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Techno-Economic Evaluation of Simulated Matrix Acidizing Methods for Enhancing Well Productivity in Iranian Carbonate Reservoirs

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Highlights

- The selection of acid type significantly affects the production rate and well productivity in Iranian carbonate reservoirs.
- 15% emulsified acid (SXE) produced a more favorable wormhole regime than HCl 15% acid.
- The technical and economic results demonstrated that emulsified acid outperformed HCl 15% in terms of production rate and overall economic performance.

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Abstract

Matrix acidizing is an effective stimulation method for carbonate reservoirs that aims to reduce formation damage, enhance well productivity, and improve hydrocarbon recovery. Although numerous studies have investigated acid fluid types and their interactions with reservoir rocks, few have integrated the technical evaluation of matrix acidizing with an economic assessment for Iranian reservoirs. This study addresses this gap by providing a simulation-based technical and economic comparison of two acid systems—15% hydrochloric acid (HCl) and 15% emulsified acid (SXE)—applied to a carbonate reservoir well in Khuzestan Province, Iran. The performance of the two scenarios in terms of production rate, acid penetration, and wormhole development was modeled using WellBook software under identical conditions. The technical results indicated that emulsified acid achieved deeper wormhole penetration (approximately 5 ft compared with 2.5 ft for HCl), a greater reduction in skin factor (from +7 to −2.85 compared with +0.31 for HCl), and a larger increase in production rate (from 0.44 to 1.13 bbl/min compared with 0.75 bbl/min for HCl). Subsequently, the two scenarios were economically evaluated based on two procurement methods: domestic supply in Iranian rials and imported supply in U.S. dollars. The economic analysis was conducted using key financial indicators, including net present value (NPV), internal rate of return (IRR), modified internal rate of return (MIRR), and profitability index (PI). The technical and economic analyses demonstrated that emulsified acid outperformed 15% HCl in terms of production rate, wormhole penetration, and overall economic performance.

Keywords: Matrix acidizing, Carbonate reservoirs, Emulsified acid, Hydrochloric acid, Simulation, Wormhole propagation, Economic evaluation

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1. Introduction

Maximizing the economic recovery of oil and gas from reservoirs has become increasingly important in today's energy industry. Overcoming barriers that hinder production is therefore essential for achieving optimal reservoir performance. One of the key challenges that causes additional pressure drop and consequently reduces production rates in oil wells is formation damage. A primary approach to mitigating formation damage is the application of well stimulation techniques. Well stimulation encompasses a wide range of methods, among which acidizing is one of the most commonly used approaches for dissolving deposits and removing formation blockages (Hadadi et al., 2015).

Acidizing is performed to dissolve deposits and remove blockages within the damaged zone of the formation. The efficiency of this method, particularly matrix acidizing, depends directly on the structure of the generated pore channels, or wormholes, as well as on the injection parameters. Owing to its relatively low cost, matrix acidizing is widely used to stimulate carbonate reservoirs. Numerous experimental and theoretical studies have investigated methods for optimizing matrix acidizing and have shown that acidizing can reduce the skin factor and pressure drop, thereby enhancing well productivity (Golfier et al., 2001; Liu et al., 1997; Qiu et al., 2018). The type and concentration of the injected acid play critical roles in determining the effectiveness of the treatment. Hashemi et al. (2014) reported that acidizing can increase the ultimate recovery of a field using existing wells. In addition, acidizing may mitigate certain production challenges, such as asphaltene precipitation and particle production, while extending the effective production period. These benefits can reduce field development costs. Therefore, accurate characterization of the formation before finalizing the field development plan can help reduce both the cost and risk associated with well stimulation operations.

Although numerous studies have investigated acidizing fluids and their interactions with reservoir rocks, most have focused primarily on technical outcomes, such as wormhole propagation and skin factor reduction. Economic considerations, including procurement costs, exchange rates, and profitability indicators, are rarely integrated into these analyses. For Iranian carbonate reservoirs, where operating costs and supply routes can strongly influence project viability, a combined techno-economic evaluation is essential. Operators require not only evidence of technical effectiveness but also assurance of economic feasibility to support investment decisions. Few studies have simultaneously evaluated the technical performance and economic outcomes of matrix acidizing in Iranian reservoirs. This study addresses this gap by jointly evaluating 15% hydrochloric acid (HCl) and 15% emulsified acid (SXE) under identical reservoir conditions.

The remainder of this paper is organized as follows. Section 2 reviews the existing literature on matrix acidizing techniques, wormhole formation, and related economic assessments. Section 3 describes the research methodology, including the data sources, WellBook simulation setup, acid scenarios, and economic evaluation framework. Section 4 presents and discusses the technical and economic results, together with the sensitivity analysis. Finally, Section 5 summarizes the key findings and highlights their practical implications for Iran's oil industry.

2. Literature review

2.1. Matrix acidizing mechanisms and wormhole formation

The selection of acid type and concentration has a significant impact on production rate and well productivity in Iranian carbonate reservoirs (Rabani et al., 2017; Nazari Sarram et al., 2022). Among acidizing techniques, matrix acidizing has attracted considerable attention from both international and domestic researchers. Daccord et al. (1989) investigated wormhole formation in carbonate rocks and

demonstrated that the optimal conditions for achieving the greatest reduction in formation damage are associated with wormhole development and depend primarily on fluid reactivity and injection rate. Wang et al. (1993) showed that the optimal acid volume for matrix acidizing in carbonate reservoirs is a function of formation composition, reaction temperature, and pore-size distribution. Acid pumping conditions and acid concentration can also affect the optimal acid injection rate; when the pumping rate is insufficient, increasing the acid concentration does not improve well performance (Abdolahi et al., 2021). The high reactivity and corrosiveness of conventional hydrochloric acid, particularly in tight reservoirs at elevated temperatures, limit its applicability. Under such conditions, advanced approaches, such as low-rate injection of in situ generated hydrochloric acid, can promote the formation of longer wormholes (Kiani et al., 2021). Nearly two-thirds of the world's oil reserves and substantial gas reserves are contained in carbonate reservoirs. Therefore, selecting an appropriate acid system based on reservoir conditions is a key factor in achieving successful matrix acidizing in carbonate formations. In carbonate rocks, acid dissolution creates conductive channels known as wormholes. The resulting wormhole pattern depends on the flow rate, thermodynamic conditions, and several parameters governing rock–fluid interactions, including acid concentration, reaction rate, temperature, core sample dimensions, and formation heterogeneity (dos Santos Lucas et al., 2023).

2.2. Simulation and technical studies of carbonate acidizing

Chacon and Pournik (2022) compared the performance of hydrochloric acid and emulsified acid in the matrix acidizing of carbonate reservoirs. Their results showed that emulsified acid is more effective under high-temperature and low-permeability conditions. Kordoni and Jamshidi (2022) evaluated wormhole propagation and skin factor during acidizing in horizontal wells in Iranian carbonate reservoirs. Their study revealed that wormhole propagation decreases with increasing depth within a horizontal reservoir layer. The results also showed that cased-hole completion, compared with open-hole completion, enhances wormhole propagation. Yoo et al. (2022) developed an improved wormhole prediction model to estimate the optimal injection rate and wormhole propagation velocity by incorporating characteristics of wormhole-tip spreading obtained from X-ray computed tomography (CT) images. They found that a lower pumping rate reduces acid consumption while still enabling the formation of an optimal wormhole that reaches the damaged region at the desired distance from the wellbore. Consequently, more cost-effective carbonate acidizing can be achieved by determining the optimal injection rate. Yousefi et al. (2024) reviewed various types of emulsified acids used for matrix acidizing of carbonate formations, focusing on innovations introduced to improve their performance under different conditions, their limitations, and potential development strategies, such as hybrid emulsifiers and applied collector emulsions. Their study showed that macroemulsions are more suitable for matrix acidizing than microemulsions because of their lower emulsifier concentration and greater acid-volume retention.

2.3 Economic evaluations of acidizing treatments

Previous studies have emphasized the influence of technical factors, such as reservoir composition, temperature, injection rate, and acid type, on wormhole formation and overall acidizing efficiency. Comparative investigations have also demonstrated the advantages of emulsified acids over conventional hydrochloric acid under specific conditions, particularly in high-temperature and low-permeability environments. In one of the few global techno-economic studies, Ardiansyah et al. (2018) showed that matrix acidizing was substantially more cost-effective than the NZBP method in an Indonesian field. However, to the best of our knowledge, only a limited number of previous studies have conducted techno-economic analyses of matrix acidizing in Iranian oil fields (Safari et al., 2014). The novelty of the present study lies in integrating detailed WellBook simulations of wormhole

propagation, skin factor reduction, and production enhancement with a dual-scenario economic analysis based on domestic procurement in Iranian rials and imported procurement in U.S. dollars for a specific field case in Khuzestan Province. This integrated technical and economic evaluation, which compares 15% HCl with 15% emulsified acid for matrix acidizing in an Iranian carbonate reservoir, provides practical insights into optimizing stimulation strategies under the specific operational and economic constraints faced by Iranian operators.

3. Research methodology

A carbonate production well from a reservoir in Khuzestan Province, Iran, was selected for this study based on key screening criteria, including carbonate lithology, a declining production trend, a positive skin factor indicative of formation damage, data availability, and overall suitability for matrix acidizing evaluation. The required reservoir, completion, production history, and treatment design data were obtained in collaboration with the field operating contractor. The selected well is a vertical producer completed in the Bangestan Formation, a major Oligocene–Miocene carbonate reservoir in southwestern Iran characterized by limestone intervals with variable porosity (2–30%) and permeability (0.1–100 mD). The target intervals exhibit typical near-wellbore damage associated with drilling and completion operations in mature fields, making them suitable candidates for matrix acidizing stimulation.

Acidizing simulations were conducted using WellBook Stimulation & CTS (Version 9.0, Schlumberger Limited, 2021), an integrated well stimulation platform for the design and evaluation of matrix acidizing treatments. The software incorporates modules for treatment design, acid selection, injection modeling, near-wellbore flow behavior, productivity forecasting, and wormhole propagation in carbonate formations. It was selected because of its integrated workflow capabilities and reduced reliance on full-physics reservoir simulation, thereby enabling efficient engineering-level assessment of stimulation scenarios under field constraints.

Two acidizing scenarios were investigated under identical reservoir and operational conditions: (i) 15 wt.% HCl and (ii) 15 wt.% emulsified acid. Simulation outputs, including production rate, acid penetration depth, and wormhole development, were systematically compared to evaluate the relative performance of the two scenarios.

Finally, a techno-economic assessment was performed using net present value (NPV), internal rate of return (IRR), profitability index (PI), and modified internal rate of return (MIRR), considering both domestic procurement in Iranian rials and imported procurement in U.S. dollars.

3.1. Data collection

The technical data required for this study were obtained from oilfield operating contractors and included reservoir properties, well completion data, production history, and stimulation design parameters. Economic data, including capital expenditure (CAPEX) and operating expenditure (OPEX), for the first scenario, representing domestic procurement, were obtained from the operating company in Iranian rials. For the second scenario, representing imported procurement, cost data were collected from verified commercial and supplier databases.

Monthly Brent crude oil prices from December 2022 through December 2023 were obtained from the U.S. Energy Information Administration (EIA).

A discount rate of 10% was applied to all economic calculations. Several project durations were considered, with a one-year period identified as the most probable case based on expert opinion.

The production improvement resulting from the acidizing operations was obtained from the output of the WellBook Stimulation & CTS simulator.

3.2. Materials

3.2.1. Pre-flush

To ensure consistent initial conditions across both scenarios, the same types of pre-flush fluids were used. Xylene, diesel, and water were selected as the pre-flush fluids in both cases. Although the overall treatment sequence was identical, minor differences in pre-flush volumes were applied to account for variations in the main acid systems and to ensure proper fluid compatibility and formation conditioning.

3.2.2. Main acid

Hydrochloric acid (HCl, 15 wt.%) was selected because of its well-established field performance in carbonate formations, high reactivity, and effective carbonate dissolution capability during matrix acidizing operations. Emulsified acid (SXE, 15 wt.%) was selected as an alternative system to enable a comparative assessment of treatment performance.

The emulsified acid system consisted of 70% hydrochloric acid and 30% diesel, providing a retarded reaction rate and greater penetration depth, which are particularly beneficial in heterogeneous carbonate reservoirs. The same acid strength of 15 wt.% was used for both systems to provide a consistent basis for comparison under equivalent reactive conditions.

3.2.3. Diverter fluid

In both scenarios, VDA10, a viscoelastic surfactant-based diverting agent compatible with HCl systems, was used to promote uniform acid distribution throughout the formation. VDA-type diversion systems temporarily restrict fluid flow into high-permeability zones and redirect acid toward lower-permeability or damaged intervals, thereby improving acid placement and stimulation efficiency in carbonate reservoirs (Chang et al., 2001; Liu et al., 2013). VDA10 exhibits pH-dependent viscoelastic behavior, maintaining a relatively low viscosity during pumping and forming temporary gel-like structures as the acid reacts with the formation. This behavior enhances fluid diversion while leaving minimal residue after treatment (Liu et al., 2013). To ensure a fair comparison between the two acid systems, the same VDA10 concentration and volume were used in both scenarios. Given its relatively high cost, the injection volume was optimized to balance diversion efficiency and operational cost.

3.2.4. Spacer fluid

Water was used as the spacer fluid in both scenarios to ensure adequate separation between treatment stages. In the SXE scenario, a higher spacer volume was applied because of the presence of diesel in the acid formulation, which may increase the risk of phase interaction and fluid incompatibility. The increased spacer volume was therefore used to provide sufficient fluid separation and improve treatment efficiency.

3.2.5. Over-flush

Diesel was used as the over-flush fluid in both scenarios. The required over-flush volume was determined using the simulation software. A higher diesel volume was required in the hydrochloric acid scenario because of its greater acid leakoff tendency and the associated need for more extensive near-wellbore cleanup compared with the emulsified acid system.

3.3. Methods

The reservoir layer properties used in this study are presented in Table 1.

Table 1

Reservoir layer information

Zone name	Permeability (mD)	Porosity (%)	Zone pressure (psi)	Zone temperature (°F)	Temp gradient (°F/100ft)	Interval (MD) (ft)	Fracture gradient (psi/ft)
C-ILAM-1	11	10	4500	221	1	246	0.7
C-ILAM-2	11	10	4600	223	1	410.1	0.7

The fluid properties of the reservoir layers are presented in Table 2.

Table 2

Fluid properties in the layers

Zone	Fluid	Viscosity (cP)	Compressibility (1/psi)	Specific gravity
C-ILAM-1	oil	2	6.30E-06	0.83
C-ILAM-2	oil	2	6.30E-06	0.83

The formation damage characteristics are presented in Table 3. Mineralogically, both layers are composed entirely of calcite.

Table 3

Formation damage information

Zone	Damage skin for open hole	Damage depth(ft)
C-ILAM-1	7	6
C-ILAM-2	7	6

In Scenario 1, hydrochloric acid was used as the main acid under the injection conditions presented in Table 4.

Table 4

Hydrochloric acid scenario

Step	Fluid label	Step liquid volume (gal)	Liquid rate (bbl/min)
Pre-flush	Xylene	4000	2
Pre-flush	Diesel	4000	2
Pre-flush	Fresh water	4000	2
Main fluid	HCL 15.0	3000	2
Diverter	VDA 10.0	1000	2
Main fluid	HCL 15.0	3000	2
Diverter	VDA 10.0	1000	2
Main fluid	HCL 15.0	3000	2
Displacement	Diesel	18849	2

In Scenario 2, emulsified acid was used as the main acid under the injection conditions presented in Table 5.

Table 5
Emulsified acid scenario

Step	Fluid label	Step liquid volume(gal)	Liquid rate (bbl/min)
Pre-flush	Xylene	3000	2
Pre-flush	Diesel	3000	2
Pre-flush	Fresh water	3000	2
Main fluid	SXE 15.0	3000	2
Spacer	Fresh water	500	2
Diverter	VDA 10.0	1000	2
Spacer	Fresh water	500	2
Main fluid	SXE 15.0	3000	2
Spacer	Fresh water	500	2
Diverter	VDA 10.0	1000	2
Spacer	Fresh water	500	2
Main fluid	SXE 15.0	3000	2
Spacer	Fresh water	500	2
Displacement	Diesel	18849	2

3.4. Economic analyses

Two scenarios were defined for the economic analysis. In Scenario 1, the materials required for acidizing were sourced domestically, and their costs were based on domestic prices. In Scenario 2, the materials were assumed to be fully imported, and their costs were calculated in U.S. dollars. To ensure comparability between the two scenarios, the costs of domestically purchased materials were converted to U.S. dollars using the NIMA exchange rate of USD 1 = IRR 372,000 for 2023.

The NIMA exchange rate was the rate used within Iran's NIMA foreign exchange system to facilitate the foreign currency requirements of importers and exporters. It generally fell between the official government exchange rate and the free-market exchange rate and was intended to support legitimate commercial transactions. In this study, the NIMA exchange rate was selected as a subsidized intermediate rate provided within Iran's regulated foreign exchange framework to support oil and gas projects. This approach enabled a comparison of acidizing costs under regulated domestic procurement and free-market import conditions.

The economic analysis required several key inputs, including the discount rate, evaluation period, acidizing performance, capital cost, variable cost, and international oil price. The economic performance of each scenario was evaluated using net present value, internal rate of return, modified internal rate of return, and profitability index. Evaluation periods of 6 months, 1 year, 18 months, and 2 years were considered in the sensitivity analysis. From a technical perspective, the one-year period was considered the most probable evaluation horizon. Based on the literature on investment in oil projects, a discount rate of 10% was applied (Sahebbonar et al., 2017).

3.4.1. Net present value

Net present value is one of the principal criteria used in the economic evaluation of investment projects. It represents the sum of the present values of all project cash flows, including both inflows and outflows, discounted at a rate that reflects the project's risk (Arshad, 2012). NPV was calculated using the following formula:

$$NPV = \sum \left(\frac{Rt}{(1 + i)^t} \right) \quad (1)$$

Where Rt is the net cash flow at time t , i indicates the discount rate, and t represents time period; The difference between cash inflows and cash outflows is referred to as net cash flow. Cash inflows include revenues generated from the sale of produced oil or gas.

$$\text{Cash Inflow} = \text{Total Production (bbl)} \times \text{Sale Price of Produced Fluid (\$/bbl)} \quad (2)$$

$$\text{Cash Outflow} = \text{CAPEX} + \text{OPEX} \quad (3)$$

Where capital expenditure (CAPEX) are fixed costs: the total cost of materials, including diesel, 28% HCl, 28% SXE, xylene, VDA, and other fixed costs. Operating expenditure (OPEX) are variable costs; an OPEX of USD 10 was assumed for each additional barrel of oil produced.

3.4.2. Internal rate of return

The internal rate of return is the discount rate at which the net present value of all project cash flows equals zero. It represents the expected rate of return generated by the project.

3.4.3. Modified internal rate of return

In calculating the internal rate of return, a single discount rate is applied to determine the rate at which the net present value of all project cash flows equals zero. However, this approach implicitly assumes that intermediate positive cash flows can be reinvested at the IRR, which may not reflect actual capital market conditions. When the financing rate applied to negative cash flows differs substantially from the reinvestment rate applied to positive cash flows, the IRR may provide a misleading indication of project profitability. In such cases, the modified internal rate of return provides a more realistic measure by explicitly accounting for separate financing and reinvestment rates. MIRR was calculated using the following formula:

$$MIRR = \left[\frac{\text{FV(positive cash flows, reinvestment rate)}}{\text{PV(negative cash flows, finance rate)}} \right]^{1/n} - 1 \quad (5)$$

3.4.4. Profitability index

The profitability index is the ratio of the present value of expected future cash flows to the initial investment cost. It is used to assess the profitability and economic attractiveness of a project.

$$PI = \frac{\text{Present Value of Future Cash Flows}}{\text{Initial Investment}} = 1 + \frac{\text{Net Present Value}}{\text{Initial Investment Required}} \quad (4)$$

If $PI > 1$, the project is considered economically acceptable; if $PI < 1$, the project is considered economically unattractive and should be rejected.

3.5. WellBook simulation model

In the present study, matrix acidizing simulations were performed using WellBook, a specialized commercial platform widely used in the oil and gas industry for designing and evaluating stimulation treatments in carbonate formations. The software employs a radial semi-analytical framework to model acid transport, mineral dissolution, and the development of dissolution channels. Dimensionless parameters, such as the Damköhler number, are used to predict different rock-dissolution patterns, including face dissolution, conical wormholes, dominant wormholes, and branched wormholes, based on the governing principles of reactive flow and mass transfer. To ensure a fair comparison, the two acid systems were simulated under consistent conditions using the same reservoir properties, including porosity, permeability, and interval thickness; fluid properties; initial formation damage, represented by a skin factor of +7; and pumping schedules, as detailed in Tables 4 and 5. The formation was assumed to consist entirely of calcite, with homogeneous properties and constant thermal conditions. The principal simplifying assumptions included one-dimensional radial flow, rapid reaction kinetics localized at the wormhole fronts, negligible buoyancy effects, absence of unintended hydraulic fracturing, and no compositional heterogeneity or layering effects. The main limitations of this modeling approach include its simplified representation of complex three-dimensional wormhole networks and natural reservoir heterogeneity, its sensitivity to input parameters, and the omission of post-treatment phenomena such as mineral reprecipitation. Nevertheless, these simplifications are consistent with those commonly adopted in industry-standard matrix acidizing simulation tools.

4. Data analyses and discussions

4.1. Technical analyses

Analysis of the simulation results showed that emulsified acid was more effective than hydrochloric acid in reducing formation damage. Figure 1 presents a comparison of formation damage over time.

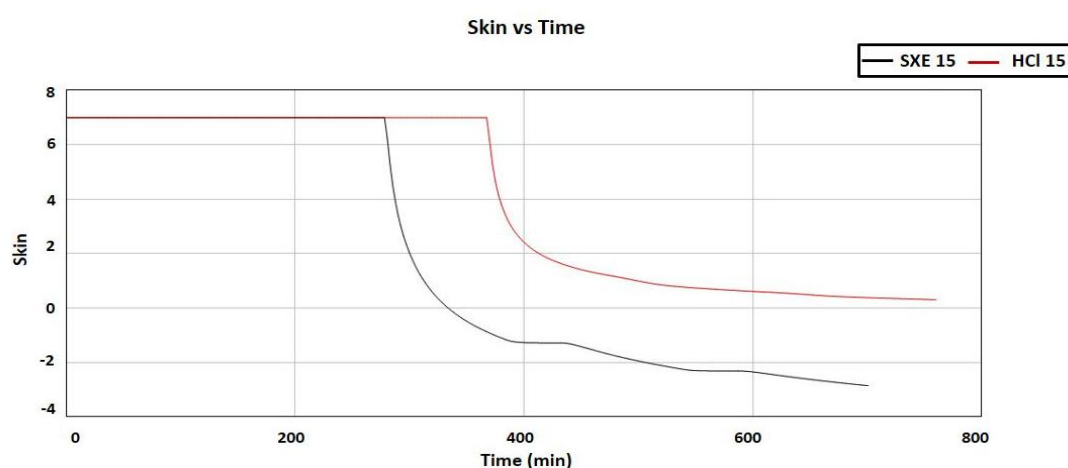


Figure 1

Formation damage over time.

Figure 2 shows the wormhole penetration rate for the two defined scenarios.

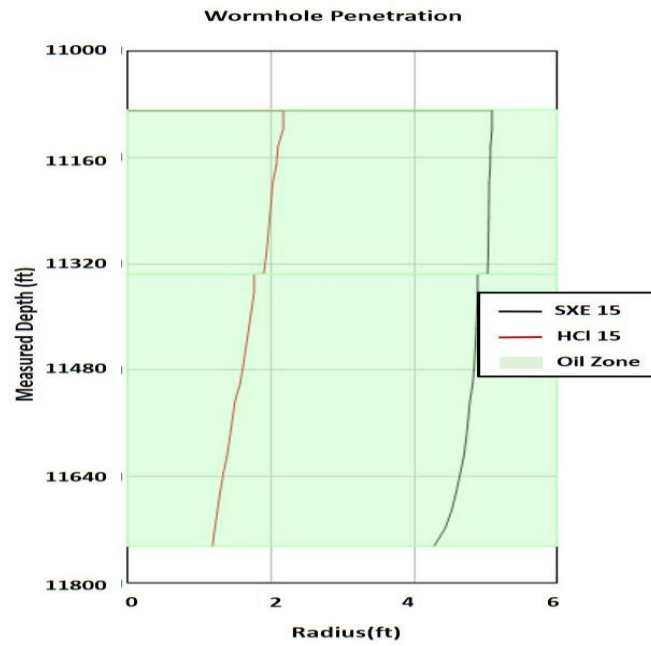


Figure 2

Rate of wormhole penetration.

According to Figure 2, wormhole penetration reached approximately 2.5 ft in the hydrochloric acid scenario and approximately 5 ft in the emulsified acid scenario. Figure 3 presents the wormhole regime diagrams for the two acidizing scenarios.

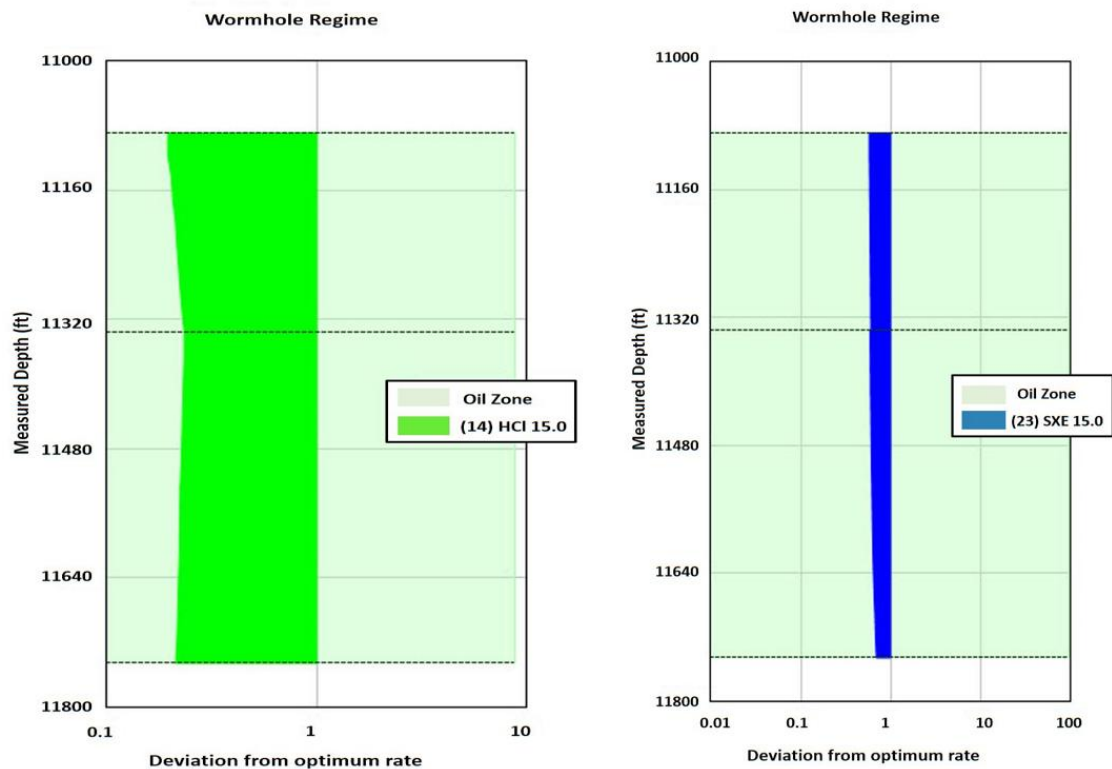


Figure 3

Wormhole regimes for the two injection scenarios.

Figure 3 shows that as the wormhole regime shifts further to the left, wormhole penetration becomes shallower, as illustrated in the left-hand diagram. A wormhole regime value of 1 indicates that the acid has propagated to the desired extent and that the wormhole has reached an optimal state, as shown in the right-hand diagram. Overall, 15% SXE produced a more favorable wormhole regime than 15% HCl.

Figure 4 compares the increase in production rate for the two acid injection scenarios. In the hydrochloric acid scenario, the initial skin factor of +7 was reduced to +0.31, while the production rate increased from 0.44 to 0.75 bbl/min. Similarly, in the emulsified acid scenario, the skin factor decreased from +7 to -2.85, while the production rate increased from 0.44 to 1.13 bbl/min.

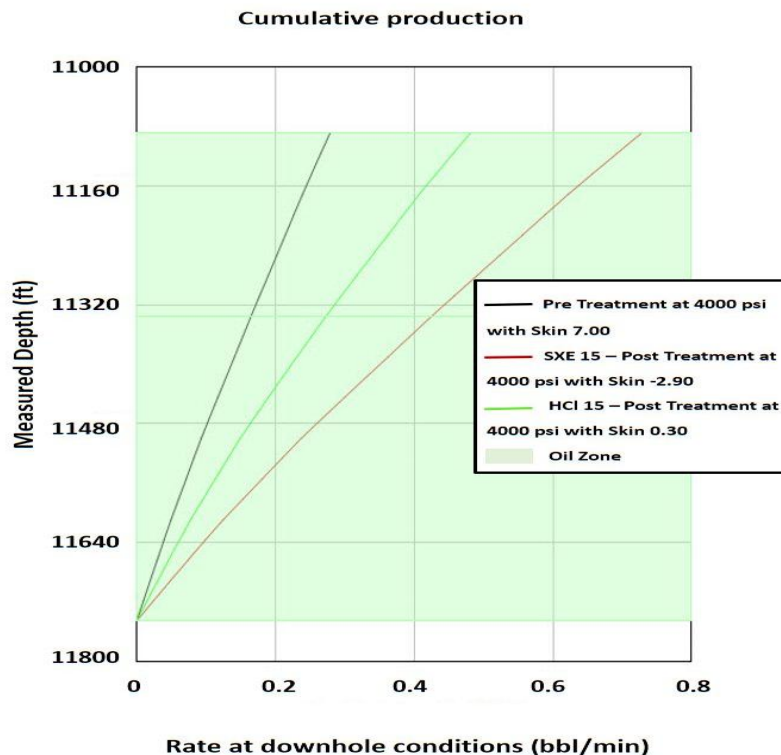


Figure 4

Comparative production increase chart.

The superior performance of SXE can be attributed to its chemical and physical properties. The emulsified system consists of hydrochloric acid dispersed in a continuous diesel phase, forming an oil-external emulsion. This configuration significantly retards the acid reaction rate with calcite by limiting direct contact between the acid and the rock surface. Consequently, mass transfer becomes more diffusion-controlled than reaction-rate-controlled, resulting in lower effective Damköhler numbers and the formation of longer, more dominant wormholes with greater penetration depth. In contrast, straight 15% HCl reacts rapidly at the rock face, promoting face dissolution or compact dissolution patterns and thereby limiting penetration depth. This retarded reaction mechanism explains the greater reduction in skin factor, including the negative post-treatment skin value, and the higher post-treatment production rate achieved with the emulsified acid.

Although the WellBook simulations predicted sustained production increases over the evaluated 12-month period, the long-term persistence of these gains remains uncertain and was not explicitly modeled in this study. Potential adverse effects over longer timeframes include secondary precipitation, fines remigration, and gradual reservoir pressure depletion, all of which may reduce the conductivity of the generated wormholes and diminish incremental production beyond the first year. Previous studies on

carbonate acidizing have reported that, although short-term production gains are generally robust, their longevity depends on reservoir-specific factors such as fluid compatibility and production management.

4.2. Economic analyses

4.2.1. Economic evaluation of acidizing using domestic material procurement

The costs of domestically procured materials were converted to U.S. dollars using the NIMA exchange rate of USD 1 = IRR 372,000. The fixed capital expenditure for both acidizing methods was estimated at IRR 30,000,000,000, equivalent to USD 80,645.16.

4.2.1.1. Hydrochloric acid (15% HCl) scenario under domestic procurement

Table 6

Material costs for the 15% hydrochloric acid scenario

Step	Total volume (gal)	Price (Rials/gal)	Capex (Rials)	Capex (USD)
Diesel	22849	140000	3198860000	8599.086
HCL 28%	3413	80000	273040000	733.978
Xylene	4000	1720000	6880000000	18494.624
VDA	664	17000000	11288000000	30344.086
Total cost of consumables			21639900000	58171.774

Total CAPEX = USD 58,171.77 + USD 80,645.16 = USD 138,816.93.

Table 7 presents the 12-month economic estimates for the 15% HCl scenario for 2023.

Table 7

12-Month economic estimates for the 15% hydrochloric acid scenario

Month	Oil production (bbl/month)	Excess oil production (bbl/month)	Brent oil price (\$/bbl)	Capex (\$)	Opex (\$)	Net cash flow (Rt)
0	19008.00	0.00	80.92	138816.93	00.00	(138816.93)
1	32832.00	13824.00	82.50	0.00	138240.00	1002240.00
2	31575.27	12567.27	82.58	0.00	125672.73	912132.65
3	30318.55	11310.55	78.43	0.00	113105.45	773980.63
4	29061.82	10053.82	84.63	0.00	100538.18	750316.45
5	27805.09	8797.09	75.46	0.00	87970.91	575857.57
6	26548.36	7540.36	74.83	0.00	75403.64	488841.77
7	25291.64	6283.64	80.10	0.00	62836.36	440482.91
8	24034.91	5026.91	85.87	0.00	50269.09	381391.59
9	22778.18	3770.18	86.90	0.00	37701.82	289926.98
10	21521.45	2513.45	87.93	0.00	25134.55	195873.51
11	20264.73	1256.73	88.96	0.00	12567.27	99231.19
12	19008.00	0.00	89.99	0.00	0.00	0.00

Table 8

12-Month economic evaluation of 15% HCl using domestic material procurement

NPV	\$3,537,121.23
IRR	712%
MIRR	46%
PI	26.48

4.2.1.2. Emulsified acid scenario (domestic procurement)**Table 9**

Material costs for the 15% emulsified acid scenario

Step	Total volume (gal)	Price (Rials/gal)	Total cost (Rials)	Total cost (USD)
Disel	21849	140000	3058860000	8222.742
SXE 28%	5121	100000	512100000	1376.613
Xylene	3000	1720000	5160000000	13870.968
VDA	664	17000000	11288000000	30344.086
Total cost of consumables			20018960000	53814.409

Total CAPEX = USD 53,814.41 + USD 80,645.16 = USD 134,459.57.

Table 10 presents the 12-month cost estimates for the 15% emulsified acid scenario.

Table 10

12-Month cost estimates for the 15% emulsified acid scenario

Month	Oil production (bbl/month)	Excess oil production (bbl/month)	Brent oil price (\$/bbl)	Capex (\$)	Opex(\$)	Net cash flow (Rt)
0	19008.00	0.00	80.92	134459.57	0.00	(134459.57)
1	48816.00	29808.00	82.50	0.00	298080.00	2161080.00
2	46106.18	27098.18	82.58	0.00	270981.82	1966786.04
3	43396.36	24388.36	78.43	0.00	243883.64	1668895.72
4	40686.55	21678.55	84.63	0.00	216785.45	1617869.85
5	37976.73	18968.73	75.46	0.00	189687.27	1241692.89
6	35266.91	16258.91	74.83	0.00	162589.09	1054065.08
7	32557.09	13549.09	80.10	0.00	135490.91	949791.27
8	29847.27	10839.27	85.87	0.00	108392.73	822375.62
9	27137.45	8129.45	86.90	0.00	81294.55	625155.05
10	24427.64	5419.64	87.93	0.00	54196.36	422352.26
11	21717.82	2709.82	88.96	0.00	27098.18	213967.24
12	19008.00	0.00	89.99	0.00	0.00	0.00

Table 11

12-Month economic evaluation of the 15% emulsified acid scenario using domestic material procurement

NPV	\$7,776,794.42
IRR	1598%
MIRR	56%
PI	58.84

4.2.2. Economic evaluation of acidizing using imported materials**4.2.2.1. Hydrochloric acid (15% HCl) scenario under import procurement**

The fixed capital expenditure for both acidizing methods under the import procurement scenario was estimated at USD 715,000.

Table 12 presents the CAPEX components for the 15% hydrochloric acid scenario in U.S. dollars.

Table 12

Material costs for the 15% HCl scenario

Materials	Total volume of materials (gal)	Cost per gallon (\$)	Total cost (\$)
Disel	22849	2.53	57807.97
HCL 28%	3413	0.138	470.994
Xylene	4000	1.659	6636
VDA	664	18.34	12177.76
Total cost of materials (\$)			77092.724

Total CAPEX = USD 77,092.72 + USD 715,000 = USD 792,092.72.

Table 13 presents the 12-month cost estimates for the 15% hydrochloric acid scenario under import procurement.

Table 13

12-Month cost estimates for the 15% HCl scenario under import procurement

Month	Oil production (bbl/month)	Excess oil production (bbl/month)	Brent oil price (\$/bbl)	Capex (\$)	Opex (\$)	Net cash flow (Rt)
0	19008.00	0.00	80.92	792092.72	0.00	(792092.72)
1	32832.00	13824.00	82.50	0.00	138240.00	1002240.00
2	31575.27	12567.27	82.58	0.00	125672.73	912132.65
3	30318.55	11310.55	78.43	0.00	113105.45	773980.63
4	29061.82	10053.82	84.63	0.00	100538.18	750316.45
5	27805.09	8797.09	75.46	0.00	87970.91	575857.57
6	26548.36	7540.36	74.83	0.00	75403.64	488841.77
7	25291.64	6283.64	80.10	0.00	62836.36	440482.91

Month	Oil production (bbl/month)	Excess oil production (bbl/month)	Brent oil price (\$/bbl)	Capex (\$)	Opex (\$)	Net cash flow (Rt)
8	24034.91	5026.91	85.87	0.00	50269.09	381391.59
9	22778.18	3770.18	86.90	0.00	37701.82	289926.98
10	21521.45	2513.45	87.93	0.00	25134.55	195873.51
11	20264.73	1256.73	88.96	0.00	12567.27	99231.19
12	19008.00	0.00	89.99	0.00	0.00	0.00

Table 14

Economic evaluation of 15% HCl using imported material procurement

NPV	\$2,943,234.15
IRR	116%
MIRR	26%
PI	4.72

4.2.2.2. Emulsified acid (15% SXE) scenario under import procurement

Table 15 presents the CAPEX components for the 15% emulsified acid scenario in U.S. dollars.

Table 15

Material costs for the 15% emulsified acid scenario

Materials	Total volume of materials (gal)	Cost per gallon (\$)	Total cost (\$)
Disel	21849	2.53	55277.97
SXE 28%	5121	0.856	4383.576
Xylene	3000	1.659	4977
VDA	664	18.34	12177.76
Total cost of materials (\$)			76816.306

Total CAPEX = USD 76,816.31 + USD 715,000 = USD 791,816.31.

Table 16 presents the 12-month cost estimates for the 15% emulsified acid scenario under import procurement.

Table 16

12-Month cost estimates for the 15% emulsified acid scenario under import procurement

Month	Oil production (bbl/month)	Excess oil production (bbl/month)	Brent oil price (\$/bbl)	Capex (\$)	Opex(\$)	Net cash flow (Rt)
0	19008.00	0.00	80.92	791816.31	0.00	(791816.31)
1	48816.00	29808.00	82.50	0.00	298080.00	2161080.00
2	46106.18	27098.18	82.58	0.00	270981.82	1966786.04
3	43396.36	24388.36	78.43	0.00	243883.64	1668895.72
4	40686.55	21678.55	84.63	0.00	216785.45	1617869.85
5	37976.73	18968.73	75.46	0.00	189687.27	1241692.89

Month	Oil production (bbl/month)	Excess oil production (bbl/month)	Brent oil price (\$/bbl)	Capex (\$)	Opex(\$)	Net cash flow (Rt)
6	35266.91	16258.91	74.83	0.00	162589.09	1054065.08
7	32557.09	13549.09	80.10	0.00	135490.91	949791.27
8	29847.27	10839.27	85.87	0.00	108392.73	822375.62
9	27137.45	8129.45	86.90	0.00	81294.55	625155.05
10	24427.64	5419.64	87.93	0.00	54196.36	422352.26
11	21717.82	2709.82	88.96	0.00	27098.18	213967.24
12	19008.00	0.00	89.99	0.00	0.00	0.00

Table 17

12-Month economic evaluation of 15% emulsified acid using imported material procurement

NPV	\$7,178,946.10
IRR	263%
MIRR	34%

A comparison of Tables 7–13 shows that the NPV of the emulsified acid scenario was approximately twice that of the 15% HCl scenario under both procurement methods. The very high IRR values indicate the strong economic potential of matrix acidizing projects in Iranian oil fields, particularly when supported by the regulated NIMA exchange rate. However, as discussed earlier, exceptionally high IRR values may reflect differences between the financing conditions of project costs and the market conditions governing oil revenues. Therefore, the modified internal rate of return provides a more appropriate measure of economic performance. Both MIRR and PI indicate that the two acidizing methods are economically viable; however, emulsified acid outperformed 15% HCl in all evaluated scenarios.

4.2.3. Sensitivity analyses

A sensitivity analysis was conducted to evaluate the effects of the main economic variables, including oil price, capital expenditure, operating expenditure, and discount rate, on the NPV of matrix acidizing. Each variable was varied from 50% to 150% of its base-case value. Figure 5 presents the resulting NPV values for the emulsified acid scenario.

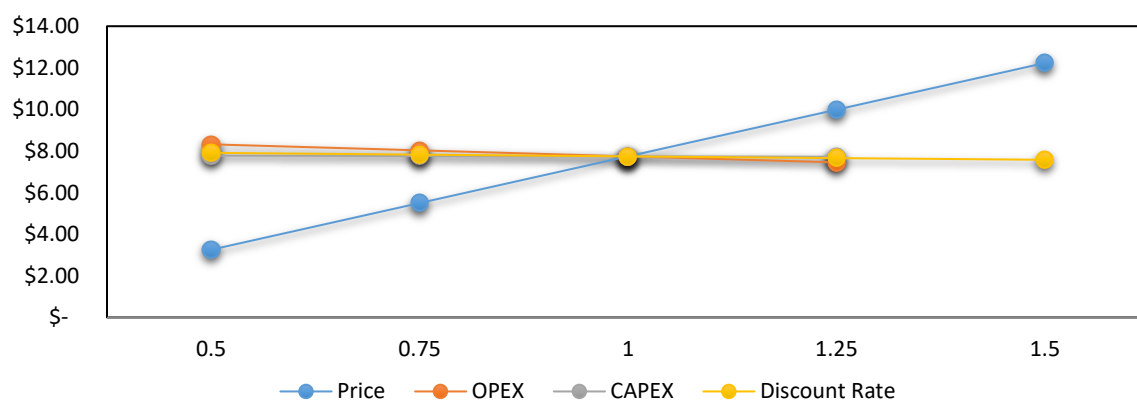


Figure 4

Sensitivity analysis of the NPV for the emulsified acid scenario

The sensitivity analysis results show that the NPV of the matrix acidizing project is more sensitive to changes in oil prices than to the other evaluated factors.

Overall, the findings indicate that acid injection remains economically viable even when the materials required for acidizing are imported at the free-market exchange rate. Furthermore, emulsified acidizing using 15% SXE is more profitable than hydrochloric acidizing under both procurement scenarios.

5. Conclusions

This study presented an integrated technical and economic evaluation of matrix acidizing using 15% hydrochloric acid and SXE in a carbonate reservoir well in Iran. The technical simulations showed that emulsified acid significantly outperformed conventional HCl, achieving deeper wormhole penetration (approximately 5 ft compared with 2.5 ft), a more favorable dissolution regime, a greater reduction in skin factor (from +7 to -2.85, indicating the development of conductive channels beyond the damaged zone), and a larger increase in production rate (from 0.44 to 1.13 bbl/min compared with 0.75 bbl/min for HCl). These improvements can be attributed to the retarded reaction rate of the emulsified acid system, which promotes the formation of efficient dominant wormholes in carbonate formations. From a practical perspective, emulsified acid may therefore provide a more effective stimulation option for Iranian operators, particularly under procurement and import constraints.

The 12-month economic analysis further demonstrated the superiority of emulsified acid, which generated higher net present value, internal rate of return, modified internal rate of return, and profitability index under both domestic procurement in Iranian rials and import procurement in U.S. dollars. These results indicate that the additional production generated by emulsified acid more than offsets its treatment costs, making it the more economically attractive option under the evaluated conditions.

Although these findings provide useful guidance for stimulation design in similar Iranian carbonate reservoirs, several limitations should be acknowledged. The results were based on commercial simulation without direct field validation because of data confidentiality constraints. In addition, reservoir heterogeneity and long-term post-treatment effects were not explicitly modeled, and the primary economic evaluation was limited to a one-year time horizon.

Nomenclature

CTS	Completion and treatment simulator
HCl	Hydrochloric acid
IRR	Internal rate of return
MIRR	Modified internal rate of return
NPV	Net present value
NZBP	New zone behind pipe
PI	Profitability index
SXE	Emulsified acid system
VDA	Viscoelastic diverting agent

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