PETROLEUM SCIENCE AND TECHNOLOGY, 20(3&4), 425–434 (2002)

IMPROVING SANDSTONE MATRIX STIMULATION OF OIL WELLS BY GAS PRECONDITIONING

M. A. Aggour, M. Al-Muhareb,*
S. A. Abu-Khamsin, and A. A. Al-Majed

King Fahd University of Petroleum & Minerals,
Saudi Aramco, Dhahran, Saudi Arabia

ABSTRACT

Experience has shown that for sandstone formations, oil wells respond to matrix acidizing in a different manner as compared to gas wells. For oil wells, the improvement in permeability resulting from the stimulation treatment peaks at a certain acid volume and then drops as the volume of acid injected increases. For gas wells, however, the resulting improvement in permeability is roughly proportional to the volume of acid injected, and is normally better than that obtained with oil wells. It is, therefore, expected that stimulation of oil wells in sandstone formations could be improved by displacing the oil in the zone to be treated with gas. Gas injection prior to acidizing is sought to minimize the formation of emulsions or sludge resulting from reactions between the spent acid products and the oil that otherwise would be contacted. This paper presents the results of an experimental investigation on the effect

*Corresponding author.

of gas pre-conditioning of the damaged oil-bearing sand on permeability improvement by matrix acidizing. Experiments were conducted on Berea sandstone cores saturated with 29.2°API crude oil at actual reservoir temperature of 180°F and pressure of 3000 psi. Carbon dioxide and nitrogen were separately used for pre-conditioning prior to stimulation and the results were compared against stimulation without gas pre-conditioning. It was found that with regular stimulation, improvement in permeability peaked at a certain acid volume. With gas (CO_2 or N_2) pre-conditioning, however, continuous improvement in permeability was obtained with increasing the volume of acid injection. Further, using gas pre-conditioning with a small volume of acid (that would otherwise not be sufficient to even recover the original permeability with regular acidizing) resulted in permeability improvements of up to 200% of the original pre-damage permeability. At an acid volume that would just restore the original permeability with regular stimulation, gas pre-conditioning resulted in permeability improvement close to 300% of the original permeability. Pre-conditioning with either CO_2 or N_2 provided superior results compared to regular stimulation. However, CO_2 was found to be more effective than N_2. This is attributed to the fact that CO_2 has better miscibility than N_2 and would, therefore, provide more efficient displacement of the oil out of the zone to be stimulated.

INTRODUCTION

Sandstone matrix acidizing, employing mud acid systems, is a common operation in oil and gas fields. The main objective of this stimulation operation is to remove near wellbore damage, caused by drilling and/or workover operations, in order to restore or, perhaps improve the permeability of near-wellbore formation. Typically, sandstone matrix stimulation involves three stages: (1) a preflush stage where an aqueous solution of HCl is injected to displace formation brine and dissolve any carbonates that may be present, (2) a mud acid treatment to dissolve siliceous and damaging material, and (3) an afterflush where a solution of HCl is injected to displace the reaction products. Mutual solvents have also been used in the latter stage to restore "Wettability".

Sandstone matrix stimulation has been investigated extensively over the past 40 years. Experimental work has been conducted to investigate the reactions of various mud acid systems with damaging and formation materials (Monaghan et al., 1958; Smith and Hendrickson, 1965; Farley et al., 1970; Gidley, 1971; Sutton and Lasater, 1972; McCune et al., 1975). Some investigators presented theoretical and modeling studies of the stimulation process (Guinn and Schechter, 1971; McCune et al., 1975; Hill et al., 1981). Others presented procedures and design criteria for effective stimulation operations (Shaughnessy and Kunze, 1981; Muecke, 1982; Lea and Sepehrnoori, 1993). An interesting experimental study that explained the formation of sludge and its effect on stimulation efficiency has been presented (Suzuki, 1993). Acid stimulation treatments of horizontal wells and the combined effect of formation damage and presence of impermeable barriers on well productivity have also been investigated (Malekzada et al., 1993).

The above-mentioned studies and many others have provided good understanding of the mechanism of acid stimulation and the means for designing effective acid-stimulation treatment.

The response of sandstone formations to the individual components of the acid system employed was examined for many oil and gas wells in several fields (Gidley, 1985). In this study it was observed that gas wells and oil wells responded differently to the volume of mud acid used in the treatment. For oil wells, the response to the treatment peaked at a certain acid volume (averaging about 75 gal/ft per foot of formation thickness). However, for gas wells, in the range of acid volumes studied (20 to 200 gal/ft), the stimulation response was roughly proportional to the acid volume used. Based on these observations, it was believed that the response of oil wells to matrix stimulation could be improved if the oil well was conditioned, by gas injection prior to the stimulation process, to simulate a gas well for the stimulation treatment. Accordingly, a laboratory study and some field tests were conducted where CO_2 gas was injected prior to the stimulation treatment (Gidley et al., 1993). Gas injection displaced the oil from the zone to be treated and, therefore, eliminated the formation of sludge that otherwise would be produced from reactions between the spent acid and oil. This resulted in appreciable improvement in stimulation response.

It is evident, from the published work, that the crude oil present in the zone to be stimulated reacts with the spent acid products to produce precipitates that are capable of plugging the pore spaces and limiting fluid conductivity. Gas preconditioning of oil wells has been shown to have a potential for improving oil-well stimulation treatments. However, only the work of (Gidley et al., 1993) on this subject has been reported. The objective of the present work is to further study oil-well stimulation improvement by gas preconditioning and to investigate the possibility of using gases other than CO_2 for preconditioning. For this purpose, an experimental study was conducted to investigate the effect of acid volume on permeability improvement resulting from regular acid stimulation and acid stimulation with gas preconditioning. Experiments were conducted under the temperature and pressure conditions of an oil reservoir in the Middle East. The sandstone cores used in the experiments were saturated with crude oil obtained from that reservoir and damaging of the cores was induced using the typical drilling mud used in that field. The effect of the type of gas used for preconditioning was also examined by using carbon dioxide and nitrogen as preconditioning gases.

EXPERIMENTAL SETUP

A schematic of the experimental setup used in the present study is shown in Figure 1. Ruska-type, high-pressure, high-temperature rated core holder was used to hold the 1 in. diameter, 4 in long Berea sandstone core that was placed inside a rubber sleeve. A hand pump was used to apply a 4000 psi confining pressure on the core. A Nitrogen cylinder equipped with a pressure multiplier and backpressure regulator was used to maintain the core at an average pore pressure of 3000 psi. Four transfer cells were

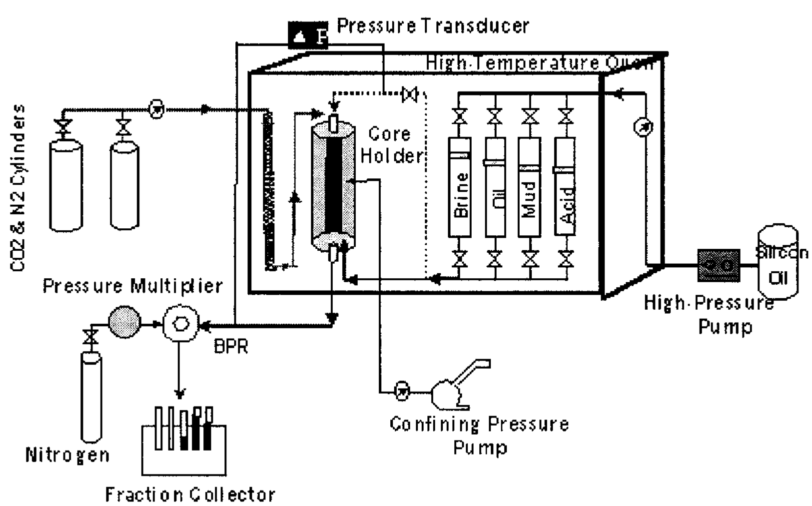

Figure 1. Schematic of the experimental setup.

manifold to a high-pressure positive displacement pump, and to the core holder in such a way that the transferred fluid could be directed to either ends of the core holder.

The cells were used to transfer brine, oil, drilling mud, and acid to the core holder. High-pressure nitrogen and carbon dioxide cylinders, equipped with a pressure regulator and a flow meter, were manifold and used to supply gas to the core holder through a 30 ft stainless steel coil. The core holder, gas supply coil and transfer cells were placed inside a temperature-controlled high-temperature oven. Produced fluids were collected in a fraction collector.

Berea sandstone cores, crude oil having 29.2°API gravity and 5.3 cP viscosity (at 3000 psi and 180°F) and 2% KCl brine were used in the experiments. The drilling mud, having a density of 60 Pcf, was formulated with Bentonite and fresh water. The mud acid used was an aqueous solution of 12% HCl and 3% HF. Nitrogen and carbon dioxide were used separately for gas preconditioning.

EXPERIMENTAL PROCEDURE

Three sets of experiments were conducted. The first set constituted regular acid stimulation treatments using different volumes of acid. This was taken as the base case. The second and third sets of experiments involved N_2 and CO_2 preconditioning, respectively, prior to acidizing.

A fresh core sample was first saturated with brine while under vacuum. Next, the core permeability was determined first at room conditions. Then the pressure and temperature were raised to reservoir conditions and the absolute permeability was again determined using brine. Oil flow was then started to displace the brine and bring its saturation to residual saturation, and the effective oil permeability was determined. Mud circulation was then started to create damage to the core. This was followed by flowing oil through the core and determining the after-damage effective oil permeability. The stimulation process was then implemented using a specific volume of mud acid. Finally, the post stimulation effective oil permeability was determined. The procedure was repeated using different acid volumes to determine the effect of the acid volume used on permeability recovery/improvement.

The same procedure was followed for the second and third sets of experiments, but with the additional step of gas injection (preconditioning) being implemented prior to acidizing.

RESULTS AND DISCUSSION

Stimulation without Gas Preconditioning

A total of seven regular acid stimulation (stimulation without gas preconditioning) experiments were conducted using mud acid volumes ranging from 25 to 320 pore volumes. The results are summarized in Table 1. The last column of Table 1 shows the post treatment permeability as a percent of the original, pre-damage permeability versus pore volumes of mud acid used. The results show that using small volumes of acid (from 25 to less than 150 pore volumes) removed some damage, but did not restore the original permeability. A complete restoration (recovery) of permeability was obtained with 150 pore volumes of acid. At higher acid volumes, improvement over the original permeability was obtained reaching a peak of about 143.6% at 235 pore volumes of acid. The improvement in permeability then dropped with increasing the volume of acid used. This trend is in line with the results of previously published work.

Stimulation with N_2 Preconditioning

Five experiments with N_2 preconditioning were conducted using different acid volumes and different volumes of N_2. The results are summarized in Table 2. With 100 pore volumes of acid used, where regular stimulation could restore only 65% of the original permeability, preconditioning the core with 100 pore volumes of N_2 resulted in a post-treatment permeability of 122% of the original permeability. When 150 pore volumes of acid were used, which were just enough to restore the original permeability

Table 1. Results of Regular Stimulation Experiments

Core	Pore Volumes		Effective Oil Permeability (md)			Permeability
Number	Acid	Gas	Original	After-Dam	After-Acid	% of Original
M-5	25	0	204	45	69	33.8
M-7	50	0	202	23	51	25.2
M-8	75	0	204	50	93	45.6
M-13	100	0	484	135	315	65.1
M-14A	150	0	475	50	478	100.6
M-14B	235	0	475	50	682	143.6
M-14C	320	0	475	50	495	104.2

Table 2. Results of Stimulation with N_2 Preconditioning

Core Number	Pore Volumes		Effective Oil Permeability (md)			Permeability
	Acid	Gas (N_2)	Before-Dam	After-Dam	After-Acid	% of Original
M-19	100	100	200	100	244	122.0
M-25	150	100	315	120	450	142.9
M-26	150	200	320	118	460	143.8
M-33	235	75	550	180	1370	249.1
M-34	320	75	550	140	1778	323.3

without preconditioning, N_2 preconditioning resulted in 143.8% restoration in permeability. Comparing the results of experiments number M-25 and M-26, where 100 and 200 pore volumes of N_2 were respectively used with 150 pore volumes of acid, Table 2, shows that increasing the preconditioning gas volume did not have any effect on permeability improvement. Therefore, the experiments conducted with larger acid volumes employed even smaller preconditioning gas volumes than previously used. The improvement in permeability continued to increase with increasing the treatment acid volume and reached 323% at an acid volume of 320 pore volumes with only 75 pore volumes of N_2 used for preconditioning. Comparing this with the corresponding permeability improvement of 104% with regular stimulation, the advantage of N_2 preconditioning is evident.

Stimulation with CO_2 Preconditioning

Six experiments with CO_2 preconditioning were conducted; the results are summarized in Table 3. Comparing these results with those for regular acid stimulation, Table 1, shows again that stimulation with gas preconditioning results in significant improvement in permeability as compared to regular stimulation. With 100 PV of acid used with CO_2 preconditioning, a post-treatment permeability of 200% of the original permeability was obtained compared to 122% with N_2 preconditioning and only 65% with regular stimulation. The same improvement in permeability was obtained at the two gas volumes used. At 320 PV of acid, the improvement in permeability was 382% compared to 323% for nitrogen preconditioning and only 104% for regular stimulation.

The results show that CO_2 preconditioning has an advantage over N_2 preconditioning. This is believed to be due to the fact that CO_2 has better miscibility than N_2 and, therefore, will be more effective in displacing the

Table 3. Results of Stimulation with CO_2 Preconditioning

Core Number	Pore Volumes: Acid	Pore Volumes: Gas (CO_2)	Effective Oil Permeability (md): Before-Dam	After-Dam	After-Acid	Permeability % of Original
M-35	320	75	550	170	2100	381.8
M-36	235	75	500	135	1650	330.0
M-37	150	100	500	143	1450	290.0
M-38	100	125	550	115	1100	200.0
M-39	150	75	500	180	1500	300.0
M-40	100	75	500	120	1000	200.0

oil from the zone to be treated. The results also show that there was no significant improvement obtained by increasing the preconditioning gas volume above 75 pore volumes.

CONCLUSIONS

To summarize the findings of the present study, the post-stimulation permeability expressed as a percent of the original, pre-damage permeability is plotted versus the pore volumes of acid used for the three sets of experiments in Figure 2.

Examination of the figure leads to the following conclusions:

1. The response to regular matrix stimulation of oil-bearing sandstone formations increases with increasing the volume of acid used, reaches a peak at certain acid volume and, then drops with further increase of acid volume.
2. Gas preconditioning of the damaged oil zone results in a stimulation response similar to that obtained with gas-bearing sandstones, i.e., the response is roughly proportional to the volume of acid used.
3. Preconditioning the damaged zone by gas (either CO_2 or N_2) injection results in significant improvement in the response to matrix stimulation as compared to regular stimulation.
4. With acid volumes, that would not even restore the original permeability in regular stimulation, gas preconditioning would result in improvements over the original permeability.
5. Preconditioning the damaged zone by CO_2 injection produces better response to stimulation treatments as compared to that obtained

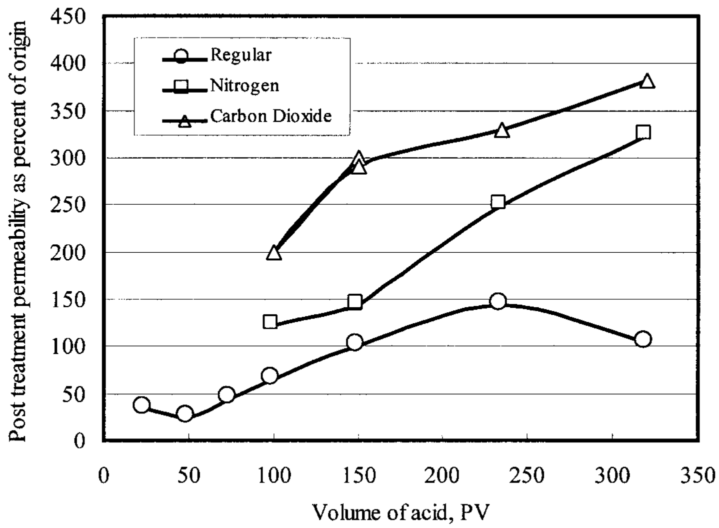

Figure 2. Post-treatment permeability (% of original) vs. PV of acid used.

with N_2 preconditioning. However, N_2 preconditioning may be preferred in some situations to avoid corrosion problems and reduce treatment cost.

ACKNOWLEDGEMENT

The authors would like to acknowledge King Fahd University of Petroleum & Minerals for supporting the present research. One of the authors, Mr. Al-Muhareb, acknowledges Saudi Aramco for sponsoring him during the course of this work. The authors acknowledge the Society of Petroleum Engineers for permission to publish this work, which was presented as paper No. SPE 63180 at the 2000 SPE-ATC held in Dallas, Texas.

REFERENCES

Farley, J.T., Miller, B.M. and Schoettle, V. 1970. Paper No. SPE 2621, JPT. 4: 433–440.

Gidley, J.L. 1971. Paper No. SPE 3007. JPT. 5: 551–558.

Gidley, J.L. 1985. Paper No. SPE 14164. The 60th SPE Annual Technical Conference and Exhibition, Las Vegas, NV, Sept. 22–25.
Gidley, J.L., Brezovec, E.J. and King, G.E. 1993. Paper No. SPE 26580. The 68th SPE Annual Technical Conference and Exhibition, Houston, Texas, October 3–6.
Guinn, J.A. and Schechter, R.S. 1971. Paper No. SPE 3091, SPEJ. 5: 390–398.
Hill, A.D., Lindsay, D.M., Silberberg, I.H. and Schechter, R.S. 1982. Paper No. SPE 6607, SPEJ.
Lea, C.M., Hill, A.D. and Sepehrnoori, K. 1993. Paper No. SPE 22853, SPE Production and Facilities.
Malekzadeh, D., Azari, M. and Day, J.J. 1993. Paper No. SPE 26038, Western Regional Meeting, Anchorage, Alaska, USA, May 26–28.
McCune, C.C., Fogler, H.S., Cunningham, J.R. and Ault, J.W. 1975. Paper No. SPE 5157. The 45th SPE-AIME Annual California Regional Meeting, Ventura, Calif., April 2–4.
Monaghan, P.H., Salathiel, R.A., Morgan, B.E. and Kaiser, A.D. 1958. Paper No. SPE 1162-G, Fall Meeting of Los Angeles Basin Section, Calif., Oct. 16–17, 1958.
Muecke, T.W. 1982. Paper No. SPE 10038. Int. Petroleum Exhibition And Tech. Sym. of the SPE, Beijing, China, March 18–26.
Shaughnessy, C.M., and Kunze, K.R. 1981. Paper No. SPE 9388, JPT. 7.
Smith, C.F. and Hendrickson, A.R. 1965. Paper No. SPE 980.
Sutton, G.D. and Lasater, R.M. 1972. Paper No. SPE 4114. The 47th SPE Annual Fall Meeting, San Antonio, Texas.
Suzuki, F.1993. Paper No. SPE 26036, Western Regional Meeting, Anchorage, Alaska, USA, May 26–28.

Received April 25, 2001
Accepted May 18, 2001