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Prediction of wax precipitation region in wellbore during deep water oil well testing

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Abstract: During deep water oil well testing, the low temperature environment is easy to cause wax precipitation, which affects the normal operation of the test and increases operating costs and risks. Therefore, a numerical method for predicting the wax precipitation region in oil strings was proposed based on the temperature and pressure fields of deep water test string and the wax precipitation calculation model. And the factors affecting the wax precipitation region were analyzed. The results show that: the wax precipitation region decreases with the increase of production rate, and increases with the decrease of geothermal gradient, increase of water depth and drop of water-cut of produced fluid, and increases slightly with the increase of formation pressure. Due to the effect of temperature and pressure fields, wax precipitation region is large in test strings at the beginning of well production. Wax precipitation region gradually increases with the increase of shut-in time. These conclusions can guide wax prevention during the testing of deep water oil well, to ensure the success of the test.

Key words: deep water oil and gas development; oil well testing; wellbore wax precipitation; temperature field; pressure field; wax precipitation region prediction

Introduction

Well testing is an important part in the oil and gas exploration which can provide reliable data for the evaluation of oil and gas reservoirs and the selection of development mode[1–2]. However, in the test operation of deep-water oil wells, the special low temperature environment is likely to cause wax precipitation in the wellbore. When the temperature of the crude oil drops to the initial crystallization temperature of the wax during well testing, wax crystal particles begin to precipitate[3]. The precipitation of wax will increase the fluid viscosity in the wellbore and increase the pressure loss[4]. The wax crystal precipitation and deposition on the wall of the wellbore will reduce the effective diameter of tubing and increase the frictional resistance[3,5–6], and in turn influence the accuracy of the test data and the efficiency of test operation.

Researchers in China and abroad have done a lot of studies on the prediction of wax precipitation region and the calculation of wax deposition rate in waxy oil pipeline and wellbore during production. The wax thermodynamic model plays an important role in predicting the wax precipitation region. Combining with the crude oil components, the wax thermodynamic model can be used to determine the wax precipita-

tion temperature at a given pressure or the wax precipitation pressure at a given temperature[7]. A lot of experimental and theoretical studies have been carried out to based on the wax thermodynamic model and a series of mathematical models have been proposed to calculate the conditions of wax precipitation. The wax thermodynamic models can be roughly divided into four types: regular solution model[8–11], polymer solution model[12–15], state equation model[16–18] and crude oil composition model[19–21]. Nowadays, the understanding of wax deposition rate in single-oil phase flow has been mature. But the study on wax deposition rate under the gas-liquid two-phase flow is still at the initial stage, and mainly focuses on the case of horizontal pipeline[22–26]. Moreover, there is less research on wax deposition rule in the gas-liquid two-phase wellbore flow.

In this study, a numerical method was proposed to predict the wax precipitation region during deepwater oil well testing based on the temperature and pressure fields calculation model combining the conditions of wax precipitation. And the effects of production rate, geothermal gradient, water depth, formation pressure, water-cut of produced fluid, and well shut-in and opening etc. on the wax precipitation region are analyzed.

1. Calculation models for temperature and pressure fields and wax precipitation

1.1. Temperature and pressure calculation models

The distributions of temperature and pressure in the test string are important factors affecting the wax precipitation region. By solving the basic model of gas-liquid two-phase flow, the distribution of temperature and pressure in the test string can be obtained. Four types of the basic models of gas-liquid two-phase flow are: homogeneous flow model, separated flow model, drift-flux model and double-fluid model[27–28]. In the homogeneous flow model, the gas-liquid two-phase mixed fluid is assumed as homogeneous medium, and its characteristic parameters are calculated according to the mean value of the gas-liquid two-phase medium. In the separated flow model, the differences between different phases are taken into account, the gas and liquid phases are treated separately, and the fluids of different phases are considered to have independent flow rate and physical parameters. The drift-flux model considers not only the relative motion between the gas and the liquid phases, but also the distribution of the void fraction and velocity along the cross section. The double-fluid model regards each phase fluid as continuous medium, and establishes continuity equations, momentum conservation equations and energy conservation equations for the gas and liquid phases respectively, which are coupled with each other through the action of phase interface. In these types of models, the homogeneous flow model is simple in calculation and convenient in application, but without considering the difference between gas phase and liquid phase, leading to large error. The flow characteristics of each phase in the separated flow model are isolated. The drift-flux model cannot accurately represent the movement and spatial distribution of every phase. The double-fluid model is always appropriate as long as the assumption that the gas-liquid phase is continuous medium in the local area is met. It is suitable for any binary mixture that can be considered as continuous medium and can be used for a variety of flow patterns. The established equation including comprehensive content, rich parameters and extensive application[28].

In this study, the modified double-fluid model was used to calculate the temperature and pressure fields. By solving three separate mass conservation equations (respectively on gas phase, liquid droplet and wall film, as Eqs.1-3), two momentum equations (respectively on gas phase and liquid droplets mixture, liquid film, as Eqs. 4-5) and one mixture energy conservation equation (as Eq. 6), the parameters of the multi-phase flow can be calculated. The above equations were obtained according to the law of conservation on the basis of the double-fluid model, and selecting the microelements[29].

$$\frac{\partial}{\partial t}\left(\beta_g \rho_g\right) = -\frac{1}{A}\frac{\partial}{\partial s}\left(A\beta_g \rho_g v_g\right) + \psi_m + G_g \tag{1}$$

$$\frac{\partial}{\partial t}\left(\beta_d \rho_l\right) = -\frac{1}{A}\frac{\partial}{\partial s}\left(A\beta_d \rho_l v_d\right) - \psi_m \frac{\beta_d}{\beta_l + \beta_d} + \psi_e - \psi_d + G_d$$

$$\frac{\partial}{\partial t}\left(\beta_l \rho_l\right) = -\frac{1}{A}\frac{\partial}{\partial s}\left(A\beta_l \rho_l v_l\right) - \psi_m \frac{\beta_l}{\beta_l + \beta_d} - \psi_e + \psi_d + G_l \tag{2}$$

$$\frac{\partial}{\partial t}\left(\beta_g \rho_g v_g + \beta_d \rho_l v_d\right) = -\left(\beta_g + \beta_d\right)\frac{\partial p}{\partial s} - \tag{3}$$

$$\frac{1}{A}\frac{\partial}{\partial s}\left(A\beta_g \rho_g v_g^2 + A\beta_d \rho_l v_d^2\right) - \frac{1}{2}\lambda_g \rho_g v_g |v_g|\frac{S_g}{4A} -$$

$$\frac{1}{2}\lambda_{in}\rho_g v_r |v_r|\frac{S_{in}}{4A} + \left(\beta_g \rho_g + \beta_d \rho_l\right)g\cos\alpha +$$

$$\psi_m \frac{\beta_l}{\beta_l + \beta_d}v_a + \psi_e v_{in} - \psi_d v_d \tag{4}$$

$$\frac{\partial}{\partial t}\left(\beta_l \rho_l v_l\right) = -\beta_l \frac{\partial p}{\partial s} - \frac{1}{A}\frac{\partial}{\partial s}\left(A\beta_l \rho_l v_l^2\right) - \frac{1}{2}\lambda_l \rho_l v_l |v_l|\frac{S_l}{4A} +$$

$$\frac{1}{2}\lambda_{in}\rho_g v_r |v_r|\frac{S_{in}}{4A} + \beta_l \rho_l g\cos\alpha - \psi_m \frac{\beta_l}{\beta_l + \beta_d}v_a - \psi_e v_{in} +$$

$$\psi_d v_d - \beta_l D\left(\rho_l - \rho_g\right)g\frac{\partial \beta_l}{\partial s}\sin\alpha \tag{5}$$

$$\frac{\partial}{\partial t}\left[\beta_g \rho_g \left(E_g + \frac{1}{2}v_g^2 + gh\right) + \beta_l \rho_l \left(E_l + \frac{1}{2}v_l^2 + gh\right) +\right.$$

$$\left.\beta_d \rho_d \left(E_d + \frac{1}{2}v_d^2 + gh\right)\right] = -\frac{\partial}{\partial s}\left[\beta_g \rho_g v_g \left(H_g + \frac{1}{2}v_g^2 + gh\right) +\right.$$

$$\left.\beta_l \rho_l v_l \left(H_l + \frac{1}{2}v_l^2 + gh\right) + \beta_d \rho_d v_d \left(H_d + \frac{1}{2}v_d^2 + gh\right)\right] + H_s + U \tag{6}$$

In Eqs.1-6, there are seven basic unknown variables, p, T, v_g, v_l, β_g, β_l and β_d, and other unknown variables can be expressed or solved by these basic variables. The pressure equation can be expressed as:

$$\left(\frac{\beta_g}{\rho_g}\frac{\partial \rho_g}{\partial p} + \frac{1-\beta_g}{\rho_l}\frac{\partial \rho_l}{\partial p}\right)\frac{\partial p}{\partial t} = -\frac{1}{A\rho_g}\frac{\partial}{\partial s}\left(A\beta_g \rho_g v_g\right) -$$

$$\frac{1}{A\rho_l}\frac{\partial}{\partial s}\left(A\beta_l \rho_l v_l\right) - \frac{1}{A\rho_l}\frac{\partial}{\partial s}\left(A\beta_d \rho_l v_d\right) +$$

$$\psi_m \left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right) + G_g \frac{1}{\rho_g} + G_l \frac{1}{\rho_l} + G_d \frac{1}{\rho_l} \tag{7}$$

Eqs.1-7 can be simplified as functions of the seven basic unknown variables and written in the form of Eq. 8.

$$a_1 \frac{\partial p}{\partial t} + a_2 \frac{\partial T}{\partial t} + a_3 \frac{\partial v_g}{\partial t} + a_4 \frac{\partial v_l}{\partial t} + a_5 \frac{\partial \beta_g}{\partial t} + a_6 \frac{\partial \beta_l}{\partial t} + a_7 \frac{\partial \beta_d}{\partial t} +$$

$$b_1 \frac{\partial p}{\partial s} + b_2 \frac{\partial T}{\partial s} + b_3 \frac{\partial v_g}{\partial s} + b_4 \frac{\partial v_l}{\partial s} + b_5 \frac{\partial \beta_g}{\partial s} + b_6 \frac{\partial \beta_l}{\partial s} + b_7 \frac{\partial \beta_d}{\partial s} = c \tag{8}$$

1.2. Calculation model of wax precipitation

The wax precipitation conditions were calculated by the extended model proposed by Rønningsen et al.[30] based on the Pedersen model[16].

When the liquid phase (oil) and the solid phase (wax) reach the thermodynamic equilibrium state, the fugacity of a component in the liquid phase and the solid phase is equal, as shown in Eq. 9:

$$f_{li} = f_s \tag{9}$$