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A numerical study on the non-isothermal flow characteristics of superheated steam in ground pipelines and vertical wellbores

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ABSTRACT

Traditional heavy oil recovery method of saturated steam injection faces many challenges. Present study on wellbore modeling of superheated steam (SHS) flow is still at the early stage.

In order to fill this gap, a series of works were conducted to study the non-isothermal flow characteristics of SHS in ground pipelines and vertical wellbores. Firstly, a flow model inside the wellbores was proposed based on the energy and momentum balance equations. Then, coupled with heat transfer model in formation or atmosphere, a comprehensive model was developed. Then, type curves of SHS flow in ground pipelines and vertical wellbores were obtained by solving the model with finite difference method. Finally, model validation and sensitivity analysis were conducted.

The results show that: (a). there exist a good agreement between predicted results and field data. (b). superheat degree increases with increasing of injection rate. (c). superheat degree increases with increasing of injection temperature. (d). superheat degree decreases with increasing of injection pressure. Consequently, practicing engineers are suggested to increase the injection rate and temperature and to decrease the injection pressure.

1. Introduction

The study of heat transfer characteristics is one of the main problems encountered in Engineering (Sheikholeslami and Ganji, 2014, 2015; Sheikholeslami et al., 2015; Satyanarayana et al., 2016). At present, heavy oil resource is showing its importance with the increase of energy demand (Gu et al., 2014; Sun et al., 2017a, 2017b). Thermal methods, such as steam assisted gravity drainage (Yang et al., 2016), steam flooding (Mahood et al., 2016) and cyclic steam stimulation (Sandler et al., 2014; Sun et al., 2017c), have been proved effective by field practice. When these methods are selected, wet steam is always chosen as the heat carrier. However, SHS has shown the distinctive advantages for heavy oil recovery in the laboratory (Zhou, 2010; Xu et al., 2013), and has been proved successful in pilot field experiments (Song et al., 2009; Fan et al., 2016). In thermal recovery engineering, precisely predicting the thermophysical properties of thermal fluid at well-bottom is one of the most important tasks. However, the task is never easy due to the complexity of the non-isothermal flow characteristics of thermal fluid in wellbores (Dong et al., 2014; Gu et al., 2015a).

Ramey (1962) proposed a model to analyze the flow behaviors of saturated steam in the vertical wellbores based upon hydrodynamic equations. Focusing on the two-phase flow behaviors of saturated steam in vertical wellbores, Satter (1965) presented an improved heat transfer model to predict wellbore heat loss rate during the downward flow process of saturated steam. Pacheco et al. (1972) proposed a comprehensive model to predict wellbore heat loss rate and pressure drop in wellbores based on the energy balance equation. Hasan (1995), Hasan and Kabir (2007, 2012), Hasan et al. (2010) did a series of works on the heat transfer model in formation and the two-phase flow characteristics of saturated steam in vertical wellbores.

While these previous works revealed some important flow characteristics of thermal fluid in wellbores, they were only focused on the conventional saturated steam. The study on SHS flow in wellbores is still at its early stage. Zhou et al. (2010) and Xu et al. (2013) proposed numerical models for predicting the distributions of pressure and

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temperature of SHS in vertical wellbores. However, their models cannot be directly used to ground pipelines. Xu (2011) proposed a numerical model to analyze the flow characteristics of SHS in ground pipelines. However, these three models violated the law of energy conservation (Liu, 2013; Gu et al., 2014, 2015a, 2015b; Rafael et al., 2017). Gu et al. (2015a) presented a mathematical model focusing on the SHS flow in horizontal wells, but their model was focused on the variable-mass flow process, which is quite different from the constant-mass flow process in ground pipelines. Fan et al. (2016) presented an improved model to predict the thermophysical parameters of SHS in the vertical and horizontal section of the wellbores considering the wellbore/formation coupling effect. However, their energy balance equation also violated the law of energy conservation (Wei et al., 2015). Sun et al. (2017d, 2017e, 2017f, 2017g) presented numerical models to analyze the flow and heat transfer characteristics of SHS in vertical wellbores (for both onshore and offshore conditions). However, these studies were focused on the formation section of the wellbores. That is to say, effect of SHS flow in ground pipelines on the profiles of pressure and temperature in the formation section of wellbores are neglected. When the ground pipelines are short, this effect is negligible. However, the SHS generator is not always near the wellhead. In oil field, one SHS generator is usually transporting SHS to several wells simultaneously (Zhou, 2010; Xu, 2011). At this point, effect of heat loss of ground pipelines is non-negligible. Besides, the energy balance equation must be re-built based on the law of energy conservation.

In this paper, a series of works were conducted to study the non-isothermal flow characteristics of SHS in ground pipelines and vertical wellbores. This work has three main contributions to the existing body of literature: (1). A new energy balance equation in ground pipelines was developed. (2). The coupling effect of ground pipelines and vertical wellbores was taken into consideration. (3). New type curves of SHS flow in ground pipelines and vertical wellbores were compared against previous ones.

2. Model description

2.1. General assumptions

A schematic of SHS generator and flow pipelines are shown in Fig. 1. Basic assumptions used to establish the model are listed below:

(1) SHS output parameters from boiler are kept unchanged during the injection period.
(2) The ground pipelines are insulated and overhead (Xu, 2011).
(3) Packer is used at well-bottom to stop SHS from flowing into annuli.
(4) Heat transfer rate from SHS to the outside wall of insulation layer is steady-state.
(5) Heat transfer rate from SHS to the outside wall of cement sheath is steady-state.
(6) Heat transfer rate in the formation is assumed to be transient (Liu, 2013).

2.2. Modeling of SHS flow in ground pipelines

Firstly, the mass conservation equation. The process of SHS flow from boiler to wellhead through ground pipelines is constant mass flow (Zhou, 2010; Xu, 2011). Therefore, the gradient of mass flow rate in ground pipelines is equal to zero. The mass conservation equation is given as:

$$\frac{\partial w_{\rm sup}}{\partial L} = \pi r_{Li}^2 \frac{\partial(\rho_{\rm sup} v_{\rm sup})}{\partial L} = 0 \quad (1)$$

where $w_{\rm sup}$ denotes the mass flow rate of SHS in ground pipelines, kg/s; r_{Li} denotes the inside radius of ground pipelines, m; $\rho_{\rm sup}$ denotes the SHS density (Junkai and Youting, 1992), which can be found in detail in

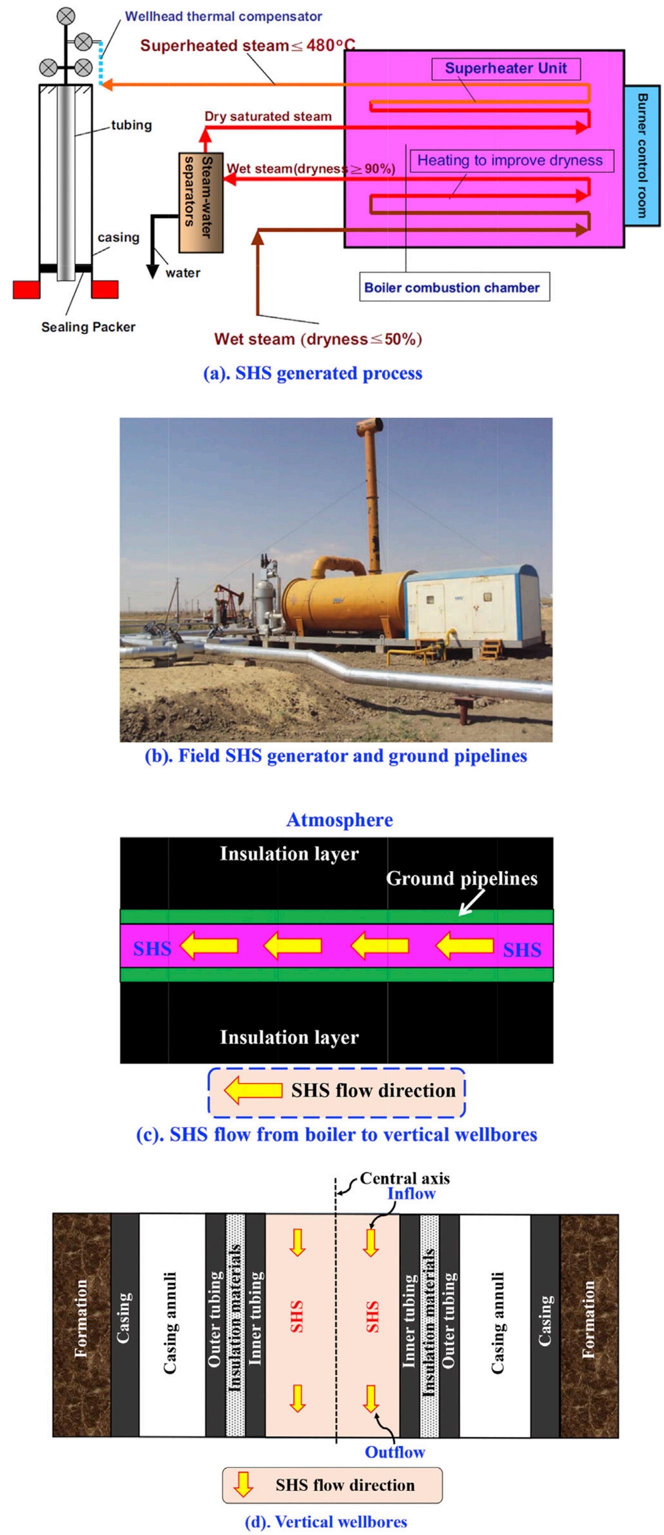

Fig. 1. Physical background of the presented mathematical model: (a). SHS generating principle (Xu et al., 2013). (b). Field SHS generator (Xu, 2011). (c). SHS flow in ground pipelines (Xu, 2011). (d). SHS flow in vertical wellbores (Zhou et al., 2010; Xu et al., 2013; Sun et al., 2017e).

Appendix A, kg/m^3; $v_{\rm sup}$ denotes the SHS flow velocity in ground pipelines, m/s; L denotes the horizontal length of ground pipelines, m.

Secondly, the energy conservation equation. As SHS flows in ground pipelines, its specific enthalpy, kinetic energy and gravitational potential energy are constantly changing due to heat loss to atmosphere. This