Stimulation of Low Pressure Carbonates Reservoirs with a Triphase Emulsified Acid System "3PEA" of Southern Iran -Case Studies

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Abstract

Matrix acidizing tries to enhance oil wells productivity as one of the main kind of well stimulation techniques in petroleum industry. This method of acidization is being implemented by stepwise injection of high rate stimulation fluids through the wellhead into the target zone of reservoir rock.

Acid penetration depth and consequently the treated radius are the key factors to reach the maximum effectiveness of stimulation operations on production improvement and it can be optimized by an exact design of: fluid type, stimulation fluid volume, job stages and operating pressure.

Based on recorded data and job reports, recent conventional matrix acidizing jobs had low effect on improving oil production rate in some old Iranian oil fields, especially depleted with low reservoir pressure ones. Firstly a possible reason of this problem was assessed as shallow acid penetration radius and insufficient treated area around the wellbore and well testing data confirmed this probability. Depth of damaged zone and acid penetration directly related on the porosity type, permeability, lithology, injection rate and production history of matrix acidizing candidate wells.

In this study, successful application of a new kind emulsified acid system is evaluated in a low pressure, carbonates reservoirs in south of Iran. Application of nitrogen in stimulation treatments has gained wide acceptances in recent years. The applied triphase emulsified acid increases stimulated radius of near wellbore area by retardation the reactivity of acid system by adding a gaseous phase to emulsion of HCl and gasoil. Use of this acid system made it possible to achieve a 137% greater well productivity than traditional systems, in this study.

Introduction

A common concern in all matrix acidizing operations is the job effect on oil production rate. This purpose is achieved by reducing the pressure draw down and increasing the down hole pressure with passing the damaged zone of near wellbore area (Chang et al. 2008;Letichevskiy et al. 2017; Alvarez et al. 2000).

Different kinds of retarded acids have been used in matrix acidizing operations to enlarge the treated zone of near wellbore area so far. Some of famous retarded acid types are: Emulsified Acid, Gelled acid, Hybrid Acid system, Organic acid, Chemically Retarded Acid & GLDAs (Moid et al. 2020; Li et al. 2008; Shuchart et al. 2009).

The mentioned retarded system acids have been used in recent years In Field "M" (an Iranian southern oil field) but desired results was not achieved; in other words an acceptable and stable production raise was not observed by matrix acidizing in candidate wells of field-M and made it necessary to revise job designs.

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Applying foam or gaseous phase in stimulation fluids seems to help stimulation designers solving the issue based on literature and experimental studies (Alvarez et al. 2022).

Foam has different applications in acidizing operations. Some of its main usages are: controlling fluid-loss, as a diverting agent, lifting fluid and foamed acid (Economides and Nolte 1989; Parlar et al. 1995). One of the main retarded acids is the emulsified composition of HCl and gasoil by various percentages. But mixture of these two phases could not solve the issue to stimulate farther radius around the wellbore. A triphase emulsified acid system is made by adding a gaseous phase of nitrogen (N_2) to the mentioned emulsion (Economides and Nolte 1989). Adding this phase reduces the reactivity of the acid system based on the laboratory tests. It seems that nitrogen agitate reservoir rock merely by reducing contact area of triphase acid and rock (Liu et al. 2022; Parlar et al. 1995).

The recommended composition of triphase emulsified acid system in recent studies are: 50% HCL (15% concentration), 25% Gasoil + 25% N_2. Liquid volumes are pumped as a wide range of 150 to 500 gal/ft (in this paper triphase emulsified acid is abbreviated as "3PEA").

The desirable flow characteristics of emulsified foam acid enhances the fluid movement in porous media, it happens by rapid expansion of gaseous phase of acid and pushing the liquid phase to deeper radii. Also, recovery of acid and flowing well back are annoying parts of acidizing jobs in low pressure reservoirs; and hereby foam conveniences cleaning and flow back by expansion and lightening the well column (Hung et al.1989; Abou-Sayed et al. 2007).

The surveyed parameters to evaluate acidizing operations performance in this study are: Q (production rate of oil), p_{wf} (flowing wellhead pressure), p_{Dh} (downhole/sand face pressure) and S (skin factor). These parameters have been followed up and compared before and after the acid jobs.

Case Studies

Field characteristics: Field-M is located in southwest of Iran and the first well was drilled 40 years ago in the field. Reservoir pressure has been declined to less than 60% of its initial pressure and critical condition is faced to exploit producing wells of the field. Field-M is divided to 8 sectors but the general characteristics do not show a sharp variation through the sectors. In this article the performance of 3 acidizing scenarios have been compared in 15 producing oil wells (5 wells by each scenario) and we tried to choose similar case studies for all 3 scenarios to make it possible having a fair and reliable assessment. All candidate wells of matrix acidizing were completed cased hole with perforated interval less than 50 ft, to make it possible to perform a single stage acidizing without diverting agent. The summary of general information of candidate wells are as follow:

Well no. 1: located in sector 2 of the field. Its drilling had been finished 11 years ago and had a continuous production of oil about 500 BPD till last year and dead last year. The perforated interval is 45 ft. completed in mixed lithology of carbonate (55% Dolomite & 45% Limestone). The last injectivity of well was reported 8 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 2: located in sector 5 of the field. Its drilling had been finished 23 years ago and had a periodic production of oil between 0 - 500 BPD in recent years. The perforated interval is 34 ft. completed in mixed lithology of carbonate (30% Dolomite & 70% Limestone). The last injectivity of well was reported 10.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 3: located in sector 3 of the field. Its drilling had been finished 2 years ago and did not produce oil till now. The perforated interval is 38 ft. completed in mixed lithology of carbonate (35% Dolomite & 65% Limestone). The last injectivity of well was reported 4 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 4: located in sector 1 of the field. Its drilling had been finished 8 years ago and had a periodic production of oil between 0 - 500 BPD in recent years. The perforated interval is 43 ft. completed in mixed lithology of carbonate (40% Dolomite & 60% Limestone). The last injectivity of well was reported 7.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 5: located in sector 8 of the field. Its drilling had been finished 9 years ago and had a continuous production of oil about 400 BPD in recent years. The perforated interval is 29 ft. completed in pure lithology of

Limestone. The last injectivity of well was reported 9.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 6: located in sector 1 of the field. Its drilling had been finished 11 years ago and had a continuous production of oil about 300 BPD till last year and dead last year. The perforated interval is 26 ft. completed in mixed lithology of carbonate (50% Dolomite & 50% Limestone). The last injectivity of well was reported 6 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 7: located in sector 8 of the field. Its drilling had been finished 16 years ago and had a periodic production of oil between 0 - 500 BPD in recent years. The perforated interval is 38 ft. completed in mixed lithology of carbonate (15% Dolomite & 85% Limestone). The last injectivity of well was reported 10 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 8: located in sector 2 of the field. Its drilling had been finished 3 years ago and did not produce oil till now. The perforated interval is 43 ft. completed in pure lithology of Limestone. The last injectivity of well was reported 5.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 9: located in sector 5 of the field. Its drilling had been finished 7 years ago and had a continuous production of oil about 500 BPD in recent years. The perforated interval is 47 ft. completed in pure lithology of Dolomite. The last injectivity of well was reported 6.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 10: located in sector 3 of the field. Its drilling had been finished 11 years ago and had a continuous production of oil about 400 BPD in recent years. The perforated interval is 41 ft. completed in pure lithology of Limestone. The last injectivity of well was reported 8.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 11: located in sector 5 of the field. Its drilling had been finished 28 years ago and after changing the production interval, it did not produce oil in recent years. The perforated interval is 44 ft. completed in mixed lithology of carbonate (45% Dolomite & 55% Limestone). The last injectivity of well was reported 5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 12: located in sector 3 of the field. Its drilling had been finished 2 years ago and did not produce oil till now. The perforated interval is 49 ft. completed in pure lithology of Limestone. The last injectivity of well was reported 7 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 13: located in sector 8 of the field. Its drilling had been finished 9 years ago and had a periodic production of oil between 0 - 500 BPD in recent years. The perforated interval is 40 ft. completed in mixed lithology of carbonate (25% Dolomite & 75% Limestone). The last injectivity of well was reported 6 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 14: located in sector 1 of the field. Its drilling had been finished 15 years ago and had a continuous production of oil about 400 BPD in recent years. The perforated interval is 37 ft. completed in pure lithology of Dolomite. The last injectivity of well was reported 3.5 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Well no. 15: located in sector 2 of the field. Its drilling had been finished 6 years ago and had a continuous production of oil about 500 BPD till now, but the Pwf has been declined recently. The perforated interval is 40 ft. completed in mixed lithology of carbonate (40% Dolomite & 60% Limestone). The last injectivity of well was reported 9 bbl per minute (by maximum injection pressure of 1500 to 2000 psi) before matrix acidizing.

Acidizing Job Design

The first 5 wells (well no.1 to 5) have been acidized with conventional acid systems, the next 5 wells (well no.6 – 10) were designed by low volume 3PEA and the last ones (well no.11 to 15) were done by high volume 3PEA. Conventionally the main acid stage is designed as HCl 28% (or HCl 15%) and hybrid acid (70% HCl 15% + 30% Acetic acid) or emulsified acid (70% HCl 15% + 30% Gasoil) with total volume 150 to 200 US Gal/ft for this stage. Also displacing stage contained water and gasoil in previous designs.

The 3PEA jobs have been designed in 4 stages:

1. Pre-flush: carrier fluid of water with the mixture of surface tension reducing agent and mutual solving agent as its additives (Karimi et al. 2018).

2. Main acid: this stage contains two main parts; at first the strong acid of HCl 28% is injected to remove near wellbore damages by volume of 80 to 150 US Gal/ft and then the three phase emulsified acid (3PEA) is injected to create wormhole in farther distances and increase the stimulated radius (Hoefner and Fogler 1987). The volume of this section is as twice as the previous HCl acid. In first 5 jobs we used HCl 28% with volume 80 to 100 US Gal/ft and 3PEA with volume 160 to 200 US Gal/ft, that we named it low volume 3PEA in this article; and then by revising job designs, the acid volumes increased to 130 to 150 US Gal/ft for HCl 28% and 260 to 300 US Gal/ft for 3PEA, and it is named high volume 3PEA.
3. Post-flush: carrier fluid of water with additive of surface tension reducing agent (Al-Rekabi et al. 2020).
4. Displacing fluid: this stage is used to push the job design fluids to the formation (Ma et al. 2022). And contains two parts, here. Firstly gasoil is being injected as equivalent volume 20% of well column and finally the sub-stage of foam with quality of 65 to 70% is injected as same volume of well column.

Operation Results

It should be mentioned that the first jobs of new acid system was done with HCl 28% volume of 80-100 US Gal/ft and 3PEA volume of 160-200 US Gal/ft in main acid stage. But based on previous researches and regarding the new acid system job results (especially skin reduction amount and pressure drop), it was decided to revise the acid volumes by increasing HCl 28% to 130-150 US Gal/ft and 3PEA to 260-300 US Gal/ft.

One sample of job injection data for each mentioned designs is shown in **Figures 1** to **3**. First graph refers to the conventional acid system and an ordered general trend can be observed through the injection period. The second and third graphs belong to low volume 3PEA and high volume 3PEA acid systems respectively and the fluctuations could be due to existence of gaseous phase in 3PEA.

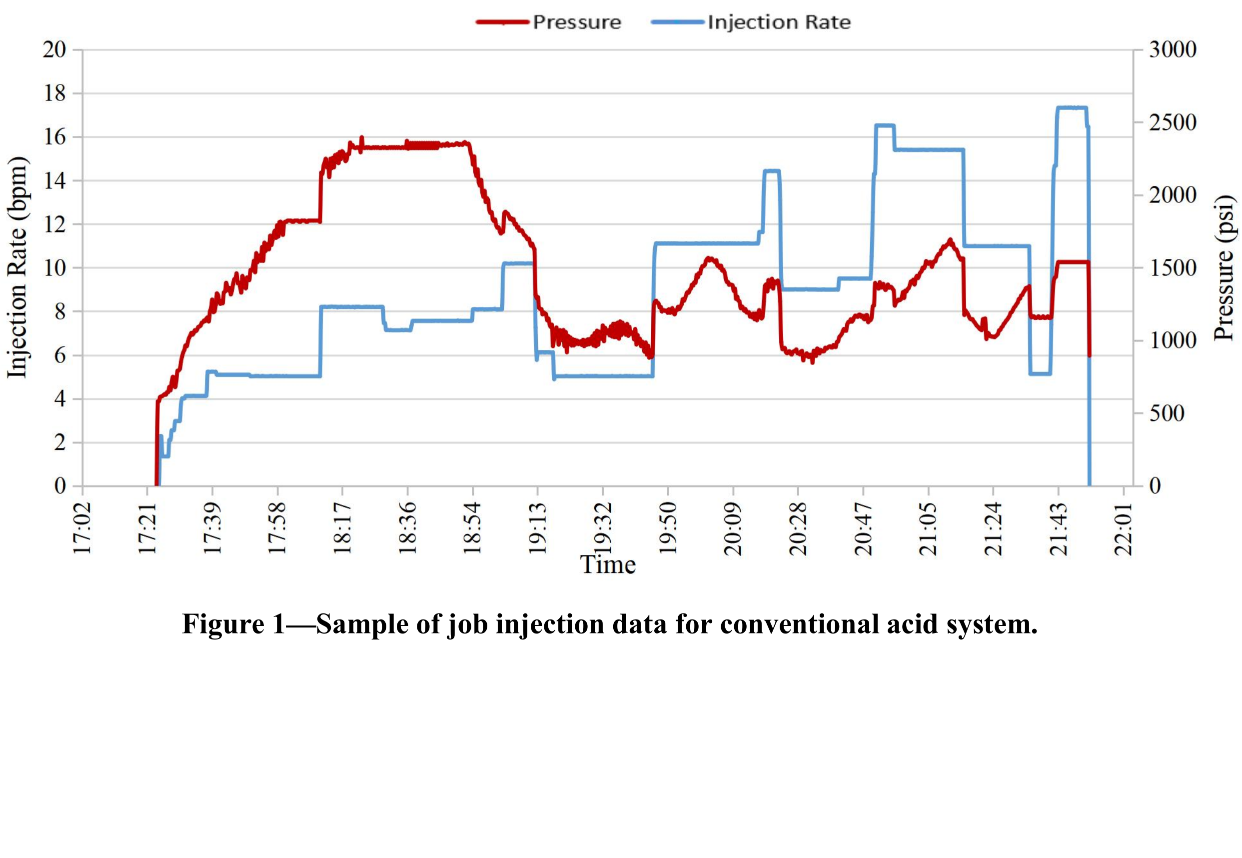

Figure 1—Sample of job injection data for conventional acid system.

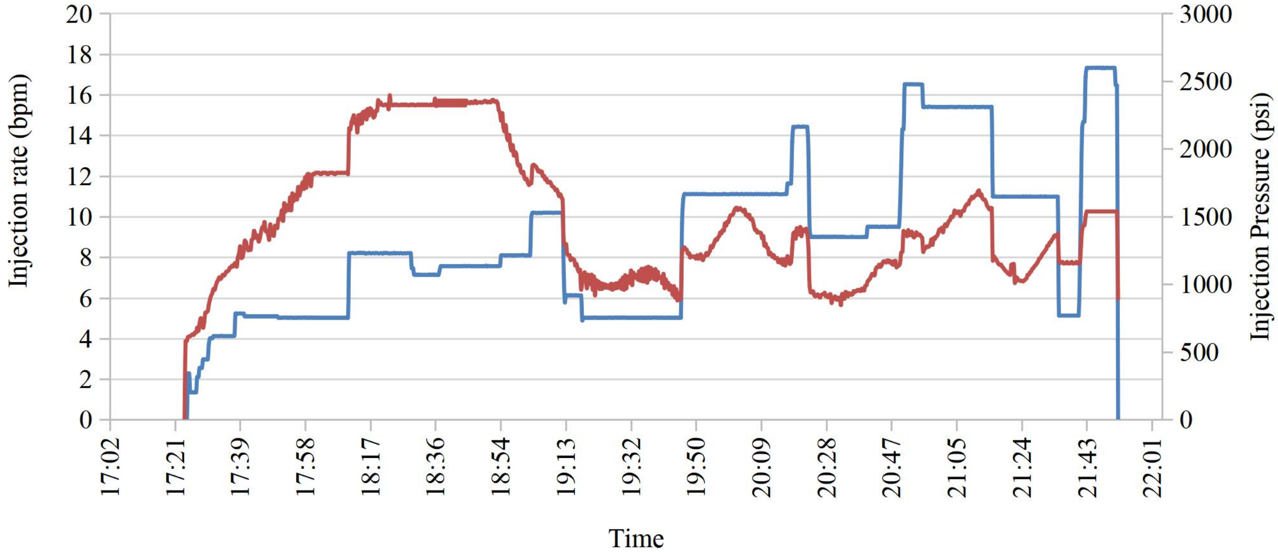

Figure 2—Sample of job injection data for low volume 3PEA system.

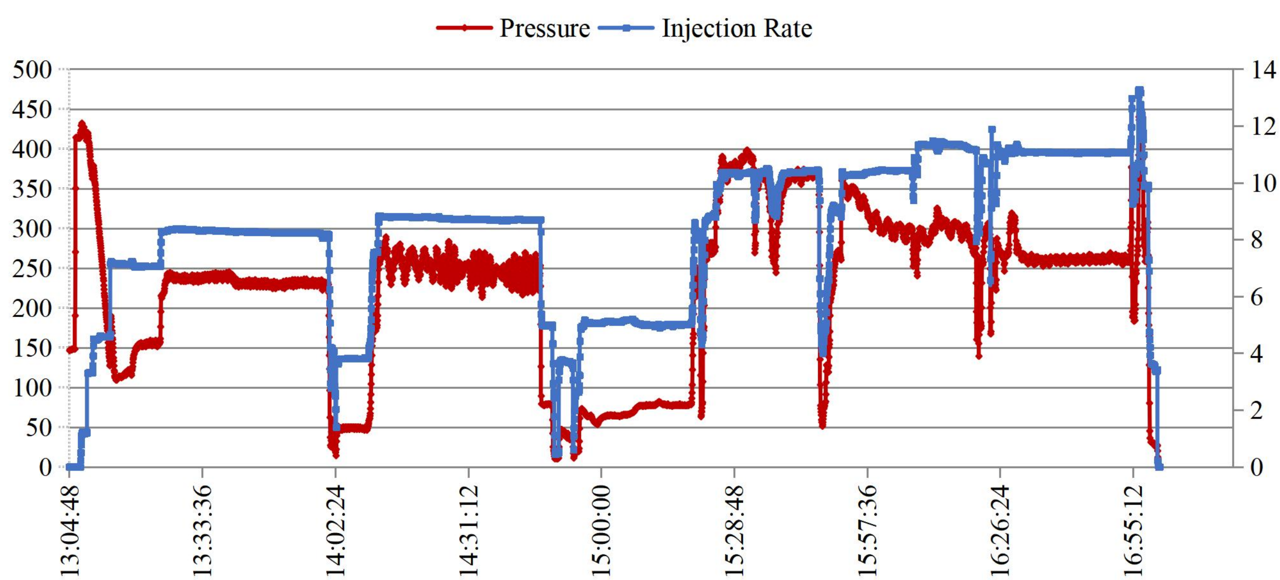

Figure 3—Sample of job injection data for high volume 3PEA system.

Table 1 shows the average skin factor measured in candidate wells of matrix acidizing. It can be seen an average skin factor reduction of -4.6 by conventional acidizing, whereas this parameter is improved in acidizing with low volume "3PEA" by 45% and high volume "3PEA" enhances the parameter by 78%. So a clear improvement can be observed in "3PEA" acid system usage for the matrix acidizing candidate wells of Field-M.

Table 1—The average skin factor of matrix acidizing candidate wells.

Acid Type	Pre-operation average skin factor	Post-operation average skin factor	Skin reduction due to Acidizing operation
Conventional acid systems	6.1	1.5	- 4.6
Low volume "3PEA"	5.5	-1.2	- 6.7
High volume "3PEA"	6.3	-1.9	- 8.2

Production Rate. All post-operation rates have been monitored for 6 months after acidizing operation and the final acceptable rate has been validated if it was stable through last 2 months. System acids used in conventional design: hybrid acid (mixture of HCl and organic acids), emulsified acid (HCl emulsion in gasoil), HCl 15% and HCl 28%.

Conventional Acid System Job Results. **Table 2** and **Figure 4** show the amount of pre-operation and post-operation rate of acidizing jobs with Conventional acid system. Data shows the 59% increase of oil production rate (and Average rate rise per job of 160 (bbl/day)) by conventional acidizing. This amount is very close to matrix acidizing results of recent 10 years in field-M which is 52% increase of oil production rate (and Average rate rise per job of 145 (bbl/day)). So a key reasons of necessities to acidizing design revisions was low production improvement of matrix stimulation jobs.

Table 2—Pre-operation and post-operation rate of acidizing jobs with Conventional acid system.

Well no.	Pre-operation rate (bbl/day)	Post-operation rate (bbl/day)
1	500	500
2	200	500
3	0	0
4	250	250
5	400	900
Total rate	1350	2150
Total production increase: 800 (bbl/day)		
Average of rate rise per job: 160 (bbl/day)		

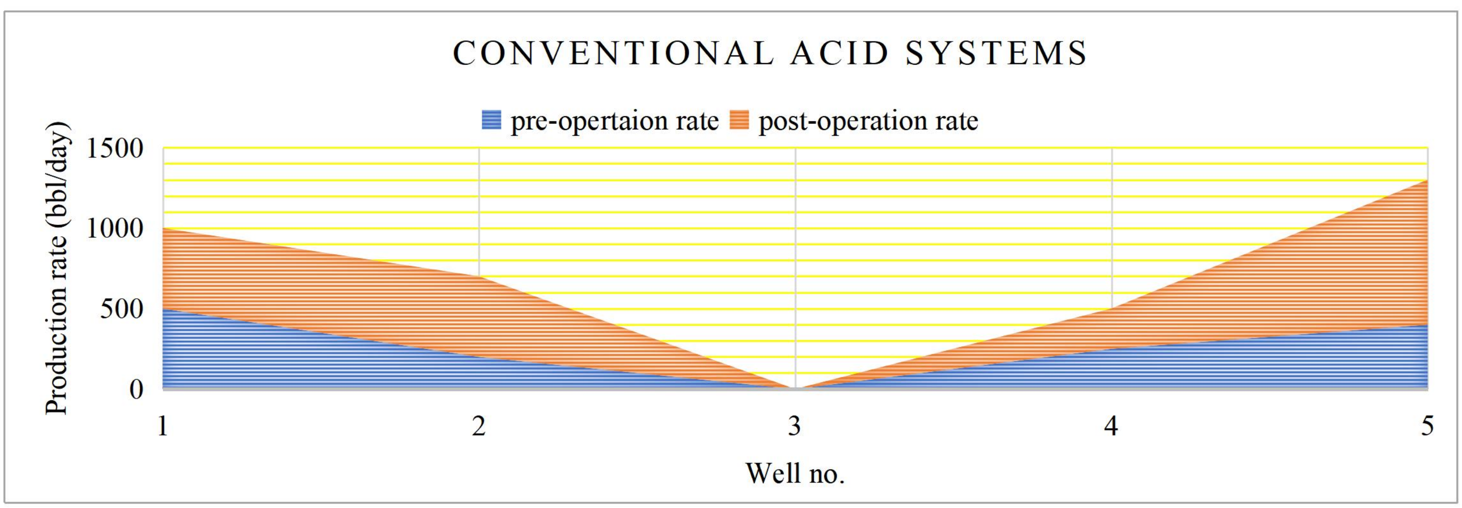

Figure 4—Changes of oil rate in acidizing jobs candidate wells with conventional acid system.

Low Volume 3PEA Job Results. The first jobs of "3PEA" have been done with this composition: 50% HCL (15% concentration), 25% Gasoil + 25% N_2 with total fluid volume of about 250 US Gal/ft. A job success rate achieved by this method was about 40% and average increase of 270 bbl/day production rate per job. **Table 3** and **Figure 5** pre-operation and post-operation rate of acidizing jobs candidate wells with low volume 3PEA system. These results confirm the improvement of stimulation jobs with this acid type with respect to the conventional one by 68% increase in production rate, due to its deeper effect on target zones. But we decided to design 3PEA acidizing jobs with higher volumes to evaluate the its performance in next jobs.

Table 3—Pre-operation and post-operation rate of acidizing jobs candidate wells with low volume 3PEA system.

Well no.	Pre-operation rate (bbl/day)	Post-operation rate (bbl/day)
6	0	250
7	250	500
8	0	0
9	500	1000
10	400	750
Total rate:	1150	2500
Total production increased: 1350 (bbl/day)		
Average of rate increased per job: 270 (bbl/day)		

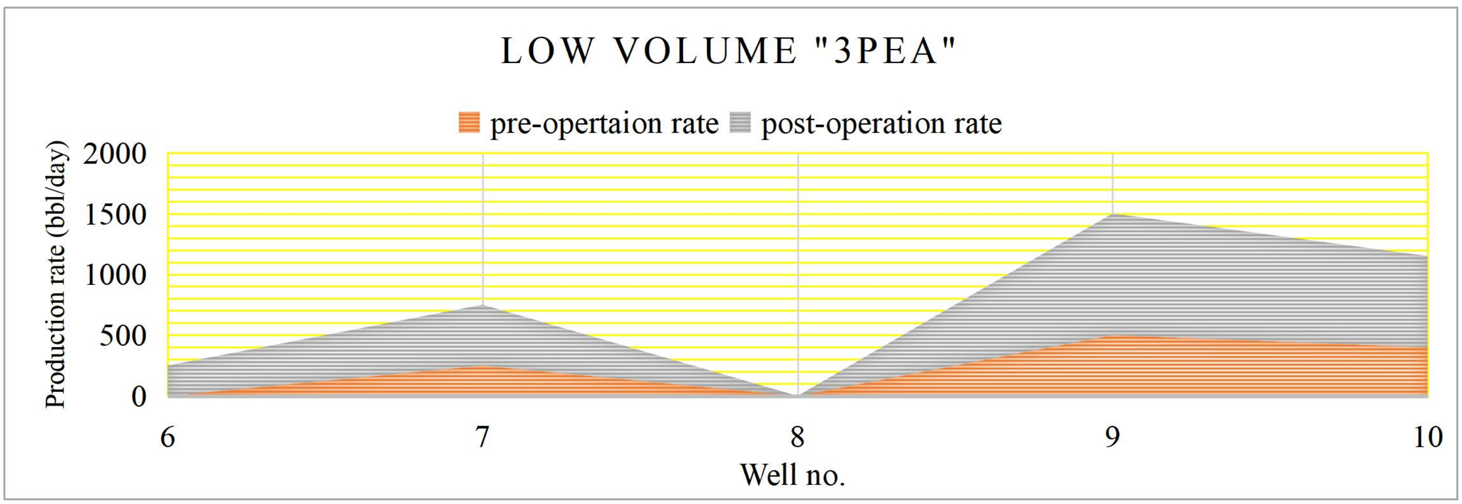

Figure 5—Changes of oil rate in acidizing jobs candidate wells with low volume 3PEA system.

High Volume 3PEA Job Results. Next jobs were designed with higher ratio of gaseous phase and higher volume: 40% HCL (15% concentration), 20% Gasoil + 40% N_2 with total fluid volume of about 400 US Gal/ft. A job success rate achieved by this method was about 65% and average increase of 380 bbl/day production rate per job. **Table 4** and **Figure 6** pre-operation and post-operation rate of acidizing jobs candidate wells with high volume 3PEA system. The total acid volume has been doubled and the amount of production rate is increased 40% due to acidizing by high volume 3PEA system with respect to the low volume 3PEA. This result show the positive effect of N2 gaseous phase to push acid phase more and make deeper penetration radios around the wellbore.

Table 4—Pre-operation and post-operation rate of acidizing jobs candidate wells with high volume 3PEA system.

Well no.	Pre-operation rate (bbl/day)	Post-operation rate (bbl/day)
11	0	1000
12	0	0
13	300	600
14	400	1000
15	500	500
Total rate:	1200	3100
Total production increased: 1900 (bbl/day)		
Average of rate increased per job: 380 (bbl/day)		

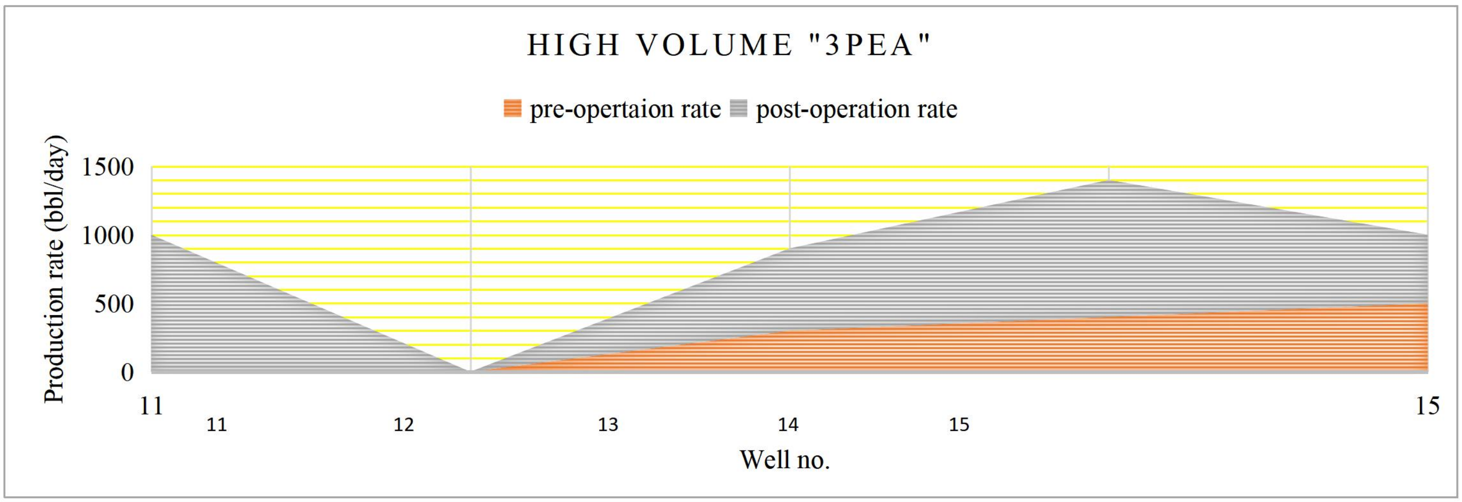

Figure 6—Changes of oil rate in acidizing jobs candidate wells with high volume 3PEA system.

Pressure. Changes of pre-operation and post-operation pressure of acidizing jobs candidate wells are discussed. Well flow pressure and down hole pressure are two nodes parameters to evaluate the effect of acidizing jobs on well performance; where ever the amount of down hole pressure is more crucial in technical analysis because it presents the pure effect of stimulation job on flow conditions without the effect of well column or well completion design on it. So we consider this parameter here to evaluate the effect of different acid systems.

Table 5—Pre- and post-operation pressure of acidizing jobs candidate wells with Conventional acid system.

Well no.	P_{dh1}	P_{dh2}	$\Delta P_{sandface}$	P_{wf1}	P_{wf2}	$\Delta P_{wellhead}$
1	1245	1290	45	240	315	75
2	1185	1350	165	210	350	140
3	0	0	0	0	0	0
4	1160	1205	45	290	310	20
5	1345	2450	1105	270	510	240
Total downhole pressure increased: 1360				Total wellhead pressure increased: 475		
Average of downhole pressure increased per job: 272				Average of wellhead pressure increased per job: 95		
* The unit of all parameters in this table is "psi"						

Table 6—Pre-operation and post-operation pressure of acidizing jobs candidate wells with low volume 3PEA system.

Well no.	P_{dh1}	P_{dh2}	$\Delta P_{sandface}$	P_{wf1}	P_{wf2}	$\Delta P_{wellhead}$
6	0	1370	1370	0	295	295
7	1150	1710	560	230	330	100
8	0	0	0	0	0	0
9	1450	2345	895	265	575	310
10	1385	1890	505	270	430	160
Total downhole pressure increase: 3330				Total wellhead pressure increase: 865		
Average of downhole pressure increased per job: 666				Average of wellhead pressure increased per job: 173		
* The unit of all parameters in this table is "psi"						

Table 7—Pre- and post-operation pressure of acidizing jobs candidate wells with high volume 3PEA system.

Well no.	P_{dh1}	P_{dh2}	$\Delta P_{sandface}$	P_{wf1}	P_{wf2}	$\Delta P_{wellhead}$
11	0	2510	2510	0	545	545
12	0	0	0	0	0	0
13	1290	1780	490	220	385	165
14	1360	2470	1110	235	520	285
15	1315	1365	50	250	320	70
Total downhole pressure increased: 4160				Total wellhead pressure increased: 1065		
Average of downhole pressure increased per job: 832				Average of wellhead pressure increased per job: 213		
* The unit of all parameters in this table is "psi"						

Changes of pre-operation and post-operation pressure of acidizing jobs candidate wells is presented in **Tables 5** to **7**. Down hole pressure data shows the improvement of stimulation jobs with low volume 3PEA system with respect to the conventional acid type by 140% increase (Tables 5 and 6); also we can see 80% rise in it by high volume 3PEA system with respect to the low volume 3PEA system (Tables 6 and 7).

Pressure analysis in wellhead and downhole of the candidate wells confirms the previous results of production rate and skin factor analysis (**Figures 7** and **8**).

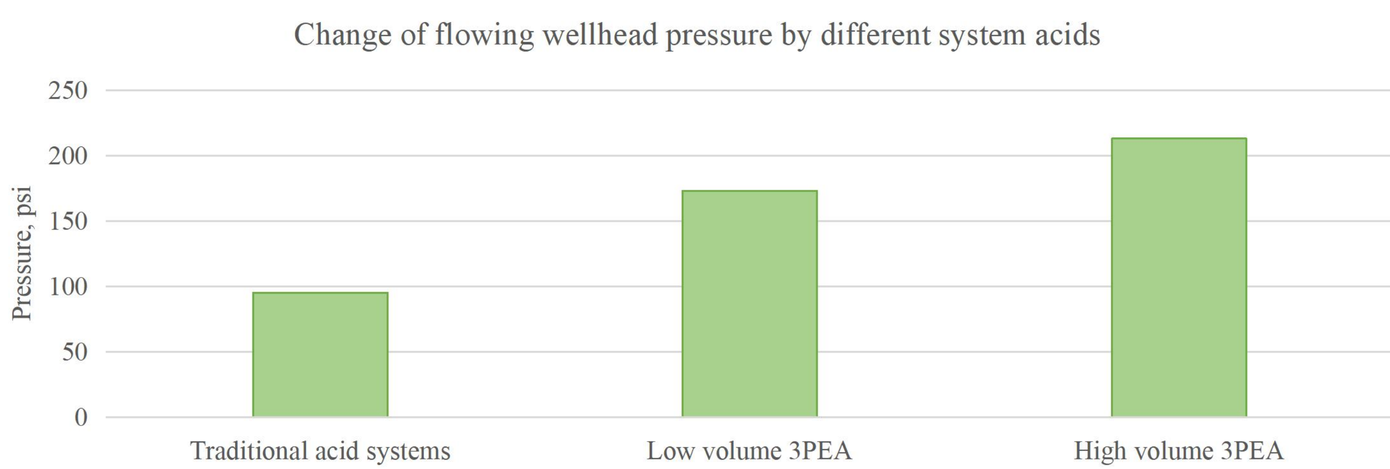

Figure 7—Changes of flowing wellhead pressure by acidizing jobs with different acid system.

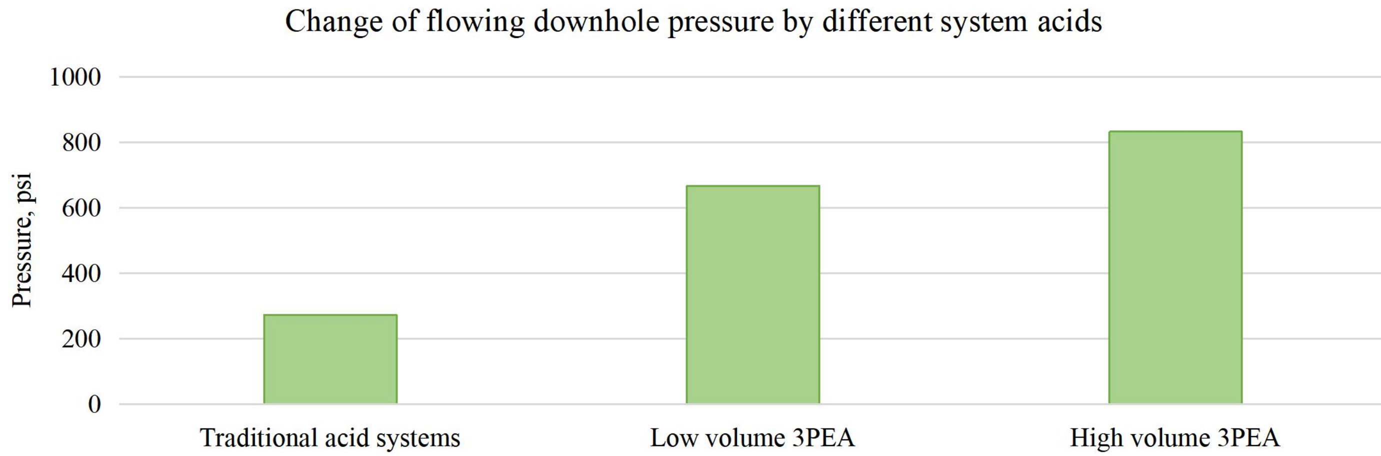

Figure 8—Changes of flowing down hole pressure by acidizing jobs with different acid system.

Conclusions

Acidizing job results confirm the effectiveness of triphase emulsified acid (3PEA) in carbonate reservoirs especially depleted ones with low damage radius around the well bore. Different indices have shown improvement of job performance by using 3PEA. It can be recommended the main acid stage with two sub-stages; firstly an strong 28% HCl to make ready the path fluid and secondary 3PEA with optimum acid volume of about 150 US Gal/ft for HCl 28% and 300 US Gal/ft for 3PEA. We achieved more than 100% increase in production rate and flowing pressure and about 80% higher reduction amount of skin factor by this acid system. The current experience recommends 3PEA application in the wells with perforated interval shorter than 50 ft and in a single stage job. Next surveys can be done to evaluate the effect of 3PEA in longer intervals with an optimum diverter.

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