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PHYSICOCHEMICAL TRANSFORMATION PROCESSES IN THE NEAR-WELLBORE ZONE OF DIFFERENT RESERVOIR TYPES

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Abstract. *The near-wellbore zone of reservoirs of various types is characterized by complex physical and chemical processes that determine well productivity and the efficiency of stimulation methods. This study examines three independent directions of near-wellbore transformation typical for oil and gas-condensate reservoirs of Uzbekistan. The first direction focuses on the influence of an electrical field on heavy-oil systems, where notable changes in rheological properties, threshold pressure, and filtration behavior are observed. The second direction is based on mathematical modeling of acid treatment in carbonate formations, incorporating dissolution kinetics, channel (wormhole) development dynamics, and the impact of geological heterogeneity on acid distribution. The third direction analyzes hydrochloric-acid technologies applied in low-pressure gas-condensate reservoirs, where mineralogical characteristics and reservoir fluid composition define specific mechanisms of rock–acid interaction.*

Keywords: *electrical stimulation, heavy oil, acid treatment, mathematical modeling, carbonate formations, hydrochloric-acid technologies, gas-condensate reservoirs, near-wellbore zone, filtration properties, physicochemical processes.*

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TURLI TIPDAGI KOLLEKTORLARNING QUDUQ TUBI ZONASIDA KECHADIGAN FIZIK-KIMYOVIY TRANSFORMATSIYA JARAYONLARI

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Annotatsiya. *Turli tipdagi kollektorlarning quduq tubi zonalarida kuzatiladigan fizik va kimyoviy jarayonlar ularning mahsuldorligiga sezilarli ta’sir ko‘rsatadi. Ushbu maqolada O‘zbekistonning yuqori qovushqoqli neft, karbonat hamda o‘ta past bosimli gazkondensat kollektorlariga xos bo‘lgan jihatlar o‘rganilgan. Birinchi yo‘nalishda elektr maydonining yuqori qovushqoqli neft uyumlariga ta’siri ko‘rib chiqiladi; bunda reologik xususiyatlarning o‘zgarishi, bosim chegarasining kamayishi va filtratsiya ko‘rsatkichlarining oshishi aniqlangan. Ikkinchi yo‘nalishda karbonat kollektorlarida kislotali ishlov berish jarayonining matematik modellari tahlil qilinadi; model tarkibida eritilish kinetikasi, kanal hosil bo‘lish dinamikasi hamda geologik tuzilmaning reaktivning taqsimlanishiga ta’siri o‘rganilgan. Uchinchidan, o‘ta past qatlam bosimli gazkondensat konlarida qo‘llaniladigan tuz-kislotali texnologiyalarning samaradorligi o‘rganilib, minerallashuv darajasi va qatlam suyuqliklarining tarkibi bilan bog‘liq o‘ziga xos reaksiyalar yoritilgan.*

Kalit so‘zlar: *elektr ta’siri, yuqori qovushqoqli neft, kislotali ishlov berish, matematik modellashtirish, karbonat kollektorlar, tuz-kislotali texnologiyalar, gazkondensat qatlamlari, quduq atrofi zonasi, filtratsiya xususiyatlari, fizik-kimyoviy jarayonlar.*

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ФИЗИКО-ХИМИЧЕСКИЕ ПРОЦЕССЫ ТРАНСФОРМАЦИИ ПРИЗАБОЙНОЙ ЗОНЫ В РАЗЛИЧНЫХ ТИПАХ КОЛЛЕКТОРОВ

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Аннотация. *Призабойная зона пластов различного типа характеризуется сложными физическими и химическими процессами, определяющими продуктивность скважин и эффективность методов воздействия. В настоящей работе рассматриваются три самостоятельных направления трансформации призабойной зоны, типичных для нефтяных и газоконденсатных коллекторов Узбекистана. Первое направление связано с влиянием электрического поля на высоковязкие нефтяные системы, где наблюдаются изменения реологических характеристик, порогового давления и фильтрационных свойств. Второе направление основано на математическом моделировании кислотной обработки карбонатных пластов, охватывающем кинетику растворения, динамику формирования каналов и влияние геологического строения на распределение реагента. Третье направление посвящено анализу соляно-кислотных технологий, применяемых в газоконденсатных залежах с пониженным пластовым давлением, где минералогические особенности и состав пластовых флюидов формируют специфические механизмы взаимодействия реагентов с породой.*

Ключевые слова: *электрическое воздействие, высоковязкая нефть, кислотная обработка, математическое моделирование, карбонатные пласты, соляно-кислотные технологии, газоконденсатные залежи, призабойная зона, фильтрационные свойства, физико-химические процессы.*

Introduction

The physicochemical properties of the near-wellbore zone in oil and gas reservoirs are governed by a combination of natural reservoir energy, pore–fracture architecture, mineral reactivity, and a wide range of processes that evolve during well operation. Because the condition of the near-wellbore zone directly affects both the initial production rate and the long-term performance of a well, it is essential to examine the underlying mechanisms separately for different reservoir types [1, 3, 9].

In heavy-oil reservoirs, severe flow retardation, increased capillary forces, and pressure depletion significantly reduce fluid mobility within the near-wellbore zone. Recent laboratory and field studies have shown that the application of an external electrical field can substantially soften rheological properties and decrease viscosity, thereby improving flow initiation and transport behavior [7]. Numerous investigations report reductions in viscosity, activation of dipole alignment, and decreases in threshold pressure gradients under electrical stimulation.

In carbonate reservoirs, chemical processes dominate. Acid–rock interaction alters the pore structure extensively, and the dissolution kinetics of calcite and dolomite, combined with the spatial heterogeneity of reactive surface area and transport phenomena, define the fundamental mechanisms of carbonate stimulation [4, 5, 11]. Wormhole development–evaluated through the Damköhler number and predictive channel-growth models–remains one of the most widely studied topics in carbonate acidizing [5].

In gas-condensate reservoirs, low-pressure conditions promote salt precipitation, ion exchange, and hydrate-related phenomena, which can sharply reduce near-wellbore permeability [6]. In formations containing dolomite and mixed carbonate–sulfate minerals, hydrochloric-acid treatments are affected by complex reaction equilibria, making the choice of reagent composition and treatment sequence particularly critical.

Therefore, this study examines three distinct directions of near-wellbore transformation:

1. the influence of electrical stimulation in heavy-oil reservoirs;
2. mathematical modeling of acid treatment in carbonate formations; and;

3. salt–acid interactions in gas-condensate reservoirs.

For each direction, field observations, laboratory measurements, and computational models are compared to develop a scientifically grounded basis for selecting stimulation strategies suited to different geological settings [9].

Materials

This study incorporates a set of data characterizing the physicochemical state of the near-wellbore zone across different reservoir types. The primary focus is directed toward: assessing the influence of electrical fields on heavy-oil reservoirs, modeling acid treatment processes in carbonate formations, and identifying distinctive salt–acid reaction mechanisms in gas-condensate reservoirs.

The obtained results were benchmarked against values reported in international literature [1–7, 9, 11, 12].

Laboratory and field measurements from heavy-oil reservoirs enabled the evaluation of rheological changes induced by electrical stimulation. Samples obtained from the "South Mirshadi" field exhibited notable reductions in viscosity, shifts in dielectric properties, and decreases in threshold pressure required to initiate flow, as summarized in Table 1. These observations are consistent with established results in electrorheological systems reported in the literature [7].

Table 1.

Viscosity variation of crude oil under different electrical field intensities

No.	Electrical field intensity, E (kV/m)	Initial viscosity μ_0 (mPa·s)	Final viscosity $\mu(E)$ (mPa·s)	Viscosity reduction $\Delta\mu(E)$, %
1	0	1520	1520	0.0%
2	5	1520	1340	11.8%
3	10	1520	1210	20.4%
4	12	1520	1180	22.4%
5	15	1520	1105	27.3%

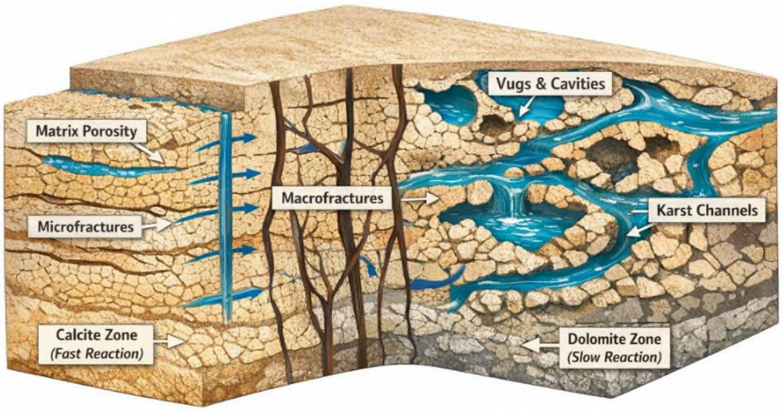

Figure 1. Structural model of carbonate reservoirs.

The materials used for the carbonate-reservoir investigation rely on field datasets obtained from operational studies and on internationally recognized research in carbonate stimulation [4, 5, 10–13]. Information on mineral composition and pore–fracture network architecture, schematically illustrated in Figure 1, formed the structural basis for the modeling efforts. The dissolution kinetics of calcite and dolomite were identified as primary controlling factors for stimulation effectiveness. Field observations on acid-injection rate, pressure response, wormhole evolution, and channel-length development, together with representative ion-composition data summarized in Table 2-3, were incorporated to validate the modeling results.

Table 2.

Major ion composition in gas-condensate reservoirs

Ion	Unit	Typical concentration range	Most representative value
Na^+	mg/L	18 000 – 62 000	41 500
K^+	mg/L	250 – 1 100	620

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Ca^{2+}	mg/L	450 – 2 900	1 750
Mg^{2+}	mg/L	80 – 1 150	540
Cl^{-}	mg/L	32 000 – 145 000	96 000
SO_4^{2-}	mg/L	0 – 120	10
HCO_3^{-}	mg/L	40 – 620	210
CO_3^{2-}	mg/L	0 – 15	2
Br^{-}	mg/L	50 – 220	130
I^{-}	mg/L	2 – 12	7
Total Dissolved Solids (TDS)	mg/L	60 000 – 230 000	148 000
pH	–	5,4 – 7,1	6,2
Density of formation water	g/cm³	1,10 – 1.24	1,18

Table 3.

Generalized parameters for the three reservoir types

Parameter	**Sandstone reservoirs**	**Carbonate reservoirs**	**Fractured–vuggy carbonate reservoirs**
Porosity, φ (%)	12–28	4–18	2–25 (highly heterogeneous)
Permeability, k (mD)	20–500	1–100	0.1–5 000 (dual/triple porosity)
Reservoir temperature, °C	40–95	55–120	60–150
Reservoir pressure, MPa	8–25	12–35	15–45 (often anomalous)
Dominant chemical composition	Quartz, feldspar, clay minerals	Calcite/dolomite	Calcite, dolomite, secondary minerals, karst-fill material
Major ionic content of formation water	Na^{+}, Ca^{2+}, HCO_3^{-} (mode-rate salinity)	Ca^{2+}, Mg^{2+}, HCO_3^{-} (carbonate buffering)	Cl^{-}, Na^{+}, Br^{-}, high TDS (deep basin brines)
Reaction–kinetic characteristics	Slow reaction with acids; $k = 10^{-6}–10^{-5}$	Moderate dissolution rates; $k = 10^{-4}–10^{-3}$	Fast heterogeneous dissolution; wormholing; $k = 10^{-3}–10^{-2}$
Energy-consumption indicator for stimulation (kWh per m³ treated)	0,5–1,5	1,0–3,5	2,5–7,0 (due to fracture–vug network)
Flow model	Matrix flow	Matrix + microfractures	Triple system: matrix + fractures + vugs
Stimulation efficiency sensitivity	Moderate	High	Very high (nonlinear response)

Data from gas-condensate reservoirs included ion-composition analyses, mineralization levels, and pH-variation profiles during reactions with hydrochloric-acid blends. Observations from the Shurtan gas–condensate complex revealed that the redistribution of Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^{-} ions significantly influenced the extent of the reactive zone expansion. Formations rich in dolomite and mixed carbonate–sulfate minerals showed an elevated risk of precipitation.

To facilitate comparison across reservoir types, additional datasets were collected, including baseline porosity and permeability values, reservoir temperature and pressure, chemical composition variations, reaction-kinetic parameters, and energy-consumption indicators [3, 5, 9]. These parameters play a crucial role in the comparative assessment framework applied in subsequent sections.

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Methods

The methodological framework adopted in this study enables a systematic comparison of the physicochemical processes occurring in three distinct reservoir types. For heavy-oil reservoirs, the impact of electrical stimulation was evaluated through laboratory measurements of viscosity and dielectric parameters under varying electric-field intensities. This approach is consistent with international studies on electrorheological systems and aims to quantify molecular polarization effects as field strength increases [7]. The measurements supported the determination of dielectric permittivity, polarization coefficients, and electrical conductivity of reservoir fluids and rock samples. These parameters served as input for the computational model describing the effect of electrical fields on heavy-oil flow behavior, in which the influence of electromagnetic fields on the system energy was described using

$$\Delta G^* = \Delta G_0 - \alpha E^2 - \beta B^2 \tag{1}$$

Where: ΔG^* – modified Gibbs free energy of the reaction under electromagnetic influence, J/mol; ΔG_0 – standard Gibbs free energy of the reaction at reservoir conditions, J/mol; E – electric field intensity, V/m; B – magnetic flux density, T; α – electric-field interaction coefficient (polarizability term), $J \cdot m^2/V^2$; β – magnetic-field interaction coefficient, J/T^2;

To assess rheological variations, time-dependent viscosity curves were constructed. A gradual viscosity decline with increasing electric-field intensity was observed, supporting the hypothesis that electrical stimulation alters reaction kinetics and molecular mobility. This behavior aligns with models describing reaction-rate modification in external electromagnetic fields [7]. For this purpose, the reaction-rate function k(E) was employed, as defined by equation (2).

$$k(E) = k_0 \exp\left[-\frac{E_a - \gamma E}{RT}\right] \tag{2}$$

Where: *k(E)* – reaction rate constant under electric-field influence, s^{-1}; k_0 – pre-exponential (frequency) factor, s^{-1} ; E_a – intrinsic activation energy of the reaction, J/mol; γ – electric-field activation coefficient (J·m/V), reflecting reduction of the activation barrier; E – applied electric field strength, V/m; R – universal gas constant (8.314 J/mol·K); T – absolute temperature, K.

Modeling acid treatment in carbonate formations utilized a classical reactive-transport approach that incorporates the heterogeneous pore structure of carbonate media. Experimental dissolution rates of calcite and dolomite were compared with field-derived datasets collected by Samatov Sh.Sh. [10]. The mathematical formulation was based on differential equations governing the spatial distribution of acid concentration and describing the coupling between reaction kinetics and advective–diffusive transport processes, as expressed by equation (3). This method is widely applied in studies on carbonate stimulation and wormhole formation [4, 5].

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} = -k_r C \tag{3}$$

Where: C – concentration of the reacting species (mol/m^3); t – time (s); x – spatial coordinate along the flow path (m); v – linear flow velocity in the porous medium (m/s); k_r – reaction rate constant (s^{-1}), which in EIAHGT can depend on electric-field-modified kinetics

Evaluation of acid-treatment efficiency relied on the Damköhler number, which compares reaction rate to the characteristic transport timescale. This dimensionless parameter, defined by equation (4), is essential for determining the likelihood and morphology of wormhole formation [4, 5].

$$D_a = \frac{k_r L}{v} \tag{4}$$

Where: D_a – Damköhler number (dimensionless), characterizing the ratio of reaction rate to transport rate; k_r – reaction rate constant (s^{-1}); L – characteristic length of the reaction zone (m);
v – linear flow velocity in the reservoir (m/s).

For gas-condensate reservoirs, the analysis considered ion-exchange processes, salt-precipitation mechanisms, and abrupt pH shifts. Field measurements from the Shurtan gas–condensate complex were used to quantify the behavior of Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^- ions under reactive conditions. Precipitation mechanisms were compared with those reported in international

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gas-well studies [6]. A functional relationship was employed to evaluate precipitation propensity as a function of ion concentration, pH, and temperature, as expressed by equation (5).

$$S = f\,(C_{ion}, pH, T) \quad (5)$$

Where: S – solubility of mineral/reactant in the formation fluid (mol/L or g/L); C_{ion} – ionic composition of the solution (e.g., Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-); pH – acidity of the fluid; T – temperature (K or °C).

Through these methodological components, the physicochemical behavior of the three reservoir types was examined and compared, providing a structured basis for the subsequent Results and Analysis section.

Results and Analysis

Laboratory investigations demonstrated that the application of an external electrical field in heavy-oil reservoirs directly influences the initiation and development of fluid flow. One of the most stable observations was a progressive decrease in viscosity as field intensity increased, indicating the weakening of intermolecular interactions. These findings are consistent with international electrorheological studies [7]. The viscosity reduction led to a corresponding decline in threshold pressure required for flow initiation, resulting in enhanced near-wellbore permeability. This effect was further reinforced by localized thermal elevation associated with energy exchange under electrical stimulation; even minor temperature increases were found to accelerate rheological softening

In carbonate reservoirs, numerical modeling provided deeper insight into the spatial distribution of acid and the temporal evolution of dissolution patterns. The heterogeneous structure of carbonate formations produced non-uniform acid penetration, particularly within fracture-dominated or highly porous intervals. Model outputs indicated that wormhole formation proceeded through three major developmental phases: (1) initial surface dissolution, (2) moderate channel propagation, and (3) accelerated deep penetration, schematically illustrated in Figure 2. These findings correspond well with the theoretical models established in the Fogler and Kovscek schools [5]. The quantitative relationship between reaction–transport conditions and the intensity of channel development was further evaluated using the Damköhler number, as illustrated in Figure 3.

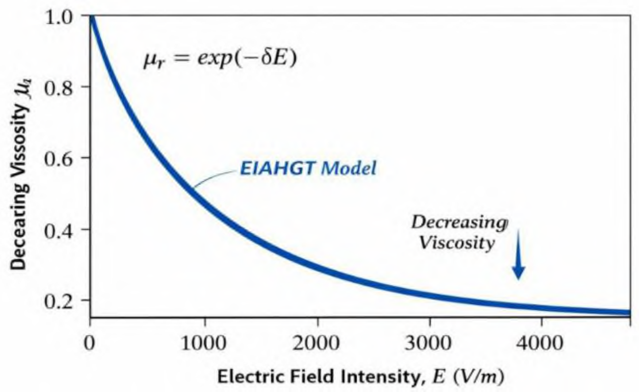

Figure 2. Relative viscosity variation as a function of electric-field intensity.

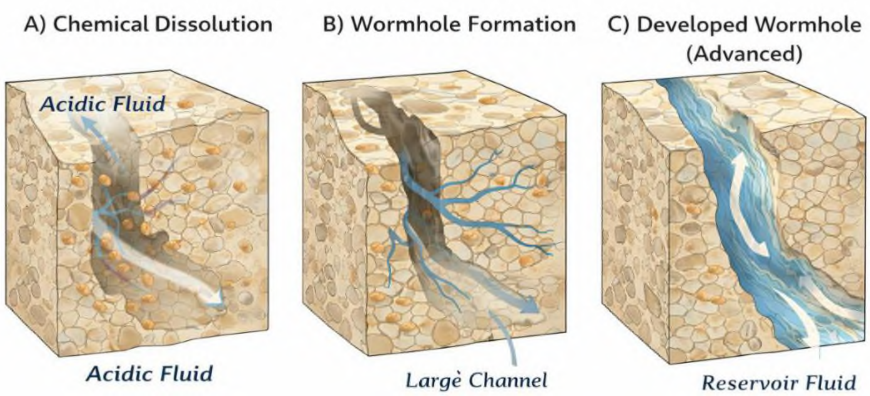

Figure 3. Stages of wormhole development in carbonate reservoirs.

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The influence of the Damköhler number was validated as a key determinant of carbonate-stimulation outcomes, as illustrated in Figure 4. In regions where Da exceeded unity, the process was controlled primarily by reaction kinetics, leading to rapid wormhole formation. Conversely, in areas where Da was low, mass-transport limitations dominated, resulting in slow acid penetration. Comparative evaluation of model predictions with field data from the Matonat and Western Kruk fields confirmed strong agreement in terms of channel length, diameter, and required acid volume [10–12].

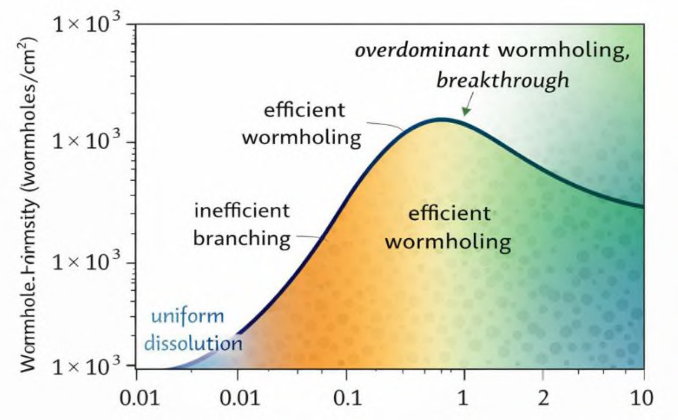

Figure 4. Correlation between Damköhler number and wormhole-formation intensity.

Analysis of gas-condensate reservoirs revealed that hydrochloric-acid treatments are constrained by complex reaction equilibria that evolve rapidly under low-pressure conditions. Accelerated redistribution of Ca^{2+} and Mg^{2+} ions intensified precipitation processes, especially in formations with elevated mineralization. Sharp variations in pH significantly increased the probability of salt deposition, which is known to reduce near-wellbore permeability over short operational intervals, as illustrated in Figure 5.

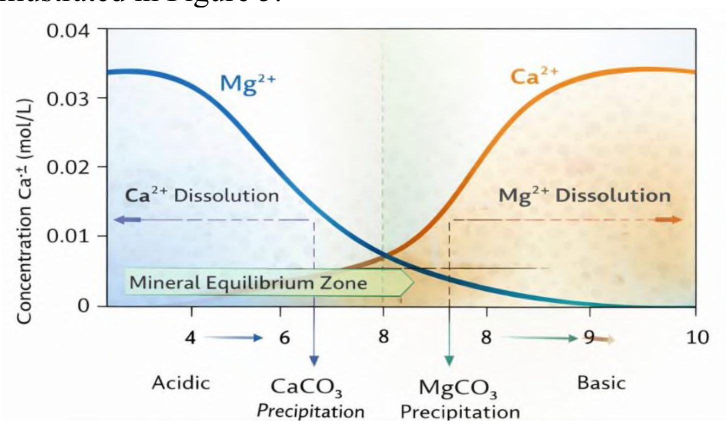

Figure 5. Relationship between pH variation and Ca^{2+}–Mg^{2+} redistribution".

Dolomite-rich formations exhibited slower reaction rates and limited effectiveness of hydrochloric-acid blends. Ion-exchange intensity and differing mineral reactivity reduced stimulation depth and efficiency. Comparative analysis showed that salt–acid systems can restore near-wellbore conductivity in the short term but require careful application where ion migration is high, as summarized in Table 4 [6].

Table 4.

Comparative summary of mechanisms across three reservoir types

Mechanism / Property	Sandstone Reservoirs	Carbonate Reservoirs	Fractured–Vuggy Carbonate Reservoirs
Dominant flow mechanism	Matrix flow	Matrix + microfractures	Triple flow system: matrix + fractures + vugs
Primary pore structure	Intergranular porosity	Intercrystalline & dissolution porosity	Cavernous, karstic, frac-ture-enhanced porosity
Heterogeneity level	Low–moderate	High	Very high (multi-scale)

Reaction mechanism during acidization	Surface-limited dissolution	Conical dissolution + wormholing	Rapid wormhole propagation, breakthrough effects
Sensitivity to pH	Moderate (mainly silica dissolution)	High (calcite/dolomite dissolution kinetics)	Very high (karst channels rapidly develop)
Dominant mineral dissolution	Quartz, feldspars (slow kinetics)	Calcite/dolomite (fast–moderate kinetics)	Calcite-dominated fast dissolution + Mg redistribution
Energy requirement for stimulation	Low	Moderate	High (due to need for deep wormhole penetration)
Impact of electric-field (E-field) stimulation	Low (weak electro-rheological response)	Moderate (viscosity reduction + enhanced dissolution)	Strong (amplified wormholing + increased Da + rapid reactivity)
Damköhler number behavior	Typically Da < 0.1	Da ≈ 0.1–1	Da > 1 (efficient wormholing regime)
Resulting stimulation pattern	Uniform displacement improvements	Selective wormhole development	Large-scale breakthrough wormholes; non-linear enhancement

Across all three reservoir types, a common observation was the existence of reservoir-specific dominant mechanisms controlling near-wellbore transformation. The nature of flow development differed substantially: in heavy-oil reservoirs, physical mechanisms dominated; in carbonate reservoirs, reactive transport processes were key; and in gas-condensate reservoirs, chemical-equilibrium shifts dictated treatment outcomes.

The collective results indicate that no universal stimulation technology exists for all reservoir conditions. Each reservoir type requires tailored stimulation strategies that consider geological heterogeneity, mineral composition, and fluid–rock interactions; otherwise, treatment efficiency may decline or remain short-lived [9].

Conclusions

This study provides a comprehensive evaluation of the physicochemical processes governing near-wellbore transformation across three major reservoir types. Based on the obtained laboratory evidence, field observations, and numerical modeling, the following key conclusions were drawn:

1. In heavy-oil reservoirs, electrical stimulation significantly softens rheological properties within the near-wellbore zone.

A marked reduction in viscosity led to lower threshold pressure gradients and enhanced permeability. This behavior was driven by changes in dielectric characteristics and localized thermal effects, confirming the practical value of electrical stimulation for heavy-oil reservoir applications [7].

2. In carbonate reservoirs, modeling revealed the complex kinetics of acid–rock interaction and the mechanisms of wormhole development.

Acid penetration depth, Damköhler-number variability, pore–fracture heterogeneity, and localized dissolution pathways were identified as the principal controls on stimulation efficiency. Strong agreement between modeling results and field data highlights the necessity of reservoir-specific optimization strategies [4, 5, 13].

3. In gas-condensate reservoirs, hydrochloric-acid treatments are constrained by rapid ion redistribution and salt-precipitation processes under low pressure.

Accelerated crystallization of Ca^{2+} and Mg^{2+} salts, influenced by mineralogical composition and pH instability, can rapidly impair near-wellbore permeability. Treatment performance depends heavily on fluid chemistry and mineral reactivity [10, 13].

4. Near-wellbore transformation mechanisms differ fundamentally among the three reservoir types. Physical processes dominate in heavy oils, reactive transport governs carbonate stimulation, and chemical-equilibrium shifts control treatment outcomes in gas-condensate formations. These distinctions emphasize the necessity of aligning stimulation techniques with reservoir-specific geological and fluid properties [9].

Practical Recommendations. Based on the findings, the following practical guidelines are proposed:

For heavy-oil reservoirs:

1. Determine the optimal electrical-stimulation regime for each reservoir.
2. Establish reservoir-specific ranges for electric-field intensity (E_{opt}).
3. Monitor local temperature increases to avoid overheating and potential sand production.
4. Implement continuous monitoring of dielectric parameters during treatment.

For carbonate reservoirs:

1. Optimize acid consumption based on the Damköhler number.
2. For Da > 1 zones, use modified or retarded acid systems to promote deep wormhole formation.
3. For Da < 1 zones, apply diffusion-enhancing additives to improve reactant transport.
4. Employ in-situ tracers to estimate actual penetration depth and validate model predictions.

For gas-condensate reservoirs:

1. Utilize pH-control additives to reduce precipitation risks.
2. Add ion-stabilizing agents to hydrochloric-acid blends to prevent early permeability loss.
3. Apply inhibitors to lower Ca^{2+} and Mg^{2+} redistribution rates.
4. Model reaction equilibria under CO_2-rich and low-pressure conditions to anticipate precipitation.

General recommendation:

No universal stimulation technology is applicable across all reservoir types. Each formation requires a differentiated stimulation strategy based on lithology, mineralogy, pressure–temperature conditions, and fluid composition. Hybrid stimulation approaches–especially combined electrical–chemical methods–represent a promising direction for improving treatment efficiency in complex reservoirs.

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