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A numerical model for predicting distributions of pressure and temperature of superheated steam in multi-point injection horizontal wells

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ABSTRACT

In order to make full use of the advantages of superheated steam (SHS), SHS injection in multi-point injection wells (MPIW) is proposed in this paper.

Firstly, a mathematical model comprised of SHS flow model in inner tubing (IT) or long tubing (LT) and annulus, transient heat transfer model in oil layer is established. Secondly, type curves of SHS flow in MPIW is obtained by finite difference method on space and the iteration technique. Then, the effect of injection temperature on distributions of thermophysical properties of SHS in MPIW is discussed in detail. Results show that: (a) When the heat exchange between IT and annulus is taken into consideration. SHS temperature in IT has a decrease while SHS temperature in annulus has an increase. (b) With the help of MPIW, heating effect at both heel and toe points of the horizontal wellbores can be enhanced. (c) While the increase of SHS temperature certainly benefits the formation heating effect through the increase of both SHS temperature and superheat degree, the following decrease of SHS pressure in annulus will lead to the decrease of SHS absorption rate.

This paper unravels some intrinsic flow characteristics of SHS in MPIW, which has a significant impact on the optimization of SHS injection parameters and analysis of heat transfer law in MPIW.

1. Introduction

SHS is showing its advantages in heavy oil recovery [1–4]. When SHS is injected from ground to oil layer, one of the foremost tasks for engineers is to predict the distributions of pressure and temperature along the wellbores. However, the predicting task is never easy due to the complexity of SHS flow in wellbores [5,6].

Before the studies were focused on SHS, a series of works were done on conventional saturated steam. Holst et al. [7] proposed an important model for predicting heat transfer rate from steam in wellbores to formation, which laid a basic reference for following studies. In their model, the heat transfer rate inside the wellbores is assumed to be steady-state, while the heat transfer rate in the formation is unsteady-state. Willhite [8] proposed a basic formula for calculating heat flow coefficient from steam in wellbores to formation, which is widely used for predicting heat transfer rate in later studies. With the development of computers, Ejiogu et al. [9] and Tortike et al. [10] presented convenient empirical formulas for calculating enthalpy, etc. of wet steam. Based upon the Coulter-Bardon equation, Sagar et al. [11] developed an improved model for analyzing the effect of heat transfer rate on distributions of pressure and temperature in wellbores. Alves et al. [12] studied the influence of injection pressure on the profiles of enthalpy in wellbores. Bahonar et al. [13,14] proposed a more precise model for predicting wet steam temperature in wellbores by considering heat conducting in the vertical direction.

Satter et al. [15] studied the distribution of saturated steam quality in the vertical wellbores. However, their model was based on the assumption of kinetic energy is unchanged. Pacheco et al. [16] studied the effect of friction loss on steam temperature in wellbores. Farouq et al. [17] conducted the research of flow behaviors of saturated steam under upward and downward conditions. Focusing on the transient heat transfer characteristics in the formation, Durrant et al. [18] presented a mathematical model for estimating wellbore heat loss rate, which was later adopted by Livescu et al. [19,20] in predicting distributions of pressure and

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temperature of multi-phase thermal fluid in the wellbores. Cheng et al. [21–24] presented several models for predicting transient heat flow rate in the formation based upon well log data. However, the temperature of saturated steam is the function of its pressure, which is different from SHS. The studies on SHS flow characteristics in wellbores is still at the early stage.

From 2010 till now, Zhou et al. [25], Xu et al., [26,27], Fan et al. [28] and Sun et al. [3,29,30] presented numerical models focusing on the flow behaviors of SHS in onshore or offshore SHS injection wellbores. However, these models were focused on the equal mass flow process of SHS in the vertical section of the wellbores, which is quite different from the variable mass flow process in the horizontal wellbores, where SHS is constantly injected into the oil layer. Besides, these models cannot calculate the heat transfer rate between IT and annulus.

Dong et al. [31] proposed a numerical model to predict thermophysical properties of multi-component thermal fluid in the horizontal wellbores with conventional heel-point injection method. Their model cannot be used to deal with heat transfer between IT and annulus. Dong et al. [32] proposed an improved model for horizontal wells with toe-point injection technique. However, their model neglected the heat exchange between IT and annulus. Gu et al. [33] presented a simple model for analyzing flow behaviors of SHS in conventional heel-point injection horizontal wells. However, their model cannot deal with heat exchange between IT and annulus in multi-point injection conditions. Based upon Gu et al.'s work [33], Sun et al. [4] presented an improved model by considering the effect of non-condensing gases on the profiles of pressure and temperature in wellbores. In conclusion, these models are not applicable to multi-point injection horizontal wells. Wu et al. [34] proposed a numerical model for predicting distributions of pressure and steam quality in MPIW. However, the energy balance equation in their model violated the law of energy conservation [42–46]. Besides, their model was focused on the conventional saturated steam.

In this paper, a numerical model is presented to analyze the heat and mass transfer characteristics of SHS in MPIW. There are mainly three contributions of this paper to the existing body of literature: (1). A numerical model is established to predict the distributions of pressure and temperature, etc. of SHS in MPIW. (2). Type curves of SHS flow in MPIW is obtained by finite difference method. (3). Effect of injection temperature on the profiles of thermophysical properties of SHS in IT and annulus is discussed in detail.

2. Model description

2.1. General assumptions

The physical background of this study is shown in Fig. 1. Conventional heel point injection method encounters relatively serious steam channeling phenomenon especially when the horizontal section of the wellbore is very long or the oil layer is of severe heterogeneity [1,5,34,35,36]. For instance, when the formation permeability near the heel point of the horizontal wellbore is higher, more steam will be injected into the near wellbore area. Therefore, the heating effect of formation near the toe point of the wellbore is poor. Steam injection in concentric/parallel dual-tubing wells is proposed to alleviate the problem. This is because a part of steam will be transported to the toe point of wellbore through IT before it is injected into the oil layer. Therefore, both of the toe and heel point become the steam injection point. In addition to this advantage, specific steam injection parameters for the heel and toe point can be determined according to the characteristics of the reservoir. These two advantages are the key to the application of concentric/parallel dual-tubing wells [36]. At present, Liaohe Oilfield, China has adopted the concentric dual-tubing wells, and has achieved good development results [35,36]. However, the study of concentric/parallel dual-tubing wells is very limited.

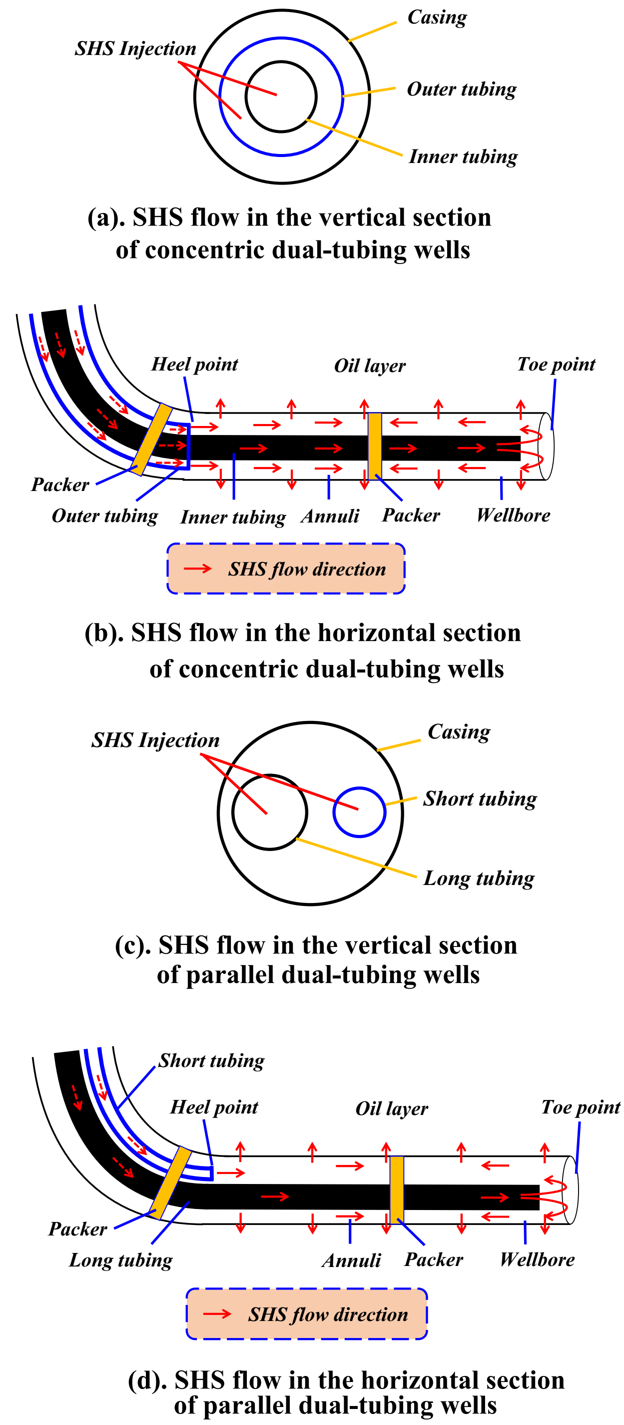

Fig. 1. A schematic of SHS flow in MPIW.

Based on previous studies [25,26], some basic assumptions are listed below. Based on these assumptions, the model agrees well with oil field [27–36].

(1) Injection parameters of SHS at the heel-point of MPIW is constant.
(2) Heat flow from SHS in annulus to the outside wall of casing is steady-state.