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Simultaneous initiation and growth of multiple radial hydraulic fractures from a horizontal wellbore

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ABSTRACT

Multi-stage fracturing is the current preferred method of completion of horizontal wells in unconventional hydrocarbon reservoirs. Its core component consists in simultaneously initiating and propagating an array of hydraulic fractures. We develop a numerical model for the initiation and growth of an array of parallel radial hydraulic fractures. The solution accounts for fracture growth, coupling between elastic deformation and fluid flow in the fractures, elastic stress interactions between fractures and fluid flow in the wellbore. We also take into account the presence of a local pressure drop (function of the entering flow rate) at the connection between the well and the fracture, i.e., a choke-like effect due to current well completion practices, also referred to as entry friction. The partitioning of the fluid into the different fractures at any given time is part of the solution and is a critical indicator of simultaneous (balanced fluid partitioning) versus preferential growth. We validate our numerical model against reference solutions and a laboratory experiment for the initiation and growth of a single radial hydraulic fracture. We then investigate the impact of stress interaction on preferential growth of a subset of fractures in the array. Our results show that a sufficiently large local entry friction provides a strong feedback in the system and thus can counteract elastic stress interaction between fractures, thereby ensuring simultaneous growth. We propose a dimensionless number capturing the competition between stress interaction and local entry friction. This dimensionless number is a function of rock properties, fracture spacing and injection parameters. We verify that it captures the transition from the case of simultaneous growth (entry friction larger than interaction stress) to the case of preferential growth of some fractures (interaction stress larger than entry friction). We also discuss the implication of these results for multi-stage fracturing engineering practices.

1. Introduction

More than 10,000 horizontal wells per year have been drilled and hydraulically fractured in the continental United States since 2007, with up to a hundred hydraulic fractures placed in the horizontal section of the well. In order to reduce operational cost, it is customary to create several hydraulic fractures at once. The well is therefore stimulated in stages, with one stage consisting of a single pumping operation aimed at initiating and propagating simultaneously N (typically between

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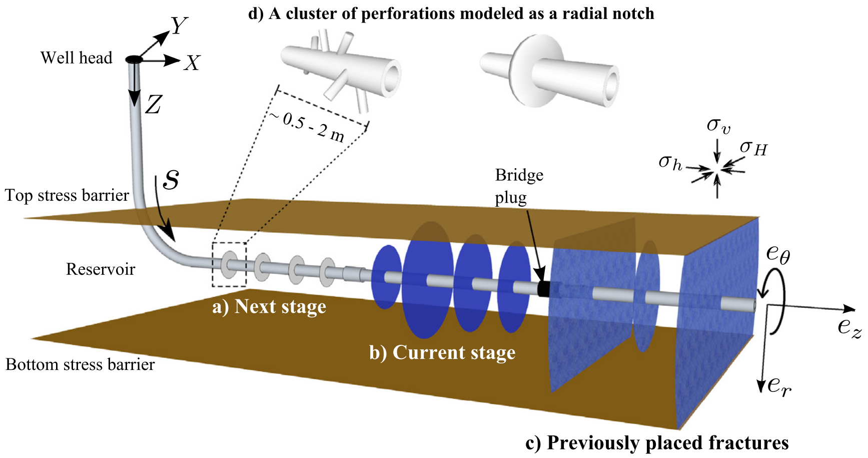

Fig. 1. Sketch (not to scale) of a multi-stage fracturing operation in a horizontal cased and cemented wellbore (drilled in the direction of the minimum horizontal in situ stress σ_h). One pumping operation consists in setting a bridge plug to hydraulically isolate the previously stimulated part of the well, pumping and firing perforation guns to control the location of the fractures along the wellbore. Fluid is then pumped from surface to simultaneously initiate and propagate a number (N) of hydraulic fractures (e.g., $N=4$ in this sketch). The hydraulic fractures can be assumed to grow radially transverse to the cased and cemented wellbore until they encounter a change of stress (stress barriers).

three and eight) fractures spaced about 10–30 m apart (see Fig. 1). The desired initiation point of a fracture is localized at a short section of the cemented casing where a cluster of perforations is shot to connect the well to the formation (typically 6–20 perforations over 1/2 to 2 m). Although such a multistage fracturing technique has enabled important cost savings, analysis of production logs over several basins indicates that about 30 percent of perforation clusters might not contribute to production (Miller et al., 2011). One possibility is that the process of simultaneously initiating and propagating an array of N fractures necessarily leads to preferential growth of some fractures, even under the assumption of a perfectly homogeneous medium. In this paper, we present a numerical model specifically developed to explore that process assuming a homogeneous isotropic medium.

The horizontal section of the well is typically drilled in the direction of the minimum horizontal in situ stress (see Fig. 1). It is therefore expected that hydraulic fractures will propagate perpendicular/transverse to the cased and cemented wellbore (Hubbert and Willis, 1957; Haimson and Fairhurst, 1969). At early time, the hydraulic fracture geometry will thus be radial. By early time, we mean prior to the fracture hitting a fracture height growth barrier (see, e.g., chapter 9 in Economides and Nolte, 2000). We will limit ourselves to such a geometry in the following.

There has been an extensive body of work on the growth of a single radial hydraulic fracture (Geertsma and De Klerk, 1969; Abé et al., 1976; Cleary and Wong, 1985; Spence and Sharp, 1985; Desroches and Thiercelin, 1993; Savitski and Detournay, 2002). In particular, it has been shown by Savitski and Detournay (2002) that the growth of a radial hydraulic fracture transitions from a regime dominated by viscous flow dissipation (viscosity dominated) to a regime dominated by fracture energy (toughness dominated) as the fracture perimeter increases with time. For a typical hydraulic fracturing treatment in an unconventional reservoir (even with water as a fracturing fluid), the toughness dominated regime is never reached for usual pumping duration (Savitski and Detournay, 2002; Bunger et al., 2007; Lecampion et al., 2013b). Therefore, to obtain any applicable results, the full fluid–solid interaction needs to be accounted for, strongly complicating the solution of the problem. The assumption of a uniformly pressurized fracture (the inviscid fluid limit) just does not hold.

In the case in which multiple fractures grow simultaneously, the elastic stress interaction between the growing fractures may shield some of them and promote preferential growth of a smaller subset of fractures. Such a shielding has been observed in the propagation of an array of fractures. Geyer and Nemat-Nasser (1982) have reported experimental results for crack growth driven by thermal stresses in a glass plate qualitatively in agreement with theoretical predictions (Nemat-Nasser et al., 1978; Nemat-Nasser and Oranratnachai, 1979; Bažant et al., 1979) – see also Santhanam (1993) for an axisymmetric configuration. Bunger (2013) has recently investigated the power required to propagate N hydraulic fractures and showed that fluid viscous dissipation is as important as the stress interaction on the evolution of the system. Recent numerical results by Bunger et al. (2014) for the simultaneous propagation of planar hydraulic fractures suggest that multiple growth is partly enhanced when the fractures are propagating in the viscosity dominated regime of propagation. In contrast, in the toughness dominated regime, where most of the energy is spent in creating new surfaces (and where the fluid pressure is uniform as a result), the effect of stress interactions between fractures results in preferential growth of some fractures (Bunger, 2013), a situation similar to dry cracks. However, as mentioned previously, toughness dominated propagation is the exception rather the rule in practice for hydraulic fracturing.

Our aim is to investigate some aspects of the initiation and propagation of simultaneous hydraulic fractures in order to try to better understand the robustness of multistage hydraulic fracturing. Contrary to all previous modeling studies which implicitly (Dahi Taleghani, 2011; Wu and Olson, 2015) or explicitly (Germanovitch et al., 1997; Gu et al., 2000; Weng et al., 2011; Xu and Wong, 2013; Bunger et al., 2014) assume that initially all hydraulic fractures are propagating and already much