Journal of Natural Gas Science and Engineering 25 (2015) 140–147

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Multiphase flow mechanism of sand cleanout with supercritical carbon dioxide in a deviated wellbore

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ARTICLE INFO

Article history:
Received 28 October 2014
Received in revised form
20 April 2015
Accepted 20 April 2015
Available online 15 May 2015

Keywords:
Supercritical carbon dioxide
Inclination
Multi-phase flow
Sand size distribution
Sand-transporting efficiency

ABSTRACT

Supercritical carbon dioxide (CO_2) is of great interest as a sand-flushing fluid with significant potential advantages; therefore, it is of fundamental and practical importance to investigate its sand transporting mechanism. Numerical simulation was conducted to analyse the heat transfer along the whole deviated wellbore, and the results served as boundary conditions for the multiphase flow model of CO_2 transporting sand. In addition, the physical properties of CO_2 as a function of temperature and pressure were considered in the numerical simulation. The multiphase flow model was solved to investigate the effects of various factors on the sand transporting efficiency of CO_2, including displacement, sand production rate and annulus eccentricity, in which the sand size distribution at the annulus entrance was set based on the measurement data from the experiments. The computed results show that the sand transporting efficiency decreases with inclination abruptly at first and subsequently increases, which is consistent with the experimental results. The inclination where sand is most difficult to transport varies from 48° to 72° and depends on the sand's diameter and production rate at the bottom hole. The efficiency can be improved by increasing displacement with a trend that is greater at first and later slows. A larger sand production rate at the bottom hole means it is more difficult to transport sand. The efficiency decreases with increasing eccentricity at first and subsequently begins to increase when the eccentricity reaches 0.8. Under the same conditions, the pressure drop of sand-flushing with CO_2 is 52.3% that observed with water. The results lay an important foundation for practical application.

1. Introduction

Increasing numbers of unconventional/offshore gas reservoirs have been exploited to meet the world's need for energy, and a portion of the need is met by uncemented horizontal wells intersecting multi-stage fractures to obtain enhanced recovery. Hydraulic fracturing sand or shallow formation sand, alone or mixed with reservoir fluids, can easily penetrate into the annulus/tubing during production. Sand can induce flow resistance and negatively affect gas production (Li et al., 2010). Hence, sand cleanout has developed into a standard practice in oilfield operations (Heinrichs and Dedora, 1995) and is generally conducted with coiled tubing and circulating out the fills with carrying fluid (Falk and Fraser, 1995; Ozbayoglu et al., 2005).

Water or brine is most commonly used as the circulation fluid in oil reservoirs due to the low cost; however, it is limited in low bottom-hole pressure (BHP) gas reservoirs and unconventional reservoirs due to potential damage (e.g., lost circulation) (Li et al., 2010; Lage et al., 1996). Stable foams have been successfully applied in both vertical and inclined wells as sand/cutting transporting fluids since the mid-1980s (Hall and Roberts, 1984; Fraser and Moore, 1987; Falk and McDonald, 1995; Nakagawa et al., 1999; Wang et al., 2009). Foams transport the fills in high temperature and pressure conditions and may get polluted by various formation fluids penetrating into the annulus. The difficulties lie in how to keep foams stable economically (Doane et al., 1996; Negrao and Lage, 1997; Li et al., 2014).

Carbon dioxide (CO_2) has been used as a drilling and fracturing fluid with potential advantages and insignificant corrosion (Kolle, 2000; Gupta et al., 2005; Lillies. 1982; Gupta and Bobier, 1998), and it is now drawing more interest. CO_2 changes into the supercritical state in bottom hole (when the temperature is 304.2 K or higher and the pressure is above 7.38 MPa), which provides significant benefits, including increased rate of penetration (ROP) (Du

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http://dx.doi.org/10.1016/j.jngse.2015.04.022
1875-5100/

et al., 2012, 2013) and productivity (by reducing formation damage and competitive adsorption with methane) (Sun et al., 2013). Thus, CO_2 is one of the most promising sand cleanout fluids (Li et al., 2013). However, knowledge of cutting/sand transporting with supercritical carbon dioxide is inadequate to support field application. Former investigations mainly focused on how temperature and pressure (by changing the density and viscosity of CO_2) influenced the cutting transporting efficiency in horizontal sections, and the experimental results and simulation were in good agreement (Shen et al., 2011; Li et al., 2011). However, how the engineering factors (including inclination and displacement) influence multiple phase flow is not known. Additionally, the density/viscosity change of CO_2 in the flow field and the variation of the cutting diameter were neglected in the earlier simulations, which contradicted the actual engineering conditions.

In hydraulics calculations, the compressibility of CO_2 and heat transfer along the wellbore must be considered because liquid CO_2 is pumped into tubing whose temperature is much lower than that of formation. Span and Wagner (1996) presented a new equation of state for CO_2 covering the fluid region from the triple-point temperature to 1100 K at pressure up to 800 MPa. Based on the Span–Wagner equation and Vesovic model (Vesovic and Wakeham, 1990), Wang and Ni (2013) investigated the heat and pressure transferring mechanism of CO_2 in vertical wellbores. The preliminary research lays the foundation for this study.

With consideration of the sand size distribution and eccentricity of the annulus, this paper investigates the sand transporting mechanism with CO_2 in the whole inclined wellbore. For the hydraulics calculations, we developed a closed mathematical model to fully couple the hydrostatic pressure, temperature, density and viscosity of CO_2 and friction. The study offers a theoretical basis for field application.

2. Mathematical models

In the sand-cleanout process, hypothermic liquid CO_2 is pumped down to the bottom and then jetted into the tubing and casing annulus. Fills are flushed and dispersed, and then CO_2 carries sand and flows back to the surface via the annulus. Sand can continue to penetrate into the annulus via perforations, and heat transfers from the formation into the tubing through the cement sheath, metal casing and annulus (Fig. 1). The inside diameter of the tubing is 50 mm, the outside diameter of the tubing (r_o) is 60 mm and the inside diameter of the casing (R_i) is 100 mm. The eccentricity ε is defined as

$$\varepsilon = \frac{D}{R - r} \tag{1}$$

2.1. Physical properties of CO_2

As documented in earlier research (Kolle, 2000; Gupta, 2005), CO_2 changes into the supercritical state in bottom hole when the temperature is 304.2 K or higher and the pressure is above 7.38 MPa (Fig. 2). The phase change of CO_2 is reflected by the thermodynamic properties changes. Li et al. (2011) experimental results show that the cutting/sand transporting capability of CO_2 can be improved by reducing temperature or increasing pressure. The coupling relationship between temperature/pressure (attributed to well depth) and the thermodynamic properties of CO_2 was considered to ensure accuracy. The coupling relationship is illustrated in this section.

The implicit equation of CO_2 density can be expressed as (Span and Wagner, 1996)

$$P(\delta, \tau) = \rho RT\left(1 + \delta \Phi_\delta^r\right) \tag{2}$$

where $\delta = \rho/\rho_c$ is the dimensionless reduced density and $\tau = T_c/T$ is the inverse reduced temperature. Dimensionless Φ_δ^r is the partial derivative of the Helmholtz energy $\Phi(\delta,\tau)$. After the pressure P and temperature T are obtained, the density ρ can be calculated by numerical algorithms.

The isobaric heat capacity of CO_2 can be written as

$$\frac{M \cdot c_p}{R} = -\tau^2\left(\phi_{\tau\tau}^o - \phi_{rr}^r\right) + \frac{\left(1 + \delta\phi_\delta^r - \delta\tau\phi_{\delta\tau}^r\right)^2}{1 + 2\delta\phi_\delta^r + \delta^2\phi_{\delta\delta}^r} \tag{3}$$

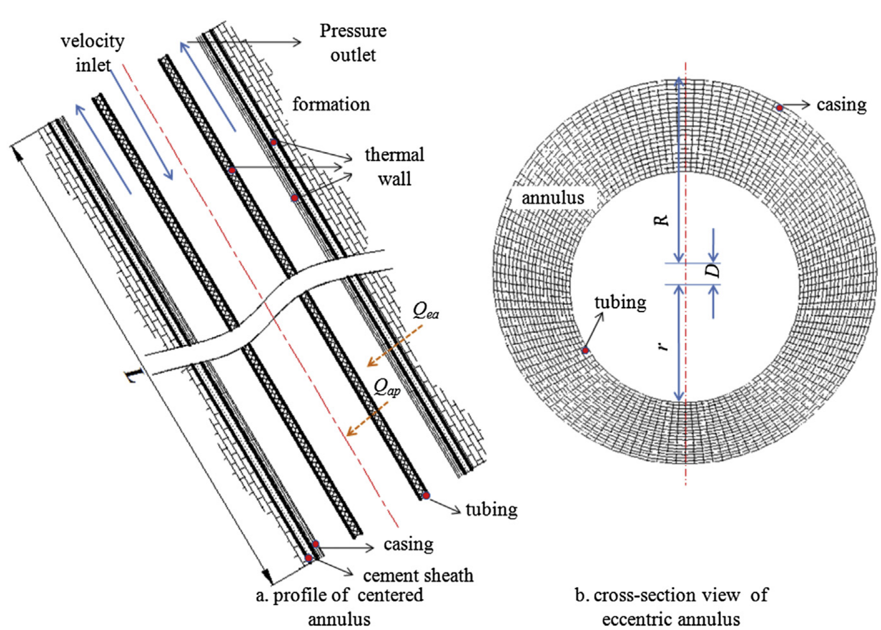

Fig. 1. Physical model of flow field.