ANNOTATION

for the dissertation thesis submitted on the Requirements for the Degree of Doctor of Philosophy (Ph.D.) in Petroleum Engineering (8D07202)
by Sagyndikov Marat Serikovich
titled "**Systematic Approach Investigation for Improving Polymer Flood Technology at the Kalamkas field**"

General overview. Only 3-5% of global oil production can be attributed to enhanced oil recovery (EOR). This fraction is expected to grow, even for reservoirs with harsh conditions that do not allow for efficient oil production. There are commonly several directions of EOR: gas (CO2, N2, hydrocarbon, immiscible), thermal (steam, hot water, in-situ combustion, SAGD), chemical (polymer (P), surfactant polymer (SP), alkaline surfactant polymer (ASP) floods) and others (microbiological). Gas injection is used as an agent for a pressure maintenance system, and usually starts near the beginning of the field production (secondary recovery). Also, a central aspect is the availability of a gas source. For example, most EOR gas projects in the USA, Canada, and China are neighboring huge CO_2 reservoirs/fields. Some operators inject gas for utilization purposes and mask it as an EOR technique. Thermal EOR is generally effectively applicable for heavy oil fields, where viscosity ranges from 100-10 000 cp or even higher. But implementation of thermal methods is mainly limited by heat losses. Heat losses can occur due to the initial reservoir condition (high thermal conductivity of the upper and/or lower impermeable layers, reservoir depth), development stage (high formation water saturation near injection wells), and infrastructure (well construction type, completion, tubing). Also, another critical issue is the obtainability of the freshwater source. In contrast, chemical EOR does not have the limitations mentioned above. Hence it has been widely used in sandstone fields, especially at the late development stage. Furthermore, polymer flooding (PF) is often the most feasible chemical EOR technology. Especially, polymer flooding has prominance, where ASP/SP flooding is not profitable and causes serious on-site problems (scaling, uptime decrease, injectivity issue, hard-to-break emulsions). The principle of polymer flooding is to increase the viscosity of injected water and thereby develop a more favorable mobility ratio between displacing water and oil in place. This approach reduces or avoids water fingering caused by geological heterogeneity.

The relevance of the work. The majority of giant oil fields in Kazakhstan are entering or already in the brownfield development stage, and the Kalamkas oilfield is one of them. The field was discovered in 1976 and developed commercially since 1979 according to the Field Development Project – FPD. Oil and gas reservoirs were established in Jurassic deposits. Reservoirs mainly consist of sandstones deposited in deltaic, fluvial, and shallow marine environments. The reservoirs' main geological and physical features are highly-layered heterogeneity and unfavorable mobility ratio (>7) in reservoir conditions. The permeability ranges from 0.055 to 1.273 Darcy. The oil viscosity is at least 16 cp at reservoir temperature (38-43°C). These factors explain non-uniform depletion and relatively low recovery factor for the Kalamkas oilfield. To date, the water cut is significantly higher than expected considering the depletion of recoverable reserves.

To improve hydrocarbon production and enhance oil recovery, a polymer flood pilot design started in 2011. The design of the injected polymer viscosity was based on the optimum economic output (i.e., net present value) according to reservoir modeling and feasibility studies, and on concepts presented in literature sources. Pilot projects were conducted since September 2014. As a result, pilots showed no injectivity loss; polymer injection unit up-time high; sweep efficiency increased (based on injection and production logging tests); water-cut decreased to 10%; and oil production rates doubled. The estimated incremental recovery factor over waterflood was 9%.

Although polymer flooding worldwide has been applied ~60 years, and it still requires further investigation to provide improvements. Thus, this dissertation describes a systematic approach investigation for improving polymer flood technology at the Kalamkas field. The systematic approach investigation includes the combination of data analysis, laboratory studies, field observations, numerical & analytical modeling, and feasibility studies.

Research Objectives. The objective of this dissertation was to investigate polymer flood at the Kalamkas field to develop a systematic approach for improving technology. Therefore, the research scope of this dissertation was focused on the following aspects:

1. A comprehensive literature review of recent worldwide polymer EOR projects focusing on the Kalamkas field polymer flood aspects.
2. Assess polyacrylamide solution chemical and mechanical stability during a polymer flood in the Kalamkas field.
3. Develop a novel method for the field assessment of polymer degradation during a polymer flood of an oil reservoir.
4. Experimental and numerical studies of the Kalamkas polymer flood technology. Examine the oil recovery at various simulation scenarios.
5. The Kalamkas polymer flood projects feasibility studies and choose most rational scenario for full field deployment.

Novelty. The novelty in this work resides in field demonstration of the correctness of previous conceptual ideas—(1) that the vertical HPAM injection wells contained fractures that were necessary for polymer injection, (2) that the fractures substantially reduced mechanical degradation, and (3) that injected polymer solutions were quickly stripped of dissolved oxygen (thereby promoting oxidative stability). These demonstrations have value in countering arguments by others that polymer injectivity into vertical wells could be acceptable without fractures. To our knowledge, this is the first published report demonstrating that backflowed HPAM samples from an injection well showed no detectable dissolved oxygen. Also, to our knowledge, this is the first published report demonstrating that backflowed samples from an injection well showed no HPAM mechanical (or oxidative) degradation. Finally, we developed an unconventional approach to model a polymer flood that can be used to optimize technology at the Kalamkas field.

Defending hypotheses:

1. Vertical HPAM injection wells contained fractures that were necessary for polymer injection. And these fractures substantially reduced polymer mechanical degradation.
2. Injected polymer solutions were quickly stripped of dissolved oxygen, thereby promoting oxidative (or chemical) stability.
3. At Kalamkas conditions, residual resistance factor (RRF) is not significantly different from unity, i.e., post chase water injection will not benefit oil recovery. Therefore, polymer injection should be underway as far as net present value (NPV) is positive.
4. Polymer flood at oil price volatility is a long-term project that extends the field's economically feasible lifetime and enhances oil recovery.

Practical value. A developed novel method for the field assessment of polymer degradation can be used to understand in-situ polymer EOR mechanisms better. Provided mitigation plan to eliminate chemical degradation that can save 25% of OPEX at the Kalamkas field conditions, thereby improving project economics. In addition, a novel approach to model polymer flood can be used to optimize polymer injection parameters, thereby improving technology efficiency.

Personal contribution. The dissertation's author contribution consists of the literature review, geological & reservoir dynamics data analysis, laboratory studies, field observations, and numerical & analytical modeling. The research results presented in the dissertation were obtained by the author personally or with his direct participation. Finally, the author formulated conclusions and recommendations.

Approbation. The main results of the dissertation were reported and discussed at the following conferences and workshops: International Scientific Conference "Satbayev Readings – 2020" and "Satbayev Readings – 2021" (Kazakhstan, Almaty, April 2020 and April 2021); SPE Virtual Improved Oil Recovery Conference (USA, Tulsa, April 2022); Workshop organized by GazPromNeft "Chemical Enhanced Oil Recovery: challenges and prospects" (Russia, Kazan, June 2022)); International Scientific Conference titled "Prospects for the use of chemical methods for enhanced oil recovery (cEOR) at a late stage of development" (Kazakhstan, Astana, September 2022).

Publications. The main hypotheses of the dissertation have been published in 7 articles, which include 1 – in the Scientific Journal cited in the Scopus base (Q1, 94 percentile), 2 – in the Scientific Journals listed in the recommended by the Committee for Quality Assurance in the Sphere of Education and Science of the Ministry of Science and Higher Education RoK, 3 – International Conferences, 1 – Patent for the utility model (KazPatent):

1. **Sagyndikov**, M., Seright, R.S., Kudaibergenov, S., and Ogay, E. 2022. Field Demonstration of the Impact of Fractures on Hydolyzed Polyacrilamide

Injectivity, Propagation and Degradation. SPE Journal 27 (02): 999-1016. SPE-208611-PA. https://doi:10.2118/208611-PA

2. **Sagyndikov**, M., Kushekov, R.M., Seright, R.S. 2022. Review of Important Aspects and Performances of Polymer Flooding versus ASP Flooding. Bulletin of the Karaganda University Chemistry Series 105 (3). https://doi.org/10.31489/2022Ch3/3-22-13
3. **Sagyndikov**, M., Salimgarayev, I., Ogay, E., Seright, R.S., Kudaibergenov, S. 2022. Assessing polyacrylamide solution chemical stability during a polymer flood in the Kalamkas field, Western Kazakhstan. Bulletin of the Karaganda University Chemistry Series 105 (1). https://doi.org/10.31489/2022Ch1/99-112
4. **Sagyndikov**, M., Seright, R.S., Tuyakov, N. 2022. An unconventional approach to model a polymer flood in the Kalamkas oilfield. Paper presented at the SPE Virtual Improved Oil Recovery Conference to be held 25-29 April 2022. SPE-209355-MS. https://doi.org/10.2118/209355-MS
5. **Sagyndikov**, M., Imanbayev, B., Salimgarayev, I., Baipakov, S. 2022. Method for the field assessment of polymer degradation during a polymer flood of oil reservoir. Patent for Utility Model №7054, National Institute Of Intellectual Property RoK (in Russian) – APPENDIX A.
6. **Sagyndikov**, M., Ogay, E., Kudaibergenov, S. 2021. Feasibility study of polymer flooding application in the heavy oil reservoir. Proceedings of the International Scientific Conference "Satbayev Readings – 2021" (in Russian)
7. **Sagyndikov**, M., Ogay, E., Kudaibergenov, S. 2020. Evaluation of Polymer Flooding Efficiency at Brownfield Development Stage of Giant Kalamkas Oilfield, Western Kazakhstan. Proceedings of the International Scientific Conference "Satbayev Readings – 2020"

Dissertation Organization. The dissertation is composed of six chapters. The introduction presents the general overview, relevance, objectives, hypotheses, and dissertation organization. Chapter I provides the Kalamkas oilfield geological properties and reservoir dynamics features. Chapters II, III, IV, and V are based on published papers, of which I am the first author, about topics of the Kalamkas polymer flood key aspects and EOR technology optimization. Chapter VI is conclusions. A summary of each chapter is shown as follows:

Chapter II is a comprehensive literature review of recent worldwide polymer EOR projects. Chapter III examines polymer in-situ mechanical stability and describes the development of a novel method for the field assessment of polymer degradation during a polymer flood of an oil reservoir. Chapter IV assesses polymer chemical stability and recommends mitigating viscosity loss and optimizing OPEX. Chapter V describes an unconventional approach to model a polymer flood at the Kalamkas oilfield.

The total volume is 165 pages, including 55 figures, 27 tables, references of 168 titles, and 6 appendices.

Executive Summary.

The Introduction presents the general overview, relevance, objectives, hypotheses, and dissertation organization.

Chapter I presents the dissertation research objectives – the Kalamkas oilfield and the polymer flood pilot. Reservoir features, formation fluids properties, and reservoir dynamics analysis show considerable potential for enhancing oil production by polymer flooding. Recent tertiary pilots are conducting in the West and East parts of the field. The pilot performance analysis shows high technical and economic success. The polymer flood has been recognized as a perspective EOR technique for the Kalamkas field that requires further development. The development requires (1) a comprehensive literature review of recent worldwide polymer EOR projects focusing on the Kalamkas field polymer flood aspects, (2) assess polyacrylamide solution chemical and mechanical stability, (3) experimental and numerical studies of the Kalamkas polymer flood technology for examining the oil recovery at various simulation scenarios, (4) feasibility studies for choosing the most rational concept for full field deployment.

Chapter II reviews important aspects and performances during polymer flooding. These aspects include reservoir conditions for effective implementation, polymer injection, and reservoir development parameters. The growing large-scale application polymer flooding demonstrates that it is the most feasible chemical EOR technology. In contrast, ASP/SP flood is not profitable and causes severe on-site problems. The primary novel finding from this review and analysis of field projects is to cast doubt on the economic feasibility of ASP flooding—especially in Kazakhstani oilfields, including the Kalamkas field. This work also provides a perspective on the TAN (total acid number) for Kazakhstan oilfields, especially for applicability to ASP flooding. Many insights into applicability of polymer flooding were also noted. In particular, the fact that HPAM prices are actually lower now than they were 40 years ago has greatly aided the ability for polymer flooding to be applied on a large scale today. The development of horizontal wells has greatly enhanced polymer injectivity and allowed the upper limit of oil viscosity for polymer flooding to be increased from ~150 cp to over 3 000 cp. Controlled injection above the formation parting pressure has also played a major role in this regard. Until recently, commercially available EOR polymers were not sufficiently stable in reservoirs with temperatures exceeding ~70°C. However, the recent availabity of an ATBS polymer has the potential to allow feasible polymer flooding in reservoirs at temperatures up to 120°C. A major difference from waterflooding is that the dissolved oxygen level as close to zero as practical—certainly less than 200-400 parts per billion. Above 60°C, dissolved oxygen levels must be much closer to zero. In theory, polymer flooding can be applied in formations with any water salinity. However, practical considerations favor using the least saline water that is available. Field experience, as well as laboratory and theory, consistently reveal that the polymer bank size should be as large as practical (typically ~1 pore volume). Once injection is switched from polymer back to water injection, water cuts will quickly rise to high values. The vast majority of polymer floods have been applied in moderate-to-high permeabilty reservoirs (>100 md). This fact is due first to the need for high polymer injectivity and second because high-Mw polymers exhibit difficult in penetrating into less-permeability rock. However, Song et al. (2022) [50] showed promising laboratory results, where HPAM can effectively propagate through the tight low permeable (<50 md) carbonate rocks. The novel polymers can extend the minimum applicability range of permeability, and it has high relevance for future research & development.

Chapter III demonstrated certain predictions about the existence and effects of fractures on injectivity during injection of HPAM solutions into vertical wells during a polymer flood in the Kalamkas field. This chapter provides field evidence to clarify the utility of near wellbore fractures to promote injectivity and mitigate mechanical degradation of HPAM solutions. It also provides a sampling methodology that demonstrated minimum mechanical and oxidative degradation under field circumstances, whereas previous sampling methods may have provided overly pessimistic indications of HPAM stability. The following findings were noted:

- Step rate tests indicated that fractures were not open during water injection before polymer injection. In contrast, during polymer injection, open fractures were confirmed using step rate tests, pressure transient analysis, and comparison of actual injectivities versus those calculated using the Darcy radial flow equation coupled with laboratory measurements of HPAM rheology in Kalamkas cores.
- We developed a novel method to assess in-situ polymer solution mechanical stability during a polymer flood. Under Kalamkas field conditions, we demonstrated the collection of formation samples using the natural energy of a reservoir at the wellhead. This process protected polymer solution samples from oxidative degradation. Compared to other lab and field methods, this novel method is quick, simple, and inexpensive. Compared with other field tests where substantial degradation was observed, one could argue that our methods are more reliable since they revealed only minor mechanical and/or oxidative degradation of HPAM samples and since laboratory and theoretical findings suggested that degradation should not have occurred under the conditions of the other field tests.
- Rheology measurements of back-produced polymer solutions showed the absence of the mechanical degradation. This finding provided further confirmation that polymer injection occurred above the formation parting pressure and that the injection area associated with the fracture was large enough to ensure the stability of the solution.
- These findings confirm that the advantages of fractures or fracture-like features during a polymer flood (i.e., little or no injectivity loss; mechanical stability of the polymer solution) can outweigh their disadvantages (e.g., possible severe channeling, jeopardized sweep efficiency).
- Polymer solutions that were back-produced from injection wells were depleted of dissolved oxygen, even though injected solutions contained 200-300 ppb of dissolved oxygen and the polymer solutions only penetrated

a few meters into the formation. Presumably, the 2-4%-iron mineral content of the reservoir rock caused this oxygen depletion. Even though this process added dissolved iron to the solutions, the HPAM did not degrade so long as the dissolved oxygen level remained low.

- As will be shown later in Chapter IV, polymer solutions that propagated over 400 meters through a fracture from an injector to a producer were also depleted of dissolved oxygen, but suffered only minor viscosity loss (15%) after traveling all the way through the formation.
- The significance and novelty of the last four conclusions may be appreciated by realizing that virtually all previous field tests (where produced samples were analyzed from production wells or back-produced samples were analyzed from injection wells) indicated substantial HPAM degradation (as revealed in our literature review). If accepted at face value, those previous results would cast serious doubt on the viability of all HPAM floods. In contrast, our results alleviate those doubts by demonstrating that HPAM stability in a field application is consistent with present and previous laboratory and theoretical expectations. Our results suggest that the lack of stability observed in the previous tests may have been due to problems with the sampling procedures—rather than degradation that jeopardized the polymer in the reservoir.

Chapter IV provides a methodology for assessing chemical degradation in the field, and the methodology is demonstrated for the field application at the Kalamkas. This study indicates the possibility of optimizing operational expenditure by 25% and increasing the economic efficiency of the polymer flood project operated by an eductor type unit. Consistent with (Seright and Skjevrak 2015), 300-400 ppb oxygen in polymer preparation and injection process does not degrade polymer viscosity. In addition, this chapter provides additional field-based support that dissolved oxygen of the injected polymer solution is effectively consumed by surrounding rock and provides further chemical stability in the formation. Polymer solutions that propagated over 400 meters through a fracture from an injector to a producer were depleted of dissolved oxygen, but suffered only minor viscosity loss after traveling all the way through the formation.

Chapter V shows developed an unconventional method for modeling a polymer flood that accounts for more realistic conditions that occur during polymer injection into vertical wells. These conditions include (a) fractured injection wells, (b) no mechanical degradation of injected polymer solutions, (c) no significant permeability reduction caused by the injected polymer, and (d) no polymer inaccessible pore volume. This model was applied in the Kalamkas oil field. The model focuses on history matching of bottom-hole injection pressures and forecasts far better than conventional models that assume no fractures are present. The model correctly predicts very rapid deterioration of water cuts and oil production rates after switching from polymer back to water injection—better than conventional models that assume a significant permeability reduction by the polymer. An empirical equation matched oil production reasonably well for most wells in six areas of the

Kalamkas oil field. This equation allows easy predictions in place of the expense and effort required for simulation. Given oil-price volatility, feasibility studies reveal that our polymer flood should be a long-term project that extends the field's economic lifetime and enhances oil recovery.

Conclusions. The goal of this Ph.D. thesis was to investigate polymer flood at the Kalamkas field to develop a systematic approach for improving technology. To achieve this, we analyzed Kalamkas oilfield development features and current stage of the polymre flood pilot, reviewed recent worldwide polymer EOR projects focusing on the Kalamkas field polymer flood aspects, assessed polyacrylamide solution chemical and mechanical stability, developed a novel method for the field assessment of polymer degradation, experimentaly and numericaly studied Kalamkas polymer flood implementation, and conducted project feasibility studies.

A field review shows that the Kalamkas oil reservoirs have a high layered permeability contrast and unfavorable water-oil mobility ratio, which jeopardizes uniform depletion and oil recovery. In view of the low reservoir temperature, elevated mobility ratio, and high formation permeability, it was recognized that the Kalamkas field has considerable potential for enhancing oil production by polymer flooding. Recent tertiary pilot results show positive performances. However, it still requires further investigation to provide improvements.

A comprehensive literature review shows that for the polymer flood project dissolved oxygen level should be as close to zero as practical – certainly less than 200 parts per billion. This technology can be applied in formations with any water salinity. However, practical considerations favor using the least saline water that is available. Field experience, as well as laboratory and theory, consistently reveal that the polymer bank size should be as large as practical (typically ~1 pore volume). Once the injection is switched from polymer back to water injection, water cuts will quickly rise to high values. Other chemical EOR such as ASP/SP flooding at the Kalamkas conditions will be too risky relative to polymer flood, especially in terms on-site production/injection problems and high cost of chemicals & water treatment. Using horizontal wells can greatly enhace polymer injectivity and controll injection above the formation parting pressure.

Dedicated field polymer stability studies provides field evidence to clarify the utility of near wellbore fractures to promote injectivity and mitigate mechanical degradation of HPAM solutions. Also, we provided a new sampling methodology that demonstrated minimum mechanical and oxidative degradation under the Kalamkas field circumstances, whereas previous sampling methods may have provided overly pessimistic indications of HPAM stability. Also, the research provides additional field-based support that the dissolved oxygen of the injected polymer solution is effectively consumed by surrounding rock and provides further chemical stability in the Kalamkas formation. Based on field studies, we recommended modifying the East eductor injection unit to ensure an undetectable or acceptable oxygen level that will save 25% cost of chemicals.

An unconventional method for modeling a polymer flood was developed that accounts for more realistic conditions that occur during polymer injection into vertical wells. These conditions include (a) fractured injection wells, (b) no mechanical degradation of injected polymer solutions, (c) no significant permeability reduction caused by the injected polymer, and (d) no polymer inaccessible pore volume. This model was applied in the Kalamkas oil field. Also, we developed an empirical equation for analytical forecasting of polymer flood performance based on geological parameters and reservoir dynamics. This analytical tool can be used for pattern selection and ranking during full field deployment.

Finally, feasibility studies show that at given oil-price volatility, the Kalamkas polymer flood should be a long-term project that extends the field's economic lifetime and enhances oil recovery.