-condensate mixtures at pressures above retrograde condensation pressure were presented.

Experiments involved a recombined gas-condensate mixture consisting of natural gas and normal hexane (dew point pressure 17.5 MPa at 333 K, gas-condensate factor 4800 nm^3/m^3). The filtration study of the gas-condensate system was conducted using an experimental setup that included a column with a porous medium (reservoir model)[1] [1]. Different pressures (P_i and P_0, respectively) were applied at the inlet and outlet of the porous medium column, and the studied gas-condensate system was filtered under a constant pressure drop of 0.8 MPa until a stable gas flow rate was established. The dependence of gas flow rate on the average reservoir pressure $P = (P_i + P_0)/2$ was determined.

Following steady-state and unsteady-state studies, the system pressure was reduced to the next level, and similar measurements were repeated at each pressure level. Experiments continued until the system pressure reached 20.8 MPa. Thus, studies were performed within the pressure interval P/P_c (P_c– dew point pressure).

Graph 1 shows the dependence of gas flow rate and relative gas flow rate $Q_0 = Q/Q_{P=32\,MPa}$ on pressure.

As seen from the figure, at a pressure 1.5 times higher (27.2 MPa) than the dew point pressure, the gas flow rate increases by nearly 30% compared to the flow rate at 20.8 MPa, and by 25% compared to the flow rate at 32 MPa.

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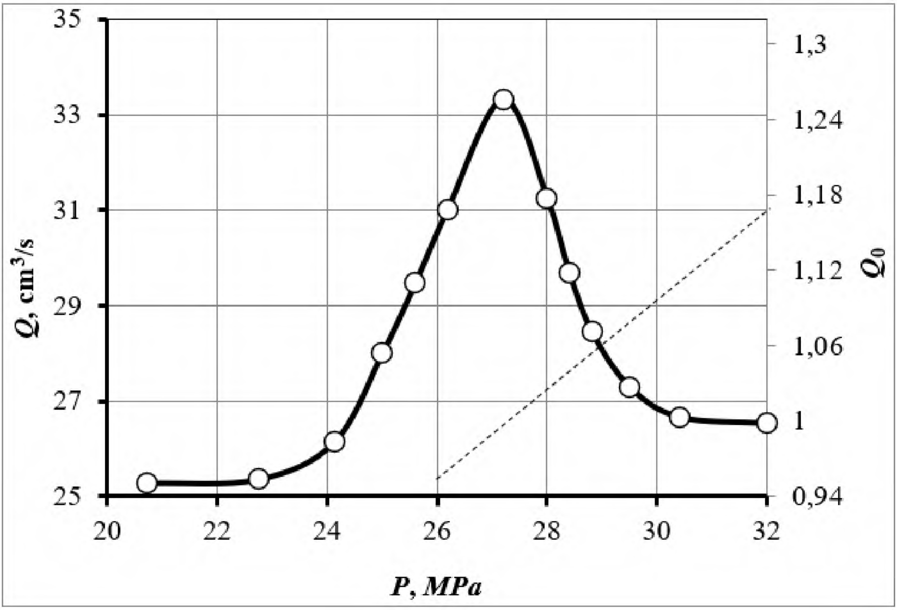
[1] Suleimanov, B.A., Suleymanov A.A., Abbasov, E.M., Baspayev, E.T. A mechanism for generating the gas slippage effect near the dewpoint pressure in a porous media gas condensate flow // Journal of Natural Gas Science and Engineering, - 2018, №5- p.237-248.

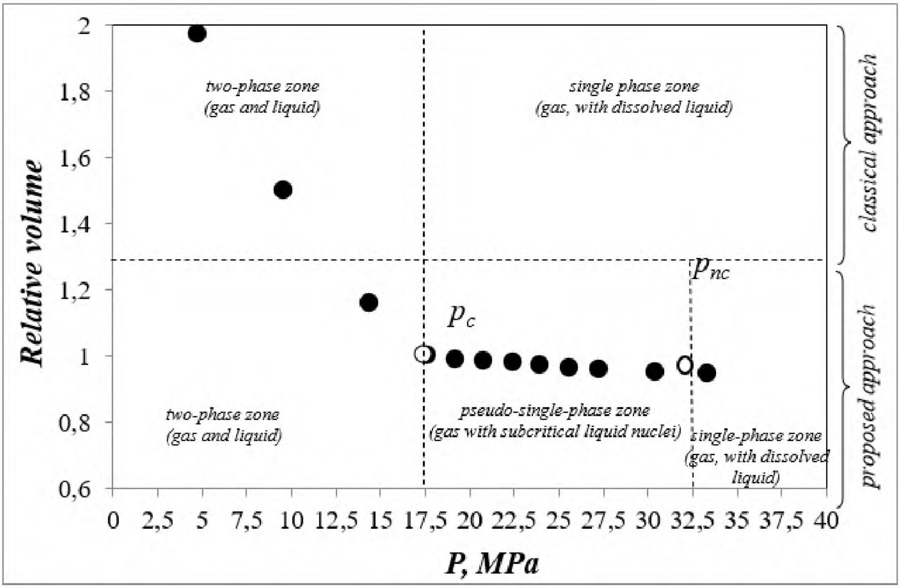


Graph 1. Dependence of gas flow rate on pressure

As seen from the figure, at a pressure 1.5 times higher (27.2 MPa) than the dew point pressure, the gas flow rate increases by nearly 30% compared to the flow rate at 20.8 MPa, and by 25% compared to the flow rate at 32 MPa. The increase in liquid flow rate begins already at a pressure 1.74 times higher (30.4 MPa) than the dew point pressure. The dependence of gas flow rate on pressure is non-monotonic, with higher flow rates observed within the pressure ratio interval of $P/P_c = 1.4 - 1.7$ (24.5-30 MPa).

Studies have shown that reducing the pressure level significantly increases the pressure recovery time and system piezo conductivity. As the pressure decreases, the compressibility coefficient significantly increases.

Graph 2 shows the phase diagram (isotherm) of the gas-condensate mixture (relative volume – V_i/V_d, where V_i is the current volume, and V_d is the volume of the gas-condensate mixture at the dew point pressure), obtained using the reservoir model.



Graph 2. Phase diagram (isotherm) of the studied gas-condensate mixture

As illustrated in Graph 2, under a classical approach, the system remains single-phase (gas with dissolved liquid) until reaching the dew point pressure; below this point, it transitions to a two-phase system (gas and liquid). Traditionally, filtration of gas occurs until reaching the dew point pressure. According to Darcy's law, the gas flow rate should linearly decrease with decreasing average pressure, as shown in Graph 1 (dashed line).

Thus, the classical approach fails to explain the obtained results. Considering that nucleation theory applies to pure single-component and multiphase systems (gas emulsions, aerosols, etc.), the following explanation is proposed. It suggests the existence of three zones (see Graph 2): at pressures above $P > P_{nc}$ (where P_{nc} is the experimentally determined pressure at which subcritical condensate nuclei formation begins, from Graph 1 pm $P_{nc} = 32$MPa), a single-phase zone (gas with dissolved liquid); at pressures $P_{nc} \geq P \geq P_c$, a pseudo-single-phase zone (gas with subcritical liquid nuclei); and below $P < P_c$, a two-phase zone. Although the existence of subcritical liquid clusters is experimentally confirmed, the practical aspects of their formation and stabilization remain understudied. Therefore, we propose a mechanism for stabilizing subcritical nuclei and describe the flow of the gas-condensate system in porous media in the presence of these nuclei.

Several studies indicate that surface tension and electric charges, formed by selective ion adsorption on the nuclei surfaces, play a critical role in stabilizing subcritical nuclei. Consequently, this study, for the first time, examines subcritical nucleation during retrograde condensation, incorporating surface and electrical effects.

It was determined that surface electric charges enable stable liquid nuclei formation at pressures above the dew point. Below the dew point pressure, subcritical nuclei formation from the vapor to the liquid phase is significantly influenced by surface electric charges.

It is known that new phase nuclei primarily form on existing surfaces, and the work of a heterogeneous process is always less than that of a homogeneous process. Assuming that subcritical liquid nuclei formed (adsorbed) on capillary surfaces are mobile, the resulting boundary layer exhibits higher viscosity than gas flowing in the channel center. It is logical to presume that as pressure approaches the dew point, nucleation becomes easier, and the volumetric content of nuclei increases, potentially thickening the boundary condensate layer.

Several studies suggest even perfectly smooth surfaces are only partially covered by subcritical nuclei. On nanoscale rough surfaces, nucleation decreases further, with surface coverage around 20%. Lower values may occur in porous media. This study determined the fluid flow rate under conditions of incomplete capillary surface coverage by condensate nuclei.

The boundary layer, even in single-phase systems such as water in fine pores, exhibits variable viscosity. In our case, nuclei form on the pore channel surface within the gas phase. Thus, viscosity at the contact line between condensate nuclei and gas approximates gas viscosity, while at the capillary wall, it matches condensate viscosity.

Based on the obtained results, the following mechanism of the observed effects can be proposed. During filtration of the gas-condensate mixture in the subcritical region, stable condensate nuclei form a boundary layer on the surfaces of pore channels at the wetting angle $\theta > 0°$. This results in a slip effect and increased gas flow rate as pressure decreases towards the retrograde condensation pressure. Concurrently, the cross-sectional area of fluid flow normal to the flow direction decreases proportionally due to the increased thickness of the boundary layer. The competition between these two effects leads to a non-monotonic relationship between fluid flow rate and pressure. Initially, the slip effect dominates, reaching a maximum; thereafter, the reduction in effective cross-sectional area due to the boundary layer thickness becomes predominant, resulting in a subsequent decrease in flow rate[2] [5].

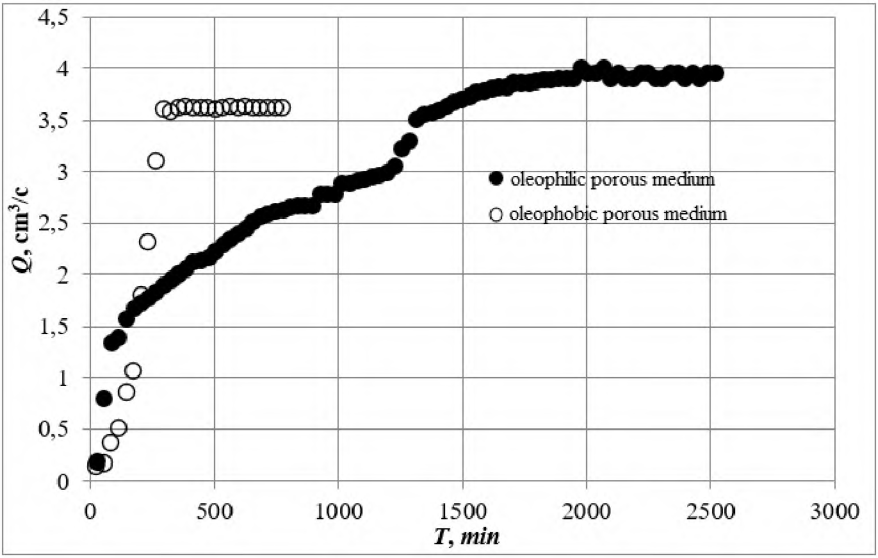
Using relative permeabilities, the generalized Darcy's law can be applied to determine the key parameters of the gas-condensate mixture filtration process in real porous media, accounting for slip effects and variable viscosity of the boundary layer.

It is well known that nuclei of a new phase primarily form on existing surfaces. When the contact angle lies within the range of $0° < \theta < 180°$, the work required for a heterogeneous nucleation process is always lower than that of a homogeneous one. Specifically, when the porous medium (in this case, composed of quartz sand) is wetted by condensate ($0° < \theta < 90°$), intensive nucleation occurs on the surfaces of the pore channels, resulting in the manifestation of the slip effect. In contrast, when the porous medium is not wetted by the condensate ($90° < \theta < 180°$), nucleation on the surfaces of the pore channels is practically absent. As a result, the porous medium becomes gas-wet, leading to complete removal of the condensate from the porous structure by the gas phase, and the slip effect is not observed. To validate this assumption, we conducted experimental investigations in both oleophilic and oleophobic porous media. The results of these experiments are presented in Graph 3.

As seen from Graph 3, in the oleophilic porous medium, there is a significant increase (almost 20%) in gas flow rate compared to the

[2] Suleimanov, B.A., Suleymanov A.A., Abbasov, E.M., Baspayev, E.T. A mechanism for generating the gas slippage effect near the dewpoint pressure in a porous media gas condensate flow // Journal of Natural Gas Science and Engineering, - 2018, №5- p.237-248.

pre-injection rate of n-hexane. In the oleophobic medium, no such increase is observed, and after displacement of n-hexane, the gas flow rate returns to the value observed prior to the injection. Thus, the experiment confirms the proposed mechanism of the wettability effect on steady-state filtration of gas-condensate systems.



Graph 3. Dynamics of gas flow rate in oleophilic (steady-state gas flow rate before injection of n-hexane: 3.27 cm³/s) and oleophobic porous media (steady-state gas flow rate before injection of n-hexane: 3.62 cm³/s)

The determining factor in pressure recovery is compressibility, and in our case, the compressibility of the gas-condensate mixture increases as pressure decreases. This can be attributed only to condensate formation and the accompanying drying of the gas. Accordingly, it is assumed that after liquid separation, only gas flows through the porous medium.

As a result of the experimental studies on steady-state filtration of the gas-condensate mixture, it was found that even at pressures significantly above the retrograde condensation point (P = 1.74Pc), the gas flow rate begins to increase. At P = 1.5Pc, the flow rate reaches its peak and is nearly 30% higher than the flow rate near the critical pressure. The dependence of gas flow rate on pressure level is non-monotonic, with increased flow rates observed within the pressure range P = 1.4–1.74Pc. It was confirmed that in an oleophobic porous medium, such an increase in gas flow rate does not occur. It was demonstrated that during unsteady-state filtration, a decrease in pressure results in a significant reduction of piezoconductivity and an increase in system compressibility.

A mechanism of the observed effects was proposed, based on the formation of stable subcritical condensate nuclei, the accompanying slip effect, and changes in system compressibility. A mechanism for stabilizing subcritical nuclei through the combined action of surface and electrical forces was also considered. Mathematical models were proposed to describe the obtained experimental results.

The operation of gas production wells becomes more complicated when liquid accumulates at the bottomhole and in the wellbore as a result of condensation from the gas phase. At the early stages of development, when the gas velocity is high and the volume of accumulated liquid is small, the entire liquid collected at the bottomhole is carried to the surface by the gas flow. As the liquid column increases, the bottomhole pressure rises, leading to a significant decline in gas production rate, and eventually to a complete cessation of gas inflow. To avoid this, it is necessary to remove the accumulated liquid from the bottomhole of gas wells in a timely manner.

At present, the most effective and economically advantageous technology for removing accumulated liquid from the bottomhole of gas wells and restoring the free flow of gas is the introduction of solid surfactants (SAS) into the bottomhole in spherical or cylindrical form (chemical pellets). These substances promote the foaming of the gas-liquid mixture at the bottomhole and its subsequent lifting to the surface.

A composition of solid SAS has been developed, including the following components: sulfonol – 70%, liquid glass – 10%, carboxymethyl cellulose (CMC) – 15%, soda – 4.9%, and aluminum nanoparticles – 0.1%. The foam system obtained by adding 1% of this composition to 100 mL of technical water is characterized by high expansion ratio and stability. It was found that the selected formulation exhibits high surface activity and wettability. For this composition at concentrations of 0.015–0.06% and at a temperature of 20°C, the surface tension at the hydrocarbon–water interface ranges from $9.5 \cdot 10^{-4}$ to $1.2 \cdot 10^{-4}$ N/m. The proposed composition was tested as a reagent for preventing scale formation and corrosion. The reagent concentration in the formation water was 0.05%. The results are presented in Table 1.

Table 1

Effect of the proposed composition on scale formation and corrosion

Sample	**Rate, g/m³·h**		**Protective effect, %**	
	Scale formation	Corrosion	Scale formation	Corrosion
Formation water	2,7	0,76		
With proposed composition	1,02	0,49	62,3	35,5

The study showed that the composition reduces scale formation by more than a factor of two, achieving a protection efficiency of 62.3%. The corrosion protection efficiency of the proposed reagent reaches 35.5%.

Studies on the effect of the proposed composition on asphaltene-resin-paraffin (ARP) deposits were carried out using the “cold finger” method. The results are presented in Table 2.

Table 2

ARP deposition protection with the addition of the proposed composition

Composition	**Reagent concentration in oil, %**	**Amount of ARP, g**	**ARP protection, %**
Untreated oil	-	24,5	-
With proposed composition	0,01	16	34,6
	0,02	17	30,6
	0,05	18,5	24,5
	0,1	22	10,2

Based on the conducted research, it can be concluded that the developed solid surfactant composition exhibits high surface activity, wettability, and multifunctional protective properties [12].

A method has been proposed for delivering solid rods to the bottomhole of inclined or horizontal gas wells. For this purpose, a lubricator is pre-installed on the Christmas tree assembly, into which an assembly of units is placed, rigidly connected in series. The assembly consists of a capsule containing the required amount of solid SAS rods, a mechanical hammer, a weight bar, and a cable fixing unit connected to the winch cable, which passes through a regulating sheave. To activate the rods, the entire assembly is lowered into the well using the winch cable until it reaches the constriction point of the production tubing. Then, the cable is slightly raised and sharply dropped. Under the impact force created by the mechanical hammer, the capsule strikes the narrowed tubing section and opens. Upon lifting the cable, the capsule gradually releases the rods, which, once in the liquid environment, dissolve in the accumulated bottomhole fluid and become activated. As the gas flows through the liquid column containing dissolved surfactant, foam is formed consisting of gas bubbles separated by liquid films. After a certain technological holding time, the well is cleaned to remove foam and mechanical impurities, followed by commissioning.

Chapter two presents an analysis of well killing methods. It is well known that kill fluids (KF) used in well interventions, workovers, and conservation must meet specific requirements. One of the most critical requirements is the absence or minimization of negative impact on the reservoir properties of productive formations they come into contact with. To meet these criteria, KFs must possess specific physicochemical and technological properties tailored to the geological conditions, which is achieved through careful selection of component composition.

Studies on chemical agents for well killing were conducted using actual formation waters from the Uzen field. At the current stage of oil field development, water-based KFs, particularly aqueous solutions of mineral salts, play a key role. Water-based KFs are the most technologically convenient, non-toxic, and environmentally safe options[3] [3].

To improve the well-killing technology applied at the Uzen field, chemical reagents were investigated with regard to reservoir characteristics. Research included determining the consumption rates of the studied mineral salts, their density, compatibility with hydrochloric acid and formation water, the mass of precipitate formed, the mass fraction of alkaline earth metal ions, and their impact on the filtration-capacity properties of the rock. Based on a comprehensive set of laboratory studies, the most effective mineral salt-based KF formulations were selected [6].

To improve the effectiveness of well killing in gas-influx wells, enhance the stability of the foam gel, reduce cost and corrosion activity, and ensure environmental safety, a new technology has been developed. The proposed method includes sequential injection of foam gel and displacement fluid into the well, with a technological holding period prior to displacement fluid injection. The foam gel is formed by mixing polyacrylamide (PAA), aluminum sulfate, whey, activated sludge, and OP-10 surfactant.

Biological reagents are used as gas-generating components: whey, a byproduct of lactic acid production, and activated sludge, a byproduct of wastewater treatment, which contains a large number of microorganisms. These microorganisms are activated by the supplied nutrient medium (whey), resulting in significant gas generation. The presence of OP-10 surfactant promotes foaming of the injected composition. The polymer PAA increases foam stability by forming films on the surface of bubbles, while aluminum sulfate enhances the mechanical strength of the resulting foam gel. Biogenic surfactants and biopolymers produced through microbial activity also contribute to the durability and strength of the foam gel. After injection into the well, a holding time is necessary to allow microbiological processes to occur and produce a robust foam gel. The foam gel is displaced into the well

[3] Баспаев, Е.Т., Аяпбергенов, Е.О., Рзаева, С.Д. Анализ влияния жидкостей глушения скважин на фильтрационные свойства пород месторождения «Узень» / Е.О.Аяпбергенов, С.Д.Рзаева // SOCAR Proceedings, – 2018. № 3. – с.38-44.

using brine solutions with densities selected based on the reservoir pressure (1200–1800 kg/m^3).

It is important to note that the use of bioreagents in the foam gel composition leads to the gradual formation of biosurfactants and biopolymers, thereby maintaining foam stability over an extended period. The addition of bioreagents ensures low corrosive activity and environmental compatibility of the composition, which is another advantage of the proposed well-killing method.

The proposed foam gel does not contaminate the porous medium, does not reduce its permeability, and is easily removed from the well either by reservoir pressure during natural flow or gas-lift production, or by pumping during mechanized oil recovery.

The method is carried out as follows: all foam gel components are mixed using an ejector installed on a line connected to the auxiliary pump of the cementing unit. The resulting mixture is then pumped into the well by the main pump. After injecting the required volume of foam gel, the well is shut in for a holding period. Subsequently, displacement fluid is injected, followed by well intervention or workover. Upon completion of underground or major well repairs, the foam gel is flushed out of the well.

The foam gel is prepared by adding dry polyacrylamide (PAA), aluminum sulfate, and OP-10 to the calculated amount of bioreagents and mixing continuously using a laboratory stirrer until completely dissolved. The foam gel formation time, density, expansion ratio, and stability are determined. The results of the research are presented in Table 3.

As seen from Table 3, the proposed formulations (1–5) exhibit lower density and significantly higher expansion ratios and stability compared to the prototype, thereby improving the efficiency of the well-killing process in gas-influx wells. The formation time of a stable foam gel is approximately 3 hours. In the known method, the foam gel forms immediately, which complicates its injection into the well.

Experimental studies were conducted to determine the permeability recovery of the porous medium after well killing using the proposed foam gel. The results showed that permeability was restored up to 96% following the application of the proposed well-killing method, whereas the permeability recovery was only up to 68% when a conventional foam gel was injected.

The effect of the foam gel on the corrosion rate was also evaluated. The studies demonstrated that the corrosion rate was very low, ranging from 0 to 0.02 g/m²·h, due to the inclusion of industrial byproducts in the proposed foam gel formulation, unlike the conventional composition. In the prototype experiment, the corrosion rate was 0.08 g/m²·h, attributed to the presence of hydrochloric acid in the formulation.

Table 3

Composition and properties of the foam gel

Composition No	Composition Components, wt.%					Formation time, h	Density, kg/m^3	Expansion Ratio	Stability, days
	PAA, %	Aluminum sulfate	OP-10	Whey	Activated sludge				
1	1	0,5	0,3	50	48,20	3,0	0,68	2,0	5,3
2	1,5	1	0,2	48	49,30	2,8	0,70	1,9	5,6
3	2	1,5	0,15	45	51,35	3,0	0,70	2,0	6,1
4	2,5	2	0,1	43	51,40	2,9	0,69	2,1	5,7
5	3	2,5	0,05	40	54,45	2,9	0,72	2,0	6,2
Prototype	CMC 1000 – 5.0; Cross-linker – 3.0; Gas-releasing agent – 6.0; Gas-forming agent – 10.0; Foaming agent – 0.01; Water – remainder					-	0,81	1,6	2,5

Chapter Three of the dissertation presents new technologies for stimulating the near-wellbore zone of wells operating at bottomhole pressures below the saturation pressure.

Recently, various techniques have been applied to improve the permeability of the near-wellbore formation zone in oil production and injection wells, including wave, vibrational, hydro-impulse, and acoustic methods. These methods rely on different mechanisms for transmitting energy from wellbore-based vibration sources to the productive formation through wellbore fluids. They are simple to implement, cost-effective, and can be used in combination with other stimulation techniques such as acid treatment, thermal stimulation, etc.

Among the most promising and environmentally safe methods for enhancing oil and gas inflow are wave-based stimulation techniques, which involve the generation of a shock wave. Shock-wave stimulation methods applied to the productive formation target the near-wellbore zone and can be categorized into two types: direct stimulation of the near-wellbore zone by a source of elastic waves and remote stimulation from a distant source. When a shock wave is generated from the wellhead, it travels down the wellbore, reflects off the bottom, and generates a pressure impulse. The intensity of the pressure at the bottomhole is determined by the waveform and frequency of pressure changes at the surface.

All fundamentally different sources of shock-wave field excitation ultimately utilize the nonlinear interaction effect of high-intensity elastic wave fields with oil-saturated and gas-water-saturated formations. This interaction leads to a reduction in pore fluid viscosity, an increase in filtration velocity, improved formation permeability, and enhanced hydrocarbon displacement efficiency.

Shock-wave stimulation, by activating creep processes in the rock, causes a change in the stress-strain state of the reservoir. This, in turn, leads to the reconfiguration of local filtration flow patterns in the formation and mobilization of oil from stagnant zones.

Oil and gas production and injection wells that do not exhibit inflow after drilling, or during operation due to clogging of the near-wellbore zone, can be suitable candidates for the application of shock-wave stimulation technologies in the perforation intervals. The type of reservoir, degree of water salinity, salt composition, and well operation method does not limit the applicability of these technologies.

Studies on the application of shock-wave stimulation to the near-wellbore zone have shown that it eliminates contamination (colmatage), increases oil and gas inflow, and enhances injectivity in injection wells, ultimately improving well productivity.

Various devices exist for applying shock-wave stimulation to the formation; however, they do not provide sufficient resonance oscillation of the wellbore fluid column to generate pressure and rarefaction waves, nor do they offer sufficient efficiency or reliability.

To reduce filtration resistance and restore hydrodynamic connectivity between the formation and the well, a new design of a wellhead device for shock-wave stimulation has been developed. It can be used to enhance oil recovery by acting on the productive formation during well completion or workover. The proposed solution achieves an increased frequency of valve opening and closing through a reliable design and continuous delivery of compressed air at lower pressure, enabling generation of pressure and rarefaction shock waves in the well.

The developed wellhead device consists of two main components: a gate valve and an automatic valve control actuator[4] [11]. The device, suitable for both injection and production wells, is installed on the wellhead via flanged connections located on the valve lid and body. Once the well is started, the valve's orifice periodically opens and closes. This cyclic operation generates alternating pressure and rarefaction waves through the tubing. These waves propagate from the wellhead to the bottomhole and back, impacting the near-wellbore zone.

Thus, the application of the developed wellhead device for shock-wave stimulation improves hydrodynamic communication, thereby enhancing filtration in the formation-well system and mobilizing low-permeability and previously isolated zones of the reservoir. This results in increased oil recovery and reduced production costs.

The developed wellhead device was field tested in wells No. 2013 and No. 2067 of OGPD "Neft Dashlary". A drop in bottomhole pressure below the saturation pressure had previously deteriorated the filtration properties of the near-wellbore zone, reducing productivity. Following shock-wave stimulation, the additional oil production amounted to 283 tons.

Development of reservoirs composed of weakly cemented terrigenous rocks is often accompanied by intensive sand production. Currently, effective equipment is used to prevent sand ingress, significantly improving well productivity. However, in mature fields,

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[4] Исмайлов, Ф.С., Сулейманов, Б.А., Ибадов, Г.Г., Тастемиров, А.Р., Баспаев, Е.Т. Устьевое устройство для ударно-волнового воздействия на призабойную зону пласта, Евразийский патент № 032854– 2019.

the use of such costly equipment is economically inefficient. As a result, at low water-oil flow rates, sand actively settles at the bottomhole, forming a sand plug that may reach several hundred meters in height.

The formation of a sand plug occurs as follows. During sand transport from the reservoir by the fluid flow, water accumulates at the bottomhole. Clay particles adhere to the inner and outer surfaces of the tubing. Sand grains stick to these clay particles, gradually forming a sand plug.

To prevent clay adhesion, the tubing surface must be coated with a metallic film possessing a negative standard electrode potential. In this case, negatively charged clay particles will be repelled by the similarly charged metal surface and will be carried out of the well by the fluid flow.

In the proposed method for sand plug prevention, involving the installation of tubing made from metal with a negative electrode potential, the internal surface of the tubing is coated with metal having an electrode potential less than -0.7 V. The coating height corresponds to the maximum observed sand plug height in a given well [8].

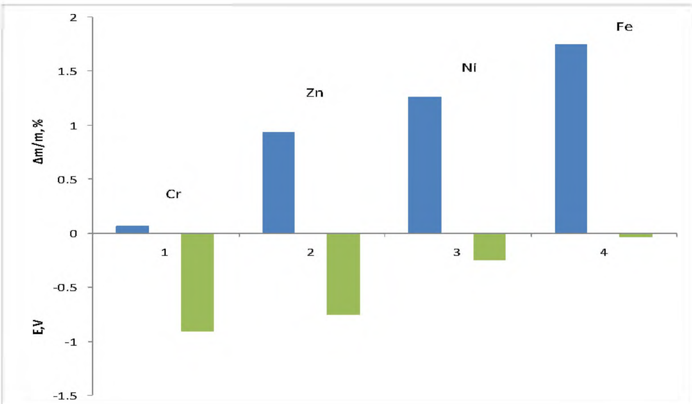
When this method is implemented, clay particles with negative charge do not adhere to the tubing walls but are instead repelled and removed from the well by the fluid stream. Selecting a coating height equal to the maximum sand plug height ensures complete removal of the accumulated plug.

To experimentally validate the method, filters with identical shapes and surface areas but made of different metals (chromium – Cr, zinc – Zn, nickel – Ni, and iron – Fe) were placed in a bentonite clay solution (3.4% concentration). After 3 hours, the mass of clay particles deposited on the filter surfaces was measured. It was found that the relative mass of clay on filters coated with Cr or Zn (electrode potential < -0.7 V) was significantly lower than on those coated with Ni or Fe.

Graph 4 shows the relationship between the relative mass of adhered clay particles and the standard electrode potentials of the metals used in the experiment. The results demonstrated that the relative mass of clay deposited on Cr- and Zn-coated surfaces (electrode potential < -0.7 V) was substantially lower than on Ni- and Fe-coated surfaces (electrode potential > -0.7 V). As the standard electrode potential becomes more negative, clay deposition decreases—i.e., the more negative the electrode potential, the lower the relative mass of accumulated clay particles.

As seen from Figure 4, the mass of clay particles deposited on the metal surface decreases with decreasing standard electrode potential of the metal.

To explain the observed results, the interaction forces between a sand particle (SiO_2) and a metal particle (Cr, Zn, Ni, and Fe) in an aqueous medium were analyzed. According to DLVO theory (Derjaguin–Landau–Verwey–Overbeek), the formation of particle aggregates is governed by the balance between Van der Waals attractive forces and electrostatic repulsive forces arising from the overlap of electrical double layers surrounding the particles.



Graph 4. Relative mass of clay particles deposited on the surface of filters coated with films of different metals: 1 – Cr, 2 – Zn, 3 – Ni, 4 – Fe, and the standard electrode potential of the metals

Van der Waals interactions between two particles in water differ from those in a vacuum due to the presence of disjoining pressure exerted by the aqueous medium.

It should be noted that in all considered cases, the Van der Waals interaction between a metallic particle (A: Cr, Zn, Ni, Fe) and a clay particle (B: SiO_2) in water is attractive. Therefore, the only viable mechanism for preventing the deposition of clay particles on metal surfaces is through the repulsive potential energy associated with the overlap of their electrical double layers.

It was determined that the highest repulsive potential energy is observed for the particle pairs (Cr–SiO_2) and (Zn–SiO_2). This means that coating the internal surface of production tubing with Cr or Zn can prevent the deposition of clay particles and the formation of sand plugs. To achieve this effect, the coating height of the metal with negative electrode potential on the inner surface of the tubing should correspond to the maximum height of the sand plug observed in the given reservoir[5] [9].

Thus, a method is proposed to prevent the formation of sand plugs in wells using metals with negative electrode potentials. It has been demonstrated that applying a film of metals with low negative standard electrode potentials (below −0.7 V) to the inner surface of production tubing effectively prevents sand plug formation. Furthermore, the height of the coating should equal the maximum height of the sand plug expected in the well. A mechanism explaining the observed effects is proposed based on DLVO theory.

[5] Сулейманов, Б.А. Гасанов, Ф.Г., Аббасов, Х.Ф., Баспаев, Е.Т. Способ предотвращения образования песчаных пробок в скважине, Евразийский патент № 036356, – 2020.

CONCLUSIONS

1. A mechanism for gas-condensate system flow in porous media has been proposed, according to which the formation of stable subcritical condensate nuclei leads to a slip effect and changes in system compressibility. A stabilization mechanism for subcritical nuclei through the combined action of surface and electrostatic forces has been examined.

2. The following findings were obtained from steady-state filtration of a gas-condensate mixture:

At a pressure significantly exceeding the retrograde condensation onset pressure (P = 1.74Pc), gas flow begins to increase;

At P = 1.5Pc, gas flow reaches its peak and is approximately 30% higher than the flow near the critical pressure;

The dependence of gas flow rate on pressure is non-monotonic, with increased flow values observed in the pressure interval P = 1.4-1.74Pc;

In an oleophobic porous medium, no increase in gas flow rate is observed.

3. Unsteady-state filtration of the gas-condensate system was experimentally studied. It was shown that with decreasing pressure, there is a significant reduction in piezoconductivity and an increase in system compressibility.

4. A solid surfactant (SAS) formulation was developed for removing liquid from the bottomhole of inclined gas wells, exhibiting high surface activity, wettability, and multifunctional protective properties.

5. A new well-killing method based on foam gel was proposed for gas-influx wells operating at bottomhole pressures below the saturation pressure.

6. A wellhead device was developed for shock-wave stimulation of the near-wellbore zone, consisting of a gate valve and an automatic valve control actuator, enabling the generation of pressure and rarefaction shock waves in the well. The device was successfully field-

tested on two wells of the "Neft Dashlary" field, resulting in an additional oil recovery of 283 tons.

7. A method was proposed to prevent sand plug formation in wells by coating the inner surface of production tubing with a metal having a negative electrode potential. The coating height should correspond to the maximum expected height of the sand plug in wells of the respective reservoir.

The main content and findings of the dissertation have been published in the following publications:

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The Applicant's Personal Contribution

Publications [8,9,11,12] were carried out independently;

in publications [3,4,6,10,13], the author contributed to problem formulation, conducting the research, and summarizing the results;

in publications [1,2,5,7], the contribution involved problem formulation and result interpretation.

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