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Research Paper

Investigation of directional hydraulic fracturing based on true tri-axial experiment and finite element modeling

J.Q. Deng [a,*], C. Lin [a], Q. Yang [a], Y.R. Liu [a], Z.F. Tao [a], H.F. Duan [b]

[a] State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China
[b] Datong Coal Mine Group Co., Ltd., Datong, Shanxi 037003, China

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ABSTRACT

The initiation and propagation of directional hydraulic fracturing (DHF) was investigated based on true tri-axial experiment and finite element modeling. The influences of notch angle, notch length and injection rate on the DHF were investigated. The initiation and propagation of DHF was modeled by a 3D nonlinear finite element method. A comparison between experimental investigation and numerical modeling results indicates that there is a good correlation between unbalanced force (UF) and fracturing. UF can be used to predict the hydraulic fracture initiation and propagation.

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1. Introduction

Hydraulic fracturing (HF) has become a valuable and effective technique with a variety of applications, including measurement of in-situ stress [1–5], heat production for geothermal power generation [6], stimulation of oil and shale gas resources in the petroleum industry [7–9]. HF is widely used in the energy industry for increasing the permeability of oil, natural gas and shale gas systems. Another important application of HF is mining [10–15]. HF is used to reform the structure of rock roof and control the caving of hard roof at the working face in coal mine.

Usually, an artificial notch is prefabricated at the wellbore surface when an HF operation is conducted. Then, the hydraulic fracture grows up from the peripheries of the artificial notches. When an artificial notch is prefabricated in the wellbore, the stress is concentrated near the notch-tip. As a result, fractures initiate from the periphery of the notch by hydraulic fracturing. This is customarily called directional hydraulic fracturing (DHF). DHF is widely used to weaken the rock for eventual mining by caving techniques. DHF has become one of the key technologies for coal mining strata control [14–16].

A typical HF operation is to inject the highly pressurized fluid into low-permeability rock mass to create a fracture system that provides channels for fluid flow [17]. As HF becomes increasingly widespread, many methods have been developed to investigate the HF process. These methods are mainly classified into two types: physical experiments and numerical simulations. Notably, the experimental investigations of HF have the advantage to really simulate the HF parameters (in-situ stress, injection rate and discharge, etc.). The experimental investigations of HF can also provide the numerical modeling of HF with a basis for test and verify.

Many experimental investigations of HF have been conducted. Blanton performed HF experiments in the laboratory in pre-fractured material under triaxial states of stress. It is found that hydraulic fractures tend to cross pre-existing fractures only under high differential stresses and high angles of approach and the hydraulic fractures were either diverted or arrested by the pre-existing fractures in most cases [18]. Chen et al. investigated the hydraulic behavior of natural fractures/joints, especially the relationships among fracture offset, mechanical aperture and hydraulic aperture under different stress conditions through laboratory experiments [19]. Beugelsdijk et al. investigated the interaction of a propagating hydraulic fracture with natural discontinuities in scaled laboratory experiments [20]. Zhou et al. studied the hydraulic fracture propagation behavior and fracture geometry in naturally fractured reservoirs and then investigated the effect of random natural fractures on hydraulic fracture through a series of servo-controlled tri-axial fracturing experiments [21,22].

The finite element method is employed extensively to model the HF numerically. Wangen suggested a procedure based on the

* Corresponding author. Tel.: +86 10 15001120925.
E-mail address: dengjq@aliyun.com (J.Q. Deng).

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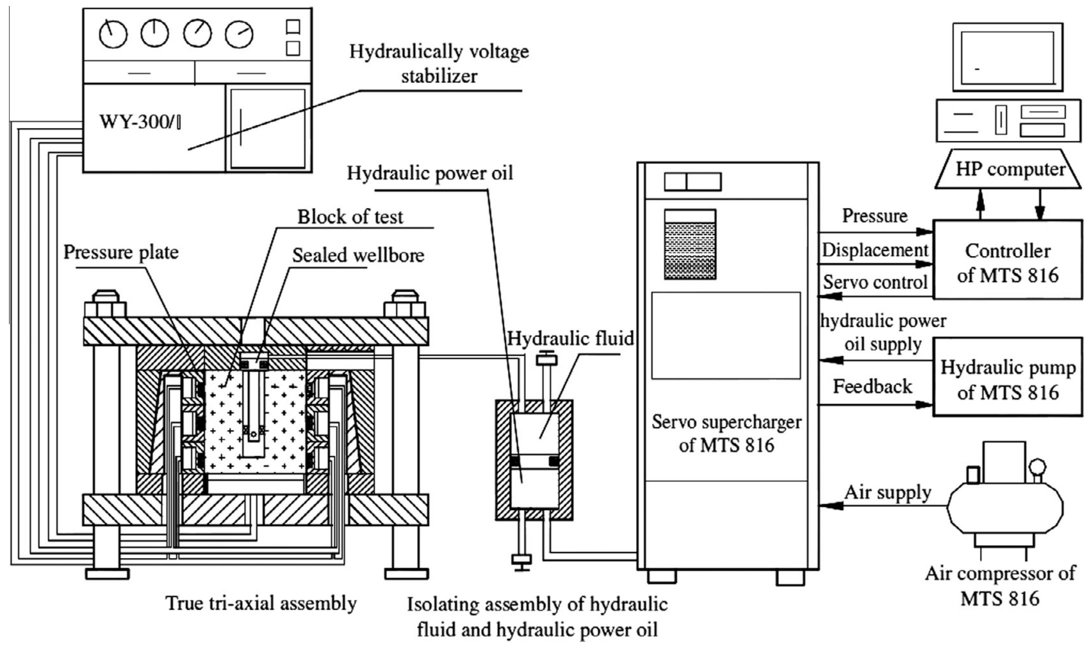

Fig. 1. Schematic of the true tri-axial hydraulic fracturing test system [21].

finite element method for modeling of 2D [23] and 3D [24] hydraulic fracturing. Boone and Ingraffea [25] proposed a procedure for the numerical simulation of two-dimensional, hydraulically driven fracture propagation in a poroelastic material using the finite element method in conjunction with the finite difference method. Schrefler et al. [26] presented a generalized finite element formulation incorporating solid and fluid phases together with a temperature field. And then Secchi et al. [27] presented a numerical procedure for the hydraulic cohesive crack growth in a multiphase system. Segura and Carol [28,29] developed and presented a coupled hydro-mechanical formulation for geomaterials with discontinuities based on the finite element method with double-node, zero-thickness interface elements.

In addition, the extended finite element method (XFEM) is used to model the HF. Lecampion [30] investigated the XFEM for the solution of hydraulic fracture problems. Mohammadnejad and Khoei [31,32] developed a fully coupled numerical model for the modeling of the hydraulic fracture propagation in porous media using the XFEM in conjunction with the cohesive crack model.

In this paper, we focus on the investigation of directional hydraulic fracturing (DHF) [15,16,33] based on true tri-axial experiment and finite element modeling. A series of true tri-axial experiments of hydraulic fracture are first conducted to investigate the fracture propagation behaviors of DHF. The influences of notch angle, notch length and injection rate on the DHF were investigated. And then the initiation and propagation of DHF was modeled by a 3D nonlinear finite element method. A vector criterion of unbalanced force (UF) was proposed to predict the hydraulic fracture initiation and propagation. The comparison between experimental investigation and numerical modeling of DHF indicates that there is a good correlation between the UF and fracturing and UF can be used to predict the position and direction of the hydraulic fracture initiation and propagation visually and accurately.

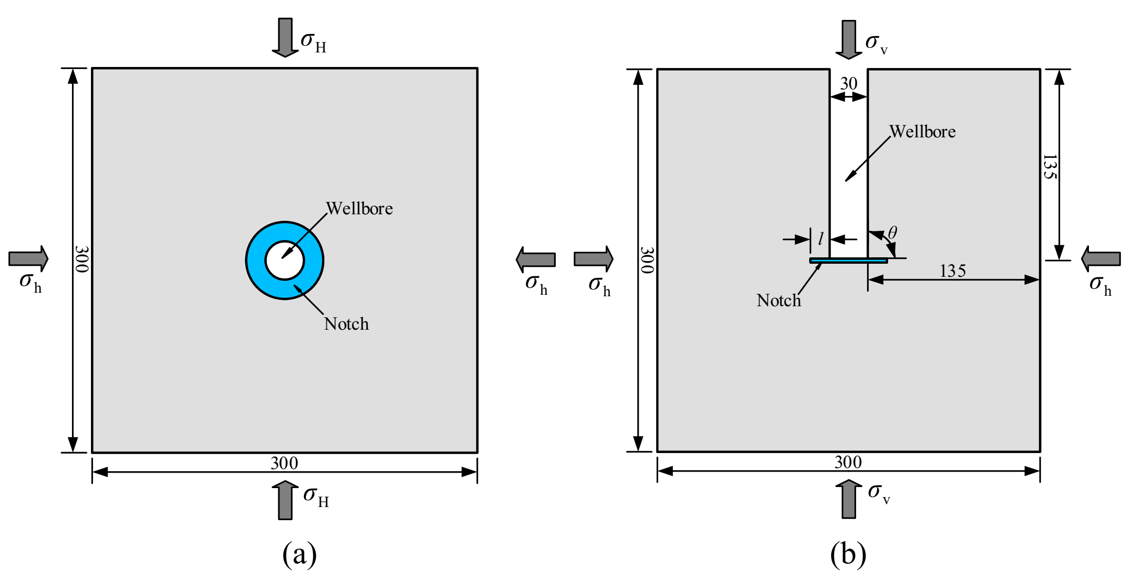

Fig. 2. Diagram of the specimens (Unit: mm): (a) transverse profile and (b) longitudinal profile.

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