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A coupled extended finite element approach for modeling hydraulic fracturing in consideration of proppant

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ABSTRACT

Due to its influence on the stress field around the propped fractures in horizontal well and the final conductivity of the created fracture network, the transport and packing of proppant plays a significant role in hydraulic fracturing. Therefore, it is important to describe the distribution of proppant in fractures and to accurately model the propped fractures. To this aim, a two-dimensional fully coupled model based on the extended finite element method (XFEM) is established, which takes into account some crucial physical processes, including rock deformation, fracturing fluid flow, fracturing fluid leak-off, propagation of fractures, proppant transport and proppant packing. The fluid-solid coupling equations are solved by the Newton-Raphson method and the proppant transport is evaluated by the upwind scheme. The hexagonal close packing of proppant is used to calculate the width of propped fracture. By taking advantage of the characteristic features of XFEM, an efficient strategy to model the propped fracture is proposed by directly enforcing the displacement boundary conditions on relevant enriched degrees of freedom without adding additional elements. The proposed coupled approach is validated by comparison with existing literature. The results of the sequential fracturing show that the propagation path of the subsequently created fracture is strongly affected by the boundary conditions (i.e., sliding contact, filled with constant pressure fluid, or propped open by proppant) imposed on the previously propped fracture, and the proposed XFEM-based strategy to model the propped fracture is an accurate and efficient alternative. Further sensitivity analysis reveals that the fracture spacing and the proppant concentration of the injected slurry also have significant influence on propagation path of the subsequently created fracture. The advantages of XFEM make the proposed coupled approach an attractive tool for the design of hydraulic fracturing.

1. Introduction

Hydraulic fracturing is a widely applied technology for enhancing production of conventional and unconventional oil and gas reservoirs. It usually involves using a high-pressure fluid to pressurize the wellbore until fractures emerge, which is followed by continuous injection of thousands gallons of fluid into emerged fractures to drive them to extend farther into the formation. During the injection process, proppant is added to the fracturing fluid at the right time to prevent fracture surfaces from fully closing when the fluid pressure drops (Britt, 2012). For a better understanding of hydraulic fracturing, many researchers have devoted their efforts to numerical simulation studies of this problem.

Many numerical methods have been adopted for the simulation of hydraulic fracturing, among which the most widely used are the displacement discontinuity method (DDM) (Kresse et al., 2013; McClure and Horne, 2013; Sesetty and Ghassemi, 2015; Weng et al., 2014; Zhang and Jeffrey, 2006), the finite element method (FEM) (Carrier and Granet, 2012; Chen, 2012; Guo et al., 2015a, 2015b; Papanastasiou, 1999; Wangen, 2011), and the recently developed extended finite element method (XFEM) (Dahi-Taleghani and Olson, 2011; Gordeliy and Peirce, 2013; Lecampion, 2009; Mohammadnejad and Khoei, 2013). The DDM is developed on the basis of linear elastic fracture mechanics as well as a variant of the conventional boundary element method (Wrobel and Aliabadi, 2002), and is suitable to model fracture. The finite

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element method is a flexible, effective and widely used numerical method. However, numerical simulation of large number of fractures in unconventional reservoirs using FEM is time consuming due to the remeshing process as fractures propagate. Some improvement strategies have been proposed to solve the shortcomings of FEM, among which the most effective one is the extended finite element method.

The XFEM (Daux et al., 2000; Moës et al., 1999; Stolarska et al., 2001; Sukumar and Prevost, 2003) allows fractures to propagate along arbitrary paths without explicit remeshing, thus the computational cost can be dramatically reduced in comparison to the conventional finite element method. The XFEM has not been applied to model hydraulic fracturing until recently. The XFEM was adopted to investigate the solution of hydraulic fracturing problem considering pressure inside the fracture and special tip enrichment functions (Lecampion, 2009). Then, the XFEM was used to model hydraulic fracture propagation accounting for the effect of the natural fracture (Dahi-Taleghani and Olson, 2011). Afterwards, a fully coupled XFEM model was established to describe the hydraulically driven fracture growth in porous formation (Mohammadnejad and Khoei, 2013). Recently, Gordeliy and Peirce (2013) developed two different schemes for fracture with fluid lag and fracture with singular tip pressure. Overall, in view of the flexibility of XFEM, many researchers are focusing on the development of XFEM-based hydraulic fracturing simulators.

Proppant transport plays an important role in hydraulic fracturing, especially for sequential fracturing where previously created fractures are propped by the injected proppant. This is because the opening of the propped fracture in a horizontal well will cause the stress reorientation in its adjacent region, which will influence the propagation paths of subsequent fractures. On the other hand, the final conductivity of the created fracture network is also related to the distribution of proppant. Over the years, some studies have been done for the modeling of proppant transport in a single planar fracture. A numerical model together with an adaptive finite element procedure was developed to simulate the proppant distribution in an expanding hydraulic fracture by Ouyang et al. (1997). A model based on finite difference method and finite volume method was developed to simulate fracture propagation, closure, contact and proppant transport by Zhou et al. (2014). Recently, a model capable of capturing both gravitational settling and tip screen-out effects was developed by Dontsov and Peirce (2015). In these studies, their research efforts are mainly focused on proppant transport in a single fracture, but not on the stress interference induced by the propped fractures for multistage fracturing. In practice, during the process of sequential fracturing, the subsequently created fractures will deviate from the desired propagation paths and turn to non-planar fractures due to the stress field induced by the propped fractures. The DDM-based unconventional fracture model (UFM) (Kresse et al., 2013; Weng et al., 2014) is able to model the creation of complex fracture network considering the proppant transport, but the width of fracture is calculated from the analytical solution. Recently, Sesetty and Ghassemi (2015) studied the effect of stress interference in the horizontal well based on DDM, but the proppant transport and the width of the propped fracture had not been considered in their model. In fact, the width of the propped fracture is directly related to the distribution of proppant (Bose et al., 2015). On the other hand, when dealing with hydraulic fracturing problems, the XFEM is a promising choice because fractures are completely independent of the mesh topology in XFEM and remeshing can be avoided. Therefore, it would be very useful and necessary to develop an XFEM-based model for hydraulic fracturing in consideration of proppant.

In this paper, we propose a two-dimensional fully coupled model which is able to consider a variety of physical processes, including fluid flow in fractures, fluid leak-off into surrounding rock formation, mechanical deformation of fracture walls induced by fluid pressure, propagation of fractures, proppant transport in fractures and proppant packing. This paper is focused on the proppant, so some other important topics such as the impact of in-situ natural fractures (Dahi-Taleghani and Olson, 2011; Guo et al., 2015a; Kresse et al., 2013; Weng et al., 2014) and the production performance (Sun and Schechter, 2015) are not discussed in the present study. In this paper, the proposed model is first validated by comparison with existing literature. Then, the simulation of sequential fracturing in a horizontal well is carried out to investigate the influence of proppant on stress distribution and propagation path of fracture. Further, sensitivity analysis is performed to investigate the effect of fracture spacing and proppant concentration of the injected slurry for sequential fracturing.

2. Problem formulation and numerical modeling method

Consider a fracture Γ_{frac} filled with high-pressure incompressible fluid in a domain Ω, as illustrated in Fig. 1. The boundary of the domain is Γ and the outwards unit normal vector of Γ is represented by $\boldsymbol{n}_{\Gamma}$. The prescribed tractions $\boldsymbol{t}$ and the displacements $\overline{\boldsymbol{u}}$ are imposed on the boundary Γ_t and Γ_u, respectively. The two surfaces of the fracture are expressed by the positive "+" and the negative "−" signs, and the outwards unit normal vectors of the positive and negative faces are donated by $-\boldsymbol{n}_{\Gamma_{frac}}$ and $\boldsymbol{n}_{\Gamma_{frac}}$, respectively. Slurry (for convenience, fluids with and without proppant are both named as slurry in this paper) are injected at the rate of $Q(t)$ at different time instants t. We define a one-dimensional curvilinear coordinate system (donated by s) along the fracture, and the coordinate origin is placed at the injection point.

Some assumptions are made for simplicity. In general, the slurry is not a Newtonian fluid. However, in terms of computer simulation, slurry can be treated as Newtonian fluid for simplicity (Adachi et al., 2007; Hammond, 1995; Tomac and Gutierrez, 2013). Besides, we assume that the propagation of the fracture is a quasi-static process, and there is no fluid lag between the fracture tip and the fluid front. The gravitational settling of proppant, which might not be particularly significant for the relatively lightweight proppant or the relatively high viscosity slurry (Mansoor, 2015), is not taken into account. In addition, the proppant flow back after the injection is finished is also not taken into consideration in this paper.

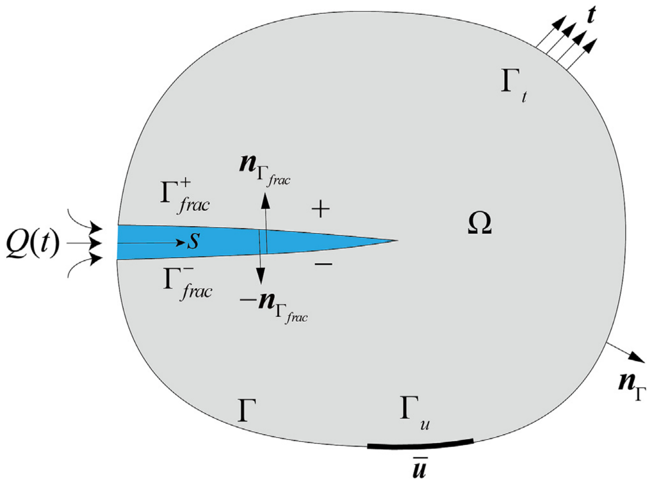

Fig. 1. Illustration of a domain containing a fracture filled with high-pressure fluid.