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Prediction and Simulation of Wax Deposition in Oil and Gas Wells

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Abstract: Wax formation in oil and gas wells can limit the recovery rate of the well and can lead to well shutdown in severe cases. It is therefore important to predict the deposition of waxe during oil and gas production. In order to study the deposition pattern of wax in the wellbore, the wellbore flow and heat transfer processes were analysed, and a method for predicting the wellbore flow, temperature, and pressure was developed and coupled to the pressure and temperature. By analysing the thermodynamic equilibrium conditions of the system, the point of wax precipitation is determined based on the change in phase state of the system. A new simplified wax deposition prediction model incorporating diffusion, shear deposition, and the effects of ageing and stripping was developed by writing a program based on Fick's diffusion theory. A sensitivity analysis of wax deposition revealed that the thickness of wax formation increases as the production time gets longer, decreases as water content and fluid production increases, and the depth of the wax formation point becomes shallower, while the variable of dissolved oil to gas ratio has little effect on wellbore wax formation.

1. Introduction

Wax deposition in oil and gas development has always been a problem in the petroleum industry. Wax formation in oil and gas wells can lead to smaller oil and gas flow paths and increased formation back pressure, limiting the recovery rate of the well and ultimately leading to lower oil and gas recovery rates[1]and, in severe cases, to shutdown of the well[2].

Therefore, it is essential to study and predict the wax precipitation law of oil and gas wells. The main reason for wax precipitation is the change of pressure and temperature during the transportation of oil and gas in the wellbore, which destroys the initial temperature and pressure balance system, resulting in the mutual conversion of solid phase and liquid phase[3], HSU JJ, Matzain A, Antonio Bruno and other scholars[4-7]. have studied the above problems. In this paper, the wellbore flow and heat transfer process will be analyzed, the prediction method of wellbore flow temperature and pressure will be established, the wax deposition model will be established, and the main factors affecting wax deposition will be analyzed.

2. Prediction Model of Wellbore Flow Pressure and Temperature

2.1. Pressure Prediction Model

With the increasing number of large slope and horizontal bottom-hole directional wells, there will be large errors if the horizontal and vertical two-phase flow correlation fitting equations continue to be used to calculate the inclined two-phase flow pressure. And the two-phase flow correlation equation for inclined pipe proposed by Mukherjee-Brill [8] improves and simplifies the calculation of directional pressure. The M-B pressure equation:

$$\left(\frac{dp}{dz}\right)=\frac{g\rho_{tp}\sin\theta+\left(f_{tp}G_m v_m\right)/2D}{1-\left(\rho_{tp}v_{sg}\right)/P} \tag{1}$$

Where p is the fluid pressure, pa; ρtp is the mixture density, kg/m3; ftp is the friction coefficient, dimensionless; vsg is the fluid velocity, m/s; D is the pipe diameter, mm ; vm is the gas flow rate, m/s.

2.2. Temperature Prediction Model

Simplifying the mass, momentum, and energy conservation equations, as well as the heat transfer equation of the wellbore, we obtain the equation as the following:

$$\begin{cases}\dfrac{d\rho}{dz}=\dfrac{-\dfrac{RZg\rho}{C_pM}\left[2a\left(T-T_{ei}\right)-g\sin\theta\right]+\dfrac{f\rho v|v|}{2d}-\rho g\sin\theta}{v^2-\left(\dfrac{RZgv^2}{CpM}+\dfrac{RZgT}{M}\right)}\\ \dfrac{dv}{dz}=-\dfrac{v}{\rho}\dfrac{d\rho}{dz}\\ \dfrac{dp}{dz}=\rho g\sin\theta-\dfrac{f\rho v|v|}{2d}+V^2\dfrac{d\rho}{dz}\\ \dfrac{dT}{dz}=\left[\dfrac{v^2}{\rho}\dfrac{d\rho}{dz}+g\sin\theta-2a\left(T-T_{ei}\right)\right]/C_p\end{cases} \tag{2}$$

Where D is the inner diameter of the pipeline, m; V is the modulus of velocity v; rti is the inner diameter of the tubing, mm; f(tD) is the dimensionless time of Remay function; Tei is the initial temperature of formation, K; Ke is the thermal conductivity of the formation ring, J/m·K; T is the fluid flow temperature, K; Z is the depth, m; tD is the dimensionless time, dimensionless quantity; $a=\frac{2\pi r_{ti}U_{ti}K_e}{w[r_{ti}U_{ti}f(t_D)+K_e]}$; state equation of gas $\rho=\frac{Mp}{RTZ_g}$.

2.3. Pressure-Temperature Coupled Equations

From the above temperature and pressure equations, the coupled gradient equation of wellbore pressure[9]and temperature[10]can be obtained as the following:

$$\begin{cases} \dfrac{dp}{dz} = \left(\rho_{tp} g \sin\theta + f_{tp} \dfrac{\rho_{tp} v_m |v_m|}{2D} \right) \Bigg/ \left(1 - \dfrac{\rho_{tp} v_m v_{sg}}{p} \right) \\ \dfrac{dT}{dz} = \left\{ g \sin\theta + \dfrac{v_m v_{sg}}{p} \dfrac{dp}{dz} + c_p \alpha_J \dfrac{dp}{dz} - \dfrac{2\pi r_{to} U_{to} K_e \left(T - T_{ei} \right)}{w_t \left[r_{to} U_{to} f\left(t_D \right) + k_e \right]} \right\} \Bigg/ c_p \end{cases} \tag{3}$$

3. Establishment of Prediction Model of Wax Deposition

3.1. Diffusion Deposition of Wax

According to the diffusion law of Fick[11], the model of wax diffusion deposition on the tube wall can be represented by the following equation (4):

$$N_d = C_d C_1 \frac{\rho_s A}{\mu} \left(\frac{dc}{dT} \right) \left(\frac{dT}{dr} \right) \tag{4}$$

Where Cd is the deposition constant; C1 is the Molecular diffusion constant; ρs is the waxy density, kg/m3; A is is the wax deposit surface area, m2; μ is the Viscosity of the fluid, $\mathrm{mPa \cdot s}$; c is the Wax concentration in crude oil, %; $\frac{\mathrm{dc}}{\mathrm{dT}}$ is the Wax concentration gradient in crude oil, (℃)-1; $\frac{\mathrm{dT}}{\mathrm{dr}}$ is the Radial temperature gradient, ℃/m.

3.2. Shear Deposition of Wax

According to the wax shear deposition model proposed by Weingarten and Euchner[12], it can be expressed as the following equation (5):

$$N_s = C_d k^* c^* \gamma A \tag{5}$$

Where Cd is the unit conversion factor; Ns is the mass of crystalline wax deposited by shear dispersion in unit time, kg/s; K* is the shear deposition rate constant;γ is the shear rate, s-1; C* is the volume concentration of wax grains at the wall, fractional.

3.3. Shear Stripping and Aging Effect of Wax

According to the experimental study, it can be obtained that there is a linear relationship between the peeling effect during the deposition of wax, the effect of the aging effect of the wax deposition layer on the deposition thickness and the molecular diffusion, so that the empirical coefficient of aging and peeling can be introduced, as follows in the formula:

$$D_e = \frac{D_{wo}}{1 + \dfrac{\left(1 + K_\alpha f_w\right)^2 f_w}{1 - f_w}} \tag{6}$$

Where fw is the water content, decimal; Dwo is the empirical coefficient of wax setting, no dimensional. The wax layer peeling and aging loss can be represented by the following formula:

$$N_e = -D_e \frac{\rho_s A}{\mu} \left(\frac{dc}{dT} \right) \left(\frac{dT}{dr} \right) \tag{7}$$

Where Ne is the mass of crystalline wax deposited by peeling and aging in unit time, kg/s.

3.4. Total Wax Deposition Thickness

The deposition of wax in the actual flow is partly due to precipitation of the crude oil by the decrease of temperature and deposited on the solid phase surface by Brownian motion and shear dispersion, and partly by direct diffusion of wax molecules and deposition on the solid phase surface. In this process, there is also a stripping and aging effect of wax, so the deposition rate of paraffin wax[13]is expressed as the following equation (8):

$$N = N_d + N_S + N_e \tag{8}$$

3.5. Wax Deposit Amount at Wellbore Wall

The deposition amount of paraffin on the pipe wall per unit time is expressed as the following formula:

$$dG = NFd\tau \tag{9}$$

Assuming that the caking wax is a cylindrical shell, the amount of paraffin deposited can be expressed as the following equation:

$$dG = FdD_L \rho_s \tag{10}$$

It can be seen from formula (9), (10):

$$NFd\tau = FdD_L \rho_s \tag{11}$$

Substituting (6), (7), (8) into the above formula gives the following formula:

$$\left[C_d \cdot C_1 \frac{A}{\mu} \left(\frac{dc}{dT} \right) \left(\frac{dT}{dr} \right) + C_d k^* c^* \gamma A \right] d\tau = dD_L \tag{12}$$

The wax concentration[14] in the above equation can be determined from the following equation:

$$\frac{dc}{dT} = \frac{1 - Ae^{nT} - (a + bT)}{\phi} \tag{13}$$

The radial temperature gradient can be solved by the principle of thermodynamic equilibrium and expressed as the following formula:

$$\frac{dT}{dr} = \frac{V\rho_L C_p}{\pi Kd} \cdot \frac{dT}{dL} \tag{14}$$

The axial temperature gradient is obtained using the pressure coupling model provided in this paper.

4. Numerical Simulation of Real Oil Well

4.1. Well-Based Data

The basic data of the oil well is shown in Table 1 below, and the system component data in the oil well is shown in Table 2 below.

Table 1: Basic data of oil wells

Well deep	2700 m	Saturation pressure	9.8 MPa
Oil layer temperature	80°C	Oil and gas ratio	10 m^3/ m^3
Oil pressure	0.55 MPa	Liquid yield	50 m^3/d
Pipe diameter	62 mm	Crude Oil Density	873.5kg/ m^3
Bottom hole pressure	16 MPa	Paraffin density	942 kg/ m^3

Table 2: System components.

Component	CO_2	N_2	C_1	C_2	C_3	IC_4
Molar composition	0.50	4.97	56.38	0.61	6.17	2.05
Component	NC_4	IC_5	NC_5	C_6	$C_{7}+$	
Molar composition	2.11	0.90	0.87	1.23	24.01	

4.2. Wax Precipitation Point Distribution

According to the composition of the formation system, the thermodynamic equilibrium model can be used to obtain the wax precipitation points at different pressures and temperatures, as shown in Fig. 1. As can be seen from the figure 1, the lower left part of the curve is the wax deposition area, and the upper right part is the non-wax deposition area. When the pressure is constant, with the increase of temperature, the fluid in the wellbore is not easy to form wax after exceeding the cloud point of wax. When the temperature is constant, as the pressure decreases, the gas is easily precipitated from the liquid, which reduces the solubility of paraffin in the liquid and makes it easier for the wax to deposit in the wellbore.

The range of wax deposition depths can be determined by the distribution of wellbore pressure, temperature, and the distribution of wax deposition points.

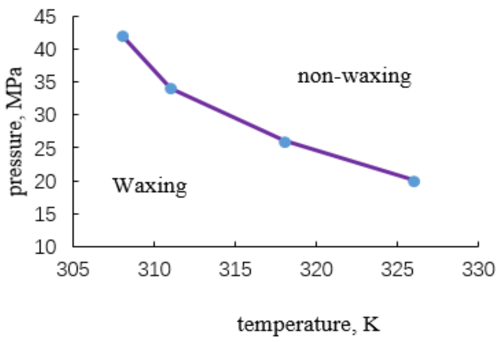

Figure 1: Distribution of waxing points.

4.3. Wellbore Temperature and Pressure Distribution Profile

The temperature-pressure coupling calculation of the wellbore was performed to obtain the temperature-pressure coupling profile of the well, as shown in Fig 2 below.

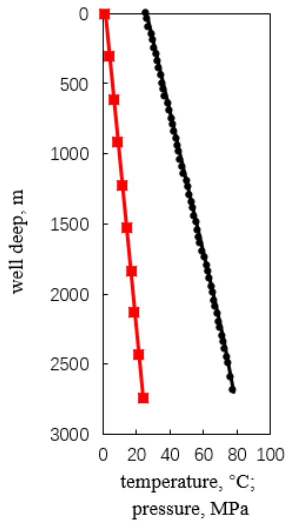

Figure 2: Temperature distribution coupled with pressure.

The temperature and pressure at any point in the wellbore are coupled with the wax precipitation point to obtain Fig. 3 below.

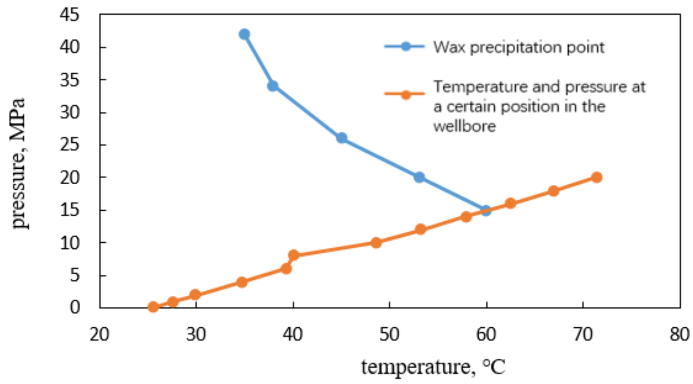

Figure 3: Coupling of wax precipitation point and wellbore pressure and temperature.

It can be seen from the above coupled curve that the temperature at the bottom of the well is 74.0436℃, the pressure is 23.86MPa, and it intersects with the curve of the wax precipitation point, so there must be wax precipitation at a certain position in the wellbore.

4.4. Wax Deposition Simulation Results

Using the established wax formation prediction model, the variation pattern of wax formation thickness in the wellbore was predicted. As can be seen in Fig. 4, wax deposition mainly occurs above the initial wax deposition point and the thickness of wax deposition in the wellbore increases and then decreases along the wellhead direction. This is because during the upward flow of fluid in the wellbore, both the fluid and the wall temperature gradually decrease, but the temperature difference between the fluid and the wall gradually increases, resulting in an increase in the difference between the wall temperature and the initial crystallisation temperature of the wax, and therefore an increase in the thickness of the wax deposit. However, when the wellhead section is reached, the flow rate increases, the scouring effect is enhanced, and the wax is not easily deposited on the pipe wall, so the rate of wax deposition is reduced. And the longer the production time, the greater the crystallisation thickness. In this paper, we believe that the most serious section of wax crystallisation occurs near 800m.

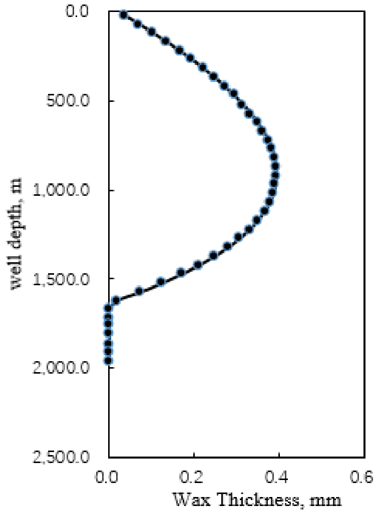

Figure 4: Wax deposition prediction simulation curve.

5. Wax Deposition Sensitivity Analysis

5.1. Sensitive Analysis of Liquid Production

A sensitivity analysis was carried out on the variable of fluid production of the well and four different groups of fluid production were selected at 40t/d, 50t/d, 60t/d, and 70t/d. The simulated result curves are shown in Fig. 5 below.

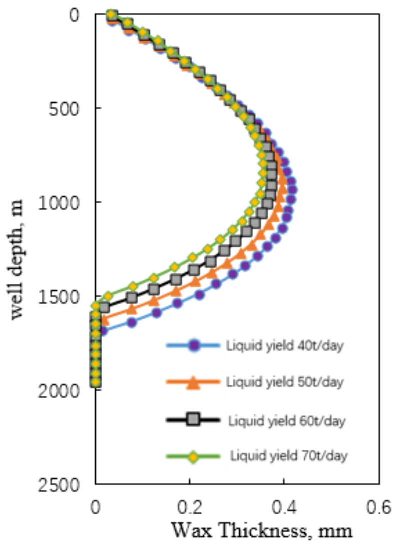

Figure 5: Sensitivity analysis of liquid yield.

As can be seen from the data curve above, when this new model is applied, the thickness of the wax deposit decreases as the production volume increases and the wax deposit point moves upwards in the direction of the wellbore. Therefore, when the production volume is increased, the thickness of wax deposition gradually decreases and the depth of the waxing point becomes shallower.

5.2. Sensitivity Analysis of Moisture Content

Sensitivity analysis is carried out on the variable of water cut of oil well, and four groups of different water cuts are selected as 0.1, 0.2, 0.4, and 0.6, respectively. The resulting curve of the simulation is shown in Fig. 6 below.

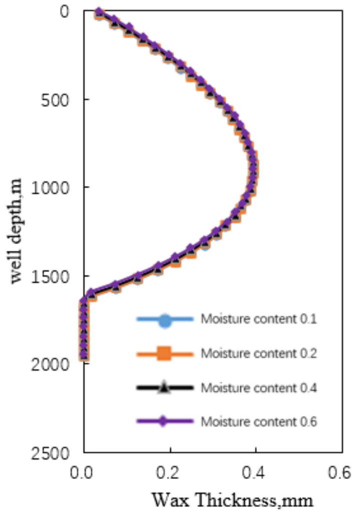

Figure 6: Moisture content sensitivity analysis.

As can be seen from the data curve above, although the wax thickness does not change much with this new model, the wax thickness decreases as the water content rises, and the wax point moves upwards in the direction of the wellbore. Therefore, as the water content increases, the thickness of wax deposited in the wellbore decreases and the waxing point becomes shallower.

5.3. Sensitivity Analysis of Production Time

A sensitivity analysis was carried out on the variable of production time of the well and four different sets of production times were selected for 1day, 20days, 30days, and 50days. The simulated result curves are shown in Fig. 7 below.

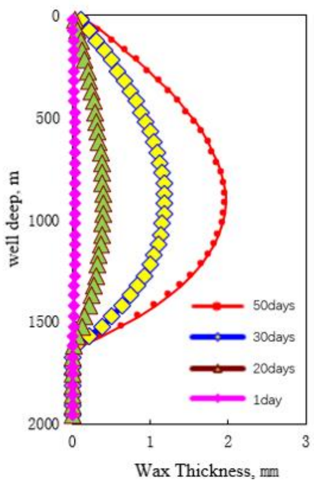

Figure 7: Sensitivity analysis of production time.

As can be seen from the data curve obtained from the graph above, when this new model is applied, the thickness of the wax formation becomes progressively greater as the production time increases, and the longer the production time, the greater the thickness and the wax formation point in the wellbore hardly moves. Therefore, there is a significant increase in the thickness of the wax knots when the production time is longer.

5.4. Sensitivity Analysis of Dissolved Oil/Gas Ratio

A sensitivity analysis was carried out on the variable dissolved gas to oil ratio of the well and four different sets of dissolved oil-to gas ratios of 5 m3/m3, 10 m3/m3, 15 m3/m3 and 20 m3/m3 were selected. The simulated result curves are shown in Fig. 8 below.

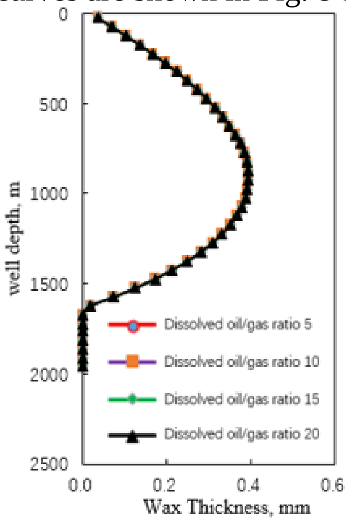

Figure 8: Sensitivity analysis of dissolved oil/gas ratio.

As can be seen from the data curves obtained from the graph above, the thickness of the wax formation in the wellbore did not change much when this new model was selected. Therefore, when the variable dissolved oil -to-gas ratio was changed, it had little effect on the deposition of wax in the wellbore.

6. Conclusion

In this paper, the heat transfer process, wellbore flow, and heat transfer process in the wellbore are analysed, and a method for predicting the pressure and temperature of wellbore flow is established and coupled to the pressure and temperature. By analysing the thermodynamic equilibrium conditions of the system, the precipitation point of the wax is determined according to the change of the phase state of the system. A new predictive model for wax deposition incorporating diffusion, shear deposition, and the effects of ageing and stripping was developed by writing a program based on Fick's diffusion theory. Finally, wax deposition simulations of example wells were carried out to analyse wellbore wax deposition, production, water content, production time, and dissolved oil-to--to-gas ratio sensitive parameters to summarise the main factors affecting wax deposition and to draw the following conclusions.

(1) The above simulation study curves show that the wax formation prediction model proposed in this paper can better match the actual wax deposition in the wellbore, and the wax formation thickness varies along the wellhead downwards, increasing first and then decreasing, with a convex distribution, and the thickest point of wax formation is near 800m.

(2) Using this wax deposition model, sensitivity analyses were obtained for each of the four variables: fluid production, dissolved oil -to-gas ratio, water content, and production time. As the production time increases, the wax thickness increases; as the water content and fluid production

increase, the wax thickness decreases and the depth of the wax point becomes shallower; and the variable dissolved oil to gas ratio has little effect on wellbore wax formation.

(3) The above calculations show that this new model is not only able to predict the depth of wax formation and the thickness profile of wax formation in the wellbore, but also to determine the period of wax cleaning and prevention. Therefore, the model can provide more accurate data for wax cleaning and prevention operations, preventing excessive wax build-up that can prevent production and thus affect oilfield production operations.

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