Simulation and application analysis of gravel packing in deepwater HT/HP wells

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Abstract
Gravel packing is one of the main sand control methods for deep-water high-temperature and high-pressure (HT/HP) reservoirs. According to the specific characteristics of deep-water HT/HP and multichannel, considering the influence of slurry flowing through long-distance multichannel and the slurry temperature alternation along the flow path, based on α-β wave packing theory, a coupling model of gravel packing in deep-water HT/HP horizontal wells is established. The packing simulation algorithm and calculation process are designed to realize the gravel packing temperature pressure simulation and multistage refined friction calculation of deep-water HT/HP horizontal wells. The influence of each packing parameter on the packing process is fully studied. Furthermore, the application simulation of the A10H well of the South China Sea deepwater HP well is carried out. The simulation results show that in the slurry injection stage and α wave packing stage, the packing pressure is low and the residual pressure window is large. In the β wave packing stage, the packing pressure increases rapidly, the residual pressure window shrinks rapidly, and finally, at the end of β wave packing, the residual pressure window becomes narrow. The viscosity of carrier fluid has a significant impact on the pressure window of packing operation. For the design pump rate of 5.6 bpm, the packing cannot be completed with 5.0 cp viscosity carrier fluid. For the carrier fluid with high viscosity, the multi-β wave packing technique of pump reduction control pressure at the end of the β wave packing stage is used, and this process is simulated in this paper. Considering three constraints: not sand packed in the drilling string, without premature bridging in the α wave packing stage, and α and β wave packing pressure control conditions, the safe range of pump rate is determined under different operation safety margin conditions, which can provide technical support for on-site operation.

KEYWORDS
deepwater, gravel pack, HT/HP formation, simulation
1 | INTRODUCTION

Although, openhole gravel packing is now viewed as a means of enhancing the reliability, efficiency, and longevity of horizontal sand control completions, there are still considerable risks in horizontal well gravel packing, especially in extreme cases such as long horizontal well and unconsolidated sandstone reservoir. It is mainly manifested as premature bridging in the openhole/screen annulus before the gravel packing reaches the toe of the horizontal well, resulting in the failure of the operation. This is mainly due to the long horizontal section requiring higher pump rates to transport gravel to the end of the wellbore, resulting in higher pump pressure. The formation with low fracture pressure is easy to be fractured, resulting in the loss of carrier fluid to the formation. If the pump rate is low and the gravel transport is not efficient, a premature bridge can occur. Both of these conditions can lead to premature plug and pack failure, which can make the packing process very complicated and difficult to control.

In extreme situations, such as significant temperature variation of the deep water reservoir (low temperature near the mud line → HT in a deep reservoir), low fracture pressure at high-pressure (HP) formation, and medium and high permeability, gravel packing operation faces extremely high operational risks and key technical difficulties. Mainly because high porosity and high permeability lead to large sand production, and low fracture pressure at HP formation leads to narrow operation windows. The significant temperature change phenomenon leads to significant changes in the physical properties of carrier fluid, resulting in drastic changes in packing friction and packing pressure. So how to overcome the operation contradiction of gravel packing in deepwater horizontal wells and achieve high quality and effective packing has become a key technical problem for effective offshore oil and gas development. According to the specific characteristics of deepwater high-temperature and high-pressure (HT/HP) and multichannel, a gravel packing coupling model for deepwater HT/HP horizontal well based on the α-β wave packing theory is established, the influence of slurry flowing through long and multichannel and temperature alternation along flow path are considered. The packing simulation algorithm and calculation process are designed to realize the temperature–pressure simulation and multistage fine friction calculation of gravel packing in deepwater HT/HP horizontal Wells. Through the simulation calculation, the influence of each packing parameter on the packing process is fully studied. Furthermore, the application simulation is carried out for the South China Sea deepwater HP well A10H well, which verifies the accuracy of the simulation results and can effectively guide the gravel packing operation of deepwater HT/HP horizontal wells.

2 | A MULTIFIELD COUPLED GRAVEL PACK MODEL FOR DEEPWATER HT/HP HORIZONTAL WELLS

2.1 | Calculation model of slurry flow along the flow path

In the process of deepwater gravel packing, the slurry is injected into the string from the wellhead, through the seawater section, and reaches the mud line in a process of gradual cooling. After passing the mud line, the surrounding environment gradually warms up until it reaches the HT reservoir. The slurry begins to cool down gradually in the string. After reaching the mud line, the temperature of the external environment heats up the slurry in the string gradually. After reaching the downhole cross-tool, the slurry enters the wellbore annulus to carry out open-hole gravel packing. The carrier fluid enters the washpipe through the heating of the lower formation and returns through the seawater section. In the process of injection of slurry, the heat exchange with seawater cools down at first and then heats up in the formation. In this regard, the basic theory of heat transfer should be combined with the actual drilling and completion operations to study. First, according to the physical background of the actual problem, the physical process of the problem is defined, and then the mathematical model of the problem. For specific problems, it is necessary to combine other specific conditions to solve the established mathematical model.

Hypothesis: (1) Considering only heat conduction in seawater and formation, without considering heat source; (2) The density, specific heat, and thermal conductivity of seawater do not vary with temperature and are isotropic; (3) The carrier fluid is incompressible, and the thermal conductivity and specific heat capacity are independent of temperature; (4) Seawater temperature is not affected by the heat transfer process in the wellbore, and always maintains a constant temperature distribution.

2.1.1 | The calculation model of the slurry temperature in pipe string during injection

\[
Q_c - \rho_i q C_i \frac{\partial T_c}{\partial z} - 2\pi r_{cl} h_c \left( T_c - T_w \right) = \rho_i C_i r_{cl}^2 \frac{\partial T_c}{\partial t},
\]

where \( \rho_i \) is the fluid density (kg/m\(^3\)); \( q \) is pump rate (m\(^3\)/s); \( C_i \) is specific heat capacity (Cal/(kg·°C)); \( r_{cl} \) is pipe string inner radius (m); \( T_w \) and \( T_c \) are respectively
pipe string inner wall and liquid temperature (°C). \( Q_c \) is the power per unit length (W); \( h_{cw} \) is the convective heat transfer coefficient between pipe string inner wall and carrier fluid (W/(m²·°C)). \( z \) is the position along pipe string (m); \( t \) is the injection time (s).

2.1.2 | The temperature calculation model of horizontal open-hole section packing

During the packing process, the slurry flows in the annulus, and the heat entering the annulus from the outside includes the heat carried by the slurry flow into the annulus and the net heat transferred by radial convection through the openhole wall. Horizontal openhole packing temperature model\(^{18}\)

\[
\rho_l Q_c \frac{\partial T_{an}}{\partial z} + 2\pi r_w h_w \left( T_b - T_a \right) + 2\pi r_{co} h_{co} \left( T_{cw} - T_b \right) + Q_a = \rho_l C_l \pi \left( r_w^2 - r_{co}^2 \right) \frac{\partial T_{an}}{\partial t},
\]

where \( T_b, T_a, \) and \( T_{cw} \) are respectively annulus liquid temperature, bottom temperature, and washpipe wall temperature (°C); \( r_w \) and \( r_{co} \) are respectively openhole radius and washpipe outside radius (m); \( h_w \) and \( h_{co} \) are respectively convective heat transfer coefficient between openhole wall, washpipe wall and annulus fluid (W/(m²·°C)); \( Q_a \) is the power per unit length (W).

The above set of equations must be solved together with the initial and boundary equations. A finite difference scheme is used to solve the system of equations.

2.2 | The multistage friction calculation model for the packing process

2.2.1 | The calculation model for the carrier fluid viscosity

The HT/HP in deep water reservoirs have high requirements for carrier fluid, and the cross effects of temperature change on the rheological properties of carrier fluid and slurry during circulating flow, and the effects of flow friction and sand carrying performance are complex. For deepwater and deep formation with HT and HP, the carrier fluid and the slurry flow through long-distance and change from low temperature to HT. So the viscosity of the carrier fluid is characterized by obvious temperature variation. Through data fitting, the relationship between the viscosity change is

\[
\mu(t) = 0.001003e^{-0.04899t} + 0.0007912e^{-0.01068},
\]

where \( t \) is temperature along the flow path (°C).

2.2.2 | The calculation model of friction in different stages of the whole packing process\(^{19-22}\)

The whole packing process is divided into three stages: slurry injection stage, \( \alpha \) wave packing stage and \( \beta \) wave packing stage. According to their flow characteristics and momentum conservation equation in corresponding stages, the corresponding friction calculation model can be obtained.\(^{21-23}\)

The friction loss of slurry in pipe string

\[
\Delta P_{col.inj} = \frac{32\rho_l Q_a^2 L_{inj}(t)}{\pi^2 D_{int.col}^2} + \frac{32\rho_l Q_a^2 (L_{cs} - L_{inj}(t))}{\pi^2 D_{int.col}^2},
\]

where \( L_{inj}(t) \) is slurry flows through distance at \( t \) time (m); \( Q_p \) is the pump rate (m³/s); \( D_{int.col} \) is pipe string inner diameter (m); \( \Delta P_{col.inj} \) is the pressure drop on upper casing shoe at \( t \) time (Pa); \( \rho_{mix} \) and \( \rho_l \) are respectively the slurry density and carrier fluid density (kg/m³); \( L_{cs} \) is the casing shoe depth (m); \( f \) is the friction coefficient, dimensionless.

The calculation model of the friction in \( \alpha \) wave packing stage

\[
\Delta P_{oh.\alpha} = \frac{2\rho_{mix} Q_p^2 L_{\alpha}(t)}{A_{up}^2 D_{h.up}^2} + \frac{2\rho_l Q_a^2 (L_{oh} - L_{\alpha}(t))}{A_{an}^2 D_{h.an}^2},
\]

where \( L_{\alpha}(t) \) is the \( \alpha \) wave front distance at \( t \) time (m); \( C_{mix} \) is slurry concentration (kg/m³); \( A_{up} \) and \( A_{an} \) are respectively cross-sectional area above sand dune and the openhole/screen annulus area (m²); \( D_{h.up} \) and \( D_{h.an} \) are respectively the hydraulic diameter above sand dune and the openhole/screen annulus (m).

The calculation model of friction in \( \beta \) wave packing stage

\[
\Delta P_{oh.\beta} = \frac{2\rho_{mix} Q_p^2 (L_{oh} - L_{\beta}(t))}{A_{up}^2 D_{h.up}^2} + \frac{32\rho_l Q_a^2 L_{\beta}(t)}{\pi^2 \sqrt{2/3} \left( D_{int.scr}^2 - D_{ext.wp}^2 \right)^{5/2} \left( D_{int.scr}^2 - D_{ext.wp}^2 \right)},
\]

where \( \Delta P_{oh.\beta} \) is the pressure drop in the \( \beta \) wave packing stage (Pa); \( L_{\beta}(t) \) is the \( \beta \) wave packing front distance at
2.3 | The flow model for gravel packing

2.3.1 | The solid–liquid two-phase flow model of the slurry

In the gravel packing process, the carrier fluid and gravel maintain their respective mass conservation, their mass conservation equations are as follows:

The carrier fluid mass conservation equation

\[(1 - C_i)\rho q_i - (1 - C_s)\rho q_s - \rho q_{ip} - \rho q_{ls} = 0.\] (7)

The gravel mass conservation equation

\[C_i q_i - C_s q_s = 0,\] (8)

where \(q_i, q_s, q_{ip}, q_{ls}\) are respectively initial injection rate of slurry, slurry rate above sand dune, the rate of carrier fluid in the washpipe/screen annulus, and the rate of leakage to the formation (m³/s); \(C_i\) and \(C_s\) are respectively the volume concentration of the initial gravel injection and the volume concentration above the balanced dune (m³/m³); \(\mu\) is the viscosity of the carrier fluid (Pa·s).

2.3.2 | The sedimentation—suspension model of gravel particles

Gravel particles are accelerated at the beginning of the free settling process, and with the increase of settling velocity, the resistance increases gradually until the forces acting on the particles reach an equilibrium state, that is, \(\frac{du}{dt} = 0\), and then the velocity is

\[u_p = \left[\frac{4g(\rho_g - \rho)d_g}{3C_\delta\rho}\right]^{\frac{1}{2}},\] (9)

where \(u_p\) is the free settling velocity of gravel particles (m/s); \(d_g\) is gravel particle diameter (m); \(C_\delta\) is the resistance coefficient; \(\mu\) is fluid viscosity (Pa·s).

2.3.3 | The carrier fluid loss model

Assuming that the horizontal well is far away from the boundary or the surrounding injection wells and the fluid loss to the formation is stable seepage, the fluid loss rate to the formation can be expressed by the following equation:

\[q_{ls} = \frac{2\pi K_h h(P_w - P_e)}{\mu \ln \left[\frac{a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2}}{L/2} + \frac{\beta h}{L} \ln \left(\frac{\beta h}{2\nu}\right)\right]} \times 10^{-3},\] (10)

where \(K_h\) and \(K_v\) are respectively the formation horizontal and vertical permeability (µm²); \(h\) and \(L\) are respectively the formation thickness and the horizontal section length (m); \(P_w\) and \(P_e\) are respectively the wellbore pressure and boundary pressure (MPa); \(r_e\) and \(r_w\) are respectively the wellbore radius and boundary supply radius (m).

Combined with the temperature Equation (1)–(3), friction calculation model (4)–(6), and flow model (7)–(10), a multifield coupling model of gravel packing for deepwater HT/HP horizontal wells was established.

3 | COMPUTATIONAL PROCESS DESIGN FOR TEMPERATURE FIELD AND DIFFERENT STAGES OF FRICTION FOR GRAVEL PACKING IN DEEPWATER HT/HP RESERVOIRS

According to the \(\alpha–\beta\) wave packing theory, the packing calculation method and process are realized. The overall calculation process is as follows.

As shown in Figure 1, the simulation process can be divided into six steps:

(1) Given well structure parameter, and size parameters of washpipe, screen system.
(2) Select carrier fluid (density and viscosity) and gravel parameters, and specific pump rate.
(3) According to the governing equation of temperature variation, the temperature distribution of carrier fluid in the seawater section and horizontal packing section during the packing process is calculated.
(4) According to the temperature distribution data, the physical parameters of carrier fluid under corresponding conditions were calculated.
(5) The horizontal packing section is discreted, according to the critical balance flow velocity model, and the packing calculation is carried out step by step.
The annular cross-sectional area and packing friction were obtained, and the packing pressure was calculated according to the accumulation of each section's friction.

(6) According to the critical equilibrium velocity model, the equilibrium velocity and the height of the upper sand bed are calculated.

Using the above model, combined with the calculation method and process, the corresponding computer simulation software is compiled. Combined with specific reservoir and well data, the simulation is performed.

### 4 | FIELD CASE AND NUMERICAL SIMULATION

#### 4.1 | Overview of LS 25-1 gas field

LS 25-1 gas field is mainly composed of medium pore and medium permeability reservoirs, with a small number of medium pore and low permeability reservoirs locally. The water depth is ~850–990 m. The porosity is ~13.1%–24.2%, and the permeability is ~4.3–154.4 mD. The lithology is mainly of medium and fine sandstone. The median grain size of II_lower gas group is ~58.96–83.24 μm, the uniformity coefficient is ~12.19–21.85, and the sorting coefficient is ~49.24–92.29. The median grain size of III gas group is ~39.02–52.18 μm, the uniformity coefficient is ~14.55–17.23, and the sorting coefficient is ~48.04–184.74. According to the reservoir characteristics, the gravel packing sand control method is adopted as the main completion.

#### 4.2 | Basic data and packing simulation parameters of well A10H

A10H is located in the IV gas group of LS 25-1, a HP formation with reservoir pressure of 60.43 MPa, fracturing pressure of 70.04 MPa, and a feasible pressure window of 9.61 MPa. The basic data and packing simulation parameters of well A10H are shown in Tables 1 and 2. The well body and pressure profile are shown in Figure 2.
4.3 The gravel packing simulation results for A10H

Based on the above data, the basic packing simulation results of well A10H are shown in Table 3.

4.3.1 The simulation results of the slurry temperature with well displacement under different pump rate

As the slurry is injected from the wellhead string, the temperature decreases with water depth. After entering the formation, the temperature still has a cooling process in the shallow layer at 1500 m, and the temperature increases rapidly after 1500 m. At different pump rates, 4.5–7.0 bpm were used to simulate the change of carrier fluid temperature with well depth. As can be seen from Figure 3, in the cooling stage (<1500 m), the smaller the pump rate, the lower the temperature; the heating stage (>1500 m), the opposite is true.

4.3.2 The pressure simulation calculation results of the A10H packing process

Figure 4 shows the wellhead pressure over time with conventional (2.2 sg) gravel packing. During the slurry injection stage (0–63.11 min), where slurry displacement the original fluid in the wellbore, due to the density difference between the two fluids, the pack pressure decreased slightly during this stage, lowering wellhead pump pressure from 749 to 582.08 psi. When the slurry enters the wellbore annulus, part of the gravel will be deposited and form a sand dune due to the increase of the cross-section flow area. At this time, it is the α wave packing stage (63.11–136.83 min). At this stage, the pressure is relatively stable and wellhead pump pressure slowly increased from 582.08 to 593.44 psi. Within the parameters of the design, if the sand bed height meets the upper limit during the α wave packing stage, once the α wave packing reaches the toe of the wellbore successfully, the β wave packing stage begins immediately (136.83–184.44 min). As while, the packing pressure increases rapidly, and the wellhead pump pressure increases rapidly from 593.44 to 900 psi. For well A10H, the packing pressure did not exceed the fracture pressure during the whole packing process.

4.3.3 The analysis of the effect of viscosity of the carrying fluid on packing pressure

Three kinds of carrier fluid with a viscosity of 1.0, 2.0, and 5.0 cp were selected for simulation calculation to analyze the influence of carrier fluid viscosity on the packing operation pressure window. Figure 5 shows the residual pressure window for the viscosity of 1.0, 2.0, and 5.0 cp, respectively.

According to the results in Figure 5, when the viscosity of carrier fluid was 1.0, 2.0, and 5.0 cp, respectively, the residual pressure windows between the bottomhole packing pressure and formation fracture pressure at the end of packing were 230.1, 118.9, and 37.29 psi. The results show that the residual pressure window of the HP well A10H is narrower, and the risk of fracturing formation is high during the packing process. Multiple β wave packing techniques can be used. The basic principle is as follows: (1) After the completion of the α wave packing, the packing pressure increases rapidly in the β wave stage. When packing pressure is about to approach the formation fracture pressure, the pump rate is reduced to reduce the packing pressure.

| **TABLE 1** Basic data for well A10H |
|-----------------|-----------------|-----------------|
| **Parameter**   | **Value**       |
| Well depth (m)  | 4664.4          | Fracture pressure gradient (MPa) 1.75 |
| Vertical depth (m) | 4002.2          | Pore pressure (MPa) 60.43 |
| Water depth (m) | 890             | Fracture pressure (MPa) 70.04 |
| Horizontal section length (m) | 362.8          | Formation temperature (°C) 137.3 |
| Screen ID (mm)  | 111.96          | Pressure coefficient 1.51 |
| Washpipe OD (mm) | 88.9           | Loss-off ratio (%) 5 |
| Washpipe ID (mm) | 75.9           | |

| **TABLE 2** Packing simulation parameters for well A10H |
|-----------------|-----------------|-----------------|
| **Parameter**   | **Value**       |
| Initial design pump rate (bpm) | 5.6             |
| Sand ratio (ppg) | 0.5             |
| Gravel diameter (mm) | 0.334 (40–60 mesh) |
| Carrier fluid density (kg/m³) | 1600            |
| Gravel volume density (kg/m³) | 1260            |
| Apparent density of gravel (kg/m³) | 2260           |
With the decrease of pump rate, the equilibrium state of the original $\alpha$ wave sand bed is broken, and a new $\alpha$ wave reconstruction is formed in the upper part of the $\alpha$ wave sand bed; (3) After the new $\alpha$ wave sand bed is rebalanced, the $\beta$ wave reverse packing is started.

(4) When the new $\beta$ wave reverse packing pressure approaches the formation fracture pressure again, the process of (1)–(3) discharge control is repeated.

Figure 6 shows the results of multiple $\beta$ wave packing for AH10.

Figure 6 shows that if the viscosity of the carrier fluid is 5 cp, the entire pack can be completed with only one rate reduction in the late $\beta$ wave packing stage. And if the viscosity of carrier fluid is increased to 10 cp, three rate reductions are required. Further study is needed on the mechanism of viscosity increase and drag reduction.

### 4.3.4 The results of safe interval simulation analysis of pump rate

To effectively design the pump rate of packing operation, for A10H HP well, the comprehensive consideration is the following three points, not sand packed in the drilling string, without premature bridging during $\alpha$ wave packing stage, and $\alpha$ and $\beta$ wave packing pressure control conditions (< formation fracture pressure). The safe range of gravel packing pump rate in deepwater HT/HP is
further studied. For the selected gravel (the density of 2.2 sg) and carrier fluid (the density of 1.6 sg), the analysis results of the safe interval of pump rate in A10H HP well under different safety allowances are given.

(1) Without considering the operation safety margin, Figure 7 presents the analysis curve of the safe interval of the pump rate. The simulation results show that the safe interval of the pump rate is 3.25–6.5 bpm.

(2) Consider the operation safety margin of 50 psi. Simulation results show that the safe range of pump rate is 3.25–6.25 bpm. Compared with the case without considering the safety margin, the pump rate range is narrowed and the upper rate limit is reduced by 0.25 bpm.

(3) In the case that the operation safety margin is set to 100 psi and other conditions are the same as above, simulation calculation results show that the safe interval of the pump rate is 3.25–6.0 bpm. Compared with the case without a safety margin, the pump rate range is narrower and the upper rate limit is reduced by 0.5 bpm, as shown in Figure 7.

From the calculation results of the above three cases, it can be seen that because the safety margin of formation fracture pressure is set, the upper limit of pump rate is lower. At the same time, because the lower limit of pump rate is unchanged, the safe pump rate range is narrowed.

5 | CONCLUSIONS

(1) For the characteristics of deepwater HT/HP reservoir, considering the influence of slurry temperature alternation along the long-distance and multichannel flow path, a gravel packing coupling model of deepwater HT/HP horizontal well was established based on the $\alpha$–$\beta$ wave packing theory.

(2) The gravel packing temperature-pressure simulation and multistage fine friction calculation of deepwater HT/HP horizontal well were studied, and the packing parameters were analyzed and evaluated.

(3) For the A10H HT/HP well of LS 25-1 gas field, the simulation results in temperature and pressure and friction resistance, the influence of carrier fluid viscosity on packing operation pressure window, and the safe range of pump rate under different operation safety allowance conditions are determined.
The results can provide a theoretical basis for further field operation.

(4) The safe operation window of open-hole gravel packing for long horizontal wells in HT/HP reservoir is narrow. The feasibility of multiple $\beta$ wave packing in well A10H is simulated. Further study is needed on the mechanism of viscosity increase and drag reduction.

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