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Effect of Flowing Seawater on Supercritical CO_2 - Superheated Water Mixture Flow in an Offshore Oil Well Considering the distribution of heat generated by the work of friction

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ABSTRACT

The modeling of thermal fluid (mostly reported for saturated steam) flow in wells involving steady-state heat transfer inside wellbores and transient heat transfer in sea water or formation is reviewed and inherited. It is a good addition of modeling of supercritical/superheated fluid to the existing body of literature. The flow of supercritical CO_2 coupled with superheated water (SHW) in offshore wells is described by means of the differential mass, energy and momentum balance equations along the vertical wellbores. The effect of supercritical CO_2 on pressure and temperature of the multi-component thermal fluid is expressed in terms of the real gas model (the S-R-K model). The differential equations are solved with finite difference method on space involving the constant injection parameters at wellhead. It is found out that: (a). while seawater has a significant influence on temperature drop in wellbores, its effect on pressure profiles is weak. (b). both temperature and superheat degree decrease with increasing of the content of supercritical CO_2. Besides, study of the effect of injection rate and pressure is conducted.

1. Introduction

Carbon dioxide has been widely adopted for EOR in petroleum industry (Mohsenzadeh et al., 2016; Mostafa et al., 2017). The correct use of CO_2 can not only reduce the greenhouse effect but also bring considerable economic benefits in the oil & gas industry (Chen et al., 2015a; Seyyedsar and Mehran, 2017). On the other hand, heat injection and viscosity reduction is an effective method in development of heavy oil resources (Gu et al., 2015a, 2015b; Sun et al., 2017a, 2017b).With the study of oil displacement mechanism by supercritical CO_2 and SHW, a model is needed to estimate the thermophysical properties of supercritical CO_2 – SHW mixture in a vertical tube. Different from fluid flow mechanisms in micro or nanoscale channels (Zhang et al., 2017a, 2017b; Sun Z et al., 2017j, 2017k, 2018b; Feng et al., 2018; Huang et al., 2017, 2018a, 2018b), fluid flow in macro tubes obeys the law of macroscopic fluid mechanics.

Lesem et al. (1957) developed a model for predicting fluid temperature in gas production wells. Moss and White (1959) focused on hot water flow in wellbores and developed a model based on the law of energy conservation. Ramey (1962) developed a model for steam flow in wellbores assuming that the kinetic energy is constant. Later, Willhite (1967) presented a model for predicting heat transfer rate from fluid to formation. Satter (1965) improved previous models by presenting a model which can be used to analyze the flow behaviors of two-phase fluid in wellbores. However, these early models laid latter attention to momentum balance equation. That is to say, the pressure drop in wellbores was neglected. Holst and Flock, 1966 presented a model considering pressure drop in wellbores. However, the gas slippage effect was neglected in the model. Earlougher (1969) and Hagedorn and Brown (1965) presented an improved model for saturated steam flow in wellbores. Based on Beggs and Brill (1973) work, Fontanilla and Aziz (1982) presented a model for predicting steam quality in wellbores with consideration of gas slippage effect. Ali (1981) and Wooley (1980) developed models for two-phase steam flow in wells with complex structure. Sagar et al. (1991) developed a model for predicting temperature of two-phase steam along the wellbores with deviated structure. Based on the energy conservation law, Stone et al. (1989, 2001) developed a wellbore/formation coupled model for saturated steam flow. Livescu et al.

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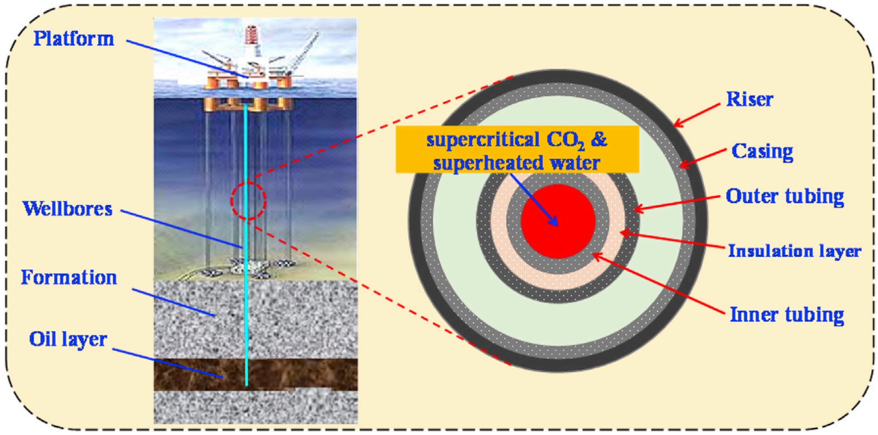

Fig. 1. Offshore wellbore structure (Huang et al., 2015; Sun et al., 2017c, 2017d, 2017e, 2017i).

(2009, 2010) presented a model considering multi-phase flow characteristics in reservoir. Bahonar et al. (2010) developed a model for estimating downward-flow steam pressure in wellbores considering axial and radial heat transmission. Xiong et al. (2016) and You et al. (2016) developed models for estimating heat loss rate from horizontal wellbore to oil layer.

There works laid a solid foundation in wellbore modeling. However, all of these previous works were focused on the single-component saturated steam. Barelli et al. (1982) studied the effect of CO_2 on the profiles of pressure and steam quality in wellbores. Civan (2006) and Michel and Civan (2008) presented a model and an improved model for multi-phase flow. In their works, the rate of gas transfer from the metastable liquid phases to gas phase is expressed in terms of the relaxation time determined by the prevailing gas phase volume fraction and the temperature, pressure conditions. It is found out that the inclusion of the non-equilibrium relaxation effect in the mathematical model is necessary. Fidan (2011) developed a numerical model focusing on heat transmission, pressure drop and steam quality when saturated steam and non-condensable gases are co-injected. Rafael et al. (2017) presented an improved model which can predict pressure distribution when saturated steam and solvent are co-injected.

However, these works were focused on the effect of CO_2 and N_2 on conventional saturated steam with limited discussion on supercritical condition. In recent years, Zhou et al. (2010), Xu et al. (2013), Fan et al. (2016) and Sun et al. (2017b, 2017c, 2017d, 2017e, 2017f, 2017g) developed numerical models to estimate SHW pressure and temperature in wellbores. However, these models cannot analyze the effect of supercritical CO_2 on SHW pressure and temperature. Sun et al. (2017h, 2017i, 2018a) studied the effect of non-condensing gases/supercritical CO_2 on SHW flow in vertical/horizontal wellbores. But their models cannot be used to deal with offshore condition. Dong, 2014 presented a numerical model to estimate thermophysical properties of multi-thermal fluid in offshore parallel dual-tubing wells. While their model has high calculation precision at low injection speed condition, the relative error of temperature values calculated by their model at high injection speed is non negligible. Based on Huang et al's (2015) work, Sun et al. (2017c) presented a numerical model for SHW flow in offshore wellbores and their model also has the similar problem.

In this paper, based upon previous works, a comprehensive but simple model is presented to analyze the unique flow behaviors of supercritical CO_2 coupled with SHW in offshore wellbores. The predicted results are compared against field data and results from previous models. Then, sensitivity analysis are conducted to further reveal the flow behaviors in offshore wellbores.

2. Model description

2.1. General assumptions

The offshore thermal injection wellbore is shown in Fig. 1. Some basic assumptions are listed below (Sun et al., 2017c, 2017d, 2017e, 2017i).

(1) The injection parameters at the platform are steady-state.
(2) Heat transfer rate from thermal fluid to the outside wall of riser is steady-state.
(3) Thermal parameters of seawater are independent from sea depth.

2.2. Mathematical modeling

The flow process of supercritical CO_2 coupled with SHW in vertical wellbores can be regarded as equal-mass state (Huang et al., 2015; Gu et al., 2015a, 2015b; Sun et al., 2017a, 2017b, 2017c, 2017d, 2017e, 2017f, 2017g, 2017h, 2017i, 2018c). Therefore, the mass balance equation can be expressed as:

$$\frac{dw_{fluid}}{dz} = \pi r_{ai}^2 \frac{d(\rho_{fluid} v_{fluid})}{dz} = 0 \tag{1}$$

where w_{fluid} is the mass flow rate of supercritical CO_2 coupled with SHW in wellbores, kg/s; r_{ai} is the inside radius of the inner tubing, m; ρ_{fluid} is the density of the mixed fluid, kg/m^3; v_{fluid} is the flow velocity of the mixed fluid in wellbores, m/s; z denotes the well depth, m.

The total heat loss rate from the mixture to seawater/formation should be equal to the total energy change rate of the mixed fluid (Huang et al., 2015; Gu et al., 2015a, 2015b; Sun et al., 2017e). Therefore, the energy balance equation can be expressed as:

$$\frac{dQ_{fluid}}{dz} = q_{fluid} = -w_{fluid}\frac{dh_{fluid}}{dz} - w_{fluid}\frac{d}{dz}\left(\frac{v_{fluid}^2}{2}\right) + w_{fluid} g \cos\theta \tag{2}$$

Where Q_{fluid} denotes the heat flow rate from thermal fluid to seawater/formation, J/s; q_{fluid} denotes the heat transfer rate per unit depth, J/(s·m); h_{fluid} denotes the specific enthalpy of the mixed fluid, which is shown in Appendix A, J/kg; g is the gravitational acceleration, m/s^2; θ denotes the well angle from vertical, rad.

Based on the law of momentum conservation (Huang et al., 2015; Gu et al., 2015a, 2015b; Sun et al., 2017e), the momentum balance equation can be expressed as:

$$\pi r_{ai}^2 dp_{fluid} = \rho_{fluid} \pi r_{ai}^2 g \cos\theta dz - \tau_f - \pi r_{ai}^2 d\left(\rho_{fluid} v_{fluid}^2\right) \tag{3}$$

Where τ_f denotes the shear stress in the vertical wellbores (Yuan, 1982; Sun et al., 2017a).

Eqs. (2) and (3) are the governing equations of the mathematical model, and Eq. (1) is the auxiliary equation, which is used to calculate the flow velocity. Distributions of pressure and temperature can be obtained by solving the mathematical model with numerical method.