

**MODELING HYDROCHLORIC ACID STIMULATION IN
CARBONATE RESERVOIRS BY ACCOUNTING FOR
NEAR-WELLBORE GEOLOGICAL HETEROGENEITY**

Gayrat Abdiraimovich Khushvaqtov

Karshi, Uzbekistan

gayratxushvaqtov2210@gmail.com

Sherzod Shavkatovich Samatov

Karshi, Uzbekistan

sh.sh.samatov@gmail.com

ABSTRACT. Carbonate reservoirs often show uneven response to hydrochloric acid (HCl) stimulation because the near-wellbore zone is geologically heterogeneous and contains permeability streaks, fractures, vugs, and mineralogical contrasts that redirect flow and concentrate dissolution. Such preferential flow can trigger early dominant wormholes in high-conductivity sub-volumes while leaving other intervals under-stimulated. This paper presents a practical reactive-transport modeling workflow that explicitly integrates near-wellbore heterogeneity into matrix acidizing design. The workflow couples single-phase flow, acid transport, and mineral dissolution with dynamic updates of porosity and permeability, and uses dimensionless groups (Damkyuler and Pekle numbers) alongside pore volumes to breakthrough (PVBT) as efficiency metrics; PVBT is widely used as an indicator of acid volume required to achieve a conductive dissolution path. The approach supports scenario screening (layered vs fractured vs vuggy near-

wellbore structures), sensitivity analysis, and optimization of injection rate and acid schedule to improve volumetric coverage and skin reduction.

KEYWORDS: *carbonate acidizing; near-wellbore zone; geological heterogeneity; reactive transport; PVBT; wormholes; Damkyuler; Pekle; skin.*

INTRODUCTION

Matrix acidizing with hydrochloric acid is a standard stimulation method in carbonate reservoirs because dissolution can create highly conductive channels (“wormholes”) that bypass near-wellbore damage and enhance productivity. Classic field and laboratory evidence shows that acid–carbonate reaction kinetics and mass transfer strongly control dissolution patterns and, ultimately, stimulation performance. At the same time, the near-wellbore zone is rarely uniform: thin high-permeability streaks, localized fractures, and vuggy porosity can dominate flow, leading to premature breakthrough along a limited fraction of the treated interval, reduced coverage, and inconsistent well-to-well results.

Reactive-transport modeling has become a primary tool to analyze wormhole growth and acid placement. In particular, two-scale continuum (TSC) and related Darcy-scale formulations are widely used to simulate carbonate acidizing by coupling flow, transport, and reaction while representing dissolution-driven property evolution. Furthermore, domain geometry and heterogeneity can constrain wormhole competition and affect growth dynamics, implying that near-wellbore geological realism matters for prediction and design.

PROBLEM STATEMENT AND OBJECTIVES

Problem: Many design calculations assume a homogeneous near-wellbore zone or use averaged rock properties. In heterogeneous carbonates, such averaging can mispredict (i) the injection rate window for efficient wormholing, (ii) the acid volume needed to reach target radius, and (iii) the distribution of stimulation effectiveness across layers/intervals.

Objective: Develop an engineering workflow for modeling carbonate HCl matrix acidizing while explicitly accounting for near-wellbore geological heterogeneity, using:

- a coupled flow–transport–reaction model with dynamic porosity/permeability update,
- PVBT as a treatment efficiency metric, and sensitivity/optimization loops to improve coverage and reduce skin.

MODELING WORKFLOW AND GOVERNING EQUATIONS

1. Geological heterogeneity model of the near-wellbore zone

Represent heterogeneity at the scale relevant to stimulation decisions (decimeters to meters):

Layering / streaks: $k(r, \theta, z)$, $\phi(r, \theta, z)$ from logs/core-based facies.

Fractures: discrete fractures (DFN) or equivalent permeability tensor k .

Vugs / karst features: dual-porosity/dual-permeability or explicit high- ϕ inclusions.

Mineralogy contrasts: spatially varying calcite/dolomite fractions affecting reaction rate.

A practical approach is to build a **near-wellbore sector model** (radial-angular-vertical) and populate properties using geostatistics constrained by core, image logs, and production history, then refine around perforations/intervals.

2. Flow model (single-phase)

Assume slightly compressible aqueous phase during pumping (acid + brine). The Darcy (Darsi) velocity:

$$u = -\frac{k}{\mu} \nabla p \quad (1)$$

Mass conservation:

$$\frac{\partial(\phi\rho)}{\partial t} + \nabla \cdot (\rho u) = q_m \quad (2)$$

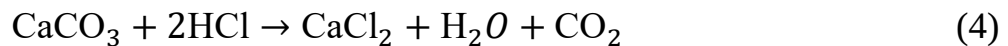
where k is permeability tensor, μ viscosity, p pressure, ρ density, and q_m is mass source/sink.

3. Acid transport and reaction

Transport of acid species (e.g., C_a for HCl equivalent concentration):

$$\frac{\partial(\phi C_a)}{\partial t} + \nabla \cdot (u C_a) = \nabla \cdot (\phi D \nabla C_a) - R(C_a, T, \text{mineralogy}) \quad (3)$$

A common overall dissolution reaction for calcite:



Reaction term:

$$R = a_s \cdot k_r(T) \cdot f(C_a) \cdot g(\text{mineral fraction}) \quad (5)$$

where a_s is reactive surface area per bulk volume, k_r kinetic rate constant.

4. Porosity and permeability evolution

Mineral dissolution increases porosity:

$$\frac{\partial \phi}{\partial t} = \left(\frac{1}{\rho_s} \right) \cdot v \cdot R \quad (6)$$

A common closure links permeability to porosity (choose/calibrate per rock type):

$$k = k^0 \left(\frac{\phi}{\phi^0} \right)^n \quad (7)$$

where n is calibrated from coreflood or micro-CT diagnostics when available.

5. Dimensionless diagnostics: Damkyuler, Pekle, and PVBT

Use dimensionless numbers to interpret regimes:

Damkyuler (Da): ratio of reaction to transport time scales.

Pekle (Pe): ratio of advective to diffusive transport.

Treatment-efficiency metric:

PVBT (pore volumes to breakthrough): the injected pore volume required to form a through-going conductive dissolution path; smaller PVBT typically indicates less acid volume needed for effective channel creation.

6. Numerical solution strategy

A practical engineering implementation:

discretize Eqs. (2)–(7) with a finite-volume scheme on a near-wellbore grid;

apply operator splitting per timestep: pressure → velocity → transport
→ reaction → property update;
stabilize high-Pe transport with flux limiters;
treat strong reaction nonlinearity with implicit or semi-implicit updates.

RESULTS AND DISCUSSION

Why heterogeneity changes the “optimal rate” window

In homogeneous cores, PVBT often shows a non-monotonic trend with injection rate, producing an optimal window for wormholing efficiency. In heterogeneous near-wellbore volumes, simulations typically show:

Early channeling in high-k streaks/fractures → PVBT may appear favorable locally, but coverage is poor across the interval.

Shift of optimum rate: the rate that minimizes PVBT in an averaged model may over-favor fast breakthrough in a streaked model, requiring additional stages/diversion to stimulate low-k sub-volumes.

Geometry/structure control

If the near-wellbore zone contains connected high-conductivity features, wormhole competition is constrained by geometry and boundary conditions, changing growth dynamics and pattern selection.

Practical design outputs from the workflow

The proposed modeling workflow produces directly actionable outputs:
Predicted stimulated radius vs. acid volume (per layer/interval),
PVBT vs. rate curves under heterogeneous scenarios,
Skin reduction estimates (from post-treatment effective permeability around the well),

Coverage maps highlighting under-stimulated sub-volumes,

Sensitivity ranking: which uncertainty (fracture connectivity, streak contrast, mineralogy, temperature) drives the design.

CONCLUSIONS

1. Near-wellbore geological heterogeneity can dominate acid placement, causing preferential flow and uneven dissolution; ignoring it can mispredict treatment efficiency and coverage.

2. A coupled reactive-transport model with dynamic porosity/permeability updates provides a consistent framework to simulate carbonate HCl matrix acidizing under heterogeneous near-wellbore conditions.

3. PVBT is a practical efficiency metric for screening designs and comparing scenarios, but it should be complemented with coverage-based indicators in heterogeneous intervals.

4. Dimensionless diagnostics (Damkyuler, Pekle) help interpret regime shifts and explain why “optimal rate” windows move when heterogeneity is introduced.

5. Heterogeneity-aware simulations support design optimization (rate, stages, and interval strategy) to improve volumetric stimulation and reduce skin.

NOMENCLATURE

φ porosity; k permeability; $\mathbf{k}$ permeability tensor; μ viscosity; p pressure; ρ density; u Darcy velocity; C_a acid concentration; D dispersion/diffusion tensor; R reaction rate; PVBT pore volumes to breakthrough; Da Damkyuler number; Pe Pekle number.

REFERENCES

[1] G. A. Axatova, Sh. Sh. Samatov, and G. Ch. Jo‘rayeva, “Karbonat kollektorlarda kislotali ishlov berish samaradorligini quduq atrofi zonasining

geologik tuzilishi bilan uyg'un modellashtirish [Integrated modeling of carbonate acidizing efficiency with near-wellbore geological structure],” *Ta'lim Innovatsiyasi va Integratsiyasi*, vol. 54, no. 1, pp. 217–222, 2025.

[2] C. E. Cohen, D. Ding, M. Quintard, and B. Bazin, “From pore scale to wellbore scale: Impact of geometry on wormhole growth in carbonate acidization,” *Chemical Engineering Science*, vol. 63, pp. 3088–3099, 2008, doi: 10.1016/j.ces.2008.03.021.

[3] A. Y. Dustov and Sh. Sh. Samatov, “Bir jinsli bo'lmagan muhitda kislotali ishlovni modellashtirish va optimallashtirish [Modeling and optimization of acid stimulation in a heterogeneous medium],” in *Proc. Republican Scientific-Practical Conf. “Zamonaviy texnologiyalar va barqaror rivojlanish: muammolar va yechimlar”*, Fergana, Uzbekistan, Sep. 17–18, 2025, pp. 325–328.

[4] N. X. Ermatov, Sh. Sh. Samatov, and G. Ch. Jo'rayeva, “Karbonat kollektorlarida kislotali ishlov berish jarayonining geologik xususiyatlarni hisobga olgan holda modellashtirilishi [Modeling acid stimulation in carbonate reservoirs considering geological features],” in *Proc. Republican Scientific-Practical Conf. “Raqamli sanoat va avtomatlashtirish: texnologik jarayonlar va ishlab chiqarishni boshqarish tizimlarida innovatsion yechimlar”*, Qarshi, Uzbekistan, Apr. 18–19, 2025, pp. 165–170.

[5] N. X. Ermatov, Sh. Sh. Samatov, and U. S. Bozorov, “Damkyuler soni asosida karbonat kollektorlarning kislotali ishlov jarayonini modellashtirish (Matonat va G'arbiy Kruk konlari misolida) [Modeling carbonate acidizing based on the Damkyuler number: Matonat and G'arbiy Kruk fields],” in *Proc. 4th Int. Conf. “Yashil iqtisodiyot va raqamlashtirish davrida neft va gaz*

sanoatini rivojlantirishning zamonaviy tendensiyalari”, Tashkent, Uzbekistan, Oct. 30–31, 2025, pp. 103–104.

[6] N. X. Ermatov, Sh. Sh. Samatov, M. M. Boyqobilova, and G. A. Axatova, “Karbonat kollektorlarga kislotali ishlov berishni modellashtirish (Matonat va Gʻarbiy Kruk konlari misolida) [Modeling acid stimulation in carbonate reservoirs: Matonat and Garbiy Kruk fields],” *Innovatsion texnologiyalar*, no. 3(59), pp. 7–15, 2025.

[7] P. Liu, X. Ren, L. Kong, and J. Yao, “Three-dimensional simulation of acidizing process in carbonate rocks using the Darcy–Forchheimer framework,” *Oil & Gas Science and Technology – Revue d’IFP Energies nouvelles*, vol. 75, Art. no. 48, 2020, doi: 10.2516/ogst/2020035.

[8] P. Liu, X. Yan, J. Yao, and S. Sun, “Numerical simulation of the wormhole propagation in carbonate reservoir acidizing considering coupled rock mechanics,” *Water*, vol. 14, no. 24, Art. no. 4117, 2022, doi: 10.3390/w14244117.

[9] S. Lohrasb and R. Junin, “Pore volumes to breakthrough estimation in carbonate acidizing with hydrochloric acid by using an analytical derivation method,” *Petroleum*, vol. 6, no. 4, pp. 362–367, 2021, doi: 10.1016/j.petlm.2019.08.001.

[10] D. E. Nierode and B. B. Williams, “Characteristics of acid reaction in limestone formations,” *SPE Journal*, vol. 11, no. 4, pp. 406–418, 1971, doi: 10.2118/3234-PA.

[11] Sh. Sh. Samatov and L. K. Xayitov, “Karbonat kollektorlarda kislotali ishlov berishning geologik asoslangan modellashtirilishi [Geologically grounded modeling of carbonate acid stimulation],” in *Proc. Int. Scientific-*

Practical Conf. “Kimyoviy texnologiyada texnik–iqtisodiy muammolarning zamonaviy yechimlari”, Qo‘qon, Uzbekistan, Oct. 31, 2025, pp. 181–184.

[12] Sh. Sh. Samatov, L. K. Hayitov, and G. Ch. Jo‘rayeva, “Karbonat kollektorlarida quduq atrofi zonasiga kislotali ishlov berishni modellashtirish [Modeling acid stimulation in the near-wellbore zone of carbonate reservoirs],” in *Proc. 10th Int. Scientific-Practical Conf. “Ijodkor yoshlar va innovatsion taraqqiyot”*, Bukhara, Uzbekistan, Jun. 10–11, 2025, pp. 229–237.

[13] Sh. Sh. Samatov and S. I. Maxmudov, “Optimization of acidizing in carbonate reservoirs with explicit account of near-wellbore geological structure and hydrodynamic conditions,” *Universum: Technical Sciences (electronic scientific journal)*, no. 10(139), pp. 45–49, 2025. [Online]. URL: <https://7universum.com/ru/tech/archive/item/20968>

[14] Sh. Sh. Samatov, “Qudug atrofı zonasıning geologik tuzilishini inobatga olgan holda karbonat kollektorlarga kislotali ishlov berishni modellashtirish [Modeling acid stimulation of carbonate reservoirs accounting for near-wellbore geological structure],” in *Proc. Scientific-Practical Conf. “O‘zbekistonning innovatsion taraqqiyotida yoshlarning o‘rni”*, Qarshi, Uzbekistan, Jun. 17–18, 2025, pp. 78–81.

[15] Sh. Sh. Samatov, “Qudug atrofı zonasıning geologik tuzilishini inobatga olgan holda karbonat kollektorlarga kislotali ishlov berishni modellashtirishning nazariy asoslari [Theoretical foundations for modeling carbonate acid stimulation accounting for near-wellbore geological structure],” in *Proc. Int. Scientific-Practical Conf. “Kimyoviy texnologiyada texnik–iqtisodiy muammolarning zamonaviy yechimlari”*, Qo‘qon, Uzbekistan, Oct. 31, 2025, pp. 185–188.