Evaluation model of two-stage gravel packing sand control well based on additional pressure drop

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Abstract. Two-stage gravel pack sand control technology solves the problem of silt sand blockage in traditional high-pressure gravel pack, effectively improves the effective period and flow conductivity of the gravel pack. This technique has been widely used in the development of unconsolidated sandstone reservoirs, but the related studies still remain insufficient. In this paper, a sand control evaluation model based on additional pressure of the gravel packed layer is proposed for two-stage gravel packing sand control wells. Firstly, the complex mechanisms of sand plugging in gravel pack is divided into two types, horizontal and vertical, and the calculation model of dynamic permeability of the gravel pack is established. The finite element model of two-stage gravel packing sand control wells based on fluid-solid coupling is established by multi-physical coupling software COMSOL. The additional pressure drop of the sand control wells under various construction parameters is evaluated. Applying this method to evaluate a two-stage gravel packing well in Shengli Oilfield, it is concluded that after 200 days of production, the gravel pack’s additional pressure drop of the traditional packing increases to 2.5 MPa, while the overall additional pressure difference of two-stage gravel packing is stable at about 1.3 MPa. It is proved that two-stage gravel packing sand control technology can effectively reduce the additional pressure drop and improve the productivity of oil well after completion.

1. Introduction

Sand production in oil and gas wells has become one of the main factors restricting the efficient development of unconsolidated sandstone reservoirs, which mainly reflected in the damage of near region of the wellbore, artificial lifting and ground equipment. High-rate gravel-packing sand control technology has been widely used in wells with serious sand production issue because of its high sand control efficiency, long validity period and alleviation of the productivity impairment caused by the sand blocking material [1-3]. But after a period of well production, the gravel pack will be blocked by silty sands. Sparlin [4] studied the permeability of common size gravel with different percentage of silty sand. He claimed that the permeability of the gravel would be seriously decreased after mixing a small amount
of silty sand. When the gravel pack blockage occurred in tubing-casing annulus and perforation hole, the additional pressure in gravel layer will increase significantly, resulting in unnecessary reservoir energy loss and seriously affecting well productivity. As one of the most important moderate sand-control completion technique, variable grain size two-stage gravel packing effectively realizes the integration of sand blocking, drainage and settlement of high argillaceous and silty sand reservoir. The gravel bed I with smaller grain size are packed to prevent the invasion of particles with a larger grain size. The bigger grain size of gravel bed II makes the silt particles that are transported to gravel bed II discharged with the produced fluid of well, which effectively avoids the gravel pack blockage (see Figure 1). This technology has been applied in some high argillaceous and high silty sand reservoirs in Shengli Oilfield, China currently, and good application results have been achieved [5-6]. However, there is still a lack of research on this technique, which cannot provide guidance for the field completion design.

![Figure 1. Diagram of two-stage gravel packing well](image)

For conventional gravel packed sand control wells, predecessors have proposed a series of flow resistance and pressure drop calculation models to predict the productivity of oil wells after sand control and evaluate gravel packed completion effect [7-9]. However, the widely used method for calculating the additional pressure difference is usually based on the steady-state physical parameters of the gravel pack, or using the skin factor to modify the dynamic permeability, which cannot accurately reflect the physical process of dynamic particle blockage in gravel pack. Previous studies mostly used theoretical model deduction, which could not visually show the dynamic pressure characteristic of each gravel packs. In this paper, a set of evaluation model for the effect of two-stage gravel packed sand control wells is proposed. Firstly, the prediction model of dynamic physical parameters of gravel packed sand control wells is introduced, taking the mechanism of the formation sand plugging fully into account. On this basis, the multi-physical field coupling software Comsol Multiphysics is applied to simulate the pressure distribution under the consideration of the dynamic process of two-stage gravel packed sand control wells.

2. Prediction Model of Sand Capturing in the Gravel Pack

2.1. Control equation of formation sand production and plugging

For incompressible fluids, it is usually assumed that the change rate of the concentration of flowing sand body is much larger than the decrease rate of porosity. According to the above assumptions, the mass conservation equation of the concentration of flowing sand in the gravel pack is as follows:

$$ -\nu_e \frac{\partial c}{\partial x} = \phi \frac{\partial c_s}{\partial t} + \frac{\partial c}{\partial t} $$

(1)

In the equation, \( c \) is the concentration of flowing sand in the unit pore volume, dimensionless; \( c_s \) is the concentration of plugging sand, that is, the volume fraction of plugging sand in the unit pore volume, dimensionless; \( \phi \) is the porosity, dimensionless; \( \nu_e \) is the horizontal injection rate, m/s.
Among them, the relationship between the change rate of $c_f$ concentration of plugging sand and the concentration $c$ and the injection rate of flowing sand can be characterized by the plugging coefficient of flowing sand.

$$\frac{\partial c_s}{\partial t} = \lambda c v_c$$

(2)

In the equation above, $\lambda$ is the capture coefficient of flowing sand, m$^{-1}$.

The blocking mechanism of sand particles in the pore throat of gravel layer is determined by many mechanisms. According to the theoretical research results of predecessors, each mechanism can be characterized by a trapping coefficient. The total trapping coefficient of flowing sand is the sum of the coefficients, as shown in the following formula [10].

$$\lambda = \lambda_1 + \lambda_2 + \cdots + \lambda_n$$

(3)

According to the research results of Li Yanchao et.al [11-12], the mechanism of complex particle blockage in porous media is integrated into vertical and horizontal blockage. The following two blocking coefficients are solved respectively.

2.2. Vertical and horizontal sand capturing coefficient

Firstly, the stress balance equation in equation (4) can be obtained by analyzing the vertical force of sand particles in the fluid.

$$4\pi r^3 (\rho_m - \rho_f) g - 6\pi f \mu R v_s = m \frac{dv_s}{dt}$$

(4)

In the equation, $r$ is particle size, m; $\rho_m$ is particle density, kg/m$^3$; $\rho_f$ is fluid density, kg/m$^3$; $r$ is pore diameter of packing gravels, m; $\mu$ is sand-carrying fluid viscosity, Pa$\cdot$s; $v_s$ is particle settling velocity, m/s; $f$ is friction coefficient, dimensionless, and its value is related to Reynolds number of fluid, $f = 24/\text{Re}$.

The constant terms known in equation (4) are defined as coefficients:

$$ a = g \left( \frac{\rho_m - \rho_f}{\rho_m} \right) \quad b = \frac{9 f \mu}{2 r^2 \rho_m}$$

(5)

Therefore, equation (4) can be simplified as follows:

$$a - bv_s = \frac{dv_s}{dt}$$

(6)

By substituting the boundary conditions, the relationship between the concentration of plugging sand $c_s$ and flowing sand $c$ can be obtained as follows:

$$c_s = c - ce^{\frac{-a}{bR} (e^{\frac{b}{v_s}} - 1)}$$

(7)

According to the definition of vertical flow sand plugging coefficient, when only vertical plugging of formation sand is considered, there are the following relations:

$$\frac{\partial c_s}{\partial t} = \lambda_v c v_c$$

(8)

The expression of vertical capturing coefficient can be obtained:

$$\lambda_v = \frac{a}{b} \left( 1 - e^{-\frac{b}{v_s}} \right) e^{\frac{a}{bR} (e^{\frac{b}{v_s}} - 1)}$$

(9)

According to Kuhnen et al.’s deep filtration particle adsorption model [13], a horizontal capturing coefficient model is carried out. The dynamic equilibrium equation of the captured particle is as follows:

$$\frac{\partial c_s}{\partial t} = [k_{pc} B(\theta) + k_{pp} \theta] c$$

(10)

In the equation, $k_{pc}$ is the particle capturing coefficient caused by pore throat wall of gravel pack, s’
$k_{pp}$ is the particle capturing coefficient caused by blocked particle surface, s$^{-1}$; $\theta$ is the volume fraction of sand in pore throat of gravel pack, dimensionless; $B(\theta)$ is the dynamic plugging term of flowing sand.

The rate of variation of $\theta$ with time in equation (10) is determined by the dynamic blocking equation:

$$\frac{\partial \theta}{\partial t} = k_{pc} B(\theta) \pi r^2 c$$

(11)

According to Langmuir sorption equation, the dynamic plugging function of flowing sand is as follows:

$$B(\theta) = 1 - \beta \theta$$

(12)

According to the definition of horizontal capturing coefficient of production sand in gravel pack, when only horizontal blockage of formation sand is considered, there are the following relationships:

$$\frac{\partial c_c}{\partial t} = \lambda_h c v_c$$

(13)

By substituting equation (10) - (12) for equation (13), the horizontal capturing coefficient can be written as follows:

$$\lambda_h = \frac{k_{pc} - (k_{pc} \beta - k_{pp} \theta) c}{v_c}$$

(14)

3. Evaluation model of two-stage gravel packing effect based on additional pressure drop

The solid mechanics module and porous media and groundwater flow module in COMSOL multi-physical coupling software are used to solve the gravel blockage and dynamic pressure change model caused by the production of two-stage gravel packed sand control wells. In order to show the additional pressure produced by gravel pack inside casing, outside casing and in perforation accurately and intuitively, two models are established to study the macro-seepage process from reservoir supply boundary to bottom hole and the gravel bed I to bottom hole, respectively, as shown in Figure 2.

Figure 2. (a) Finite element model from reservoir supply boundary to bottom hole (b) Geometric model and mesh near the wellbore

The model is applied to evaluate the additional pressure drop of a two-stage gravel packing well in Shengli Oilfield, and compared with the conventional gravel packing method to evaluate the effect of two-stage gravel packing sand control technology on reducing the additional pressure difference. The perforation and well section data of the example wells are shown in Table 1.
Table 1. Perforation and reservoir data of the example well

| Formation | Perforation section/m | Layer thickness/m | Permeability /μm² | Perforated thickness /m | Perforation density /holes/m |
|-----------|------------------------|-------------------|-------------------|------------------------|-----------------------------|
| 1         | 841.0-843.0            | 4.5               | 121.967           | 2.0                    | 40                          |
| 2         | 849.5-853.5            | 5.6               | 198.571           | 4.0                    | 40                          |

Gravel size of the gravel bed I is designed according to Saucier criterion, that is, the median size of selected industrial gravel is 5-6 times of that of the production sand of the well. Referring to the coring data in this area, the median grain size of ground sand is 0.14 mm, and the D50 of the packing gravel should be 0.7 mm. Considering the need of effective sand control, permeability improvement and filling compactness, the quartz sand and ceramsite is selected for two-stage packing during this construction, and the grain size of packing quartz sand ranges from 0.425 mm to 0.850 mm. The size of ceramics ranges from 0.6 mm to 1.12 mm.

In the construction process of two-stage gravel packing, 9.8 m³ quartz sand is first packed and 10.2 m³ ceramsite is added. According to the inversion of construction parameters, the length of the gravel bed I is 0.30 m and that of gravel bed II is 0.73 m. After gravel packing, the average daily liquid volume is 29.5 m³/d, which greatly improves the productivity of the well with the initial gravel packing.

Based on the given data, the pressure distribution law in the gravel pack is obtained. As shown in Figure 3, it can be seen that the additional pressure mainly comes from the perforations. Therefore, the key point of the two-stage gravel packing design is to ensure that the size of gravel that packed in the perforation is reasonable.

The pressure distribution of the well after sand control with conventional gravel packing is simulated under the same control of fluid production. The comparison results are shown in Figure 4. The influence of two-stage gravel packing and conventional gravel packing on additional pressure drop can be clearly seen from the figure. Conventional gravel packing uses gravel of single grain size. The blocked silt and fine sand cannot be discharged with the produced fluid of oil wells. The blocked degree of gravel pack increases gradually with the production, resulting in a large additional pressure drop between the outside-casing and perforation packing zone. For sand control with two-stage gravel packing, because the fine and silt particles that passing through gravel bed I will not cause obvious blockage in gravel bed II, the effect of particle migration on fluid supply is minimized, thus the additional pressure difference between the gravel packing zone and perforation is obviously reduced, and the oil well production after completion is improved significantly.
Fig. 5 shows that the additional pressure difference of the gravel packed layer with two packing modes changes with time. It can be seen that with the blockage of gravel packs, the additional pressure drop of traditional gravel packing increases obviously with time. After 200 days of production, the pressure drop increases to about 2.5 MPa. The gravel bed II of the two-stage gravel packing will not be blocked by silt and fine sand basically. The overall additional pressure difference is about 1.3 MPa, which is no obvious change with the well production time.

4. Conclusion
In this paper, an evaluation model of two-stage gravel packing sand control well considering dynamic permeability of the gravel bed and fluid-solid coupling effect of reservoir is proposed, which can be used to predict the additional pressure drop of the gravel packs intuitively and accurately. Considering the sedimentation and blockage of production sand in gravel pack, a prediction model of captured sand
concentration distribution is established, and the capturing under various mechanisms are integrated into vertical and horizontal coefficients. Pressure distribution model considering fluid-solid coupling of reservoir and gravel filling layer is established and solved by COMSOL software by finite element method. The model is applied to evaluate the additional differential pressure of a two-stage gravel packing sand control well in Shengli Oilfield, and the conventional gravel packed method is compared. The simulation results show that the two-stage gravel packing sand control technology can effectively reduce the additional pressure drop of the gravel bed and improve the productivity of oil well after completion significantly.

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