Journal of Petroleum Science and Engineering 170 (2018) 643–654

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

A comprehensive model for dynamic characteristic curves considering sulfur deposition in sour carbonate fractured gas reservoirs

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ARTICLE INFO

Keywords:
Sulfur deposition
Stress sensitivity
Fractured carbonate gas reservoir
Finite differences
Characteristic curve

ABSTRACT

Calculating sulfur deposition is a key issue in developing sour gas reservoirs, where sulfur solubility plays an important role. However, prediction of sulfur solubility is a difficult problem due to the toxic of H_2S. In this work, an analytical model for dual porosity media considering the influence of sulfur deposition was proposed. The Douglas-Jones predictor-corrector method is used to calculate a relationship between time and pressure, which can avoid solving the system of nonlinear equations. The effects of sulfur deposition on well performance were analyzed and some dynamic characteristic curves for predicting sulfur deposition were provided. The results show that the fastest pressure drop appears near the wellbore, which is the primary damage zone for elemental sulfur precipitation and deposition. Flow parameters and storage ratio play the significant influences on the sulfur saturation curve shape. In addition, the reduction of flow parameters and storage ratio lead to the increase of sulfur saturation and decrease of permeability, resulting in the damage of sour gas formation. The advantage of this approach is that it can be used to describe a characteristic curve without considering the sulfur solubility issue. This paper provides a novel method to analyze the impacts of sulfur deposition on well performances in sour carbonate fractured gas reservoirs.

1. Introduction

Sour gas reservoir reserves up to $7.358 \times 10^{13} m^3$, accounting for 40% of the total gas reserves in the world and it's widely distributed in Russia, Germany, France, China, Canada, America, Iran et al. (Wei et al., 2015). As the reserve and production of the sour carbonate fractured gas reservoirs gradually, the sulfur deposition has given increasing attention in developing these gas reservoirs. With a decrease in pressure and temperature, elemental sulfur may precipitate and deposit in reservoir pores. Precipitated sulfur cannot easily be carried by flowing gas (Hu et al., 2013a), which may decrease reservoir permeability and porosity. Elemental sulfur solubility is a significant problem in sour gas reservoirs, which differ from normal gas reservoirs.

As H_2S is a toxic gas, there is a need for a theoretical model to describe sulfur solubility. Many scholars have studied this problem (Brunner and Woll, 1980; Brunner et al., 1988; Kennedy and Wieland, 1960; Roof, 1971; Swift and Manning, 1976; Gu et al., 1993; Yang et al., 2009; Sun and Chen, 2003). Roberts' sulfur solubility model (1997) was often used to describe sulfur precipitation and deposition. Recently, Yang et al. (2009), Bian et al. (2011), Hu et al. (2014), and Guo and Wang (2015) presented new sulfur solubility models and their results are closer to experimental data.

A relationship between a sulfur volume and reservoir permeability and porosity is a key issue in sour gas reservoir development. Kuo (1972) created a relationship between sulfur and permeability. Adin (1978) established a permeability and porosity model based on solid particle deposition. Gruesbeck and Collins (1982) described the effect of fine particles on reservoir permeability using a plugging pathway fraction. Later, Roberts (1997), Mei and Zhang (2006), Hu et al. (2013b), and Mahmoud (2014) calculated and analyzed the effect of sulfur deposition on permeability, porosity and production performance on the basis of the steady percolation theory. Hu et al. (2013a) illustrated the results that precipitated sulfur cannot be easily carried, and elemental sulfur may deposit in situ, block pores, and decrease permeability.

When pressure and temperature decrease, elemental sulfur precipitates from sour natural gas, blocking pores, decreasing the reservoir permeability. Stress sensitivity is defined as a decrease in reservoir permeability with a decrease in reservoir pressure. From the viewpoint of reservoir damage, the physical phenomenon of sulfur deposition

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https://doi.org/10.1016/j.petrol.2018.07.010
Received 19 April 2018; Received in revised form 5 June 2018; Accepted 3 July 2018
Available online 04 July 2018

(Roberts, 1997; Mahmoud, 2014) has a strong similarity to stress sensitivity (Pedrosa, 1986; Zhang et al., 2014a), permeability will decrease with a decrease in pressure.

Pedrosa (1986) showed a transient pressure response in an infinite radial system with pressure-dependent rock properties. Approximate analytical solutions of a nonlinear flow equation with a constant well production rate were obtained by the use of a perturbation technique. Kikani and pedrosa (1991) used a regular perturbation technique to solve a nonlinear equation to the third order of accuracy. Yeung et al. (1993) considered a constant pressure test in an infinitely large system, and found the solutions to flow problems in linear, cylindrical and spherical systems, respectively. Berumen and Tiab (1997) focused on the investigation of pressure responses in a well producing through a composite system of stress-sensitive vertical symmetric or asymmetric fractures interacting with a stress-sensitive permeable porous medium. Wu and Pruess (2000) presented an integral method for analyzing transient fluid flow through a porous medium, which had pressure-dependent permeability. Franquet et al. (2004) simulated pressure-dependent permeability using an exponential form for permeability vs. a pressure drop in a gas reservoir. However, the detailed solutions steps were not given.

The perturbation solutions for constant pressure production and a constant production rate of a linear-source well were obtained by using a self-similarity solution method and the regular perturbation method in an infinitely large system, and used a changing rule of pressure when fractal and deformation parameters changed (Zhang and Tong, 2008). Zhang et al. (2014b) presented the results of a study on a pressure buildup analysis of a vertically fractured well with the consideration of stress-sensitive permeability and a hysteresis effect in fractures. Su et al. (2015) conducted a comprehensive study of gas flow in shale reservoirs to improve the performance analysis of multistage horizontal fractured wells. Specifically, a stress-sensitivity effect of a fracture system was considered. Chen et al. (2015) proposed a semi-analytical method to predict the performance of horizontal wells with fracture networks in a shale gas formation. The effect of stress sensitivity of permeability was considered. In the above literature, one key point in their mathematical analysis is the perturbation technique. However, to study dual porosity media, just the perturbation technique is not enough for analyzing their nonlinear equations. The Douglas-Jones predictor-corrector is an effective method to solve nonlinear equations (Haverkamp et al., 1997; Ikoku and Ramey, 1982; Babajimopoulos, 1991).

The physical phenomenon of the influence of sulfur deposition on reservoir permeability is similar to that of stress sensitivity. Moreover, the stress sensitivity research is relatively mature compared to sulfur deposition. The novelty of this paper is the first time to apply theories of stress sensitivity to study problems of sulfur deposition. In this paper, firstly, based on the unsteady percolation mechanics theory and mathematical physics method, an analytic model for a dual media gas reservoir was established considering the influence of sulfur deposition. Secondly, due to the difficulty in nonlinear equation solution, the method of the Douglas-Jones predictor-corrector is used to calculate a relationship between time and pressure. Finally, the effect of sulfur deposition on well performance is obtained and some characteristic curves are provided.

2. Methodology

2.1. Relationship between precipitated sulfur and permeability

Precipitated sulfur may reduce reservoir permeability and porosity. Kuo's model (1972) is used:

$$k_f = k_{fi} e^{-6.22\left(1-\varphi_f/\varphi_{fi}\right)} \tag{1}$$

Elemental sulfur particles precipitate and their deposits in pores decrease reservoir porosity. Porosity may change with time and can be calculated by using Eq. (2).

$$\varphi_f = \varphi_{fi} - \varphi_{fi}(C_{ri} - C_r)/\rho_s \tag{2}$$

The elemental sulfur saturation can be given:

$$S_s = 1 - \varphi_f/\varphi_{fi} \tag{3}$$

Sulfur saturation (Ss) is defined as the ratio between deposited sulfur volume and pore volume. Substituting Eq. (3) into Eq. (1), proper arrangements give a relationship between permeability and sulfur saturation expressed as follows:

$$k_f = k_{fi} e^{-6.22 S_s} \tag{4}$$

2.2. Relationship between stress sensitivity and sulfur deposition

The pseudo pressure is presented in Eq. (5). The fracture permeability modulus is defined in Eq. (6).

$$\psi = 2\int_{p_0}^{p} \frac{p}{\mu z} dp \tag{5}$$

$$\beta = \frac{1}{k_f}\frac{dk_f}{d\psi_f} \tag{6}$$

Coefficient β plays an important role in the influence of the effective stress on permeability, which is the description of fracture permeability dependent on pressure. In order to use it more easily, the coefficient β may be assumed as constant during production in the development of a gas field.

$$k_f = k_{fi} e^{-\beta(\psi_i - \psi)} \tag{7}$$

As mentioned, the stress sensitivity is a relatively mature topic compared to sulfur deposition, especially sulfur solubility prediction. The latter is still a hot research issue. Fortunately, the physical phenomenon of stress sensitivity is similar to that of the influence of sulfur deposition on permeability. Therefore, it is reasonable that the method of stress sensitivity can be used to study the problem of sulfur deposition:

$$k_f = k_{fi} e^{-6.22 S_s} = k_{fi} e^{-\beta(\psi_i - \psi)} \tag{8}$$

An arrangement of Eq. (9) is given by

$$S_s = \beta(\psi_i - \psi)/6.22 \tag{9}$$

2.3. Mathematical models

For a fracture system, a continuity equation can be expressed as follows (Warren and Root, 1963),

$$-\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r) + q_m = \frac{\partial}{\partial t}(\varphi\rho)_f \tag{10}$$

The total elastic energy is deemed as $(\phi c)_m$in a unit matrix volume matrix system. According to mass conservation and Darcy's law, fluid flow in matrix can be ignored in a carbonate fractured reservoir compared to the fluid flow in a fracture system. Matrix pore volume change (q_m) is equal to fluid flow rate which from matrix to fracture. Then a continuity equation in rock matrix can be expressed as follows (Warren and Root, 1963).

$$q_m = -\frac{\partial(\rho\varphi)_m}{\partial t} = -(\varphi c)_m \frac{\partial p_m}{\partial t} = \alpha\frac{k_m}{\mu}(p_m - p_f) \tag{11}$$

Due to a good flow capacity in fracture, gas flow is assumed as laminar flow. The flow obeys the Darcy's law:

$$v_r = -\frac{k_f}{\mu}\frac{\partial p_f}{\partial r} \tag{12}$$

Substitution of Eqs. (6)–(9) into Eq. (10), for ease of calculations, a