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Research Article

Influence of perforation erosion on multiple growing hydraulic fractures in multi-stage fracturing

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Abstract

In multi-stage hydraulic fracturing, the limited-entry method is widely used to promote uniform growth of multiple fractures. However, this method's effectiveness may be lost because the perforations will be eroded gradually during the fracturing period. In order to study the influence of perforation erosion on multiple growing hydraulic fractures, we combined the solid–fluid coupled model of hydraulic fracture growth with an empirical model of perforation erosion to implement numerical simulation. The simulations show clearly that the erosion of perforation will significantly deteriorate the non-uniform growth of multiple fractures. Based on the numerical model, we also studied the influences of proppant concentration and injection rates on perforation erosion in multi-stage hydraulic fracturing. The results indicate that the initial erosion rates become higher with the rising proppant concentration, but the growth of multiple hydraulic fractures is not sensitive to the varied proppant concentration. In addition, higher injection rates are beneficial significantly to the limited-entry design, leading to more uniform growth of fractures. Thus, in multi-stage hydraulic fracturing enough high injection rates are proposed to keep uniform growths.

Keywords: Unconventional oil and gas reservoir; Horizontal well; Perforation friction; Perforation erosion; Multi-stage hydraulic fracturing; Numerical simulation; Mathematic model; Uniform growth of fractures

0. Introduction

Multi-stage hydraulic fracturing of horizontal wells has been widely used in developing unconventional reservoirs in recent years [1]. In order to improve operating efficiency and reduce costs, multi-cluster perforations are arranged in each fracturing section, and then, fracturing fluid is pumped to create multiple hydraulic fractures simultaneously. Affected by reservoir heterogeneity or stress shadow effect, some hydraulic fractures rapidly propagate in multi-stage hydraulic fracturing, while others are inhibited and stunted, finally leading to a poor fracturing performance. Therefore, it is challenging to maintain a uniform growth of hydraulic fractures, for optimizing multi-stage hydraulic fracturing of horizontal wells.

With consideration to non-uniform growth of fractures, many scholars have implemented numerical simulations of multiple fracture growth for optimization of multi-stage hydraulic fracturing [2–9]. Numerical simulation performed by Wu et al. [10], Lecampion and Desroches [11], Cheng et al. [12], Zhao et al. [13,14] revealed that the limited-entry method which optimizes perforating parameters to control the fluid influx of fractures can effectively promote the uniform growth of fractures in multi-stage hydraulic fracturing.

In recent years, rational design of perforation parameters has remarkably improved the performance of multi-stage hydraulic fracturing in horizontal wells. However, part of perforation clusters still failed to form hydraulic fractures in some horizontal wells after fracturing, although the limited-

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entry method was used for optimization. Fiber-Optic diagnostics data [15,16] show that the perforation clusters in these horizontal wells were successfully cracked and hydraulic fractures were formed, but some fractures began to propagate at a lower rate or even stopped growing after proppants were pumped. This indicates that the sand-carrying fracturing fluid flowing at a high speed erodes the perforations during fracturing, making the perforations lose their ability of limited entry. As a result, the influx into each fracture is non-uniform, leading to reduction of treatment effectiveness.

Some experimental studies systematically investigated the perforation erosion mechanism [17,18] and proposed corresponding theoretical models. These studies illustrated the relationship between perforation parameters and fluid pressure loss, but did not couple the mechanism with hydraulic fracture propagation. Present numerical investigations related to multiple fracture propagation typically neglect or simplify the process of perforation erosion. Therefore, in this paper, we have coupled our previous fracture propagation model [13] with the perforation erosion model built by Long et al. [19] to construct a multi-fracture propagation model taking account of perforation erosion. Based on the proposed model, the authors analyzed the effect of perforation erosion on multi-fracture propagation in multi-stage hydraulic fracturing.

1. Multiple fracture propagation model with considering of perforation erosion

1.1. Perforation erosion model

When fracturing fluid rapidly flows through the perforations, pressure loss occurs due to frictional resistance. Rationally designed perforations may induce proper pressure loss, and thus effectively control the fluid influx flowing into fractures. Early in the 1960s, Murphy and Juch [20] and Lagrone et al. [21] advocated the optimizing of perforation parameters to restrict influx in the multi-layer fracturing of vertical wells, so as to promote the uniform growth of fractures. The so-called limited-entry method has also been widely used in the optimization of multi-stage hydraulic fracturing of horizontal wells in recent years due to its convenience in use, remarkable effectiveness and low risk.

In order to further understand the interaction between fracturing fluid and perforations, Crump and Conway [17] conducted an experimental study and established a relationship between friction pressure loss (p_{pi}) and perforation parameters as follows:

$$p_{pi} = \alpha_f q_i^2 \tag{1}$$

where, $\alpha_f = 0.808\,1 \times 10^{-6} \frac{\rho}{n_p^2 d_p^4 K_d^2}$; q_i represents the fluid influx, m^3/s; similarly α_f: the friction factor of perforation, MPa·s^2/m^6; ρ: fracturing fluid density, kg/m^3; n_p: the number of perforations for each cluster; d_p: perforation diameter, m; K_d: discharge coefficient.

Note that discharge coefficient (K_d) reflects the effect of shape of perforation entry on the flow of fracturing fluid. The experiment conducted by Crump and Conway [17] shows that the proppant pumped together with fracturing fluid would bring erosion damage to perforation (Fig. 1) based on two mechanisms. First, the perforation wall will be slowly damaged due to the erosion of proppant, resulting in an increase of perforation diameter d_p. Second, the edge of perforation entry will become smoother due to the erosion of proppant, resulting in a rapid growth of discharge coefficient (K_d). The experimental data show that K_d = 0.5–0.6 for undamaged perforations and K_d = 0.95 for perforations completely eroded are consistent with actual situation.

In the numerical simulation of multi-stage hydraulic fracturing, the perforation friction factor (α_f) is usually assumed to be a constant or neglected, which is rational when the perforation is not seriously eroded. However, in the unconventional reservoirs, high injection rate is usually used for multi-stage hydraulic fracturing, which may result in relatively severe perforation erosion. When perforation erosion occurs, d_p and K_d in Equation (1) would continuously increase with the inflow of proppant, meanwhile the pressure loss induced by friction would continuously decrease, finally changing the influx distribution of the fractures and affecting the fracture morphology. In such a case, if the perforation erosion is neglected, the fracture propagation simulation results would greatly deviate from the actual situations.

In order to determine the variation of d_p and K_d with the erosion of perforation, the authors used the perforation erosion model built by Long et al. [19] based on experimental parameters to calculate the dynamic process of perforation erosion. The variation rate of d_p and K_d can be expressed as:

$$\frac{\partial d_p}{\partial t} = \alpha C v^2 \tag{2}$$

$$\frac{\partial K_d}{\partial t} = \beta C v^2 \left(1 - \frac{K_d}{K_d^{max}}\right) \tag{3}$$

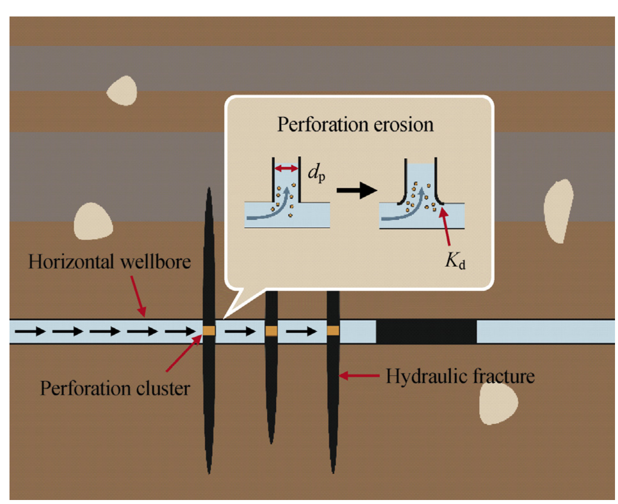

Fig. 1. Perforation erosion in multi-stage hydraulic fracturing of a horizontal well.