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A semi-analytical model for predicting screen-out in hydraulic fracturing horizontal wells

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ABSTRACT

Proppant Screen-out has been generally recognized as an issue affecting the performance of hydraulic fracturing in horizontal well completion. There is lack of a method that can be used to predict the screen-out. This paper provides a semi-analytical model for describing the configuration of proppant pile in ideal fracture conditions and predicting the time at which the screen-out occurs during fracturing horizontal wells. Result of case study is consistent with field data with certain error. Sensitivity analyses with this semi-analytical model indicate that optimizing fluid viscosity, injection rate, proppant density, proppant size, distribution of proppant size and the ratio of proppant volume to fracturing fluid volume can eliminate or at least delay the occurrence of screen-out. This semi-analytical model provides engineers a method for optimizing fracturing parameters to minimize the detrimental effect of screen-out to horizontal well performance.

1. Introduction

Hydraulically fractured horizontal wells have enhanced the recovery of oil and gas from various types of reservoirs. Over the last decades, hydraulic fracturing in horizontal wells has resulted in a revolution in the petroleum industry. However, there are still different issues occurring in the design and implementation of hydraulic fracturing of horizontal wells. Proppant screen-out is one of the most impediments that prevent the creation of long fractures. It is a condition that a rapid rise in pump pressure is generated by the blockage of flow by the proppant inside the wellbore, perforations and fractures (Daneshy, 2011). Massaras and Massaras (2012) classified the screen-out pressure behavior into the gradual screen-out pressure behavior and the abrupt screen-out pressure behavior. The gradual screen-out pressure behavior is resulted from the inability of the proppant to pass through the near wellbore area in the fracture. This is referred as the tip screen-out. The abrupt screen-out pressure behavior is caused by the complete blockage of the entire perforated interval, and it is referred as the "wellbore screen-out". This paper focuses on the study of the blockage to the movement of proppant in the fracture, which causes the gradual screen-out pressure behavior.

Numerous causes are believed to be responsible for the screen-out in hydraulic fracturing. Cleary et al. (1993) indicated that the near-wellbore tortuosity is the dominant source of most screen-out problems in hydraulic fracturing treatments, which can be generated by the deviatoric stress, natural fractures and perforation-dominated creation of complex fracture patterns in the wellbore vicinity. In addition, their study showed that the tortuosity is not limited to deviated wells but to the vertical wells. Daneshy (2011) reviewed the reasons of the screen-out, especially the wellbore screen-out in horizontal wells. He reported that the type of well completion can largely affect the details and frequency of screen-outs. Massaras et al. (2011) listed 6 major causes for the premature screen-outs in propped hydro-frac treatments. 1) They demonstrated that the main cause for screen-out is the tortuous path in the near wellbore area which generates high near wellbore frictional pressure looses. 2) Withdrawal of hydrocarbons or injection of fluid may potentially affect the compaction of the reservoir rock and surface subsidence. The compaction can influence the stress field far from the wellbore, which is referred as backstress. They indicated that backstress due to depletion of reservoir pressure can increase the potential for screen-outs. 3) Long perforated intervals result in the initiation and propagation of multiple fractures. The multiple fractures promote reduced individual fracture widths, increasing the probability of screen-out. 4) Fractures in no-compliant reservoir formation are usually not wide enough to receive proppant, which may cause screen-out. 5) Segmented en-echelon fractures are very small fractures generated by the tensile forces on the wellbore during drilling, which can be viewed as the pre-existing fractures. Reopening the small pre-existing segmented en-echelon fractures requires a much higher pressure, which is one of the major reasons for screen-outs. 6) Dilatancy is defined as a

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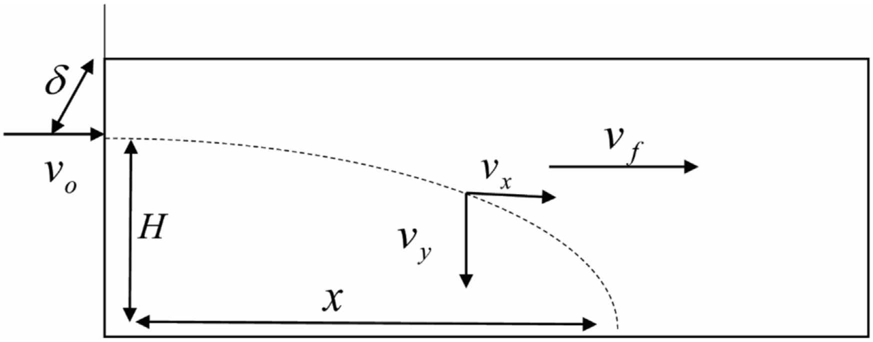

Fig. 1. Trajectory describing single proppant drifting in fracture.

non-linear rock expansion. The dilatancy at the fracture tip requires increased pressure to reopen the fracture tip region, increasing the potential of screen-out.

The screen-out requires the cession of pumping and the conduction of flush procedure, which will disrupt the operation of hydraulic fracturing in horizontal well. Subsequently, cost overruns are generated due to the remedial operation and loss of production days. Even more serious problems are the failure of fracturing equipment and the injuries of personnel. Because of its negative effects, predicting the probability of screen-out becomes more and more desirable. Several methods have been proposed for analyzing the potential of screen-out. The post-minifrac diagnostic methods are performed after the minifrac diagnostic procedure has been conducted (Massaras and Massaras, 2012). The real-time diagnostic methods can be conducted in real-time. Chipperfield et al (2000) defined the magnitude of near wellbore pressure loss as the difference between the final bottom hole pumping pressure and the instantaneous shut-in pressure. The causes of near wellbore pressure loss include the near wellbore tortuosity and perforation friction. Their relative contribution can be qualitatively measured by the step-rate 'step-up' test. Massaras et al (2007) performed a fracture entry friction analysis along with the rate step-down test for calculating the friction values to each flow path segment. They also proposed a general decision control guideline to reduce screen-out based on the statistical analysis of a huge amount of data. Yang et al. (2008) utilized the leak-off test information to predict the screen-out and demonstrated that pressure declining gradients (PDG) is the key factor influencing the screen-out. The pressure declining gradients (PDG) can be obtained through drawing a tangent line at the stabilized part of the pressure declining curve of leak off test. They illustrated that higher PDG means higher leak off rate of clear fluid into the formation. Patankar et al (2002) defined three types of fluid and sand bodies within the fracture plane: an immobile sand bed on the bottom; a mobile sand bed in the middle; and a clear fluid at the top. Two major observations are made by Patankar: 1) The combined thickness of both mobile sand bed and immobile bed is inversely related to the velocity of clear fluid. 2) Sand grains constantly settles down from mobile sand bed to immobile sand bed. The velocity of clear fluid can inversely affect the settling speed. High leak off rate of clear fluid can reduce the volume of clear fluid and then reduce the velocity of clear fluid. Subsequently, premature accumulation of immobile sand will be generated due to the decreased clear fluid velocity and cause screen-outs. Nordgren (1972) correlated the fracture width with fluid loss co-efficiency and indicated that fracture width is inversely related with the fluid loss co-efficiency. Therefore, a high PDG will results in a narrow fracture opening, which can probably lead to screen-out. Nolte and Smith (1981) interpreted different behaviors of fracture treating pressure. Their work was widely used in the real-time diagnosis of screen-out. Massaras and Massaras (2012) indicated that Nolte's method cannot be properly implemented in real-time treatment because of some improper assumptions and ignorance. They proposed an inverse slope method through the visual observation of surface pressure plots to obtain a warning of screen-out during hydraulic fracturing.

The literature review shows that a few methods have been proposed to analyze the potential of screen-out in hydraulic fracturing. However, the existing methods have following deficiencies: 1) None of the existing methods can be directly applied in the design of hydraulic fracturing without any extra data from other tests performed prior to a main fracturing job or the plot of actual fracture treating pressure. 2) None of the methods can provide a relatively accurate time of the occurrence of screen-out. 3) None of the methods can provide a rough description of the flow condition in the fracture. This paper proposes a semi-analytical method for describing the configuration of proppant pile and predicting the screen-out time in fractures. A case study is conducted using data from a horizontal well to prove the validity of this model. Sensitivity analyses were carried out to identify the key parameters affecting the screen-out.

1.1. Mathematical model

This section describes the new mathematical model used to predict the screen-out time for the purpose of preventing screen-out condition or minimizing the detrimental effects of screen-out. The mathematical model consists of an analytical model for proppant transport and a numerical model for proppant pilling.

1.1.1. Proppant transport model

Fig. 1 shows a two-dimensional trajectory of a proppant particle discharged to fracture with an inclination angle δ from the vertical direction. After the proppant discharged from the perforations, it moves vertically and horizontally. The v_o represents the initial velocity of proppant. v_x denotes the velocity component in the horizontal direction, and v_y shows the velocity component in vertical direction. The v_f is the velocity of the fracturing fluid and H is the height of point at which the proppant is discharged.

An analytical model was derived in this study to describe the motion of a proppant particle in a Newtonian fluid flowing at a constant velocity in the horizontal direction. Model derivation is presented in Appendix A. The traveling distance x from the discharge point (perforations) is expressed as

$$x = v_f t + \frac{2m_p}{fA\rho_f} \ln\left(\frac{C_x}{t + C_x}\right) \tag{1}$$

where

$$C_x = \frac{2m_p}{fA\rho_f(v_f - v_{xo})} \tag{2}$$

t is the traveling time, m_p is the proppant mass, v_f is the velocity of fracturing fluid in fracture, ρ_f is the density of fracturing fluid, v_{xo} is the initial velocity of proppant in horizontal direction. A is the characteristic area of proppant particle and it is defined as

$$A = \frac{1}{4}\pi\left(\frac{d_p}{12}\right)^2 \tag{3}$$