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The flow and heat transfer characteristics of superheated steam in concentric dual-tubing wells

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ABSTRACT

In this paper, a numerical model is presented to estimate the thermophysical propertes of superheated steam (SHS) in concentric dual-tubing wells (CDTW).

Firstly, a model comprised of mass, momentum and energy balance equations in the integral joint tubing (IJT) and annuli is proposed for CDTW. Secondly, distributions of temperature, pressure and superheat degree along the wellbores are obtained by finite difference method on space and solved by iteration technique. Finally, based upon the validated model, sensitivity analysis is conducted.

The calculated results show that: (1) In CDTW, the difference of injection temperature between the IJT and annuli has a strong influence on the profiles of temperature and superheat degree in wellbores. (2) Temperature in the IJT and annuli rapidly tends to be consistent. (3) SHS temperature in each tubing increases with increasing of injection temperature in IJT. (4) Superheat degree in IJT decreases rapidly near the wellhead, but the superheat degree in annuli has an increase.

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

1. Introduction

Thermal methods, such as steam-assisted gravity drainage [1] and cyclic steam stimulation [2,3], have been proved effective for heavy oil recovery. In order to obtain a satisfactory development effect, practicing engineers need to predict the thermophysical properties of thermal fluid at well bottom before the project starts. However, the predicting task is never easy due to the complexity of thermal fluid flow in the wellbores.

In 1960s, Satter et al. [4] developed an early model for predicting steam quality along the wellbores based upon the energy balance equation. Pacheco et al. [5] proposed a comprehensive mathematical model for predicting pressure along the wellbores with consideration of friction loss. Farouq Ali [6] developed an improved model to analyze the pressure profiles for both upward and downward flow. Adopting iteration technique, Durrant et al. [7] presented a numerical model for fast estimation of transient heat transfer rate along the wellbores, which laid a solid fundation for later studies [8–13].

Then, huge amount of researches were conducted by Hasan et al. [14–23] on the flow and heat transfer characteristics of saturated steam in the vertical wellbores, which gave a basic reference for later studies [24–28]. All of these previous studies on single-tubing steam injection wells laid a solid fundation for the later concentric dual-tubing study.

Field practices have already shown that single-tubing steam injection wells often cause serious fingering phenomena [29–33], especially for long horizontal wells or severely heterogeneous reservoirs. Therefore, CDTW was proposed to alleviate these shortcomings and it has been proved to be an effective and economical efficiency [29,34].

Caetano et al. [35] developed an early model for predicting pressure drop in annuli, which presented a basic reference for later studies [36–41]. Based on the concept of equivalent radius, Griston et al. [30] presented an improved model for predicting pressure drop in annuli, which was proved to be useful in practice [42]. In 2014, Gu et al. [32] presented a numerical model to estimate the pressure profile in annuli.

However, all of these previous studies were focused on the conventional saturated steam. The study on SHS flow in wellbores is still at its early stage. In recent years, with the rapid development of technology, SHS has shown its advantages in heavy oil recovery.

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Nomenclature

a	the geothermal gradient, K/m
g	the gravitational acceleration, 9.81 m/s^2
h	specific enthalpy of SHS, J/kg
h_c	the convective heat transfer coefficient, W/(m^2·K)
h_r	the radiative heat transfer coefficient, W/(m^2·K)
p	SHS pressure, Pa
Q_{an}	the heat loss rate from annuli to formation, W
q_{ij}	the heat exchange rate between the IJT and annuli per unit depth, W/s
Q_{ij}	the heat exchange rate between the IJT and annuli, W
r	radius of tubing, m
T	SHS temperature in the tubing, K
T_0	the ground temperature, K
T_{ij}	SHS temperature in the IJT, K
T_{an}	SHS temperature in annuli, K
T_h	temperature at the interface of cement sheath and formation, K
T_e	initial formation temperature, K
U_{ijo}	comprehensive heat transfer coefficient between the IJT and annuli, W/(m^2·K)
v	flow velocity of SHS in the tubing, m/s
w	mass flow rate of SHS in each tubing, kg/s
z	well depth from the surface, m

Greek alphabet

ρ	SHS density, kg/m^3
θ	well angle from vertical, rad
λ	wellbore thermal conductivity, W/(m·K)
λ_e	formation thermal conductivity, W/(m·K)
τ_f	the shear stress, N
μ_{ij}	SHS viscosity, Pa·s

Subscripts

a	inner tubing
an	the annuli
b	outer tubing
c	the casing
cas	the casing
cem	the cement sheath
i	inner radius
ij	the integral joint tubing
in	inlet of the segment
ins	insulation materials
o	outer radius
out	outlet of the segment
tub	the Metallic tubing

Zhou et al. [43], Xu et al. [44,45], Gu et al. [46], Fan et al. [47] and Sun et al. [48–51] presented progressive models to predict the thermophysical properties of SHS in conventional single-tubing wells. But the flow and heat transfer characteristics of SHS in single-tubing wells are quite different from that in CDTW. Dong et al. [52,53] presented a numerical model for estimating SHS pressure and temperature in CDTW. However, their energy balance equation has a limitation in energy conservation [33,49–51,54]. More researches need to be conducted urgently.

In this paper, a mathematical model is established for predicting thermophysical properties of SHS in CDTW. The pressure and temperature profiles are obtained by finite difference method on space and solved by iteration technique. Then, the predicted results are compared against field data. Finally, the effect of injection temperature in each tubing on the profiles of thermophysical properties of SHS in CDTW are studied.

2. Model description

2.1. General assumptions

A schematic of CDTW is shown in Fig. 1. Some basic assumptions are listed below:

(1) The injection parameters at wellhead are steady-state.
(2) Heat transfer rate inside the wellbore is steady-state, while it is transient in the formation.
(3) Thermal parameters of formation are independent from well depth.

2.2. Mathematical model of SHS flow in the IJT

Firstly, based on the work [32,33] and the mass conservation law, the mass balance equation of SHS flow in the IJT can be given as:

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

Secondly, the energy balance equation of SHS in the IJT can be expressed as:

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

The heat exchange rate between IJT and annuli, Q_{ij}, in Eq. (2) can be expressed as [32,33]:

$$\frac{dQ_{ij}}{dz} = q_{ij} = 2\pi r_{ijo} U_{ijo} (T_{ij} - T_{an}) \tag{3}$$

where

$$U_{ijo} = \left[\frac{r_{ijo}}{\lambda_{tub}} \ln\frac{r_{ijo}}{r_{iji}} + \frac{r_{ijo}}{h_{fiji} r_{iji}} + \frac{1}{h_{fijo}}\right]^{-1} \tag{4}$$

Finally, the momentum balance equation of SHS in the IJT can be expressed as:

$$\frac{dp_{ij}}{dz} - \rho_{ij} g \cos\theta + \frac{\tau_f}{\pi r_{iji}^2 dz} + \frac{d(\rho_{ij} v_{ij}^2)}{dz} = 0 \tag{5}$$

Thus, the mathematical model of SHS flow in the IJT is established.

2.3. Mathematical model of SHS flow in annuli

Firstly, based on the work [32,33], the mass balance equation of SHS in annuli can be given as:

$$\frac{\partial w_{an}}{\partial z} = \pi (r_{ai}^2 - r_{ijo}^2) \frac{\partial (\rho_{an} v_{an})}{\partial z} = 0 \tag{6}$$

Secondly, the energy balance equation of SHS in annuli can be expressed as:

$$\frac{dQ_{an}}{dz} - \frac{dQ_{ij}}{dz} = -w_{an}\frac{dh_{an}}{dz} - w_{an}\frac{d}{dz}\left(\frac{v_{an}^2}{2}\right) + w_{an} g \cos\theta \tag{7}$$