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Type curve analysis of superheated steam flow in offshore horizontal wells

Fengrui Sun [a,b,*], Yuedong Yao [a,b], Xiangfang Li [b], Lin Zhao [a,b]

[a] State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, 102249 Beijing, PR China
[b] College of Petroleum Engineering, China University of Petroleum, 102249 Beijing, PR China

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ABSTRACT

In order to estimate the distributions of temperature and pressure of superheated steam (SHS) in offshore horizontal wells, a series of theoretical studies are conducted.

Based upon the mass, energy and momentum conservation equations in wellbores, and heat transfer models in seawater and formation, a mathematical model is established. Numerical method is then adopted to solve the model. The distributions of temperature and pressure are obtained by finite difference method on space under the controlling of iteration accuracy. The predicted results are compared against field data, which shows the maximum relative errors for temperature and pressure are 0.76% and 4.21%, respectively.

Some main findings from the model show that: (1). Superheat degree along the horizontal section of the wellbore increases with increasing of injection rate at platform; (2). Superheat degree increases with increasing of injection temperature at platform; (3). Superheat degree decreases with increasing of injection pressure at platform; (4). The flow of seawater can obviously reduce the superheat degree in wellbores.

1. Introduction

Thermal technique for heavy oil recovery has been proved effective by field tests [1–3]. And when thermal methods are used, SAGD [4–7], steam flooding [8,9] and steam huff and puff [10–14] are the most common ones. In addition, saturated steam is always selected as heat carrier. However, in recent years, with the increasing demand for heavy oil and progress of technology, SHS gets the attention it deserves [15–18]. In order to improve engineering benefit, how to obtain the optimal thermal parameters at well-bottom is one of the most important tasks for engineers in the development of engineering programs. However, the study on thermal fluid flow in wellbores encounters many difficulties due to the complexity of non-isothermal non-equal mass flow in wellbores [19–26].

In the early 1960s, Ramey [27] proposed a mathematical model to analyze wellbore heat transfer characteristics, which laid a solid foundation for later studies [28,29]. In 1967, based upon momentum conservation equation, Orkiszewski [30] proposed a useful model to predict pressure drop of wet steam in vertical wells. In 1973, Beggs et al. [31] presented an important model to estimate pressure distribution of wet steam in inclined pipes, which gave a basic reference for following researchers [32–36]. Tortike and Farouq Ali [37] brought convenience to computer solution by presenting some useful formulas for calculating thermo-physical parameters of wet steam. Based upon previous studies, Sagar et al. [38] presented an improved model to analyze temperature distribution characteristics in the wellbores, which gave a basic reference for later researchers [39–41]. Based on previous findings, Hasan and Kabir [42–50] did huge amount of works on the flow and heat transfer characteristics of wet steam in the wellbores, All of these early works on wet steam flow in the wellbores presented a solid foundation for later studies [51,52].

However, all of these pioneer researchers focused on the flow of conventional saturated steam in the wellbores. The study on the flow and heat transfer characteristics of SHS in the wellbores is still at its early stage. Zhou et al. [16], Xu et al. [15] and Fan et al. [18] proposed early models for predicting pressure of SHS in onshore vertical wells. However, their models lead to non-negligible errors when the mass flow rate is large enough [23–26]. Besides, these early works were focused on the onshore conditions, which cannot be adapted directly to offshore conditions [53]. Given the fact that

* Corresponding author at: State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, 102249 Beijing, PR China.
E-mail address: 13126682711@163.com (F. Sun).

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Nomenclature

g	gravitational acceleration, m/s^2
h_{sup}	specific enthalpy of SHS, J/kg
I_{sup}	volume flow velocity of SHS from horizontal wellbores to oil layer, m^3/s
L	length of the horizontal segment, m
p_{sup}	SHS pressure in the horizontal wellbores, Pa
$p_{sup,out}$	SHS pressure at outlet of the segment, Pa
Q_{sup}	heat transfer rate from SHS in the vertical wellbores to seawater/formation, J/s
q_{sup}	heat transfer rate from SHS to seawater/formation per unit depth, J/(s·m)
r_{ai}	the inside radius of the inner tubing, m
r_w	the radius of the horizontal wellbores, m
$T_{sup,out}$	SHS temperature at outlet of the segment, K
v_{sup}	flow velocity of SHS in the vertical wellbores, m/s
v_r	radial injection rate, m/s
w_{sup}	mass flow rate in the vertical wellbores, kg/s
w_0	mass flow rate of SHS at heel point of the horizontal wellbores, kg/s
z	well depth, m

Subscripts

sup	superheated steam
ai	inside wall of the inner tubing
r	radial flow
out	outlet of the segment

Greek letters

ρ_{sup}	density of SHS, kg/m^3
θ	well angle from vertical, rad
$\tau_{f,vertical}$	shear stress in the vertical wellbores, N
$\tau_{f,horizontal}$	shear stress in the horizontal wellbores, N
α	well angle from horizontal, rad

the offshore wellbore structure is quite different from onshore wells and the heat transfer characteristics in the flowing seawater is also quite different from that in the formation, there are still many unknowns needed to be explored.

Although there exist deficiencies in previous studies, some meaningful findings are listed below: (1) Basic expression form of governing equations (energy and momentum conservation equations) of thermal fluid flow in wellbores; (2) Heat transfer model in seawater; (3) Heat transfer model in formation.

In this paper, a series of works are conducted to study the flow and heat transfer characteristics of SHS in offshore horizontal wells. This paper has mainly three contributions to the existing body of literature: (1). A mathematical model is presented for predicting pressure and temperature of SHS in offshore horizontal wells. (2). Effect of seawater on the profiles of thermo-physical parameters of SHS in the entire wellbores is analyzed in detail. (3). Type curves of SHS flow in the entire offshore horizontal wells are obtained and analyzed under various injection conditions.

The main motivation and objective of this paper is to unravel some intrinsic flow characteristics of SHS in offshore horizontal wells, which will be useful for engineers to obtain optimal injection parameters at platform and to better understand the flow and heat transfer characteristics of SHS in offshore horizontal wells.

2. Model description

2.1. General assumptions

A schematic of an offshore SHS injection horizontal well is shown in Fig. 1. In order to establish the mathematical model, some basic assumptions are shown below:

(1) The SHS injection process at the platform is assumed to be steady-state.
(2) Heat transfer rate from SHS to the outside wall of the riser/cement sheath is steady-state.
(3) Seawater parameters are assumed to be independent from sea depth.
(4) Thermo-physical parameters of SHS from the platform to sea surface are assumed to be unchanged.

2.2. Modeling of SHS flow in the vertical wellbores

As SHS flows down the vertical wellbores, its mass flow rate is kept unchanged due to the fact that there is no mass exchange. However, SHS energy is constantly changing due to heat loss, friction loss and gravitational potential loss. The mass, energy and momentum balance equations are established to describe the downward flow process.

Firstly, the mass conservation equation:

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

where w_{sup} is the mass flow rate in the vertical wellbores, kg/s; r_{ai} is the inside radius of the inner tubing, m; ρ_{sup} is the density of SHS [54], which can be seen in Appendix A; kg/m^3; v_{sup} is the flow velocity of SHS in the vertical wellbores, m/s; z denotes the well depth, m.

Secondly, the energy balance equation:

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

where Q_{sup} denotes the heat transfer rate from SHS in the vertical wellbores to seawater/formation, which is discussed in detail in Appendix B [55], W; h_{sup} denotes the specific enthalpy of SHS [54], J/kg; g is the gravitational acceleration, m/s^2; θ denotes the well angle from vertical, rad.

Thirdly, the momentum balance equation:

$$\pi r_{ai}^2 dp_{sup} = \rho_{sup}\pi r_{ai}^2 g\cos\theta dz - \tau_{f,vertical} - \pi r_{ai}^2 d(\rho_{sup} v_{sup}^2) \tag{3}$$

where $\tau_{f,vertical}$ denotes the shear stress in the vertical wellbores, which is discussed in detail in Appendix C [56].

Finally, the mathematical model of SHS flow in vertical section of the offshore wells is established.