ACID STIMULATION TECHNOLOGY FOR RESERVOIR FORMATIONS TO GRADUALLY INCREASE PRODUCTION IN SMALL GAS FIELDS.

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ABSTRACT. Carbonate reservoirs often respond inconsistently to hydrochloric acid treatments because near-wellbore heterogeneity causes preferential flow and uneven dissolution. This paper proposes an integrated design workflow that combines (i) laboratory indicators of wormhole efficiency expressed through pore volumes to breakthrough (PVBT), (ii) micro-CT–based quantitative diagnostics of pore-space restructuring, and (iii) selection logic for self-diverting acid systems to expand coverage across intervals. The workflow is synthesized from open Russian-language sources and is illustrated using published coreflood results obtained at formation temperature and pressure, where both acid concentration and injection rate affect breakthrough volumes and wormhole geometry [1]. PVBT calculations are demonstrated using reported pore volumes and breakthrough acid volumes; the resulting trends show that minimal 15% HCl-equivalent consumption may occur at lower acid concentrations for a fixed rate, while the PVBT-rate dependence is non-monotonic and features an optimum pumping window [2]. Micro-CT metrics provide an objective diagnostic layer for validating whether stimulation created through-going dissolution features rather than only local caverns. Finally, the manuscript explains when viscoelastic-surfactant (VES) self-diverting acids are justified to mitigate channeling and improve treatment uniformity [3].

KEYWORDS: carbonate reservoir; acidizing; wormholes; PVBT; micro-CT; diversion; viscoelastic surfactants; near-wellbore zone; Damkyuler number

АННОТАЦИЯ. Карбонатные коллекторы нередко демонстрируют нестабильный отклик на обработки соляной кислотой (HCl), поскольку гетерогенность околоскважинной зоны приводит к преимущественному течению и неравномерному растворению. В статье предложен интегрированный рабочий процесс проектирования, объединяющий: (i) лабораторные индикаторы эффективности формирования «червоточин», выраженные через число поровых объёмов до прорыва (PVBT), (ii) количественную диагностику перестройки порового пространства на основе микро-КТ (micro-CT), и (iii) логику выбора самоотклоняющихся (self-diverting) кислотных систем для расширения охвата по интервалам. Подход синтезирован по открытым источникам и проиллюстрирован опубликованными результатами фильтрационных экспериментов на керне при пластовых температуре и давлении, где как концентрация кислоты, так и темп закачки влияют на объём до прорыва и геометрию «червоточин» [1]. Расчёты PVBT выполнены по опубликованным поровым объёмам и объёмам кислоты до прорыва; полученные тенденции показывают, что минимальный расход в пересчёте на эквивалент 15% HCl может достигаться при более низких концентрациях кислоты при фиксированном темпе, тогда как зависимость PVBT от темпа является немонотонной и характеризуется наличием оптимального «окна» закачки [2]. Метрики микро-КТ обеспечивают объективный диагностический слой для валидации того, что обработка сформировала сквозные каналы растворения, а не только локальные каверны. В заключение поясняется, в каких случаях применение самоотклоняющихся кислот на основе вязкоупругих ПАВ (VES) обосновано для снижения каналирования и повышения равномерности обработки [3].

КЛЮЧЕВЫЕ СЛОВА: карбонатный коллектор; кислотная обработка; червоточины; PVBT; микро-КТ; диверсия; вязкоупругие ПАВ (VES); околоскважинная зона; число Дамкулера

INTRODUCTION

Hydrochloric acidizing in carbonate formations aims to create highly conductive dissolution channels (wormholes) that reconnect the wellbore with undamaged rock. In heterogeneous carbonate reservoirs, acid preferentially invades the most conductive paths, limiting volumetric coverage and making the outcome sensitive to pumping schedule, fluid design, and the evolving condition of the near-wellbore zone [2,4]. Consequently, modern laboratory work emphasizes identifying the operational window that produces long, weakly branched wormholes with minimal acid consumption rather than simply maximizing reaction intensity [5].

Two recurring limitations reduce predictability in practice. First, some field-scale workflows represent acidizing primarily via a skin-factor reduction or a productivity multiplier, which can be insufficient for long horizontal intervals where stimulation effects vary spatially [4]. Second, many operations lack objective diagnostics of pore-space transformation; micro-CT makes it possible to quantify pore-space restructuring and through-going features, especially for complex carbonate collectors and low-permeability samples [1].

MATERIALS AND METHODS

The manuscript synthesizes ten open sources that complement one another: reservoir-condition coreflood data on acid concentration and injection rate effects [2], micro-CT evaluation of wormholes in complex carbonate collectors [1], representative modeling studies linking regime selection to transport–reaction competition (Damkyuler-type control) [6-10], and publications describing VES-based self-diverting acids and their application criteria [5].

A. Efficiency metrics (PVBT and 15% HCl-equivalent)

We compute pore volumes to breakthrough (PVBT) as:

$$PVBT = \frac{V_{acid,bt}}{PV_{core}} \qquad (1)$$

To compare different acid strengths on a common basis, we also use the 15% HCl-equivalent breakthrough volume:

$$PVBT_{15eq} = \frac{V_{acid,bt}^{15eq}}{PV_{core}} \quad (2)$$

B. Field-scale bridge (skin-factor abstraction)

When a field simulator uses a skin-factor representation, the productivity index ratio can be expressed as:

$$\frac{J}{J_0} = \frac{\ln\frac{r_e}{r_w} + s_0}{\ln\frac{r_e}{r_w} + s} \quad (3)$$

C. Dimensionless control (Damkyuler-type similarity)

Reactive-transport modeling commonly uses a Damkyuler-type group that captures the competition between reaction and transport; this similarity helps interpret optimal regimes and scale laboratory outcomes to field settings [6]. We retain a generic form:

$$Dam \sim \frac{k\ a_s\, L}{u} \quad (4)$$

RESULTS

Core parameters used for PVBT calculations

Table 1 reproduces a subset of reported core parameters used in reservoir-condition wormholing experiments [2].

Sample No.	Stratum	Depth (m)	Length (cm)	Sample volume (cm³)	Pore volume PV (cm³)	Porosity (%)	Gas perm (mD)
88	B	4528.97	3.83	42.7	5.89	13.8	2.65
90	B	4530.15	3.51	38.98	6.03	15.5	2.75
102	B	4532.24	3.59	39.77	5.31	13.3	3.38

124	D	4596.37	3.19	35.49	5.53	15.6	7.25
131	D	4597.45	3.36	36.36	5.93	16.3	9.14
135	D	4597.78	3.46	38.26	6.31	16.5	10.1

Table 1. Core sample parameters used in reservoir-condition wormholing experiments (subset) [2].

Acid concentration effect at fixed injection rate

Using reported breakthrough volumes and 15% HCl-equivalent volumes, Table 2 presents computed PVBT and $PVBT_{15eq}$ values [2]. In the shown examples, $PVBT_{15eq}$ increases with concentration in stratum B at a fixed nominal rate, illustrating that higher acid strength does not necessarily minimize 15%-equivalent consumption at breakthrough.

Sample	**Stratum**	**Acid conc. (%)**	**Rate (cm³/min)**	**PV (cm³)**	**Vbt (cm³)**	**PVBT**	**V_{bt15eq} (cm³)**	**$PVBT_{15eq}$**
88	B	5	0.090	5.890	3.500	0.594	1.167	0.198
90	B	10	0.090	6.030	2.500	0.415	1.667	0.276
102	B	15	0.090	5.310	2.000	0.377	2.000	0.377
124	D	5	0.090	5.530	3.000	0.542	1.000	0.181
131	D	10	0.092	5.930	2.250	0.379	1.500	0.253
135	D	15	0.090	6.310	1.500	0.238	1.500	0.238

Table 2. PVBT calculations for acid concentration tests (computed from reported breakthrough volumes) [2].

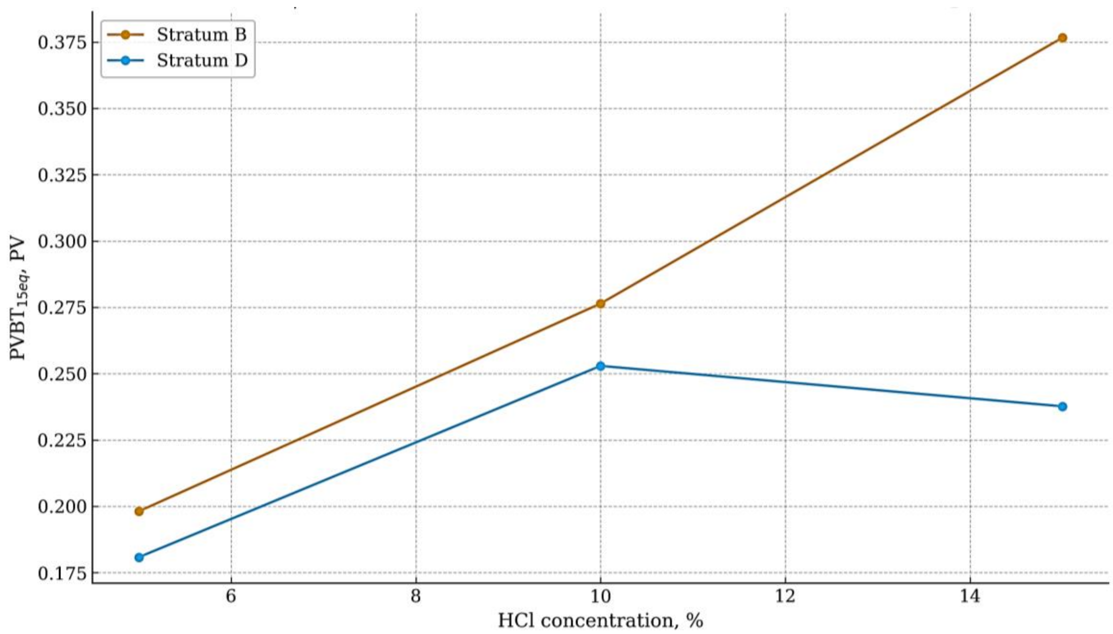

Figure 1. $PVBT_{15eq}$ vs HCl concentration (reservoir-condition coreflood examples) [2].

Injection rate effect at 15% HCl (non-monotonic PVBT)

Figure 2 summarizes computed PVBT values versus injection rate for 15% HCl examples reported under reservoir conditions [2]. The dependence is non-monotonic, consistent with the existence of an optimum pumping window that minimizes acid volume at breakthrough.

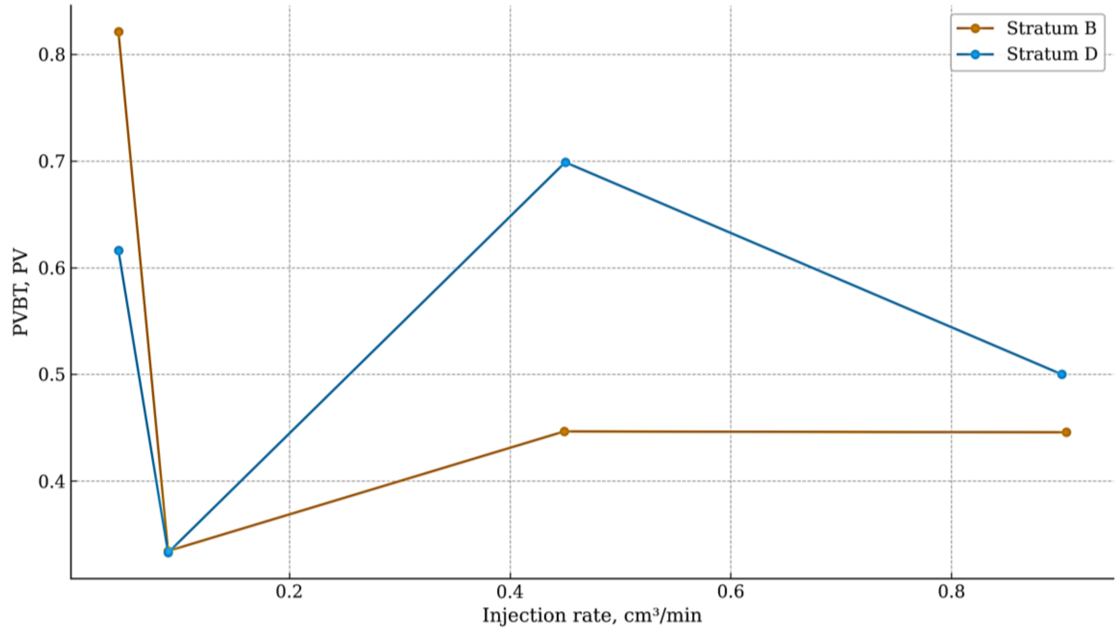

Figure 2. PVBT vs injection rate for 15% HCl examples (non-monotonic behavior) [2].

Micro-CT diagnostics: quantifying pore-space restructuring

Micro-CT analysis provides quantitative evidence of pore-space restructuring after hydrochloric acidizing. Table 3 reports example metrics (pore count, specific surface, pore volume fraction, and pore size range) before and after treatment [1].

Metric	Before	After
Pore count N_p (pcs)	761	2828
Specific surface S_p (mm^2/mm^3)	2.86	17.40
Pore volume fraction K_p (%)	0.04	0.45
Pore density P_{pl} (pcs/mm^3)	18	65
Max pore size $d_{p,max}$ (µm)	129.0	566.9

Table 3. Example micro-CT pore-space metrics before/after acidizing (reported values) [1].

Figure 3 shows relative changes (After/Before) for selected micro-CT metrics, highlighting how diagnostics complement PVBT.

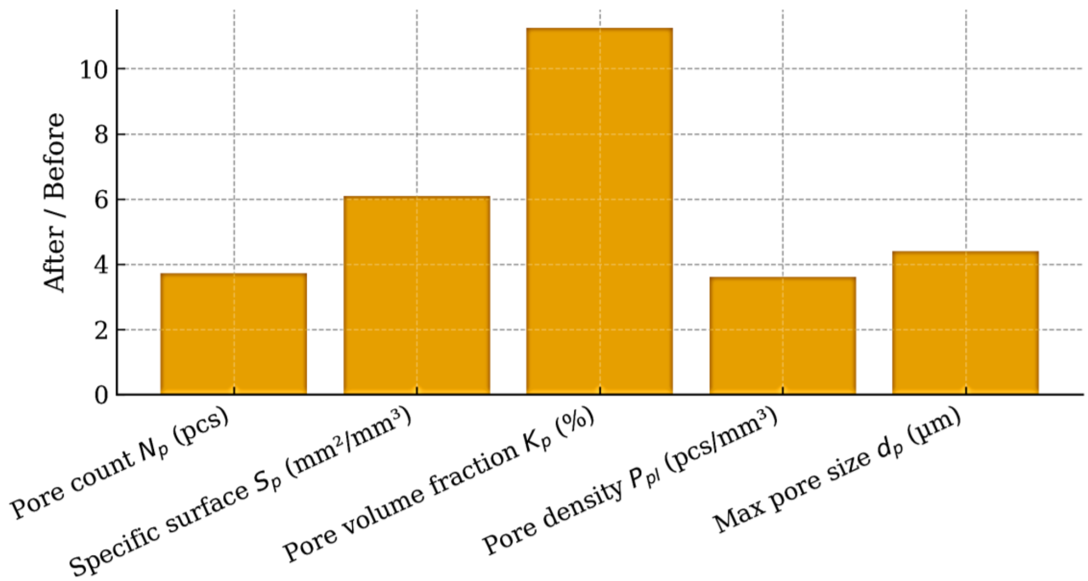

Figure 3. Micro-CT metrics: relative change after acidizing [1].

DISCUSSION

The source dataset indicates that concentration and injection rate jointly control breakthrough volume and wormhole morphology, and that normalization via a 15% HCl-equivalent basis can change the apparent efficiency ranking across concentrations [2]. From a mechanistic perspective, the optimum window emerges from transport–reaction competition, which can be interpreted through Damkyuler-type similarity: excessively slow injection enables excessive near-inlet consumption and branching; excessively fast injection can lead to face dissolution or inefficient sweeping; intermediate rates promote long, dominant wormholes at minimal acid volume [2,6].

PVBT is an efficiency metric but does not directly guarantee coverage across a heterogeneous interval. Micro-CT diagnostics provide quantitative structural evidence of pore-space restructuring–e.g., increase in pore count and specific surface and growth of maximum pore size–which supports a causal link between pumping regime and durable conductivity changes in complex carbonate rock [1].

For strongly heterogeneous or multi-layer intervals, diversion becomes a decisive design element. VES-based self-diverting acids are described as polymer-free systems that can transiently increase viscosity during reaction and thereby redirect the later stages of treatment toward previously untreated zones [5]. In repeated stimulations, the near-wellbore zone evolves (channels, damaged skins, altered flow paths), and models that explicitly represent this evolution are more appropriate than assuming constant stimulation response across treatments [7-10].

A pragmatic integrated design sequence follows: (i) PVBT-based screening of rate–concentration candidates under representative conditions [2]; (ii) diagnostic validation (micro-CT) to confirm channel formation and pore-space restructuring [1]; (iii) reservoir-scale forecasting using either reactive-transport capable models or calibrated skin-factor updates, particularly for long horizontals [4,6]; (iv) diversion decision (VES self-diverting acids or temporary isolation methods) when interval coverage is likely to be poor [5].

CONCLUSIONS

– An integrated workflow combining PVBT-based laboratory optimization, micro-CT diagnostics, and diversion-system selection can be presented as a single coherent IMRAD manuscript for carbonate hydrochloric acidizing design.

– Reported reservoir-condition coreflood data demonstrate nontrivial concentration effects under a 15%-equivalent normalization and a non-monotonic PVBT–rate dependence, supporting an optimum pumping window concept [2].

– Micro-CT metrics provide objective evidence of pore-space restructuring after treatment and strengthen the mechanism-based justification of the selected pumping regime [1].

- VES self-diverting acids are a defensible option for improving interval coverage in strongly heterogeneous intervals by redirecting flow during the treatment [5].
- Field-scale prediction can start from calibrated skin-factor representations but should be upgraded to more physics-based coupling when horizontal length and heterogeneity make spatial stimulation effects critical [4,6].

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