Fuel 233 (2018) 539–551

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

A combined stimulation technology for coalbed methane wells: Part 2. Application

Xianbo Su[a,b,*], Qian Wang[a], Haixiao Lin[a], Jinxing Song[a], Hongyu Guo[a]

[a] Henan Polytechnic University, Jiaozuo, Henan 454000, China
[b] Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Jiaozuo, Henan 454000, China

ARTICLE INFO

Keywords:
Combined stimulation technology
Coalbed methane well
Low-damage fracturing fluid
Sunan Syncline

ABSTRACT

Based on the theory and technology of combined stimulation, this paper, the second of a two-part series, presents an application of the combined stimulation technology to a low-deliverability CBM well in the Sunan Syncline, Anhui Province, China. During the stimulation, a low-damage fracturing fluid was adopted. Based on the laboratory test results, the property of the low-damage fracturing fluid is analyzed. Additionally, the stimulation effect is evaluated according to the calculation of the reservoir permeability and the drainage conditions. Results show that the low-damage fracturing fluid has good compatibility with the reservoirs, and can effectively prevent the reservoir to be damaged by water sensitivity, water blocking effect and flow rate sensitivity, and decrease the migration resistance of fracturing fluid in both tubing and reservoir fractures. The calculated reservoir permeability during the stimulation indicates good fracturing results for different kinds of reservoirs. The reservoir permeability at the early drainage stage after the combined stimulation is 3.4 times of the reservoir permeability after the first stimulation of this well. After conducted the combined stimulation, the daily gas production of the well has excessed 1000 m^3/d since 21st December 2017 which indicates a successful application of this technology.

1. Introduction

As much more attention has been paid to greenhouse-gas emission and environment protection, the development of coalbed methane has been widely considered in China. China has the third largest CBM resources after Russia and Canada in the world. During the 40 years' experience in CBM producing in China, some industrial bases in the southern Qinshui Basin and the eastern margin of the Ordos Basin have achieved commercial development of CBM [1]. However, the average single-well gas rates in Qinshui and Ordos are 1150 m^3/d and 787 m^3/d respectively, which are much lower than the average single-well gas rates in the US and Australian basins, e.g. San Juan Basin and Surat Basin [2]. Additionally, even the CBM production in China has seen a constant increasing since 2008, it's still significantly lower than the target set by the government [3]. To promote the process of industrialization of CBM development, it's urgent for China to find another CBM development strategic areas, and increase the single-well gas rate by adopting new technologies and fracturing fluids.

Fracturing fluid is the using fluid in reservoir stimulation, which is used to transmit pressure, form fractures in reservoirs and transport proppants into fractures for a better reservoir permeability and more deliverability. However, as an introduced fluid for the reservoir, the injected fracturing fluid will certainly cause damages to reservoirs, which cannot be prevented completely. As a result, how to minimize the damages and maximize the stimulation efficiency by improving the fracturing fluid's compatibility to reservoirs has been one of the core problems [4]. In China, active water-based fracturing fluid has been widely used. For this kind of fluid, only water sensitivity damage [5,6] was concerned by adding anti-swelling agent. KCl, as one of the most commonly-used anti-swelling agent, has been widely adopted in engineering and laboratory tests because of its both good performance and economic advantage [7,8]. However, other kinds of reservoir damages, especially flow rate sensitivity damage and water blocking damage, can also impose great impacts on the development of coal measure gas [9,10]. For the flow rate sensitivity damage [11], methods of optimizing drainage process and adding a hydrophilic surfactant into fracturing fluid have been adopted to mitigate fine migration in reservoir fractures [12,13]. For the water blocking damage [14], adding a surfactant to reduce the surface tension and change the wettability of fracturing fluid has been widely adopted [15,16]. In addition to mitigating reservoir damage caused by fracturing fluid, for low-permeability reservoirs' stimulation, fiction reducer has been widely used as

* Corresponding author at: Henan Polytechnic University, Jiaozuo, Henan 454000, China.
E-mail address: suxianbo@hpu.edu.cn (X. Su).

https://doi.org/10.1016/j.fuel.2018.06.086
Received 22 April 2018; Received in revised form 19 June 2018; Accepted 21 June 2018
0016-2361/

an additive of fracturing fluid [17,18], which can reduce the friction from fracturing fluid in the tubing and mitigate energy dissipation during fracturing [19]. Among friction reducers, anionic synthetic polymers (e.g., polyacrylamide polymers) have shown the best friction-reducing performance [20].

The theory of the combined stimulation technology, which is used to stimulate the coal measure gas reservoirs and produce gas from the whole coal measure in CBM wells, has been demonstrated in the first part of this two-part series. To test the efficiency of this combined stimulation technology, it was conducted to a CBM well in the Sunan Syncline, Anhui Province, China. This second part of the two-part series presents the process and result of the stimulation. Furthermore, concerning the active water-based fracturing fluid, which may cause serious water blocking damage and flow rate sensitivity to reservoirs, a low-damage fracturing fluid was adopted in the stimulation. Water blocking damage and flow rate sensitivity are maybe the causes that lead to failure of stimulation. This paper presents the stimulation mechanism of this kind of fracturing fluid.

2. Stimulation with a low-damage fracturing fluid

Low-damage fracturing fluid's preventive functions against the damages caused by water sensitivity, water blocking effect and flow rate sensitivity, and the function of friction reduction are realized by adding trace amounts of additives. The tests of water sensitivity, water blocking effect, flow rate sensitivity and friction reduction were conducted with the coal and rock samples collected from Well HN-01 which is undertook the secondary stimulation by this combined stimulation technology, in the Sunan Syncline. According to the test results, low-damage fracturing fluid with the proportioning of 1.0% KCl + 0.05% AN + 0.03% JA was selected for the combined stimulation of Well HN-01. Among the three components, KCl is the anti-swelling agent; AN, a kind of blend surfactant, is the preventive agent against the damages caused by a water blocking effect and flow rate sensitivity damage; and JA, the polymeric organic substance, is the friction reducer. In the following corresponding parts, the protective mechanisms against water sensitivity, water blocking effect and flow rate sensitivity and the friction-reducing mechanism are explained.

2.1. Stimulation mechanism for preventing water sensitivity damage

The stimulation mechanism for preventing water sensitivity damage includes mitigating clay minerals' swelling and particle migration.

2.1.1. Mitigating clay swelling

According to the petroleum industry standard in China, the centrifugal method, defined in SY/T 5971-94 (1995), was used to test the anti-swelling rate of the fracturing fluid. The centrifugal instrument is TDZ5-WS and the sample to be tested is the Na^+-montmorillonite with a purity of 98.5%.

The result of the anti-swelling test (as shown in Table 1) indicates that adding KCl with different concentrations of fracturing fluid has achieved the effective anti-swelling effect. As the concentration of KCl increases from 1.0% to 3.0%, the anti-swelling rate increases from 60.0% to 68.5%. However, considering the cost, the concentration of 1.0% is used.

KCl and NH_4Cl have been widely used as anti-swelling agents. K^+ and $NH_4{}^+$ can enter smectite's hexagonal space, formed by the six oxygen atoms of tetrahedral-octahedral smectite particles, with the incircle diameter of 0.28 nm and combine with their surrounding oxygen atoms, which can inhibit the smectite's dissociation after it contacts with water and can further avoid the forming of the diffuse electric double layers that will cause clay minerals' swelling. Compared with other cations of inorganic salts, the ionic radii of K^+ and $NH_4{}^+$ allows the two cations to enter the mentioned hexagonal space and combine with their surrounding oxygen atoms and not to easily be separated from the hexagonal space, presenting a good anti-swelling effect.

2.1.2. Mitigating clay mineral's migration

The result of the anti-swelling test (as shown in Table 1) shows that the anti-swelling rate of the fracturing fluids increases from 57.1% to over 60% after adding polymeric organic substance JA. The result indicates that JA has some effects on preventing water sensitivity damage. As JA is a flocculent, it can firmly adsorb the surfaces of clay particles and simultaneously adsorb several clay mineral particles to form a network structure. The network structure serves to stabilize clay mineral particles and inhibit the migration of particles, effectively restraining water sensitivity damage.

Additionally, adding hydrophilic surfactant AN can promote the wettability of fracturing fluid to clay particles and the cohesion between clay mineral particles. The combined action of KCl, AN and JA can effectively prevent clay mineral from swelling and argillation. Even if crumbling occurs and forms particles, the particles can also agglomerate again and settle down. As a result, the flow conductivity of the fractures, formed during fracturing, can be maintained for a long time, and the water sensitive damage can be effectively mitigated.

2.2. Stimulation mechanism for preventing water blocking damage

The stimulation mechanism for preventing water blocking damage is conducted by reducing irreducible water saturation and water blocking damage rate and promoting desorption and diffusion of coal measure gas. The methods proposed by Su et al. [16] were adopted to conduct the tests of wettability, permeability damages and adsorption/desorption.

2.2.1. Reducing irreducible water saturation and water blocking damage rate

Capillary resistance yields the increase of reservoirs' irreducible water saturation and the decrease of reservoirs' gas-phase permeability, which is the reason of water blocking damage. Capillary resistance is

Table 1
Result of the anti-swelling test.

Type of solutions	The volume of swelling samples (mL)	Anti-swelling rate (%)
Distilled water	0.80	0.0
Anhydrous kerosene	0.45	100.0
1.0% KCl + 0.05% AN + 0.03% JA solution	0.59	60.0
1.5% KCl + 0.05% AN + 0.03% JA solution	0.58	62.8
2.0% KCl + 0.05% AN + 0.03% JA solution	0.57	65.7
2.5% KCl + 0.05% AN + 0.03% JA solution	0.57	65.7
3.0% KCl + 0.05% AN + 0.03% JA solution	0.56	68.5
1.0% KCl + 0.05% AN solution	0.60	57.1
1.0% KCl + 0.05% AN + 0.01% JA solution	0.59	60.0
1.0% KCl + 0.05% AN + 0.02% JA solution	0.58	62.8
1.0% KCl + 0.05% AN + 0.04% JA solution	0.59	60.0