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ABSTRACT

of the dissertation for the degree of Philosophy Doctor

ENHANCING THE EFFICIENCY OF RESERVOIR SWEEP BY DISPLACEMENT THROUGH REGULATION OF RESERVOIR CONDUCTIVITY USING SYSTEMS WITH SWELLING PROPERTIES

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GENERAL CHARACTERISTICS

The relevance and degree of study of the topic. The extraction of minerals, which include liquid hydrocarbons (oil), is extremely important for the development and maintenance of the country's economic stability. For more than a century, hydrocarbons have remained one of the key raw materials, including various types of liquid hydrocarbons, gas, water, and other possible impurities.

One of the most pressing tasks in the oil industry is the application of new modern oil production technologies that allow for a significant increase in oil recovery from already developed deposits, where it is no longer possible to extract substantial residual oil reserves using traditional methods. ese issues, in various formulations, have been reflected in a number of scientific studies by A.Kh. Mirzajanzade, M.T. Abasov, G.I. Jalalov, A.T. Gorbunov, I.M. Ametov, R.N. Bakhtizin, R.M. Sattarov, A.B. Suleymanov, G.M. Panakhov, M.M. Khasanov, A.Kh. Shakhverdiyev, and others.

When choosing an effective enhanced oil recovery method, it is necessary to consider the forms of residual oil in the reservoir, the extraction of which is the focus of researchers' efforts. Considering the diversity of residual oil forms in the reservoir, as well as the significant differences in the properties of oil, water, gas, and filtration-capacity characteristics of oil-saturated zones of reservoirs, there cannot be a single universal method for increasing oil recovery. For each deposit, the justification of the most effective method of increasing oil recovery should be carried out on the basis of comprehensive studies, including laboratory and experimental work, numerical modeling on adequate geological and filtration models, pilot industrial work on representative sections of the deposit, and technical and economic analysis. The choice of technologies to be applied, as well as the sequence of their application, should be determined separately for each deposit, taking into account the geological and physical characteristics of the layers and based on the entire set of studies listed above.

In recent years, the structure of oil reserves has been deteriorating, and the share of fields with hard-to-recover reserves is growing. Due to the deterioration of the reserve structure and the curtailment of work on the development of effective methods for

enhanced oil recovery, there is a constant decline in the projected oil recovery rate. Due to the increased importance of active development of significant hydrocarbon resources, research into the development and application of controlled swelling systems to increase the coverage of the reservoir by water action is becoming increasingly important.

Object and subject of research.

The main object of research is to improve the efficiency of the displacement coverage by regulating the conductivity of collector systems with deep penetrating properties and to create innovative industrial technologies for use in oil-saturated reservoirs. This problem is particularly acute due to the changing structure of deposits with hard-to-recover reserves and depleted oil-saturated reservoirs. In the presented work, within the context of the proposed option, the use of these composite systems for enhanced oil recovery is considered.

Purpose of the dissertation.

The aim of the dissertation is to develop technological solutions to improve the efficiency of displacement coverage of deposits represented by heterogeneous formations by regulating the conductivity of reservoirs using systems with swelling and deep-penetrating properties.

The main objectives of the study are:

1. Development and research of regulating compositions with swelling properties in order to increase reservoir coverage by leveling the front.

2. Developing the foundations for applying technological solutions to regulate the injectivity profile using a swelling composition in injection wells.

3. Development of a composition necessary for deep-penetrating isolation of highly permeable reservoir intervals and its practical aspects.

4. Development of principles for regulating the process of capillary instability at the phase interface during liquid displacement.

Methods for solving the assigned tasks. The tasks set in the dissertation were solved by conducting laboratory experimental research, mathematical processing of the results, and analysis of the

obtained data using computer modeling. The developed compositions have been tested on model and practical examples.

Main scientific principles to be defended.

1. Development of compositions with swelling properties for leveling the displacement front in heterogeneous formations and increasing the coverage of the reservoir by displacement, as well as studying the factors of their regulation.

2. Solving the problem of regulating the injectivity of injection wells in real conditions with swelling systems.

3. Development of possible solutions for deep-penetrating isolation of formations with swelling compositions.

4. Study of the regulation of capillary instability processes at the phase boundary.

Scientific novelty.

The scientific novelty of the obtained results is as follows:

- A new composition with swelling compounds has been developed to solve the problem of regulating the injectivity profile during reservoir flooding;

- It has been established that the swelling properties of the developed composition change according to a non-linear law;

- For the first time, a composition necessary to ensure deep-penetrating isolation of highly permeable intervals of formations has been proposed, and its practical foundations have been developed;

- Improved mathematical model of the insulating agent growth process to enhance reservoir coverage;

- The possibility of regulating the process of capillary instability by changing the wetting properties at the contact boundary of liquids when acting on the formation is shown;

Theoretical and practical value and realization of the results of the work.

1. The results obtained in the dissertation work made it possible to develop methods for increasing the coverage of formations by displacement and regulating the injectivity profile, which were applied at well No. 232852 of the oil company "Binagady Oil" at the Binagady-North field.

2. Developed possible solutions for deep penetrating isolation of highly permeable reservoir intervals aimed at enhancing oil recovery.

3. The constructed mathematical model of the growth process of colmatizing agent can be implemented in field conditions to improve the coverage of reservoirs during displacement.

4.The results of the solution of capillary instability process control with the change of wetting characteristic at the contact boundary of liquids during the impact on the formation and the possibility of using them in the fields of heterogeneous formations.

Personal contribution of the applicant.

In all conducted studies, the author independently or in collaboration with others formulated the statement of the research tasks, their solutions, as well as the analysis of the obtained experimental data, etc.

The author was directly involved in conducting experimental studies on the influence of electrolyte solutions on the swelling of clay systems, as well as in the implementation of a field operation at the Binagadi oil field (Baku, Azerbaijan).

In co-authorship, the technological foundations of processes for changing the injectivity profile of depleted hydrocarbon deposits using blocking compositions were developed.

Approbation.

The main scientific results and the progress of the dissertation were reported and discussed at a meeting of the Institute of Oil and Gas; the Department of Fluid and Gas Mechanics of the Institute of Mathematics and Mechanics (2018 - 2023), as well as at national and international conferences, seminars and symposia in the form of the following theses:

– International Scientific and Practical Online Conference "Innovative Solutions in Geology and TRIZ Development" Moscow - November 16-17, 2021 - "Regulation of displacement front in heterogeneous formations by blocking high-permeability reservoir channels with swelling composition".

– II International Scientific and Practical Conference "Innovative Technologies in Oil and Gas Industry. Problems of Sustainable Development of Territories", dedicated to the 10th

anniversary of the North Caucasus Federal University, December 09-10, 2021, Stavropol, Russia - "Regulation of injectivity of injection wells by swelling compositions".

– International Conference "Modern Problems of Mathematics and Mechanics" devoted to the 60th anniversary of the Institute of Mathematics and Mechanics, 23-25 October, 2019, Baku, Azerbaijan;

– International conference dedicated to the 90th anniversary of academician Azad Mirzajanzade, Baku, Azerbaijan, December 13-14, 2018;

– International Workshop «Thermal Methods for Enhanced Oil Recovery: Laboratory Testing, Simulation and Oilfields Applications» ThEOR2022, Baku, Azerbaijan, November 3-5, 2022.

Accuracy of the obtained results

The accuracy of the obtained results is ensured by adequate formulation and solution of problems based on known filtration laws, blocking of highly permeable collector channels with a swelling composition based on experimental results, as well as control of the displacement front in heterogeneous formations by isolating highly permeable collector channels using a swelling composition and a numerical solution for the corresponding parameters.

Main provisions of the dissertation are presented in 9 articles, published in domestic and foreign scientific journals, one of which is published in journals indexed by Scopus, and the other in journals indexed by both Scopus and Web of Science. Additionally, 6 theses have been published on this work, 2 of which have been published in the proceedings of international foreign conferences.

Scope and structure of work. The dissertation consists of an introduction (16139 characters), three chapters (Chapter 1 – 53558 characters, Chapter 2 – 27205 characters, Chapter 3 – 69255 characters), which are divided into 8 sub-chapters, conclusions and recommendations (1352 characters), and a list of references. The thesis is 142 pages long and includes 24 illustrations, 9 tables, and 143 references. The work was carried out at the Oil and Gas Institute of the Ministry of Science and Education of the Azerbaijan Republic.

Acknowledgement. The author expresses deep gratitude to the scientific supervisor, Corresponding Member of the NAS of

Azerbaijan, Doctor of Technical Sciences, Professor G.M. Panahov, for his fruitful ideas, relevant formulation of research tasks, valuable advice, and constant attention during the process of working on the dissertation. I express my gratitude to colleagues of the department of "Hydrogasdynamics of Reservoir Systems" of the Institute of Oil and Gas and to the staff of the department "Fluid and Gas Mechanics" of the Institute of Mathematics and Mechanics.

CONTENT OF RESEARCH WORK

The Introduction section justifies the relevance of the dissertation from both scientific and practical perspectives, provides an overview of modern research and publications in this field, presents the purpose of the work and research questions that need to be addressed to achieve the objectives, the novelty and practical significance of the obtained results, the main provisions to be defended, the results of testing, and the main publications on the topic of the work.

The first chapter presents the results of research on the development of deep-penetrating insulating compositions for improving reservoir sweep efficiency during displacement. The issue of preventing a decrease in injectivity and identifying the main causes of its deterioration remains relevant due to the dynamics of changing reservoir conditions, economic costs, and tightening environmental requirements. This problem stimulates research into the development of effective methods for regulating the filtration-capacity characteristics of the bottomhole formation zone, allowing for the qualitative and quantitative restoration of its properties and increasing the coverage of formations by flooding. Therefore, the formation of aggregates along the walls of pore channels and within the pore volume leads to a local increase in flow resistance due to narrowing and partial or complete blocking of individual pore channels, which in turn causes a change in the direction of the filtration flow and an increase in the formation coverage by flooding.

The primary cause of low volumetric sweep efficiency is reservoir heterogeneity, which leads to the diversion of the displacing agent flow toward high-permeability zones of the reservoir. Other contributing factors include the critical mobility ratio, reservoir

compartmentalization, and various geological characteristics of the oil field. In the practice of regulating the profile of injectivity of an injection well, colmatizing compositions may be used in certain cases. However, their application requires careful selection of the object and a precisely calculated volume. It is absolutely unacceptable to apply colmatizing compositions in isotropic formations. From both physical and hydrodynamic perspectives, the cause of anomalous processes in fluid filtration is also the diversified lithological composition of the medium - quartz sands, clays. The manifestation of anomalous properties during fluid flow in porous media may likewise be attributed to physicochemical interactions between the fluid and the reservoir rock material. The likelihood of such nonlinear behavior increases when fluid moves through fine pores in low-permeability reservoirs. Another cause of filtration law nonlinearity may be the formation of numerous interfacial boundaries within the porous medium between the main phase and residual water. A critical factor governing the observed effects is the manifestation of a threshold (critical) initial pressure gradient.

In this section the filtration characteristics of a porous medium during the filtration of low-concentration suspensions, based on which permeability and the thickness of the crust formed during colmatation process were calculated. It has been established that with an increase in the permeability of the porous medium, the permeability of the filtration crust also increases, and when pumping a suspension into a heterogeneous formation, there is a tendency for the injectivity of low-permeability layers to decrease more noticeably. The justification of the method of equalizing displacement profiles by excluding highly permeable layers from the filtration area was carried out using the effect of clay swelling in various environments. In order to study some aspects of the swelling process in aqueous solutions, a series of experiments were carried out to study the interaction of clays with various electrolytes depending on the concentrations of the solutions[1].The process of clay swelling in waters (fresh, sea, and

[1]Панахов, Г.М., Аббасов, Э.М., Юзбашиева А.О., Балакчи, В.Д. Особенности набухания глин в растворах электролитов // Нефтепромысловое дело, №4, 2019. – С. 94-109.

distilled) and electrolyte solutions was investigated, using aqueous solutions of sodium carbonate Na_2CO_3 and sodium chloride NaCl (Figures 1 - 3).

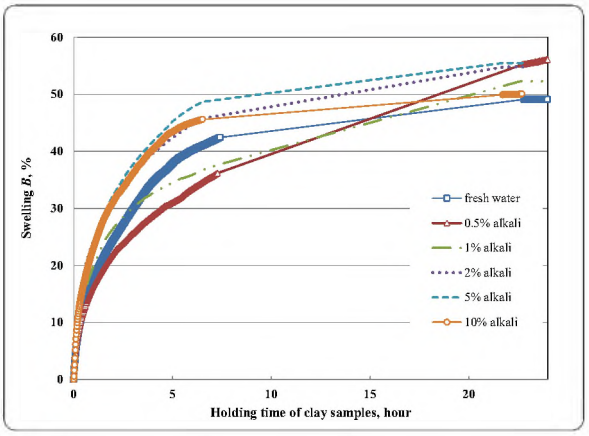

Figure. 1. Swelling of clay at different concentrations of aqueous solutions Na_2CO_3 prepared in fresh water

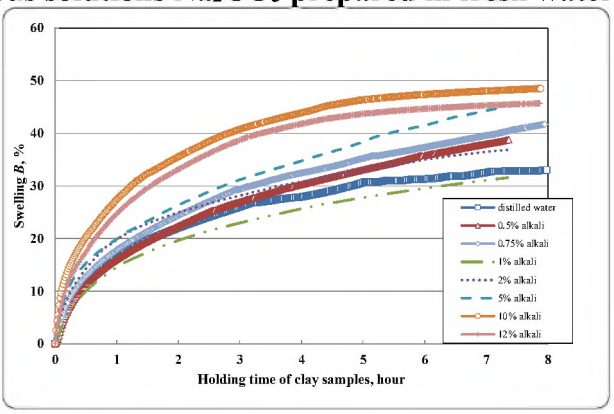

Figure 2. Dynamics of clay swelling at various concentrations of sodium carbonate aqueous solution prepared with distilled water

It has been established that the swelling coefficient of bentonite clay in fresh water exceeds the swelling value in distilled water.

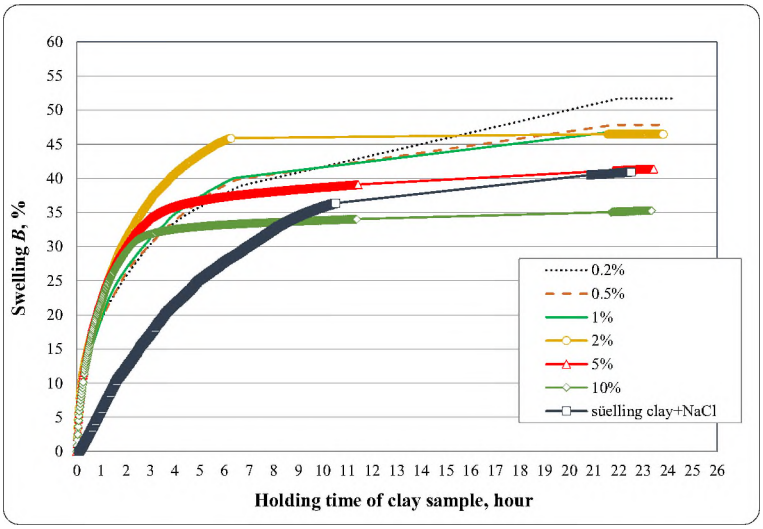

Figure 3. Swelling dynamics of clay samples in aqueous NaCl solutions of various concentrations

During the experiments, it has been established that the swelling of bentonite clay in samples of aqueous Na_2CO_3 solutions in fresh water exceeds the swellability of NaCl in fresh water. To investigate this phenomenon, the swelling behavior of clay compositions during interaction with reservoir fluids was examined. At the same time, comparative studies of some features of clay swelling in a mixture of calcined soda, prepared with seawater and freshwater, were conducted. At the first stage, the experiments were carried out at different concentrations of aqueous solutions of sodium carbonate C = 90; 80; 60; 40; 30%, in a mixture with a clay solution in fresh water, and based on the results of the studies, the change in the swelling of the composition was recorded depending on the exposure time of the composition. The results of the studies are shown in Table 1.

In the first stage, the experiments were carried out at different concentrations of aqueous solutions of sodium carbonate C = 90; 80; 60; 40; 30%, in a mixture with a clay composition in seawater. The results of the studies are shown in table 2.

Table 1. Results of the swelling study of the blocking composition prepared with fresh water

Composition, %,		Swelling of the composition in fresh water over time, hours, (%)			
$Na_2 CO_3$	Bentonite clay	1	3	5	10
90	10	18	21	22	24
80	20	20	28	32	33
60	40	26	38	39	41
40	60	32	46	47	48
30	70	34	49	50	49

Table 2. Results of the swelling study of the blocking composition prepared with seawater

Composition, %,		Swelling of the composition in seawater over time, hours, (%)			
Na_2CO_3	Bentonite clay	1	3	5	10
90	10	10	14	18	17
80	20	14	20	28	28
60	40	20	34	36	38
40	60	26	43	44	45
30	70	30	45	46	46

The swelling values of clay in an alkali mixture prepared with seawater at sodium carbonate concentrations (30–90%) are lower than in solutions prepared with fresh water.

As the concentration of electrolyte in the aqueous solution increases, the rate of clay swelling becomes non-linear.

Taking these limitations into account, a number of methods and special compositions have been developed, aimed at redirecting the water injected into the formation to areas previously unaffected by the impact.

In Chapter 2, compositions with swelling properties are investigated to improve reservoir sweep efficiency, and laboratory

studies were carried out to examine the sealing characteristics of the composition[2,3]. It was also noted that the alkaline solution significantly affects the swelling of clay minerals, while the dissolution rate of montmorillonite decreases with decreasing OH^- ion concentration in bentonite. The void ratio during saturation of samples dissolved in the same solution, over the same reaction time, can be expressed by the fractal swelling model: $e = kp_s^{Ds-3}$. The fractal dimension D_s increased slightly with increasing reaction time and concentration of the Na_2CO_3 solution due to the appearance of traces of dissolution on the surface. The greater the alkaline dissolution, the larger the surface fractal dimension of bentonite. However, the swelling coefficient k decreased with increasing Na_2CO_3 concentration and reaction time. To evaluate the technological effect of swelling of the clay component, experimental studies were conducted on a filtration model of the reservoir.

For this purpose, the pressure recovery curves were recorded on artificial samples of water-saturated porous medium with a length of 1520 mm and a diameter of 28 mm. A fraction of quartz sand (0.2 - 0.315 mm) mixed with marshalate was used as the porous medium. The results of plotting the pressure recovery curves in relation to the assessment of the technological effect are presented in Figure 4. As can be seen from the figure, when the proposed method is applied, an increase in the pressure recovery time in the system is observed (curve 2).

The obtained results can serve as a basis for developing a method of regulating the injectivity profile of porous media during the waterflooding of oil reservoirs.

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[2]Балакчи, В.Д., Селективное блокирование высокопроницаемых каналов пласта с целью увеличения охвата залежи вытеснением // Azərbaycan Neft Təsərrüfatı, № 8, 2021. – С. 22-27.

[3]Шахвердиев, А.Х., Панахов, Г.М., Балакчи, В.Д., Аббасов, Э.М. Регулирование фронта вытеснения в неоднородных пластах путем блокирования высокопроницаемых каналов коллектора набухающей композицией // Актуальные проблемы нефтегазовой отрасли. Сборник докладов научно-практической конференции журнала «Нефтяное хозяйство». г. Москва, 2022. – С. 268-281.

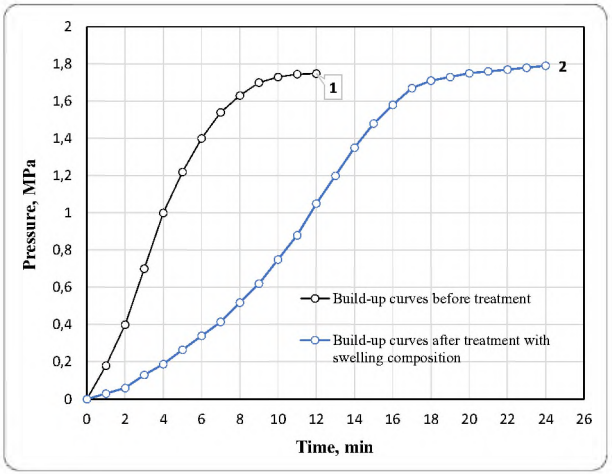

Figure 4. Pressure recovery curves on a porous medium model before and after treatment with a swelling composition

Subsequently, a series of studies was conducted on a composition with swelling properties to improve sweep efficiency. For this purpose, experimental studies were carried out on a similar linear model with a length of 1520 mm and a diameter of 28 mm. The porous medium was saturated with water to increase phase permeability (K_w), and then displaced by a hydrocarbon liquid (transformer oil). The porous medium was saturated 90% with transformer oil and 10% with water. Displacement process was terminated upon stabilization of the displacement efficiency coefficient, at which point 4 pore volumes of water had been injected through the core. The residual oil saturation (transformer oil) and water saturation of the porous medium were then determined, with values of $\sigma_{tr.oil}$ = 32% and σ_w = 68%. The results are presented in Table 3.

To obtain additional oil recovery, it was decided to inject a slug consisting of an aqueous solution of sodium carbonate (Na_2CO_3) at a concentration of 10% and bentonite clay at 5%. The slug volume was equal to ¼ of the total pore volume. In this case, the aqueous sodium carbonate solution created an alkaline environment at the displacement front, which in turn caused the clay to swell. This also reduced the phase permeability of fluids in that direction.

Table 3. Studies on the displacement of transformer oil by distilled water

T, hour	V_l sm^3	V_w sm^3	V_o sm^3	ΣV_l sm^3	ΣV_w sm^3	ΣV_o sm^3	H	P MPa	ΔP MPa
10:30								0,4	0,3
11	160		160	160		160		0,65	0,55
11:15	187	171	16	347	171	176		0,96	0,86
11:30	197	183	14	544	354	190		0,96	0,86
11:45	260	250	10	804	604	200		0,96	0,86
12:00	242	234	8	1046	838	208		0,96	0,86
12:10	288	285	3	1334	1123	211		0,96	0,86
12:20	224	222	2	1558	1345	213	0,64	0,96	0,86

One day after injecting the slug mixture into the porous medium, displacement was resumed under the initial pressure differential of 0.3 MPa. For 1.5 hours no flow response was observed, indicating pore plugging within the porous medium. To overcome the resistance caused by the swollen clay, the pressure differential was increased to 0.86 MPa. After 0.5 hours, fluid breakthrough was observed at the outlet of the model. The displacement process continued for 3.5 hours. During this period, four pore volumes of water were injected through the porous medium. The produced water contained traces of transformer oil.

Thus, the injection of the slug mixture leads to an increase in the pressure differential in the formation and to an effective reduction in permeability to transformer oil. The results are presented in Table 4.

Thus, as seen from the table, the filtration experiments on hydrocarbon displacement demonstrated a 26% increase in the oil displacement efficiency coefficient when a blocking slug was used.

The study further examines the results of experiments on regulating the injectivity of injection wells using swelling systems. The achievement of design targets in oilfield waterflooding largely depends on the effective operation of injection wells under stable injectivity.

Table 4. Studies on the displacement of transformer oil using a blocking composition

T, hour	V_l sm³	V_w sm³	V_o sm³	ΣV_l sm³	ΣV_w sm³	ΣV_o sm³	H	P MPa	ΔP MPa
12:00								0,4	0,3
12:30								0,65	0,55
14:00								0,96	0,86
14:30	340	300	40	340	300	40	0,12	0,96	0,86
15:00	285	257	28	625	557	68	0,20	0,96	0,86
15:30	223	213	10	848	770	78	0,23	0,96	0,86
16:00	160	160	0	1008	930	78	0,26	0,96	0,86
16:30	150	150	0	1158	1080			0,96	0,86
17:00	140	140	0	1298	1220			0,96	0,86
17:30	140	140	0	1438	1360		0,26	0,96	0,86

However, during the injection of water agents used in flooding systems, silting of the filtration surface occurs due to suspended particles, petroleum products, and other external impurities, which leads to contamination of the near-wellbore zone (NWZ). As a result, injectivity decreases and, in some cases, may be completely lost. In addition, the issue of severe and persistent water channeling may arise.

This problem largely depends on the geological structure of the reservoirs, their heterogeneity, and the reservoir rock properties, in particular the anisotropy of reservoir rock permeability. For this reason, the main volume of injected water filters through high-permeability washed-out channels, leaving the less permeable zones of the productive formation under-swept.

Therefore, the development of technological solutions that meet environmental requirements by preventing injectivity loss remains highly relevant. In this context, it is necessary to design effective methods for regulating the filtration–capacity properties of the near-wellbore zone (NWZ), enabling increased reservoir sweep during waterflooding.

In this regard, during field operations, the first stage involved injecting a weak aqueous solution of sodium bicarbonate (with a concentration of up to 2%) into the near-wellbore zone (NWZ),

followed by a sealing composition designed to level the injectivity profile of injection wells. This composition was based on a mixture of sodium bicarbonate and clay[4]. The system is characterized by maximum strength at optimal swelling time and low cost of the constituent components, which are delivered into the formation as a ready-made composition.

As a result of barrier formation in the highly permeable water-swept interlayer, the mobility of the fluid decreases, and the injected water is forced to flow through the less permeable layers, thereby displacing the residual oil more effectively.

This technological operation was carried out at Well No. 232852 of the Binagady Oil Company in the Binagadi-Sever field. The initial geological and physical parameters of the well are presented in Table 5.

Table 5. Geological and physical characteristics of the well

Field	Binagadi -Sever
Horizon	PK
Well depth (TD)	900 м
Perforation interval	858- 836 m (858-857, 852-850, 847-844, 838-836 m)
Casing diameter	7" - 178 мм
Tubing diameter/length	2,5" – 80 joints (773,2 м)
Formation pressure/temperature	35 atm / 32°C
Porosity	0,28
Wellbore condition	cleaned up to 900 m
Surface equipment	Azinmash/SKN-3 ground equipment

The effectiveness and efficiency of the operation were evaluated by subsequent injectivity tests, in which the well's flow characteristics were measured. The studies in Well No. 232852 were conducted using

[4]Балакчи, В.Д. Изоляционные композиции для селективного регулирования приемистости нагнетательных скважин // Нефтегазовое дело, № 1, 2023. – С. 193 -208.

a downhole flowmeter and thermometry to quantitatively assess the injectivity profile of the perforated intervals. During the investigation, a series of measurements was carried out under injection mode at three different rates: 20 m/min, 30 m/min, and 40 m/min.

The current distribution of injection intervals and a comparison with the results of the previous study are presented in table 6. According to the results of well logging and injectivity profile testing, a significant technological effect was achieved after the isolation of high-permeability streaks in the near-wellbore zone.

Table 6. Current distribution of injectivity intervals

Test date		**19.08.18**		**11.01.19**	
Perforation interval, m	**Net pay thickness, m**	**Flow distribution, %**	**Rate, m^3/day**	**Flow distribution, %**	**Rate, m^3/day**
836-838	2	0	0	0	0
842-847	5	0	0	18,01	-15
850-852	2	84,6	-65,87	55,64	-46,34
857-858	1	15,4	-11,99	26,35	-21,94
Total	10	100	-77,86	100	-83,28

The redistribution of injected water across the perforated intervals was observed as follows:

- The injectivity of the 842–847 m interval increased from 0 to 15 m^3/day, indicating that a previously unswept zone was successfully involved in the waterflood process.
- The flow rate through the high-permeability interval 850–852 m decreased from 65.87 to 46.34 m^3/day, confirming the effectiveness of the selective isolation treatment.
- The injectivity of the 857–858 m interval increased from 11.99 to 21.94 m^3/day, demonstrating a favorable redistribution of the injected water into less depleted zones.

Thus, the results of the well injectivity profile test confirmed the effectiveness of the method for isolating washed-out zones of the formation using a composite mixture of chemical reagents.

Chapter 3 examines methods for modeling processes aimed at improving oil recovery. Particular attention was given to the regulation of reservoir conductivity in order to enhance areal sweep efficiency through physicochemical methods. The issue of deep-penetrating isolation of high-permeability reservoir intervals was considered. The primary objective in this context is the development of techniques for profile control of injectivity in injection wells by isolating water-swept streaks and ensuring maximum reservoir sweep coverage by preventing premature breakthrough of the displacing agent along various induced fractures.

Taking these constraints into account, a number of methods and specially formulated compositions have been developed to redirect the injected water into zones that were previously unaffected by flooding. Most of the proposed approaches and blocking compositions for high-permeability streaks are based on the injection of organic compounds that provide permanent partial or complete blocking of the most permeable reservoir layers. A novel technological solution is proposed for the deep isolation of high-permeability reservoir intervals.

Methods are known that aim to increase oil recovery from reservoirs and enhance the flow resistance of high-permeability, water-swept streaks by blocking them with various isolation compositions. Such compositions include viscoelastic gels or polymer-dispersed and fibrous formulations with a wide range of particle sizes (0.01 μm to 1.0 mm) and viscosities. The dispersed phase typically contains polyacrylamide (PAA) and a crosslinking agent (salts of polyvalent metals), and may additionally include lignosulfonate and bentonite powder that swells in the injected water.

These compositions exhibit high mechanical strength and resistance to water exposure, enabling injection to significant distances along the reservoir, thereby forming a blocking barrier of substantially greater capacity. However, their limitations include the difficulty of controlling the required composition concentration during mixing and ensuring adequate penetration depth. Consequently, there is a need to develop a method for isolating water inflows in wells that avoids these shortcomings while maintaining high blocking efficiency and barrier strength. This challenge can be addressed by enhancing the

penetration capability of the composition along the high-permeability intervals of the reservoir. To this end, the present study primarily examines methods of physicochemical treatment of layered, heterogeneous reservoirs and investigates the characteristics of two-phase, three-component flow processes, exemplified by oil displacement by water using selectively blocking compositions. To address the task of leveling the injectivity profile of injection wells, aqueous solutions of chemical agents are injected into the formation as a blocking composition. These agents include divalent chromium salts, ammonium chloride, chromium acetate, and other compounds used as crosslinking elements (CE), which react with an aqueous solution of polyacrylamide (PAA) to form a viscoelastic gel.

To address the problem of injection profile leveling in waterflooding operations, aqueous solutions of chemical agents are injected into the reservoir as isolating compositions. These include divalent chromium salts, ammonium chloride, chromium acetate, and other compounds employed as crosslinking agents (CA), which react with aqueous polyacrylamide (PAA) solutions to form a viscoelastic gel system. The initially injected solution of divalent chromium salts preferentially propagates through high-permeability flow channels, thereby ensuring penetration of the solution to the required reservoir depth. Subsequently injected PAA solution, with a concentration of 0.05–0.5 wt.%, filters through the pore space and, upon contact with the polyvalent salt solution, displaces it further into the formation while simultaneously facilitating conditions for autohesion and diffusion. This sequential process gradually reduces the permeability of the water-swept zones. During the injection of PAA as the displacing fluid, diffusion effects occur both along the flow path and in the radial direction. As a result of the in-situ crosslinking reaction, a viscoelastic water-shutoff gel composition is formed within the water-bearing intervals of the reservoir, characterized by high deformation-strength and adhesive properties. A series of experiments was conducted on the laboratory setup, the schematic of which is presented in Chapter II, in order to investigate the rheological dynamics of the composition over time. The experimental results are illustrated in Figure 5. Tests were carried out at varying concentrations

of polymer (partially hydrolyzed polyacrylamide, HPAM) and crosslinking agent (divalent chromium salts). The viscosity of the system was observed to increase significantly with increasing concentration of the crosslinking agent.

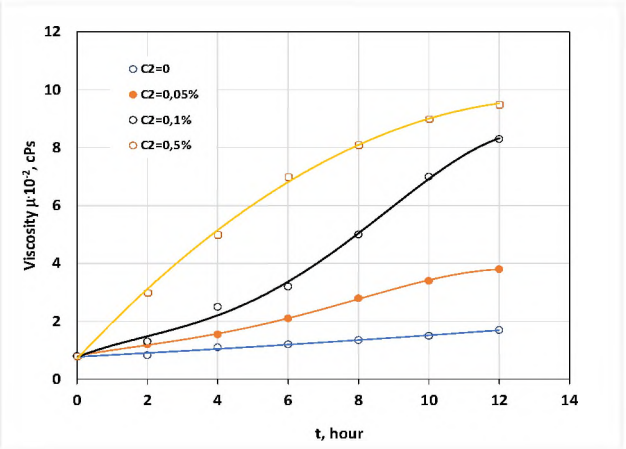

Figure 5. Viscosity of the blocking composition at different crosslinker concentrations C2: 0; 0.05; 0.1; 0.5 % (C1 = 0.05 % PAA, temperature T = 40 °C)

These results indicate the intensification of viscoelastic reactions and the formation of a gel network with increasing concentrations of the crosslinking agent (CA). The processes of autohesion and adsorption of the polymer solution play a critical role in the blocking of high-permeability pore channels in petroleum reservoirs.

The adsorption and autohesion phenomena that occur within the interfacial layers of the polymer chains lead to the development of hydrodynamic instability at the contact zone. The autohesion effect—defined as the adhesion between surfaces of identical polymer material (in this case, HPAM)—is confirmed by the linear correlation between the formation of the autohesive contact (molecular diffusion) and the

shear strength (σk) of the polymer[5]. However, as the interfacial layer thickens, the value of σk decreases. This effect can be attributed to the weakening of the self-diffusion process at the polymer boundary. Depending on the contact conditions of the injected solutions, a viscoelastic gel is formed. The rheophysical parameters of the gel can be regulated by adjusting the concentrations of both injected solutions. To address the problem of optimizing the concentration of the crosslinker solution in the HPAM system, a numerical experiment was carried out at various values of the generalized diffusion coefficient. Using the MATLAB software package, estimates of $D = 6 \cdot 10^{-11}$ and $D = 4 \cdot 10^{-4}$ were obtained. The corresponding results are presented in Figure 6 and 7.

Subsequently, employing the adsorption and convective–diffusion equations, effective algorithms were derived for solving the one-dimensional filtration problem with accumulation taken into account. A computational experiment was conducted to evaluate the variation in formation layer thickness under different values of the effective diffusion coefficient ($D = 6 \cdot 10^{-11}$ and $D = 4 \cdot 10^{-4}$). The corresponding results are presented in Figures 8 and 9 (*a* and *b*), respectively.

As evidenced by the curves presented in the figures, the build-up of the deposited layer increases exponentially from the residual (initial) level to its maximum value.

This growth also depends on the nature of the diffusion process between the PAA solution and the crosslinking agent.

A series of studies was conducted to model the growth dynamics of the plugging (colmatant) agent aimed at improving reservoir sweep efficiency during displacement processes. For this purpose, a specially formulated blocking composition was developed and subsequently evaluated through a set of experimental investigations carried out on the laboratory apparatus described in Chapter 2.

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[5]Panahov, G.M., Balakchi, V.D., Abbasov, E.M., Ismayilov, S.Z. (2021). In-depth isolation of highly permeable zones for reservoir conformance control. Journal of Dispersion Science and Technology, 44(2), pp. 359–369.

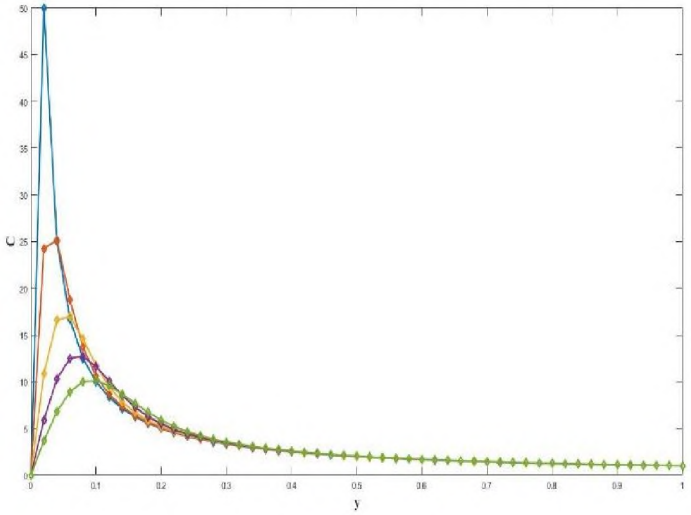


Figure 6. Variation of crosslinker concentration in the HPAM solution at $D = 6 \cdot 10^{-11}$

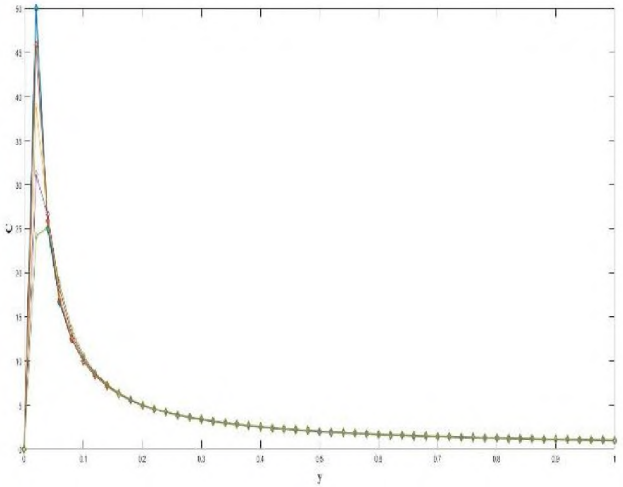
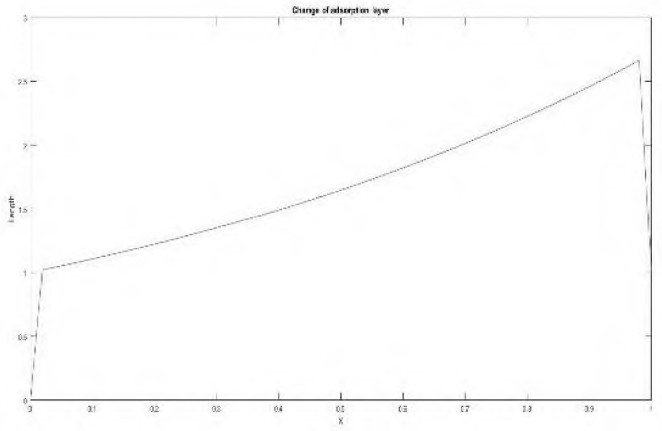
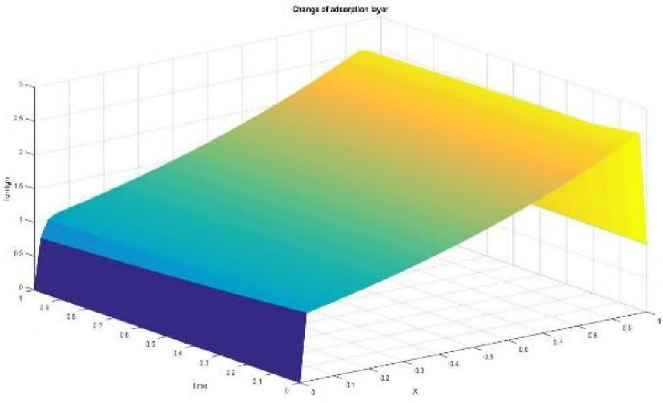


Figure 7. Variation of crosslinker concentration in the HPAM solution at $D = 4 \cdot 10^{-4}$

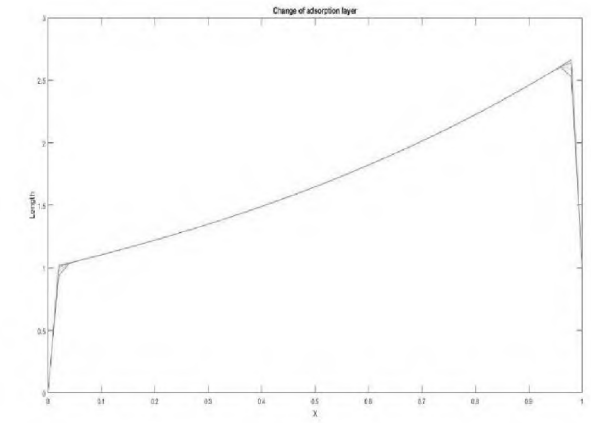


a)

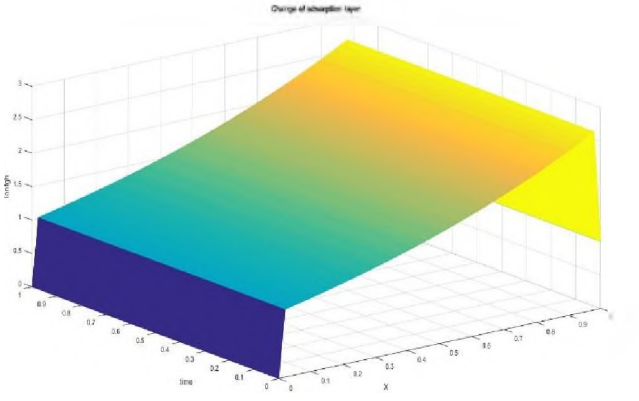


b)

Figure 8. Change in the thickness of the adsorption layer of PAA in pores at $D = 6 \cdot 10^{-11}$



a)



b)

Figure 9. Change in the thickness of the adsorption layer of PAA in pores at $D = 4 \cdot 10^{-4}$

In the course of the experimental program, the sealing efficiency of the composition was evaluated on artificial core samples of a water-saturated porous medium. During the tests, the injection sequence at

the outlet of the model consisted of aqueous solutions of Na_2CO_3 and bentonite clay prepared in various proportions (5.0% aqueous solution). The total volume of injected reactant solutions did not exceed 0.1 pore volume of the model reservoir. Following a two-hour aging period, water was subsequently injected into the inlet of the filtration model. The assessment of the treatment efficiency was performed by pressure transient analysis (PTA) before and after injection. As evidenced by the experimental results, the application of the proposed method results in an increase in the fluid pressure recovery time, thereby confirming an enhanced plugging capacity of the composition, which is attributed to the diffusion-controlled interaction of the reactants[6,7]. Furthermore, the study considers a structural formation model that incorporates both convective flow and diffusive transport processes.

The proposed model allows for several important conclusions. Hydrodynamic flows can exert a significant influence on the in-situ structural formation within the composition of the aqueous sodium carbonate solution containing clay particles. The composition promotes the formation of large, complex-shaped clay agglomerates, which in turn facilitate the plugging of high-permeability pore channels within the reservoir. Furthermore, the plugging process is initiated at locations distant from the initial injection of the colmatant, promoting the development of in-situ structural formation throughout the reservoir matrix.

Subsequently, investigations were conducted to control the process of capillary instability by altering the wettability characteristics at the fluid–rock interface during reservoir treatment. Aqueous alkaline solutions are widely employed as displacement agents for the stimulation of oil reservoirs in the late stages of production. Concentrated alkaline solutions modify the wettability of

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[6]Panahov, G.M., Balakchi, V.D., Mamedov, I.J. / Modelling of colmatant mass transfer during in situ gas generation process" / Tran. Natl. Acad. Sci. Azerb. Ser. Phys.-Tech. Math. Sci. Mechanics, 43 (8), pp. 54–61 (2023).

[7]Panahov, G.M., Balakchi, V.J., Abbasov, E.M. Modeling the growth of a colmatage agent for reservoir sweep improvement under water flooding / ANAS Transactions, Earth Sciences, Special Issue / 2023, pp. 109-112.

the porous medium within the hydrocarbon-bearing formation, thereby creating favorable conditions for the leaching and emulsification of asphaltene components present in high-viscosity crude oils. When considering the effect of reducing interfacial tension at the fluid–fluid boundary within a porous medium, it should be noted that the mobilization of trapped oil into the overall displaced fluid flow depends both on the velocity of the displacing water and on the ability to reduce the characteristic capillary pressure that arises as menisci of immiscible fluids move along the walls of the reservoir pore channels.

To validate the proposed hypotheses, laboratory experiments were conducted on an experimental model simulating pore channels. The setup included a vertical circular-section capillary with a diameter of $d = 1$ mm and a supporting medium with a diameter of $d = 4$ mm, which, when properly configured, formed an operational test cell. The chapter sets and solves the problem of controlling the hydrodynamic conditions at the displacement front by creating conditions that enhance the mobilization of oil trapped within the pore space into the overall displaced fluid flow[8]. This is achieved both through the reduction of interfacial tension and by overcoming capillary pressure at locations distant from the applied pressure source. In all experiments, variations in interfacial tension within the capillary were observed, depending on the proposed system and the applied pressure.

[8]Панахов, Г.М., Аббасов, Э.М., Юзбашиева, А.О., Балакчи, В.Д. Нестационарная конвекция Марангони в капилляре с жидкостью // Нефтегазовое дело, №6, 2018. – С. 60 – 77.

KEY CONCLUSIONS

1. Compositions with swelling properties were developed and investigated to enhance reservoir sweep efficiency during displacement [2].

2. Experimental studies examined specific aspects of the swelling process in aqueous solutions and the interactions of clays with various systems (electrolytes) as a function of solution concentration [3].

3. Laboratory investigations on a filtration setup demonstrated an increase in oil displacement efficiency by 20% when a blocking preflush was employed [7].

4. The experimental results were implemented under field conditions to regulate the injectivity of injection wells using the developed compositions. The technological operation was carried out at well No. 232852 of Binagady Oil Company in the Binagadi-North field [8].

5. Effective technological solutions based on novel composite formulations were developed to ensure deep-penetrating impact on high-permeability reservoir intervals.

6. A mathematical model of the growth of the plugging agent was constructed to improve reservoir sweep efficiency during displacement [9].

7. The autogesion and adsorption properties of the developed blocking compositions were evaluated. Computational experiment was conducted to assess the change in the thickness of the accumulation layer at different complex diffusion coefficients ($D = 6 \cdot 10^{-11}$ and $D = 4 \cdot 10^{-4}$).

8. The potential to control capillary instability by altering wettability at the contact interface during reservoir treatment was demonstrated [7].

The main content of the dissertation is reflected in the following publications:

1. Панахов, Г.М. Балакчи, В.Д., Аббасов, Э.М., Юзбашиева, А.О. Нестационарная конвекция Марангони в капилляре с жидкостью / // Нефтегазовое дело, № 6, 2018. – С. 60 - 77.

2. Панахов, Г.М., Балакчи, В.Д., Аббасов, Э.М., Юзбашиева, А.О. Особенности набухания глин в растворах электролитов / // Нефтегазовое дело, № 4, 2019. – С. 94-109.

3. Panahov, G.M., Balakchi, V.D., Abbasov, E.M., Ismayilov, S.Z. (2021). In-depth isolation of highly permeable zones for reservoir conformance control. Journal of Dispersion Science and Technology, 44(2), pp. 359–369.

4. Панахов, Г.М., Балакчи, В.Д., Аббасов, Э.М. Водоизолирующие глиносодержащие композиции с регулируемыми характеристиками набухания // Azərbaycan Neft Təsərrüfatı, № 8, 2020. - С. 27 – 33.

5. Балакчи, В.Д. Селективное блокирование высокопроницаемых каналов пласта с целью увеличения охвата залежи вытеснением // Azərbaycan Neft Təsərrüfatı, №8, 2021. – С. 22-27.

6. Шахвердиев, А.Х. Балакчи, В.Д., Панахов, Г.М., Аббасов, Э.М. Регулирование фронта вытеснения в неоднородных пластах путем блокирования высокопроницаемых каналов коллектора набухающей композицией // Актуальные проблемы нефтегазовой отрасли. Сборник докладов научно-практической конференции журнала «Нефтяное хозяйство». г. Москва, 2022. – С. 268-281.

7. Балакчи, В.Д. Изоляционные композиции для селективного регулирования приемистости нагнетательных скважин // Нефтегазовое дело, № 1, 2023. – С. 193 -208.

8. Panahov, G.M., Balakchi, V.J., G.M., Abbasov, E.M. Modeling the growth of a colmatage agent for reservoir sweep improvement under water flooding / ANAS Transactions, Earth Sciences, Special Issue / 2023, pp. 109-112.

9. Panahov, G.M., Balakchi, V.D., Mamedov, I.J. / Modelling of colmatant mass transfer during in situ gas generation process" / Tran.

Natl. Acad. Sci. Azerb. Ser. Phys.-Tech. Math. Sci. Mechanics, 43 (8), 54–61 (2023).

Author's contribution.

In publications [5, 7, 11], the candidate participated in problem formulation and synthesis of results.

In publications [1–4, 6, 7–9], the candidate contributed to conducting research, data analysis, synthesis, and field implementation of the obtained results.

The defense will be held on at October 14, 2025 11:00 at the meeting of the Dissertation council ED 2.03 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan State Oil and Industry University.

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