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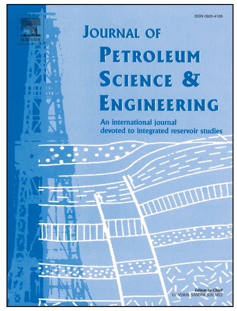

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Fluid mechanics of hydraulic fracturing: a review

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Abstract

Although hydraulic fracturing is a mature technology that has been used commercially since the late 1940s, the development of unconventional hydrocarbon fields with the combination of directional drilling and multistage hydraulic fracturing in the last two decades gave rise to a substantial progress in both operations and associated modeling. Numerical simulators, based on those models, are key to the design and evaluation of hydraulic fracturing treatments. Though hydraulic fracturing is a truly coupled phenomenon, the solid mechanics part of the problem has typically received more attention than the fluid mechanics part. Yet, that fluid mechanics field is a very rich multidisciplinary domain, presenting a number of challenges posed by the contemporary technology advancement, most of which being still unresolved. This paper aims to review the state of the art in multiphase fluid mechanics modeling of hydraulic fracturing, highlighting gaps in the body of knowledge and clarifying the questions that are still open.

This review sheds light on critical phenomena peculiar to hydraulic fracturing treatments, which are grouped into three categories (according to subsequent stages of the stimulation treatment): (i) proppant transport down the wellbore, (ii) proppant placement into the fracture, (iii) flowback from fractures into a well after the end of stimulation treatment (which is particularly important for preserving the integrity and conductivity of the fracture network). To support the modeling in these areas, constitutive relationships calibrated by experiments are of paramount importance. The list of phenomena, still not fully covered by modeling, includes: slugs dispersion in the well during alternate-slug fracturing, impact of fibers and visco-elasto-plasticity of the fracturing fluid on proppant placement in fractures, effects of complex rock fabric and real fracture morphology (roughness, steps, ledges, turns, and junctions), transition from dense suspension to close packing, dynamic bridging and mobilization, particle sedimentation to form a packed bed and re-suspension, dune transport in fracture network, overflush, and flowback into the near-horizontal well from fractures, to name a few. All these effects need to be properly accounted for in the hydraulic fracturing simulators in order for the contemporary technology of multistage fracturing to be designed, executed, evaluated, and optimized properly and safely to yield optimum production, especially in unconventional reservoirs.

Keywords: multiphase flow, flowback, hydraulic fracturing, proppant transport, shales, suspension, bridging, leakoff, well, particle, fracture, multistage fracturing, overflush, well, packing, granular rheology

1. Introduction

Hydraulic fracture propagation is a coupled problem of solid mechanics (fracture opening and growth) and multiphase fluid mechanics (slurry transport down the wellbore and placement in the fracture). The geomechanics aspect of hydraulic fracturing is thoroughly reviewed (see [18], and the most recent [49]). Whereas, the main aim of this paper is to critically review the fluid mechanics aspects of the process. We will look at the models of multiphase flows in wells and fractures, which are used in hydraulic fracture simulators, and highlight the gap between the state of the art in the development of technology and that in modeling. The latter typically advances with a certain lag behind the technology. In simulations of hydraulic fracturing, the focus is usually made on geomechanics of hydraulic fracture propagation, while fluid mechanics is deprioritized and simplistic models are used to track proppant during transport down the wellbore and placement inside the fracture.

At the same time, new technologies rolled out to the market recently, to develop both conventional and unconventional (source rocks) reservoirs utilizing complex fluid systems with solids admixtures, which are placed to keep fractures open and provide a conductive path for hydrocarbons from far field to the wellbore. The rheology of the carrier fluid is non-Newtonian and often can be characterized as visco-elasto-plastic due to added polymers [20]. The shear thinning nature of the carrier fluid helps reduce hydraulic resistance while pumping the slurry down the wellbore. On the other hand, the mixture develops a yield-stress behavior. Yield stress of the mixture can be both due to cross-linking of the polymer gel or due to the presence of the fibers. Cross-linking of the gel due to delayed chemical reactions, right about before the mixture enters the fracture through perforations, is designed on purpose to prevent undesired settling of solids to the bottom of the fracture. Fibers [69] are used as one of the key agents to keep the proppant-fluid mixture coherent and prevent proppant settling as well as creating fracture width. Fiber-laden fracturing fluids have been used routinely in the field for more than a decade now [59], and yet

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