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A New Technique for Converting Acid Core Data to Field Application

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طريقة جديدة لتحويل نتائج تحميض العينات اللبية لتطبيقها عملياً

نهاد الهمالي ومحمد نصر

تعتبر عملية تحميض نسيج الصخر من أكثر عمليات تنشيط الآبار شيوعاً وتستخدم لتحسين النفاذية الأصلية للمكامن الكربونية. تستهدف المعالجة باستخدام الحامض إزالة التضرر في الطبقات الناجم عن عمليات الحفر والإنتاج والضخ. وخلال عملية معالجة نسيج صخور المكمن بالحمض تتكون قنوات عميقة حول قاع البئر تسمى القنوات الدودية، ولإنجاح عملية المعالجة بالحمض لابد من تحديد الحجم والتركيز الأمثلين للحمض المستخدم للحصول على أقصى تحسن في نفاذية المنطقة المعالجة.

لتحقيق أقصى تحسن في النفاذية يجب إجراء تجارب معملية لعينات لبية من الصخور الجيرية يتم من خلالها تحديد كل من الحجم والتركيز الأمثلين للحمض. وقد استخلص من خلال التجارب إمكانية الحصول على منحنى بياني لفعالية الحمض يمثل العلاقة بين حجم الحمض التراكمي لملء المسامات ونسبة التنشيط وذلك لكل مكمن يراد معالجته. وباستخدام هذا المنحنى يمكن تحديد حجم الحمض المراد ضخه داخل مسام المكمن.

تشير نتائج الدراسة إلى أن نفاذية الصخور الكربونية يمكن زيادتها بزيادة كمية الحمض المحقون للعينات الصخرية، وهذه الزيادة في النفاذية تصل إلى حد أقصى عندما تكون كمية الحمض المحقون قد وصلت إلى كميات مناسبة. أي زيادة في حجم الحمض المحقون أكثر من الحجم المثالي منه، سوف ينتج عنها تأثيراً عكسياً يؤدي إلى انخفاض في النفاذية للعينة اللبية المراد تحسين نفاذيتها. تقدم هذه الدراسة طريقة جديدة لتطبيق نتائج معالجة العينات اللبية المعملية في الحقول النفطية تحت الظروف الموجودة بالمكامن النفطية.

Abstract: *Matrix acidizing is commonly used as a well stimulation process for improving the original matrix permeability of carbonate reservoirs. Acid stimulation treatment is also used for removal of formation damage resulting from drilling, injection or production operations. In matrix acidizing, deep penetration of wormholes around the well bore is formed. For successful acid treatment it is necessary to determine the optimum acid volume and concentration needed for obtaining the maximum stimulation permeability for the treated zone.*

Experimental studies should be conducted on actual carbonate cores to estimate the optimum acid concentration and the injection volume of acid to improve the permeability of the damaged area. It was concluded that acid performance curve, which is represented by cumulative acid pore volume versus stimulation ratio could be determined experimentally for each reservoir to be treated.

This curve can be used for the determination of the required acid pore volume to be injected into the reservoir.

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The results of this study indicate that there is an optimum acid volume to be injected in order to produce maximum rock stimulated permeability. Excessive injected acid volume more than the optimum value will produce an adverse effect of lowering the permeability of the stimulated core. A new correlation technique for converting acid core data to field conditions is presented in this study.

INTRODUCTION

The purpose of any stimulation technique is to increase the permeability near the wellbore for a damaged or low permeability reservoir. Acidizing increases the permeability by reacting with and removing some of the rock materials. When a well is not producing as expected, the formation may be damaged. If a production evaluation indicates the reservoir can deliver more fluid, stimulation may be needed. Typically, damage is associated with a partial plugging of the formation around the wellbore, which results in reducing the original permeability in the damaged zone. In order to restore the original production of the well, it is, therefore, necessary to remove damage or create new bypassing channels, which are called wormholes, in the damaged area. To remove damage, acid is injected into the natural porosity of the reservoir at matrix rates and at injection pressure below the matrix fracturing pressure.

Hydrochloric acid (HCl) is commonly used for acidizing carbonate reservoirs and it is also used for removing formation damage that consists of materials soluble in this type of acid. HCl acid is inexpensive, it reacts rapidly with most rock types, and the reaction by-products of the acid and rock are fairly easily removed from the wellbore and the adjacent formation.

The reaction of HCl with limestone and dolomite is presented by the following chemical formulas respectively:

$2HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O$

$4HCl + CaMg(CO_3)_2 \rightarrow CaCl_2 + MgCl_2 + 2CO_2 + 2H_2O$

An acid treatment should be designed to achieve its function at lowest possible cost. The design requires considerations of many physical and chemical interactions taking place between the injected fluids and the reservoir minerals and fluids present in the rocks. The most important of these phenomena are[1]:

- Mass transfer of acid molecules to the mineral surface. Acid reactions with minerals are termed heterogeneous reactions because they occur at the boundary between the solid and liquid rather than in bulk phases.
- The physical change in the pore structure caused by dissolution of some minerals by acid is the mechanism by which matrix acidizing increases permeability. The manner in which the pore structure changes is fundamentally different in carbonates and sandstone, which leads to radically different approaches in modeling the acidizing process.
- Secondary reactions occur in acidizing that can result in precipitation of reaction products from bulk liquid phase. Obviously, precipitated solids may block pore spaces and work against the goal of matrix acidizing.
- A successful acidizing treatment requires contacting all damaged regions around the wellbore with acid. This is usually complicated by variation in the injectivity to acid along the wellbore, which leads to the use of special acidizing techniques to obtain good acid coverage (acid diversion).
- Some other acids such as chemically retarded acids and viscous emulsified acids or hydrochloric acid containing effective fluid loss additives are used in matrix acidizing to increase the stimulation efficiency.

For a successful carbonate matrix stimulation treatment, it is important to acidize under conditions that will lead to the formation of deep penetration wormholes using minimal acid volumes. In order to achieve a successful acid treatment, the acid job should be designed at optimum field injection conditions. It is, therefore, necessary before injecting acid into the treated formation, that the concentration of the acid and the injection volume are determined before acid stimulation process is carried out[2].

Scaling-up the laboratory acid core data to field conditions is the main issue in the application of acid stimulation to field conditions. There are two methods of scaling-up acid laboratory data to field conditions, which are based on wormhole propagation and density (wormhole number per unit surface area)[3]. The simplest method involves scaling-up the reaction rate to maintain the same velocity into the matrix. This method inherently assumes that the wormhole density is the same in the field as in the laboratory experiments. The second method uses the wormhole density and surface area to scale-up the dissolution in the field[3]. If it were possible to predict the number, the diameter and the propagation of the wormholes, then the increasing permeability around the wellbore could be predicted. Unfortunately, this prediction is not possible experimentally or theoretically [2,3]. Most of the published models claim that wormhole penetration distance is predominantly controlled by formation porosity and acid volume. These methods are currently introducing many simplifications to predict the acid volume injected at optimum acid injection rate for the treated well [4,5]. These oversimplifications fail to take into account the relevant physical mechanisms of wormhole formation and propagation and therefore, the models are not reliable enough for extrapolating laboratory data to the reservoir [5].

The challenge of scaling-up the fundamental mechanics of carbonate dissolution to field conditions is the difficulty in translating the acid efficiency from one geometry and size to a different geometry and size in a manner that leads itself to easy utilization by those requiring a carbonate stimulation model[2].

For a carbonate acidizing model to be useful to the industry, it must correctly capture the fundamental characteristics of the dissolution phenomenon, correctly scale-up the phenomenon to field conditions and require basic input parameters that are readily available. Any acid treatment method or model will first be validated for fundamental consistency using laboratory data before using it in field applications [3].

THE NEW SCALING-UP PROCEDURE

In this study, a new quantitative technique for scaling-up laboratory acid core data (acid pore volume injected) to field applications is set up, based on converting the acid performance curve obtained from the laboratory experiments to field performance curve, from which acid penetration radius and injection volume can be predicted.

The scaling-up procedure is run as follows:

1- Perform acid flooding laboratory experiments on actual core samples collected from the candidate well for acid treatment.

2 - Construct the laboratory acid performance curve for all the core plugs by plotting the cumulative acid pore volume injected versus the stimulation ratio ($\overline{k_s/k_e}$).

3 - The laboratory acid performance curve is converted to field performance curve using the following technique:

a - Assume different radii (r_s) to be acidized.

b - Assume the acid will dissolve different percentage of mineral volume (χ).

c - Calculate the original reservoir rock pore volume invaded by acid including the rock pore volume generated by acid dissolution to an assumed radius (r_s), using the following equation:

$$V_r = V_{pi} + V_{rs} \tag{1}$$

$$V_r = \pi h \phi (r_s^2 - r_w^2)(1 - S_{or}) + \frac{\pi h (1-\phi)\chi (r_s^2 - r_w^2)}{\beta} \tag{2}$$

β (the dissolving power of the acid) is calculated from the following equation:

$$\beta = \frac{v_{minral}\, MW_{mineral}}{v_{acid}\, MW_{acid}} \tag{3}$$

As was mentioned before, 2 moles of hydrochloric acid (HCl) react with 1 mole of limestone (CaCO3), thus the β_{100} is:

$$\beta_{100} = \frac{(1)(100.1)}{(2)(36.5)} \tag{4}$$

The dissolving power of 28% HCl concentration is:

$$\beta_{28\%} = 0.28 \times \beta_{100} \tag{5}$$

Then, the volumetric dissolving power is:

$$\beta = \beta_{28\%} \frac{\rho_{acid\ solution}}{\rho_{mineral}} \tag{6}$$

4 - Considering the acid injection condition in the laboratory is the same as that of the reservoir, then

$$(P.V.I)_{lab.} = (P.V.I)_{field} \tag{7}$$

5 - Calculate the acid volume (V_s) knowing $(P.V.I)_{field}$ that gives the optimum increase in the stimulation ratio for the considered radius(r_s).

$$(P.V.I)_{field} = \frac{V_s}{V_r} \tag{8}$$

6 - Repeat the previous steps for each assumed acid penetration radius (r_s).

7 - Plot the relation between the acid volumes injected per foot and each acid penetration radius for each assumed, χ.

RESULTS AND DISCUSSION

The data used in this study were taken from the laboratory acid study for core samples collected from wells located in one of the biggest fields in Libya. The reservoir, from which the core samples were taken, consists of a calcareous limestone formation. Very high formation damage has been observed by the production tests on appraisal wells B1, B2, B4 and B6 in this field. An acid stimulation study was conducted on actual core samples collected from C and E layers of well B4. The acid stimulation study (the laboratory acid core tests) was carried out on these selected core samples by injecting different pore volumes of a regular acid and acid mixture at simulated reservoir conditions. The improvement of the permeability of these tested cores was determined after each acid pore volume injected.

HCl was used in this study at 28% concentration as a regular acid and mixed with different acid mixtures. The formulation of the injected acid mixture is described below:

- 28% HCl chemically retarded.
- 28% HCl in emulsion with oil.
- 28% HCl with diverting agent.

The physical properties and the perforated intervals for B1, B2 and B6 wells are illustrated in Table 1.

Experimental acid core data for layers C and E at different acid mixtures are illustrated in Tables 2 and 3 respectively. The laboratory acid performance curves for these layers C and E were constructed by plotting the cumulative acid pore volume injected versus the stimulation ratio ($\overline{k_s/k_e}$) (Figs. 1 and 2).

The acid performance curve for layer C (Fig.1) indicates that emulsified HCl and retarded HCl acids produced higher acid stimulation ratio compared to 28% HCl acid without additives. The figure also shows that 28% HCl concentration with different acid additives reached maximum stimulation ratio approximately at the same acid pore volume injected. From figure 2, the injection of 28% HCl concentration without additives causes damage to the permeability of the core. Each of the emulsified, retarded and diverted HCl acids gives different stimulation ratio improvements at varying acid pore volumes.

From figures 1 and 2, it can be noticed that the stimulation performance of each treated core is dependent on the amount of acid injected through the core. It can also be noticed that maximum stimulation ratio is reached at optimum acid volumes injected. Additional volumes of the injected acid higher than the optimum values will produce decreasing stimulation ratio values.

According to the acid laboratory performance curve for zone C (Fig. 1), the stimulation ratio starts to increase at acid pore volumes of 7.7, 8.2, 8.5 and 8.7 for 28% HCl, 28% HCl emulsified, 28% HCl retarded and 28% HCl diverted respectively. For zone E, the increase in the stimulation ratio (Fig. 2) started at injected acid pore volumes of 5.5, 5.7 and

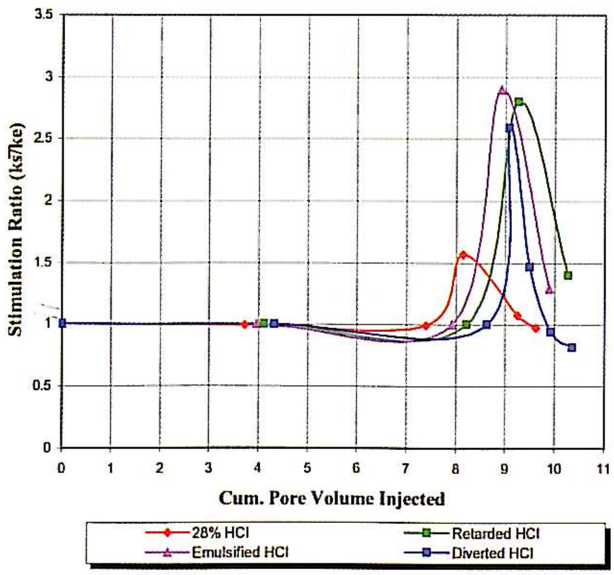

Fig. 1. Laboratory acid performance curve layer(C).

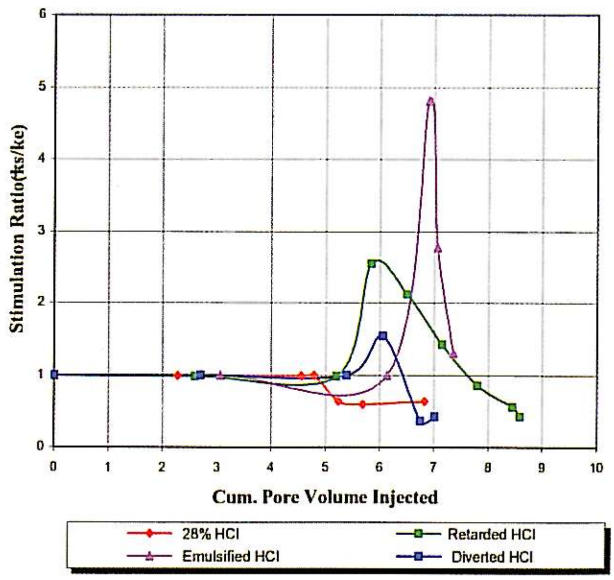

Fig. 2. Laboratory acid performance curve layer (E).

Table 1. Formation damaged intervals of the three wells.

Welll	Interval	Zone	h (ft)	ϕ (%)	S_{or} (%)	r_w (ft)
B1	(8206 – 8222)	C	16	12	10	0.35
B1	(8350 – 8440)	E	90	22	29	0.35
B2	(8525 – 8552)	E	27	28	43	0.35
B2	(8354 – 8420)	C	50	8	25	0.35
B6	(8478 – 8518)	C	40	9	20	0.35

Table 2. The laboratory acid core data for four core samples taken from layer (C) treated with different acid mixtures.

28% HCl		Emulsified 28%HCl		Retarded 28% HCl		Diverted 28% HCl	
Cum. acid pore volume	$\overline{k_s}/k_e$	Cum. acid pore volume	$\overline{k_s}/k_e$	Cum. acid pore volume	$\overline{k_s}/k_e$	Cum. acid pore volume	$\overline{k_s}/k_e$
0	1	0	1	0	1	0	1
3.7	0.99	3.95	1	4.11	1	4.31	1
7.39	0.99	7.91	1	8.22	1	8.62	1
8.13	1.57	8.9	2.9	9.25	2.8	9.06	2.59
9.24	1.07	9.88	1.29	10.27	1.4	9.49	1.47
9.61	0.97					9.92	0.94
						10.35	0.81

Table 3. The laboratory acid core data for four core samples taken from layer (E) treated with different acid mixtures.

28% HCl		Emulsifed 28% HCl		Retarded 28% HCl		Diverted 28%HCl	
Cum. acid P.V.I	$\overline{k_s}/k_e$	Cum. acid P.V.I	$\overline{k_s}/k_e$	Cum. acid P.V.I	$\overline{k_s}/k_e$	Cum. acid	$\overline{k_s}/k_e$
0	1	0	1	0	1	0	1
2.27	0.99	3.06	1	2.6	0.98	2.7	1
4.55	0.99	6.13	1	5.2	0.98	5.39	1
4.78	1	6.89	4.81	5.85	2.55	6.06	1.54
5.23	0.63	7.05	2.78	6.5	2.12	6.74	0.36
5.69	0.59	7.35	1.3	7.15	1.42	7.01	0.42
6.82	0.63			7.8	0.85		
				8.45	0.56		
				8.58	0.42		

6.4 for the 28% HCl, 28% retarded HCl, 28% diverted HCl and 28% emulsified HCl respectively.

Using the above-mentioned scale-up procedure outlined in equations 1 through 8, the laboratory acid performance curves for layers C and E, (Figs.1and 2 respectively), were utilized to calculate the required acid injection volume at radial distances of 1, 1.75, 2 and 3 ft away from the wellbore for different percentages of acid rock dissolution of 2%, 3% and 5% for the studied wells of B1, B2 and B6 from the field. The calculated acid injection volumes (gal/ft) for each acid rock dissolution percentage are presented in Tables 4 through 18. The tables contain acid stimulation ratios from each laboratory acid performance curve for each considered radius at selected acid injection pore volumes for maximum

Table 4. The minimum and maximum acid field volumes and the penetration radius of acid: well B1 zone C for rock dissolution of 2%.

		28%HCl				Emulsified 28%HCl				Retded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft
		7.7	1.15	13	34	8.3	1.3	14	37	8.5	1.2	14.5	38	8.7	1.1	15	39
1	9.58	7.9	1.3	13.5	35	8.5	1.6	14.5	38	8.9	1.7	15	39	8.9	1.3	15	39
		8.13	1.56	14	37	8.9	2.9	15	39	9.3	2.8	16	42	9.06	2.59	15	39
		7.7	1.15	44	116	8.3	1.3	47	123	8.5	1.2	48	126	8.7	1.1	50	131
1.75	32	7.9	1.3	45	118	8.5	1.6	48	126	8.9	1.7	51	134	8.9	1.3	51	134
		8.13	1.56	46	121	8.9	2.9	51	134	9.3	2.8	53	139	9.06	2.59	52	136
		7.7	1.15	58	152	8.3	1.3	62	163	8.5	1.2	64	168	8.7	1.1	65	171
2	42.3	7.9	1.3	60	157	8.5	1.6	64	168	8.9	1.7	67	176	8.9	1.3	66	173
		8.13	1.56	61	160	8.9	2.9	67	176	9.3	2.8	70	184	9.06	2.59	68	178
		7.7	1.15	133	349	8.3	1.3	143	375	8.5	1.2	147	386	8.7	1.1	150	394
3	97	7.9	1.3	136	357	8.5	1.6	147	386	8.9	1.7	154	404	8.9	1.3	152	399
		8.13	1.56	140	367	8.9	2.9	154	404	9.3	2.8	161	423	9.06	2.59	156	409

Table 5. The minimum and maximum acid field volumes and the penetration radius of acid: well B1 zone C for rock dissolution of 3%.

		28%HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft
		7.7	1.15	16	42	8.3	1.3	18	47	8.5	1.2	18	47	8.7	1.1	18	47
1	12	7.9	1.3	17	44	8.5	1.6	18	47	8.9	1.7	19	50	8.8	1.3	19	50
		8.13	1.56	17	45	8.9	2.9	19	50	9.3	2.8	20	52	9.06	2.59	19	50
		7.7	1.15	55	144	8.3	1.3	59	155	8.5	1.2	61	160	8.7	1.1	62	163
1.75	40.2	7.9	1.3	56	147	8.5	1.6	61	160	8.9	1.7	64	168	8.8	1.3	63	165
		8.13	1.56	58	152	8.9	2.9	64	168	9.3	2.8	66	173	9.06	2.59	65	171
		7.7	1.15	72	189	8.3	1.3	78	205	8.2	1.2	80	210	8.7	1.1	82	215
2	52.9	7.9	1.3	74	194	8.5	1.6	80	210	8.9	1.7	84	220	8.8	1.3	83	218
		8.13	1.56	76	199	8.9	2.9	84	220	9.3	2.8	88	231	9.06	2.59	85	223
		7.7	1.15	166	436	8.3	1.3	179	470	8.5	1.2	184	483	8.7	1.1	188	493
3	121.3	7.9	1.3	171	449	8.5	1.6	184	483	8.9	1.16	192	504	8.8	1.3	190	500
		8.13	1.56	176	462	8.9	2.9	192	504	9.3	2.7	201	528	9.06	2.59	196	514

Table 6. The minimum and maximum acid field volumes and the penetration radius of acid: well B1 zone C for rock dissolution of 5%.

		28%HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft
		7.7	1.15	23	60	8.3	1.3	25	66	8.5	1.2	25	66	8.7	1.1	26	68
1	16.8	7.9	1.3	24	63	8.5	1.6	25	66	8.9	1.7	27	71	8.8	1.3	26	68
		8.13	1.56	24	63	8.9	2.9	27	71	9.3	2.8	28	73	9.06	2.59	27	71
		7.7	1.15	77	202	8.3	1.3	83	218	8.5	1.2	85	223	8.7	1.1	87	228
1.75	56.3	7.9	1.3	79	207	8.5	1.6	85	223	8.9	1.7	89	234	8.8	1.3	88	231
		8.13	1.56	81	213	8.9	2.9	89	234	9.3	2.8	93	244	9.06	2.59	91	239
		7.7	1.15	102	268	8.3	1.3	110	289	8.5	1.2	112	302	8.7	1.1	115	302
2	74.2	7.9	1.3	104	273	8.5	1.6	112	294	8.9	1.7	118	309	8.8	1.3	116	304
		8.13	1.56	107	281	8.9	2.9	118	309	9.3	2.8	123	323	9.06	2.59	120	315
		7.7	1.15	233	612	8.3	1.3	251	659	8.5	1.2	257	674	8.7	1.1	263	690
3	170	7.9	1.3	239	627	8.5	1.6	257	674	8.9	1.7	269	706	8.8	1.3	266	698
		8.13	1.56	246	645	8.9	2.9	269	706	9.3	2.8	281	737	9.06	2.59	274	719

Table 7. The minimum and maximum acid field volumes and the penetration radius of acid: well B2 zone C for rock dissolution of 2%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	24	7.7 7.8 8.13	1.15 1.3 1.56	33 34 35	28 28 29	8.3 8.5 8.9	1.3 1.6 2.9	35 36 38	29 30 32	8.5 8.9 9.3	1.2 1.7 2.8	36 38 40	30 32 34	8.7 8.8 9.06	1.1 1.3 2.59	37 38 39	31 32 33
1.75	80.45	7.7 7.8 8.13	1.15 1.3 1.56	110 113 116	92 95 97	8.3 8.5 8.9	1.3 1.6 2.9	119 122 127	100 102 107	8.5 8.9 9.3	1.2 1.7 2.8	122 127 133	102 107 112	8.7 8.8 9.06	1.1 1.3 2.59	125 126 130	105 106 109
2	105	7.7 7.8 8.13	1.15 1.3 1.56	144 148 152	121 124 128	8.3 8.5 8.9	1.3 1.6 2.9	155 159 166	130 133 139	8.5 8.9 9.3	1.2 1.7 2.8	159 166 174	133 139 146	8.7 8.8 9.06	1.1 1.3 2.59	163 164 169	137 138 142
3	242.9	7.7 7.8 8.13	1.15 1.3 1.56	333 342 352	280 287 296	8.3 8.5 8.9	1.3 1.6 2.9	359 368 385	302 309 323	8.5 8.9 9.3	1.2 1.7 2.8	368 385 402	309 323 337	8.7 8.8 9.06	1.1 1.3 2.59	376 381 392	316 320 329

Table 8. The minimum and maximum acid field volumes and the penetration radius of acid: well B2 zone C for rock dissolution of 3%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	31.9	7.7 7.9 8.13	1.15 1.3 1.56	44 45 46	37 38 39	8.3 8.5 8.9	1.3 1.6 2.9	47 48 50	39 40 42	8.5 8.9 9.3	1.2 1.7 2.8	48 50 53	40 42 44	8.7 8.8 9.06	1.1 1.3 2.59	49 50 51	41 42 43
1.75	106.8	7.7 7.9 8.13	1.15 1.3 1.56	147 150 155	123 126 130	8.3 8.5 8.9	1.3 1.6 2.9	158 162 169	133 136 142	8.5 8.9 9.3	1.2 1.7 2.8	162 169 177	136 142 149	8.7 8.8 9.06	1.1 1.3 2.59	165 167 172	139 140 144
2	139.8	7.7 7.9 8.13	1.15 1.3 1.56	192 197 202	161 165 170	8.3 8.5 8.9	1.3 1.6 2.9	207 212 221	174 178 186	8.5 8.9 9.3	1.2 1.7 2.8	212 221 231	178 186 194	8.7 8.8 9.06	1.1 1.3 2.59	217 219 225	182 184 189
3	322.5	7.7 7.9 8.13	1.15 1.3 1.56	442 454 467	371 381 392	8.3 8.5 8.9	1.3 1.6 2.9	477 488 511	401 410 429	8.5 8.9 9.3	1.2 1.7 2.8	488 511 534	420 429 448	8.7 8.8 9.06	1.1 1.3 2.59	500 505 520	420 424 437

Table 9 . The minimum and maximum acid field volumes and the penetration radius of acid: well B2 zone C for rock dissolution of 5%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	47.7	7.7 7.9 8.13	1.15 1.3 1.56	65 67 69	55 56 58	8.3 8.5 8.9	1.3 1.6 2.9	70 72 76	59 60 64	8.5 8.9 9.3	1.2 1.7 2.8	72 76 79	60 64 66	8.7 8.8 9.06	1.1 1.3 2.59	74 75 77	62 63 65
1.7 5	159.6	7.7 7.9 8.13	1.15 1.3 1.56	219 224 231	184 188 194	8.3 8.5 8.9	1.3 1.6 2.9	236 242 253	198 203 212	8.5 8.9 9.3	1.2 1.7 2.8	242 253 264	203 212 222	8.7 8.8 9.06	1.1 1.3 2.59	247 250 257	207 210 216
2	209.3	7.7 7.9 8.13	1.15 1.3 1.56	287 294 303	241 247 254	8.3 8.5 8.9	1.3 1.6 2.9	309 317 332	259 266 279	8.5 8.9 9.3	1.2 1.7 2.8	317 332 347	266 279 291	8.7 8.8 9.06	1.1 1.3 2.59	324 328 338	272 275 284
3	481.8	7.7 7.9 8.13	1.15 1.3 1.55	661 678 698	555 569 586	8.3 8.5 8.9	1.3 1.6 2.9	712 729 764	598 612 642	8.5 8.9 9.3	1.2 1.7 2.8	729 764 800	612 642 672	8.7 8.8 9.06	1.1 1.3 2.59	627 755 777	627 634 652

Table 10. The minimum and maximum acid field volumes and the penetration radius of acid: well B6 zone C for rock dissolution 2%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	$P.V.I_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	20.4	7.7	1.15	28	29	8.3	1.4	30	31	8.5	1.2	31	33	8.7	1.1	32	34
		7.9	1.3	29	30	8.5	1.6	31	33	8.9	1.7	32	34	8.8	1.3	32	34
		8.13	1.56	29	30	8.9	2.9	32	34	9.3	2.8	34	36	9.06	2.59	33	35
1.75	68.3	7.7	1.15	94	99	8.3	1.4	101	106	8.5	1.2	103	108	8.7	1.1	106	111
		7.9	1.3	96	101	8.5	1.6	103	108	8.9	1.7	108	113	8.8	1.3	107	112
		8.13	1.56	99	104	8.9	2.9	108	113	9.3	2.8	113	119	9.06	2.59	110	115
2	90.2	7.7	1.15	124	130	8.3	1.4	133	140	8.5	1.2	136	143	8.7	1.1	140	147
		7.9	1.3	127	133	8.5	1.6	136	143	8.9	1.7	143	150	8.8	1.3	141	148
		8.13	1.56	131	137	8.9	2.9	143	150	9.3	2.8	149	156	9.06	2.59	145	152
3	206.3	7.7	1.15	283	297	8.3	1.4	305	320	8.5	1.2	312	328	8.7	1.1	320	336
		7.9	1.3	290	304	8.5	1.6	312	328	8.9	1.7	327	343	8.8	1.3	323	339
		8.13	1.56	299	314	8.9	2.9	327	343	9.3	2.8	342	359	9.06	2.59	333	350

Table 11. The minimum and maximum acid field volumes and the penetration radius of acid : well B6 zone C for rock dissolution of 3%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	$P.V.I_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	26.6	7.7	1.15	36	38	8.3	1.3	39	41	8.5	1.2	40	42	8.7	1.1	41	43
		7.9	1.3	37	39	8.5	1.6	40	42	8.9	1.7	42	44	8.8	1.3	42	44
		8.13	1.56	38	40	8.9	2.9	42	44	9.3	2.79	44	46	9.06	2.59	43	45
1.75	89.2	7.7	1.15	122	128	8.3	1.3	132	139	8.5	1.2	135	142	8.7	1.1	138	145
		7.9	1.3	125	130	8.5	1.6	135	142	8.9	1.7	141	148	8.8	1.3	140	147
		8.13	1.56	129	135	8.9	2.85	141	148	9.3	2.75	148	155	9.06	2.59	144	151
2	117.7	7.7	1.15	161	169	8.3	1.3	174	183	8.5	1.2	178	187	8.7	1.1	182	191
		7.9	1.3	165	171	8.5	1.6	178	187	8.9	1.7	186	195	8.8	1.3	184	193
		8.13	1.56	170	178	8.9	2.85	186	195	9.3	2.8	195	205	9.06	2.59	190	199
3	269.3	7.7	1.15	369	387	8.3	1.3	398	418	8.5	1.2	408	428	8.7	1.1	417	438
		7.9	1.3	378	393	8.5	1.6	408	428	8.9	1.7	427	448	8.8	1.3	422	443
		8.13	1.55	390	409	8.9	2.9	427	448	9.3	2.7	446	468	9.06	2.59	434	456

Table 12. The minimum and maximum acid field volumes and the penetration radius of acid: well B6 zone C for rock dissolution of 5%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	$P.V.I_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	39	7.7	1.15	53	56	8.3	1.3	58	61	8.5	1.2	59	62	8.7	1.1	60	63
		7.9	1.3	55	58	8.5	1.6	59	62	8.9	1.7	62	65	8.8	1.3	61	64
		8.13	1.56	56	59	8.9	2.9	62	65	9.3	2.8	64	67	9.06	2.59	63	66
1.75	131	7.7	1.15	180	189	8.3	1.3	194	204	8.5	1.2	198	208	8.7	1.1	203	213
		7.9	1.3	184	193	8.5	1.6	198	208	8.9	1.7	208	218	8.8	1.3	205	215
		8.13	1.56	190	199	8.9	2.85	208	218	9.3	2.8	217	228	9.06	2.59	211	221
2	172.7	7.7	1.15	237	249	8.3	1.3	255	268	8.5	1.2	261	274	8.7	1.1	267	280
		7.9	1.3	243	255	8.5	1.6	261	274	8.9	1.7	274	288	8.8	1.3	271	284
		8.13	1.56	250	262	8.9	2.85	274	288	9.3	2.8	286	300	9.06	2.59	279	293
3	395.4	7.7	1.15	542	569	8.3	1.3	584	613	8.5	1.2	598	628	8.7	1.1	613	644
		7.9	1.3	556	584	8.5	1.6	598	628	8.9	1.7	627	658	8.8	1.3	620	651
		8.13	1.55	572	601	8.9	2.8	627	658	9.3	2.8	655	688	9.06	2.59	638	670

Table 13. The minimum and maximum acid field volumes and the penetration radius of acid : well B1 zone E for rock dissolution of 2%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft
		–	–	–	–	6.4	1.25	72	34	5.5	1.18	61	28	5.7	1.1	64	30
1	62.8					6.6	2	74	35	5.6	1.6	63	29	5.8	1.3	65	30
						6.89	4.81	77	36	5.85	2.55	65	30	6.06	1.54	68	32
		–	–	–	–	6.4	1.25	240	112	5.5	1.18	206	96	5.7	1.1	213	99
1.75	210.3					6.6	2	247	115	5.6	1.6	210	98	5.8	1.3	217	101
						6.89	4.81	258	120	5.85	2.55	219	102	6.06	1.54	227	106
		–	–	–	–	6.4	1.25	316	147	5.5	1.18	272	127	5.7	1.1	281	131
2	277.3					6.6	2	326	152	5.6	1.6	276	129	5.8	1.3	286	133
						6.89	4.81	340	159	5.85	2.55	289	135	6.06	1.54	299	135
		–	–	–	–	6.4	1.25	724	338	5.5	1.18	622	290	5.7	1.1	645	301
3	635					6.6	2	746	348	5.6	1.6	633	295	5.8	1.3	656	306
						6.89	4.81	779	363	5.85	2.55	661	308	6.06	1.54	685	320

Table 14. The minimum and maximum acid field volumes and the penetration radius of acid: well B1 zone E for rock dissolution of 3%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft
		–	–	–	–	6.4	1.25	85	40	5.5	1.18	73	34	5.7	1.1	76	35
1	74.8					6.6	2	88	41	5.6	1.6	75	35	5.8	1.3	77	36
						6.89	4.81	92	43	5.85	2.55	78	36	6.06	1.54	81	38
		–	–	–	–	6.4	1.25	285	133	5.5	1.18	245	114	5.7	1.1	254	118
1.75	250.5					6.6	2	294	137	5.6	1.6	250	117	5.8	1.3	259	121
						6.89	4.81	307	143	5.85	2.55	261	122	6.06	1.54	270	126
		–	–	–	–	6.4	1.25	376	175	5.5	1.18	324	151	5.7	1.1	335	156
2	330.4					6.6	2	388	181	5.6	1.6	329	153	5.8	1.3	341	159
						6.89	4.81	405	189	5.85	2.55	344	160	6.06	1.54	357	167
		–	–	–	–	6.4	1.25	862	402	5.5	1.18	751	350	5.7	1.1	768	358
3	756.5					6.6	2	889	415	5.6	1.6	754	352	5.8	1.3	781	364
						6.89	4.81	926	432	5.85	2.55	788	368	6.06	1.54	816	381

Table 15. The minimum and maximum acid field volumes and the penetration radius of acid : well B1 zone E for rock dissolution of 5%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	P.V.I$_{field}$ (Vs/Vr)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft	P.V.I$_{field}$ (V_s/V_r)	$\bar{k}_s/k_c$	Vs (bbl)	gal/ft
		–	–	–	–	6.4	1.25	113	53	5.5	1.18	97	45	5.7	1.1	100	47
1	98..8					6.6	2	116	54	5.6	1.6	98	46	5.8	1.3	102	48
						6.89	4.81	121	56	5.85	2.55	103	48	6.06	1.54	107	50
		–	–	–	–	6.4	1.25	377	176	5.5	1.18	324	151	5.7	1.1	336	157
1.75	331					6.6	2	389	181	5.6	1.6	330	154	5.8	1.3	342	160
						6.89	4.81	406	189	5.85	2.55	345	161	6.06	1.54	357	167
		–	–	–	–	6.4	1.25	498	232	5.5	1.18	428	200	5.7	1.1	443	207
2	436..6					6.6	2	513	239	5.6	1.6	435	203	5.8	1.3	451	210
						6.89	4.81	536	250	5.85	2.55	456	213	6.06	1.54	471	220
		–	–	–	–	6.4	1.25	1139	531	5.5	1.18	979	457	5.7	1.1	1015	474
3	999..6					6.6	2	1174	547	5.6	1.6	997	465	5.8	1.3	1032	482
						6.89	4.81	1226	572	5.85	2.55	1041	486	6.06	1.54	1079	503

Table 16. The minimum and maximum acid field volumes and the penetration radius of acid: well B2 zone E for rock dissolution of 2%.

		28% HCl				Emulsified28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	$P.V.I_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	18.5	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	21 22 23	33 34 36	5.5 5.6 5.85	1.18 1.6 2.55	18 18 19	28 28 30	5.7 5.8 6.06	1.1 1.3 1.54	19 19 20	29 29 31
1.75	63.7	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	73 75 78	114 117 121	5.5 5.6 5.85	1.18 1.6 2.55	62 63 66	96 98 103	5.7 5.8 6.06	1.1 1.3 1.54	65 66 69	101 103 107
2	81.9	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	93 96 100	145 149 155	5.5 5.6 5.85	1.18 1.6 2.55	80 82 85	124 127 132	5.7 5.8 6.06	1.1 1.3 1.54	83 84 88	129 131 137
3	187.4	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	214 220 230	333 342 358	5.5 5.6 5.85	1.18 1.6 2.55	184 187 195	286 291 303	5.7 5.8 6.06	1.1 1.3 1.54	190 193 202	295 300 314

Table 17. The minimum and maximum acid field volumes and the penetration radius of acid : well B2 zone E for rock dissolution of 3%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	$P.V.I_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	21.9	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	25 26 27	39 40 42	5.5 5.6 5.85	1.18 1.6 2.55	21 22 23	33 34 36	5.7 5.8 6.06	1.1 1.3 1.54	22 23 24	34 36 37
1.75	74.9	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	85 88 92	132 137 143	5.5 5.6 5.85	1.18 1.6 2.55	73 75 78	114 117 121	5.7 5.8 6.06	1.1 1.3 1.54	76 77 81	118 120 126
2	96.6	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	110 113 118	171 176 183	5.5 5.6 5.85	1.18 1.6 2.55	95 96 101	148 149 157	5.7 5.8 6.06	1.1 1.3 1.54	98 100 104	152 155 162
3	221	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	252 260 271	392 404 421	5.5 5.6 5.85	1.18 1.6 2.55	216 220 230	336 342 358	5.7 5.8 6.06	1.1 1.3 1.54	224 228 238	348 355 370

Table 18. The minimum and maximum acid field volumes and the penetration radius of acid: well B2 zone E for rock dissolution of 5%.

		28% HCl				Emulsified 28%HCl				Retarded 28%HCl				Diverted 28%HCl			
r(ft)	Vr (ft^3)	$P.V.I_{field}$ (Vs/Vr)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft	$P.V.I_{field}$ (V_s/V_r)	$\bar{k}_s/k_e$	Vs (bbl)	gal/ft
1	28.5	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	32 33 35	50 51 54	5.5 5.6 5.85	1.18 1.6 2.55	28 28 30	43 43 47	5.7 5.8 6.06	1.1 1.3 1.54	29 29 31	45 45 48
1.75	97.2	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	111 114 119	173 177 185	5.5 5.6 5.85	1.18 1.6 2.55	95 97 101	148 151 157	5.7 5.8 6.06	1.1 1.3 1.54	99 100 105	154 155 163
2	126	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	144 148 155	224 230 241	5.5 5.6 5.85	1.18 1.6 2.55	123 126 131	191 196 204	5.7 5.8 6.06	1.1 1.3 1.54	128 130 136	199 202 211
3	288.4	–	–	–	–	6.4 6.6 6.89	1.25 2 4.81	329 339 354	512 527 551	5.5 5.6 5.85	1.18 1.6 2.55	282 288 300	439 448 467	5.7 5.8 6.06	1.1 1.3 1.54	293 298 311	456 463 484

value of the stimulation ratio and other values lower than the maximum value.

The calculations were done for three wells in the field in order to show the variation in acid performance treatment from one well to another in the same field. The difference in rock response to acid between layers C and E from one well to another is mainly related to the heterogeneity of formation rock pore structure and the variation of rock mineral composition.

The stimulation acid injection volumes corresponding to the maximum acid stimulation ratios for each treated core were plotted versus the assumed acid injection radii. Figures 3 to 20 illustrate the relationship between the acid stimulation radius and the acid injection volume required for the treatment. The figures were prepared for all types of acid used for the treatment at selected acid rock dissolution percentages, and were constructed for both the productive layers C and E in the three studied wells. These figures indicate that the acid stimulation radius is dependent on the type of acid additive used and also on the mineral composition at the matrix pore structure of the rock. The curves in these can be used to determine the volume of the treated acid required to obtain the maximum permeability improvement for selected acid radii near the wellbore.

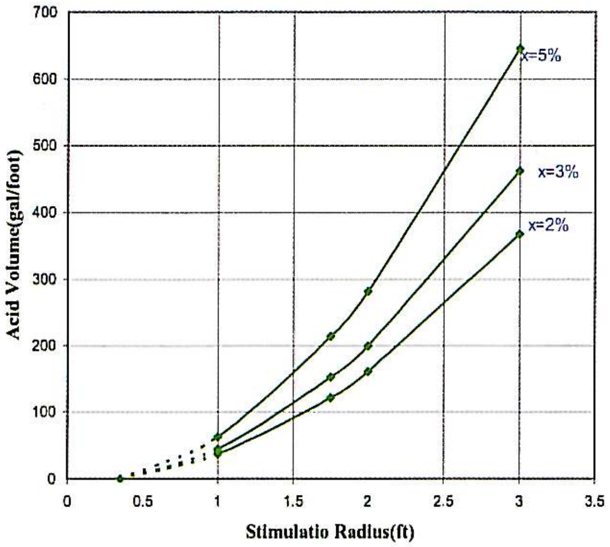

Fig. 3. The relation between stimulation radius and the acid volume for 28%HCl, well B1 zone C.

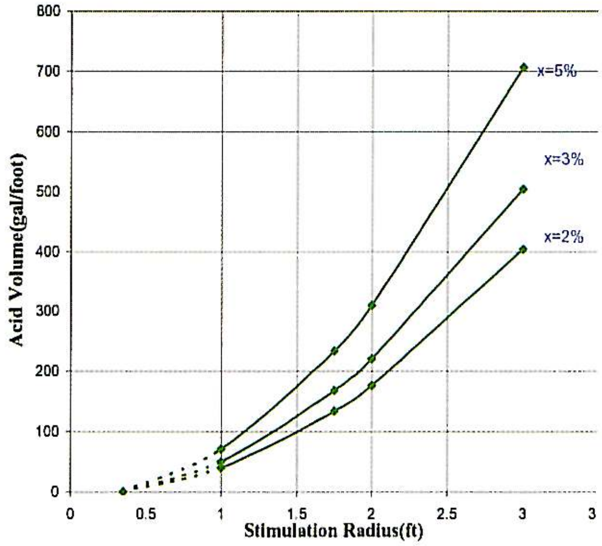

Fig. 4. The relation between stimulation radius and the acid volume for emulsified HCl, well B1 zone C.

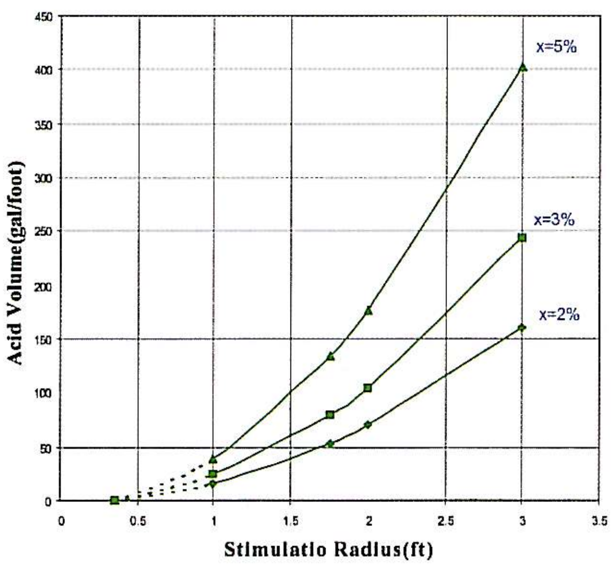

Fig. 5. The relation between stimulation radius and the acid volume for retarded HCl, well B1 zone C.

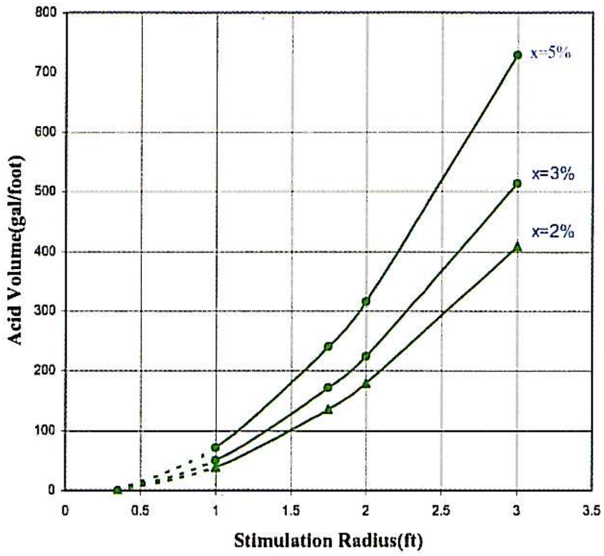

Fig. 6. The relation between stimulation radius and the acid volume for diverted HCl, well B1 zone C.

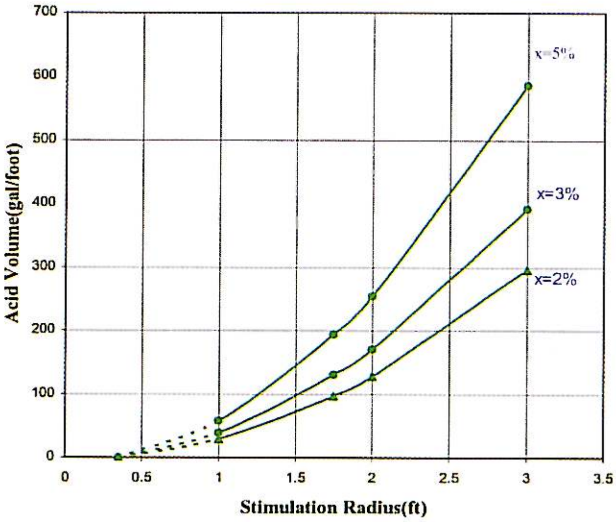

Fig. 7. The relation between stimulation radius and the acid volume for 28%HCl, well B2 zone C.

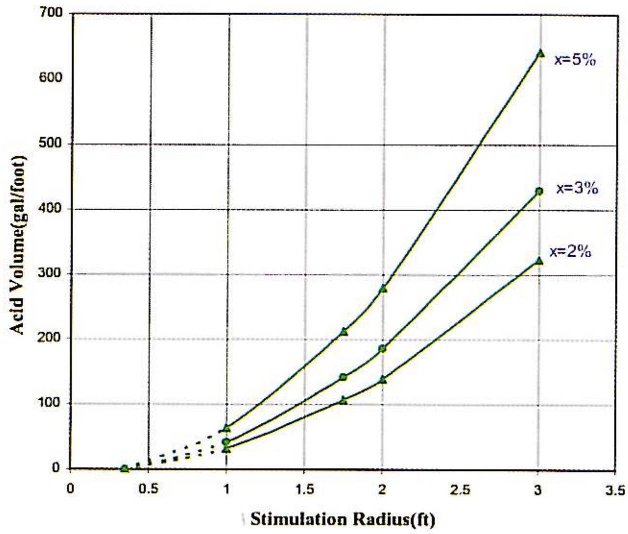

Fig. 8. The relation between stimulation radius and the acid volume for emulsified HCl, well B2 zone C.

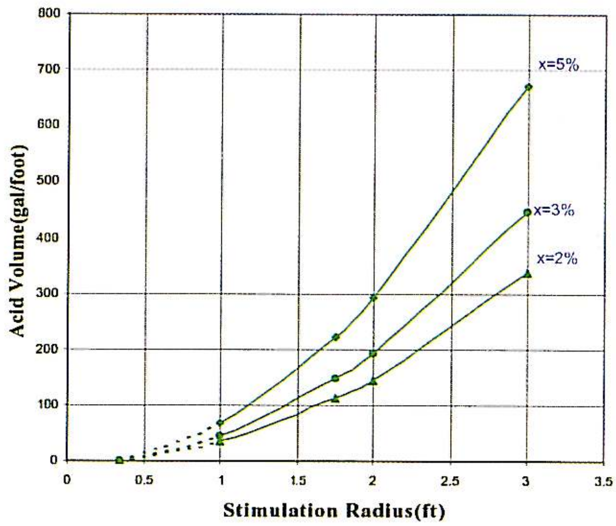

Fig. 9. The relation between stimulation radius and the acid volume for retarded HCl, well B2 zone C.

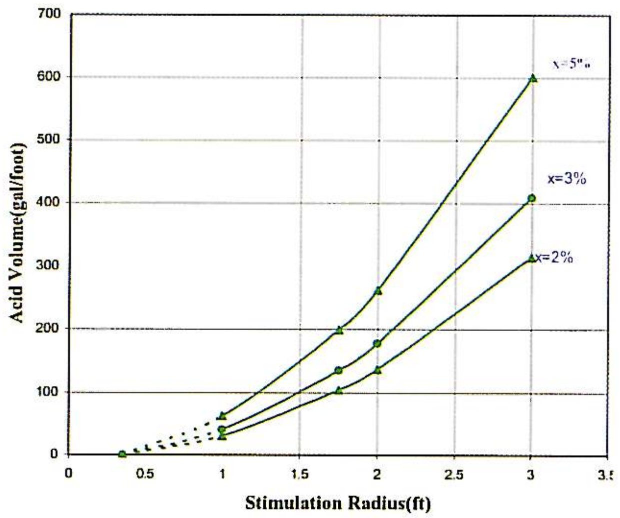

Fig. 10. The relation between stimulation radius and the acid volume for diverted HCl, well B2 zone C.

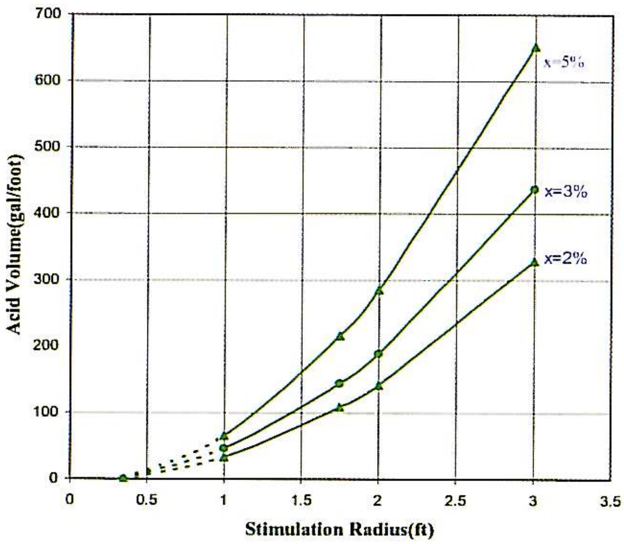

Fig. 11. The relation between stimulation radius and the acid volume for 28%HCl, well B6 zone C.

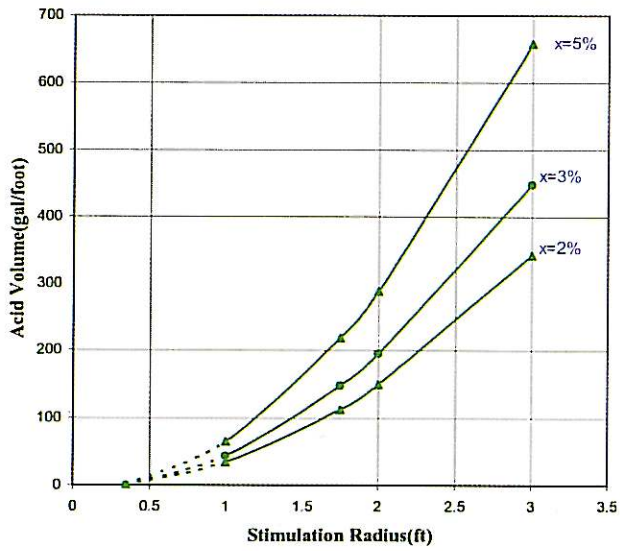

Fig. 12. The relation between stimulation radius and the acid volume for emulsified HCl, well B6 zone C.

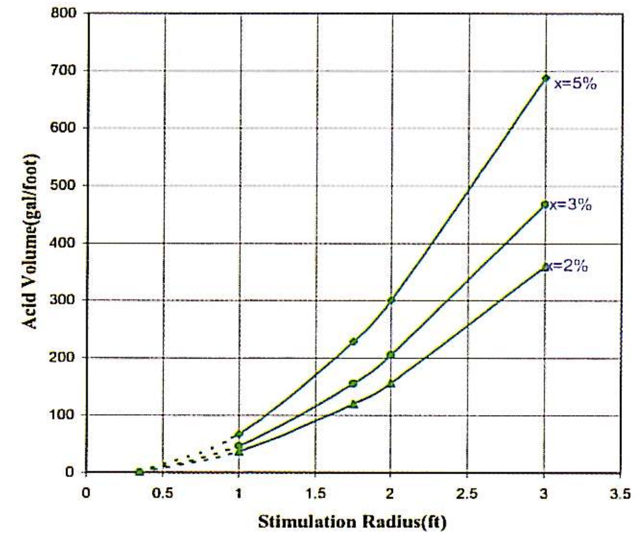

Fig. 13. The relation between stimulation radius and the acid volume for retarded HCl, well B6 zone C.

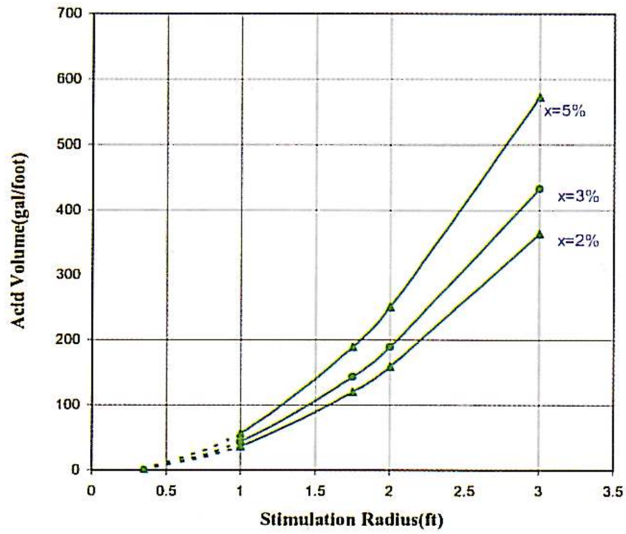

Fig. 14. The relation between stimulation radius and the acid volume for emulsified HCl, well B1 zone E.

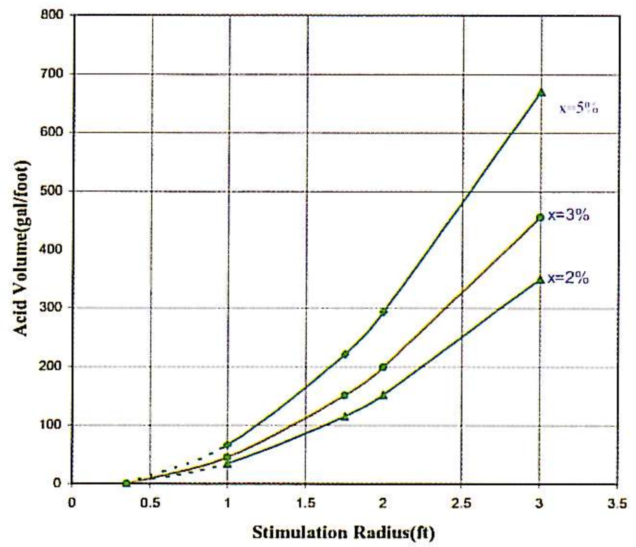

Fig. 15. The relation between stimulation radius and the acid volume for diverted HCl, well B6 zone C.

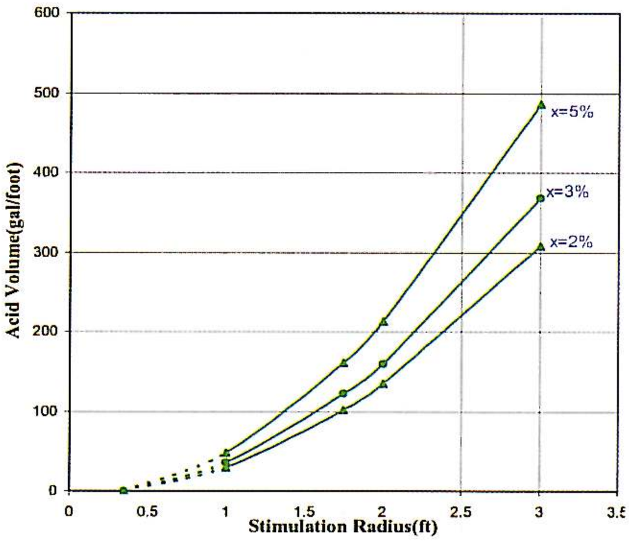

Fig. 16. The relation between stimulation radius and the acid volume for retarded HCl, well B1 zone E.

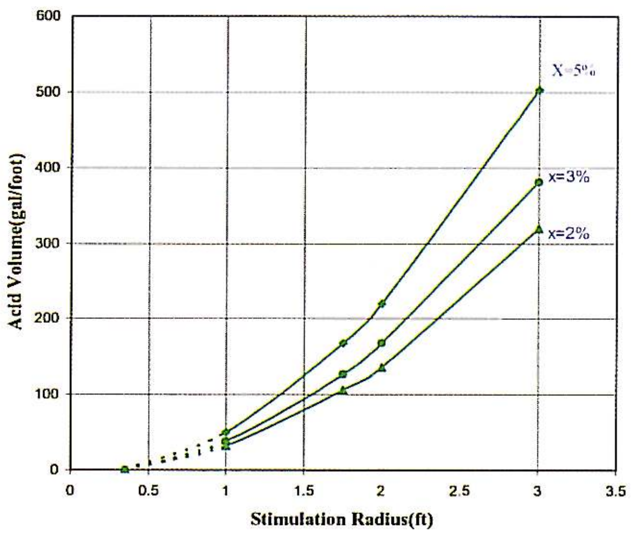

Fig. 17. The relation between stimulation radius and the acid volume for diverted HCl, well B1 zone E.

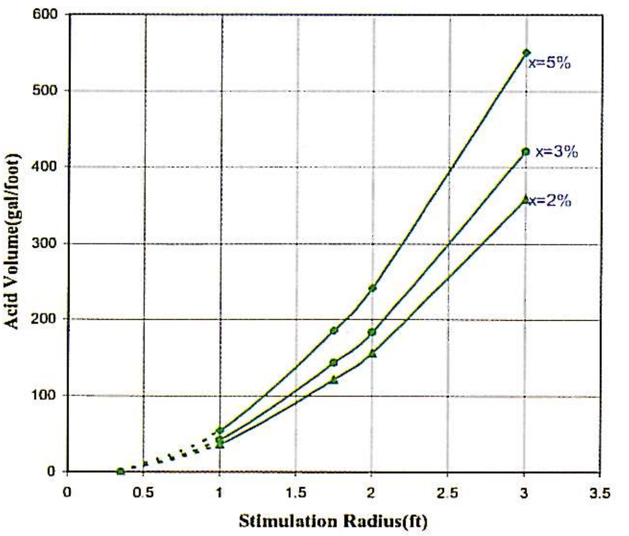

Fig. 18. The relation between stimulation radius and the acid volume for emulsified HCl, well B2 zone E.

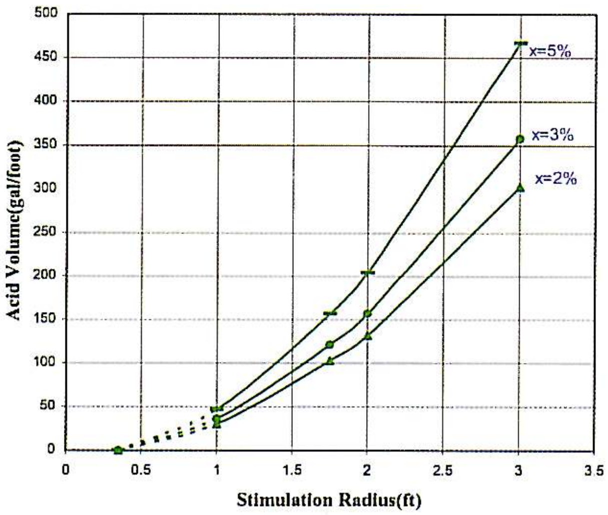

Fig. 19. The relation between stimulation radius and the acid volume for retarded HCl, well B2 zone E.

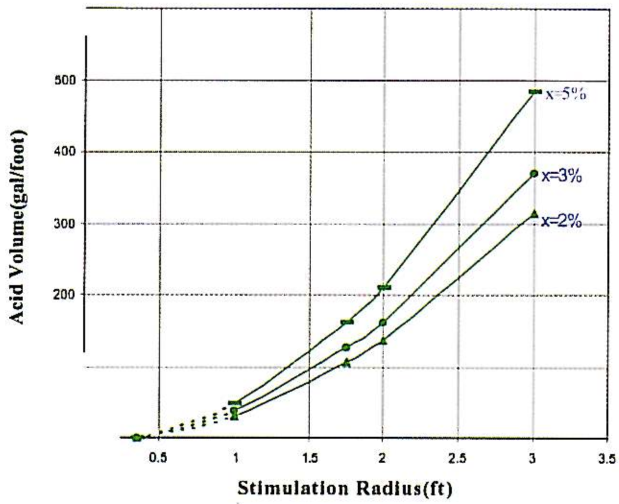

Fig. 20. The relation between stimulation radius and the acid volume for diverted HCl, well B2 zone E.

It is observed from Tables 4 to 18 that the acid stimulation ratio ($\overline{k_s}/k_e$) increases with increasing the acid pore volume injected. This increase continues until it reaches a maximum value after which any further increase in the injected pore volume will produce decreasing values of acid stimulation ratios. It is, therefore, recommended to determine experimentally the optimum required acid volume needed for any acidizing treatment.

Injecting higher acid volumes than required dissolves excessive rock minerals which the acid cannot suspend and carry, and re-precipitation of these minerals occurs which causes a damaging effect to the treated formation. In a radial geometry acid treatment, the volume of the acid needed to increase the porosity by dissolving a given percentage of the rock mineral varies with the square of the treatment radius. It is noted from Tables 4 to 18 that the acid volume needed to stimulate a reservoir should be designed according to the required percentage of the dissolution of the rock mineral and also according to the required acid penetration radius.

For reservoirs that have high residual oil saturation as is the case in well B2 zone E, it is recommended to use organic solvents and mutual solvents, along with the injected HCl acid in order to increase the contact between the acid and the rock surface which will result in decreasing the residual oil saturation of the reservoir.

CONCLUSIONS

1 - A new correlation technique for converting laboratory acid core data to field conditions is presented in this study.

2 - During any acid stimulation process, there is an optimum acid volume to be injected in order to produce the maximum stimulation ratio. Increasing the acid volume more than the optimum value causes a reduction in stimulation ratio.

3 - The designed acid volume is dependant on the required increase in the porosity as well as on the possible stimulation radius.

4 - The acid volume needed to stimulate the reservoir depends on acid type, acid additives and also on the physical properties and mineral composition of the rock.

5 - The volume of the injected acid for any acid treatment should be determined properly in order to achieve a successful acid treatment.

6 - Acid field curves that illustrate the relation between the acid stimulation radii and the required acid volumes were constructed for zones C and E.

Nomenclature

V_r	=	reservoir volume invaded by acid, ft^3.
V_{rs}	=	volume of the dissolved rock by acid, ft^3.
V_s	=	acid volume, ft^3.
V_{pi}	=	original pore volume invaded by acid, ft^3.
P.V.I	=	pore volume injected.
h	=	formation thickness, ft.
ϕ	=	reservoir porosity, fraction.
r_s	=	acid penetration radius, ft.
r_w	=	wellbore radius, ft.
S_{or}	=	residual oil saturation, fraction.

χ = rock dissolution, fraction.

$_2$ = acid dissolving power.

ν_{acid} = stoichiometric coefficient of the acid(2HCl).

$\nu_{mineral}$ = stoichiometric coefficient of the mineral($1CaCO_3$).

$\overline{k_s/k_e}$ = acid stimulation ratio.

k_s = stimulated zone permeability, darcy.

k_e = original zone permeability prior to acidizing, darcy.

$\overline{MW}_{mineral}$ = molecular weight of the mineral.

MW_{acid} = molecular weight of the acid.

$\rho_{acid\ solution}$ = density of the acid solution, lb/gal.

$\rho_{mineral}$ = density of the rock, lb/gal.

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REFERENCES

[1] Nasr M. and Elhemmali N., 1996(Jun.). Application of acid optimization technique to carbonate reservoirs. *The 6th international energy conference*, Beijing, China (890-893).

[2] Economides M. & Nolte K.G., 2000. *Reservoir Stimulation*. Third edition. Schlumberger.

[3] Fredd.C.N., 2000(Mar.). Dynamic model of wormhole formation demonstrates conditions for effective skin reduction during carbonate matrix acidizing. *SPE Permian Basin Oil and Gas Recovery Conference*, Texas.

[4] Ferdd C.N. and Miller. M. J., 2000(Feb.). Validation of carbonate matrix stimulation models. *SPE International Symposium*, Louisiana.

[5] Bazin.B., 2001(Feb.).From matrix acidizing to acid fracturing: a laboratory evaluation of acid/rock interactions. *SPE production & Facilities*, 22-29.