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Research Article

Analysis of Shunted Screen Gravel Pack Process and Calculation of Friction in Deepwater Horizontal Wells

Fei Xu,[1] Shengtian Zhou ,[2] Chong Zhang,[1] Yi Yu,[1] and Zhao Dong[1]

[1]*CNOOC China Limited, Zhanjiang Branch, Zhanjiang, Guangdong 524957, China*
[2]*China University of Petroleum, Qingdao, Shandong 266580, China*

Correspondence should be addressed to Shengtian Zhou; stzhou2008@163.com

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Shunted screen gravel packing is a kind of technology which is difficult to complete gravel packing with the conventional method in low fracture pressure formation and long wellbore length condition. According to the characteristics of LS 17-2 deepwater gas field, the shunted screen packing tool was designed and the gravel packing process and packing mechanism were analyzed. The variation law of the flow friction, flow rate distribution in multichannel, and other parameters of the shunted screen gravel packing were analyzed and calculated. The friction calculation model of different stages of gravel packing was established. A gravel packing simulation software was developed to simulate the friction in different stages of shunted screen gravel packing. The parameters such as sand-dune ratio, pumping sand amount, packing length, and packing time in the process of packing were also calculated. In deepwater horizontal well gravel packing, the results show that the friction ratio of the string is the largest in the stage of injection and α-wave packing. While the friction increases rapidly in the stage of β-wave packing because the carrier fluid needs to flow through the long and narrow washpipe/screen annulus. Particularly when the β-wave packing is near the beginning of the open hole, the packing pressure reaches the maximum. The calculated results are in good agreement with the measured results of the downhole pressure gauge. The model and software can provide technical support for the prediction and optimization of gravel packing parameters in the future.

1. Introduction

For offshore deepwater oil and gas reservoir development, in order to reduce the number of wells and obtain higher sand-free production, sand control measures need to be taken. Gravel packing is the most commonly used sand control technology in the oil and gas industry [1–3]. In a conventional gravel pack, gravel slurry is injected into the wellbore/screen annulus, where gravel is packed into the wellbore/screen annulus to control formation sand entry into the wellbore. Due to the leakage of carrier fluid into the formation or shunt into the washpipe/screen annulus, the cross-section flow rate of carrier fluid decreases gradually along the flow direction, thus reducing the sand-carrying capacity of carrier fluid. The gravel in the wellbore/screen annulus is often blocked in advance, resulting in the premature sand bridge in the wellbore/screen annulus, especially in the long wellbore or low fracture pressure formation. For these special cases, despite the use of low-density gravel, the addition of drag reducers to the carrier fluid, multiple α-wave or multiple β-wave packing, and other targeted countermeasures [4–7]. However, these methods can not ensure the success of gravel packing in some extreme cases. In the 1990s, shunted screen gravel packing was put forward [8], which was mainly used in casing gravel packing completion initially. With the extensive use of open hole completion gravel packing in offshore, gravel packing with shunted screen was gradually applied to open hole completion [9–22]. Although this technology is being used more and more widely, most of the field applications of this technology have not been specifically studied on the mechanism of shunted screen gravel packing. Particularly on the basis of this particular structural design, there is no quantitative description of the friction of each part of the shunted screen gravel packing. This paper mainly discusses the mechanism of shunted screen gravel packing, set up multichannel flow model, and friction calculation model for different flow stages. The corresponding software was developed to calculate flow parameters of the shunted screen multichannel and the friction calculation at the different stages. The calculated results are in good agreement with the data of LS 17-2 deepwater gas field in the South China Sea, which provides technical support for the design of shunted screen gravel packing in the future.

2. Gravel Packing Mechanism of Shunted Screen

The shunted screen pipe design is shown in Figure 1. Two types of tubes are welded outside the screen pipe in the wellbore/screen annulus, one is the transport tube and the other is the packing tube. The transport tube forms a continuous nonperforated pipe along the length of the screen pipe assembly. These transport tubes lead the slurry into the packing tube with the packing port through the multibranch pipe between each screen pipe joint, and then, the slurry flows to the wellbore/screen annulus through the packing tube. Both the transport tube and the packing tube are rectangular in cross section. Compared with the packing tube, the transport tube usually has a larger flow cross-section area. The cross section of the shunted screen pipe is shown in Figure 2.

The present design includes three transport tubes and two packing tubes, which are distributed in the wellbore/screen annulus as shown in Figure 2.

In the process of gravel packing, due to the loss of carrier fluid to the formation or flowing to the washpipe/screen annulus, the sand-carrying capacity of carrier fluid decreases, the gravel concentration in the wellbore/screen annulus increases, and a large amount of gravel will deposit in this annulus. At this time, the wellbore/screen annulus may be blocked, forming a sand bridge. So the flow resistance in the wellbore/screen annulus will increase, and the slurry will be then led along the lower resistance channel into the shunted screen, across the blockage, and into the annulus behind the sand bridge to continue packing, as shown in Figure 3.

3. The Establishment of Multichannel Mathematical Model

Consider shunt system, it is a multichannel flow path system. The slurry into the wellbore/screen annulus from a crossover tool located in the beginning of the open hole flow along the wellbore/screen annulus. Carrier fluid may leak off into formation, and it also diverts through the screen into the washpipe/screen annulus. Once the blockage occurs in the wellbore/screen annulus, there is increased flow resistance. Meanwhile, the slurry will pass through the transport tube, enter the packing tube at the joint, and pack behind the plugging point. Suppose Q_p, Q_w, and Q_s are the wellbore/screen annulus flow rate, the washpipe/screen annulus flow rate, and the transport pipe flow rate, respectively, m^3/s. Q_{pw}, Q_{pr}, and Q_{ps} represent the flow rate per unit length of the wellbore annulus through the screen to the washpipe/screen annulus, the leakage rate per unit length into the formation and into transport pipe flow rate, respectively, m^2/s. P_p, P_w, P_s, and P_r, respectively, represent the wellbore/screen annulus pressure, washpipe/screen annulus pressure, transport tube pressure, and reservoir pressure, Pa. There are the following conservation equations [15].

Figure 1: Shunted screen structure diagram.

3.1. Mass Conservation Equation of Carrier Fluid.

$$\begin{cases} \dfrac{\partial Q_p}{\partial x} + Q_{pw} + Q_{ps} + Q_{pr} = 0, \\ \dfrac{\partial Q_w}{\partial x} - Q_{pw} = 0, \\ \dfrac{\partial Q_s}{\partial x} - Q_{ps} = 0, \end{cases} \tag{1}$$

where Q_{pw}, Q_{pr}, and Q_{ps} are functions of pressure difference of each flow channel, respectively, which can be expressed as

$$\begin{cases} Q_{pw} = f_{pw}\left(P_p - P_w\right), \\ Q_{ps} = f_{ps}\left(P_p - P_s\right), \\ Q_{pr} = f_{pr}\left(P_p - P_r\right), \end{cases} \tag{2}$$

where f_{pw}, f_{ps}, and f_{pr} are the specific functional relationship between flow rate and pressure difference.

3.2. Mass Conservation Equation of Gravel.

$$\begin{cases} \dfrac{\partial\left(Q_p c_p\right)}{\partial x} + \dfrac{\partial\left(A_p c_p\right)}{\partial t} + Q_{ps} c_{ps} = 0, \\ \dfrac{\partial\left(Q_s c_s\right)}{\partial x} + \dfrac{\partial\left(A_s c_s\right)}{\partial t} - Q_{ps} c_{ps} = 0, \end{cases} \tag{3}$$

where A_p and A_s are the cross-sectional areas of the wellbore/screen annulus and the transport tube, m^2; c_p and c_s are the gravel concentration in the wellbore/screen annulus and the transport tube, respectively, dimensionless; and c_{ps}

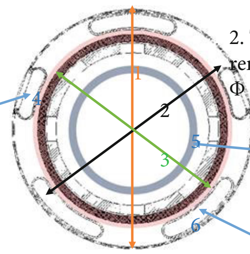


FIGURE 2: Shunted screen cross section.

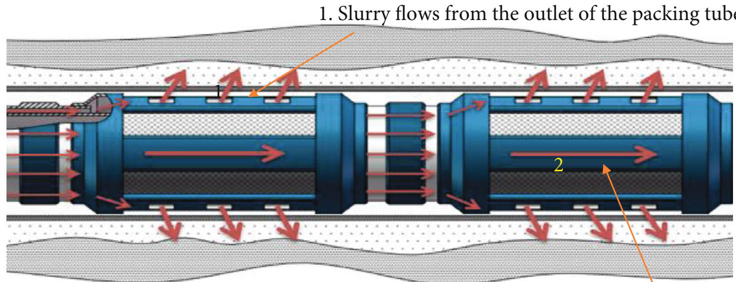


FIGURE 3: Principle of alternate path screen flow passage.

is the gravel concentration from the wellbore/screen annulus into the transport tube, dimensionless.

3.3. Momentum Conservation Equation.

$$\begin{cases} \rho_p \dfrac{Q_p}{A_p} \dfrac{\partial}{\partial x}\left(\dfrac{Q_p}{A_p}\right) = -\dfrac{\partial P_p}{\partial x} - F_p(Q_p), \\ \rho_w \dfrac{Q_w}{A_w} \dfrac{\partial}{\partial x}\left(\dfrac{Q_w}{A_w}\right) = -\dfrac{\partial P_w}{\partial x} - F_w(Q_w), \\ \rho_s \dfrac{Q_s}{A_s} \dfrac{\partial}{\partial x}\left(\dfrac{Q_s}{A_s}\right) = -\dfrac{\partial P_s}{\partial x} - F_s(Q_s). \end{cases} \tag{4}$$

Once the specific relationship between Q_{pw}, Q_{pr}, and Q_{ps} and pressure difference in (2) and the relationship between $F_p(Q_p)$, $F_w(Q_w)$, and $F_s(Q_s)$ and respective flow rate in (4) are determined, the equations composed of (1) and (4) can solve P_p, P_w, P_s, Q_p, Q_w, and Q_s and then substitute them into (3) to calculate the gravel concentration in the wellbore/screen annulus and transport tube.

During the gravel packing process of the shunted pipe, the slurry is transported from top to bottom along the wellbore, and the flow rate is related to the friction resistance. Therefore, the smaller the cross-sectional area, the less the flow rate. Whether the packing tube transmits the slurry is automatically adjusted according to the flow resistance. When the flow resistance in the wellbore/screen annulus is small, the packing tube does not transmit or transmits at the same time. Then, the shunted pipe must transmit once the sand bridge form in the wellbore/screen annulus. The packing of the section in front of the sand bridge is a complicated process. That is, part of the slurry is packed with β-wave and part of the slurry is packed to the lower part along the shunted pipe, which is continuous and simultaneous. The flow and packing process are based on the relationship between friction resistance and flow rate. The flow relationship is automatically adjusted, where the friction is large, the flow is less, and the slurry flow rate is less.

4. Friction Resistance Analysis for Gravel Packing System

Shunted screen gravel packing is a very effective gravel packing completion technology for the special situation of low formation fracture pressure and long wellbore length. The low fracture formation pressure requires that the packing pressure should not be too high in the gravel packing process, so as to avoid fracturing the formation and causing serious loss of carrier fluid. To complete the gravel packing of long wellbore, the carrier fluid should have sufficient sand carrying capacity to carry gravel to the end of the wellbore. Otherwise, the gravel may deposit too much when the slurry flows in the wellbore/screen annulus. If the height of the sand bed is too high, a sand bridge will form in the wellbore/screen annulus and the packing will stop. Sufficient sand-carrying capacity requires a sufficient pump rate, which will result in higher packing pressure. Therefore, for the horizontal open hole gravel packing, it is necessary to have the corresponding pump rate safety interval. For

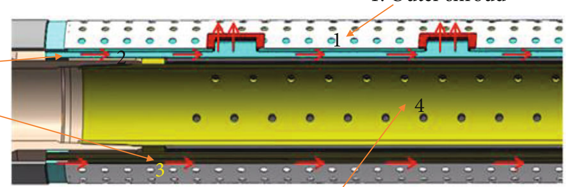


Figure 4: Schematic diagram of alternate path screen gravel packing.

Table 1: Basic parameters of A10H well in LS 17-2 gas field.

Parameter	Numerical value	Parameter	Numerical value
Open hole section (m)	3854.6-4198	Formation leakage rate (%)	4.80
Wellbore length (m)	343.4	Open hole diameter (in)	8.54
Vertical depth of horizontal section (m)	3424	Pump rate (bpm)	5.6
Reservoir pressure (MPa)	40.4	Sand ratio (ppg)	0.5
Drill pipe	5-7/8″ drill pipe + 5″ drill pipe	Density of carrier fluid (kg/m^3)	1350
Equivalent outer diameter of screen tube (in)	6.25	Apparent density of gravel (kg/m^3)	2400
Washpipe (in)	3-1/2		

extreme conditions, such as deepwater and low fracture pressure formations, such safety zones may not exist with conventional techniques. According to its unique design, the shunted screen gravel packing is equipped with transport tubes and packing tubes in the wellbore annulus. According to the self-adaptability of flow resistance, the slurry flow of different channel is automatically adjusted. If it is blocked, it will shunt the blockage through the transport tube and continue to the annulus behind the sand bridge through the packing tube. Therefore, the calculation and analysis of friction resistance are particularly important in different packing stages.

When designing gravel packing tools in the LS 17-2 gas field in the South China Sea, a pressure gauge was installed on the washpipe in order to timely and accurately analyze the changes in bottom hole pressure. Based on the packing mechanism and the friction calculation model at each stage and the actual basic data on site, the frictional resistance at each stage was calculated and the calculation results were compared with the on-site construction data in this paper. The shunted screen gravel packing diagram is shown in Figure 4.

The open hole gravel packing in horizontal wells can be divided into three stages: slurry injection stage, α-wave packing stage, and β-wave packing stage [23].

4.1. Friction Loss in String. In the slurry injection stage, slurry flows along the string after injection at the wellhead, and the flow resistance in the string can be calculated according to the flow position of the slurry front. Friction loss in the string is

$$\Delta P_i = \frac{32 f \rho_m Q_p^2 L_i(t)}{\pi^2 D_c^5} + \frac{32 f \rho_f (L_c - L_i(t))}{\pi^2 D_c^5}. \tag{5}$$

4.2. Friction Loss of Open Hole Wellbore during α-Wave Packing Stage. Once the slurry enters the wellbore/screen annulus, the frontier position of slurry is the demarcation point. Along the flow direction, slurry flows behind the frontier position, and liquid flows in the front of the frontier position. This stage is the α-wave packing stage, and the flow resistance at this stage is

$$\Delta P_\alpha = \frac{2 f \rho_m Q_p^2 L_\alpha(t)}{A_{up}^2 D_{up}} + \frac{2 f \rho_f Q_p^2 (L - L_\alpha(t))}{A_{\text{an}}^2 D_{\text{an}}}. \tag{6}$$

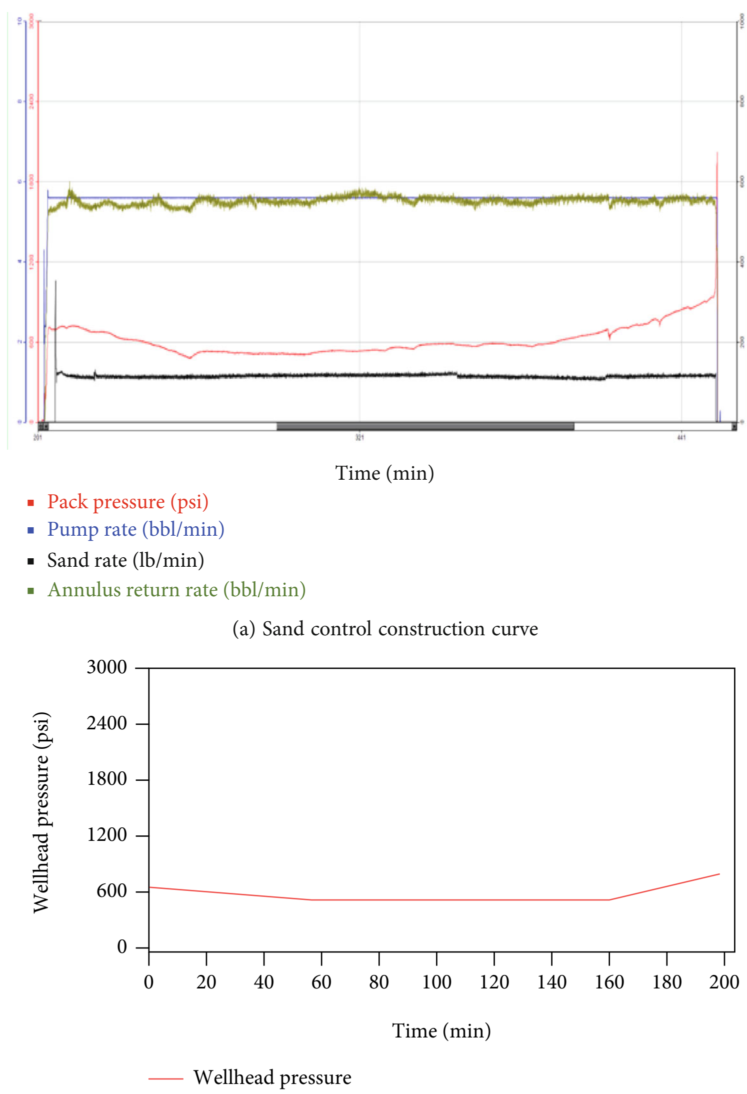
4.3. Friction Loss of Open Hole Wellbore during β-Wave Packing Stage. After α-wave packing reaches the toe of the wellbore, the β-wave reverse packing stage begins. The flow resistance of this stage is as follows:

$$\Delta P_\beta = \frac{2 f \rho_m Q_p^2 (L - L_\beta(t))}{A_{up}^2 D_{up}} + \frac{32 f \rho_f Q_p^2 L_\beta(t)}{\pi^2 (2/3)^{1/2} (D_i^2 - D_e^2)^2 (D_i - D_e)}, \tag{7}$$

where ΔP_i, ΔP_α, and ΔP_β are friction loss, Pa; Q_p is the pump rate, m^3/s; L_c is the depth of casing shoe, m; $L_i(t)$ is the depth of slurry injection at t, m; ρ_m and ρ_f are the density of slurry and carrier liquid, respectively, kg/m^3; D_c is the diameter of string, m; L, $L_\alpha(t)$, and $L_\beta(t)$ are wellbore length and α-wave packing front distance at time t, β-wave front distance at time t, m; A_{up} and A_{an} are the cross-sectional area of the upper part of the sand bed and the cross-sectional area of the wellbore/screen annulus, m^2; f is the friction coefficient; D_{up} and D_{an} are the hydraulic diameter of the upper channel of the sand bed and the hydraulic diameter of wellbore/screen annulus, m; D_i and D_e are the

Table 2: Comparison of simulation results and operation results.

Parameter	Model calculation results	Construction results	Errors and remarks
α-Wave packing length (m)	343.4	343.4	No error, packing can be completed
β-Wave packing length (m)	343.4	343.4	No error, packing can be completed
Total packing time (min)	195.03	251	100% packing is considered in the simulation, while 138% packing is achieved in the actual operation, so the simulation time is less than the actual packing time
Total sand consumption (lbs)	16371.8365	16509 (100% packing), 22800 (138% packing)	Error < 1%
α-Wave sand dune ratio	0.7921	0.79	Error < 1%



(a) Sand control construction curve

(b) Simulation calculation of wellhead pressure curve

Figure 5: Comparison of simulation results and construction results.

inner diameter of screen pipe and the outer diameter of washpipe, respectively, m.

Given the actual data and combined with formulas (5), (6), and (7), the friction calculation at different stages can be carried out. The prediction and optimization can be made by comparing the calculated results with the operation results of the actual downhole pressure gauge in the field.

Table 3: Construction and simulation results in different packing stages.

	Model calculation results	Sand control construction results	Error and remarks
When starting to add sand, the wellhead pump pressure (psi)	670.95	697	Error < 5%
α-Wave packing start pressure (psi)	528.3456	501	Error < 5%
α-Wave packing average pressure (psi)	542.346	525	Error < 5%
β-Wave packing average pressure (psi)	567.1467	580	Error < 5%
Pressure before screenout (psi)	812.75	940	The simulation calculation considers 100% packing, but the actual construction reaches 138%, which leads to some errors
Compared with the wellhead pump pressure curve, it can be seen that the simulation results have high accuracy and can meet the requirements			

Table 4: Downhole pressure gauge data logging.

Serial number	Packing state	Lower outside-inside difference (psi)	Upper outer-inner difference (psi)	Top-bottom external difference (psi)	Bottom-up internal difference (psi)
1	Prepump stage	3	1	-41	39
2	Began to sand	34	176	25	118
3	α-Wave packing	50	190	13	127
4	α-Wave packing	48	184	10	126
5	Stage 3-4	43	179	20	116
6	β-Wave initiation	45	180	19	116
7	Screenout	51	390	216	123

Table 5: Simulation results of friction distribution at each packing stage.

	Injection stage	α-Wave stage	β-Wave stage
String injection friction (max), psi	181.8335892	181.8338831	181.8338831
Total friction in horizontal section (max), psi	1.380201471	29.54096242	285.8021072
Backflow friction of washpipe (max), psi	119.5657029	119.5657029	119.5657029
Annular friction between string and casing (max), psi	81.82761718	81.82761718	81.82761718

5. Filed Case Histories and Application

5.1. Comparative Analysis of Packing Simulation Results and Construction Results. LS 17-2 gas field is a deepwater gas field in the South China Sea. Water depth is approximately 1252~1530 m, and the reservoir buried depth is approximately 3200~3400 m. The reservoir pressure coefficient is approximately 1.19~1.21, and reservoir pressure is approximately 39.0~40.3 MPa. The reservoir temperature is approximately 85~95.1°C, and the permeability is approximately 89.0~2512.3 mD; the average permeability is 543.0 mD. The physical properties are high porosity~extra high porosity, high permeability~extra high permeability. The median particle size is between 67.0 and 250.0 μm. The clay content is approximately 21.0%~27.0%. Using the prediction methods of acoustic time difference, B index, and S index, there is a great risk of sand production. So gravel packing is recommended for sand control. There are 11 development wells (6 horizontal wells and 5 vertical wells) in LS 17-2 gas field, with a total footage of 41171 m. An average well depth is 3743 m, and a maximum well depth is 4054 m. A maximum horizontal displacement is 927 m, and a maximum well inclination is 90°. A shunted screen is used for gravel packing in well A10H, and a pressure gauge is installed above and below the washpipe of the downhole packing tool to monitor the pressure change in the packing process in real time.

Corresponding gravel packing process and mechanism, the calculation software was developed to calculate and simulate the friction at different stages of the packing process. The parameters of the α-β wave packing stage and the screenout pressure and then compared with the construction results were calculated and analyzed. The basic parameters of well A10H are shown in Table 1.

The simulation calculation results are shown in Table 2. From the data in the table, it can be seen that the simulation calculation results of α-β packing length and β-wave packing length are completely consistent with the operation results. If the total packing time is considered 100% packing in theory, the error between the calculation results and the

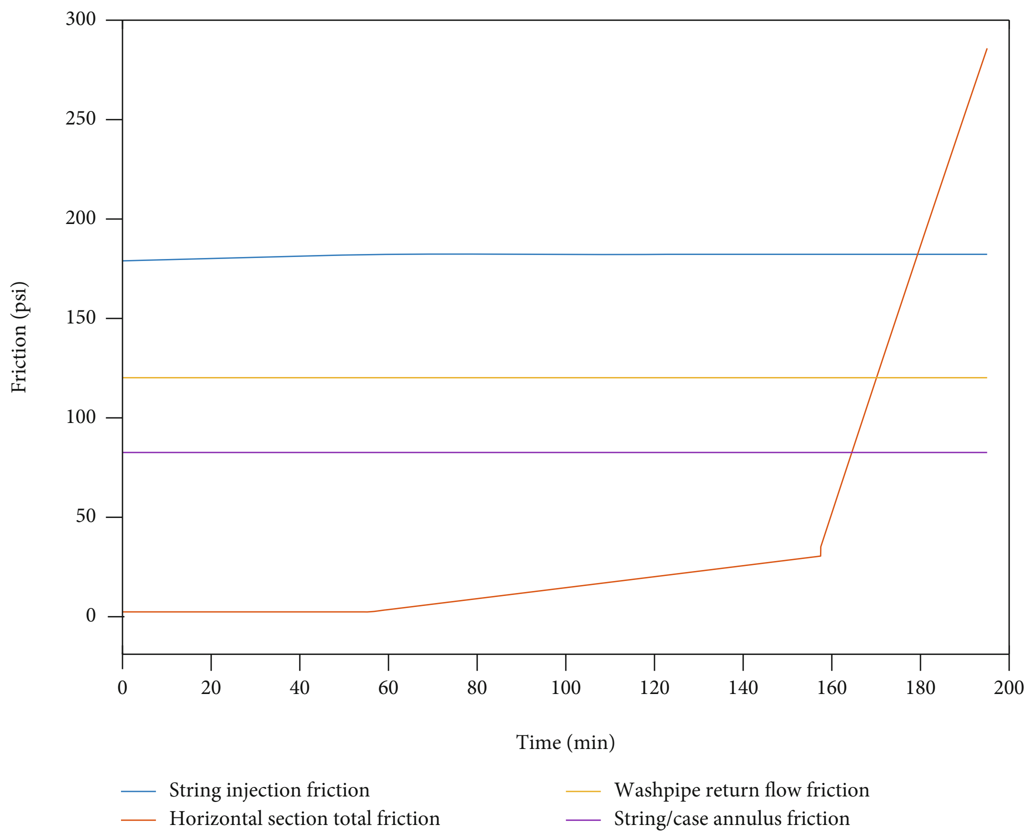


Figure 6: Friction distribution at different packing position vs. time.

operation results is less than 10%. At the same time, the total sand consumption and sand dune ratio error are both less than 1%.

5.2. Comparative Analysis of Packing Pressure. According to the friction calculation models at different stages, the corresponding software was compiled and calculated. The comparison of the packing pressure calculated by the simulation and the on-site operation results is shown in Figure 5. It can be seen from the figure that the pressure change trend tends to be consistent. At the same time, the pressure calculation and operation results before starting to add sand, α-wave packing, β-wave packing, and screenout are shown in Table 3. The error is less than 5%; the simulation accuracy is high and can meet the requirements.

Table 4 shows the data recording results of the downhole pressure gauge. According to the design position of the pressure gauge, numerical simulation calculations were carried out using the compiled software. The calculation results are shown in Table 5.

As can be seen from Tables 4 and 5, the calculation simulation results and the downhole pressure gauge test results are as follows: the maximum value of the external difference between upper and lower is 20 psi at the α-wave stage, which is roughly the horizontal packing friction and the calculated value is 29.54 psi. This calculation result should be reasonable considering the deviation of position. The maximum difference between upper and lower was 216 psi in the β-wave stage, and the calculated value of packing friction resistance in the horizontal section was 285.802 psi. The internal difference between the bottom and top is about 120 psi, which roughly reflects the friction resistance of the washpipe, and the calculated value is 119.5657 psi, which are within manageable margins of error.

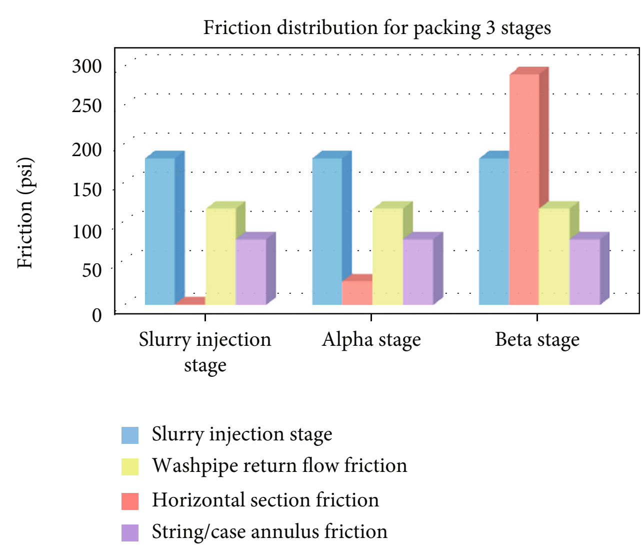


Figure 7: Friction distribution in three packing stages.

Figure 6 shows the calculated and simulated frictional distribution at different positions of gravel packing with packing time. It can be seen that the total frictional distribution in the horizontal section increases rapidly in the β-wave stage, resulting in high packing pressure and easy fracturing formation.

Figure 7 is to calculate the slurry injection stage, α-wave and β-wave packing stage corresponding friction calculation contrast. It can be seen that in deepwater wells, in the slurry injection stage and α-wave packing stage, the string friction proportion is the largest. During the β-wave packing stage, with the need of carrier fluid through a long narrow washpipe/screen annulus, friction increases quickly. Therefore, this packing stage is the stage of maximum of packing pressure.

6. Conclusions

(1) Shunted screen gravel pack uses its unique design structure, when there is a sand bridge in the wellbore annulus, according to the flow resistance and flow adaptability, the slurry can be introduced across the sand bridge to pack the back of the annulus. This technology is suitable for gravel packing in low fracture pressure formations and long horizontal wells

(2) According to the mechanism analysis of shunted screen gravel packing technology and the friction calculation model established, the developed gravel packing simulation software can accurately predict the change of friction in the packing process. According to the friction at different positions, the flow direction of slurry in the transport pipe and wellbore annulus can be judged and then the change of flow parameters in the transport pipe can be calculated. The calculated results are in good agreement with the construction results

(3) Through mutual checking of the data obtained from the downhole pressure gauge and the results of simulation calculation, the packing effect can be further predicted and the parameters can be optimized to ensure the success of gravel packing in the field

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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