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DEVELOPMENT OF SCIENTIFIC BASIS FOR INCREASING THE EFFICIENCY OF TECHNOLOGICAL PROCESSES FOR PRODUCTION AND TRANSPORTATION OF COMPLEX RHEOPHYSICAL SYSTEMS

Specialty: 2526.01 - Technology of the development of offshore mineral deposits

Branch of science: Technical sciences

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ABSTRACT

dissertation for an academic degree
Doctor of Technical Sciences

Baku – 2025

The dissertation work was carried out at the Oil and Gas Research and Design Institute SOCAR. Azerbaijan National Academy of Science

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GENERAL DESCRIPTION OF THE WORK

Relevance and level of development of the topic. Currently, the oil industry plays a key role in the global economy, exerting a significant influence on the development of other industries. For many countries, including Azerbaijan, oil production and refining remain the main source of income. However, the low level of oil recovery and the slowdown in production rates have become a significant problem.

Increasing attention is paid to the production of high-viscosity oils with non-Newtonian properties. Such oils are characterized by high viscosity and low mobility, which complicates their production and transportation. To date, existing technologies for the production of these types of oil have not been widely used due to high capital costs.

Unrecoverable residual oil reserves can make up from 55% to 75% of the initial geological reserves, which emphasizes the need to develop new methods for their efficient extraction.

In the production of oil and gas at offshore fields, additional difficulties arise associated with the presence of sand, paraffin and other impurities in the products. These factors can lead to the formation of asphalt-resin-paraffin deposits (ARPD), which increases the complexity of operation and requires frequent repairs.

All these factors create additional difficulties in the design and operation of offshore oil fields, especially in conditions of limited mobility and exposure to external factors.

As a result, difficulties arise associated with the rheological characteristics of the extracted products. ARPD in the composition of oil significantly change its rheological properties, worsening its fluidity and affecting the transportation process. To successfully solve this problem, it is necessary to take into account the features of the movement of solid particles, droplets and bubbles in the flow, as well as the processes of separation, stratification and classification of oil systems, both in horizontal and vertical flows.

In addition, the complexity of transportation and collection of products is increased by the relief conditions of offshore fields, where production wells and product collection points are located on different platforms, and transport collectors often pass-through underwater areas, which creates additional mechanical and hydrodynamic difficulties.

Such features increase the complexity of the design and operation of the pipeline and product collection system, affecting the parameters of mass and heat transfer and flow hydrodynamics.

These problems directly affect the efficiency of the process of oil and gas production and transportation. Therefore, to improve the efficiency of these processes, it is necessary to develop comprehensive solutions that take into account the specific rheological characteristics, as well as the features of marine conditions and transportation technology. In connection with the above problems, the development of scientific foundations and practical recommendations for improving the efficiency of technological processes for the extraction, collection and transportation of oil and gas, especially taking into account the complexity of working with hard-to-recover and highly viscous oils, as well as the creation of new methods for improving the rheological properties of oil flows, becomes an urgent task.

The object of research is complex rheophysical systems and the processes occurring in them. The features of the behavior of structured oils containing a significant amount of resins, asphaltenes and paraffins, which are described by mathematical models in the form of linear and nonlinear differential equations, are studied. **The subject of the study** is the problems arising during the extraction and transportation of these complex rheophysical systems, as well as problems related to the study of their rheological properties and increasing the level of extraction of crude oil resources.

The purpose of the work is to develop a scientific basis for improving the efficiency of technological processes for the extraction and transportation of complex rheophysical systems by constructing mathematical models of the processes of filtration and structuring of oils in reservoir systems of oil fields and studying the rheological features of structured oils.

To achieve the stated goal, the following tasks are solved:

1. Analysis and generalization of experience in the field of increasing the level of extraction of crude oil resources. Assessment and selection of the most significant parameters of the oil reservoir (OR), as well as the construction of appropriate mathematical models to describe the production processes.

2. Study of problems of transportation of oil and oil products associated with their rheological properties. Development of effective methods of transportation of oil emulsion (NE) through pipelines to oil treatment units, which requires the creation of mathematical models to calculate the characteristics of the NE flow.

3. Creation of mathematical models to assess the state of oil and gas production and development of methods for assessing the efficiency of field operation.

4. Study of oil filtration processes in porous media using mathematical modeling. Development of a model of oil reservoir compaction associated with the deposition of impurities and asphaltene-resinous substances on the pore surface, as well as non-stationary filtration for non-Newtonian oils. Determination of the filtration properties of oil reservoirs and development of technologies for cleaning waste oil waters from asphaltenes.

5. Study of nonlinearities of oil filtration equations in porous media, dependence of these nonlinearities on the Reynolds number and development of models for their description for different ranges of Darcy number variation.

6. Mathematical modeling of processes occurring in the intermediate emulsion layer of the settling apparatus. Study of physicochemical adsorption of natural emulsifiers on the surface of an emulsified water droplet, wetting of armor shells, formation of a double electric layer on the surface of an emulsified water droplet and mechanical impurities. Construction of mathematical models of the processes of formation and destruction of oil emulsion.

7. Development of a diffusion model of paraffin crystallization from oil and deposition of asphaltene-resinous substances on pipeline walls. Study of diffusion-migration and crystallization processes, as well as the effect of deposit thickness on hydrodynamic and heat-mass transfer parameters.

8. Study of the main parameters of structured oils to create models describing their behavior. Development of models for calculating the viscosity of rheological dispersed systems taking into account structure formation.

Research methods. In the work under consideration, the tasks were solved using structural-system analysis of particle separation and sedimentation processes in suspensions and emulsions, methods of hydrodynamics and mass transfer in dispersed media, rheology of structured oil dispersed systems and modeling of physicochemical phenomena in the processes of separation of oil emulsions.

Main provisions submitted for defense.

1. Rheophysical features of structured oils.
2. Assessment of the state of the oil deposit.
3. Modeling of the processes of filtration and structure formation of oil in porous media taking into account the precipitation of asphaltenes and the non-stationarity of oil filtration.
4. Mathematical models of the formation and destruction of oil emulsion, determination of the frequency of particle collisions in polydisperse systems taking into account the influence of physical fields and thermodynamic systems on the properties of water-oil emulsions.
5. Study of asphalt-resinous substances deposition on the walls of transportation pipes based on diffusion-migration, crystallization, as well as kinetic and dynamic processes of solid phase formation and deposition during oil flow movement.
6. Results of the study of the main parameters of structured oils, based on which rheological models of a semi-empirical nature were created that satisfactorily describe the experimental data.

Scientific novelty of the study.

1. New mathematical models of the processes of filtration and structure formation of oils in reservoir systems were developed, which describe the dynamics of oil viscosity changes depending on the time of its passage through the gap. These models are exponential in nature and can be used to solve problems of increasing the extraction of hydrocarbon resources.
2. A model was created to determine the frequency of particle collisions taking into account the distribution function of their sizes. This allows us to take into account the influence of the dispersed phase distribution on the collision frequencies, which is important for modeling processes in oil systems.

3. Models have been developed that describe the processes of coalescence and fragmentation of water droplets in an oil emulsion during turbulent flow. These models allow us to interpret changes in droplet size and their effect on the process of separation of liquid phases “oil-water”.

4. The problems of oil filtration in a porous medium have been solved, it has been revealed that asphaltenes, which form coagulation structures in the form of aggregates and clusters, significantly affect the rheological properties of oil. The deposition of asphaltenes on the surface of a porous medium changes its porosity, which leads to pulsating attenuation of the well flow rate and compaction of the structure.

5. Based on the analysis of the solubility of asphaltenes in various aromatic hydrocarbons, a solution to an important environmental problem has been proposed - the creation of a technology for cleaning and separating wastewater from asphaltenes and solid particles. Using the phenomena of coalescence and fragmentation, mass transfer in “liquid-liquid” systems and experimental studies, a liquid-phase extraction technology has been proposed. 6. A solution to the equation of non-stationary oil filtration in a porous medium for a limited region is proposed. Algorithms for estimating the coefficients of piezo conductivity and permeability of a porous medium are developed, which allows for more accurate modeling of filtration processes under oil production conditions.

7. Mathematical models describing the mechanisms of particle deposition from a dispersed flow are developed. Comparison of these models with experimental data has shown that the formation of dense layers of particles on pipe walls significantly affects the phenomena of mass and heat transfer.

8. A kinetic model of dissolution of asphaltene-resinous substances in aromatic solvents, depending on temperature, is constructed. The model is based on mass transfer under conditions of isotropic turbulence and within the boundary layer, which makes it possible to determine kinetic dependencies and dissolution coefficients for various types of concentration distribution of the dissolved substance.

9. A generalized equation is proposed for calculating the viscosity of structured dispersed systems, taking into account their rheological properties. The viscosity curve features at the initial stages of structure formation have been revealed, which allows for more accurate modeling of the behavior of oil systems with different particle dispersions.

10. A model has been developed that describes the dependence of viscosity on the volume fraction of particles. Based on this model, it has been concluded that with slow coagulation of particles, the effective viscosity of the dispersed system depends on the coagulation time, which is of practical importance for oil production and transportation processes.

11. Models have been constructed that allow for estimating changes in the size and mass of nanoaggregates over time, taking into account the molecular and turbulent diffusion of asphaltene particles. Filtration and rheology models based on the solution of Maxwell's equation for viscoelastic fluids have also been proposed. Expressions have been obtained for estimating the effective viscosity of oil and its mobility depending on temperature.

Theoretical and practical significance of the research.

The results obtained in this work can be used by specialists involved in the issues of hydrodynamics and mass transfer in structured oil disperse systems, as well as oil filtration in porous media when:

- conducting a structural-system analysis of the main phenomena occurring in disperse media;
- solving issues of diffusion deposition of asphaltene particles in pores and pipes, as well as on the surface of water droplets in oil emulsions;
- approaching aggregation- and sedimentation-unstable systems, turbulent flows in pipes, structure formation in the medium and the evolution of particle distribution over time;
- solving problems of rheology of non-Newtonian oils and modeling the processes of separation of oil emulsions.

The scientific provisions proposed in the dissertation can be used to improve the efficiency of technological processes for the production and transportation of complex rheophysical systems. The results obtained in the dissertation work were mainly reflected in the monograph by G.I. Kelbaliyev, S.R. Rasulov, D.B. Tagiev and G.R.Mustafayeva - “Mechanics and Rheology of Oil Dispersed Systems”, Moscow, Maska Publishing House, 2017. - 462 p. Based on the book, Kazan Federal University developed a program for the discipline “Fundamentals of Rheological Analysis of Oil Dispersed Systems” within the framework of the training of masters in the specialty “Oil and Gas Business”, in which the specified monograph became the basic teaching aid (see Appendix).

Testing and implementation. The main results of the dissertation were reported and discussed at the following international conferences:

- at the international scientific and technical conference dedicated to the memory of Academician A.Kh. Mirzajanzade, (Ufa, 2016, p. 295-297);
- at the International Scientific and Practical Conference dedicated to the 60th Anniversary of Higher Oil and Gas Education in the Republic of Tatarstan (Almetyevsk, 2016, p.40-43);
- at the International Conference “Rassokhin Readings” (Ukhta, 2017, part 1, p.231-234);
- at the scientific and technical conference “Problems of Geology, Development and Operation of Fields, Transportation and Processing of Hard-to-Recover Heavy Oil Reserves” (Ukhta, 2021, p.149-153).

The SOCAR “Oil and Gas Research and Design” Institute issued a certificate stating that the results obtained in this dissertation are recognized as appropriate for use in the calculation and design of technological processes in the oil and gas complex.

Publication of scientific papers. The main results of the dissertation are presented in 35 scientific papers, including 10 articles in journals included in the international database Web of Science and Scopus and one monograph in the city of Moscow.

Name of the organization where the dissertation was completed. The dissertation was completed at the Research and Design Institute “Neftegaz” of SOCAR.

The total volume of the dissertation, taking into account the volumes of individual structural sections. The dissertation consists of an introduction, 6 chapters, main results and a list of references, including 283 publications. The dissertation, including tables, figures and a list of references, is commented on 407 pages. The introduction consists of 14008 characters, Chapter I of 81065 characters, Chapter II 24398 characters, Chapter III 59351 characters, Chapter IV 96927 characters, Chapter V 65037 characters, Chapter VI 63250 characters. The total volume of dissertations is 408811 characters.

MAIN CONTENTS OF THE WORK

The introduction substantiates the relevance of the study, formulates the purpose and objectives of the work, presents the scientific novelty, theoretical and practical significance of the study. The main points to be defended, as well as the subject, object and methods of the study, the volume and structure of the work, its approbation, a summary of the chapters and the areas of application of the results obtained are indicated.

The first chapter is devoted to the analysis of the state and problems of production, collection and transportation of complex heterogeneous products from wells in marine conditions. The problems arising during the production, collection and transportation of these rheophysical systems are considered. Based on the analysis, the tasks are defined, and the need to develop mathematical models to describe the processes occurring in rheophysical systems is shown.

The relevance of the problem in the oil and gas industry of Azerbaijan is that most of the fields are at a late stage of development, characterized by high water cut and low production rates. This requires a search for effective solutions to increase oil recovery and improve technological processes.

The paper presents a review of studies related to the development of oil fields both in Azerbaijan and abroad, as well as methods of influencing oil-bearing formations. It was revealed that oils containing active components have structural and mechanical properties at low temperatures under dynamic conditions, which leads to a decrease in the efficiency of cold-water flooding of oil fields. Particular attention is paid to the fact that when using flooding, the process of development and extraction of oil from the subsoil is affected by geological and physical parameters that determine the rheological properties of reservoir oils, reservoir properties and heterogeneity of formations. This emphasizes the need to improve flooding methods to increase the efficiency of developing fields with hard-to-recover oil reserves.

Further, the physicochemical methods of influencing formations developed to increase the oil-washing capacity of the injected water are considered. These methods are used in the process of developing oil and gas fields as tertiary methods, as well as to improve oil recovery from formations under the influence of working agents (water, gas) at different stages of field development. It is important to note that these methods can be used both at the initial and late stages of development.

When analyzing the works, it was found that in the vast majority of the studied fields, due to the excess of oil viscosity compared to the viscosity of water and the heterogeneity of the reservoir, early flooding of productive wells occurs, which in turn leads to a low oil recovery factor. In this regard, physicochemical methods of influencing formations are aimed at controlling the mobility of oil and water, as well as managing their rheological properties and interaction with the rock surface.

As part of the work, an analysis of oil field development methods aimed at increasing the level of oil resource extraction was carried out. The first method considered is the technology of water injection with controlled mineralization, which refers to tertiary methods of enhancing oil recovery. This method allows increasing oil recovery due to rock hydrophilization. To study the mineral composition of the rocks that make up the formation, an extensive range of laboratory studies of core material was carried out. The mineral composition of the clays was determined by X-ray diffraction analysis, which did not reveal any minerals that cause clay to swell when exposed to water. However, it should be noted that this method has several disadvantages. These include high costs, decreased efficiency over time due to reservoir depletion, risk of reservoir clogging, negative environmental impacts from underground water supply, and the possibility of seismic events and geological changes due to additional pressure. The second method includes new effective combined and thermal technologies for influencing complex carbonate formations with hard-to-recover reserves of highly viscous oil. These methods have no analogues in the world practice of oil production and have already been industrially implemented. They include the following approaches:

- increased oil recovery using liquid-phase oxidation;
- impact on viscous oil deposits with thermopolymers;
- pulsed-dosed thermal impact on the formation;
- combined thermal cyclic impact using injection systems;
- cyclic in-situ thermal impacts.

However, these methods also have a number of disadvantages, including:

- an increase in the temperature in the formation, which can lead to deformation and destruction of rocks, complicating the extraction of oil and gas;
- steam emissions that contribute to environmental pollution and cause environmental problems;
- high energy costs, which increases the cost of oil and gas production;
- formation of reaction product deposits, which leads to well clogging and reduced reservoir productivity.

The paper also analyzes combined methods of influencing oil reservoirs, one of which is a universal method for enhancing oil recovery using surfactants. This method can be effectively used at the initial stage of increasing water cut of the product. Projects using these methods were considered.

In foreign practice, methods based on the use of polymers are widely used, since these substances are very sensitive to the content of salts, which sharply reduces the viscosity of oil. As a solution to the problems that have arisen, it was proposed to use non-ionic surfactants.

The method using surfactants has its advantages and disadvantages. The advantages include:

- preservation of reservoir properties;
- no negative impact on the preparation and transportation of oil;
- reduction of surface tension at the oil-water boundary, which facilitates the permeability of oil.

However, the method also has disadvantages, such as:

- large-scale adsorption of polymers;
- immiscibility of the polymer solution with oil, which reduces the displacement efficiency.

When transporting oil and oil products, problems associated with their rheological properties arise. To solve these problems, it is necessary to take into account the patterns of movement of solid particles, droplets and bubbles in the flow, as well as the processes of separation, stratification and classification of oil systems.

The causes of these phenomena can be conditionally divided into several factors:

1. Oil systems have a complex hydrodynamic structure, including various flow directions, as well as physical interactions of both hydrodynamic and non-hydrodynamic nature.

2. In dispersed media, various interactions occur between the particles of the dispersed phase, such as coagulation, agglomeration, crushing, as well as interactions with surfaces (wall effect) and with the carrier phase. These processes are accompanied by particle collisions, their deformation, destruction of the structure and abrasion. The intensity of these phenomena increases with a high level of flow turbulence and high particle density.

3. At high particle density in the flow, deformation of the hydrodynamic fields of the particles occurs due to their mutual influence. This limits the movement of the particles, which leads to coagulation, fragmentation and other physical processes.

4. Viscosity, density, surface tension of the components of the dispersed phase, as well as physical and chemical processes such as dissolution, evaporation, sublimation and condensation, significantly affect the behavior of particles in the system.

5. In vertical and horizontal channels, diffusion transfer of particles and their sedimentation in a turbulent flow occurs.

6. The process of transformation and dispersion of particle parameters, fluctuations in concentrations and particle directions lead to the stochastic nature of a polydisperse system.

7. Shear viscosity is a property that determines the ability of a liquid to deform under the action of shear forces. High shear viscosity can cause difficulties when passing through narrow channels or when mixing with other liquids.

8. Temperature conditions. The rheological properties of oil and oil products change depending on temperature. At low temperatures, problems with freezing are possible, which complicates transportation and can lead to blockages in pipelines.

From the above it follows that to solve this problem, a comprehensive study of all processes associated with particle migration, their sedimentation and separation is necessary.

The paper presents an overview of many expressions for calculating the coefficient of turbulent diffusion of particles, taking into account the dynamic velocity and sedimentation velocity, and an analysis of the sedimentation mechanism in rheophysical systems is carried out. Extensive experimental data are presented for determining the sedimentation rate of solid particles of various types from a flow. There is a discrepancy between the experimental and calculated data on the sedimentation rate, which depends on the density of the particles - the higher the density, the greater the difference.

A review of the studies shows:

1. The existence of many experimental studies and formulas describing them complicates the creation of a single formula for calculating the sedimentation and floating rate of particles, with the exception of Stokes particles. This is due to the variability of the size and shape of the particles, their flow around them, physical phenomena and the dependence of the drag coefficient on the Reynolds number.

2. Fluctuations in the concentration of particles, their distribution in inhomogeneous fields, fluctuations in transverse velocity and energy dissipation lead to stochastic sedimentation processes. A specialized empirical approach is required to solve this problem.

3. The study of particle sedimentation processes in an isotropic turbulent flow for different turbulence scales in pipes and channels made it possible to identify key turbulence characteristics that affect the sedimentation rate: specific energy dissipation, turbulence scale, and viscosity of the medium.

4. Changes in particle size lead to limitations in the sedimentation process, which causes frequent collisions and interactions between particles. As a result of these processes, coagulation, deformation of the particle shape, their destruction and crushing occur, which leads to the sedimentation of polydisperse particles.

5. At the current stage of oil production development, there is no universal method for increasing oil recovery that could be applied to all fields. This is due to differences in the reservoir, physical and chemical properties of the formation at different fields. Therefore, in order to increase oil recovery, it is necessary to individually develop and select the technology of action for each specific field.

Based on the analytical review, it follows that it is necessary to solve a number of important problems, such as:

- development of methods for assessing the state of oil and gas production using mathematical modeling;
- mathematical modeling of oil filtration processes in porous media;
- modeling the processes of formation and destruction of oil emulsions;
- study of diffusion-migration and crystallization processes during the deposition of asphaltene-resinous substances on the walls of pipes during transportation;
- study of rheological characteristics of structured oils and development of corresponding models.

The second chapter is devoted to the development of a method for assessing the state of an oil reservoir, which is an important production task. One of the urgent problems of oil field development is the increase in oil recovery. Low oil recovery factor from the reservoir is largely associated with molecular-surface processes occurring at the interface of oil-rock-forming minerals and buried water. This is due to the presence of hydrophobic sections of the reservoir that come into direct contact with oil, if we take into account that a significant part of the residual oil is in the reservoir in a boundary-bound state.

Based on the role of ion-exchange processes and asphaltene nanotherapy, these factors must be taken into account when developing mathematical models of oil reservoir processes. This will help to intensify oil production and increase oil recovery from reservoirs in the late stages of development. The development of adequate mathematical models for describing processes in an oil deposit requires an integrated approach, including a system analysis of subsurface processes and the selection of key parameters that must be taken into account in the model. Within the framework of this approach, a generalized structural diagram was proposed that reflects the main indicators and parameters of oil production processes.

Based on this diagram, a methodology was developed1 using a modification [1] of the Kolmogorov-Erofeev kinetic equation. This methodology allows for the first time to apply fundamental mathematical approaches to quantitatively assess the state of oil deposits. Its key feature is the ability to determine the model coefficients using an analytical solution of equations in the initial conditions. This makes the methodology practical for predicting changes in current oil production and assessing the prospective characteristics of deposits, which was previously unavailable when using classical models such as the Arps equation. Thus, the proposed approach provides a new perspective for analyzing and managing oil production processes.

The problem of increasing the viscosity of oil (oil emulsion) and, accordingly, the hydraulic resistance (friction force) arising from the movement of fluids in the tubing is considered.

A system analysis of the current state of heat transfer processes in horizontal pipelines and the wellbore of oil wells is carried out. The shortcomings of existing approaches to mathematical modeling of the process of heat transfer from the ascending flow of fluids to the rock are highlighted. When formation fluids (oil, gas and water) move in the lifting tubing from the bottomhole to the mouth of the oil producing well, a gradual decrease in the flow temperature occurs, which leads to an increase in oil viscosity and, accordingly, an increase in hydraulic resistance (friction force) when fluids move in the pipe.

Reducing the flow temperature is especially problematic for high-viscosity oils containing refractory paraffins and structured asphaltenes (in the form of clusters), since this leads not only to an increase in the viscous resistance to flow, but also to the deposition of these components on the inner surface of the tubing, which creates additional problems in the operation of the deep-well pump. Many works are devoted to solving this problem, and they have made a significant contribution to its study. However, these studies do not take into account the influence of thermal conductivity of the water-oil layer and

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[1] Rzaev, Ab.G. Development of a method for assessing the state of an oil deposit / Ab.G. Rzaev, S.R. Rasulov, G.R. Mustafayeva [et al.] // Oilfield Business, 2015. No.5, - p. 21-23.

gas cap, which are located in the space between the tubing and the casing, and their thermal conductivity is significantly lower than that of carbon steel. These factors are taken into account in works that developed an indirect method for determining the flow rate of an oil producing well based on a thermogram obtained on the well discharge line. However, these works did not develop a mathematical model of heat transfer from an ascending fluid flow to rocks through several layers with different thermal conductivities. In addition, some studies do not take into account changes in the mass flow and temperature of fluids, as well as the ambient temperature (rock) along the height of the tubing. The effect of a layer of liquid and gas in the annular space formed between the tubing and the casing is not taken into account.

The paper proposes an integrated approach and a new mathematical model[2] for determining heat transfer from the ascending flow of fluids in the oil well tubing to the surrounding rock, which eliminates the previously identified shortcomings.

First, Fourier's empirical law and Newton's empirical cooling formula are used. Then, the final mathematical model of the heat transfer process from the ascending fluid flow in the riser pipe of an oil well to the surrounding rock is derived as:

$$\frac{1}{\lambda_ф} ln r_в + \frac{1}{\lambda_{ст}} ln \frac{r_н R_н}{r_в R_в} + \left(\frac{\ell}{Н\lambda_ж} + \frac{\ell}{((\ell-Н)\lambda_г)}\right) ln \frac{R_в}{r_н} + \frac{1}{\lambda_п} ln \frac{R_к}{R_н} =$$

$$= \frac{2\pi f t[t_ф(z)-(t_з-q_z)]}{Q(z)} \quad (1)$$

λ^*-coefficient of hydrodynamic resistance; $t_з$-temperature of fluid flow at the bottom of wells; $R_к$-radius of the power circuit; D-is the diameter of the pump-compressor pipe; Q^*-fluid flow rate in the tubing; ρ-density of fluids; C-specific heat capacity of fluids; E-mechanical equivalent of heat; i-hydraulic slope (dimensionless); v-is the velocity of fluid flow in the wellbore; g-is the acceleration due to gravity; $t_ф$-is the temperature of the fluids; $\lambda_ф, \lambda_{ст}, \lambda_ж, \lambda_г, \lambda_п$ -are the thermal conductivity of the fluid, liquid, gas, rock and the walls of the tubing

[2] Guluev, G.A. Mathematical modeling of the heat transfer process in the oil wellbore / G.A. Guluev, Ab.G. Rzaev, G.R. Mustafayeva [et al.] // Automation, telemechanization and communication in the oil industry, 2015. No.1, - p. 44-47.

and casing, respectively; z-is the vertical coordinate; ℓ-is the length of the cylinder wall; Q -is the amount of heat transferred; $R_{\text{в}}, R_{\text{н}}$-are the inner and outer radius of the casing; $r_{\text{в}}$, $r_{\text{н}}$-are the inner and outer radii of the wall of the tubing.

The proposed mathematical model takes into account the geometric gradient of the rock and the temperature change from the bottomhole to the discharge line of the oil producing well. It also takes into account the liquid content in the intertube space formed between the tubing and casing, as well as their thermal conductivity.

The model describes the process of heat transfer from the ascending flow of fluids through the tubing of the oil producing well to the surrounding casing.

The third chapter presents the results of mathematical modeling of the processes of filtration and structure formation of oils in the reservoir systems of oil fields. The purpose of this study was:

- Development of a rheological model of compaction and non-stationary filtration for non-Newtonian oils, modeling of filtration rate attenuation;
- Determination of filtration properties of an oil reservoir;
- Study of nonlinearities of oil filtration equations in porous media depending on the Reynolds number and development of models for their description for various regions of Darcy number variation.

The paper studies the processes occurring at the interface between liquid and gas with rock-forming minerals.

It has been established that one of the reasons for low oil recovery from a reservoir is considered to be molecular-surface processes occurring at the interface between oil, rock-forming minerals and buried water. The distribution of hydrophilic and hydrophobic areas, their number and alternation are determined by the nature of rock-forming minerals, the physicochemical properties of the liquids saturating the reservoir and the content of buried water.

It should be noted that a significant part of the pore channels (65-85%) has hydrophobic properties and is hydrophobized by oil and gas. Taking into account the above features, the process of oil structure formation in reservoir capillaries was described through the change in viscosity over time. This change in viscosity, in turn, affects the hydrodynamic characteristics of the oil flow and oil emulsions, which plays an important role in the process of their transportation.

Thus, a rational approach to the transportation of produced oil emulsion through pipelines to an oil treatment plant requires the development of mathematical models that take into account the structural features and rheological properties of oil as a non-Newtonian fluid. Experimental data on the dependence of shear stress on shear rate are taken from literary sources, and an exponential law[3] is proposed to describe this process

$$\tau = A\left[1 - exp\left(\frac{\dot{\gamma}}{\lambda}\right)\right] + B, \qquad (2)$$

Where τ-is the friction (shear) stress;A, B and λ-are experimental coefficients, $\dot{\gamma}$-is the displacement speed.

Formula (2) describes the experimental data and can be used to model the behavior of abnormal oils and oil emulsions with non-Newtonian flow.

The flow of non-Newtonian oils in porous media is characterized by the precipitation of asphaltene-resinous and paraffin compounds, as well as solid particles contained in crude oil, in the pores, which significantly affects the porosity of the medium. Asphaltene precipitation is a serious problem in all areas of the oil industry: production, collection, transportation, preparation and refining of oil.

The mechanism of formation of a dense layer on the liquid-solid interface is very complex and is determined by many factors, including the presence of a boundary layer on the liquid-solid wall interface, diffusion and turbulent transfer of asphaltene particles to the interface, temperature conditions in the boundary layer and on the pipe wall, etc.

It should be noted that particle deposition occurs by migration-diffusion and migration-gravitational mechanisms (in vertical and horizontal pipes).

It is obvious that the process of asphaltene deposition on the surface is a mass-exchange process, and the rate of mass transfer is

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[3] Rasulov, S.R. Mathematical modeling of the process of oil structure formation in the reservoir of oil fields / S.R. Rasulov, Ab.G. Rzayev, G.R. Mustafayeva [et al.] // Bulletin of the Azerbaijan Engineering Academy, 2016, No.3, - p. 98-101.

determined by the total molecular and turbulent diffusion, complicated by gravitational sedimentation in inclined and horizontal pipes. In addition, the mass transfer process is the coagulation of asphaltene particles during their collision, resulting in the formation of nanoaggregates, clusters, as well as their destruction and fragmentation, which significantly affects the flow of structured oil.

The migration-diffusion mechanism of asphaltene-resin particles sedimentation accompanies all sedimentation processes, including those that occur in a porous formation, as well as the processes of separation of oil emulsion and others. The precipitation of asphaltenes in the pores of the formation leads to a change in its porosity, which, in turn, leads to compaction of the porous structure, clogging and deposition of various impurities contained in oil (asphaltenes, resins, solid phase).

The paper[4] considers the problem of compaction of a porous medium as a result of its compression and deformation under the action of external deforming stresses, for example, mass forces of the overlying layers, as well as pore clogging due to the deposition of asphaltene-resinous substances and finely dispersed solid phase on the inner surface of the pores.

This study models the attenuation of the filtration process as a result of a change in the porosity of the reservoir over time for laminar and turbulent fluid flow in pores.

It is noted that with turbulent fluid flow in pores, the attenuation of the filtration process in a porous medium occurs faster than with laminar flow. Contamination of an oil reservoir directly affects the change in its porosity, on which the hydrodynamic properties and well flow rate depend. The paper proposes a technique that takes this dependence into account for calculating the change in well flow rate.

Based on literature data, a formula was used in which the permeability coefficient is defined as a complex function of porosity.

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[4] Kelbaliev, I.G. Modeling of oil filtration in a porous medium and technology of liquid-phase extraction of asphaltenes / G.I. Kelbaliyev, S.R. Rasulov, G.R.Mustafayeva [et al.] // Theoretical Foundations of Chemical Technology, 2016. Vol. 50, No.6, - p. 673-682.

The Kozeny-Karman equation specified that the permeability of a porous medium depends on the surface area of the particles, the tortuosity coefficient, and the shape of the pores. Thus, the developed model relates changes in well flow rate to porosity and time, which makes it a practical tool for assessing filtration processes in real formations.

Numerous studies and experimental data obtained during the operation of a real well for the production of Azerbaijani oil have shown that changes in well flow rate over time can have a pulsating, damping nature.

Numerous studies and experimental data obtained during the operation of a real well for the extraction of Azerbaijani oils have shown that changes in the well flow rate over time can have a pulsating damping nature.

The paper considers the solution of the equation of non-stationary filtration of oil in a porous medium for a limited area. Based on this solution, algorithms for estimating the coefficients of piezo conductivity and permeability of a porous medium and have been developed

$$\chi = -\frac{0{,}1729\varepsilon R_k^2}{t} ln \frac{0{,}626(P_k - P)}{P_k - P_c}. \quad (3)$$

$$k = \chi \eta_c \beta^*. \quad (4)$$

Here t -is time; P, P_k, P_c -are pressure, contour pressure, bottomhole pressure, respectively; R_k^2 -is the radius of the formation contour; β^* -is the reduced coefficient of elastic capacity of the formation, η_c -is the dynamic viscosity of oil.

For a more in-depth analysis of filtration processes, criteria of similarity of a porous medium are proposed, such as the number $Kr = \frac{V_0 R_k}{\chi} = ReQ_k$, where Kr characterizes the ratio of convective transfer to the transfer of momentum by piezo conductivity and is similar to the Peclet number for mass transfer and heat transfer.

Additionally, the criterion $Q_k = \frac{V_s}{\chi}$ is introduced, similar to the Prandtl number for heat transfer and the Schmidt number for mass transfer, which reflects the physical properties of a porous medium.

Comparison of the proposed models with experimental data showed their high accuracy and good convergence of calculations with real results.

The regularities of filtration of liquids and gases in a porous medium are affected not only by the interface between oil, gas and water, but also by surface phenomena occurring at the boundaries of solids and liquids. These phenomena significantly affect the linear nature of the filtration law in a wide range of changes in the Reynolds number.

In work[5], a study was conducted of nonlinearities of oil filtration equations in porous media and models for their description were developed for various regions of Darcy number variation. Filtration nonlinearities are caused by the complexity of the porous medium structure, the anisotropy of its properties and the nature of the flow.

In real oil and gas reservoirs, anisotropy can be associated with fracturing, layering and random changes in the pore space. This requires taking into account the differences in filtration properties in three directions, which complicates the practical solution of Darcy equations due to the difficulties of determining the permeability distribution. Even under the assumption of isotropy of the medium, the presence of viscous and convective flows leads to nonlinearities, which emphasizes the importance of studying these processes.

Numerous studies devoted to the analysis of the limits of applicability of Darcy's law made it possible to identify the following critical boundaries:

a) the upper boundary associated with the manifestation of inertial convective forces at sufficiently high filtration rates;

b) the lower boundary associated with the manifestation of non-Newtonian rheological properties of the liquid, its interaction with the solid skeleton of the porous medium at sufficiently low filtration rates and viscous flow. The upper and lower limits of applicability of Darcy's law are usually associated with some critical (limit) value of the Reynolds number Re_{cr}.

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[5] Келбалиев, Г.И. Проблемы нелинейностей уравнений фильтрации нефтей в пористых средах / Г.И. Келбалиев, С.Р.Расулов, Г.Р. Мустафаева [и др.] // Нефтепромысловое дело, 2015. №8, - с.23-26.

For a general description of the Darcy number in a wide range of Reynolds number variation, a semi-empirical expression is proposed:

$$Da = 1 - \exp(-5 \times 10^6 Re^3) - 0{,}01Re \times$$

$$\times (1 + 0{,}000122Re^2)^{-0{,}5} \quad (5)$$

To calculate the Darcy number, all formulas use the expression for the Reynolds number in the form:

$$Re = \frac{Va}{(0{,}75\varepsilon + 0{,}23)\nu_c}. \quad (6)$$

Where V-is the flow or filtration velocity; a-is the characteristic particle size; ε-is the porosity; ν_c-is the kinematic viscosity of the medium.

This study examines the description of oil reservoir compaction processes associated with the deposition of various impurities and asphaltene-resinous substances on the inner surface of pores. The equation for changing porosity is constructed based on mass transfer phenomena in laminar and turbulent regimes. The attenuation of the filtration process is described by a model associated with a change in the permeability coefficient and porosity of the layer over time. The presented comparisons of the calculated values of flow rate changes with practical data showed satisfactory agreement and revealed a pulsating attenuating nature of the dependence of the filtration rate on time.

The fourth chapter is devoted to modeling the processes of formation, destruction and hydrodynamic features of the flow of oil emulsions in the pipeline network of offshore oil production.

The mechanism of formation, stabilization and destruction of oil emulsions as heterogeneous media is the subject of many studies. However, many problems associated with phenomena occurring at the oil-water interface, coalescence and fragmentation of water droplets, stratification and sedimentation, still do not have correct solutions. Important factors affecting the efficiency of separation of oil emulsions are the conditions of thinning, rupture of the interphase film and the rate of coalescence associated with the destruction of the adsorbed film of asphaltene-resinous substances on the surface of the droplets, as well as the participation of demulsifiers in this process. In order to theoretically solve the problem associated with the flow of suspensions and emulsions, some simplifications of the real picture of the flow of a polydisperse medium with particles of different composition and size were made.

Systems of differential equations describing general cases of suspension and emulsion motion must take into account the fundamental discontinuity of the medium, as well as the physicochemical processes of heat and mass transfer occurring in it.

A general equation of motion of multiphase systems with certain simplifications and assumptions is proposed, which facilitate the solution of hydrodynamic problems both in turbulent and laminar flows. A differential equation of motion of a single i-th spherical particle in a suspension is also proposed.

The processes occurring in a multiphase system are analyzed, and a conclusion is made about the mutual influence of phases, which leads to a change in interphase exchange. The motion of finely dispersed suspensions in a turbulent flow is considered. It is noted that the presence of particles of different types in a liquid complicates the solution of hydromechanics problems both in turbulent and laminar flows.

A formula is proposed for determining the drag force of a solid spherical particle in the surrounding liquid.

$$F_T = 6\pi\rho_c v_c a V_0. \qquad (7)$$

Where ρ_c-is the density of the medium; a-is the particle diameter; V_0-is the initial particle velocity.

The process of separating oil emulsions is an important stage in the preparation and purification of crude oil from water, mineral salts and various accompanying impurities. In calculating the processes and apparatuses of chemical technology, such as liquid extraction, separation of heterogeneous systems, reactions in systems of insoluble liquids and others, there is a need to determine the kinetics (velocity) of coagulation of dispersed particles. Despite the theoretical significance of the formulas for calculating the frequency of collisions of droplets and particles in a flow, their use for specific practical applications is a labor-intensive task.

For this purpose, we have provided formulas from various authors that are suitable only for describing the frequency of particle collisions in monodisperse systems. However, real systems, including oil emulsions, are polydisperse, and the size distribution of dispersed particles has a wide range (the size of the smallest particles can be about 100 times smaller than the size of the weight-average particles). This makes the use of the above formulas for calculating the collision frequency of dispersed particles in polydisperse systems problematic, since they can lead to underestimated results.

An attempt to solve this problem was made by Hans Müller, who, using Smoluchowski's theory and the coefficient characterizing the probability of collision of two particles of different sizes (a function of the ratio of their radii), derived a formula that takes into account only two distribution spectra. However, this formula is limited in application, since it is discrete (only two particle distribution spectra are taken into account) and, therefore, is simplified for more complex polydisperse systems.

$$\theta_{\Gamma} = 4\pi a D n \gamma_{ik} = \frac{4\pi a D n\left(1+\frac{r_i}{r_k}\right)^2}{4\frac{r_i}{r_k}}, \tag{8}$$

where r_i, r_k -are the average radius of the i-th and k-th particles, respectively; θ_{Γ}-is the collision frequency of dispersed particles; D-is the diffusion coefficient, which describes the rate of particle diffusion in the medium; n-is the number of particles per unit volume; γ_{ik}-is the factor characterizing the probability of a collision between two particles of different sizes, a-is the radius of the particles in the system.

In order to eliminate this drawback (or improve the formula), it is proposed to derive an equation that takes into account the influence of the characteristics of the initial particle size distribution on the frequency of their collisions. Having carried out a theoretical analysis of the frequency of droplet collisions in polydisperse systems and making the appropriate assumptions, we obtain an expression for the frequency of particle collisions, taking into account their initial distribution

$$\frac{\theta^x}{\theta} = \left[\left(\frac{\sigma}{r_{cp}}\right)^2 + 1\right]^3 = z^x, \tag{9}$$

where θ^x-is the particle collision frequency taking into account their initial redistribution; θ-is the particle collision frequency per unit time, σ-is the particle collision radius; z^x-is the polydispersity coefficient and characterizes the influence of the characteristics of the initial particle distribution (r_{cp}, σ) on the collision frequency.

The resulting formula[6] fully takes into account the influence of the dispersed phase distribution by the size of dispersed particles on the frequency of their collisions. This formula shows that with an increase in the polydispersity of colloidal systems, the collision frequency (z^x) also increases, and vice versa. Further, the paper examines the problems underlying the modeling of the processes of separation and stratification of oil emulsion, accompanied by coalescence and fragmentation of water droplets in a turbulent flow. The influence of the asphaltene-resinous substances content on the formation of adsorption films on the surface of water droplets, as well as their influence on coalescence, droplet fragmentation and the evolution of the droplet size and time distribution function are considered. Analysis of the composition armoring shells on the surface of water droplets of crude oil of various deposits, contributing to the stabilization of oil emulsions, showed that the main stabilizers are asphaltenes and resins, which include high-melting paraffins and inorganic mechanical impurities. The mechanism of formation of adsorption films on the surface of drops was considered, which includes the stages of diffusion transfer of the mass of the substance (asphalt-resinous substances and solid phase) from the volume of oil to the surface of water droplets, adsorption of the substance on the surface of the droplets with the formation of a film, desorption and destruction of the adsorption layer with the participation of surfactants.

Equations are proposed for estimating the evolution of the number of droplets and their sizes over time, depending on the frequencies of fragmentation and coalescence

[6] Rzaev, Ab.G. Determination of the particle collision frequency in polydisperse systems / Ab.G. Rzaev, S.R. Rasulov, G.R. Mustafayeva [et al.] // Scientific Notes of the Research Institute “Geotechnological Problems of Oil, Gas and Chemistry”, 2015. Vol. XVI, - p.433-438.

$$N(t) = \frac{N_{0\,exp(\omega_d\,t)}}{1+\frac{1}{2}\omega_k \upsilon N_0 C}. \qquad (10)$$

Where ω_k and ω_d -are the frequencies of coalescence and fragmentation, respectively; υ-is the current volume of the droplet; N_0-is the initial number of droplets per unit volume, (t)-is the time that affects the change in $N(t)$.

When $\omega_k \gg \omega_d$-coalescence processes predominate.

$$N(t) = \frac{N_0}{1+\omega_k \upsilon N_0 t}. \qquad (11)$$

When $\omega_d \gg \omega_k$-crushing processes predominate.

$$N(t) = N_0 exp(\omega_d t) \qquad (12)$$

The proposed mathematical models allow us to interpret the change in the size of water droplets in an oil emulsion, which affects the processes of separation of liquid phases oil-water. The main parameters that affect the distribution of water droplets and phase separation are the physical properties of the emulsion itself (density, viscosity) and turbulence parameters (energy dissipation, scale of turbulent pulsations).

Intensification of the processes of separation of oil emulsions is primarily associated with the turbulence of the flow in the intermediate layer, since turbulent velocity pulsations contribute to the weakening of intermolecular bonds between the adsorbed components of the armor shells, their destruction and reduction, as well as an increase in the frequency of droplet collisions.

Today, there are many methods for intensifying the processes of separation of oil emulsions, among which special attention should be paid to the use of a constant electric field. When examining the process of separating oil emulsions using a constant electric field, it was found that, unlike an alternating electric field, polarity does not change in a constant field. Therefore, special measures must be taken to destroy conductive chains.

For separating oil emulsions, a constant electric field is used in dilute systems with a volume fraction of water less than 1-2%, i.e., in oil refining processes, when the distances between individual droplets are equal to several of their diameters. Under such conditions, the influence of local electric fields becomes so insignificant that the probability of forming conductive chains between the electrodes tends to zero.

A characteristic feature of the behavior of dispersed systems in a constant electric field, even if it is spatially uniform (not gradient), is that water droplets of the dispersed phase tend to move in a directed direction toward one of the electrodes. This is explained by the presence of an electrokinetic potential caused by a double electric layer.

Based on the analysis of oil emulsions and the influence of physical fields on them, important properties of the processes of coalescence and fragmentation of droplets are identified, such as aggregative instability, the associated spatial heterogeneity, deformation and sedimentation of droplets, the nucleation of new particles and other factors. It is shown that in real conditions, a quasi-equilibrium state can exist between the processes of coalescence and fragmentation, which leads to stationary distribution functions.

The efficiency of oil treatment, including dehydration and desalination, depends on the removal of armor shells from emulsified water droplets and their separation into oil and water. Armor shells formed by natural emulsifiers prevent droplets from coalescing, and their destruction at the molecular level (0.1-100 nm) is a key stage. The stability of emulsions is affected by the physicochemical properties of emulsifiers, charge interactions, wettability, temperature, consumption of demulsifiers and the properties of formation water.

The intermediate emulsion layer, located between the water and oil layers, performs important technological functions, promoting coalescence and filtration. The processes of formation and destruction of armor shells depend on the adsorption of natural emulsifiers, wetting of the shells and the formation of a double electric layer.

The conducted studies have shown that the intermediate emulsion layer consists of many emulsions and contains mechanical impurities (sulfides, clays, etc.). A method for assessing the efficiency of the intermediate emulsion layer has been developed, which consists of comparing finely dispersed emulsified water droplets at the inlet and residual water at the outlet of the settling tank. The main stages include:

1. Determining the critical radius of droplets based on Stokes' law.

2. Calculating the theoretical water content at the outlet of the settling tank.

3. Determining the actual water content.

4. Assessing the efficiency of the PES through the water retention index.

Mathematical models based on the Fokker-Planck, Darcy and Kozeny-Carmen laws describe the processes of coagulation, droplet fragmentation and their size distribution. It has been established that the stability of oil emulsions is associated with the formation of a double electrical layer, as well as with the function of the intermediate emulsion layer as a hydraulic filter. Algorithms have been developed for calculating the residence time of oil in horizontal and spherical settling tanks

$$\tau_{H1} = (nl/x_1)\sqrt{[6R_1(2R_1 - h_1^*) + (2R_1 - h_1^*)^2]\,R_1^2/3} -$$

$$-\sqrt{[2R_1(2R_1 - h_1^*) + (2R_1 - h_1^*)^2](R_1 - h_1^*)^2} \qquad (13)$$

$$\tau_{H2} = \pi(2R_2 - h_2^*)^2\,(R_2 + h_2^*)/3x_1 \qquad (14)$$

where n-is the coefficient reflecting the number of flows; l-is the length of the horizontal apparatus; R_1 and R_2-are the radii of the horizontal and spherical apparatuses; h_1^* and h_2^*-are the total level of the water cushion and water in the intermediate emulsion layer of the horizontal and spherical apparatus; x_1-is the coefficient reflecting the flow rate or resistance to flow in the system.

The models make it possible to predict the content of residual water in dehydrated oil and optimize the processes of thermochemical treatment of oil.

The proposed mathematical models[7] provide a comprehensive description of the processes of thermochemical dehydration of oil, including coagulation, droplet fragmentation and their size distribution.

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[7] Rzayev, A.G. Modeling of Emulsion Formation and Breaking in Thermochemical Oil Treatment Process / A.G., Rzayev, G.I. Kelbaliyev, G.R. Mustafayeva [et al.] // Chemistry and Technology of Fuels and oils, 2018. Vol.54, No.3, - p.249-264.

These models not only reflect the dynamics of emulsion destruction, but also create a scientifically based platform for the development and optimization of oil treatment technologies.

Chapter 5 is devoted to diffusion-migration and crystallization processes during sedimentation of substances in pipelines of complex configuration used for collection and transportation of oil in marine conditions. The processes of sedimentation and phase displacement form the basis of the processes of separation and stratification of oil emulsions in the gravitational field. These processes are closely related to the hydrodynamic structure and flow direction, interaction of particles with each other, distribution of sizes of polydisperse particles, their shape and concentration, as well as with the physicochemical properties of the particles themselves and the carrier medium. An important role is also played by physicochemical transformations, diffusion transfer and sedimentation of particles in turbulent flows, as well as the stochastic nature of polydisperse systems.

The paper[8] considers the features of sedimentation of particles from a liquid flow. It is shown that with an increase in particle size, the degree of their entrainment by a pulsating turbulent medium tends to zero (Figure 1).

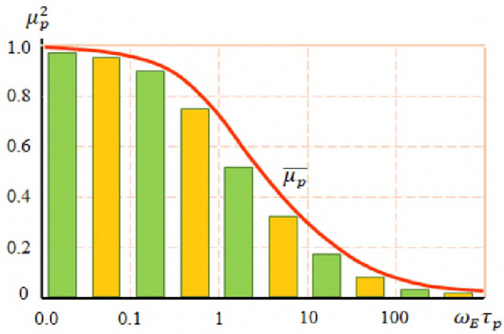

Figure 1. Degree of particle entrainment in a pulsating turbulent medium

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[8] Mustafaeva, G.R. Sedimentation of solid particles from a suspension flow // Transport and storage of oil products and hydrocarbon raw materials, 2017. No.1, - p. 33-37.

Finely dispersed particles, reacting to turbulent media, perform pulsating motion relative to the molecules of the carrier phase and random motion in all directions due to turbulent diffusion.

These parameters play an important role in determining the degree of particle migration and sedimentation in a turbulent flow. The issues of single particle sedimentation in a slow flow and in a concentrated dispersed flow are studied.

The solution to the problem of particle sedimentation on the inner surface of tubular devices is well known for small Reynolds numbers, and difficulties arise only at moderate and large Reynolds numbers, when nonlinear terms appear in the model, characterizing the general picture of the flow around the particle. Based on the basic formulas, a model is proposed that is acceptable for describing the sedimentation rate of single solid spherical particles, which was adapted to solve a specific problem related to particle sedimentation under turbulent flow conditions, which is an important contribution to the description of the processes of separation and stratification of emulsions.

The paper also studies the sedimentation of particles from a concentrated dispersed flow, typical of suspensions with a high concentration. Such systems are accompanied by particle interaction, sedimentation constraint, coagulation and agglomerate formation. The main problem is gravitational coagulation, in which small particles are captured by larger ones.

The Richardson-Zeki formula is traditionally used to describe the sedimentation rate of spherical particles, where the exponent n depends on the particle size and their volume fraction. Based on this and using various empirical relationships, the rate of constrained sedimentation of particles is presented as:

$$\frac{V_p}{V_s} = \xi(\varphi, \alpha). \qquad (15)$$

Where φ-is the volume fraction of particles in the flow; $\xi(\varphi, \alpha)$-is a function characterizing the influence of the medium parameters and sizes on the constraint of movement.

At a volume fraction of $\phi > 0{,}8$, a scatter of data is observed, caused by an increase in the viscosity of the suspension. The index n also depends on the Galileo number (Ga) and other factors. The literature provides complex dependencies of the index n on the Galileo number, but in this paper a simplified expression for n is developed:

$$n = \frac{4{,}75}{(1+0{,}0005Ga^2)^{1/25}}. \quad (16)$$

Where n-is the exponent, $Ga = \frac{a^3 \rho_c(\rho_d - \rho_c) g}{\eta_c^2}$ -Galileo's number.

It is simple, includes fewer empirical coefficients and approximates experimental data more accurately, especially at high Ga values. The proposed model simplifies calculations and improves the description of sedimentation processes in concentrated flows.

Analysis of particle sedimentation processes from dispersed flows revealed two key mechanisms: migration-diffusion and migration-gravity. Particle sedimentation can occur in several ways: through direct sedimentation from the flow volume due to the migration-gravity mechanism, particle transfer to the boundary layer and the pipe wall with subsequent formation of a dense layer, as well as sedimentation on the pipe wall due to turbulent diffusion. Such processes, often encountered in the oil industry, are accompanied by the formation of a dense layer on the inner surfaces of pipes, which affects hydrodynamics, mass and heat transfer. The resulting layer has low thermal conductivity, reduces the efficiency of heat exchange and increases hydraulic resistance, which leads to an increase in material and energy costs.

The purpose of this study is to model these particle deposition mechanisms and analyze their impact on pipeline processes. To achieve this goal, equations were developed to describe the migration-diffusion transfer of particles in turbulent flows and their deposition on the pipe surface. These equations provide a more accurate understanding of the dynamics of the processes, which is important for creating effective technologies and equipment used in the transportation and processing of oil.

As a result of the study, a formula for calculating the particle flux per unit pipe surface is presented, which has the form:

$$J = -D_T \left(\frac{\partial C}{\partial y}\right)_{y=R} = D \left(\frac{RV_D}{\nu_c}\right)^4 \left(\frac{DV_D^2 R}{\nu_c^3}\right)^{3/4} x^{-1/4}\left(C_p - C_0\right). \quad (17)$$

Where C-is the particle concentration; D_T, D-are the turbulent and molecular diffusion coefficients; V, V_D-are the flow velocity and dynamic velocity; R-is the pipe radius; C_p and C_0-are the current and initial particle concentration; x-is the characteristic pipe length.

This formula allows us to quantitatively estimate the particle deposition process on the pipe surface, depending on the flow characteristics, viscosity and diffusion properties.

One of the key problems in pipeline systems is the crystallization and deposition of paraffins from oil in transport pipes. In this paper[9] the mechanisms of this process are investigated, the diffusion kinetics of paraffin crystallization and a model of their deposition in both pipes and heat exchangers are proposed.

Paraffin deposition from oil at low temperatures negatively affects the flow parameters. The process begins with the crystallization of paraffins and asphaltene-resinous substances on the pipe walls, first in the boundary layer and then on the formed deposit. Radial temperature and concentration gradients promote the diffusion of paraffins to the wall, where they crystallize. The key factors in deposition are temperature, flow velocity, oil properties, and pipe roughness. Paraffins crystallize as the temperature decreases, and adhesion increases on rough surfaces. Asphaltene-resinous substances play a binding role, changing the structure of the deposit and increasing its strength. Taking this into account, a diffusion model of paraffin crystallization has been developed, describing their deposition and the effect of deposits on hydrodynamics. Unlike empirical models, the proposed diffusion model takes into account the kinetics of the processes and allows for a more accurate assessment of the formation and growth of deposits.

The paper presents an equation for the kinetics of paraffin crystallization from oil, which takes into account both the transfer of paraffin from the liquid phase to the solid phase and its migration to the pipe surface. The solution of which was presented as follows

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[9] Kelbaliyev, G.I. Crystallization of paraffin from the oil in a pipe and deposition of asphaltene-paraffin substances on the pipe walls / G.I. Kelbaliyev, S.R. Rasulov, G.R. Mustafayeva [et al.] // Journal of Engineering Physics and Thermophysics, 2018. Vol.91, No.5, - p.1227-1232.

$$C(t) = C^*(T)[1 - exp(-\beta t^n)] \quad (18)$$

where β-is the mass transfer coefficient; C-is the paraffin concentration in the boundary layer volume; C^* -is the equilibrium paraffin concentration in the liquid and solid phases, depending on temperature.

As follows from equation (18), when the maximum paraffin layer thickness is reached, the paraffin concentration on the layer surface reaches the limiting value corresponding to equilibrium. This state determines the maximum paraffin layer thickness on the surface. If the maximum thickness of the deposited paraffin layer becomes equal to the pipe radius, its cross-section becomes completely clogged, which completely blocks the flow.

The mechanism of deposit formation on the pipe surface consists in the formation and growth of paraffin crystals at low temperatures, as well as the deposition of asphalt-resinous substances directly on the surface in contact with oil, that is, in the boundary layer volume. As these deposits form on the surface, a resin-paraffin layer is formed, which increases in thickness over time. It is important to note that this process has a significant impact on the hydrodynamic and heat-mass transfer characteristics of the system. As the thickness of the deposits increases, the heat exchange and hydrodynamic parameters deteriorate, which leads to additional energy and material costs.

The model [10] of paraffin and asphalt-resinous substances deposition in transport pipes and heat exchanger pipes can be expressed taking into account these factors, which allows for a more accurate prediction of the development of deposits and their impact on the functioning of pipeline systems.

$$\delta_s(t) = R[1 - exp(-m_s t)], \quad (19)$$

[10] Kelbaliyev, G.I. Modeling of phase separation processes during the flow of oil dispersed systems / G.I. Kelbaliyev, V.I. Kerimli, G.R. Mustafayeva [et al.] // Equipment and technologies for the oil and gas complex, 2019, No.1, - p.68-71.

where $m_s = \frac{I_{s0}}{2\pi\rho_s R_0^2}$, δ_s -thickness of the deposited paraffin layer. Comparison of the models with the available experimental data showed satisfactory results.

The above expressions demonstrate that in the case of laminar flow, an increase in the thickness of deposits in pipes leads to hydrodynamic instability, and in turbulent flow, this factor contributes to an increase in energy dissipation, a decrease in the scale of turbulence and, as a result, to the attenuation of the intensity of turbulent pulsations. Thus, crystallization, sedimentation and formation of a dense layer on the surface of pipes have an inverse effect on the hydrodynamics of the flow and the processes of heat and mass transfer in the pipes. Over time, if a decrease in the temperature in the core of the flow is observed, paraffin particles, together with asphaltene particles, begin to significantly affect the formation of structures in the flow.

This, in turn, changes the rheological properties of oil. The presence of asphaltenes and the formation of coagulation structures, such as nanoaggregates and their clusters, have a significant effect on the rheological characteristics of oil.

These structures can change its viscosity, which complicates the transportation of oil and affects production indicators. In addition, asphaltenes, deposited on the surface of the porous medium, change its porosity and can lead to clogging of the pores of the formation, which creates additional problems in the processing and transportation of oil, reducing the efficiency operation of wells and equipment. To solve these problems, it is important to develop effective methods for cleaning and separating asphaltenes and other solid phases that can be sources of pollution.

In this regard, based on the analysis of the solubility of asphaltenes in various aromatic hydrocarbons, a liquid-phase extraction technology was proposed aimed at cleaning wastewater from asphaltenes and solid particles. Using the phenomena of coalescence and crushing, as well as mass transfer processes in "liquid-liquid" systems, an extraction technique using toluene was developed.

The efficiency of this technology depends on the optimal extraction conditions, such as the water to solvent ratio (1:35-40), as well as phase separation in settling systems and separation in a rectification column. The use of this technology allows us to solve environmental problems associated with wastewater pollution and improve the efficiency of oil refining and oil well operation. The technology can be implemented in three series-connected extractors, with toluene supplied to each unit and the extractant withdrawn from each settling tank (Fig. 2). The use of a coagulant allows us to develop an effective scheme for separating the finely dispersed solid phase from water, improving the quality of extraction and reducing the amount of insoluble residues in the aqueous phase. To assess the kinetics of dissolution of asphaltene-resinous substances in toluene, a model was proposed based on the phenomena of diffusion mass transfer, which allows us to more accurately predict the behavior of the system and optimize the extraction process.

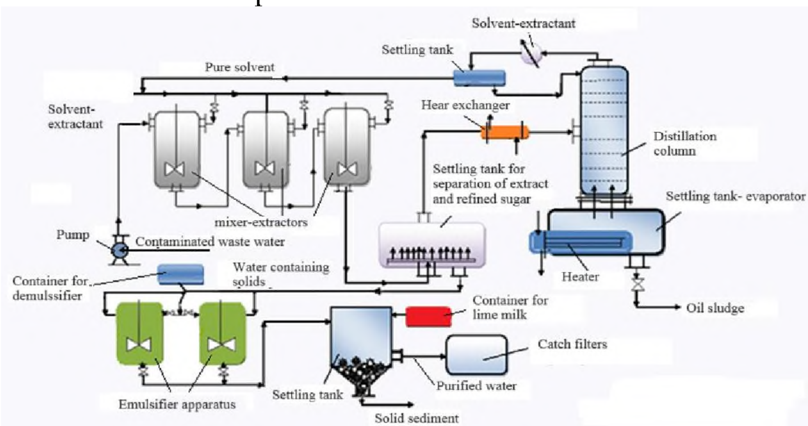

Figure 2. Scheme of liquid phase extraction during purification of oil wastewater from asphaltene-resinous compounds

Due to the fact that the time of complete dissolution of asphaltene particles is 50-60 minutes, which indicates a high diffusion coefficient and extraction efficiency in the proposed system. This confirms that the proposed extraction technology using toluene can be an effective tool for wastewater purification from asphaltenes and other solid phases. The results also show that with the help of properly adjusted extraction conditions and subsequent phase separation, it is possible to achieve a high degree of purification, minimizing environmental risks and increasing the productivity of oil refining.

To describe the kinetics of the process, a mass transfer equation was developed that takes into account temperature and diffusion parameters. Experimental data collected in the temperature range of 20-60°C confirm the applicability of the proposed model for describing the dissolution of asphaltene-resinous substances.

The equation for the dissolution of asphaltene-resinous substances in toluene can be represented as follows:

$$C(t) = C^* \left(1 - exp\left(-\alpha t^{\frac{3}{2}}\right)\right). \quad (20)$$

Where C-is the concentration of the absorbed substance, C^*-is the equilibrium concentration, α-is the coefficient of turbulent pulsations.

This equation takes into account the diffusion process of particle dissolution in the solvent and allows predicting the dynamics of dissolution, which is important for optimizing extraction and increasing the efficiency of wastewater treatment. Figure 3 shows the kinetic curves of dissolution of asphaltene and resinous substances in toluene at different temperatures.

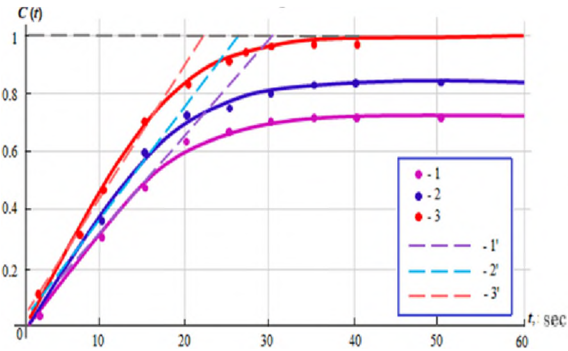

Figure 3. Kinetic curves of asphaltene and resinous substances dissolution in toluene at temperatures:

1 - 20°C; 2 - 40°C; 3 - 60°C. Straight lines correspond to the linear kinetics of asphaltene substances dissolution in toluene at temperatures equal to: $1'$ – 20°C; $2'$– 40°C; $3'$– 60°C.

The sixth chapter is devoted to the study of rheological characteristics of structured oils and modeling of their properties. Particular attention is paid to dispersed systems in which aggregation and sedimentation stability determine the structure of the medium. The formation of structures in such systems is associated with the formation of particle aggregates or clusters, which has a significant effect on their physical properties.

The process of structure formation is considered, including the interaction of particles, leading to the formation of coagulation structures, a change in viscosity and other rheological parameters. The paper identifies key areas characterizing viscosity changes depending on particle concentration and studies the features of each of them. The aim of the study is to develop models describing the viscosity of dispersed systems taking into account the processes of structure formation. This allows for a deeper understanding of the mechanisms of formation of rheological properties and the creation of approaches to predicting the behavior of structured oils under various conditions.

Structuring of dispersed systems is a complex process associated with the formation of coagulation structures, aggregates and framework networks of particles. This process determines the rheological properties of the medium, including its viscosity, mobility and thixotropic characteristics.

With an increase in the concentration of particles, the distance between them decreases, which contributes to an increase in the probability of their interaction and coagulation. As a result, structured systems with high viscosity and low mobility are formed.

The destruction of such structures can occur under the influence of external mechanical factors, such as an increase in shear rate, pressure or flow turbulence. These processes affect not only the destruction of framework structures, but also the dynamics of the formation of new aggregates. Turbulent pulsations increase the frequency of particle collisions, which contributes to both the fragmentation of existing structures and the formation of new coagulation bonds.

Finely dispersed particles, approaching each other at a distance of the order of their diameter, interact due to hydrodynamic forces and Brownian diffusion, which leads to coagulation and the formation of new structures. The rate of formation of such structures is determined by convective and diffusion transfer of particles.

To describe the process, equations[11] are used, which relate the movement of particles to shear stress.

Based on experimental data from the literature, it is possible to obtain a semi-empirical dependence of the viscosity of a dispersed medium on the Peclet number, which is expressed by the following formula:

$$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty} = exp\left(-mPe^{\frac{1}{2}}\right), \quad (21)$$

where η-is the effective viscosity of the system; η_0,η_∞-are the initial $(\tau \leq \tau_0)$ and final dynamic viscosity of oil $(\tau \gg \tau_0)$; m-is the mass of the spherical particle; $Pe = \frac{\alpha}{D}\dot{\gamma} = \frac{6\pi\alpha^3\eta}{k_BT}\dot{\gamma}$ -is the Peclet number or the dimensionless shear flow velocity.

At high Peclet numbers (Pe) the system is characterized by dense packing of particles, which corresponds to complete structure formation. This expression describes the nature of the viscosity dependence curve on the volume concentration in the region of its deformation and further structure formation.

The region of decreasing viscosity during shear flow is observed near the Peclet number $(Pe = 1)$, when the hydrodynamic and Brownian forces have equal values. When $Pe > 1$, the viscosity tends to the value $\eta \to \eta_\infty$, which is possible at large values of the yield strength $(\dot{\gamma})$.

Thus, studying coagulation in a shear field allows us to describe the dynamics of structure formation and the effect on the rheological characteristics of dispersed systems, which is an important stage in modeling structured oils.

Viscosity is a key parameter of rheological fluids, determining their mobility. In dispersed systems, it depends on the shear stress, concentration, size and shape of the particles. For extremely dilute media with finely dispersed spherical particles, the Einstein equation is used. However, for more complex systems, numerous empirical formulas have

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[11] Kelbaliyev, G.I., Rasulov, S.R., Mustafayeva, G.R. Viscosity of Structured disperse Systems // Theoretical Foundations of Chemical Engineering, 2018. No.3, - p.404-411.

been proposed that describe the dependence of viscosity on the concentration of particles, for example, the Barney and Mazrahi equation.

Most formulas do not take into account the structure formation, which deforms the viscosity curve. In this paper, a model has been developed for calculating the viscosity of dispersed systems taking into account their structure formation. From the analysis of the experimental data, it follows that the viscosity in the region of the onset of structure formation obeys the semi-empirical equation:

$$\frac{\eta}{\eta_c} = \frac{\eta_0 - \eta_s}{\eta_c} exp\left[-\frac{k}{2}(\varphi - \varphi_s)^2\right]. \quad (22)$$

Here η_c-is the viscosity of the media; η_s-is the shear viscosity; φ-is the volume concentration of particles; φ_s-is the concentration of particles at which structure formation begins; k-is the coefficient determined experimentally.

This formula allows us to take into account the change in the viscosity of a dispersed system during the transition from laminar flow to conditions where structure formation begins. This is critically important for systems with thixotropic properties, such as asphalt compositions with polyethylene additives or oil emulsions.

The dependence of viscosity on concentration during structure formation demonstrates the influence of the volume fraction of particles on the rheological characteristics. It also shows the possibility of destruction of aggregates with a decrease in concentration or an increase in shear stress. These dependencies find practical application in modeling and optimizing the properties of dispersed systems.

Figure 4 shows the dependence of viscosity on the content of water droplets in an oil emulsion, which is described by the following equation:

$$\eta = (-11{,}6 + 0{,}6\varphi)\, exp\left[\frac{2{,}8\varphi}{(\varphi - 100)^2}\right] - 7\, exp[-0{,}01(\varphi - 60)^2] \quad (23)$$

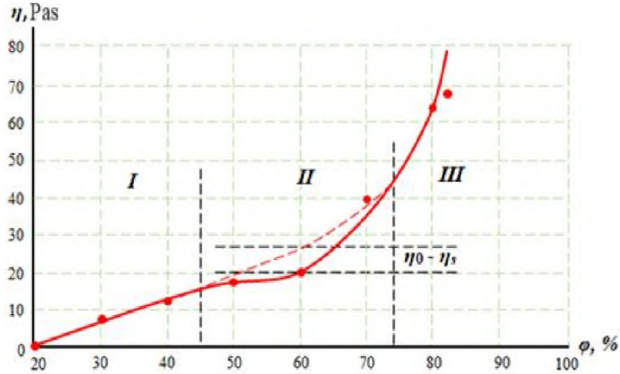

Figure 4. Oil viscosity versus water cut

This formula allows calculating the relative viscosity of a dispersed medium, where the dynamic viscosity of oil from the Muradkhan field (Azerbaijan) serves as the initial value and is equal to $\eta_c \approx 14$ Pas The graphs clearly show the areas of structure formation, as well as the sharp increase in viscosity.

A generalized form of the dependence of viscosity on the volume concentration of particles can be expressed through the formula:

$$\frac{\eta}{\eta_c} = 1 + 2.5\varphi + A_0\varphi \exp\left(\frac{m\varphi}{(\varphi-\varphi_\infty)^2}\right) - A_1 \exp(k(\varphi - \varphi_s)^2) \quad (24)$$

The last term in this formula is responsible for the beginning of structure formation in the system and shows how, with an increase in the concentration of particles, their compaction and formation of structure begins, which causes deformation of the viscosity curve.

Structure formation in a fixed bed of solid particles and shear flow differs in the degree of particle freedom. In a fixed bed, shear flow is characterized by viscosity, shear stress, and changes in bed porosity.

It follows from experimental data and equations in the literature that the effective viscosity of a dispersed system depends significantly on the volume fraction and size of particles. As the particle size increases, the effective viscosity increases. This is due to the fact that large particles do not form coagulation structures or aggregates, and the system forms a simple dense packing of particles, which leads to an increase in viscosity.

A fixed bed can be considered as a chain of elastically connected particles with liquid between them. In this case, the bulk viscosity of a structured layer of particles is defined as:

$$\eta_{\upsilon} = \frac{4}{3}\eta_{c}\frac{1-\varepsilon}{\varepsilon} \quad (25)$$

It should be noted that the given formulas for calculating viscosity are not phenomenological, but are semi-empirical expressions reflecting experimental data. Nevertheless, they successfully describe the nature of the change in the viscosity curve under the conditions of structure formation of a dispersed medium, especially at the stage of the beginning of structuring. It is important to emphasize that the process of formation of structured systems depends on the content (volume fraction) of particles in oil, the interval and strength of interaction between particles. Particle aggregation occurs at a certain probability of their collision, which, in turn, contributes to the formation of coagulation structures and the formation of aggregates.

Aggregate-unstable oil dispersed systems change due to structure formation, coagulation and destruction of asphaltene particles, which affects their volume and size. The interaction of particles leads to the formation of a viscoelastic framework, which affects the viscosity and rheological properties of oil.

Asphaltene particles coagulate, forming floccules that can settle on the walls of pipes and collectors. Nanoaggregates form a structure with high viscosity, possessing thixotropic properties: when the pressure decreases, structuring occurs, and when the stress increases, the framework is destroyed.

In this case, there is a need to develop a rheological model of oil systems taking into account the aggregation of particles and their effect on viscosity.

The principle of studying the coagulation of asphaltene particles in the volume of oil is based on their transfer due to molecular diffusion in a laminar flow and turbulent diffusion. In this process, a stationary particle is released, enclosed in a sphere of radius $R \simeq (1{,}5 - 2{,}0)$. It is assumed that any particle crossing this sphere, with a high probability, collides and coagulates with the released particle. Based on this condition, models[12] of coagulation of asphaltene particles and calculation of the sizes of nanoaggregates are proposed, which can be presented in the form of the following equations for calculating their growth and sizes:

$$a_g = a_{g_\infty}\left[1 - exp\left(-C_0\varphi_0\left(\frac{\varepsilon_R}{\nu_c}\right)^{1/2} t\right)\right]^{1/3} \qquad (26)$$

where a_g, a_{g_∞}-are the current and final sizes of the aggregate; C_0-is the coefficient determined from experimental data; ε_R-is the specific energy dissipation per unit volume.

The aggregates formed asa result of coagulation and aggregation consist of many tiny particles connected to each other and have a loose structure, although their density increases toward the center. To improve the rheological properties of structured oil, disperse systems, it is necessary to mechanically destroy the viscoelastic framework of asphaltenes under the action of external forces, such as a velocity or pressure gradient. The destruction of the framework leads, first of all, to a significant decrease in viscosity and an increase in the mobility of the disperse system, which makes it more convenient for further processing and transportation. The conditions for the destruction of the structure are considered, and rheological models of filtration of oil disperse systems are proposed taking into account the Maxwell equation and models of viscosity and mobility changes.

The influence of these factors on the filtration properties of oil systems is analyzed using parameters, for structured oil systems, in which coagulation and aggregation of asphaltene particles, as well as their deformation and destruction, occur, the filtration law deviates from the classical form. This is explained by a change in the structure of oil when the viscoelastic framework of asphaltenes is exposed to external forces, such as velocity or pressure gradients of the models. The results are compared with existing experimental data, which confirms the relevance of the proposed models.

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[12] Kelbaliev, G.İ. Rheology of structured oils / G.I. Kelbaliyev, S.R. Rasulov, G.R. Mustafayeva [et al.] // Journal of Engineering Physics and Thermophysics, 2017. Vol.90, No.4, - p.996-1002.

For structured oil systems, the filtration rate equation is:

$$V = K_1(T)\big(1 - exp(-\alpha_1(T)(z/z_0)^6)\big)z \qquad (27)$$

Where K_1-is the filtration coefficient; T-is the temperature; $z = gradP$, $z_0 = (gradP)_0$; $K_1 = 3{,}01 \times 10^{-5} exp(0{,}01824T)$.

The change in the effective viscosity of abnormal oil from the pressure gradient based on experimental data can be described by the empirical formula:

$$\frac{\eta^* - \eta_\infty}{\eta_0 - \eta_\infty} = exp(-30z^6) \qquad (28)$$

At low flow rates, the effective viscosity of oil changes depending on the shear rate or pressure gradient: it decreases from the maximum value to the minimum, and then stabilizes. These results confirm the dynamics of viscosity change during filtration and demonstrate how its behavior depends on the pressure gradient.

The formulas given are applicable for calculating the filtration process of oils in porous layers of different deposits, where the viscosity and permeability coefficient of oil can significantly affect its mobility.

CONCLUSIONS

1. To describe the behavior of non-Newtonian (anomalous) oils, a mathematical model has been developed that allows one to determine the values of shear stress with its abrupt change using an exponential law [2].

2. A systems analysis of the current state of heat transfer processes in horizontal pipelines and oil wellbores has been conducted. Taking into account the geometric gradient and thermal conductivity of liquid and gas located in the intertube space, a new adequate mathematical model of the heat transfer process has been proposed [3].

3. It has been shown that the process of oil structure formation in the capillaries of the reservoir formation can be described through a change in viscosity over time. An exponential mathematical model has been proposed that adequately describes this change, taking into account the effect of oil viscosity on the residual oil saturation of the formations. The resulting model can be used to solve the problem of developing hard-to-recover oil reserves [10].

4. Models of compaction of a porous medium during precipitation of asphaltenes in pores have been developed, and solutions to the equation of non-stationary filtration have been obtained. Based on these solutions, expressions have been proposed for estimating the filtration characteristics of a porous medium. An equation has been proposed for estimating the attenuation of the filtration rate in a formation with a pulsating nature. It has been noted that the pulsating nature of the attenuation of oil filtration in a formation is associated with its natural compaction under the action of the weight of the overlying layers [11].

5. A semi-empirical expression has been proposed for a general description of the Darcy number in a wide range of Reynolds numbers [5].

6. A model has been developed for determining the particle collision frequency taking into account the distribution function of dispersed particles. This formula fully takes into account the effect of the distribution of the dispersed phase by particle size on the frequencies of their collisions [7].

7. A diffusion model has been proposed for the formation of an adsorption layer of asphaltene-resinous substances on the surface of

water droplets, and a formula for estimating its thickness has been given. A model of combined coalescence and fragmentation of droplets in an isotropic turbulent flow has been developed. To estimate the evolution of the number of droplets and their sizes over time, equations dependent on the fragmentation and coalescence frequencies have been proposed [25].

8. A technology for cleaning oil wastewater using solvent recycling has been developed, which is environmentally and economically advantageous, since it allows for the efficient neutralization of oil waste that pollutes the environment. In addition, the proposed process is waste-free [12].

9. Mathematical models have been developed to describe the deposition mechanisms, which have been compared with the available experimental data. The work has investigated the diffusion kinetics of paraffin crystallization and proposed a model for their deposition in both transport pipes and heat exchanger pipes [18,27].

10. A kinetic model of asphaltene-resinous substances dissolution in an aromatic solvent depending on temperature has been constructed, based on mass transfer under conditions of isotropic turbulence within the boundary layer. A kinetic equation has been developed that takes into account the equality of diffusion and convective flows on the particle surface. Kinetic dependences and dissolution coefficients have been determined for both linear and nonlinear distributions of dissolved substance concentration in the boundary layer [21].

11. A generalized equation for calculating the viscosity of structured disperse systems with their inherent rheological properties has been proposed. Characteristic features of the viscosity curve region at the stage of structure formation have been revealed. Various versions of viscosity equations for structured disperse systems have been considered and compared with experimental data [24]. 12. Based on the considered problems of rheology of structured oils, equations are obtained that allow us to estimate changes in the sizes and mass of nanoaggregates over time, using molecular and turbulent diffusion of asphaltene particles. Filtration models and rheological models based on the solution of Maxwell's equation for a viscoelastic fluid are also

proposed. Two semi-empirical rheological models are given that satisfactorily describe the experimental data [20].

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Personal contribution of the applicant:

[16,17,18,22,23,28,33] -works completed independently.

[10,11,15,19,20,21,24,32,34,35] -in the works the applicant formulated the problem, participated in setting the task, proposed a solution and participated in checking the correctness of the results.

The defense of the dissertation will take place on April 15, 2025, at 11:00 at the meeting of the Dissertation Council BED 2.03, operating on the basis of Azerbaijan State Oil and Industry University

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The dissertation can be found in the library of Azerbaijan State Oil and Industry University

The electronic version of the dissertation and abstract is posted on the official website of Azerbaijan State Oil and Industry University

Abstract was sent to the required addresses on 11 March 2025.

Signed for print: 10.03.2025
Paper format: A5
Volume: 77460
Number of hard copies: 20