HOSTED BY

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Natural Gas Industry B 1 (2014) 192–196

www.elsevier.com/locate/ngib

Research article

An experimental study on the CO_2/sand dry-frac process

Song Zhenyun [a,b], Su Weidong [a,b,*], Yang Yanzeng [a,b], Li Yong [a,b], Li Zhihang [a,b], Wang Xiaoyu [a,b], Li Qianchun [a,b], Zhang Dongzhe [a,b], Wang Yu [a,b]

[a] *Drilling & Production Engineering Technology Research Institute, CNPC Chuanqing Drilling Engineering Co., Ltd., Xi'an, Shaanxi 710018, China*

[b] *National Engineering Laboratory for Low-permeability Oil & Gasfield Exploration and Development, Xi'an, Shaanxi 710018, China*

Received 18 March 2014; accepted 25 July 2014

Available online 1 February 2015

Abstract

The CO_2/sand dry-frac process is a waterless fracturing technology in which CO_2 instead of water is used as fracturing fluid. The application of the technology abroad (in the USA and Canada) shows that it works well in stimulating low-pressure, low-permeability, strong water-locking/water sensitive reservoirs. Thus, a series of experimental studies were carried out on its production increase mechanism, fracturing fluid system, pressurized air-tight sand blender, and fracturing process. Some conclusions were made. First, the CO_2 viscosity enhancement technology can raise the critical CO_2 viscosity by 240–490 times, significantly improving the sand-carrying and fracture-making capacities of CO_2 fracturing fluid, so it is a key technique in CO_2/sand dry-frac process. Second, with the development of CO_2 pressurized air-tight sand blender, a complete set of key devices for the CO_2/sand dry-frac process can be made in China, meeting the requirements of the fracturing operation. Third, fully automatic flowback is also realized. Fourth, CO_2 instead of water is used in this fracturing operation, saving a large amount of water consumed in fracturing, and lowering cost. Fifth, the CO_2/sand dry-frac process is feasible and suitable for the stimulation of low-pressure, low-permeability and strong water-locking reservoirs, with substantial production increase.

Keywords: CO_2; Dry fracturing; Waterless fracturing; Pressurized air-tight blender; Viscosity; Application; Sulige gas field

1. Introduction

CO_2/sand dry-frac is a waterless fracturing technology in which water in conventional hydraulic fracturing fluid is replaced by CO_2.

The technology has several leading edges over conventional hydraulic fracturing, namely relatively low damage to reservoir permeability, high retention coefficient of propped fracture conductivity, high post-frac flowback rate, and high desorption rate of adsorbed gas. It works better in enhancing the productivity of water-sensitive/strong water-locking reservoirs and adsorbed gas reservoirs (shale gas, coal-bed methane, etc.) than conventional fracturing technology, so it is a very promising stimulation technology.

By the end of 2003, CO_2/sand dry-frac had been applied more than 1100 well-times in North America led by the United States and Canada, which is peculiarly effective in the stimulation of shale gas reservoirs [1].

The study on CO_2/sand dry-frac technology in China is still at the very beginning. The main difficulties in CO_2/sand dry-frac lie in the following aspects: difficulty in reaching large proppant and high proppant concentration due to poor sand-carrying (proppant transport) capacity and high filtration rate of fracturing fluid; high requirements on frac-string, wellhead and surface equipment due to high surface operation (treatment) pressure; the need to develop special pressurized air-tight blender matching [2] surface equipment and wellbore string because blending equipment (blender) used in

* Corresponding author. National Engineering Laboratory for Low-permeability Oil & Gasfield Exploration and Development, Xi'an, Shaanxi 710018, China.

E-mail address: suweidong456@163.com (Su WD).

Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2014.11.011

conventional fracturing cannot meet the requirements of CO_2/sand dry-frac.

2. Production increase mechanism of CO_2/sand dry-frac

Water-based fracturing fluid filtration would lead to relatively high damage to permeability (permeability damage) in strong water-sensitive/water-locking reservoirs, undermining the results of fracturing. Water-locking damage is commonly seen in low-pressure and low-permeability gas reservoirs [3]. For example, the water-locking permeability loss ratio reaches 24.9%–68.2% in Upper Paleozoic sandstone reservoirs of Sulige gas field [4].

CO_2/sand dry-frac is able to dramatically increase the post-frac production of strong water-sensitive/water-locking reservoirs, because: (1) the fracturing fluid has ultra-low interfacial tension, and can completely and rapidly flowback from reservoirs after vaporizing when subjected to heat; (2) the fracturing fluid without residuum can well clean the conductive bed of propped fractures, which will maintain high fracture conductivity and large effective fracture length; (3) high solubility of CO_2 in formation crude oil can decrease the viscosity of formation crude [5] and improve oil mobility; and (4) theoretically, ultra-low interfacial tension of CO_2 in supercritical state can accelerate the desorption of adsorbed gas in reservoirs.

3. Fracturing fluid system of CO_2/sand dry-frac

CO_2 has a low viscosity of 0.1 mPa s in liquid state, and a viscosity of about 0.02 mPa s in gas state and supercritical state. Low viscosity of CO_2 would lead to high filtration, poor sand-carrying (proppant transport) and fracture-making capacity of fracturing fluid, so it is necessary to improve fracturing fluid performance by increasing its viscosity. The method to increase CO_2 viscosity is to add miscible agents [6,7]. Non-polar liquid CO_2 is a very stable solvent with ultra-low dielectric constant, viscosity and surface tension [8]. Conventional thickener cannot be miscible with CO_2 to increase its viscosity, so new thickeners special in structure need to be developed.

The variation pattern of CO_2 viscosity with temperature and pressure in microscopic, mesoscopic and macroscopic scales was studied by using molecular simulation technique [9], and the microscopic mechanisms of the effect of chemical type and concentration on CO_2 viscosity were also examined. Moreover, the molecular structure of thickener was designed, combining with laboratory experiments, a new CO_2 thickener TNJ was developed, and the corresponding CO_2/sand dry-frac fluid system was formulated with the formula of: 1.5%–2.0% TNJ+ (98.5%–98.0%) liquid CO_2.

3.1. Viscosity

At 62–63 °C and 15–20 MPa in the experiment, the fracturing fluid viscosity of 1.5% TNJ + 98.5% CO_2 was 5–9 mPa s and the fracturing fluid viscosity of 2.0% TNJ + 98% CO_2 was 6–10 mPa s. The experimental results indicate that the CO_2 viscosity in supercritical state was dramatically increased by 240–490 times with a thickener content of 1.5%–2.0% (Figs. 1 and 2).

3.2. Friction loss in pipeline

According to field test results, the friction loss of CO_2/sand dry-frac fluid in 88.9 mm diameter tubing (internal diameter of 76 mm) was approximately calculated and the corresponding friction loss factors at different pumping-rates are listed in Table 1.

3.3. Filtration

Since CO_2/sand dry-frac fluid has no residuum (residue) and far higher viscosity than natural gas, the fracturing fluid filtration in gas reservoirs is mainly affected by fracturing fluid viscosity and formation fluid compressibility. As there is no experimental measuring apparatus to test CO_2/sand dry-frac fluid filtration currently, theoretical formula was used to calculate the filtration coefficient of the fracturing fluid. At the reservoir permeability of 0.4–1.2 mD, reservoir porosity of 14.0%, formation temperature of 104.6 °C, and pressure differential of 5–14 MPa, the magnitude order of filtration coefficient is 10^{-3}–10^{-2} m/min$^{0.5}$.

3.4. Matrix permeability loss-ratio of core samples

Only the permeability loss ratio caused by CO_2 thickener TNJ to core matrix was evaluated because there is no experimental measuring apparatus to test the core sample matrix permeability loss ratio caused by CO_2/sand dry-frac fluid at present.

Experimental results indicate that the CO_2 thickener YNJ caused an average permeability loss of 2.75% to cores (Table 2), which is quite insignificant.

4. Pressurized air-tight blender

Fracturing pump used in CO_2 fracturing can pump liquid CO_2 and fracturing pump will malfunction in the case of CO_2 vaporization. Therefore, CO_2 in surface pump set system must be kept in liquid state during fracturing.

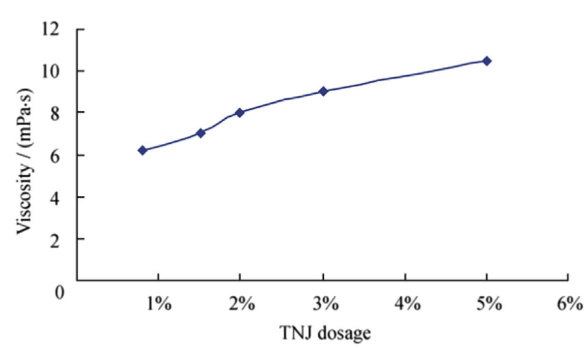

Fig. 1. Relationship between CO_2 viscosity and thickener dosage of TNJ.

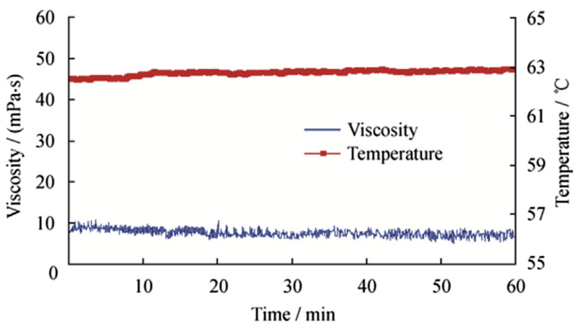

Fig. 2. Relationship between CO_2 fracturing fluid (2%TNJ + 98%CO_2) viscosity and time.

CO_2 phase state is sensitive to temperature and pressure, and blenders used in conventional hydraulic fracturing cannot meet the requirements of CO_2/sand dry-frac operation. Therefore, a pressurized air-tight blender was developed independently, which has heat preservation, pressure holding, sand control, flow measurement, sand concentration-monitoring functions.

4.1. Components of pressurized air-tight blender

A pressurized air-tight blender is composed of a blending tank assembly, a power system, a monitoring and controlling system and a manifold system.

The blending tank assembly with heat-preservation function is used to store proppant for fracturing. Proppant is transported to the frac-string by sand-transporting screw in the blending tank. The power system, providing driving force for the hydraulic motor installed on the sand-transporting screw, features low rotating-speed and large torque, and allow stepless regulation of rotating speed in a certain range.

Designed with a manual and automatic remote control, the blending tank assembly has the functions to monitor tank internal pressure, fluid flow rate, proppant concentration etc. It also can do fine adjustment of the valves and rotating speed of sand-transporting screw remotely.

The manifold system consists of gas manifold, liquid manifold, liquid level control manifold, liquid pressurized manifold, and gas intake and discharge manifold etc., which is used in conjunction with the controlling system to complete proppant filling, cooling, and flowback, etc.

Table 1
Pipeline friction losses of CO_2/sand dry-frac fluid in tubing of 88.9 mm diameter.

Pumping rate/(m^3 min^{-1})	Friction loss (pressure)/(MPa km^{-1})
2.4	10.8
2.0	9.6
1.7	5.7
1.4	4.0

Table 2
Core sample matrix permeability loss ratio caused by CO_2 thickener TNJ.

Core sample no.	Matrix permeability/mD	Porosity	Permeability loss ratio
1	0.075	5.578%	1.58%
2	0.093	9.287%	3.92%

4.2. Key technical parameters

Key technical parameters of the blender: working pressure is 2.5 MPa, working temperature is −20 °C, capacity is 10 m^3, and maximum sand-transporting rate is 0.5 m^3/min.

5. CO_2/sand dry-frac process

Reservoir characteristics, fracturing fluid properties, wellbore string, fracturing equipment, post-frac production and other factors need to be comprehensively considered in CO_2/sand dry-frac operation to ensure good fracturing result and operation safety.

5.1. Fracturing model

The fully three-dimensional (3D) fracturing software (stimulator) which has CO_2 fracturing fluid description module was used to simulate and design CO_2/sand dry-frac operation, and it can fulfill the design and analyses of compressible fracturing fluid.

5.2. Fracturing parameter design

Pumping rate is a key factor affecting the result of CO_2/sand dry-frac. The sand-carrying and fracture-making capacities of fracturing fluid can be improved by increasing pumping rate, thus enhancing fracturing fluid efficiency [10].

Since CO_2/sand dry-frac fracturing fluid has high propped fracture conductivity retention coefficient, conductivity comparable to conventional hydraulic fracturing can be created at relatively low sand concentration. Generally, the average sand concentration is kept below 10% in the CO_2/sand dry-frac operation.

A relatively high proportion of pad fluid is needed in the CO_2/sand dry-frac treatment to lower temperature in reservoir fractures, improve fracture-making capacity and ensure safe sand fracturing.

5.3. Fracturing string design

CO_2 fracturing fluid has high friction loss in fracturing strings [11], so tubing of 73.02 mm in diameter cannot meet the requirement of large pumping rate and tubing of 88.9 mm in diameter is used as fracturing strings in general.

In view of the low temperature and relatively high penetration of CO_2, packers need to be set at the lower end of tubing to ensure casing safety [12].

5.4. Fracturing equipment matching and surface pipeline designing

The surface equipment flowchart of CO_2/sand dry-frac operation is shown in Fig. 3.

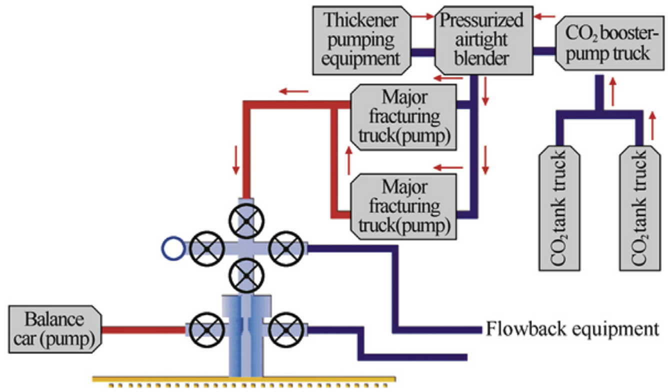

Fig. 3. Surface fracturing equipment flowchart of CO_2/sand dry-frac treatment.

The CO_2 storage tanks and the water chamber of fracturing pump are connected by a high pressure hose in which the pressure is 2.0–2.5 MPa during fracturing treatment.

The fracturing fluid in the fracturing pump is supplied by CO_2 circulating booster-pump. Connecting the fracturing pump and the CO_2 storage tanks, the CO_2 circulating booster-pump supplies sufficient fracturing fluid to the fracturing pump.

A desander must be installed in the surface flowback flow to remove the proppant carried by post-frac flowback fluid and ensure safe running of surface flowback equipment. A needle valve is installed behind the desander to control CO_2 flowback rate.

5.5. Fracturing operation procedures

First, pressure testing was conducted on surface flowback pipelines and high-pressure fracturing hard pipelines with a nitrogen booster-pump truck.

Second, pressure testing was carried out on the high-pressure hoses with gas phase CO_2 in storage tanks.

Third, cool the surface pipelines and fracturing equipment.

Fourth, perform fracturing treatment according to the pumping schedule.

Fifth, shut the well.

Sixth, disassemble fracturing pipelines and equipment.

5.6. Post-frac flowback control

After the CO_2/sand dry-frac treatment, flowback operation can be initiated until the wellbore temperature recovers after shut-in Ref. [12]. Flowback rate must be carefully controlled to prevent sand production during the flowback operation.

6. A field test

On August 12, 2013 the first CO_2/sand dry-frac field test in China was conducted in $P_1s_1^1$ reservoir of Well XX-22 in Sudong block of Sulige gas field. P_1s_1 in this well is a sandstone reservoir of 8.8 m thick, with a matrix permeability from electric log of 0.4–1.2 mD and a formation pressure coefficient of 0.86, representing low-pressure, low-permeability and strong water-locking damage reservoirs.

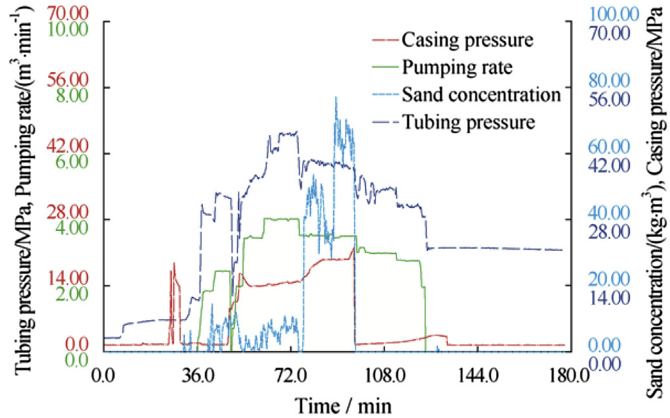

Fig. 4. Fracturing operation curves of the 1st Member of the Lower Permain Shanxi Fm (P_1s_1) in Well XX-22 of the Sudong block.

The pumping rate was 2.0–4.0 m^3/min, the injected sand volume was 2.8 m^3 and the average sand concentration was 3.5% (Table 3) in this fracturing treatment. The fracturing operation went smoothly and the CO_2 pressurized air-tight blender ran stably. The corresponding fracturing parameters and operation curve are shown in Fig. 4.

The field test indicates that effective fractures were created by the CO_2/sand dry-frac treatment and the fracture width can meet the requirements of proppant injection. The instantaneous shut-down pressure was 22.0 MPa in the fracturing treatment of Well XX-22 in Sudong block, and the corresponding reduced bottomhole pressure is 52.7 MPa, which, much higher than formation closure pressure, can open up fractures. The dynamic fractures created at the CO_2 pumping rate of 2.0–4.0 m^3/min (CO_2 thickener concentration is 1.5%–2.0%) can meet the demand of proppant injection of 70 kg/m^3.

Well XX-22 in Sudong block started to open flowback after shut-in for 24 h. In the second day, the flowback gas was flammable. In the third day, the CO_2 completely flowed back, realizing completely automatic flowback. The maximum shut-in pressure was 16.4 MPa, and the absolute open flow from single-point test was 3.0×10^4 m^3/d.

After guar gel fracturing treatment, the adjacent Well XX-20 and Well XX-21 in Sudong block were disable to flowback with low wellhead pressure (the shut-in wellhead pressure of Well XX-20 and Well XX-21 in Sudong block was 0 MPa and 3.5 MPa respectively), and gas test of them failed to yield any gas production. Compared with conventional guar gel

Table 3
Fracturing parameters of Well XX-22 in the Sudong block.

Pumping rate/(m^3 min^{-1})	Sand volume/m^3	Average sand concentration	Total fluid volume/m^3	Thickener concentration
2.0–4.0	2.8	3.5%	254.0	1.5%–2.2%

Table 4
Petrophysical parameters and well productivity of Well XX-22 and adjacent wells in Sudong block.

Well no.	Horizon (formation)	Thickness/m	Porosity	Matrix permeability/mD	Gas saturation	Interpretation	Absolute open flow (AOF)/(10^4 m^3 d^{-1})
Sudong	P_1s_1	4.0	13.99%	1.18	66.0%	Gas reservoir	3
XX-22	P_1s_1	4.8	9.04%	0.40	55.6%	Gas-bearing reservoir	
Sudong	$P_1s_1^1$	5.5	7.05%	0.14	46.8%	Gas reservoir	No productivity
XX-20	$P_1s_1^3$	4.4	7.74%	0.24	53.6%	Gas reservoir	
Sudong	$P_1s_1^2$	1.8	7.15%	0.34	36.3%	Poor gas reservoir	No productivity
XX-21	$P_1s_2^2$	3.6	8.22%	0.29	45.2%	Poor gas reservoir	

fracturing treatment, the CO_2/sand dry-frac significantly improved reservoir productivity (Table 4).

The field test shows that the CO_2 thickener reached the expected goal of improving CO_2 fracturing fluid properties. The pressurized air-tight blender ran stably and reliably, and data was recorded continuously during the fracturing treatment. Process and design agreed with actual situations, which provided good guidance to the field fracturing operation. Compared with conventional hydraulic fracturing treatment in adjacent wells, the CO_2/sand dry-frac treatment of P_1s_1 reservoir in Well Sudong XX-22 of increased well production more substantially.

7. Conclusions

(1) CO_2/sand dry-frac process is feasible, and works well in improving the productivity of low-pressure, low-permeability and strong water-locking damage reservoirs [13,14].
(2) CO_2 viscosity enhancement technology can increase the viscosity of supercritical CO_2 by 240–490 times, a key technology for CO_2/sand dry-frac improving the sand-carrying and fracture-making capacities of CO_2 fracturing fluid.
(3) The development of CO_2 pressurized air-tight sand blender realizes the matching of key fracturing devices and can meet operation requirements of CO_2/sand dry-frac.
(4) CO_2/sand dry-frac technology realizes completely automatic flowback.
(5) CO_2 is used in the CO_2/sand dry-frac technology to replace water-based fracturing fluid, which can substantially save water in fracturing treatment and achieve recycling economy.
(6) Increasing sand injection volume and lowering costs are the future direction of CO_2/sand dry-frac technology.

References

[1] Yost II AB, Mazza RL, Remington II RE. Analysis of production response to CO_2/sand fracturing: a case study//paper 29191 presented at the 1994 Eastern Regional Meeting. 8–10 November 1994 [Charleston, West Virginia, USA].
[2] Tudor R, Vozniak C, Peters W, Banks M. Technical advances in liquid CO_2 fracturing//paper PETSOG 94-36 presented at the Annual Technical Meeting. 12–15 June 1994 [Calgary, Canada].
[3] Lestz RS, Wilson L, Taylor RS, Funkhouser GP, Watkins H, Attaway D. Liquid petroleum gas fracturing fluids for unconventional gas reservoirs. J Can Petroleum Technol 2007;46(12):68–72.
[4] Wang Zhenduo, Wang Xiaoquan, Lu Yongjun. Application of carbon dioxide foam fracturing technology in low-permeability and low-pressure gas reservoirs. Acta Pet Sin 2004;25(3):66–70.
[5] Cai Bo, Wang Xin, Jiang Tingxue, Lǚ Xueqing. Application of hydraulic CO_2 fracturing technique in coalbed gas fracturing. Nat Gas Technol 2007;1(5):40–2.
[6] Stevens Jr., James F. Fracturing with a mixture of carbon dioxide and alcohol. US Patent 4887671. 1989-12-19.
[7] Shen Z, McHugh MA, Xu J, MacPhearson H, Kilic S, Mesiano A, et al. CO_2-solubility of oligomers and polymers that contain carbonyl group. Polymer 2003;44(5):1491–8.
[8] Trickett K, Xing Dazun. Rod-like micelles thicken CO_2. Langmuir 2010;26(1):83–8.
[9] Chatzis G, Samios J. Binary mixtures of supercritical carbon dioxide with methanol: a molecular dynamics simulation study. Chem Phys Lett 2003;374(1/2):187–93.
[10] Settari A, Bachman RC, Morrison DC. Numerical simulation of liquid CO_2 hydraulic fracturing//paper PETSOG-86-37-76 presented at the 37th Annual Technical Meeting. 8–11 June 1986 [Calgary, Canada].
[11] Su Weidong, Song Zhenyun, Ma Dehua, Jia Jianpeng, Bai Peng, Tang Liping. Application of CO_2 fracturing technology in Sulige gas field. Drilling Prod Technol 2011;34(4):39–44.
[12] Lillies AT, King SR. Sand fracturing with liquid carbon dioxide//paper 11341-MS presented at the SPE Production Technology Symposium. 8–9 November 1982 [Hobbs, New Mexico, USA].
[13] King SR. Liquid CO_2 for the stimulation of low-permeability reservoir//paper 11616-MS presented at the SPE/DOE Low Permeability Gas Reservoirs Symposium. 14–16 March 1983 [Denver, Colorado, USA].
[14] Yost AB, Mazza RL, Gehr JB. CO2/sand fracturing in Devonian shales//paper 26925-MS presented at the SPE Eastern Regional Meeting. 2–4 November 1993 [Pittsburgh, Pennsylvania, USA].