ABSTRACT

of the dissertation,
submitted for the degree of Doctor of Philosophy (Ph.D.)
in the field of 6D070800 – Petroleum Engineering
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«Study of the fluid flow in a porous medium based on the pore-scale modeling»

The main content of the work. This work is devoted to determining the characteristics of a porous medium and fluid flow in a porous medium at the pore-scale using pore-scale modeling based on digital core models built using micro-computed tomography (μ-CT), as well as determining the dependence of absolute permeability on other characteristics of the porous medium for carbonate core samples.

Assessment of the current state of the scientific or scientific-technological problem (task) being solved. Currently, the process of fluid filtration in porous media is of increased interest to researchers all over the world, since filtration fluid flows in porous media are widespread in nature and technology. Abroad, a direction such as digital rock physics is dynamically developing, which makes it possible to determine the characteristics of rocks and predict the characteristics of fluid flow at the pore-scale. There are two common approaches: direct numerical simulation and pore-network modeling. However, in the territory of Kazakhstan at this point, standard laboratory tests are mainly used to determine the characteristics of a porous medium, although they are labor-intensive and resource-intensive in terms of time and financial costs. A large number of works are devoted to current problems of fluid and gas mechanics all over the world, at the same time, research in the field of pore-scale modeling of fluid flow in a porous medium at the pore-scale is a new direction for research in the Republic of Kazakhstan.

For the non-destructive study of the structure of a porous medium, it is possible to use the μ-CT. In Kazakhstan, X-ray tomography, with which it is possible to study core samples, is available only in the laboratory of KazNIPImunaigas LLP (Aktau). The resolution of X-ray tomography in this laboratory does not allow high-quality studies at the pore-scale. Thus, X-ray tomography has limited application and a limited range of uses in Kazakhstan.

Studying changes in pore structure due to acid treatment of rocks is an urgent task in the context of intensifying the production of hydrocarbons from carbonate formations and injecting CO_2 into aquifers for subsequent storage. Research is required to achieve the maximum increase in absolute permeability with small volumes of acid injection into oil-bearing formations to enhance oil recovery. The patterns of dependencies of the characteristics of a porous medium for carbonate rocks can be used for hydrodynamic modeling by oil and oil service companies, as

well as for assessing geological reserves of oil and gas by the Department for Oil Development and Production of the Ministry of the Republic of Kazakhstan.

Basis and initial data for developing the topic. Traditionally, the characteristics of a porous medium and fluid flow are determined by experimental methods using special laboratory equipment, but this requires significant time (up to 3-5 months) and financial resources. Inaccurate measuring instruments, incorrect experimental conditions, incorrect data processing, and random and human errors during laboratory experiments can lead to incorrect results. The use of computer modeling will reduce the amount of time and resources spent; at the same time, modeling is a less expensive and resource-intensive method.

There are a large number of studies devoted to the dependence of permeability on other characteristics of a porous medium, but they are not always applicable to carbonate rocks, since they are calculated for ideal porous media.

In Kazakhstan, equipment for μ-CT is available only in the Aktau laboratory, but at the time of the experimental stage, it was out of order. One experiment was conducted using medical tomography (625-micron resolution) before and after acid treatment of core samples with hydrochloric acid. Since its resolution is coarse, the data obtained did not allow us to see the pore structure in 3D and carry out pore-scale modeling to determine the characteristics of the porous medium and fluid flow, as well as to identify patterns in the dependence of permeability on other characteristics of the porous medium. That is why it was decided to conduct μ-CT abroad in the X-ray tomography laboratory at Kazan Federal University.

In this work, 8 carbonate core samples were scanned using μ-CT to build a digital model and conduct pore-scale modeling. The change in the characteristics of the porous medium and fluid flow after acid treatment of carbonate core samples with hydrochloric acid was investigated and the dependence of absolute permeability on other characteristics of the porous medium was studied.

Justification of the need for this research work. In the Republic of Kazakhstan, most of the hard-to-recover reserves are concentrated in fields with carbonate reservoirs. To improve such an enhanced oil recovery method as acid treatment of wellbore wells, it is necessary to study the effect of acid compositions on carbonate rocks (injection rate and acid concentration) to achieve the highest oil recovery factor. There is a need to identify the dependence of absolute permeability on other characteristics of the porous medium specifically for carbonate rocks. The existing dependences of absolute permeability on porosity were determined for ideal porous media, which precludes obtaining reliable results for samples of real carbonate rocks. The study of fluid flow in a porous medium at the pore-scale using pore-scale modeling allows one to extract the characteristics of the porous medium (absolute permeability, porosity, specific surface area, hydraulic tortuosity, pore radius, pore throat radius, coordination number) and fluid flow (relative phase permeabilities.

Currently, to study the porous structure of rocks in detail in 3D and perform calculations to determine the characteristics of rocks, X-ray μ-CT is popular. One of the advantages of μ-CT is the ability to visualize dynamic processes within a porous

medium by recording images of the sample at different points in time. This approach is non-destructive for rocks and at the same time relatively inexpensive. Through pore-scale modeling, macroscopic characteristics of samples are determined, which can subsequently be used for well or field analysis. In addition, it becomes possible to carry out multiple simulations of fluid flow processes on one rock sample (for example, polymer flooding, acid treatment, surfactant injection, etc.), which is of strategic importance for the efficient use of natural oil and gas resources.

The use of μ-CT will allow oil and oil service companies to create a digital database of core samples, which will greatly facilitate the access process for subsequent work. It is important to note that modeling on digital models of core samples obtained using μ-CT is carried out for the first time in Kazakhstan.

Thus, currently in the Republic of Kazakhstan and throughout the world, studies of fluid flow in a porous medium are needed precisely at the pore-scale to optimize the processes occurring in a porous medium. In other words, it is necessary to find an alternative method for determining the characteristics of porous media and fluid flow, which will be reliable and at the same time effective in terms of time, finances, and resources.

Information about the planned scientific and technical level of development. The scientific results obtained in the framework of this dissertation will make it possible to determine the characteristics of a porous medium and fluid flow based on pore-scale modeling without conducting resource-intensive laboratory experiments. The patterns of dependence of absolute permeability on other characteristics of the porous medium for carbonate rock will be established.

Patent studies and conclusions from them. As part of this dissertation, it is planned to obtain an author's certificate for an alternative method for determining the characteristics of a carbonate core sample.

Information about metrological support of the dissertation. Laboratory studies were carried out using the equipment of the X-ray micro-computed tomography laboratory of the Kazan Federal University, Kazan. The equipment undergoes annual verification and calibration.

Relevance. Absolute and relative phase permeabilities play an important role in the development of oil and gas fields, the injection of CO_2 into formations for further storage, as well as the migration of pollutants in underground aquifers. There is a need for specific relationships between absolute permeability and other properties of the samples. A widely used relationship is the Kozeny-Carman equation, which relates absolute permeability to porosity, specific surface area, and hydraulic tortuosity. However, the Kozeny-Carman equation predicts incorrect values of absolute permeability for most real rock samples since it was obtained empirically for an idealized porous medium of identical capillary tubes, and therefore there is a need to study the dependence of absolute permeability on other properties, which will be applicable for a wide range of samples.

Changing the microstructure of rock samples can have a strong effect on the co-flow of fluids in the pore space. In the context of the constant development of oil and gas production and the need for effective methods for capturing and storing CO_2,

the study of the pore structure of carbonate samples when interacting with acid solutions becomes especially relevant. Not only are carbonate rocks an integral part of the oil industry, but they can also contribute to environmental sustainability by capturing and storing carbon dioxide within them.

The scientific novelty of the dissertation lies in establishing the pattern of the influence of acid treatment of carbonate samples on the flow characteristics of single- and two-phase fluids using X-ray tomography and pore-scale modeling. There are no analogs of such studies in Kazakhstan.

Relationship of this work with other research works. This dissertation was carried out within the framework of the scientific projects "Study of the influence of dissolution modes of carbonate core samples on the characteristics of the flow of two-phase fluid through it at the pore-scale" from the Ministry of Education and Science of the Republic of Kazakhstan under the priority "Rational use of natural resources, including water resources, geology, new materials and technology, safe products and structures", under the subpriority "Geology and development of mineral deposits" IRN No. AP08052055 (2020-2022) and "Forecasting the characteristics of a porous medium taking into account rock dissolution regimes at the pore-scale based on machine learning" from the Ministry of Education and Science of the Republic of Kazakhstan under the priority "Geology, extraction and processing of mineral and hydrocarbon raw materials, new materials, technology, safe products, and structures", under the subpriority "Geology and development of mineral deposits", IRN No. AP09058419 (2021-2023).

The purpose is to study the influence of changes in the pore structure of carbonate samples due to interaction with acid solutions on the flow characteristics of single- and two-phase fluids, as well as the impact on the geometric parameters of the samples.

The subject of this dissertation is the characteristics of single- and two-phase fluid flow in porous media and the geometric parameters of samples.

The object of study of this dissertation is carbonate core samples.

Research objectives:

1. Conduct a review and analysis of the current state of the topic being studied in the world and Kazakhstan;
2. Simulate the flow of single- and two-phase fluids in idealized porous media;
3. Develop a procedure for conducting laboratory experiments and conduct a series of experiments on the injection of acid solutions into carbonate core samples and scanning them using an X-ray tomograph before and after acid treatment;
4. Carry out a statistical reconstruction of images of samples before and after acid treatment, as well as create their 3D digital models;
5. Calculate the characteristics of samples based on statistical image reconstruction;
6. Calculate absolute permeability and hydraulic tortuosity using pore-scale modeling;
7. Calculate the relative phase permeabilities during the flow of a two-phase fluid using pore-scale modeling.

Scientific hypothesis. The goal of replacing physical experiments to determine the characteristics of fluid and porous medium flow using pore-scale modeling will be achieved if, using μ-CT and pore-scale modeling, such characteristics of fluid and porous medium flow as absolute permeability, porosity, pore size distribution, pore radius, hydraulic tortuosity, specific surface area, relative phase permeabilities are determined with sufficient accuracy.

The practical significance of the work lies in determining the dependence of absolute permeability on other characteristics of the porous medium for carbonate rocks, since many of the existing dependencies were obtained for ideal porous media, and not based on the use of real core samples. An alternative method for determining the characteristics of a porous medium and fluid flow will at least partially replace time-consuming and resource-intensive physical experiments using special laboratory equipment. The obtained dependences of absolute permeability on other characteristics of the porous medium for carbonate rocks can be used in predicting the development and production of oil from fields with carbonate rocks.

The place of tasks in the performance of scientific research work or experimental research work in general. During the research, a review and analysis of the current state of the topic under study in the world and Kazakhstan will be carried out, modeling of the flow of one- and two-phase fluids in idealized porous media will be carried out, a procedure for conducting laboratory experiments will be developed, and experiments will be conducted on injection of acid solutions into carbonate core samples, scanning will be carried out using an X-ray tomograph, statistical reconstruction of images of carbonate core samples before and after acid treatment will be carried out, and their 3D digital models will be created; the following calculations will be carried out: calculation of sample characteristics based on the statistical reconstruction of images, calculation of absolute permeability and hydraulic tortuosity, relative phase permeabilities during the flow of a two-phase fluid.

Methodological basis. Within the framework of this dissertation, to achieve the set goals, the following were used: OpenFoam®, a tool for modeling the flow of single- and two-phase fluids; methods/methodologies for conducting physical experiments on carbonate core samples; statistical reconstruction of samples based on their tomographic images; single- and two-phase fluid flow modeling tools Avizo® and PnFlow®; analytical methods. Therefore, the methods used within the dissertation are descriptive and experimental.

Provisions for defense:

1. The greatest increase in the absolute permeability of carbonate core samples is achieved by pumping an 18% hydrochloric acid solution at rates of 4 and 8 ml/min with a minimum solution flow rate;
2. The relationship between the connected and total porosities of carbonate core samples obeys a parabolic law;
3. Acid treatment of carbonate core samples changes the relationship between absolute permeability and porosity, while the power exponent significantly exceeds the value of this indicator in the Kozeny-Karman equation;

4. With an increase in the increase in absolute permeability of carbonate core samples, the residual oil saturation decreases.

The author's contribution consists of conducting a review and analysis of the literature on the topic of the dissertation work, implementing tasks to achieve the stated goals, conducting pore-scale modeling, μ-CT scanning, a series of laboratory experiments, processing tomographic data, constructing 3D models of core samples, processing and analyzing the results obtained, interpretation of the results obtained and writing articles and monographs.

Approbation of work. The dissertation materials were presented and discussed at international conferences:

- International scientific and practical conference "Satbayev Readings - 2019", (Almaty, Kazakhstan, 2019);
- 2nd international scientific conference "Alternative energy sources, materials, and technologies" (AESMT'19), (Sofia, Bulgaria, 2019);
- 7th international conference "Nanomaterials and advanced energy storage systems" (INESS-2019), (Almaty, Kazakhstan, 2019);
- International scientific and practical conference "Satbayev Readings – 2020", (Almaty, Kazakhstan, 2020);
- International scientific and practical conference "Computing and information technologies in science, technology and education" (CITech-2020), (Almaty, Kazakhstan, 2020);
- SPE 2020 Virtual Annual Caspian Technical Conference (online, 2020).

Publications. The main results of the study are presented in 1 article in international, peer-reviewed journals included in the Scopus/Web of Science database, 5 articles in publications from the list approved by the Committee for Quality Assurance in Science and Higher Education of the Republic of Kazakhstan, 6 reports at international scientific and practical conferences, 6 articles in other scientific journals, 1 copyright certificate, and 1 monograph.

Scope and structure of the dissertation. The dissertation consists of an introduction, four sections, a conclusion, a list of used sources containing 185 items, and 5 appendices. The work is presented on 98 pages of typewritten text and contains 46 figures and 18 tables in the main part, as well as 26 figures and 1 table in the appendix.

The main conclusions of this dissertation. Foreign and domestic scientific literature in the field of application of pore-scale modeling to study the characteristics of fluid flow and porous media was analyzed. Physical experiments were conducted on 8 carbonate core samples for injection of acid solutions, which were scanned before and after acid treatment of the rock using microcomputed tomography to build digital models of the core samples. Based on the constructed digital models of carbonate core samples, the characteristics of the porous medium and fluid flow before and after acid treatment were determined.

The pattern of dependence of absolute permeability on other characteristics of the porous medium before and after acid treatment for carbonate core samples was determined. It was found that before and after HCl injection, the absolute

permeability k of homogeneous and heterogeneous samples has a good correlation with porosity and average pore radius. This has an important advantage since the average pore radius and the porosity of the medium are relatively easy to determine.

Calculated tortuosities τ have been shown to correlate poorly with tortuosities derived from existing empirical models, remaining essentially constant in porosity before and after acid treatment of the rock. The average tortuosity values for homogeneous and heterogeneous samples were ~1.9, and for fractured samples ~1.8.

The relationship between absolute permeability k, hydraulic tortuosity τ and specific surface area S is described by the power laws $k \sim \tau^{-\alpha}$ and $k \sim S^{-\beta}$, where $\alpha = 7 - 42$ and $\beta = 5 - 18$, which are much larger than these in the Kozeny-Carman equation ($\alpha = \beta = 2$). Relatively high values of α compared to β indicate that hydraulic tortuosity τ has a greater influence compared to specific surface area S in estimating the absolute permeability.

As the results showed, the relationship between connected and total porosity is more reliably described by the parabolic equation $\phi_{con} = a\phi^2 + b\phi + c$ before and after acid treatment. It was shown that as a result of acid treatment of the rock, the connection between pores increases for homogeneous and heterogeneous samples, which is evident from the decrease in the percolation porosity threshold.

The results showed an intense decrease in the number of smaller pores and an increase in the number of larger pores as a result of acid treatment of the rock in all sub-samples. In addition, there is an expansion of the range of pore radius distribution towards enlargement of pores due to acid treatment of the rock, which means the formation of new large pores, although practically no new small pores have appeared. The increase in the average pore radius ranged from 6.5 to 17% for sample 7 and from 6.6 to 9% for sample 10.

The increase in porosity and absolute permeability is, on average, higher for sub-samples of sample 10 (24%; 201%) when injecting an 18% hydrochloric acid solution at a rate of 2 ml/min than for sub-samples of sample 7 (13%; 127%) when injecting a 12% hydrochloric acid solution at a rate of 8 ml/min, although the average initial porosity and absolute permeability for sub-samples from 10-1 to 10-5 are significantly less than for sub-samples from 7-1 to 7-5. The increases in porosity and absolute permeability for sub-samples of sample 7 were 1-33% and 44-331%, respectively, while these indicators for sub-samples of sample 10 were, respectively, 18-30% and 114-368%.

The influence of the concentration of hydrochloric acid in the solution and the rate of injection of the solution into the samples on the relative phase permeabilities is observed. Thus, the relative phase permeabilities of sub-samples 7-2 and 7-3, which are distinguished by small increases in porosity and absolute permeability, increased significantly as a result of acid treatment of the rock. In sub-sample 7-3, there was a change in wettability from water-wet to mixed, which is characterized by a strong increase in the relative phase permeability of water after acid treatment. The relative phase permeability of oil increased for all sub-samples of sample 10, into which a more concentrated solution of hydrochloric acid was injected at a low rate.

In most sub-samples, the residual oil saturation decreased from 20 to 46% as a result of acid treatment, while in some it increased (by 7-17%). The residual water saturation for all sub-samples decreased by 25-60%. There is a clear influence of the increase in absolute permeability on the residual saturation of oil and water - with an increase in absolute permeability, the residual saturation decreases rapidly.

Brief conclusions based on the results of dissertation research.

- Acid treatment of the rock significantly changed the distribution of pore sizes.
- The presence of natural fractures significantly affects the dependence of absolute permeability on other characteristics of the samples. The relationship between absolute permeability, hydraulic tortuosity and specific surface area is described by power laws. The found dependence between the connected and total porosities made it possible to find the percolation porosity threshold.
- As a result of the acid treatment of the rock, the residual saturations of oil and water in all sub-samples of both samples changed significantly.
- The proposed alternative method for determining the flow characteristics of one- and two-phase fluids allows one to obtain reliable results.
- The use of microcomputed tomography is effective in constructing digital models of carbonate core samples for further pore-scale modeling and determining the characteristics of a porous medium without the use of specialized laboratory equipment.
- The found dependences of absolute permeability on other characteristics of the porous medium can be successfully used in calculations of CO_2 sequestration and hydrodynamic modeling of reservoirs with carbonate rocks.

Assessment of the completeness of solutions to assigned problems. The assigned tasks were completed in full.

Recommendations and background data for the specific use of the results. The dependence of absolute permeability on other characteristics of the porous medium for carbonate rocks can be used for hydrodynamic modeling by oil and oil service companies, as well as for assessing geological oil and gas reserves by the Department for Oil Development and Production of the Ministry of the Republic of Kazakhstan. The results obtained can also be used in the form of educational materials in universities. Pore-scale modeling coupled with microcomputed tomography can be an alternative to standard laboratory experiments to characterize porous media and fluid flow.

Assessment of technical and economic efficiency of implementation. The obtained dependence of absolute permeability on other characteristics of the porous medium for carbonate rocks will allow for obtaining reliable results of hydrodynamic modeling. An alternative method for determining fluid flow characteristics will help reduce time and financial resources compared to laboratory research.

Assessment of the scientific level of the work performed in comparison with the best achievements in this field. Since the study of the characteristics of a porous medium and fluid flow at the pore-scale level using microcomputed

tomography is carried out for the first time in Kazakhstan, this study is of high relevance. The obtained results of studying the dependence of absolute permeability on other characteristics of the porous medium will allow them to be used in the hydrodynamic modeling of fields with a carbonate type of reservoir.

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