Journal of Natural Gas Science and Engineering 30 (2016) 414–420

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Coupling model for carbon dioxide wellbore flow and heat transfer in coiled tubing drilling

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form
23 February 2016
Accepted 23 February 2016
Available online 26 February 2016

Keywords:
Supercritical carbon dioxide
Coiled tubing drilling
Heat transfer
Hydraulics calculations
Pressure profile

ABSTRACT

In order to drill with carbon dioxide as the circulation fluid, a mathematical model was proposed to investigate the flow field in both tubing and annulus. Based on finite volume method, the closed model fully couples the hydraulics, heat transfer and physical properties of carbon dioxide. According to field application, the model is solved and discussed with a case study. The results show that, the pressure is in positive correlation with well depth in both tubing and annulus. The fluid temperature increases fast after liquid carbon dioxide is pumped into tubing and then the increasing rate slows down with increasing depth. Carbon dioxide changes into supercritical state when the depth equals 780 m. The pressure drop of bit jet is 9.78 MPa and the temperature difference between carbon dioxide and formation rock is 12.11 K at bottom hole. In the annulus, the temperature decreases as carbon dioxide flows upward and it is higher than geothermal temperature when depth is less than 927 m. The changes in physical properties are mainly dominated by temperature change in the tubing and by pressure change in the annulus. The density, viscosity and thermal conductivity all witness a constant decrease along the flow route, and the changing trends develop faster at shallow well section in the tubing. At bottom hole, the density is large enough to drive down-hole motors. The heat capacity changes little in the tubing and then increases rapidly when flowing upward along the annulus. The capacity is much larger than that of air in wellbore. Carbon dioxide maintains in supercritical state in the annulus and provides advantages for reservoir exploitation. This study aims to lay theoretical foundation for practical application.

1. Introduction

Generally, water or oil based mud is utilized as the drilling fluid to exploit oil reservoirs economically, however, they have some limitations for unconventional reservoirs and low bottom-hole pressure (BHP) gas reservoirs because of associated damages (e.g., mud leakage and formation damages) (Lage et al., 1996; Li et al., 2010). Meanwhile, increasing numbers of shale-gas reservoirs are being exploited to meet human's need for energy. Shale gas will certainly draw more interests worldwide in the future (Weijermars, 2013; Arora and Cai, 2014), which introduces the need for lighter and formation-harmless circulation fluid in both drilling and fracture field to get enhanced recovery (Li et al., 2013; Tanmay, 2014; Richard et al., 2015). Stable foam (Fraser and Moore, 1987; Falk and McDonald, 1995) and dry gas (e.g., air and nitrogen) (Supon et al., 1987; Ford et al., 2011) were introduced as drilling fluid and they both have their advantages and limitations. Similar with brine, aqueous phase in foam could induce the hydration swelling of clay minerals in shale and flow restriction of gas. As one kind of dry gas drilling fluid, the feasibility and advantages of carbon dioxide have already been validated both in experiments and field applications (Kolle, 2000; Gupta et al., 2005).

Drilling with carbon dioxide could get increased rate of penetration (ROP) by 3.3 times larger than general mud (Kolle, 2000), other benefits include enhanced oil recovery (EOR) by mitigating formation damage and competitive adsorption with methane (Lim et al., 1992; Zhang et al., 2014). Researchers have investigated the impact of inclination, displacement and other engineering factors on cutting-transporting ability of carbon dioxide (Li et al., 2011), however the wellbore flow field of carbon dioxide is still not well illustrated. Hypothermic liquid carbon dioxide is pressurized into tubing in drilling field application, and then get heated by formation rocks (Kolle, 2000). It is nearly impossible to test and record the temperature and pressure along the whole wellbore during

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http://dx.doi.org/10.1016/j.jngse.2016.02.050
1875-5100/

drilling, and the difficulties in mathematical calculation mainly lie in the compressibility of carbon dioxide. The physical properties of carbon dioxide (e.g., density, viscosity and heat capacity) all change much with temperature and pressure (Peng and Robinson, 1976; Boyle and Carroll, 2001), and then they would furthermore lay great impact on temperature and pressure when flowing in tubing and annulus. Wang and Ni (2013) have modelled the heat transfer in carbon dioxide coiled tubing drilling. Wang et al. (2014) have tested the flow friction coefficient of carbon dioxide in pipes at different Reynolds number through experiments. The preliminary results lay foundation for this study to some extent.

This paper attempts to calculate the temperature and pressure distribution in tubing and annulus during carbon dioxide drilling. A fully coupled mathematical model was set up to calculate the temperature, hydrostatic pressure, properties of carbon dioxide and flow friction. The closed model has considered the impact of temperature change in sidewall surrounding rock on temperature distribution in annulus, and the mathematical model was then solved with finite volume method. Finally, the calculation result of a case was analyzed and compared with former research to verify the reliability of the mathematical model. By this study, we aim to provide a theoretical foundation for field application.

2. Mathematical models

In the carbon dioxide drilling, hypothermic liquid carbon dioxide is pumped from wellhead to bottom hole through coiled tubing, and then it carries cuttings upward along annulus (Kolle, 2000; Song et al., 2015). Heat transfer is inevitable because of the temperature difference between formation rock and carbon dioxide. Carbon dioxide would get heated and then change from liquid state into supercritical state at certain depth, meanwhile sidewall surrounding rock would get cooled and then absorb thermal from formation rock far away from the annulus. The actual process could be illustrated with Fig. 1. It will finally reach heat balance as the circulation goes on. The temperature drop of sidewall surrounding rock was neglected in former research (Wang and Ni, 2013) and it would lead to relatively higher temperature profile in the calculation results.

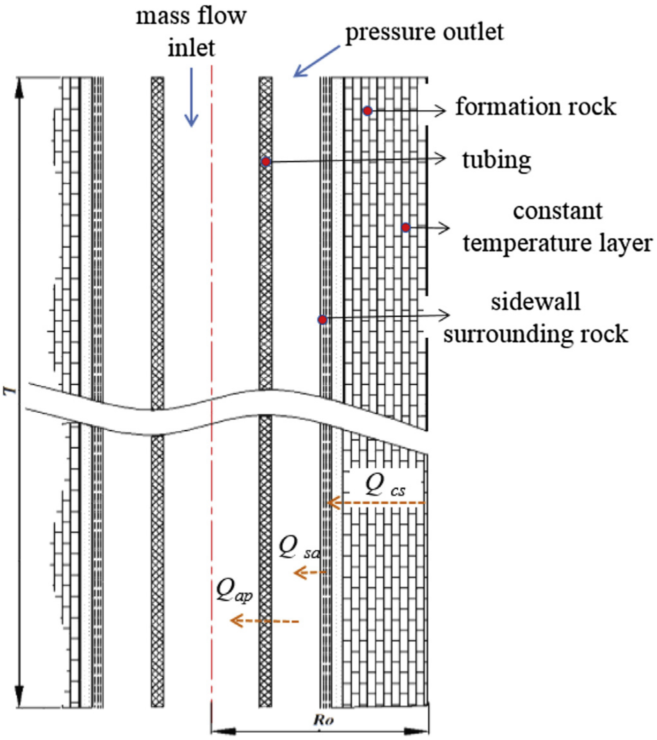

Fig. 1. Physical model of flow field.

The mathematical models are based on the following assumptions: 1) the geothermal temperature increases with constant rate; 2) the influence of cuttings on temperature and pressure distribution is negligible; 3) time effect is beyond the consideration because this study aims to reveal the steady state (when the heat balance is reached).

2.1. Governing equations

As depicted earlier, the temperature and pressure in flow field is coupled by influencing the properties of carbon dioxide. Eulerian method is one of finite volume method and it is suitable for illustrating this compressible flow model. Eulerian method is composed of the following equations.

The simplified continuity equation for compressible flow can be expressed as

$$div(\rho\vec{v}) = 0 \tag{1}$$

Where density ρ is in kg/m^3; $\vec{v}$ stands for flow velocity vector, m/s.

The modified momentum equation is given by

$$\mathrm{div}(\rho v_i\vec{v}) - \rho\vec{v}\bullet\mathrm{grad}(v_i) = 0 \tag{2}$$

where v_i represents the component of $\vec{v}$ on i axis, m/s.

The energy equation for steady flow with low velocity is represented as

$$\sum_{i=1}^{3}\frac{\partial(\rho v_i h)}{\partial x_i} - \mathrm{div}(k\mathrm{grad}T) - S_h = 0 \tag{3}$$

where specific enthalpy h can be achieved by $h = c_pT$; c_p is isobaric heat capacity, J/(kg K); T represents temperature, K; k stands for thermal conductivity, W/(m k); S_h is the heat generating rate in every flow unit.

The governing equations should also include turbulence equations and state equations to make them closed and solvable. The Standard k-ε model is introduced to illustrate turbulence, which is suitable for compressible flow.

$$\begin{cases}\dfrac{\partial}{\partial x_j}\left(\rho u_j\dfrac{\partial k}{\partial x_j} - (\mu+\mu_\tau)\dfrac{\partial k}{\partial x_j}\right) = \tau_{tij}S_{ij} - \rho\varepsilon + Q_k \\ \dfrac{\partial}{\partial x_j}\left(\rho u_j\varepsilon - \left(\mu+\dfrac{\mu_\tau}{1.3}\right)\dfrac{\partial\varepsilon}{\partial x_j}\right) = 1.45\dfrac{\varepsilon}{k}\tau_{tij}S_{ij} - 1.92f_2\rho\dfrac{\varepsilon^2}{k} + Q_\varepsilon\end{cases} \tag{4}$$

where $\tau_{tij} = 2\mu_\tau(S_{ij}-S_{nn}\delta_{ij}/3)-2\rho k\delta_{ij}/3$, and μ_τ represents eddy viscosity and is expressed as $\mu_\tau = 0.09f_u\rho k^2/\varepsilon$. The near wall attenuation functions are calculated by $f_u = e^{(-3.4/(1+0.02\mathrm{Re}_t)^2)}$ and $f_2 = 1 - 0.3e^{(-\mathrm{Re}_t^2)}$, where $\mathrm{Re}_t = \frac{\rho k^2}{\mu\varepsilon}$. The wall terms are given as $Q_k = 2\mu\left(\frac{\partial\sqrt{k})}{\partial y}\right)^2$ and $Q_\varepsilon = 2\mu\frac{\mu_\tau}{\rho}\left(\frac{\partial^2\mu_\varepsilon}{\partial y^2}\right)^2$. S_{ij} stands for the mean-velocity strain-rate tensor, and δ_{ij} is the Kronecker delta.

As the density, viscosity and thermophysical properties all change much with temperature and pressure, the state equations should include them all rather than involving density only.