Journal of Natural Gas Science and Engineering 27 (2015) 926–933

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Experimental study of water shutoff gel system field parameters in multi-zone unfractured gas-condensate reservoirs

Nasibeh Hajilary [a], Mohsen Vafaie Sefti [a,*], Ahmad Dadvand Koohi [b]

[a] Faculty of Chemical Engineering, Department of Engineering, Tarbiat Modares University, Tehran, Iran
[b] Chemical Engineering Department, Engineering Faculty, University of Guilan, Rasht, Iran

ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form
13 September 2015
Accepted 17 September 2015
Available online 25 September 2015

Keywords:
Polymer gel
WSO
Multi-zone reservoir
Gel penetration
Reservoir porosity
Gas-condensate

ABSTRACT

Excess water production during gas production causes serious operational problems and, may shutoff the wells. Polymer gel is one of the water shutoff (WSO) methods extensively used in mature gas fields in the recent years. In this research, Cr (III)-acetate sulfonated polyacrylamide hydrogels were applied in porous media with radial flow. In order to obtain gel treatment conditions with desirable performance, some sandpack-flooding tests were designed. By statistical design of the experiments using central composite, the sandpack-flooding tests were conducted to investigate the effect of gel penetrated area and reservoir porosity on the WSO efficiency. The results showed that lower gel penetrated depth led to lower gas-condensate permeability reduction and, the utmost reduction of water permeability was in a critical depth of gel penetration. In optimum conditions, a gel penetration of 0.96 cm and a porosity of 31.46% had RRF_g (gas-condensate residual resistance factor) of 1.83 and RRF_W (water residual resistance factor) of 5510, respectively. Some tests through multi-zone sandpacks were carried out to examine the effect of layers with different porosities and crossflow presence. Multi-zone sandpacks with crossflow between the gas-condensate and water-producing zones showed RRF_W in a range of 28.2–244.7. However, the selectivity increased from 90 to 99.9% without crossflow. It was found that the chance of successful WSO treatment increases when the higher permeable layers are over the lower permeable layers.

1. Introduction

Reduction in the water production of hydrocarbon reservoirs has become an increasingly important objective for oil and gas industries. Excess water production in hydrocarbon reservoirs increase the pressure drop between the top and the bottom of the wells, leading to the reduction of hydrocarbon flow from the reservoir into the production well. The produced water causes some additional problems, e.g. corrosion of equipment, and increasing the cost of water separation, effluent disposal, and transportation. These drawbacks stimulate the development of water shutoff methods (WSO), which can be classified as mechanical and chemical methods. Difficulty of mechanical methods, besides their high operation and maintain costs, deviates the global concentration on the chemical methods (Seright et al., 2001). Crosslinked polymer is one of the chemical WSO methods extensively used in the recent years (Zhao et al., 2011; Udayabhanub et al., 2012; Sengupta et al., 2014). It is typically composed of a polymer or copolymer, and a crosslinker (dissolvable in water) (Prada et al., 2000). Because of disproportionate permeability reduction (DPR) property of polymer gels, these gels can reduce water permeability without significant effect on hydrocarbon permeability (Liang et al., 1995). Various mechanisms such as gel shrinkage and swelling, segregated oil and water pathways, and dehydration of polymer gels have been reported as the causes of DPR (Nguyen et al., 2006). Polyacrylamides (PAM) are the most common polymers used for the gel treatment of gas reservoirs (Ranjbar and Schaffie, 2000; Willhite et al., 2002; Al-Muntasheri et al., 2007), and hydrolyzed PAM/Cr (III) is a well-known example of hydrogels which was used by many researchers (Rafipoor et al., 2013; Brattekas et al., 2014; Karimi et al., 2014). Properties of polymer systems such as gelation time, gel strength, and gel stability, as well as, reservoir conditions such as salinity, temperature, hardness, and pH of the formation water have been discussed as effective parameters in many researches (Winter and Chambon, 1986; Seright, 1988; Albonico et al., 1992; Vossoughi, 2000).

* Corresponding author.
E-mail address: Vafaiesm@modares.ac.ir (M. Vafaie Sefti).

http://dx.doi.org/10.1016/j.jngse.2015.09.038
1875-5100/

Polymer gel has been used successfully in fractured reservoirs (Seright et al., 2001; Sydansk and Seright, 2007). Primary studies show that hydrocarbon zone must be protected during gel placement in unfractured wells with radial flow, and selective injection occurs only in the reservoirs with linear flow and not in the layered reservoirs with radial flow (Liang et al., 1993; Seright, 1988). Possibility of selective injection in reservoirs with crossflow and radial flow has been simulated (Todd et al., 1991; Gao et al., 1993). Sydansk and Seright (2007) concluded that theoretically, polymer gel can be applied in the matrix rock reservoirs (radial flow) with RRF_O (oil residual resistance factor) less than 2 and RRF_W (water residual resistance factor) more than 20. Also Jinxiang reported that RRF_W increases with increasing of the core permeability (Jinxiang et al., 2013). Other investigations have shown that the distance of gel penetration varies approximately with the cleanup time (the time to restore oil/gas productivity after the gel treatment) (Seright, 2006).

Although huge amounts of studies have been carried out in the application of polymer gel but most of them are limited to the single zone reservoirs with linear flow, or theory and simulation. While layered reservoirs with different permeabilities are commonly observed in oil and gas fields (Vossoughi, 2000). Therefore, some challenges remain unsolved such as unfractured matrix wells with radial flow, depth of the gel treated area, porosity of the target zone, layered and heterogeneous reservoirs, and reservoirs with or without crossflow.

In this paper, the hydrolyzed PAM/Cr (III) polymer gel system was employed in a sandpack-flooding setup with radial flow and vertical well to evaluate the treatment efficiency in a pilot before the field application. To determine the effects of reservoir porosity and gel penetration radius, the statistical design of the experiments by response surface methodology was applied using central composite design (CCD) (Croarkin and Tobias, 2002). At first, the sandpack-flooding tests were carried out to determine the gas-condensate and water effective permeability, as well as the residual resistance factor in porous media. Second, the sandpack flood tests with optimum gel radius, out of the experiments of the first step, were applied on the multi-zone sandpack and permeability reduction of water to gas-condensate in porous media was measured to evaluate gel performance in multi-zone reservoirs with different porosities layers. Also the effect of the presence of crossflow between gas-condensate and water producing zone was investigated.

2. Material and methods

2.1. Materials

The hydrolyzed polyacrylamide, in the form of the crystalline powder, having an average molecular weight of 2×10^6 Dalton and sulfonation degree of 25% was provided by SNF Co. (France) under the trade name of AN125VLM. The crosslinker Chromium triacetate was obtained in green powder from Carlo Erba Co. (Italy).

The gas-condensate was prepared from the phases 2&3 of South Pars Gas Complex (Assaluyeh, Iran) with an API gravity of 59 and a viscosity of 76.26 cp (at 15 °C). The composition of gas condensate is shown in Table 1. Also, distilled water and formation water were used. Components of the formation water (pH = 6.5) are tabulated in Table 2. Finally, the porous media were built with the sand particles of 0.01–1 mm and 560-mesh glass beads.

2.2. Preparation of gelant solution

The polymer gelant was prepared by mixing crosslinker and 2.634×10^5 ppm of copolymer at 0.12 mass ratio of crosslinker/copolymer for its desirable gelation time, gel strength, and rheological behavior (Salehi et al., 2014). At first, a certain amount of polymer powder was added to distilled water at room temperature, and stirred for one day at room temperature to achieve a homogeneous polymer solution. The Cr (III)-acetate powder was mixed in distilled water using a magnetic stirrer (Stuart CB162, UK) for 5 min. Finally, the gelant was prepared by mixing the crosslinker solution with the polymer solution at a specified ratio for 10 min (Salehi et al., 2014).

Table 1
The components of gas-condensate.

Component	%mol/mol
N. Paraffine	19.42
Iso. Paraffine	30.75
Aromatics	34.08
Saturates C15+	12.32
Aromatics C15+	2.14
Unknown	1.29

Table 2
Formation water component.

Component	wt.%
NaCl	20.0460
$CaCl_2 \cdot 2H_2O$	3.9360
$MgCl_2 \cdot 6H_2O$	1.0780
$NaHCO_3$	0.0015
NH_4Cl	0.0770
H_2O	74.8620

The gelation time based on Sydansk and Argabright (1987) bottle testing method was about 48 h at 90 °C (average temperature of Iranian reservoirs). Bottle test method provides a semi-quantitative measurement of gel strength, and the gelation time is expressed as an alphabetic code.

2.3. Design of experiments

To evaluate the effect of gel penetration radius and sandpack porosity, the statistical design of the experiments was applied by response surface methodology using CCD with two factors in five levels ($-\alpha$, -1, 0, $+1$, $+\alpha$) (Table 3). α is calculated by $\alpha = 2^{(k/4)}$, and k is the factor number. In this experimental design, the center point is (0, 0), star points are ($\pm\alpha$, 0) and (0, $\pm\alpha$), and factorial points are (± 1, ± 1).

A range of porosity (30–40%) and gel penetration radius (0.5–3 cm) were applied to determine their effects on gel treatment performance. Three center points (runs 9–11) were also considered and assumed to measure the probable random errors during the experiments. In the CCD method, the statistical models were validated by fitting the actual responses into the prevailing linear, quadratic, two-factor interactions (2FI), and cubic models. The linear and quadratic equations are presented below:

$$y = \beta_0 + \sum_{i=1}^{k} \beta x_i \quad (1)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta x_i + \sum_{<i<j}^{k} \beta_{ii} x_i^2 + \sum_{1<i<j}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where k represents the number of variables, βs are coefficient parameters, $x_i x_j$ is the multiply of binary variables (interactions), x_i^2 is nonlinear term, ε is the statistical random error term, and y is the