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Full Length Research Paper

Experimental and visual simulation of gravel packing in horizontal and highly deviated wells

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Abstract

The gravel packing process in horizontal or highly deviated wells involves the solid-liquid two-phase flow and the sand-bed migration under complicated conditions, in which the sand carrier fluid filtrates into the formation and the mass exchange occurs between the fluid in screen-wash pipe annulus and the fluid in casing-screen annulus. One of the key problems in gravel packing is to predict the α wave sand-bed equilibrium height to simulate the gravel packing process and optimize operation parameters. In this paper, a full-scale simulation equipment for internal circulation gravel packing in horizontal wells is utilized for the study of the effects of screen offset, flow rate, and sand concentration on the α wave sand-bed equilibrium height. The comparison is made among the results using three empirical equations to calculate the equilibrium flow rate. Based on Gruesbeck model, a more accurate calculation method of the equilibrium sand-bed height is developed. Then, the mass and momentum conservation equations of the gravel and sand carrier fluid of two-phase flow in casing-screen annulus and single-phase flow in screen-wash pipe annulus and the flow coupled equations of these two flow systems are established. A mathematic gravel-packing model for horizontal and highly deviated wells is thus obtained. The solution of the model can lead to the development of gravel-packing simulator software package, which can be used to visually simulate the gravel packing process. The characterization of the gravel packing process and the variation of each dynamic parameter are also analyzed.

Keywords: Horizontal well, highly deviated well, gravel packing, packing of internal circulation, equilibrium sand-bed height, experimental simulation, visual numerical simulation.

INTRODUCTION

The gravel packing completion can ensure a high long-term production rate and wellbore stabilization, and prevent the sand production. It is especially applicable to the unconsolidated reservoir due to its more likely sand production from horizontal wells and highly deviated wells. The gravel packing in such wells involves the multiple solid-liquid two-phase coupled flow and sand-bed migration process under the complex conditions, such as inclined wellbore, formation filtration loss, fluid mass exchange, etc., as shown in Figure 1. The control of the sand-bed height is crucial to the success of gravel-packing(Chen Zhongming,2007; Dong Changyin, 2005, 2008). Since 1980s, some scholars have devoted great efforts in the study of mathematic description and simulation of gravel packing process in horizontal wells. Gruesbec k (1979), Peden et al. (1985) introduced the concept of equilibrium sand-bed, and established a typical mathematical model, which is, however, independent of the time. They mainly focused on the dimension analysis of simulation experiment results. In terms of mathematic simulation of gravel packing in horizontal tube, Gruesbeck (1979), Wahlmeie (1988), Penden (1985), Winterfeld (1992), Penberthy (1995), and Li Aifen (2002) also developed the analytic time-independent models which were based on the fitting of physical simulation data. Such models can't be used to descript the whole gravel packing process. With the use of full-scale gravel packing simulation

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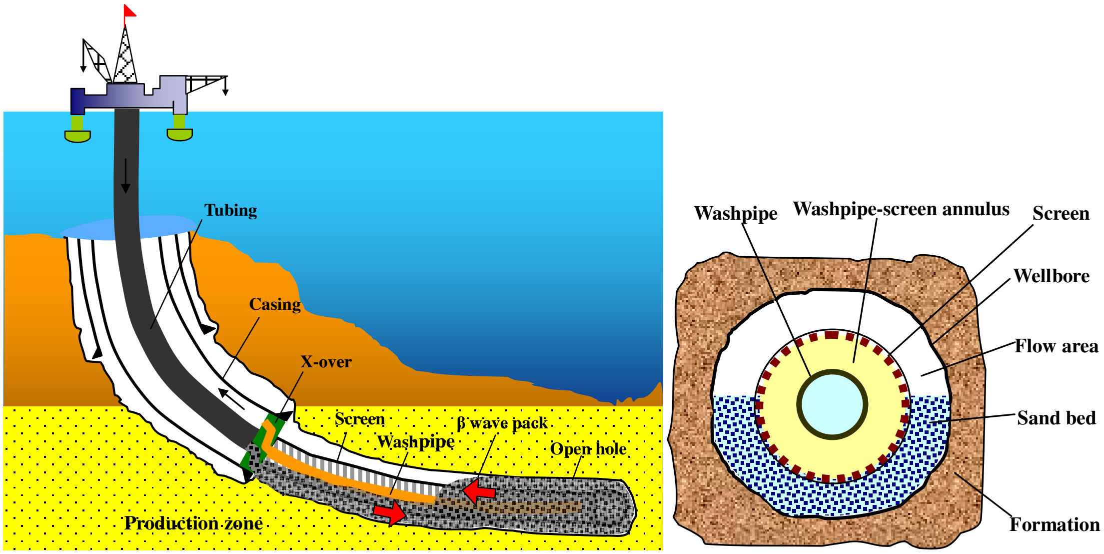


Figure 1. Internal circulation gravel-packing process in horizontal wells

equipment, the experimental study was conducted concerning the calculation of α wave equilibrium sand-bed height in horizontal or highly deviated wells and its influencing factors. By correcting the existing empirical models, a more accurate model is developed for the calculation of the equilibrium sand-bed height. On this basis, the mass and momentum conservation equations of solid-liquid two-phase flow in the annulus are established. A mathematic model of graveling packing for horizontal well or highly deviated wells and a simulation software package are developed. The software package can be used to visually simulate the gravel packing process in highly deviated wells, and to provide support for the optimization of operation parameters.

Empirical Model for α Wave Bed Height

Empirical equilibrium flow rate model

The equilibrium flow rate refers to the average flow rate of the sand slurry at the top of sand bed when the α wave sand bed reaches the equilibrium state. Gruesbeck et al(1979) developed the following empirical flow rate model based on experimental study of horizontal wellbore gravel packing:

$$v_c = 15v_t \cdot \left[\frac{D_H \cdot v_t \cdot \rho_l}{\mu_l}\right]^{0.39} \cdot \left[\frac{d_g \cdot v_t \cdot \rho_l}{\mu_l}\right]^{-0.73} \cdot \left[\frac{\rho_g - \rho_l}{\rho_l}\right]^{0.17} \cdot \left[C_g^*\right]^{0.14} \quad (1)$$

Where v_t is the particle setting velocity,m/s; μ_l is the viscosity of sand carrier fluid, Pa.s;D_H is the hydraulic radius of flow area at the top of sand bed, m;C_g^* is the volumetric concentration of sand above sand bed, dimensionless; v_c is the equilibrium flow rate at top of sand bed when the equilibrium state is reached,m/s;d_g is the particle diameter,m;ρ_l and ρ_g are the density of sand carrier fluid and gravel respectively,kg/m^3.

Oroskar(1980) developed the following equilibrium flow rate model through the experimental study on solid-liquid two-phase flow of chemicals in horizontal tubes:

$$v^* = \sqrt{gd_g \cdot \left(\frac{\rho_g}{\rho_l} - 1\right)} \quad (2)$$

$$v_c = 1.85 \times C_g^{0.1536} \cdot \left(1 - C_g\right)^{0.3564} \cdot \left(\frac{D_H}{d_g}\right)^{0.378} \cdot \left(\frac{\rho_l D_H v^*}{\mu_l}\right)^{0.09} \cdot x^{0.3} \cdot v^* \quad (3)$$

Where v^* is the intermediate variable;x is the empirical constant,and is set at 0.96 in the calculation.

Penberthy et al. (1995) conducted gravel packing experiments in horizontal wellbore and developed the following empirical equilibrium flow rate equation for the flow in annulus above sand bed:

$$v_c = \max\left(v_1, v_2\right) \quad (4)$$

$$v_1 = 0.3084 \times \left[0.0251 \times \cdot 3.28 \cdot g \cdot d_g \cdot \left(\frac{\rho_g - \rho_l}{\rho_l}\right) \cdot \left(0.3048 \cdot \frac{D_H \rho_m}{\mu_l}\right)^{0.775}\right]^{0.816} \quad (5)$$

$$v_2 = 0.3084 \times 1.35 \times \left[\frac{2gD_H\left(\rho_g - \rho_l\right)}{\rho_l}\right]^{0.5} \quad (6)$$

Where v_1 and v_2 are the intermediate variables, m/s; ρ_m is the density of sand-fluid mixture, kg/m^3;g is the gravitational acceleration ,i.e. 9.8m/s^2.

The above three models describe the relationship among the equilibrium flow rate and various flow parameters, but disregard the screen pipe offset. Therefore, taking the complicated BHA and screen offset into consideration, the calculation method for predicting α wave sand-bed height is developed on the basis of the

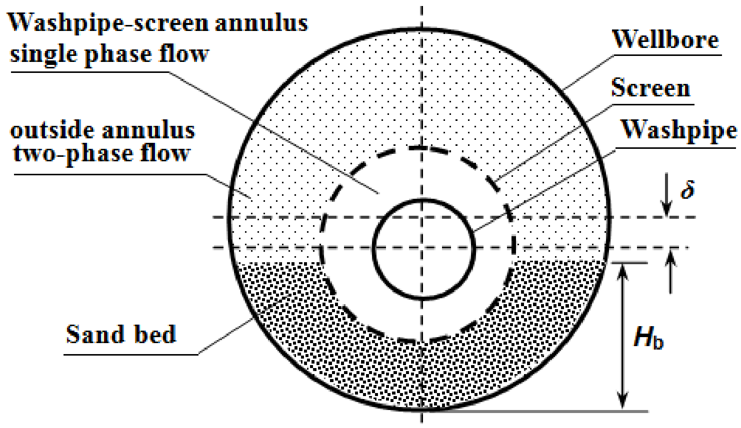


Figure. 2 The cross section of gravel packing in a horizontal well with screen offset

above three models.

Prediction of α wave sand-bed height

For a specific gravel packing BHA run in horizontal wells, one equilibrium flow rate corresponds to one equilibrium sand-bed height, which can be found from the calculation of the equilibrium flow rate and geometric dimension of each flow area. To use the above three models, the calculation is needed for determining the local diverted flow rate, sand concentration, velocity, and hydraulic geometry parameters in the casing-screen annulus when the channel flow occurs between wash pipe-sreen annulus and casing-screen annulus. All of these parameters are related to the sand-bed height, H_b, which is also the calculation objective. Therefore, a specific algorithm design is still required.

The cross section of gravel packing assembly in a horizontal wellbore is shown in Figure 2. This BHA has screen pipe offset , δ,the inlet flow rate of sand carrier fluid is Q_{mi}, and the sand concentration is C_{gi},the total local flow rate after filtration loss is Q_m.

The wellbore-screen pipe annulus is interconnected with the screen-washpipe annulus through screen mesh. Ignoring the flow resistance of screen mesh, at the equilibrium state the pressure gradient of the solid-liquid flow in the upper wellbore-screen annular space will be equal to the pressure gradient of the single phase flow of sand carrier fluid in wash pipe-screen annulus(Gruesbeck,1979) , i.e.:

$$f_{sw}\frac{\rho_l v_{sw}^2}{2D_{sw}} = f_{cs}\frac{\rho_m v_{cs}^2}{2D_{cs}} \qquad (7)$$

Where f_{cs},f_{sw} are frictional coefficient in wellbore-screen annulus, and screen-wash pipe annulus; v_{cs},v_{sw} are average flow rate in wellbore-screen annulus and screen-washpipe annulus, m/s; ρ_l, ρ_m are density of sand carrier fluid and sand slurry, kg/m^3; D_{cs}, D_{sw} are equivalent diameter of wellbore-screen annulus and screen-washpipe annulus, m.

The ratio of frictional coefficient of wellbore-screen annulus to that of screen-washpipe annulus is expressed as:

$$R_f = \frac{f_{sw}}{f_{cs}} \qquad (8)$$

Incorporating the flow area,the flow rate ratio of the wellbore-screen annulus to the screen-washpipe ratio is given by:

$$R_Q = \frac{Q_{cs}}{Q_{sw}} = \frac{A_{cs}\cdot v_{cs}}{A_{sw}\cdot v_{sw}} = \frac{A_{cs}}{A_{sw}}\cdot\sqrt{R_f\cdot\frac{\rho_l}{\rho_m}\cdot\frac{D_{cs}}{D_{sw}}} \qquad (9)$$

Based on the total local (point of calculation) flow rate, Q_m,the diverted flow rate in each subsystem can be calculated by:

$$Q_{sw} = \frac{Q_m}{1+R_Q},\quad Q_{cs} = \frac{R_Q}{1+R_Q}\cdot Q_m \qquad (10)$$

Using the solid and liquid mass equilibrium equation, the gravel concentration and sand slurry density of solid-liquid two-phase flow at the top of sand bed in the wellbore-screen annulus can be expressed as:

$$C_{gcs} = \frac{Q_{mi}C_{gi}}{Q_{cs}} \qquad (11)$$

$$\rho_m = \rho_g C_{gcs} + \rho_l\left(1 - C_{gcs}\right)$$

For actual calculation, set sand-bed height, H_b, as the objective. The detailed procedures are as following:

(1) Set H_b = 0 and increment of ΔH_b,i.e. $H_b = H_b + \Delta H_b$;

(2) Use geometric relation and H_b to calculate D_{cs}, D_{sw}, A_{cs} and A_{sw};

Figure 3. Photo of the gravel packing simulation equipment

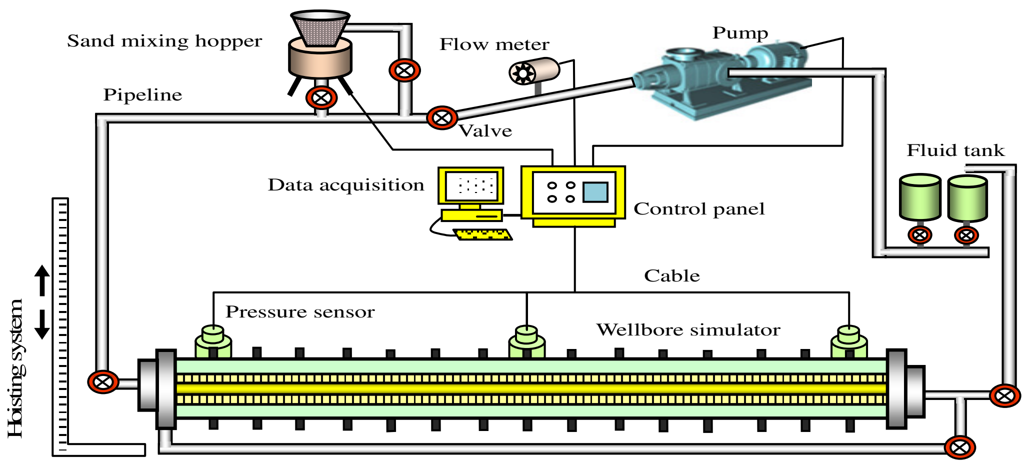


Figure 4. Schematic diagram of the gravel packing simulation equipment

(3) Use a given empirical ratio coefficient, R_f,to estimate the gravel concentration, C_{gcs}, and density of sand-liquid slurry, ρ_m;Then use equation (9) and (10) to find Q_c and Q_{sw};
(4) Recalculate C_{gcs} and ρ_m with the equation (1), and find accurate Q_{cs} and Q_{sw} with the equation (9), and (10);
(5) Calculate hydraulic radius of the flow in wellbore-screen annulus, D_H, in terms of geometric relations an H_b.;
(6) Calculate the flow rate and the average velocity, v_{cs}, in the wellbore-screen annulus;
(7) Select the equation (1), (3), and (4) in terms of D_H, ρ_m, and C_{gcs}, and calculate the average flow velocity, v_c;
(8) Compare v_c with v_{cs}:
If the first iteration shows: $v_c<v_{cs}$, then H_b=0, the calculation is completed;
If $|(v_c>v_{cs})/ v_{cs}|<\varepsilon$,then H_b is the equilibrium sand-bed height, complete calculation;
If $|(v_c>v_{cs})/ v_{cs}|>\varepsilon$,return to step (1) to recalculate.

The procedures of using above three empirical equilibrium equations to find H_b are same except that a proper model for calculating the average velocity should be selected in step (7). The comparison of the results by using these three empirical equations shows that some error occurs in the result of the equilibrium sand-bed height, therefore, the experiment means is needed for verification.

Simulation of Gravel Packing Process

Equipment and procedures

The full-scale gravel packing simulation equipment consists of the wellbore, sand mixing device, pump, fluid storage tank, hoisting system, control panel, data acquisition system, flow meter, pressure sensor, piping and valves, as shown in Figure 3 and Figure 4.

To achieve better simulation result, the size of the

Figure 5. Image of α wave sand-bed equilibrium height and packing front edge

wellbore, screen pipe, and washpipe are much closer the sizes used in oil fields. The wellbore, 140mm in ID, and 5500mm in length, is made of the transparent pressure-resistant material, and is taken as 7" casing. The wire-wrapped screen (95.2mm in OD and 74mm in ID) is mounted inside the wellbore. The wash pipe, 45mm in OD, is run inside the screen and can be placed in different offset. The inclination angle of the wellbore can be adjusted from 0°-30°. The sand (0-15% in concentration) is added after the pump is shut down. The flow meter and pressure sensors are installed to transmit data into the data acquisition system.

Fresh water and quartz sand (0.4-0.8mm in diameter, and 2.632 in relative density) as gravel are used in the test. The test procedures are as follows:

(1) Fill the fluid tank until it is full. Set data acquisition system at zero. Set sand filling rate, and start data acquisition system;

(2) Circulate and adjust flow rate control valve until the required flow rate is obtained;

(3) Open master valve to fill sand, fill sand at the predetermined rate;

(4) Observe and record the packing status. Manually adjust equilibrium sand-bed height once the α wave sand-bed is formed;

(5) Close the sand filling master valve as β wave packing is nearly over. Shut off the pump when no sand flows into the wellbore.

(6) Switch to sand-washing operation, flush the sand out of the wellbore and clean the equipment to conclude the test.

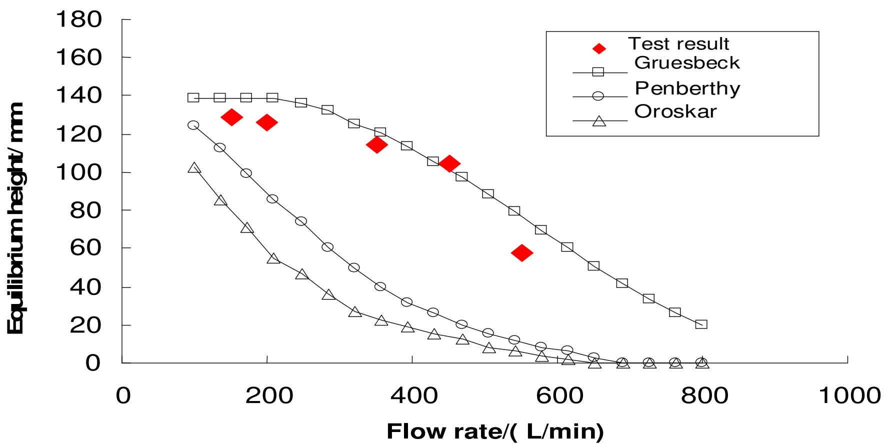
Comparison of test results with modeling results

To verify calculation accuracy of the sand-bed height obtained by the above mentioned three models, the above equipment is used to conduct simulation experiments. The test conditions are as follows: sand carrier fluid of clean water, sand concentration of 2% to 8%, screen offset of 0 and 20mm, flow rate of 150 to 600L/min.

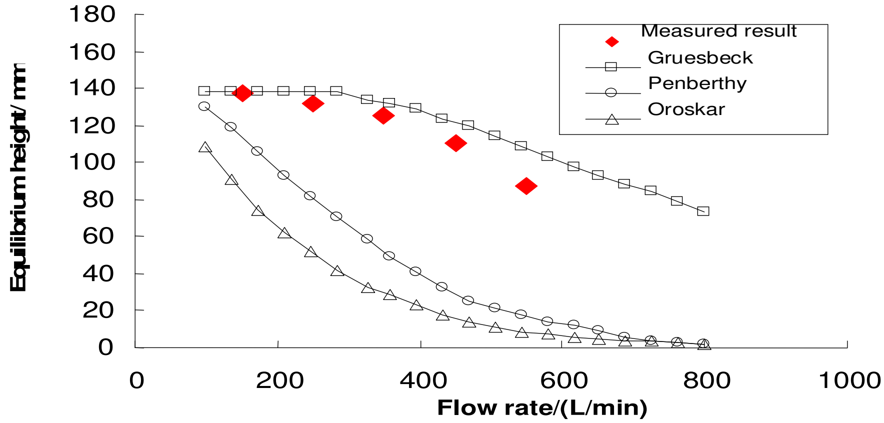
Figure 5 shows the observed sand bed formed by the α wave packing and image of the its front edge. The above test conditions are used to conduct several simulation tests, and the α wave sand-bed equilibrium height is measured in each test. The above three models are used to calculate the equilibrium heights. Figure 6 shows the comparison of the measured value with the calculated value.

The tests are performed with the flow rate of 400L/min, offset of 20mm, sand concentration of 2%-8%, and three models are also used to calculate the equilibrium sand-bed height. The results are shown in Figure 7.

It can be seen from Figure 6 and Figure 7 that the results obtained by using Penberthy model and Oroskar model differ significantly from the measured value by about 80% of the average error. The diameter of casing and screen used by Penberthy is 100mm and 50mm respectively(Penberthy,1995), smaller than that used in the test discussed here. Oroskar model was developed from the fitting of experiment data of solid-liquid flow through tubes in the field of chemical transfer(Oroskar,1980). The reason of such a big error may be due to the great difference in testing conditions, gravel packing BHA, and property of sand and fluid. Therefore, the above two models are not recommended for the prediction of equilibrium sand-bed height in horizontal wells. However, the result obtained by using Gruesbeck model is in good agreement with the measured value by the average error of 8.5%. The calculated value is slightly greater than the measured value. Nevertheless, the Gruesbeck model, if corrected as



(a) 0 screen pipe offset



(b) 20 mm screen offset

Figure 6. Comparison of the tested bed height with the calculated results with different screen offset

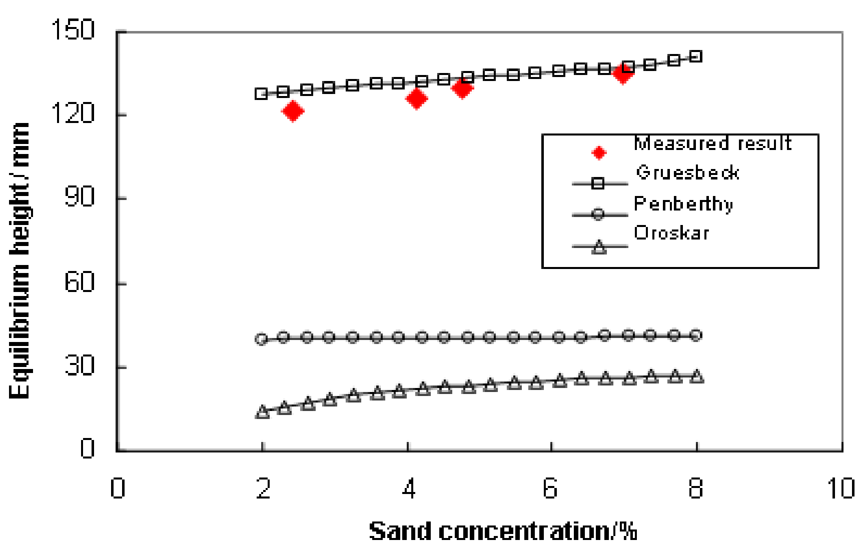


Figure 7. The α wave sand-bed equilibrium height vs. sand concentration

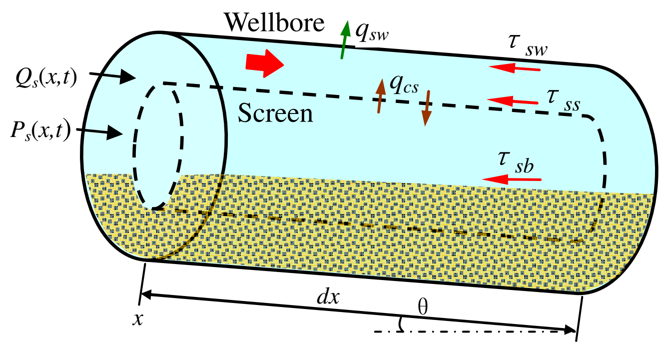


Figure 8. Schematic diagram of the wellbore annulus flow unit

necessary, can be used to predict the equilibrium sand-bed height.

Numerical Simulation Model for Gravel Packing

The normal gravel packing for high angle wells is utilized to develop the mathematic model, which is also applicable to the inverse gravel packing method. The only difference lies in the direction of sand-bed migration, i.e, the sand bed migration direction of normal gravel packing is opposite to that of reverse gravel packing.

The internal circulation gravel packing process is divided into the α wave normal packing and the β wave reverse packing. The two-phase flow of solid and liquid flows over the sand bed in the wellbore-sceen annulus, and single-phase flow of sand carrier fluid occurs in the screen-washpipe annulus. The two-phase flow filtrates into formation, and in the mean time, the mass exchange occurs between these two flow systems through the screeen mesh.

The following assumptions are made when developing equations:

(1) The flow is isothermal

(2) The wellbore is perfectly straight and the inclination remains unchanged

(3) The wash pipe and screen are placed concentrically in the wellbore

(4) The solid particles are packed once they are settled and deposited with the porosity of 48%

(5) The gravel and sand carrier fluid are both incompressible

Equation of mass and momentum conservation

A cylindrical micro control unit, dx, as shown in Figure 8, is cut from the inclined interval along the axial direction. In the wellbore-screen annulus, the sand-bed height in this dx unit is h_b. The mass conservation equation for the sand slurry flow in the annulus above the sand bed is expressed as(Dong Changyin, 2008):

$$\frac{\partial A_s(x,t)}{\partial t} = -[q_{sw}(x,t) - q_{cs}(x,t)] - \frac{\partial [A_s(x,t)V_s(x,t)]}{\partial x} \quad (2)$$

The mass conservation equation of the sand bed in wellbore-screen annulus is given by:

$$\frac{\partial A_b(x,t)}{\partial t} = \frac{q_g(x,t)}{C_b} - \frac{\partial [A_b(x,t)V_b(x,t)]}{\partial x} \quad (3)$$

The mass conservation equation of the sand carrier fluid in dx unit inside the screen-washpipe annulus is given by:

$$\frac{\partial V_c(x,t)}{\partial x} = -\frac{1}{A_c} \cdot q_{cs}(x,t) \quad (4)$$

Where x is the axial coordinate, m; t is the time, s; A_s, A_b, and A_c are the flow cross sectional areas of sand slurry in wellbore-screen annulus, sand bed, and screen-washpipe annulus respectively, m^2; q_{cs} is the flow rate exchange of sand carrier fluid per unit length between wellbore-screen annulus and screen-wash pipe annulus,m^3/(s.m); q_{sw} is the filtration loss of wellbore wall per unit length, m^3/(s.m); q_g is the settling volume velocity of the sand particles off sand slurry per unit length, m^3/(s.m); V_s, V_b, V_c are the flow rate at time t, and location x of sand slurry in wellbore-screen annulus, sand-bed migration, and sand carrier fluid in screen-wash pipe annulus respectively, m/s; C_b is the gravel volume concentration of sand bed.

The flows of sand slurry and sand carrier fluid are affected by the mass force caused by the inclined wellbore, pressure at the both ends of the micro unit, and frictional shear resistance on the outside wall of the screen, the inside wall of the wellbore, and the sand-bed surface. Taking the momentum change caused by the fluid mass exchange into consideration, the equations of mass conservation of sand slurry flow in wellbore-screen annulus and sand carrier fluid flow in screen-wash pipe annulus are obtained as below:

$$A_s\frac{\partial V_s}{\partial t} = -A_s g\sin\theta - \frac{1}{2}(S_{ss}f_{ms} + S_{sw}f_{mw} + S_{sb}f_{mb})V_s^2 - \frac{1}{\rho_m}\frac{\partial (A_s P_s)}{\partial x} - \frac{1}{2}V_s(q_{cs} - q_{sw}) - \frac{1}{2}A_s V_s\frac{\partial V_s}{\partial x} \quad (5)$$

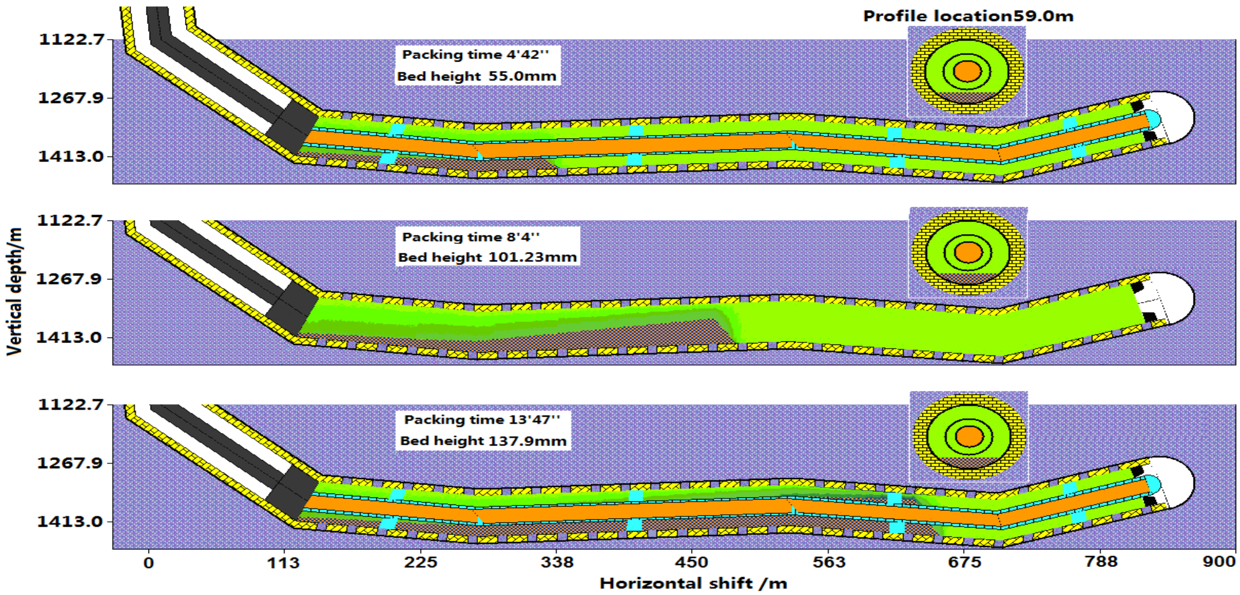


Figure 9. Visual simulation image of α wave packing process

$$\frac{\partial V_c}{\partial t} = -g\sin\theta + A_c V_c q_{cs} - \frac{1}{\rho_l}\frac{\partial P_c}{\partial x} - \frac{\pi}{2A_c}\left(D_c f_{cc} + D_{si} f_{cs}\right)V_c^2 \quad (6)$$

Where P_s and P_c are the flowing pressure of wellbore-screen annulus and screen-washpipe annulus respectively, Pa; ρ_m is the density of sand slurry, kg/m^3; S_{ss}, S_{sw}, S_{sb} are the respective circumference of contact areas between sand carried fluid and screen outside wall, sand carried fluid and wellbore inside wall, sand carried fluid and sand bed surface, m; f_{ms}, f_{mw} and f_{mb} are frictional coefficients of the sand slurry through screen outside wall, wellbore inside wall, and sand bed surface respectively; D_c and D_{si} are the washpipe OD and screen pipe ID respectively, m; ρ_l is the density of sand carrier fluid, kg/m^3; θ is the inclination angle, rad; f_{cc} and f_{cs} are the frictional coefficient of washpipe outside wall and screen inside wall respectively.

Coupled equation and auxiliary equation

The filtration of the sand carrier fluid into the formation is affected by the viscosity of the sand carrier fluid, rock and fluid compressibility. Considering the flow resistance exerted by sand bed to the filtration fluid, the filtration flow rate equation of the sand carrier fluid per unit length or the coupled equation of the flow in wellbore annulus and formation is given by:

$$q_{sw} = \frac{C}{\sqrt{t}}\left[\left(\pi D_w - S_{bb}\right) + S_{bb}\cdot R_f\right] \quad (7)$$

The mass exchange process of the fluids in the wellbore-screen annulus and screen-washpipe annulus is controlled by equalization of pressure gradients in these two flow systems. Ignoring the resistance of flow through the screen mesh, the coupled equation of these two systems is expressed as:

$$\frac{\partial P_c(x,t)}{\partial x} = \frac{\partial P_s(x,t)}{\partial x} \quad (8)$$

Where C is the formation filtration loss coefficient, m/s$^{0.5}$; S_{bb} is the circumference of sand bed and wellbore contact, m; R_f is the ratio of filtration loss with and without the sand bed.

The mathematic model consists of the model for calculating sand-bed height, mass conservation equation, momentum conservation equation, coupled flow equation, and auxiliary equations. The change of sand-bed height, sand concentration, flow rate, and flow velocity with the location and time can be determined after solution of these equations. The numerical simulation for gravel packing process in high angle wells can thus be carried out. Based on the above models, the visualized simulation software package is developed.

ANALYSIS OF VISUALIZED SIMULATION RESULTS

Visualized simulation results

One horizontal well with a high angle was cased and perforated in the horizontal section. The normal internal circulation gravel packing operation was performed in this well. Due to its complicated wellbore trajectory, the well path is simplified into numerous straight sections with a certain angle, as shown in Figure 9.

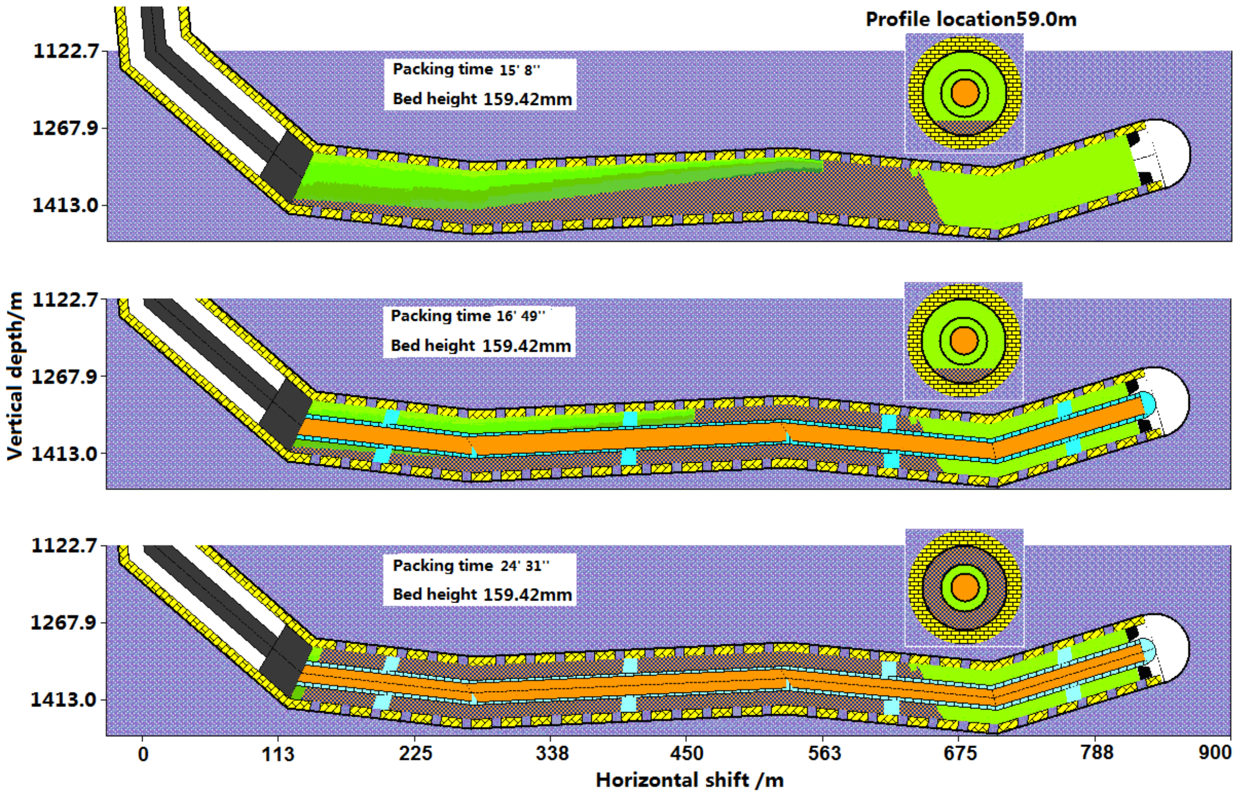


Figure. 10 Visual simulation image of β wave packing process with premature plugging

The well data include the reservoir pressure of 14.57MPa, length of production interval of 660m, hole size of 215.9mm, casing ID of 159.42m, screen size of 90/75 mm, sand carrier fluid viscosity of 6.7 mPa·s, sand carrying ratio of 20%,sand carrier fluid density of 1000kg/m^3, gravel density of 2600kg/m^3, gravel size of 0.4 - 0.8 mm, and washpipe size/screen size ratio of 0.8.

Figure 9 shows the screen shots of α wave packing image obtained from visualized dynamic simulation of gravel packing process with internal circulation. The simulation results indicate that as the sand slurry enters the wellbore part of gravel particles deposit at the bottom of wellbore-screen annulus and form the α wave sand bed. Due to the wellbore pressure greater than the formation pressure, the sand carrier fluid begins to filtrate into the formation. The reduction of the flow velocity along the wellbore axial direction due to loss of the flow rate weakens the sand carrying capability, which speeds up the deposition of sand particles, or increases the sand-bed height until a new sand carrying equilibrium state is reached. The sand-bed equilibrium height in high angel wellbore is not a fixed value because of the filtration of sand carrier fluid into the formation. The sand-bed height is increased along the wellbore direction, and a so-called "equilibrium slope" is formed. The higher angle of wellbore aggravates the sand bed deposition process. The simulation results shown **in** Figure 9 illustrate that the sand-bed height at entrance is about 22.0mm, and in 4 minutes the average equilibrium height rises to 55.0mm as the front edge of α wave packing sand bed reaches 340m. And at 14 minute, the average equilibrium height rises to 137.9mm as the front edge reaches 650m, which shows an apparent rising trend along the wellbore direction. Regarding casing ID of 159 mm, it is apparent that the top of sand bed is much close to the upper wall of wellbore.

Figure 10 shows the screen shots of inverse β wave packing image of the same simulation. At about 15 minutes, the equilibrium height is 159m when α wave packing front edge reaches about 630m, which means that the sand bed comes into contact with the upper wall of wellbore, and the flow area above the sand bed disappears. By then the front packing edge is still 150 m away from the end of production interval, which means that the sand plugging occurs prematurely before a complete α wave packing is achieved. Although the sand carrier fluid is still capable to flow through pores in the sand bed, the solid gravel particles can only be packed inversely, i.e. β wave packing is in progress. The production interval of 150m remains unpacked, and the packing fraction of 78% signifies the failure of simulated gravel packing operation. The sand carrying ratio is changed to 15%, and the packing fraction of 100% is achieved.

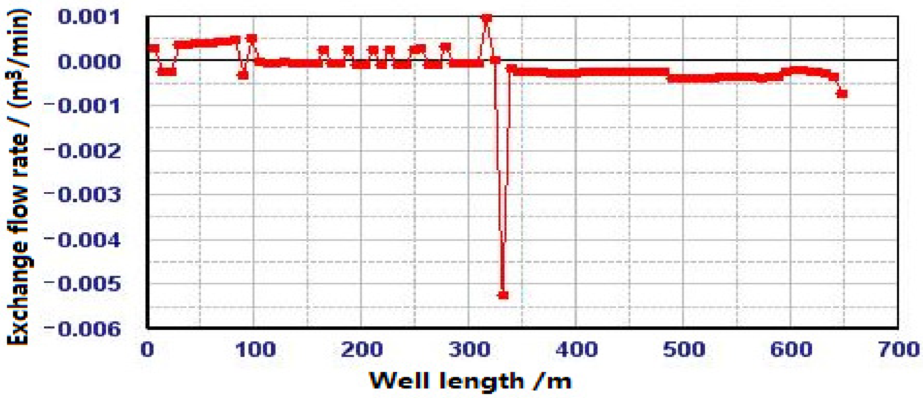


Figure 11. The channel flow rate vs. location at 8.74 min

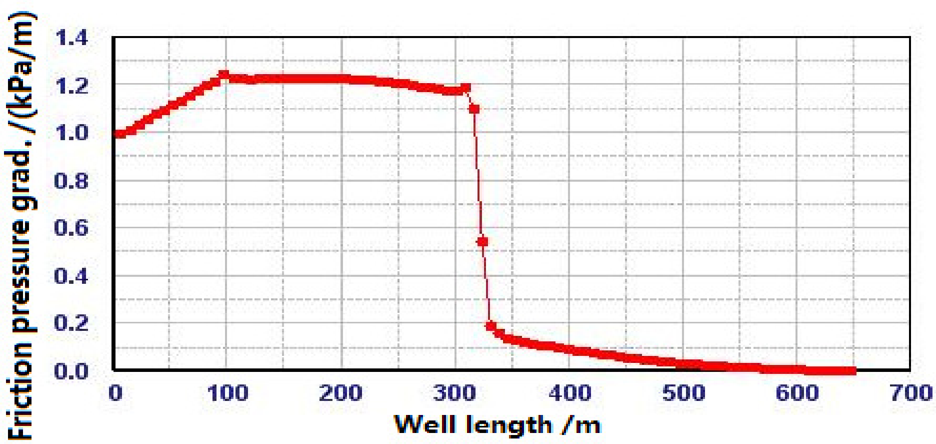


Figure 12. The distribution of wellbore frictional pressure gradient at 8.74min

The distribution of flow parameters

The numerical simulation model and visualized simulator can be used to simulate the distribution of parameters of gravel packing in high angle wells, such as flow rate, velocity, sand concentration distribution, pressure, pressure gradient and channel flow at any time in each flow system.

Figure 11. shows the distribution of channel flow rate of the sand carrier fluid which flows between washpipe-screen annulus and the wellbore-screen through the screen mesh at 8.74 minutes. Due to the significant change of flow area before and after the front edge in wellbore-screen annulus, the channel flow rate fluctuates severely at the point of packing front edge. At other location, the channel flow rate is controlled by the filtration rate of the sand carrier fluid into formation and the pressure gradient, and the channel flow rate is stable and relatively low.

Figure 12 shows the change of frictional pressure gradient with the location *x* at 8.74 minnutes. The pressure gradient in the packed interval is high because the flow in the wellbore-screen annulus is a solid-liquid two-phase flow with small flow area. The pressure gradient in front of the packing front edge is relatively low, and is dependent on the filtration rate. When the filtration rate is low, the pressure gradient remains nearly unchanged.

Figure 13 shows the change of sand concentration in the casing-screen annulus with the location *x* at 14.12 minutes. The sand concentration at entrance is equal to the concentration of sand slurry injected at surface. It gradually increases with location *x*, and decreases abruptly to 0 at some location, which is the location of the α wave packing front edge at this moment. In the α wave packed intervals, the flow area above the sand bed becomes increasingly small due to the increase of the sand-bed height. In the mean time, the sand carrier fluid filtrates into the formation, causing reduction of the sand slurry flow rate. This is the reason for the sand concentration increase with the location *x* and reaching the maximum in front of the front edge. The sand concentration right before the front edge location is down to 0.

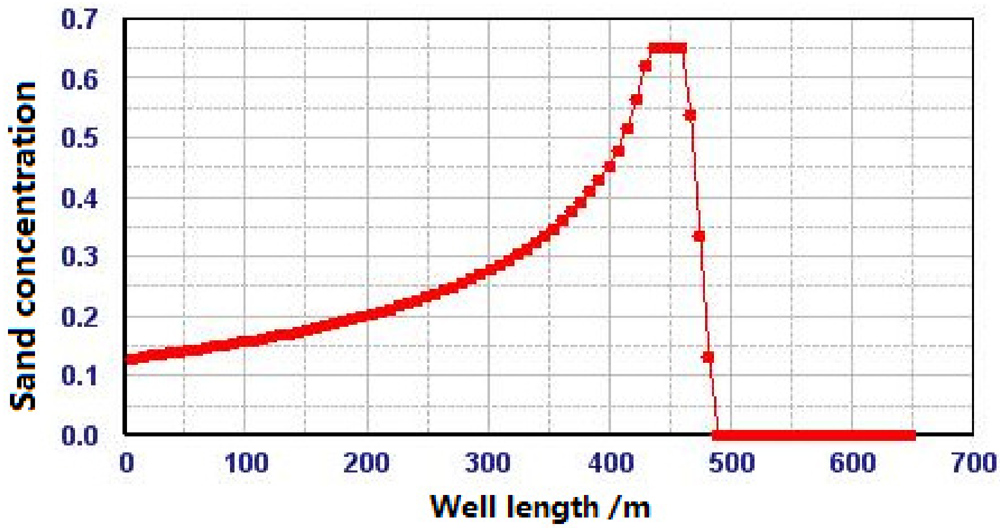


Figure 13. The distribution of sand concentration in casing-screen annulus at 14.12 min

CONCLUSIONS

(1) Based on the three existing empirical equations for calculating the equilibrium flow rate, the technique of predicting α wave sand-bed equilibrium height in horizontal well graveling packing with screen offset is developed, and the specific iteration algorithm is given.
(2) The full-scale gravel packing simulation equipment is used to study the effects of screen offset, flow rate, and sand concentration on α wave sand-bed equilibrium height. The calculated value with Penberthy model and Oroskar model is far different from the measured value, however, the calculated value with Gruesbeck model is quite close to the measured value. Nevertheless, the Gruesbeck model, after necessary correction, can be used to predict the equilibrium sand-bed height.
(3) Considering the complicated conditions, such as inclined wellbore, formation filtration loss, and fluid mass exchange, etc., a mathematic model is established by using the mass and momentum equations of two-phase flow in casing-screen annulus and single-phase flow in screen-wash pipe annulus and the coupled equation of these two flow systems, and a visualized numerical simulator software package is developed, which can be used to visually simulate the whole sand packing process in highly deviated wells.
(4) The numerical simulator is able to simulate the real packing process, predict the premature sand plugging, the packing fraction, and the distribution of various flow parameters, such as flow rate, flow velocity, sand concentration, pressure, pressure gradient, and channel flow at any time during gravel packing process. The result of visualized simulation can provide practical guidelines for optimizing the gravel packing parameters and its implementation.

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