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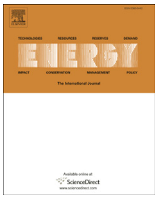

Performance analysis of superheated steam injection for heavy oil recovery and modeling of wellbore heat efficiency

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ABSTRACT

In this paper, a novel model is proposed for predicting thermo-physical properties of superheated steam (SHS) in SHS injection wells and for estimating wellbore heat efficiency.

Firstly, a novel mathematical model is proposed for predicting pressure, temperature as well as superheat degree in SHS injection wells. Secondly, the direct and indirect methods are introduced to estimate the wellbore heat efficiency. Thirdly, the model solving process is introduced in detail. After validation of the model, sensitivity analysis is conducted. Results indicate that: (1). The superheat degree at well bottom increases with the increase of injection rate. (2). The superheat degree at well bottom increases with the increase of injection temperature. (3). The superheat degree at well bottom decreases with the increase of injection pressure. In order to obtain a higher superheat degree at well bottom, the injection pressure cannot be too high.

This paper presents a basic reference for engineers in optimization of injection parameters as well as estimation of wellbore heat efficiency of SHS injection wells.

1. Introduction

The heat injection technology has been widely used in thermal recovery for heavy oil reservoirs [1–3]. For example, SAGD [4–7], steam flooding [8,9] and cyclic steam stimulation [10–14] have been proved effective by field tests. When these methods are adopted, conventional wet steam is always selected as the heat carrier. SHS, however, is becoming another good choice with the progress of technology [15–18]. In oil field, precisely predicting the thermal parameters along the wellbores are the first and foremost tasks for practicing engineers. However, the predicting work is not easy due to the complexity of the non-isothermal flow in the wellbores [19–26].

The studies on wellbore modeling were firstly conducted in the early 1960s [27–31]. Satter et al. [32] proposed an early model to estimate the quality of wet steam along the wellbores based upon the energy balance equation. With consideration of friction loss, Pacheco et al. [33] proposed a mathematical model to estimate wet steam pressure along the vertical wellbores. Based upon previous works, Farouq Ali [34] developed an improved model to predict wet steam pressure for both upward and downward flow, which laid a basic reference for following studies. Durrant et al. [35] proposed an improved model for predicting heat transfer rate along the wellbores based upon the iteration technique. Ejiogu et al. [36] and Tortike et al. [37] proposed useful empirical formulas for calculating density and enthalpy of wet steam, which brought great convenience to the programming calculation. Based on previous works, Sagar et al. [38] presented an improved model to estimate the wet steam temperature along the wellbores. All of these early researches laid a solid foundation for follow-up studies [39–41].

Hasan et al. [42] developed an early model for estimating heat transfer rate in the formation and proposed an important expression of transient temperature as a function of injection time and radius distance. Then, Hasan et al. [43–50] conducted a series of researches on the heat transfer model in the formation as well as its influence on the profiles of thermo-physical parameters in the

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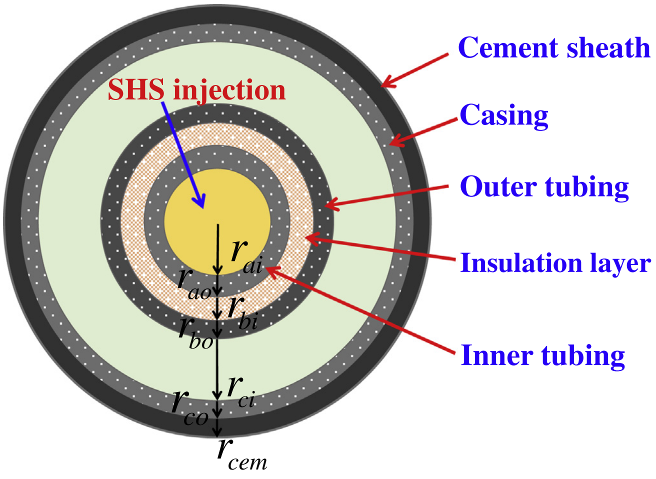

Fig. 1. A schematic of a SHS injection well.

wellbores. All of these pioneer researches a presented fundamental reference for later studies [51,52].

However, all of these previous were focused on conventional wet steam. Little work has been done to focus on the flow and heat transfer characteristics of SHS in the wellbores. As SHS flows down the wellbores, its thermos-physical properties are always changing. More importantly, it may undergo phase change to wet steam or even hot water in a certain position of the wellbores due to heat loss. Given the fact that the thermos-physical parameters of SHS are the functions of both pressure and temperature, which is quite different from that of saturated steam, the model developed for wet steam is no longer useful for SHS. Consequently, there are still many unknowns need to be explored.

In this paper, a novel model is presented for predicting the thermo-physical properties of SHS in the wellbores. There are mainly four innovations in this paper: (1). Taking phase change into consideration, a novel mathematical model is proposed for predicting the thermo-physical properties of SHS in the wellbores. (2). A new analytical model is introduced for estimating wellbore heat efficiency of SHS injection wells. (3). Type curves of SHS flow in the wellbores are obtained. (4). The influence of injection parameters on superheat degree at well bottom are studied in detail.

This study unravels some important intrinsic flow characteristics of SHS in the wellbores, which will be useful for oil field.

2. Model description

2.1. General assumptions

A schematic of a SHS injection well is shown in detail in Fig. 1. In order to study the flow and heat transfer characteristics of SHS in the wellbores, some basic assumptions are listed below:

(1) The injection parameters at wellhead remain unchanged during the whole injection period.
(2) Heat transfer rate inside the wellbores is assumed to be steady-state, while heat transfer rate in the formation is transient-state.
(3) Radiation and natural convection are the two primary heat transmission paths between the outer wall of tubing and the inner wall of casing.
(4) The physical and thermal properties of the formation are independent of temperature and the well depth.

2.2. A non-isothermal flow model of SHS in the wellbores

Firstly, the mass balance equation. The mass flow rate is a constant as SHS flows down the wellbore. The mass conservation equation can be expressed as:

$$\frac{\partial w_{\mathrm{sup}}}{\partial z} = \pi r_{ai}^2 \frac{\partial\left(\rho_{\mathrm{sup}} \upsilon_{\mathrm{sup}}\right)}{\partial z} = 0 \tag{1}$$

where w_{sup} denotes the mass flow rate of SHS, kg/s; r_{ai} denotes the inside radius of inner tubing, m; ρ_{sup} denotes the density of SHS [53], kg/m^3; υ_{sup} is the flow velocity of SHS, m/s; z denotes the variable well depth from ground, m.

Secondly, the energy balance equation. The potential energy, kinetic energy and specific enthalpy of SHS are constantly changing with well depth. The energy conservation equation can be expressed as:

$$\frac{dQ_{\mathrm{sup}}}{dz} = -w_{\mathrm{sup}} \frac{dh_{\mathrm{sup}}}{dz} - w_{\mathrm{sup}} \frac{d}{dz}\left(\frac{\upsilon_{\mathrm{sup}}^2}{2}\right) + w_{\mathrm{sup}} g \cos\theta \tag{2}$$

where Q_{sup} denotes the heat flow rate from SHS to the formation, which is discussed in detail in Appendix A, W; h_{sup} denotes the specific enthalpy of SHS [53], J/kg; g is the gravitational acceleration, m/s^2; θ denotes the well angle from vertical, rad.

Thirdly, the momentum balance equation can be given as:

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

where τ_f denotes the shear stress in the wellbores, which is discussed in detail in Appendix B.

Finally, the governing equations of the non-isothermal flow model is established. What is to stress is that SHS may undergo phase change due to energy loss. If this happens, the model proposed by Beggs et al. [31] is adopted. Moreover, the mathematical model for predicting wellbore heat efficiency of SHS injection wells is shown in Appendix C.

3. Solving method of the mathematical model

Firstly, in order to get the distribution of thermal parameters along the wellbore, the wellbore is evenly divided into m segments. Then, the function zero method is adopted to obtain the thermal parameters at outlet of the segment. Based on Eq. (3), the difference equation for pressure solving can be expressed as:

$$f\left(p_{\mathrm{sup},out}\right) = \pi r_{ai}^2\left(p_{\mathrm{sup},out} - p_{\mathrm{sup},in}\right) - \pi r_{ai}^2 g \cos\theta\left(\rho_{\mathrm{sup},out} - \rho_{\mathrm{sup},in}\right)\Delta z + \tau_f + \pi r_{ai}^2\left(\rho_{\mathrm{sup},out}\upsilon_{\mathrm{sup},out}^2 - \rho_{\mathrm{sup},in}\upsilon_{\mathrm{sup},in}^2\right) \tag{4}$$

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

In order to solve Eq. (4), an outlet temperature must be