Wellbore Temperature-Pressure Coupling Model Under Deep-Water Gas Well Intervention Operation

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Abstract. The accurate forecast of wellbore temperature and pressure during intervention operations is critical to the long-term exploitation of deep-water oil and gas resources. A wellbore temperature prediction model was constructed in the seawater and formation sections based on Hasan and Kerber's gas-liquid two-phase flow heat transfer model and integrated with the features of intervention operations. Simultaneously, the heat exchange produced by the change in fluid flow rate caused by the tool placement was evaluated. The wellbore pressure prediction model is developed in the intervention tool and intervention operation sections, and the friction gradient is modified by introducing the intervention operation. The established temperature and pressure model is coupled and solved iteratively, and the disturbance law of the wellbore temperature and pressure field induced by the intervention operation is investigated. The results show that the pressure in the wellbore gradually decreases when the tool is removed; the temperature at the mudline of the wellbore with high gas production is higher, and the wellhead pressure is low; the tool size is weakly sensitive to the wellbore; and the wellbore temperature and pressure are weakly sensitive to the running speed. The aforesaid findings have some guiding relevance for the design of the intervention operation plan, as well as the prediction and prevention of hydrate in the wellbore during deep-water gas well cleaning and blowout.

Keywords. Deep water gas well, intervention operation, wellbore temperature and pressure model, disturbance law

1. Introduction

At a time when the focus of oil and gas resource development has shifted from land to ocean, and marine oil and gas resource exploration and development has shifted from shallow water to deep water, the efficient and stable exploitation of deep-sea oil and gas resources plays an important role in national energy use [1]. Deep-water oil and gas wells frequently require intervention operations during the production phase. Intervention operations are unexpected oil well operations that are undertaken in a timely manner owing to downhole problems or the necessity for well management, and are frequently

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performed with steel wire and coiled tubing. Because deep-water oil and gas wells are in a complex deep-water environment with low temperature and high pressure, the intervention tool's release will disrupt the original flow state and disturb the complex temperature and pressure (symbolized TP) environment in which the deep-water wellbore is located, making the TP in the wellbore more difficult to predict.

At present, the intervention operation model for deep-water oil and gas wells is lacking, and the quantitative characterization is difficult. The calculation and analysis of the TP fields of deep-water oil and gas wells mainly use the steady-state model, but the intervention operation is obviously a transient problem. Using the steady-state model or simplifying it to a quasi-transient model will generate large errors. Scholars at home and abroad have carried out extensive research on the coupled model of TP in deep-water oil and gas wells, but they have rarely considered transient flow factors such as formation inflow, wellbore flow law, heat transfer changes of intervention tools, and gradient changes in frictional resistance changes. Accurate understanding of the temperature, pressure and flow state of the wellbore under operation cannot establish a TP coupling model under intervention operation.

There are two temperature fields in the wellbore of deep-water oil and gas wells, one in the low temperature section of the riser and the other in the high temperature section of the formation section, and the two temperature fields and pressure fields influence each other. There are currently two calculation methods for the TP field calculation model: one is to consider the temperature field and the pressure field separately. When calculating the wellbore temperature field, the change of the pressure field is not considered, and the temperature field is also not considered when calculating the pressure field [2-4]. The second step is to take into account the static temperature field estimated based on the geothermal gradient when computing the wellbore pressure field [5].

In order to ensure the accuracy of the wellbore TP coupling prediction analysis of deep-water high temperature and high-pressure gas wells, this paper analyzes the seawater section and formation section of these wells. It then proposes the corresponding calculation model of temperature field and pressure field under intervention operation. Intervention operations change the fluid flow section of the wellbore, resulting in changes in flow rate, increased friction, and pressure gradient changes; the temperature is also redistributed with the change in flow rate. In addition, the heat transfer between the intervention operation tool itself and the wellbore fluid needs to be considered, and well clearance is established based on energy conservation. The fluid temperature model in the wellbore of the blowout operation is introduced, and the pressure gradient change caused by the change of the flow rate and the frictional resistance caused by the intervention operation is introduced, and the fluid pressure model of the wellbore of the well cleaning and blowout operation is established. The study on the evolution law of wellbore TP under intervention operations during deep-water well cleanout and blowout prevention was carried out, and the variation laws of wellbore TP fields under deep-water oil and gas well intervention operations were analyzed as a guide, using the wellbore parameters of a well in the South China Sea as an example.

2. TP Coupling Model for Deep-Water Gas Well Intervention

The heat transfer of the wellbore is split into two categories based on the deep-water gas well’s structure: the heat transfer between the wellbore and the formation and the heat transfer between the wellbore and seawater. The heat transmission within the wellbore
is considered steady, but the heat transfer outside of the wellbore is considered unstable. There are three different ways to transmit heat to the surrounding formation when fluid moves through the wellbore due to the temperature differences between the gas, the surrounding formation, and the marine environment. There are three types of heat transfer: conduction, radiation, and convection. When objects of different temperatures come in direct and intimate contact, phenomenon known as heat conduction occurs in which heat is transported from the high temperature region of the material through the thermal motion of molecules, atoms, and free electrons inside the material. The phenomenon of solid surface to low temperature part. Convective heat transfer refers to the heat transfer process that occurs when a fluid is in contact with solid surfaces of different temperatures. The surface of an object can transfer heat through photons, and all objects have the ability to absorb radiant energy and emit radiant energy. When the heat received by the heat of the high-temperature object is less than the heat output, or the heat output of the low-temperature object is less than the heat received, this radiative heat transfer process relying on temperature difference is radiative heat exchange.

The blowout stage of deep-water gas wells is a typical unsteady flow stage. Under the action of pressure difference, high-temperature fluid enters the bottom of the well from the formation and then migrates to the surface along the wellbore. The biggest difference from land gas wells is that the fluid in the wellbore is above the mudline. It is mainly affected by the external seawater environment, and the wellbore fluid below the mudline is mainly affected by formation factors. The structure of deep-water gas wells is shown in Figure 1. As shown in Figure 1b, the fluid heat in the seawater section of deep-water gas wells is transferred into the oil casing annulus through the tubing, and is transferred to the seawater through the outer casing, insulation layer, and riser casing. As shown in the sectional view of the formation section in Figure 1c, the fluid heat in the wellbore of the formation section of the deep-water gas well is transferred to the oil casing annulus through the tubing, and then transferred to the formation through the cement loop.

The unsteady heat transfer model of the saltwater section above the mudline and the formation section below the mudline is created using the fluid micro-element with length $\Delta z$ as the study object. The fluid element’s energy change is equal to the energy difference between the system’s entering and exiting energy.

![Figure 1. Bore structure of deep-water gas well.](image-url)
In the equation, \( dQ \) is the change of the energy of the micro-element; \( H(z + \Delta z) \) and \( H(z) \) are the enthalpy of the fluid; \( \frac{1}{2} mv^2(z + \Delta z) \) and \( \frac{1}{2} mv^2(z) \) are the kinetic energy term of the fluid; \( mgz \) and \( mg(z + \Delta z \sin \theta) \) are the positional potential energy of the fluid in the wellbore. The fluid in the wellbore's transient heat transfer model may be produced by expressing the aforementioned equation in differential form:

\[
\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{\partial T}{\partial z}
\]

(2)

In this paper, the transient heat transfer model is used for dimensionless solution in Laplace space, and the calculation flow of the formation heat transfer model is given. Only the radial heat transfer process experiences heat loss due to the uneven heat transmission from the fluid in the wellbore to the formation. Therefore, the wellbore to wellbore heat transfer equation is:

\[
\frac{dQ}{dz} = -\frac{2\pi \rho \alpha_{tot}}{W} (T_f - T_{wb})
\]

(3)

The formula for the transport of heat from the wellbore to the formation is:

\[
\frac{dQ}{dz} = -\frac{2\pi k_e}{W T_D} (T_{wb} - T_e)
\]

(4)

The calculation equation of wellbore temperature change is:

\[
\frac{dT}{dz} = \frac{1}{c_{pm}} \frac{dh}{dz} + C_j \frac{dP}{dz}
\]

(5)

In the equation, \( r_{to} \) is the outer radius of the pipe string, m; \( U_{tot} \) is the total heat transfer function of the formation section, W/(m²·°C); \( W \) is the fluid mass flow rate, kg/s; \( k_e \) is the formation heat transfer coefficient, W/(m·°C); \( T_e \) is the formation temperature, °C; \( T_f \) is the fluid temperature, °C; \( T_{wb} \) is the wellbore temperature, °C; \( T_D \) is the formation transient heat transfer function. \( c_{pm} \) is the specific heat capacity of fluid at constant pressure, J/(kg·°C); \( C_j \) is the Joule-Thompson coefficient, °C/Pa. The formation temperature can be calculated by equation (6):

\[
T_{out} = T_h - g_T z
\]

(6)

where \( T_{out} \) is the fluid temperature at the outlet of the micro-element section \( \Delta z, °C \); \( c_{pm} \) is the constant pressure specific heat capacity of the fluid, J/(kg·°C); \( W \) is the fluid mass flow rate, kg/s; \( k_e \) is the formation heat transfer coefficient, W/(m²·°C); \( r_{to} \) is the outer radius of the tubing, m; \( U_{tot} \) is the total heat transfer coefficient of the formation section, W/(m²·°C); \( g \) is the acceleration of gravity, m/s²; \( C_j \) is the Joule-Thompson coefficient; \( v \) is the The lowering speed of the intervention operation, m/s; \( T_{in} \) is the temperature of the wellbore fluid at the entrance, °C; \( T_{ein} \) is the formation temperature at the
entrance, °C. \( T_b \) is the initial formation temperature at the bottom of the well, °C; \( \theta_T \) is the geothermal gradient, °C/m; \( z \) is the vertical height from the bottom of the well, m.

The temperature model of the fluid in the wellbore above the mudline is derived in the same way as the temperature model of the fluid in the wellbore below the mudline. The temperature of the fluid in the wellbore, as well as the heat transfer equation from the fluid to the wellbore, are as follows:

\[
\frac{dQ}{dz} = - \frac{2\pi r_o u_{toz}}{W} (T_f - T_{sea}) \tag{7}
\]

Adding the temperature change equation in the wellbore to the energy conservation equation is:

\[
\frac{dT}{dz} = \frac{(T_{sea} - T_f)(2\pi r_{toz}u_{toz})}{C_{pm}W} \frac{gsin\theta}{C_{pm}} + \frac{C_v}{C_{pm}} \frac{dP}{dz} \frac{vdv}{C_{pm}dz} \tag{8}
\]

where, \( r_{to} \) is the outer radius of the riser, m; \( U_{toz} \) is the total heat transfer coefficient of the seawater section, W/(m²·°C); the seawater temperature model \( T_{sea} \) is calculated using the Levitus statistical model of the world ocean temperature data.

Multiple factors have been demonstrated in the laboratory and in the field to control the change of TP profile in the wellbore of high temperature and high-pressure gas wells. [6-10]. Before the well cleaning and blowout, the inside of the wellbore is a static gas column and a static liquid column, and the fluid temperature is roughly the same as the ambient temperature. The fluid at the bottom of the well flows out with the fluid at the wellhead during the well clearance and blowout, and the fluid in the wellbore is a gas-liquid two-phase mass flow. Heat is released, and the fluid in the wellbore continues to flow steadily for some time [11-12]. Based on the aforementioned phenomenon, the following two-phase transient pressure calculation equation is constructed during the tool running process during well clearance and blowout:

\[
\frac{dP}{dz} = \rho_{cen}gsin\theta + \frac{f_{cen}v_g^2\rho_{cen}}{2d} + \rho_{cen}v_g \frac{dv_g}{dz} \tag{9}
\]

where \( v_g \) can be calculated as:

\[
v_g = C_g v_m + v_{rg} \tag{10}
\]

where \( C_g \) is the gas distribution coefficient; \( d \) is the inner diameter of the tubing, m; \( v_g \) is the gas velocity; \( \rho_{cen} \) is the fluid density at the center of the string, kg/m³; \( v_{rg} \) is the gas slip velocity, m/s. According to equation (10), the intervention tool alters the fluid flow section in the wellbore, resulting in inconsistent fluid flow rates in the intervention tool’s upper and lower sections. When the drilling tool is lowered and pulled out, the flow rate of the fluid in the wellbore changes. When the intervention tool is simplified as a pipe string of a specific size, the change in fluid flow rate in the wellbore with the speed of the dropping tool is as follows:

\[
v''_g = \frac{W_{d} v_g + v_{pm} (\frac{d}{2})^2}{2[(\frac{d}{2})^2 - (\frac{d}{2})^2]} \tag{11}
\]
When the intervention job tool is stopped, \( v_{sp} = 0 \). Where \( v_{sp} \) is the running speed of the tool, m/s; \( d \) is the inner diameter of the tubing, m; \( d_j \) is the diameter of the intervention tool, m. Therefore, the pressure on the working section of the intervention operation can be calculated according to the following equation:

\[
\frac{dP}{dx} = \rho_{cen}gsin\theta + \frac{f_{cen}v^2\rho_{cen}}{2d} + \frac{f_{cen}v^2\rho_{cen}}{2d_j}
\]  \( \text{(12)} \)

The down pressure of the intervention tool section can be calculated according to the following equation:

\[
\frac{dP}{dx} = \rho_{cen}gsin\theta + \frac{f_{cen}v^2\rho_{cen}}{2d}
\]  \( \text{(13)} \)

Considering that the intervention tool will affect the flow velocity in the wellbore, the friction gradient in the wellbore will be changed. According to Ning’s model, the friction coefficient of the pipeline is modified, and the modified friction coefficient is as follows:

\[
f_{cen} = 4.5 \cdot \left( \frac{\varepsilon}{3.7065d} \right) \]  \( \text{(14)} \)

\[
Re_m = \frac{\mu_m v_m d}{\mu_m}
\]  \( \text{(15)} \)

\[
\Lambda = \frac{\varepsilon^{1.1098}}{2.8257d^{1.1098}} + \left( \frac{7.149}{Re_m} \right)^{0.0981}
\]  \( \text{(16)} \)

where \( \varepsilon \) is the roughness of the pipe wall; \( Re_m \) is the dimensionless Reynolds number; \( \mu_m \) is the gas-liquid mixing viscosity, mPa·s; \( \rho_m \) is the gas mixing density, kg/m³. The density and viscosity of the mixture can be corrected by Lee et al. and Rendeiro et al. The mixture viscosity and density correction are calculated as follows:

\[
\mu_m = 10^{-4} K \exp(X \rho_m^{0.5})
\]  \( \text{(17)} \)

\[
\rho_m = \frac{28.96\rho_m p}{Z_m R T}
\]  \( \text{(18)} \)

\[
\gamma_m = \frac{\gamma_g \rho_g^{0.5} \gamma_f}{GLR}
\]  \( \text{(19)} \)

where \( \mu_m \) is the viscosity, mPa·s; \( \rho_m \) is the gas-liquid mixing density, kg/m³; GLR is the gas-liquid ratio, m³/m³; \( Z_m \) is the mixture deviation coefficient; \( R \) is the gas constant, taking the value 8.315, Pa·m³·kmol⁻¹·K⁻¹; \( T \) is the fluid temperature, K; \( \gamma_m \) is the relative density of the mixture; \( \gamma_g \) is the relative density of the gas phase; \( \gamma_f \) is the relative density of the liquid phase; \( M_g \) is the relative molecular mass of the mixed gas; \( X \) is the intermediate coefficient, \( X = 3.448 + 548 + 0.01M_g \); \( Y \) is the intermediate coefficient, \( Y = 2.447 - 0.224X \); \( p \) is the wellbore pressure, MPa; the deviation coefficient \( Z_m \) of
the mixture can be calculated iteratively using the relational equation of Dranchuk-Abou-Kassem [13].

\[
Z_m = 1 + \left( A_1 + \frac{A_1}{T_{pr}} + \frac{A_2}{T_{pr}^2} + \frac{A_3}{T_{pr}^3} + \frac{A_4}{T_{pr}^4} \right) \rho_{pr} + \left( A_6 + \frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2} \rho_{pr} \right) \rho_{pr}^2
- A_9 \left( \frac{A_{10}}{T_{pr}} + \frac{A_{10}}{T_{pr}^2} \rho_{pr} \right) \rho_{pr}^5 + A_{10} \left( 1 + A_{11} \rho_{pr}^2 \right) \text{exp} \left( -A_{13} \rho_{pr}^2 \right)
\]  

(20)

where \( A_1 - A_{11} \) is the model coefficient, \( \rho_{pr} \) is the pseudo-contrast pressure; \( T_{pr} \) is the pseudo-contrast temperature.

3. Analysis

Referring to the parameters of a deep-water gas well in the South China Sea, the water depth of the well is about 1830 m, the formation pressure is about 29 MPa, and the temperature gradient is 2.16℃/100 m. The main body adopts 114.3 mm tubing, that is, the inner diameter of the tubing is 85.7 mm, and the outer diameter of the tubing is 114.3 mm. The thermal conductivity of the formation takes the typical value of 3.12 W/(m·℃), the thermal conductivity of the oil pipe takes the typical value of 40 W/(m·℃), the thermal conductivity of the casing takes the typical value of 35 W/(m·℃), and the thermal conductivity of the cement sheath the typical value is 0.8 W/(m·°C), the total heat transfer coefficient of seawater is 18 W/(m·°C), and the total heat transfer coefficient of formation is 15 W/(m·℃).

To solve the above-mentioned wellbore TP coupling prediction model of intervention operation during deep-water gas well cleanup and blowout, and to perform the wellbore TP coupling prediction analysis for the factors of running depth, wellbore production, intervention tool diameter, and intervention tool running speed. The wellbore TP prediction program of the intervention operation during the cleanup and blowout period of the deep-water gas well was used to simulate the wellbore TP under different production rates, running speeds, and tool diameters.

The wellbore production is adjusted for production increase and production. The schematic diagram is shown in Figure 2. The TP changes in the wellbore when the production changes from \( Q_1 \) to \( Q_2 \), and the impact of production changes on the wellbore TP under intervention operations is analyzed.

The daily gas production of the wellbore is a significant factor that influences the variation of the wellbore TP field, and the wellbore TP field varies greatly depending on the production rate. As shown in Figure 3, the diameter of the running tool is set to 1% and 25%, and the running speed is set to 0.5 m/s. The wellbore TP data with production rates of \( 20 \times 10^4 \) m³/d, \( 40 \times 10^4 \) m³/d, \( 60 \times 10^4 \) m³/d, and \( 80 \times 10^4 \) m³/d were selected to analyze the influence of production on the wellbore TP field under intervention operations. When gas production is high, the pressure in the wellbore above the mud line rises, and when gas production is low, the pressure in the wellbore falls. Under high gas production, the wellbore temperature near the line is higher at the inflection point. When wellbore production is low, the temperature at the mudline is low, and it is necessary to keep the hydrate from forming ice blockage, which disrupts normal production work.
The depth of penetration of the tool is an important parameter in intervention operations. During the intervention tool’s operation, the TP profile of the wellbore changes dramatically. The daily gas production of the well is 40104 m³/d, as shown in Figure 4, and the tool running speed is 0.5 m/s. The predicted data of the wellbore TP are chosen accordingly. The TP data from the wellbore at 360 m, 720 m, 1080 m, 1440 m, 1800 m, 2160 m, 2520 m, and 2880 m were used to investigate the effect of the tool running depth on the TP field of the wellbore during the intervention operation. The temperature in the longitudinal section of the wellbore does not change significantly as the tool runs, the pressure in the wellbore gradually increases, the depth of the run increases, and the pressure in the wellbore gradually decreases. The TP in the wellbore increased the most at the initial stage of the intervention tool; when the intervention tool was run into the bottom of the well, the pressure difference between the bottom of the well and the wellhead was the lowest. The pressure change is caused by the lowering of the intervention tool, and the intervention operation is carried out when it is lowered to the corresponding position of the wellbore.

In the intervention operation, the diameter of the intervention tool is an important process parameter, and the intervention tools of different sizes have a great influence on the time of the well cleaning operation and the requirements of the surface equipment. The wellbore TP data with a daily gas production of 40×10⁴ m³/d and a running speed of 0.5 m/s are selected, and the wellbore TP data of 1%, 25%, 50%, and 75% of the tubing diameter of the running tool are selected respectively (Figure 5). The impact of tool diameter on the wellbore TP field during intervention operations was investigated. The smaller the size of the running tool, the smaller the pressure increase in the wellbore; as the working size of the running tool increases, so does the temperature of the wellbore. The temperature at the inflection point rises with the size of the running tool. The temperature in the wellbore at the mudline is more sensitive to changes in tool size. Big. The higher the mudline wellbore temperature and the faster the well cleaning, the larger the tool. Intervention tools with larger pipe diameters should be selected as far as possible to increase the well clearance speed and at the same time increase the temperature at the mudline to reduce the probability of ice blockage.
(a) Drop tool size 1% tubing diameter

(b) Drop tool size 25% tubing diameter

Figure 3. Wellbore TP profiles with different production rates.
The running speed of different tools has a great influence on the well clearing operation process. As shown in Figure 6, the wellbore’s daily gas production is $40 \times 10^4$ m$^3$/d, the running tool size is 25%, and the running speed is 0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s, and 0.9 m/s. The influence of tool running speed on the wellbore TP field during intervention operations is investigated using wellbore TP data. Under different tool running speeds, there is no discernible change in the TP in the wellbore. The wellbore TP are less sensitive to changes in tool speed and have little effect on hydrate formation.
in the wellbore. To ensure a normal well clearance operation, the running speed should be increased as much as possible to expedite the job.

Figure 5. Sectional view of wellbore TP with different tool diameters.
4. Conclusion

(1) By analyzing the wellbore structure of deepwater gas wells, considering the characteristics of intervention operations, combined with fluid heat conduction and convective heat transfer in the wellbore, a prediction model of the wellbore temperature field above and below the mud line is established, and a correction period for disturbance intervention operations is introduced. According to the actual process of the intervention operation, the fluid friction coefficient in the wellbore under the intervention operation is introduced, and the acceleration factors that cause the change of the fluid flow field are considered. The iterative method is used to solve the TP coupling model to realize the prediction of wellbore TP under intervention operation.

(2) The sensitivity analysis of the TP field of key parameters of the intervention operation was performed based on the established wellbore TP coupling prediction model during the intervention operation during deep-water gas well cleanup and blowout, combined with the intervention operation process. The pressure in the wellbore gradually increases as the tool runs deeper, the running depth increases, and the decreasing range in the wellbore increases; the temperature difference in the longitudinal section of the wellbore with different running depths is small. When gas production increases, the pressure drops in the wellbore above the mudline increase, and the pressure in the wellbore is smaller when gas production is high. When gas production increases, the temperature in the wellbore first decreases and then increases, and the temperature inflection point appears at the mudline. The temperature is higher nearby at the inflection point at high gas production. When the tool is lowered near the mudline, the closer the wellbore pressure is to the wellhead, the lower the pressure. The smaller the running tool size, the smaller the pressure drop in the wellbore; as the working size of the running tool increases, so does the temperature of the wellbore; as the size of the running tool...
increases, so does the temperature at the inflection point; and changing the tool size has a greater impact on the temperature in the wellbore at the mudline.

(3) The TP in the wellbore does not change significantly with different tool running speeds, and the TP in the wellbore is less sensitive to changes in tool running speed. The research on the coupled prediction model of wellbore TP during the intervention operation of deep-water gas wells lays the groundwork for future research on the influence of hydrate formation and hydrate risk prevention.

References