ANNOTATION

of the dissertation work submitted for the degree
of Doctor of Philosophy (Ph.D.)
in the specialty 8D07202 – Petroleum Engineering
by Assel Talgatovna Zholdybaeva

«Investigation of changes in reservoir properties of clay-bearing formations under thermal effects»

The importance of the topic. As conventional light oil reserves become depleted and hydrocarbon production progressively shifts toward hard-to-recover resources, heavy-oil accumulations are gaining increasing strategic importance. The development of such accumulations is associated with substantial geological, petrophysical, and technological constraints. One of the principal factors governing the low oil recovery factor in heavy-oil reservoirs is the combined effect of high hydrocarbon viscosity and the complex mineralogical composition of reservoir rocks, particularly the elevated content of clay minerals.

Thermal enhanced oil recovery (EOR) methods are widely applied for the development of heavy-oil reservoirs, including steam injection, hot-water injection, steam-assisted gravity drainage (SAGD), and cyclic steam stimulation. These methods promote oil mobilization by reducing viscosity and increasing fluid mobility through the transfer of thermal energy into the formation. However, field experience and laboratory investigations indicate that thermal stimulation is accompanied not only by the beneficial effect of oil mobilization, but also by pronounced alterations in the filtration–capacity (petrophysical) properties of the reservoir, resulting from physicochemical interactions between the rock matrix and the injected fluids.

One of the least investigated yet most critical processes associated with thermal stimulation is the swelling of clay minerals. This phenomenon leads to a reduction in absolute permeability, modifications in relative phase permeabilities, and deterioration of fluid-flow conditions within the porous medium. Despite the existence of isolated experimental studies, current engineering practice in the design of thermal EOR projects typically either neglects the effect of clay swelling or considers it only qualitatively, without quantitative formalization of its impact on reservoir petrophysical properties.

As a result, a scientific inconsistency currently exists between the necessity for widespread application of thermal EOR methods in the development of heavy-oil reservoirs and the absence of quantitatively substantiated relationships describing changes in the filtration–capacity properties of clay-bearing reservoirs under thermal stimulation.

Assessment of the current state of the scientific and scientific-technological problem. The development of hard-to-recover oil reserves, including heavy-oil reservoirs, remains a subject of significant interest within the scientific community. Thermal methods forming the basis of enhanced oil recovery in such formations have been extensively applied in the oil and gas industry over recent decades. These methods utilize heat delivered to the formation via steam or hot water to mobilize viscous hydrocarbons. Nevertheless, the interaction between injected fluids and reservoir rocks remains insufficiently understood.

A particularly critical aspect concerns the influence of injected-water quality and salinity on the risk of formation damage. In recent years, numerous studies have focused on optimizing injection conditions and improving the interaction between injected water and reservoir rocks, thereby enhancing the efficiency of thermal methods and reducing operational risks. However, in most studies, primary emphasis is placed on the thermal energy supplied to the formation, while the impact of injected fluids on reservoir petrophysical properties is addressed only to a limited extent.

In recent years, increased attention has been devoted to investigating interactions between injected steam, water, and reservoir rocks. Steam injection may induce formation damage, manifested by the migration of fine particles and swelling of clay minerals. Moreover, steam generation requires water of specific quality. Compliance with water-quality requirements contributes to reducing formation damage and improving the efficiency of thermal EOR methods.

The salinity of the injected agent plays a decisive role in rock–fluid interaction processes during thermal EOR operations. Variations in salinity influence electrostatic forces between the pore matrix and fine particles, as well as the structural stability of clay minerals. Under low-salinity conditions, the risk of formation damage increases due to clay swelling. Over the past two decades, research efforts have focused on optimizing injected-water salinity control strategies, which has been shown to improve oil recovery and reduce operational costs. However, these approaches are generally not accompanied by quantitative formalization of the relationship between salinity and changes in reservoir filtration–capacity properties.

Rationale and initial data for the research topic. The present study is motivated by the need to optimize development strategies for heavy-oil accumulations in reservoirs with elevated clay-mineral content, using the East Moldabek area (Republic of Kazakhstan) as the study object. This reservoir is characterized by a combination of high oil viscosity and a substantial proportion of clay components within the reservoir rocks, which significantly complicates the application of thermal EOR methods.

The presence of swelling clay minerals leads to changes in formation permeability and consequently affects hydrocarbon recovery efficiency. This necessitates a detailed investigation of the mechanisms governing alterations in reservoir filtration–capacity properties under thermal stimulation, as well as the development of methods for their quantitative representation.

To investigate the identified mechanisms and validate them at the reservoir scale, geological and hydrodynamic modeling techniques are employed. These approaches enable the integration of laboratory-derived data and mineralogical analysis results into a unified computational framework.

Justification for conducting the research. This research is driven by the presence of substantial hard-to-recover heavy-oil resources in Kazakhstan, estimated at approximately 0.7 billion tonnes. The development of such resources presents significant technical challenges associated with high oil viscosity, clay swelling, low oil recovery factors, and complex geological reservoir architectures. The study aims to evaluate the effectiveness of technologies applied to enhance oil recovery in hard-to-recover reservoirs, specifically those containing heavy oil. Under conditions of increasing global energy demand, improving hydrocarbon recovery from complex reservoirs becomes increasingly critical. Accordingly, the research focuses on improving steam-injection technologies in reservoirs with high clay-mineral content.

The results of this study provide a scientific basis for the further development and adaptation of thermal stimulation methods, enabling more efficient utilization of oil resources not only in Kazakhstan but also in other regions with similar geological and petrophysical characteristics.

Planned scientific and technical level of the research. The dissertation involves an in-depth investigation of the influence of clay-mineral swelling on reservoir filtration–capacity properties and on the performance of thermal development methods. The study establishes quantitative relationships between clay swelling and permeability, thereby enhancing the accuracy of predictive reservoir models.

Metrological support of the dissertation. The metrological framework of the dissertation is based on numerical modeling using high-precision data obtained through modern experimental equipment. Mineralogical composition of reservoir rocks is characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM), ensuring reliable interpretation of clay-mineral swelling mechanisms.

The scientific novelty of the dissertation is as follows:

- quantitative relationships governing changes in the permeability of clay-bearing reservoirs under thermal stimulation as a function of injected-water salinity have been established;
- an empirical permeability model has been developed that captures the effect of clay-mineral swelling;
- a scientifically substantiated approach has been proposed for integrating the clay-swelling effect into geological–hydrodynamic reservoir models;
- it has been demonstrated that neglecting clay-mineral swelling processes leads to overestimation of predicted oil recovery when applying thermal enhanced oil recovery methods.

The objective of the dissertation research is to establish the governing patterns of changes in the filtration–capacity (petrophysical) properties of clay-bearing reservoirs under thermal stimulation and to develop a scientifically substantiated approach for incorporating these changes into the modeling of thermal enhanced oil recovery (EOR) methods. To achieve this objective, the study addresses the scientific problem of quantitatively describing the impact of clay-mineral swelling on reservoir permeability and multiphase fluid flow under steam-injection conditions.

The subject of the research is the set of relationships governing the influence of clay-mineral swelling on the filtration–capacity properties of the reservoir and on multiphase fluid flow during the application of thermal enhanced oil recovery methods.

The object of the research is the terrigenous reservoir of the East Moldabek area, characterized by the presence of clay minerals and heavy (high-viscosity) oil.

Research objectives:

1. To analyze the current state of research on thermal enhanced oil recovery methods applied to reservoirs with a high content of clay minerals.
2. To investigate the mineralogical composition of the clay-bearing rocks of the studied reservoir using X-ray diffraction (XRD) and scanning electron microscopy (SEM), and to assess their swelling potential.
3. To experimentally determine the effect of injected-water salinity on changes in the permeability of clay-bearing reservoirs.
4. To develop an empirical relationship describing permeability variation as a function of salinity and thermal stimulation conditions.
5. To develop and adapt a geological–hydrodynamic reservoir model that accounts for clay-swelling processes.
6. To evaluate the impact of clay-mineral swelling on fluid-flow dynamics and oil recovery during steam injection.
7. To perform a techno-economic assessment of the effectiveness of accounting for clay swelling when selecting thermal EOR methods.
8. To identify optimal thermal EOR technologies that minimize the adverse effects of clay swelling and enhance oil recovery from heavy-oil reservoirs.

Scientific hypothesis. The scientific hypothesis of the dissertation is that clay-mineral swelling under thermal stimulation represents a systematic process that predictably alters reservoir permeability as a function of injected-fluid salinity and temperature, and that this process can be quantitatively described and integrated into geological–hydrodynamic reservoir models.

Theoretical significance of this research lies in advancing the understanding of fluid-flow processes in clay-bearing porous media under thermal stimulation. The results contribute to the development of concepts describing the evolution of filtration–capacity (petrophysical) properties of reservoirs subjected to thermal enhanced oil recovery (EOR) methods.

The practical significance of the study consists in the applicability of the obtained relationships and the developed modeling methodology to the design and optimization of thermal enhanced oil recovery methods in heavy-oil reservoirs.

Role of the Research Tasks within the Overall Scientific Work. Within the scope of this study, an analysis of the current state of steam-injection modeling methodologies and their application to reservoirs with a high content of clay minerals was carried out. The mineralogical composition of the reservoir rocks of the study object and the physicochemical properties of the fluids were analyzed. In addition, a digital reservoir model of the study object was developed that accounts for clay-swelling processes under thermal EOR conditions. Laboratory experiments and data analysis made it possible to identify key relationships between the properties of clay minerals and rock permeability, which formed the basis for developing recommendations aimed at optimizing thermal EOR methods.

The methodological framework of the research includes numerical reservoir modeling using Schlumberger Intersect™ software and analysis of laboratory experimental results, which enabled a quantitative assessment of the impact of clay-mineral swelling on reservoir permeability.

Main Provisions Submitted for Defense

1. It has been established that clay-mineral swelling under thermal stimulation leads to a systematic reduction in reservoir permeability, significantly affecting fluid-flow dynamics and the efficiency of heavy-oil recovery.
2. It has been demonstrated that the mineralogical composition of clays is a determining factor governing changes in the filtration–capacity properties of the reservoir during steam and hot-water injection.
3. A quantitative relationship has been established between permeability variations in clay-bearing reservoirs and the salinity of the injected agent under thermal stimulation conditions, enabling formalization of the clay-swelling effect.
4. A scientifically substantiated approach has been proposed for incorporating clay-mineral swelling processes into hydrodynamic modeling of thermal EOR methods, thereby improving the reliability of oil recovery forecasts.

Author's Contribution. The author conducted a comprehensive review of the relevant literature, developed a numerical reservoir model based on laboratory data, and performed computational simulations using a high-resolution reservoir simulator. The obtained results formed the basis for recommendations aimed at improving the efficiency of thermal development methods for heavy-oil reservoirs. The formulation of the research objectives and tasks, as well as the techno-economic justification of the proposed approach, was carried out jointly with the scientific supervisors.

Approbation of the Research. The main results of the study have been published in peer-reviewed scientific journals, confirming the relevance and significance of the conducted research.

Publications. The research results are published in the journal "Energies", which is indexed in the Scopus database in the first quartile (Q1) and corresponds to the 82nd percentile. This indicates the high reputation of the journal in the fields of engineering and energy research.

Scope and Structure of the Dissertation. The dissertation consists of an introduction, six chapters, conclusions, a list of references comprising 90 sources, and five appendices. The total length of the dissertation is 105 pages and includes 39 figures and 15 tables in the main text, as well as 11 figures in the appendices.

Main Findings and Conclusions of the Dissertation. Based on a combination of laboratory investigations, numerical modeling, and techno-economic analysis, the dissertation establishes that clay-mineral swelling has a significant impact on changes in the filtration–capacity properties of the reservoir and, consequently, on the effectiveness of thermal enhanced oil recovery methods. The obtained results pertain to the conditions of the study object, which is characterized by heavy oil and the presence of clay minerals prone to swelling when the salinity of injected fluids changes.

The study demonstrates that clay-swelling processes lead to a reduction in absolute permeability and deterioration of filtration conditions, which adversely affects the technological performance of thermal stimulation methods, including steam injection. Laboratory experiments confirmed the decisive role of injected-agent salinity in governing clay-mineral swelling processes. It was established that a successive decrease in injected-fluid salinity results in a sustained reduction in core-sample permeability. In the experimental part of the dissertation, permeability was shown to decrease from 518 mD to 11.2 mD with an increasing fraction of distilled water in the injected agent, indicating a high sensitivity of reservoir filtration properties to fluid chemical composition.

The results of numerical modeling and techno-economic evaluation revealed that, despite the potentially higher oil recovery associated with cyclic steam stimulation, the presence of swelling clays significantly limits its practical and economic efficiency. Under the conditions of the studied reservoir, the internal rate of return (IRR) for steam injection was approximately 2%, indicating low investment attractiveness. In contrast, hot-water injection, characterized by less intensive thermal impact, provided a substantially higher economic performance with an IRR of approximately 25%.

Thus, the results of the dissertation substantiate the necessity of a differentiated approach to selecting thermal enhanced oil recovery methods that accounts for the mineralogical composition of the reservoir and the properties of injected agents. For heavy-oil reservoirs containing swelling clays, hot-water injection may be considered a more technologically robust and economically viable alternative to conventional steam-injection technologies.

Assessment of the Completeness of the Research Tasks. All objectives formulated in the dissertation were fully achieved. Within the framework of the study, a relationship between reservoir permeability and injected-agent salinity was obtained and experimentally validated for heavy-oil reservoirs containing swelling clays.

Recommendations and Areas of Practical Application. The obtained results and established relationships can be used by oil and oilfield service companies in reservoir development modeling and in the evaluation of oil and gas reserves in fields with similar geological and petrophysical conditions. The dissertation materials may also be applied by specialized departments involved in reservoir development planning, including authorized bodies of the Republic of Kazakhstan. In addition, the results are suitable for use in the educational process of higher educational institutions specializing in oil and gas engineering. The developed modeling methodology, in combination with the established permeability–salinity relationship, may be considered an alternative to traditional laboratory methods for determining rock filtration characteristics.

Assessment of Techno-Economic Efficiency. Application of the developed permeability–salinity relationship improves the reliability of numerical modeling of thermal EOR methods in clay-bearing reservoirs. The use of the proposed alternative approach for evaluating filtration characteristics contributes to reductions in both time and financial costs compared with full-scale laboratory investigations.

Assessment of the Scientific Level of the Work. The investigation of the influence of clay-mineral swelling on the efficiency of thermal enhanced oil recovery methods under the conditions of Kazakhstan's oil fields has been conducted for the first time. This determines the scientific novelty and practical significance of the dissertation. The obtained results expand existing understanding of the mechanisms governing changes in reservoir filtration–capacity properties under thermal stimulation and may be applied in the design of field development strategies for reservoirs with similar characteristics.

Acknowledgements. The author expresses sincere gratitude to the scientific supervisor, Ph.D. A.Kh. Syzdykov, the international supervisor, Associate Professor I.V. Panfilova, and Ph.D., Associate Professor Peyman Pourafshary, for their valuable guidance, consultations, and constructive feedback during the preparation of the dissertation.