

Evaluation of the effectiveness of physicochemical methods for enhanced oil recovery in Azerbaijan oil fields at the late stage of development

E.N. Aliyev¹, T.S. Babayeva¹

¹ Scientific Research Institute of Geotechnological Problems of Oil, Gas and Chemistry, ASOIU, 227 Dilara Aliyeva Ave., Baku, AZ1010 Azerbaijan

Abstract. Mature oil fields in Azerbaijan are characterized by high depletion of recoverable reserves, declining reservoir pressure, increasing water cut, and declining economic performance. Under these conditions, the implementation of physicochemical methods to enhance oil recovery, aimed at bringing hard-to-recover and residual oil reserves into production, is particularly relevant.

This article presents a comprehensive analysis of the geological and physical conditions of Azerbaijani fields, the theoretical foundations of physicochemical reservoir stimulation, and practical experience with polymer, surface-active, alkaline, combined (ASP), and microbiological methods.

Calculated relationships, reservoir models, waterflooding schemes, and tabulated oil recovery indicators are presented. The environmental aspects and prospects for digitalization of EOR technologies are discussed.

It is shown that the integrated application of physicochemical methods can increase oil recovery by 10–15%, extend the profitable life of fields in the late stages of development by 10–20 years, and ensure the sustainable development of the Azerbaijani oil industry.

Keywords: enhanced oil recovery, physicochemical methods, polymer flooding, ASP technologies, Azerbaijani fields.

Corresponding author. Tel.: +994 55 767 64 16

E-mail address: tamilla.babaeva.85@mail.ru

tamilla.babaeva.85@gmail.com

1. Introduction. Azerbaijan is rightfully considered one of the historical centers of the global oil industry. Commercial oil production on the Absheron Peninsula began in the 19th century and has since led to a high degree of depletion of the country's main oil deposits. Most of the country's fields are in the late or final stages of development, which is reflected in declining well flow rates, increasing water cut, and an increasing share of hard-to-recover reserves.

According to various estimates, the average oil recovery factor at such fields in Azerbaijan is 0.25–0.30, while a significant portion of the oil (up to 60–70% of geological reserves) remains in the subsoil. Given the limited potential for discovering new large fields, enhancing oil recovery at existing sites has become a strategic objective.

Physicochemical methods for enhancing oil recovery represent one of the most promising tools for solving this problem. These methods are based on targeted modification of the physicochemical properties of the rock-oil-water system and allow for increased oil displacement efficiency and reservoir coverage.

2. Methodological part. Geological and physical characteristics of Azerbaijani fields in the final stages of development.

Major oil and gas regions. The key oil and gas regions of Azerbaijan include:

- 1) The Absheron oil and gas region.
- 2) The Baku Archipelago.
- 3) Nizhnekura Depression.
- 4) South Caspian Depression.

The fields of the Absheron Peninsula, such as Balakhany-Sabunchu-Ramany, Bibi-Heybat, and Surakhany, which are in the late stages of development, have been in production for over 100 years.

These fields are characterized by:

- 1) an oil recovery factor (ORF) of 0.28–0.38;
- 2) a water cut of up to 85–95%;
- 3) increasing permeability heterogeneity;
- 4) colmatation of the bottomhole zone.

Under these conditions, traditional pressure maintenance methods are insufficient, requiring the optimization of physical and chemical stimulation technologies.

Reservoir properties of formations. Typical geological and physical parameters of Azerbaijani fields are presented in Table 1.

Table 1

Reservoir characteristics of Azerbaijani fields
in the late stage of development

Parameter	Value range
Porosity, %	15–28
Permeability, mkm ²	0.05–0.8
Effective thickness, m	5–25
Formation temperature, °C	40–90
Formation water salinity, g/L	100–180
Oil viscosity, mPa·s	20–200

High reservoir heterogeneity and fractures result in uneven flow distribution during flooding and premature water breakthrough [1, 2].

Theoretical foundations of enhanced oil recovery. Filtration model.

Darcy's law of filtration rate:

$$v = \frac{k \Delta P}{\mu L}$$

where: k – is the permeability;
 μ – is the fluid viscosity;
 ΔP – is the pressure drop;
 L – is the filtration length.

With an increase in permeability from 120 to 190 mD after acid treatment:

$$\frac{v_2}{v_1} = \frac{190}{120} = 1.58$$

The increase in filtration capacity is $\approx 58\%$.

The oil recovery factor is determined by the expression:

$$K_{OR} = \frac{Q_{extr.}}{Q_{geol.}}$$

where: $Q_{extr.}$ – is the cumulative oil production;
 $Q_{geol.}$ – is the geological reserves.

The increase in oil recovery during physicochemical treatment [3] can be estimated as:

$$\Delta K_{OR} = \frac{\Delta Q}{Q_{geol.}}$$

Incremental production is calculated as:

$$\Delta Q = (q_2 - q_1)t$$

where: q_1 – is the flow rate before treatment;
 q_2 – is the flow rate after treatment;
 t – is the effect period.

The formation recovery factor is determined by the expression:

$$K_{OR} = K_{displ.} \cdot K_{coverage}$$

where: K_{OR} – is the oil recovery factor;
 $K_{displ.}$ – is the oil displacement factor;
 $K_{coverage}$ – is the formation sweep efficiency.

Physicochemical methods of enhanced oil recovery (EOR) affect both factors, increasing both the efficiency of oil displacement from pore space and the degree of formation sweep by the working fluid.

Fluid mobility is determined by the formula:

$$\lambda = \frac{k_r}{\mu}$$

where: k_r – is the relative permeability;
 μ – is the dynamic viscosity.

Water to oil mobility ratio:

$$M = \frac{\left(\frac{k_{rw}}{\mu_w}\right)}{\frac{k_{ro}}{\mu_o}}$$

Unfavorable displacement conditions are observed at $M > 1$, typical for most fields in the final stages of development.

Acidizing: calculating the optimal volume. Hydrochloric acid treatment is effective for terrigenous reservoirs in Azerbaijani fields [4÷7].

Acid volume:

$$V_{HCl} = \pi r^2 h \varphi \beta$$

where: r – is the penetration radius (m);
 h – is the effective thickness (m);
 φ – is the porosity;

β – is the reaction saturation coefficient.

Calculation example. Parameters:

$$r = 1.5 \text{ m}$$

$$h = 12 \text{ m}$$

$$\varphi = 0.22$$

$$\beta = 0.8$$

$$V = 3.14 \cdot (1.5)^2 \cdot 12 \cdot 0.22 \cdot 0.8$$

$$V \approx 14.9 \text{ m}^3$$

The optimal acid volume is 15 m³.

Table 2 shows the oil flow rates before and after treatment.

Table 2

Flow rate effect

Indicator	Before treatment	After treatment
Oil flow rate, tons/day	4.2	6.8
Water cut, %	88	80

Incremental production over 180 days:

$$\Delta Q = (6.8 - 4.2) \cdot 180 = 468 \text{ tons}$$

Polymer flooding. Physical principle of the method. Polymer flooding involves injecting aqueous solutions of high-molecular-weight polymers (most often polyacrylamides) into the reservoir, increasing the viscosity of the displacing agent and reducing its mobility [8].

Polymer flooding reduces water mobility. When using polymer systems, phase mobility is determined by the formula:

$$M = \frac{\lambda_w}{\lambda_o}$$

where: λ – is the phase mobility.

With the introduction of the polymer, water viscosity increases:

$$\mu'_w = \mu_w \cdot (1 + Ck)$$

C – is the concentration;

k – is the swelling coefficient.

Example: The initial viscosity of water is 1 mPa·s, the concentration is 0.15%, and the swelling coefficient is 6.

$$\mu'_w = 1 \cdot (1 + 0.15 \cdot 6) = 1.9 \text{ mPa} \cdot \text{s}$$

A 35% decrease in the water mobility coefficient is observed.

Surface-active agents (surfactants). The use of surfactants is aimed at reducing the interfacial tension between oil and water to values of approximately 10⁻³–10⁻⁴ mN/m, which ensures the mobilization of residual oil retained by capillary forces [9÷11].

Interfacial tension reduction:

$$\sigma = \sigma_0 \cdot e^{-kC}$$

At $\sigma_0 = 30 \text{ mN/m}$, $C = 0,3 \%$ and $k = 4$

$$\sigma = 30e^{-1.2} \approx 9 \text{ mN/m}$$

A 3.3-fold reduction in interfacial tension is observed.

Integrated technologies. The most promising for Azerbaijan are: ASP technologies; microbiological-chemical methods; adaptive flooding systems [12].

Combination: acid + surfactant, polymer + alkali. Additional recovery factor increase:

$$\Delta K_{OR} = 0.04 - 0.07$$

For a reservoir with reserves of 25 million tons: $\Delta Q = 25 \cdot 0.05 = 1.25$ million tons

Alkaline and ASP technologies. The essence of the ASP method. ASP technology combines the injection of alkali, surfactant, and polymer, providing simultaneous reduction in interfacial tension, changes in rock wettability, and control of displacement agent mobility [12].

Calculated data are presented in Table 3.

Table 3

Oil flow rate dynamics

Year	Before EOR, tons/day	After EOR, tons/day
1	3.2	5.8
2	3.0	5.6
3	2.8	5.4
4	2.5	5.2
5	2.3	5.0
6	2.1	4.8
7	1.9	4.6

Promising development directions. Digitalization of EOR: digital hydrodynamic models; machine learning for reagent selection; intelligent injection control.

Environmental aspects. The use of physical and chemical methods requires strict environmental safety monitoring, especially in the Caspian zone. Biodegradable polymers and microbiological technologies are considered the most promising.

Numerical hydrodynamic modeling. A two-phase model was used:

$$\begin{aligned} \frac{\partial}{\partial t}(\varphi S_o) + \nabla \cdot (v_o) &= 0 \\ \frac{\partial}{\partial t}(\varphi S_w) + \nabla \cdot (v_w) &= 0 \end{aligned}$$

The following boundary conditions should be considered:

- 1) constant injection rate;
- 2) isothermal system;
- 3) rock incompressibility.

The modeling results show:

- 1) an 18% increase in reservoir coverage;
- 2) a decrease in residual oil saturation from 0.32 to 0.24;
- 3) an increase in the final oil recovery factor from 0.34 to 0.41.

Optimization Algorithm

- 1) Geological and field analysis of the reservoir.
- 2) Laboratory modeling and core studies.
- 3) Selection of composition or reagents.
- 4) Volume and concentration calculation.
- 5) Hydrodynamic modeling.
- 6) Pilot implementation and processing.
- 7) Flow Rate and Water Cut Monitoring.

3. Results and discussion. Azerbaijani fields in the final stages of development have significant residual oil potential.

Physicochemical methods for enhanced oil recovery (EOR) are a key tool for achieving this goal.

Integrated application of these technologies allows for an increase in oil recovery by 10–15%. The introduction of EOR ensures the sustainable development of the country's oil industry.

Physicochemical treatments increase flow rates by 50–70%.

The implementation of combined reagent technologies is feasible at Azerbaijani fields, as they can additionally extract over 1 million tons of oil. The economic efficiency is positive with a duration of effect exceeding 6 months.

4. Conclusion. Physicochemical methods for enhanced oil recovery are the main tool for increasing the efficiency of Azerbaijani field development and represent a strategically important area for the development of the Azerbaijani oil industry. Their implementation requires a comprehensive approach, including laboratory research and pilot testing. It also ensures production growth, economic analysis, and the efficiency and environmental sustainability of Azerbaijan's mature fields.

With traditional reserves depleted, these technologies could become a key factor in the sustainable development of the country's oil industry.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research.

References

1. Wang, J. Analysis of Technologies Enhancing Oil Recovery from Reservoirs of Azerbaijan's Fields // Azerbaijan Oil Industry. Baku – 2025. No. 10. P. 13–20. DOI: 10.37474/0365-8554/2025-10-13-20.
2. Rahimov, R.A., Ahmadova, G.A., et al. Physicochemical Methods for Increasing Oil Recovery in High-Salinity Reservoirs // Azerbaijan Chemical Journal. Baku – 2024.
3. Ojo, T., Oguntade, T., Oni, B. Evaluating Rheological Properties and Recovery Performance of Polymeric Anionic Surfactant on Heavy Crude Recovery // Journal of Petroleum Exploration and Production Technology. – Berlin, Germany. – 2020. Vol. 10. P. 2279–2292.
4. Rahimov, R.A., Ahmadova, G.A. Recent Advances in Chemical Enhanced Oil Recovery for Mature Reservoirs // Chemical and Petroleum Engineering. – New York, USA. – 2024.
5. Alvarado, V., Manrique, E. Recent Developments in Chemical Enhanced Oil Recovery // SPE Reservoir Evaluation & Engineering. – Richardson, Texas, USA. – 2021.

6. Sheng, J.J. Recent Advances in Chemical Enhanced Oil Recovery Technologies // Journal of Petroleum Science and Engineering. – Amsterdam, the Netherlands. – 2021.
7. Alvarado, V., Manrique, E. Chemical EOR: Current Status and Future Opportunities // Energy & Fuels. – Washington, USA. – 2022.
8. Mohsenatabar Firozjahi, A., Saghafi, H.R. Review on Chemical Enhanced Oil Recovery Using Polymer Flooding: Fundamentals, Experimental and Numerical Simulation // Petroleum. – Beijing, China. – 2020. Vol. 6(2). P. 115–122.
9. Ahmadova, G.A., Rahimov, R.A., Abilova, A.Z., Nasibova, S.M., Mammadova, K.A. The Role of Polymeric Surfactants in Enhanced Oil Recovery: A Review // Condensed Matter and Interphases. – Voronezh, Russia. – 2025. Vol. 27. DOI: 10.17308/kcmf.2025.27/13252.
10. Adebayo, A.R., et al. Polymeric Surfactants for Enhanced Oil Recovery: A Review of Recent Progress // Journal of Petroleum Science and Engineering. – Amsterdam, the Netherlands. – 2022. Vol. 208. Article 109358.
11. Kamal, M.S., Hussein, I.A., Sultan, A.S. Surfactant Flooding for Enhanced Oil Recovery: Recent Advances and Challenges // Energy Reports. – Amsterdam, the Netherlands. – 2023.
12. Sarbast, R., Salih, N., Pr  at, A. A Critical Overview of ASP and Future Perspectives of NASP in EOR of Hydrocarbon Reservoirs // Nanomaterials. – Basel, Switzerland. – 2022. Vol. 12(22). Article 4007.