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Original article

Experimental study on influencing factors of acid-fracturing effect for carbonate reservoirs

Nianyin Li*, Jinxin Dai, Pingli Liu, Zhifeng Luo, Liqiang Zhao

Key State Laboratory of Oil and Gas Reservoir Geology and Exploitation in Southwest Petroleum University, China

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ABSTRACT

Acid fracturing treatment is the key technique for stimulation and stable production in carbonate reservoirs. In order to improve the carbonate reservoirs acid fracturing effect, in this paper, with a large number of experiments as the main research methods, study on influencing factors of acid-fracturing effect for carbonate reservoirs from increase the effective distance of living acid, increase acid corrosion eched fracture conductivity, reduce the acid fluid loss, etc. The effective distances of live acid calculated with reacted acid limitations measured in different acid systems are quite different from those calculated according to previous standard. Fracture conductivity is one of the key parameters that affects acid fracturing effects, but it's difficult to be predicted accurately due to the strong randomness of acid-rock reaction as well as various influence factors. Analyses of the impacts on fracture conductivity resulted from the rock embedment intensity, closure stress, acid dosage, rock-acid contact time, acid fluid loss, acid pumping rate through self-developed small-core fracture capacity test instrument. Fluid loss during acid fracture can be well controlled by thickened liquid as well as solid particles, but formation damage occurs inevitably. Foamed acid is a specific fluid with high viscosity, low fluid loss, small friction resistance, good retarding property, strong fracture making ability, easy flowback and low damage, which is an ideal acid system for low pressure and low permeability carbonate reservoirs. In this paper, the theoretical study on percolation mechanism and fluid-loss control mechanism of foam (acid) in porous medium are presented with the help of visual microscopic model fluid drive unit.

1. Introduction

Presently, the developed low permeability reservoirs is over 1/3 of total producing reserves in china, while the undeveloped ones share a greater proportion of unutilized geological reserves. However, the developed ones are mostly in low-production and low-efficiency state. How to improve the effects of developed reservoirs? How to make use of the undeveloped ones quickly and efficiently? Fracturing and acidizing technology plays an irreplaceable role.

Carbonate reservoirs are widely distributed in China, including Sichuan Basin, Tarim Basin, Bohai Bay Basin, Buried Hill Ordos Basin Palaeozoic sector, etc [1]. Compared with sandstone reservoirs, the lithology of carbonate reservoirs is relatively simple, but cracks and caves are well developed. when fracturing the carbonate reservoirs, those features may make the sand packed fracture short and narrow due to filtration, and the fracturing fluids seeping into the layer may damage reservoir, and even improper operation cause sand bridge, which bring no effect to stimulation. However, acid fracturing of carbonate reservoirs has a strong advantage.

2. Reservoir characteristics of high bridge lower Palaeozoic reservoir and the necessity of acid fracturing

According to the production test of layers, the stable productivity of single well is required to be improved by stimulation to achieve the whole development of gas reservoir. The reservoir

* Corresponding author. Southwest Petroleum University, No. 8 Xindu Ave., Chengdu, Sichuan Province 610500, China. Tel: +86 13880924239.
E-mail address: linianyin@swpu.edu.cn (N. Li).
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geological assessment analysis and test data demonstrate there is a certain degree reservoir damage, and acid fracturing is needed to eliminate the damage caused during drilling or completion. Some well layers in the gas reservoir have low effective permeability and remarkable dual-medium characters. In this case, nature fractures will significantly affect reservoir production. Thus, stimulation is needed to form long effective acid-etched cracks and improve reservoir seepage area thereby enhancing single well productivity. Small gas layers are serious heterogeneity, which need acid fracturing to improve the average contribution ability. Therefore, large acid fracturing technique is an important mean to increase the production.

3. Analysis of acid fracturing influencing factors

The two most important factors that affect the acid fracturing effects are acid effective distance and acid-etched fracture conductivity. Effective fracture length is influenced by acid filtration property, acid-rock reaction speed, acid flow velocity in the cracks as well as acid type. Acid-etched fracture conductivity is affected by closure stress, acid dissolving power, acid-etched shape of acid-rock reaction, absolute dissolved rock volume and so on. Therefore, longer acid-etched crack length and higher conductivity are needed to improve the acid fracturing effect of carbonate formation. Fig. 1 depicts the main factors to control the acid fracturing effect.

4. Testing reacted acid limit and calculating acid effective distance

During acid fracturing, acid flows into the deep formation along cracks with concentration decreasing gradually. When the acid concentration decreases to a certain value that has no corrosion capability, it becomes reacted acid, and generally, reacted acid limit is considered 10% of the live acid concentration. Before active acid becomes reacted one, the distance live acid flows is called effective distance. But indoor experiments find the reacted acid limit of retarded acid system is much higher than previous opinion about the conventional acid. The test results are shown in Table 1.

Table 1 shows the different reacted acid limit values of different acid types, among them: reacted acid limit of self-diverting acid is the maximum (5.87%); Crosslinked acid takes the second place (4.82%); Gelling acid is minimal (2.73%), closing to that of conventional acid (conventional hydrochloric acid is 2%). The final dissolution rates of crosslinked acid and self-diverting acid is found lower than that of conventional acid.

Therefore, corresponding iterative termination conditions are needed to be set according to different acid systems to get acid effective distance, instead of using 10% live acid concentration as iterative termination conditions. Author has published a paper to discuss the calculation methods of acid effective distance, but these methods all use 10% concentration of fresh acid as judge condition, therefore, for retarded acid, those methods couldn't be used to calculate the effective distance. Effective distances of different acids are simulated and calculated based on the above research and the test results of high temperature dynamics reaction, and Fig. 2 shows the calculated acid con-centration distribution along fracture.

According to previous reacted acid standard (10% of fresh acid concentration), the effective distance of Crosslinked acid, Gelling acid and Self-Diverting acid respectively are 108 m, 84 m and 90 m. But according to their own reacted acid concentration limits, the calculation results of effective distance are: Crosslinked acid is maximum (96 m); Gelling acid is the second (81 m); Self-Diverting acid is minimum (77 m). Obviously, reacted acid limit greatly affects acid-reaction distance.

Therefore, during actual acid fracturing, the acid-rock reaction rate of Crosslinked acid and Self-Diverting acid is seemed low, but when comprehensively considering reacted acid limit and the decrease of fracture conductivity caused by acid corrosion, the increasing effective distance may make no contribution to improving acidification effects, thus, various acid systems combination optimization is recommended to get longer effective distance and higher conductivity acid-etched cracks.

5. Effect factors of acid-etched fracture capacity and improving methods

Acid-etched fracture conductivity is one of the key parameters that affects the acid fracturing result, but it is difficult to be predicted accurately due to the high randomness of acid-rock reaction.

5.1. Effect factors of acid-etched fracture capacity

Many factors affect the acid-etched fracture conductivity, and self-developed FCD test instrument—DP-1 is used to research

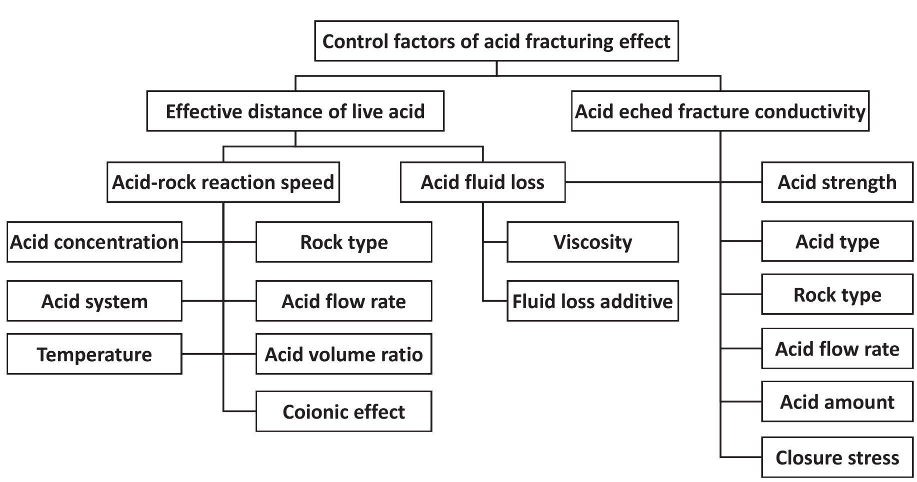


Fig. 1. Main influence influences of acid fracturing.

Table 1
The result of the residual acid limit.

Acid	Amount of reacted acid (ml)	Concentration of NaOH (mol/l)	Volume of NaOH (ml)	Concentration of reacted acid (mol/l)	The reacted acid concentration limit (%)	The average reacted acid concentration limit (%)
Crosslinked acid	1	0.297	4.4	1.3068	4.77	4.82
	1	0.297	4.5	1.3365	4.88	
	1	0.297	4.45	1.3217	4.82	
Gelling acid	1	0.297	2.5	0.7425	2.71	2.73
	1	0.297	2.55	0.7574	2.76	
	1	0.297	2.5	0.7425	2.71	
Self-Diverting acid	1	0.297	5.4	1.6038	5.85	5.87
	1	0.297	5.45	1.6187	5.91	
	1	0.297	5.4	1.6038	5.85	

the impacts on fracture conductivity resulted from the rock embedment intensity, closure stress, acid dosage, acid contact time, acid filtration and acid pumping rate affect fracture capacity [2].

(1) **Influence of rock embedment intensity on fracture capacity**

Rock embedment intensity is one of the important factors that affects the fracture capacity. Fig. 3 shows the relationship between fracture conductivity and rock embedment intensity under different closure stresses. When the rock embedment intensity value is low, crack support point will collapse, and the fracture conductivity value will be very low. Conversely, when the rock embedment intensity value is high, crack support point can withstand enough formation pressure, and the fracture capacity value is much higher.

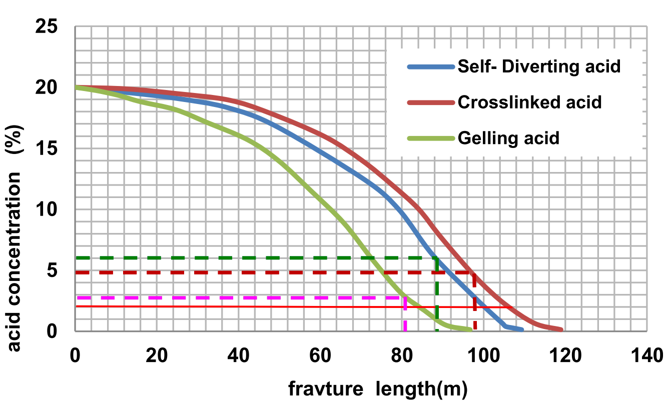


Fig. 2. Acid concentration distribution along fracture.

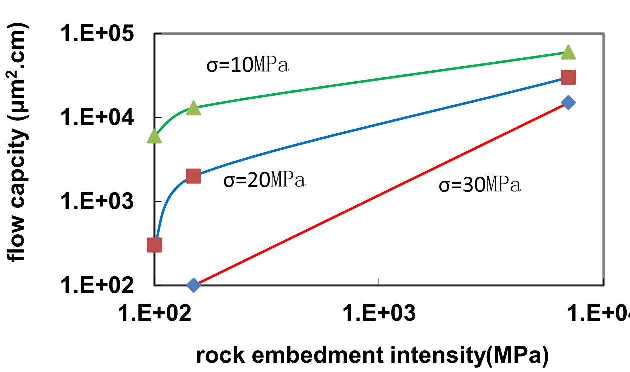


Fig. 3. The influence of rock embedment intensity on flow conductivity.

(2) **Influence of acid system on fracture capacity**

Fig. 4 shows the fracture conductivity of different acid systems under different closure stresses. When using single acid system, flow conductivity decreases quickly along with the increase of closure stress. However, when using combinatory acid system, the viscosity difference between different acids can realize heterogeneous etching, and the flow conductivity can still maintain a higher lever under high closure stress.

With the increase of closure stress, flow conductivity decreases, which re-quires to protect bottom pressure from greatly waving, so as not to decrease much fracture capacity due to the crack net pressure changes when injecting acid, flowback reacted acid and later production control [3,4].

(3) **The influence of acid dosage on fracture capacity**

Fig. 5 shows: the longer acid-rock contact time, the more rock corrosion will be. If acid is not enough or contact time is short, the corroded rock will be less, and the acid-etched fracture capacity will be lower. If acid is too much or contact time is too long, the corroded rock will be much more, and the acid-washed aisle in crack faces will be bigger, but the support areas will be lesser, and the rock structure on the fracture surface will be weaken (shown as Fig. 6), which makes rock more sensitive to closure stress. Obviously, there exists an optimal acid volume or optimal contact time, and the principle is the rock with the most corroded volume but still can maintain support effect [5].

(4) **The influence of acid filtration on fracture capacity**

Fig. 7 shows flow conductivity contrast curve of filtration and non-filtration. In experiments considering filtration, the fluid

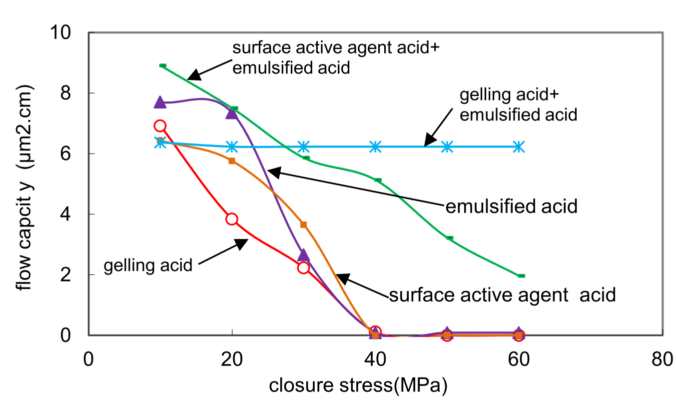


Fig. 4. The influence of different acid systems on flow conductivity.

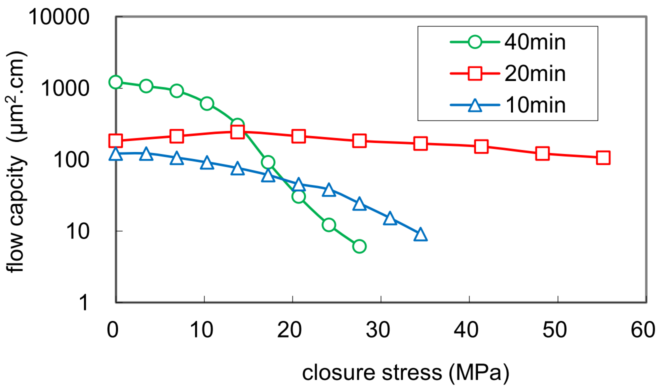


Fig. 5. The influence of acid-rock contact time on flow conductivity.

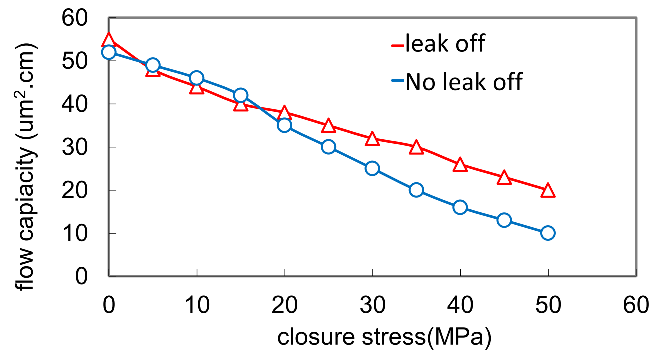


Fig. 7. The influence of acid fluid loss on flow conductivity.

loss is 15% of the acid dosage, while in experiments without thinking filtration, the filtration line is closed, and there is no acid fluid loss. When under low closure stress, two experimental results are similar, but when closure stress is more than 18 MPa, the fracture capacity with filtration is much higher than that without filtration.

(5) **The influence of acid pumping rate on fracture capacity**

Fig. 8 shows the fracture conductivities of different acid pumping rates. When in low closure stress, acid-etched fracture conductivity increases as pumping rate increases. This is because the increasing pumping rate increases acid-rock reaction rate and rock corrosion. But in high closure stress, when pumping rate is less than 15 ml/s, acid-etched fracture conductivity decreases slightly along with the increase of pumping rate. Because the nonhomogeneous mineral differences reduces reaction rate; while when pumping rate is over 15 ml/s, flow conductivity increases. Thus, properly improving pumping rate is conductive to increasing acid-etched fracture conductivity.

5.2. Measures to improve acid-etched fracture conductivity

(1) **Optimize acid system, acid dosage and acid concentration**

The size and distribution of acid-etched fracture conductivity are closely related to acid systems, the acid system with a low

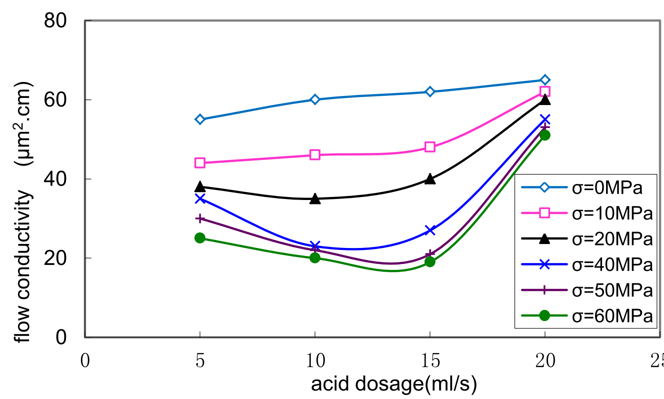


Fig. 8. The influence of acid dosage on fracture conductivity.

fluid loss and a better retarding property should be chosen to improve the flow conductivity in the entire effective acid-etched crack range. Moreover, experts at home and abroad have putted forward preflush acid fracturing or multistage alternating injection acid fracturing technology to ensure higher acid-etched fracture conductivity under high closure stress conditions, relying on viscosity differences between ahead fluid and acid, as well as viscous fingering during liquid injection process to realize heterogeneous etching [6,7]. In addition, the author prefers to use alternating injection of acid with different viscosity and reactivity to achieve heterogeneous, so that formation damage

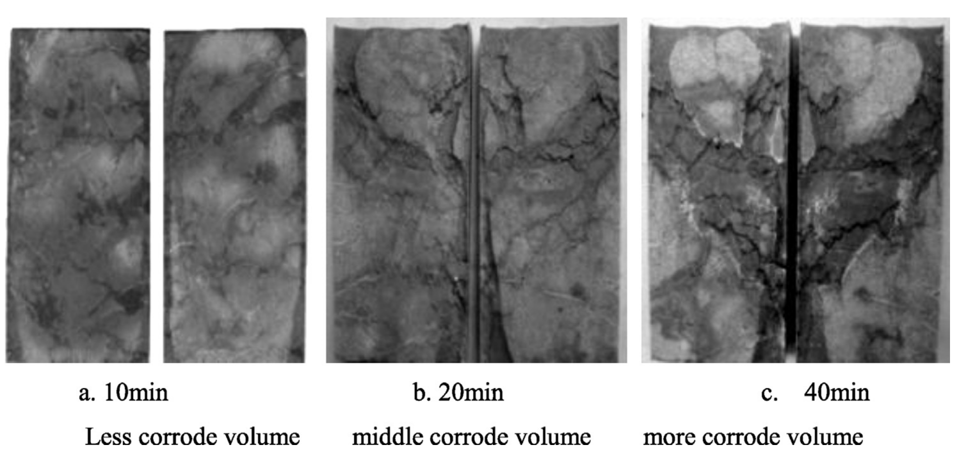


Fig. 6. Different dynamic acid-etched fracture morphology under different etching time.

caused by ahead fluid loss can be reduced, and at the same time, a lot of liquid waste caused by the non-compatibility between ahead fluid and acid can be also avoided.

For higher closure stress layer, the acid dosage and acid concentration should be appropriately increased to deeply corrode to keep higher fracture conductivity after fracture close. The principle of ideal acid dosage and reaction time is the rock with the most corroded volume but still can maintain support effect. While for looser and lower rock strength layer, the acid dosage and acid contact time should be appropriately reduced to avoid excessive corrosion, because excessive corrosion will weak the rock structure in cracks faces, which will shorten useful life of acid-etched fracture conductivity [8].

(2) **Optimize acid fracturing technology**

i. Multistage alternating injection acid fracturing technology
Multistage alternating injection acid fracturing technology can effectively reduce acid fluid loss [11]. As the result of viscosity differences, viscous fingering forms heterogeneous acid-etched patterns in cracks surface, which increases the fracture conductivity. Furthermore, using acid system with different viscosity can also achieve better non-uniform etching, relying on the viscosity difference and reactivity difference.

ii. Closed fracture acidizing technology
Injecting acid into the closed or half-closed fractures that exist in reservoir with natural fracture or reservoir experienced acid fracturing to continue deepening the previous groove, and to further aggravate the irregularities of fracture faces. Laboratory tests and field applications shows the technology is extremely effective to improve the near-wellbore fracture conductivity.

iii. Equilibrium acid fracturing technology
Equilibrium acid fracturing is a technology for low temperature, soft and high non-heterogeneous reservoir. It utilizes the difference between fracturing prolongation pressure (extension pressure) and minimum crustal stress (the pressure when fracture open or close) to control construction pumping rate after fracturing dynamic cracks, and then make injection speed equal to acid filtration speed. When the two reach balance, pressure in fracture will lower than fracturing prolongation pressure, and the fracture will keep open without extension, then, acid-rock reaction time will be longer, resulting in optimal fracture conductivity.

iv. Sand-propped acid fracturing technology
Hydraulic fracturing and acid fracturing are combined to penetrate deeply into fractures, improve flow capacity, lengthen effective time, stimulate and keep stable production. Therefore, Sand-propped acid fracturing technique is suitable for porosity reservoir or the reservoir needs deep penetration, instead of the large fractured-vuggy reservoir.

(3) **Optimize construction parameters, and choose the best acid pumping rate**

Acid-etched fracture conductivity increased with increasing pumping rate when under low closure stress; conversely, it decrease slightly when under high closure stress, but when pumping rate further increases, it increases too. Therefore, in the construction process, an appropriate increase of pumping rate under the safe range of pump pressure is beneficial for the increase of acid-etched fracture conductivity.

6. Fluid-loss control technology of acid-fracturing in fractured reservoirs

Generally, according to the three fluid-loss control mechanisms, the whole process of fracturing fluid is divided into three parts: filter cake area, filtrate invasion area and compression area. For fracturing fluid, the filtration is influenced primarily by wall building properties and secondarily by viscosity, and higher fracturing fluid viscosity results in lower filtration. Obviously, this theory is not appropriate for acid.

Acid is a reactive fluid. The fluid loss starts when it flows, and it will form more filtration area, which is different from fracturing fluid loss that just form effective filtration cake on fracture face [9,10].

Usually carbonate rock has more natural cracks than sandstone. Acid constantly etches fracture faces, selectively expands not only pores but also developing cracks, forms “wormhole” and passage perpendicular to crack face, resulting in new filtration area. Once forming these “wormhole”, a large number of acid will loss along the filtration channel thereby making the effective distance short, increasing production limited and period of validity [12]. At present, the fluid-loss control technologies during acid fracturing mainly include: thickened liquid fluid-loss control technology, solid particle fluid-loss control technology, foam acid fluid-loss control technology.

6.1. *Thickened liquid fluid-loss control technology*

Using high-viscous acid (Gelling acid, Crosslinked acid, Self-Diverting acid, etc.), on one hand, can prevent acid from flowing in the acid-etched channel; on the other hand, can help to reduce acid-rock reaction rate and slow acid-etched pours growth. The fluid-loss curve of Gelling acid and Self-diverting acid respectively shown in Figs. 9 and 10 indicate: the two acids increase the fracture percolation resistance and reduce the flow from core holder outlet because of their high-viscous, showing obvious filtration reduction. Compared the base fluid discharge before and after acid injection, the permeability recovery amplitude is found much bigger when injecting gelling acid instead of self-diverting acid, showing that self-diverting acid has relative better fluid-loss control and retarded performance (see Fig. 11).

6.2. *Solid fluid-loss control technology*

The technology is that using the working liquid with solid particles (powder pottery, removable chemical particles and solid acid) to seal and fill fracture hole, so as to prevent acid invasion. After injecting acid, most of the solid particles will be removed or flowback with the work fluid.

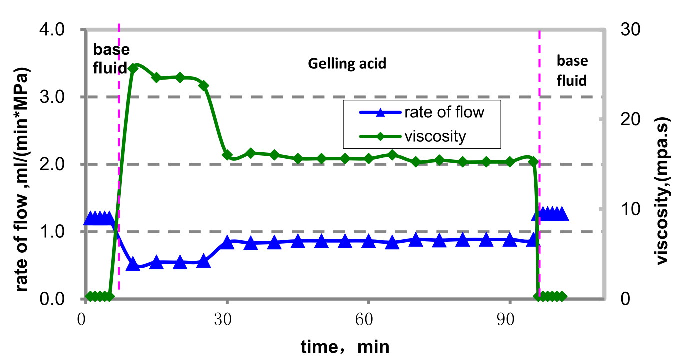


Fig. 9. The fluid-loss curve of Gelling acid.

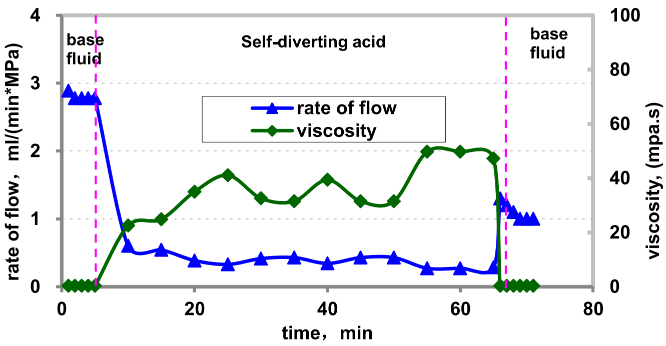


Fig. 10. The fluid-loss curve of Self-diverting acid.

(1) **Matching test of particle size and crack effective width**

Diagram 11 indicates: fracture permeability decreased to almost 40% of its initial value after injecting carrying fluids. This shows no mater what the crack initial permeability value (Ko) is, the bridge plug will formed when bridging particle size is 1/4 of crack effective flow width. K/Ko gradually decreases along with the increase of injection volume. When accumulative injection volume reaches a certain value, K/Ko obviously rebounds, and solids are found flowed out of core holder outlet during test, which shows that solid particles migrate in crack. So 1/4 matching relation can't stabilize bridge.

Compared with 1/4 matching relation, the bridge plug effect of 1/3 matching relation is significantly increased (shown in Fig. 12), and the fracture permeability has dropped by 70%–80% of its initial value. Fracture permeability obviously reduces accompanying slightly waving along with the increase of the injection volume, indicating the decrease of particle migration phenomenon and the increase of bridge plug stability (see Fig. 13).

Compared with 1/4 and 1/3 matching relation, 1/2 matching relation has best bridge plug effect, and fracture permeability in it drops by 90% of its initial value, or even higher. Along with the increase of injected fluid volume, core permeability K changes extremely small, which shows the disappear of particle migration phenomenon and the stronger bridge plug stability.

(2) **The influence of particle concentration on fluid-loss**

Along with the increase of bridging particle concentration, K/Ko decreases with a gradually reducing decrease rate in Fig. 14. When bridging particle concentration is over 6%, K/Ko basically

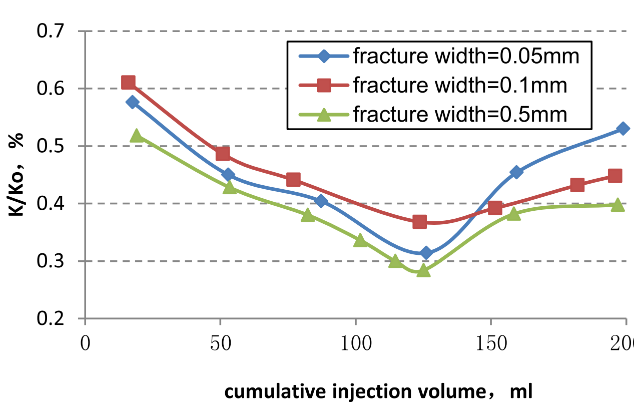


Fig. 11. The relation curve of K/Ko and Cumulative injection amount (1/4 matching relation).

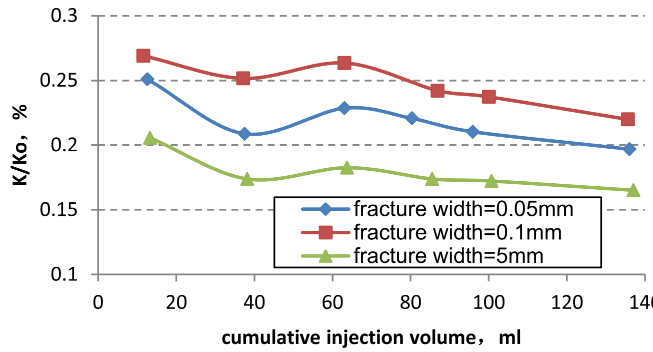


Fig. 12. The relation curve of K/Ko and Cumulative injection volume (1/3 matching relation).

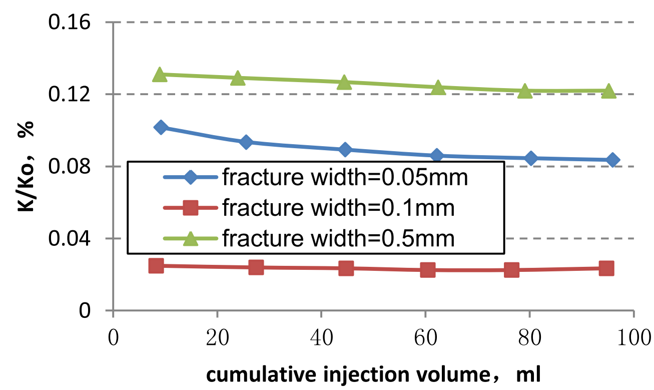


Fig. 13. The relation curve of K/Ko and Cumulative injection volume (1/2 matching relation).

tends to a certain value. Because there is no enough bridging particles to form bridge plug when the concentration is less than 6%. While when concentration is over 6%, there is enough bridging particle to obtain better bridge plug, but if particle concentration is further increased, it has little influence on fracture permeability.

6.3. Foamed acid/foamed slug fluid loss technology

Thickened liquid and solid particles can effectively reduce fluid loss, but also inevitably cause formation damage. Foamed acid is a special fluid with good reducing-filtration function. It's filtration coefficient is lower two quantity degree than conventional liquid during indoor test in low permeability reservoir [13]. Compared with conventional acid, foamed acid has higher

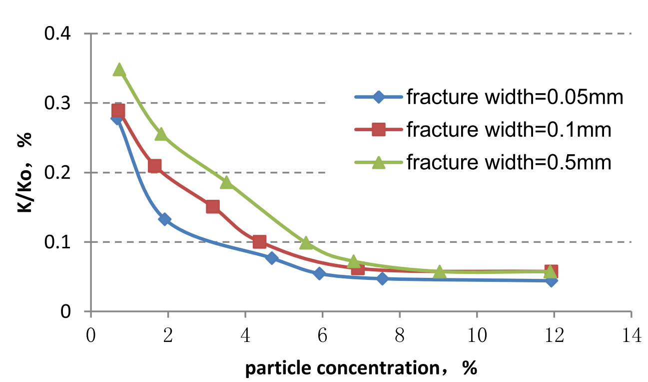


Fig. 14. The relation curve of K/Ko and particle concentration in different fracture width.

Fig. 15. Visual microscopic model fluid drive unit.

viscosity, lower fluid-loss, lower friction, better retarded effect, stronger fracture making ability, easier flowback and smaller damage, which is a ideal acid system to stimulate for low pressure, low permeability carbonate reservoir.

(1) **The advantage of foamed acid/foamed slug fluid-loss control acid fracturing**

i. Compared with other fluid-loss control technology, stable solid fluid loss additive (powder sand, etc.) is hard to be dissolved once added into acid, and the oil-dissolved or water-dissolved fluid loss additive can well control acid fluid loss, but unfit for gas well. High-viscous ahead fluid or high-viscous acid can also reduce fluid loss, but cause formation damage, too.
ii. The foam has selectivity for oil/water layer – plugging water instead of oil. Form vanishes when meeting oil, but keep stability when meeting water, which give acid privileged access to the oil-layer, improves oil-layer acidification effect, and prevents water cut from rising due to excessive water-layer acidification.
iii. Foamed acid has selectivity for the formation permeability, the greater permeability and lager fracture channel cause the greater foam resistance and lower fluid loss.
iv. Foam has high apparent viscosity and good carrying ability. When flowback, it carries out released particles and insolubles. Gas expansion in foam provides energy for reacted acid flowback, and makes it more thoroughly. At the same time the formation damage will be reduced, which is especially important for low pressure formation.
v. Foamed acid can reduce 40%–60% of water friction, and it makes up for the shortage of low hydrostatic head and high well head pressure to some extent.
vi. Foamed acid is a retarded acid, which can reduce acid-rock reaction speed and increase acid effective distance.

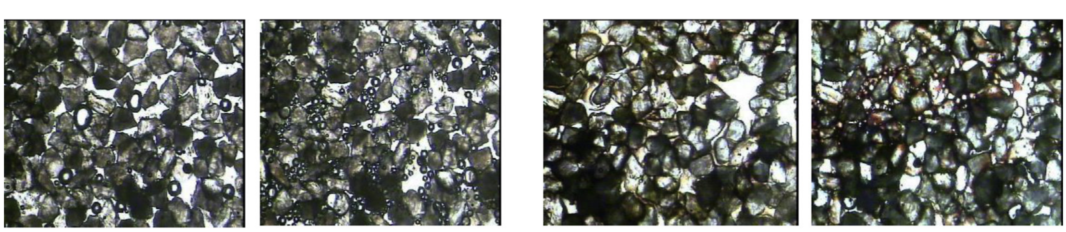
(2) **The percolation mechanism of foam (acid) in porous medium**

The foamed acid flow behaviour in porous medium is simulated under formation condition in visual microscopic model fluid drive unit (Fig. 15), and foam formation and foam decay are intuitively reflected by using image acquisition system.

i Foam continuously breaks and reforms when it flows
The phenomenon is clearly observed in transparent model that the foam moves forward with continuously breaking and re-forming, instead of in continuous shape when flowing in porous medium. While, liquid flows through porous medium along the air bubble fluid film network. Liquid is continuous phase, and gas is not.
ii Foam stability gets worse in oiliness porous medium
Foam stability in porous medium with different oil saturations can be compared and analysed by the formation of foam zonal, foam travelling speed and distance, foam breaking and reforming, and pressure, etc [14]. Fig. 16 indicates: foam stability obviously decreases and foam travelling distance relevantly shorten along with the increase of oil saturation.
iii. Foam in pore has high apparent viscosity, and it raises with increasing porosity
Foam is pseudoplastic fluid. When it flows in porous medium, apparent viscosity is much higher than that of active water and gas, and it raises with increasing porosity (or permeability), but decreases with increasing shear stress. This property is disadvantageous for foam flowing in big passage, because big passage makes low flow speed and low shear stress, resulting in high apparent viscosity.

(3) **Fluid-loss control mechanism of foamed acid**

Low foam filtration coefficient is determined by its own particular composition. The foam shape changes continuously after entering reservoir because of the surface tension exists between gas phase and liquid phase. When foam enters tiny pore, more energy is needed to overcome Jamin action and foam deformation. But after foam enter tiny pore, the foam with tiny composition will form double membrane, which will cause high differential pressure to further prevent liquid entering into formation.



Before injection 30 minutes after injection Before injection 30 minutes after injection

(water-wet medium) (oil-wet medium)

Fig. 16. Foam flows in porous medium.

(4) **Major factors that affect foamed acid fluid loss**

i. Core permeability affects foamed acid fluid loss greatly, when it broaden two quantity degrees, the filtration coefficient of foamed acid will increase one quantity degree.

ii. Liquid phase viscosity has a key influence on foamed acid filtration coefficient, and it decreases obviously with the increasing viscosity.

iii. Temperature directly influences the foamed acid filtration coefficient, and fluid loss increases slowly with increasing temperature, because the high temperature makes liquid phase viscosity decrease.

7. Conclusions

(1) Acid effective distance and acid-etched fracture conductivity are two key factors that influence the acid fracturing effect.

(2) Different acid systems have different reacted acid limits. The effective distances calculated by their own reacted acid limits are different from the ones calculated with the previous reacted acid calculate standard.

(3) Due to high randomness of acid-rock reaction as well as various influence factors, alternating injection of acid with different viscosity and reactive to can achieve heterogeneous etching and improve acid-etched fracture conductivity.

(4) Thickened liquid and solid-phase particles play important roles in reducing filtration during acid fracturing, but formation damage occurs inevitably. The foamed acid is a fluid with high viscosity, low fluid loss, small friction resistance, good retarding property, strong fracture making ability, easy flowback and low damage, which has a better adaptability to reduce filtration during acid fracturing for low pressure and low permeability carbonate reservoir.

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Li Nianyin, born in 1979, graduated from Petroleum Engineering, JiangHan Petroleum University in 2003 and received his bachelor degree. Now he is engaged in the research works on oil production and reservoir stimulation in Southwest Petroleum University.