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RESEARCH PAPER

Calculation model for on-way parameters of horizontal wellbore in the superheated steam injection

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Abstract: Due to superheated steam as a pure gas, the ordinary steam model for the calculation of horizontal well-bore parameters based on two phases flow theory isn't applicable to the superheated steam injection process. According to the conservation of mass, conservation of momentum and conservation of energy, a calculation model for on-way parameters of horizontal well-bore in the superheated steam injection considering the steam phase changing is set up. The on-way parameters of temperature, pressure and dryness of a horizontal well injected superheated steam from Kazakhstan Kumsai oilfield is calculated using the model, and the calculation result of the new model is in good agreement with that of the field data, which verifies the effectiveness of the model. Sensitivity analysis indicates that the length to the heel of horizontal well undergoing the steam phase state changing increases as the injection rate or the degree of superheat increases, but the increase extent is not significant when the injection rate is larger than 8 t/h or the degree of superheat is larger than 80 °C. In the permeability distribution pattern that the permeability increases along the horizontal well-bore, steam temperature is decreased at the lowest rate and the length to the heel of horizontal well undergoing the steam phase changing is the longest.

Key words: heavy oil; horizontal well; superheated steam; steam phase changing; on-way parameters; calculation model; steam injection rate

Introduction

Superheated steam is the steam that is superheated by the number of temperature degrees through which it has been heated above its saturation temperature[1]. In contrast with ordinary wet steam, superheated steam is characterized by high steam quality and high enthalpy, and it can enhance heating effects and expand displacement volume in formations. Accordingly, superheated steam injection has become an effective technique to recover heavy oil[2–5]. Some literatures[6–10] provided the models to determine the distribution of pressures and temperatures along vertical wellbore with injection of superheated steam. These models can also be used to calculate on-way parameters in the vertical section from wellhead to the heel of horizontal wellbore during superheated steam injection with horizontal well. However, they are no more applicable for the horizontal section from heel to toe of the horizontal wellbore, along which mass flow of steam declines gradually. Some literatures[11–13] introduced the models to calculate the distribution of pressures, temperatures and quality along horizontal wellbore with injection of ordinary wet steam. However, these models are not suitable for horizontal wellbores with injection of superheated steam, since superheated steam is significantly different from ordinary wet steam in physical properties – superheated steam is of single-phase flow, while ordinary wet steam is of gas-liquid two-phase flow. In addition, during injection of superheated steam in horizontal wellbores, heat carried by the superheated steam decreases continuously due to mass transfer and heat conduction of thermal fluids in the wellbore. Consequently, superheated steam in the wellbore is converted into ordinary wet steam. In this paper, based on the mass conservation equation and momentum theorem of fluids in wellbore and the equation of energy conservation between wellbore and formation, the authors present a calculation model for on-way parameters of horizontal wellbore in the superheated steam injection, which considers the phase change during transmission of superheated steam.

1. Mathematical model

1.1. Basic assumptions

(1) The reservoir where horizontal wellbore locates is flat in structure and has uniform thickness, and thermophysical parameters of these formations may not change with tem-

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peratures.

(2) Heat transfer from wellbore to the outer margin of cement sheath is assumed to be steady state, but heat transfer from the outer margin of cement sheath to the oil formation is assumed to be non-steady state.

(3) Horizontal wellbore is divided into N infinitesimal sections, with even absorption of injected steam in the same infinitesimal section.

1.2. Derivation of the model

With injected steam continuously absorbed by the oil formation, mass flow of steam along the horizontal wellbore declines gradually. In accordance with the mass conservation law, the mass flow rate in infinitesimal section i is expressed as follows:

$$w_i = w_0 - \left(I_1\overline{\rho_1} + I_2\overline{\rho_2} + \cdots + I_i\overline{\rho_i}\right) \tag{1}$$

In accordance with the momentum conservation law, the pressure drop gradient[14] in infinitesimal section i can be expressed as follows:

$$\frac{\mathrm{d}p_i}{\mathrm{d}L} = -f_{\mathrm{w}}\frac{\overline{\rho_i}}{D}\frac{\overline{v_i}^2}{2} - f_{\mathrm{p}}\frac{\overline{\rho_i}}{D}\frac{\overline{v_i}^2}{2} - \frac{\rho_i {v_i}^2 - \rho_{i-1}v_{i-1}^2}{\Delta L} \tag{2}$$

According to the energy conservation law, the sum of the heat transferred to the oil formation through heat conduction of the infinitesimal section in specific length within specific time, the heat transferred to oil formation through mass transfer and the energy of frictional losses equals to the sum of changes in mechanical energy and internal energy:

$$\frac{\mathrm{d}Q_{\mathrm{c}i}}{\mathrm{d}L} + \frac{\mathrm{d}Q_{\mathrm{r}i}}{\mathrm{d}L} + \frac{\mathrm{d}W_{\mathrm{f}i}}{\mathrm{d}L} = -\frac{\mathrm{d}\left(w_i h_i\right)}{\mathrm{d}L} - \frac{\mathrm{d}}{\mathrm{d}L}\left(\frac{w_i v_i^2}{2}\right) \tag{3}$$

Assuming steam injected into the same infinitesimal section is absorbed evenly into the oil formation, then:

$$\frac{\mathrm{d}Q_{\mathrm{r}i}}{\mathrm{d}L} = I_i\overline{\rho_i}\frac{\overline{h_i}}{\Delta L} \tag{4}$$

The right side of Equation (3) can be expressed as:

$$-\frac{\mathrm{d}(w_i h_i)}{\mathrm{d}L} - \frac{\mathrm{d}}{\mathrm{d}L}\left(\frac{w_i v_i^2}{2}\right) =$$

$$-\overline{w_i}\frac{\mathrm{d}h_i}{\mathrm{d}L} + \overline{h_i}\frac{I_i\overline{\rho_i}}{\Delta L} - \overline{w_i}\frac{\mathrm{d}}{\mathrm{d}L}\left(\frac{v_i^2}{2}\right) + \frac{\overline{v_i}^2}{2}\frac{I_i\overline{\rho_i}}{\Delta L} \tag{5}$$

Substituting Equation (4) and Equation (5) into Equation (3), we can get:

$$\frac{\mathrm{d}Q_{\mathrm{c}i}}{\mathrm{d}L} + \frac{\mathrm{d}W_{\mathrm{f}i}}{\mathrm{d}L} = -\overline{w_i}\frac{\mathrm{d}h_i}{\mathrm{d}L} - \overline{w_i}\frac{\mathrm{d}}{\mathrm{d}L}\left(\frac{v_i^2}{2}\right) + \frac{\overline{v_i}^2}{2}\frac{I_i\overline{\rho_i}}{\Delta L} \tag{6}$$

During transmission of superheated steam in horizontal wellbore, single-phase flow of superheated steam turns into two-phase flow of ordinary wet steam with heat losses. During injection of superheated steam, pressure and temperature may serve as controlled variables. During injection of ordinary wet steam, pressure (or temperature) and steam quality may be used as controlled variables instead.

As for the superheated steam, sensible heat can be released to compensate heat losses to surrounding formations with steam quality constant at 1. Under such circumstance, enthalpy of superheated steam can be determined by using the following equation[8]:

$$\frac{\mathrm{d}h_i}{\mathrm{d}L} = C_{\mathrm{p}i}\frac{\mathrm{d}T_i}{\mathrm{d}L} + \left[\gamma_i - \overline{T_i}\left(\frac{\partial\gamma_i}{\partial T}\right)\right]\frac{\mathrm{d}p_i}{\mathrm{d}L} \tag{7}$$

By combining Equation (6) and Equation (7), the temperature distribution of superheated steam can be determined:

$$\frac{\mathrm{d}T_i}{\mathrm{d}L} = -\frac{1}{C_{\mathrm{p}i}}\left\{\frac{1}{\overline{w_i}}\left[\frac{\mathrm{d}Q_{\mathrm{c}i}}{\mathrm{d}L} + \frac{\mathrm{d}W_{\mathrm{f}i}}{\mathrm{d}L} + \overline{w_i}\frac{\mathrm{d}}{\mathrm{d}L}\left(\frac{v_i^2}{2}\right) - \frac{\overline{v_i}^2}{2}\frac{I_i\overline{\rho_i}}{\Delta L}\right] + \right.$$

$$\left.\left[\gamma_i - \overline{T_i}\left(\frac{\partial\gamma_i}{\partial T}\right)\right]\frac{\mathrm{d}p_i}{\mathrm{d}L}\right\} \tag{8}$$

As for ordinary wet steam, latent heat of vaporization can be used to compensate the heat losses, so that every specific pressure may correspond to the only saturation temperature. Enthalpy of ordinary wet steam can be determined by the following equation[15]:

$$\frac{\mathrm{d}h_i}{\mathrm{d}L} = \left(h_{\mathrm{s}i} - h_{\mathrm{w}i}\right)\frac{\mathrm{d}x_i}{\mathrm{d}L} + \left(\frac{\mathrm{d}h_{\mathrm{s}i}}{\mathrm{d}p} - \frac{\mathrm{d}h_{\mathrm{w}i}}{\mathrm{d}p}\right)\frac{\mathrm{d}p_i}{\mathrm{d}L}x_i + \frac{\mathrm{d}h_{\mathrm{w}i}}{\mathrm{d}p}\frac{\mathrm{d}p_i}{\mathrm{d}L} \tag{9}$$

By using Equation (6) and Equation (9), steam quality distribution of ordinary wet steam can be determined:

$$x_i = -\frac{c_3}{c_2} + \left(x_{i-1} + \frac{c_3}{c_2}\right)\mathrm{e}^{-\frac{c_2}{c_1}\Delta L_i} \tag{10}$$

where $c_1 = h_{\mathrm{s}i} - h_{\mathrm{w}i}$

$$c_2 = \left(\frac{\mathrm{d}h_{\mathrm{s}i}}{\mathrm{d}p} - \frac{\mathrm{d}h_{\mathrm{w}i}}{\mathrm{d}p}\right)\frac{\mathrm{d}p_i}{\mathrm{d}L}$$

$$c_3 = \frac{\mathrm{d}h_{\mathrm{w}i}}{\mathrm{d}p}\frac{\mathrm{d}p_i}{\mathrm{d}L} + \frac{1}{\overline{w_i}}\left[\frac{\mathrm{d}Q_{\mathrm{c}i}}{\mathrm{d}L} + \frac{\mathrm{d}W_{\mathrm{f}i}}{\mathrm{d}L} + \overline{w_i}\frac{\mathrm{d}}{\mathrm{d}L}\left(\frac{v_i^2}{2}\right) - \frac{\overline{v_i}^2}{2}\frac{I_i\overline{\rho_i}}{\Delta L}\right]$$

1.3. Determination of relevant parameters

1.3.1. Outflow rate of fluid injected into the formation

The volumetric outflow rate of fluid injected into the formation in infinitesimal section i of the horizontal wellbore[16] can be expressed as follows:

$$I_i = 1.16\times10^{-5}J_{\mathrm{p}i}I_{\mathrm{p}i}\left(\overline{p_i} - p_{\mathrm{r}}\right) \tag{11}$$

In accordance with the seepage mechanics theory and method of mirror inversion, the productivity index and the injectivity ratio of infinitesimal section i of the horizontal wellbore can be expressed as follows:

$$J_{\mathrm{p}i} = \beta\frac{2\pi\sqrt{\dfrac{K_{\mathrm{h}i}}{K_{\mathrm{v}i}}}K_{\mathrm{v}i}\Delta L\left(\dfrac{K_{\mathrm{ro}}}{B_{\mathrm{o}}\mu_{\mathrm{o}}} + \dfrac{K_{\mathrm{rw}}}{B_{\mathrm{w}}\mu_{\mathrm{w}}}\right)}{\ln\dfrac{0.571\sqrt{A_{\mathrm{d}i}}}{r_{\mathrm{w}}} + S - 0.75} \tag{12}$$

$$I_{\mathrm{p}i} = \frac{2\ln\dfrac{A_{\mathrm{d}i}}{r_{\mathrm{w}}^2} - 3.86}{\ln\dfrac{A_{\mathrm{d}i}}{r_{\mathrm{w}}^2} - 2.71} \tag{13}$$

1.3.2. Heat conduction in the wellbore

In accordance with theory of wellbore heat conduction[17], the heat transferred into oil formation through heat conduction