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ORIGINAL PAPER - PRODUCTION ENGINEERING

Effect analysis of non-condensable gases on superheated steam flow in vertical single-tubing steam injection pipes based on the real gas equation of state and the transient heat transfer model in formation

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Abstract

Huge amount of efforts were done on saturated steam flow in wellbores with relatively little work on superheated multi-component thermal fluid (SMTF) flow in wellbores. In this paper, based on the continuity, energy and momentum balance equations, a flow model in the vertical wellbores is proposed. Then, coupled with the real gas model and transient heat flow model in formation, a comprehensive model is established for estimating thermophysical properties of SMTF in wellbores. Results show that (a) the effect of mass content of non-condensing gases on temperature profiles is negligible. The enthalpy of SMTF decreases rapidly with increasing of mass content of non-condensing gases. (b) When the injection rate is small, heat loss is the main factor on temperature drop, while when the injection rate is large enough, pressure drop becomes the dominant factor on temperature drop. (c) The two components of non-condensing gases and superheated steam in SMTF have a relatively independent mechanism of enhanced oil recovery, which should be selected based on the unique characteristics of each reservoir.

Keywords Multi-component · Superheated steam · Non-condensing gases · Thermophysical properties · Real gas effect · Vertical wellbores

Introduction

Superheated steam or SMTF comprised of superheated steam and non-condensing gases have been proved effective in heavy oil recovery by field practices (Sun et al. 2017a, b, c, d, e; Sun et al. 2018a). In order to obtain a satisfactory oil recovery effect, practicing engineers are requested to predict thermophysical properties of SMTF at well-bottom condition. Therefore, a series of works are done in this paper to establish a mathematical model to analyze flow behaviors of SMTF in wellbores.

Modeling of thermal fluid flow in wellbores was firstly conducted in the 1950s. Both analytical and numerical solutions were obtained of thermal fluid flow in wellbores. Alves et al. (1992) and Hasan and Kabir (1994) presented two rigorous models for estimating temperature and steam quality in wellbores by solving the continuity, energy and momentum balance equations simultaneously. Then, huge amount of works were done by Hasan et al. (Hasan and Kabir 1996, 2012; Hasan et al. 2009) and Kabir et al. (1996) on heat conduction rate in radial direction and flow models in wellbores under various injection conditions, which laid a solid foundation for following studies on multiphase flow, coupling effect of wellbore/formation and Joule–Thomson effect, etc. (Pourafshary et al. 2009; Livescu et al. 2010; Bahonar and Azaiez 2011a, b; Mao and Harvey 2013; Gu et al. 2014; Sivaramkrishnan et al. 2015).

However, these early models were focused on the conventional saturated steam, which cannot be used to predict thermophysical properties of SMTF in wellbores. In recent years, Zhou et al. (2010), and Xu et al. (2013a, b) and Fan et al. (2016) proposed models for estimating pressure and temperature of

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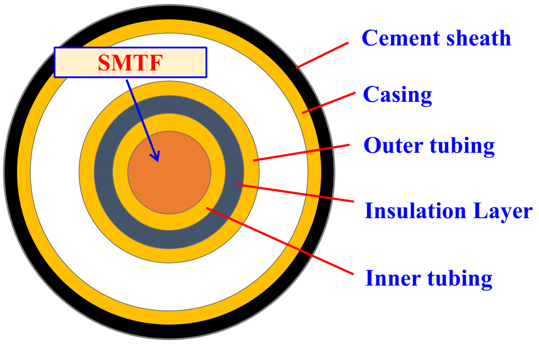

Fig. 1 Vertical section of SMTF flow in wellbores (Sun et al. 2017c, g, h, i)

superheated steam in vertical wellbores. However, predicted temperature from their models showed deviation from field data under high injection rate. Sun et al. (2017f, g, h, i, j) have done a series of works on superheated steam flow in onshore, offshore and concentric dual-tubing wells, etc. Besides, the predicted values of temperature from Sun et al.'s model showed a good agreement with field data under high injection rate, which overcame the technical difficulty in precise estimation of temperature values over a wide range of injection rate.

However, these previous models were focused on the single-phase flow of superheated steam in wellbores, which cannot be used to analyze the effect of non-condensing gases on SMTF in wellbores (de Almeida et al. 2017). Dong et al. (2014) proposed a numerical model for estimating pressure and temperature of SMTF in perforated horizontal wellbores. However, the predicted values of temperature from their model deviated from field data under high injection rate. At present, the study on SMTF flow in wellbores is still at the early stage. In this paper, based on the momentum and energy balance equations, a flow model in wellbores is established. Then, coupled with S-R-K real gas model and transient heat conduction model in formation, a comprehensive model is proposed. The new model is useful for practicing engineers to estimate key parameters of SMTF at well-bottom condition.

Model description

General assumptions

The wellbore structure is shown in Fig. 1. The model is established based on the assumptions listed below (Sun et al. 2017a, b, c, d, e; Sun et al. 2018a):

(a) Injection parameters of SMTF at well-head are kept unchanged throughout the entire injection period.
(b) Heat transfer rate from SMTF to formation is steady state.
(c) Heat transfer rate in formation is transient state.

Governing equations

The continuity equation. There exists no mass loss during the flow process of SMTF in wellbores. Therefore, the continuity equation can be expressed as (Sun et al. 2017c, g, h, i):

$$\frac{\mathrm{d}w_{\mathrm{SMTF}}}{\mathrm{d}z} = \pi r_i^2 \frac{\mathrm{d}\left(\rho_{\mathrm{SMTF}} v_{\mathrm{SMTF}}\right)}{\mathrm{d}z} = 0 \tag{1}$$

where w_{SMTF} denotes the mass flow rate of SMTF in the vertical wellbores, kg/s; r_i denotes the inner radius of the inner tubing, as shown in Fig. 1, m; ρ_{SMTF} denotes the density of SMTF in wellbores, which is discussed in "Appendix A in Electronic supplementary material", kg/m^3; v_{SMTF} denotes the flow velocity of SMTF in wellbores, m/s; z denotes the well depth, m.

The energy balance equation. As mentioned in the introduction, Zhou et al. (2010), Xu et al. (2013a, b), Fan et al. (2016) and Dong et al. (2014) proposed their energy balance equations. However, their energy balance equations showed limitation in predicting temperature values at high injection rate condition. Therefore, a new energy balance equation is established (Sun et al. 2017c, g, h, i):

$$\frac{\mathrm{d}Q_{\mathrm{loss}}}{\mathrm{d}z} = -w_{\mathrm{SMTF}} \frac{\mathrm{d}h_{\mathrm{SMTF}}}{\mathrm{d}z} - w_{\mathrm{SMTF}} \frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{v_{\mathrm{SMTF}}^2}{2}\right) + w_{\mathrm{SMTF}} g \cos\theta \tag{2}$$

where Q_{loss} denotes the heat loss rate from SMTF to formation, which is discussed in "Appendix B in Electronic supplementary material", J/s; h_{SMTF} denotes the enthalpy of SMTF in wellbores, which is discussed in "Appendix A in Electronic supplementary material", J/kg.

The momentum balance equation can be expressed as (Sun et al. 2017c, g, h, i):

$$\frac{\mathrm{d}p_{\mathrm{SMTF}}}{\mathrm{d}z} = \rho_{\mathrm{SMTF}} g \cos\theta - \frac{\tau_f}{\pi r_i^2 \mathrm{d}z} - \frac{\mathrm{d}\left(\rho_{\mathrm{SMTF}} v_{\mathrm{SMTF}}^2\right)}{\mathrm{d}z} \tag{3}$$

where p_{SMTF} denotes the SMTF pressure in wellbores, Pa; τ_f denotes the shear stress in wellbores, which is discussed in "Appendix C in Electronic supplementary material", N.

Numerical solution of the mathematical model

In this paper, the established model is solved by numerical method. The energy and momentum balance equations are represented as difference equations, as shown below:

$$\begin{aligned} f\left(p_{\mathrm{SMTF,\,out}}\right) = & \pi r_i^2 \left(p_{\mathrm{SMTF,\,out}} - p_{\mathrm{SMTF,\,in}}\right) \\ & - \frac{\rho_{\mathrm{SMTF,\,out}} + \rho_{\mathrm{SMTF,\,in}}}{2} \pi r_i^2 g \cos\theta \Delta z \\ & + \tau_f + \pi r_i^2 \left(\rho_{\mathrm{SMTF,\,out}} v_{\mathrm{SMTF,\,out}}^2 - \rho_{\mathrm{SMTF,\,in}} v_{\mathrm{SMTF,\,in}}^2\right) \end{aligned} \tag{4}$$

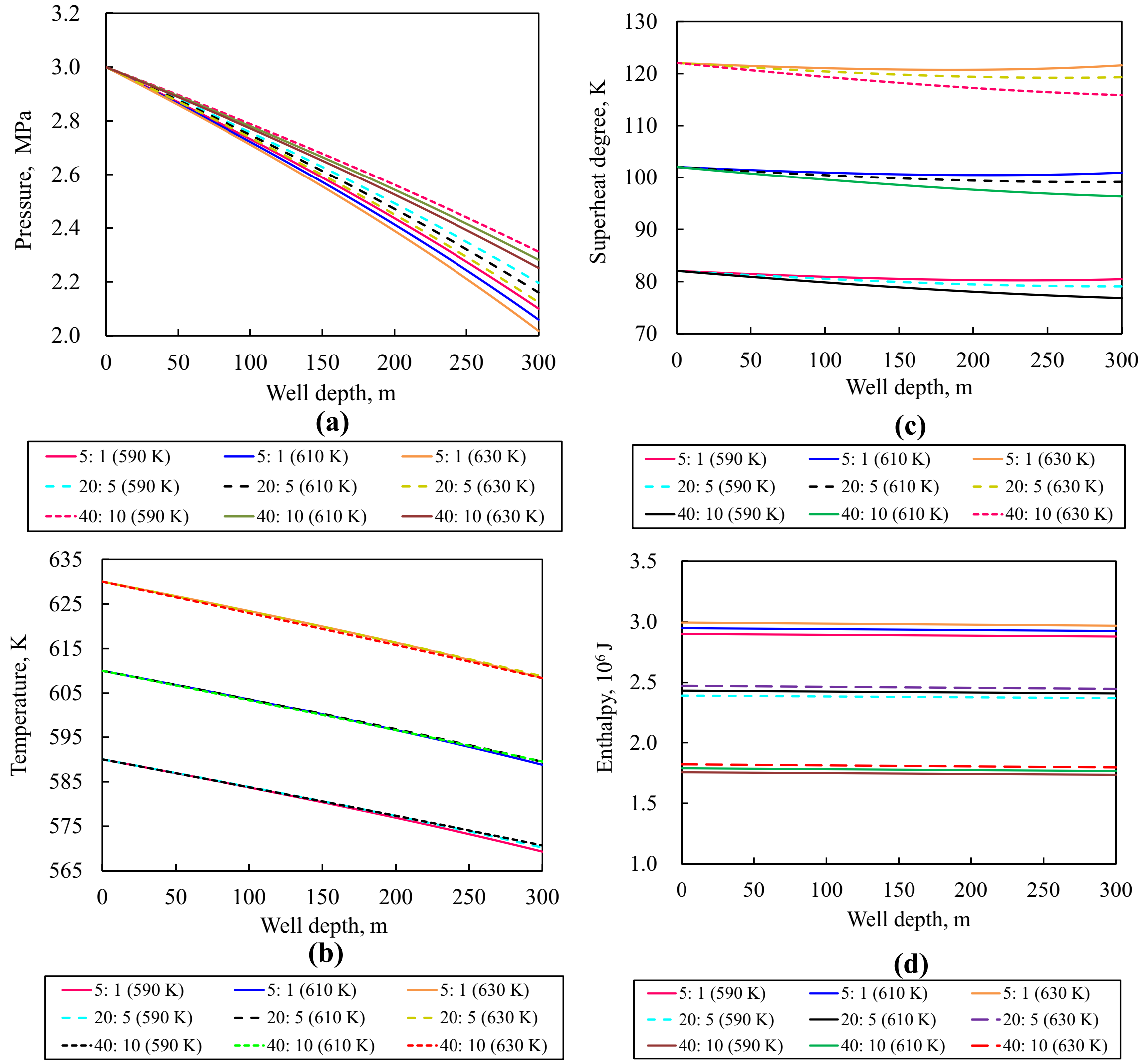

Fig. 2 Effect of injection temperature on the profiles of thermophysical properties of SMTF in wellbores under various mass content of non-condensing gases

where $p_{\mathrm{SMTF,\ out}}$ and $\rho_{\mathrm{SMTF,\ out}}$ denote the outlet pressure and density of SMTF, respectively; $p_{\mathrm{SMTF,\ in}}$ and $\rho_{\mathrm{SMTF,\ in}}$ denote the inlet pressure and density of SMTF, respectively; Δz is the length of the segment; $v_{\mathrm{SMTF,\ out}}$ and $v_{\mathrm{SMTF,\ in}}$ denote the flow velocity of SMTF at the outlet and inlet of the segment, respectively.

$$f\left(T_{\mathrm{SMTF,\ out}}\right) = \frac{q_{\mathrm{SMTF,\ out}} + q_{\mathrm{SMTF,\ in}}}{2} + w_{\mathrm{SMTF}} \frac{\left(h_{\mathrm{SMTF,\ out}} - h_{\mathrm{SMTF,\ in}}\right)}{\Delta z} + w_{\mathrm{SMTF}} \frac{1}{\Delta z} \left(\frac{v_{\mathrm{SMTF,\ out}}^2 - v_{\mathrm{SMTF,\ in}}^2}{2} \right) - w_{\mathrm{SMTF}} g \cos\theta \tag{5}$$

where $q_{\mathrm{SMTF,\ out}}$ and $q_{\mathrm{SMTF,\ in}}$ denote the heat transfer rate from SMTF to formation per unit depth at the outlet and inlet of the segment, respectively, W/m; $h_{\mathrm{SMTF,\ out}}$ and $h_{\mathrm{SMTF,\ in}}$ denote the specific enthalpy of SMTF at the outlet and inlet of the segment, respectively.

Given the fact that the injection parameters at well-head are known, pressure and temperature at outlet of the first segment can be calculated using Eqs. (4) and (5) with iteration method. Then, this pair of pressure and temperature is input for the inlet of the second segment and another iteration begins. Finally, distributions of pressure and temperature along the entire vertical wellbore are obtained.

Results and discussions

Injection temperature

In order to study the effect of injection temperature, various injection temperatures (590, 610 and 630 K) are tested based on no change in values of injection pressure and mass

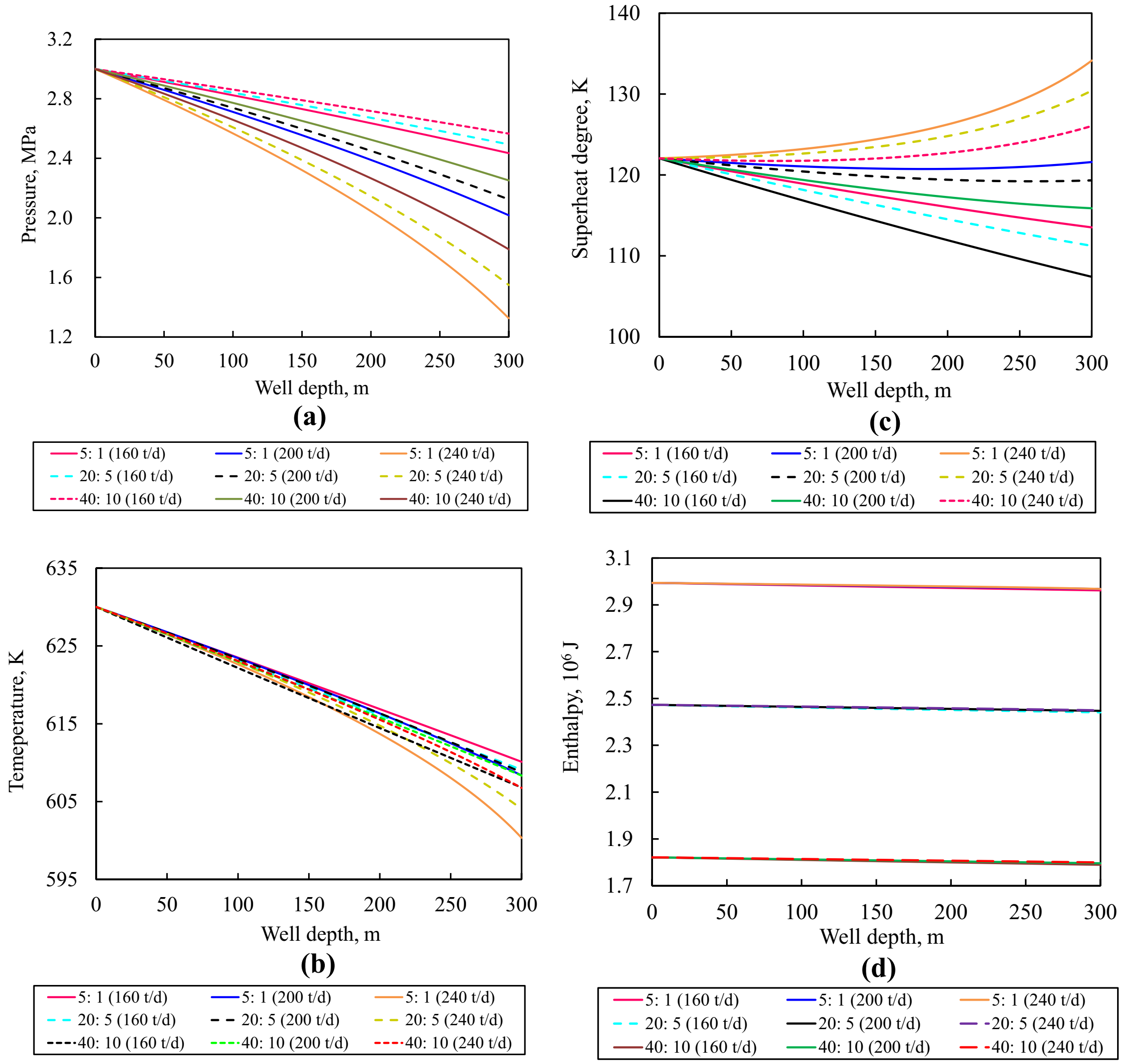

Fig. 3 Effect of injection rate on the profiles of thermophysical properties of SMTF in wellbores under various mass content of non-condensing gases

flow rate (Chen et al. 2016, 2017; Zhang et al. 2017a, b; Sun et al. 2017k, l, 2018b; Feng et al. 2018; Huang et al. 2017, 2018a, b). Besides, various values of mass content of non-condensing gases are added for comparison. In oil field, non-condensing gases are obtained by burning of diesel oil and air at a mass ratio of about 1.0:14.9. According to the relation of mass fraction of elements, the mass ratio of N_2 and CO_2 is about 4: 1 (Cheng and Han 2015). Therefore, the mass ratio of 5%:1%, 20%:5% and 40%:10% between N_2 and CO_2 are selected. The predicted results are shown in Fig. 2.

It is observed from Fig. 2 that: (a) under the condition that the mass content of non-condensing gases is kept unchanged, SMTF pressure decreases with increasing of injection temperature. This is because the density of SMTF decreases with increasing of injection temperature, which causes the increase of flow velocity. As a result, a higher flow velocity leads to a larger shear stress, which causes a higher pressure gradient. (b) Under the condition that injection temperature is kept unchanged, SMTF pressure increases with increasing of mass content of non-condensing gases. This is because the density of SMTF increases with increasing of mass content of non-condensing gases, which causes a smaller shear stress, and a smaller pressure gradient.

It is observed from Fig. 2b that the effect of mass content of non-condensing gases on temperature profiles is negligible. However, due to the decrease of SMTF pressure, superheat degree decreases with increasing of mass content of non-condensing gases, as shown in Fig. 2c. It is observed from Fig. 2d that under the condition that the mass content of non-condensing gases is kept unchanged and the effect of temperature increase on enthalpy of SMTF is negligible.

Mass injection rate

In order to study the effect of injection rate, various injection rate (160, 200 and 240 t/d) is tested based on no change in values of injection pressure and temperature. Besides, various values of mass content of non-condensing gases are added for comparison. The predicted results are shown in Fig. 3.

It is observed from Fig. 3a that under the condition that the mass content of non-condensing gases is kept unchanged, SMTF pressure decreases with increasing of injection rate. It is observed from Fig. 3b that under the condition that the mass content of non-condensing gases is kept unchanged, SMTF temperature increases at first and then turns to decrease with increasing of injection rate. This is because when the injection rate is relatively small, heat loss has a significant influence on temperature drop. However, the effect of heat loss on temperature drop becomes weaker with increasing of injection rate. It is observed from Fig. 3c that under the condition that the mass content of non-condensing gases is kept unchanged, superheat degree increases with increasing of injection rate. Besides, under the condition that the injection rate is kept unchanged, superheat degree decreases with increasing of mass content of non-condensing gases. It is observed from Fig. 3d that the effect of injection rate on enthalpy profiles is negligible, but the enthalpy decreases rapidly with increasing of mass content of non-condensing gases.

Conclusions

In this paper, a comprehensive model is proposed for estimating thermophysical properties of SMTF in wellbores under various injection conditions. Some meaningful conclusions are listed below:

(a) The effect of mass content of non-condensing gases on temperature profiles is negligible. The enthalpy of SMTF decreases rapidly with increasing of mass content of non-condensing gases. The non-condensing gas content should be selected reasonably in the mine to make full use of the superheated steam in the mixed steam.

(b) SMTF pressure in wellbores decreases with increasing of injection rate. SMTF temperature increases at first and then turns to decrease with increasing of injection rate. When the injection rate is small, heat loss is the main factor on temperature drop, while when the injection rate is large enough, pressure drop becomes the dominant factor on temperature drop.

(c) The two components of non-condensing gases and superheated steam in SMTF have a relatively independent mechanism of enhanced oil recovery, which should be selected based on the unique characteristics of each reservoir.

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