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Research Paper

Numerical simulation of fracture path and nonlinear closure for simultaneous and sequential fracturing in a horizontal well

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ABSTRACT

Reservoir stimulation requires a model to evaluate the fracture path and closure for the simultaneous or sequential propagation of the hydraulic fracture (HF). This paper presents a fluid-solid coupled model to simulate multi-stage HF propagation. A non-linear joint model is proposed to evaluate the fracture closure when the created fractures are elastically propped. HF closure continues until the balance of external stress matches the proppant's resistance. The reservoir along the horizontal wellbore is not stimulated equally by the multi-stage fracturing. The HFs in the subsequent stage are 'repelled' and restrained by the HFs in the previous stage.

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1. Introduction

Over the past few years, hydraulic fracturing has been proven to be an effective reservoir stimulation technique in developing shale gas resources. One of the main objectives of multi-stage fracturing in a horizontal well is to create transverse fractures or even fracture networks in the subsurface [8,10,28]. To hold the fracture open and facilitate hydraulic conductivity after the hydraulic fracture (HF) closure, proppant is injected in nearly all hydraulic fracturing treatments [24,25]. The opening of a propped fracture causes a reorientation of stress on the surrounding rock, which in turn affects the fracture propagation direction. This phenomenon is often referred to as stress shadow [32,13]. The stress shadow among multiple HFs is often known as stress interaction, which is an important subject in the hydraulic fracturing of horizontal wells [20].

Extensive research has been carried out to evaluate the impact of the stress shadow on the multi-fracture geometry and fracture design in recent years. The impacts of the in situ stress ratio, elastic parameters and net fluid pressure on the fracture spacing were evaluated numerically by a finite element model [13]. Meyer and Bazan [17] used a discrete fracture network model to investigate the numerical correlation between the dimensionless fracture spacing and width. Considering the stress interaction, Olson [21] and Olson and Dahi-Taleghani [22] simulated multi-fracture propagation in a naturally fractured reservoir. The stress interaction around multi-fracture has been identified as a limiting factor in determining the fracture spacing and perforation number [5], or even in choosing different fracturing methods, such as consecutive fracturing, alternative fracturing and zipper fracturing [20,2]. However, these papers did not couple the fluid flow with multi-fracture deformation because they assumed a constant pressure inside the multi-fracture. More recent papers successfully solved the fluid flow during the multi-fracture propagation [29,31,30]. Sesetty and Ghassemi [26,27] provided a series of examples to illustrate the impact of fracture spacing on the expected stimulated reservoir volume (SRV) and the multi-fracture path. The multi-fracture path is also affected by the proppant and fluid pressure in the previously created HF [8].

However, little attention has been given to the HF closure [18,19]. Shiozawa and McClure [24,25] developed a model to describe the fracture closure against proppant after the end of the injection. The residual fracture opening causes the stress interaction in its neighborhood and the nearby HFs after the injection is stopped [20]. The stress interaction and fracture conductivity will decrease drastically if the HF is subjected to the confining stresses that tend to close. Therefore, the residual opening of the HF along with the compressible proppant is an important factor in the success of multi-fracture treatment.

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Nomenclature

M	number of HF	Q_T	accumulate injection volume on time T, m^3
Q_k	fluid injection rate of the kth fracture, $k = 1, 2, 3, \ldots, M$, m^3/s	$L_k\,(T)$	length of the kth HF on time T
N_k	number of segments in the kth HF	q_L	fluid loss volume, m^3
N	total number of segments of all of the HFs	C_L	fluid loss coefficient, m^2.s$^{0.5}$
D_s^j, D_n^j	shear and normal DDs, respectively, m	$t_0(s)$	time at which HF first reaches the portion s, s
$A_{ss}^{ij}, A_{sn}^{ij}, A_{ns}^{ij}, A_{nn}^{ij}$	coefficients, representing the stresses on the ith segment due to the constant DD on the jth segment	L_f	half-length of HF, m
σ_h, σ_H	the minimum and maximum in situ stress, respectively, MPa	p_j	pressure of the jth segment, MPa
θ_i	angle of the ith segment, rad	α	weighting coefficient, dimensionless
p_i	fluid pressure on the ith segment, MPa	$[D_s^j]_0$, $[D_n^j]_0$	shear and normal DDs before the pump's shutoff, respectively, m
Q	volumetric flow rate, m^3/s	K_n	normal stiffness of fracture, MPa/m
n' and μ	fluid power-law index and consistency index, respectively	ΔD_n	normal displacement increment, m
H	fracture height, m	E_p	elastic modulus of the propped HF, MPa
s	distance along fracture path, m	ρ_o	porosity of proppant filled HF
w	fracture width or opening, m	$[D_s^j]_p$, $[D_n^j]_p$	shear and normal DDs after the pump's shutoff, respectively, m
p	pressure of fracturing fluid flow, MPa	S_k	number of segments in the kth stage
Q_c	total injection rate, m^3/s	E	Young's modulus of the formation, MPa
T	total injection time, s	v	Poisson's ratio of the formation, dimensionless
		K_{IC}	fracture toughness, MPa m$^{0.5}$
		σ_{xx}, σ_{yy}, τ_{xy}	stress components, MPa

Crouch and Starfield [7] proposed a linear joint element (assumed as a linear spring) to describe the subsurface crack with a compressible filling for compression or shear. Similarly, this paper developed a nonlinear joint element (assumed as a nonlinear spring) to evaluate the HF closure after the injection is stopped. To evaluate the influence of propped HF on the multi-fracture geometry and stress interaction in the multi-stage fracturing technology, an HF model coupling the fracturing fluid flow along the fracture and the rock deformation is adopted in this paper.

2. Numerical model

2.1. Model assumption

A horizontal well is generally fractured in multiple stages, starting from the toe to the heel. We assume that each stage includes several perforation clusters, but each cluster creates only one fracture during the fracturing process (Fig. 1).

To capture the characteristics of simultaneous fracture propagation and the stress perturbation in a horizontal well, an HF model is proposed under the following assumptions: (1) the target formation is an isotropic, linearly elastic medium; (2) the HF is allowed to propagate if the equivalent stress intensity factor exceeds the fracture toughness of rock (e.g., [14,4]; (3) the HF is a vertical fracture with a constant height, and the horizontal plane satisfies the plane strain condition; (4) the fluid flow inside an HF is equivalent to Poiseuille flow (e.g., [33]; (5) the fluid leakoff in the direction normal to the HF surface is given by Carter's model [3]; (6) the pressure loss along the borehole and perforation is ignored; and (7) the fracture closure [38,39] after pump shutoff is determined by the assumption that the elastic proppant is a nonlinear spring.

2.2. Fracture deformation

Under two-dimensional plane strain conditions, we adopt the well-established displacement discontinuity (DD) method [6] to calculate the fracture deformation. The multiple fractures in the formation are divided into N line segments in total (Fig. 2). Each fracture has N_k ($k = 1, 2, 3, \ldots, M$) segments. Each line segment represents a boundary element. According to the superposition principle, the stress perturbation created by the fracture deformation on

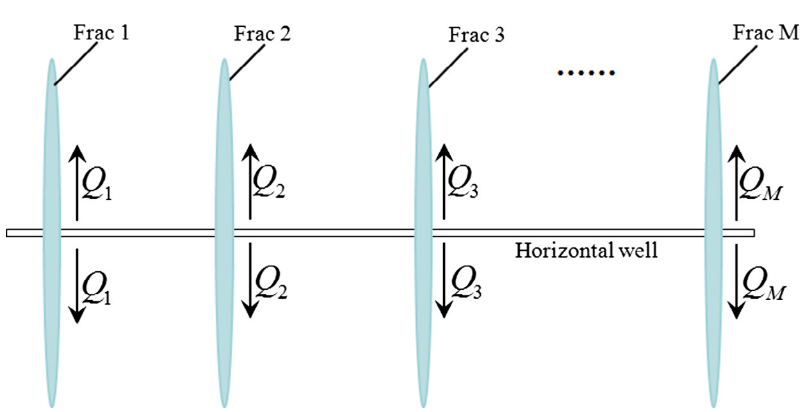

Fig. 1. Simultaneous fracturing in the horizontal well. Q_i represents the injection rate of fracturing fluid. M is the number of HFs. M fractures are produced simultaneously.

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