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Modeling of the Hydraulic Fractures in Unconsolidated Oil Sands Reservoir

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ABSTRACT: Some fundamental mechanisms of hydraulic fracturing in unconsolidated formations have not been well understood although they have been studied quite extensively for hard rock formations. Laboratory and field evidences demonstrated that during the hydraulic fracturing of the unconsolidated porous materials such as oil sands reservoirs in Alberta, Canada, a single planar fracture is unlikely to occur, and the outcome is a high-porosity zone permeated by a network of micro-cracks. Thus, the numerical approaches based on the conventional fracture mechanics have limitations in modeling such complex processes.

The purpose of this paper is to present numerical simulation techniques in modeling the progressive mechanical breakdown of, and associated fluid flow in, unconsolidated oil sands. We will follow the continuum mechanics and use elasto-plastic model with strain softening for simulating the sands matrix deformation. The intimate coupling between the deformation and fluid flow is considered via a porosity-saturation-dependent isotropic permeability model. All such theoretical approaches are tested by history matching of mini-frac tests in the oilsands reservoirs.

1. INTRODUCTION

Fractures in the earth's crust are desired for a variety of reasons, including enhanced oil and gas recovery, re-injection of drilling or other environmentally sensitive wastes, measurement of in situ stresses, geothermal energy recovery, and enhanced well water production [1]. Fracturing unconsolidated formations is an increasingly important application of hydraulic fracturing in petroleum industry. In these unconsolidated formations, hydraulic fracturing has been mostly used for creating high conductivity channels for steam injection in cyclic steam stimulation operation, determination of the in-situ stress in mini-fracture tests, disposal of petroleum drilling waste into deep unconsolidated formation and frac-pack completion in deepwater wells.

Although hydraulic fracturing in hard rock has been comprehensively studied both experimentally and numerically, some fundamental mechanisms of hydraulic fracturing in unconsolidated formation have not been well understood. Both experimental data and field testing data clearly show that fracturing in unconsolidated formations is significantly different than those encountered in hard rock. Field observations regarding the occurrence of fractured zone as opposed to one single dominant fracture have been reported in many publications. By mining back into the hydraulic fractures created in unconsolidated formations, Schmidt [2] reported a very complex fracture patterns. Abnormal fracturing pressure in massive hydraulic fracturing treatments that was observed which was attributed to the presence of zone fracturing [3]. Beattie et al. [4] reported the measurement of surface heave as large as 45 cm during steam injection in Cold Lake oil sand. This is far larger than that attributed to thermal expansion or a single tensile fracturing of the formation. Also, steam injectivity was much greater than what might be expected based on the native reservoir properties. Multiple shear fractures and the resulting dilation zone have been identified as the main cause in both cases. Based on many field observations about hydraulic fracturing in oil sands which contradicted the conventional assumptions, Settari et al [5] concluded that very high fluid leak-off in the porous materials, such as oil sand, and the creation of fractured (dilated) zone is the main reason for the observed discrepancies. Also, a worldwide survey on fracturing pressures by the Delft Fracturing Consortium indicated that net pressures encountered in the field commonly are 50% to 100% higher than their corresponding values predicted by conventional fracturing simulators based on linear fracture mechanics [6]; the difference is even higher for the case of unconsolidated formations [7]. Thus, a numerical model capable of capturing some basic mechanisms of fracturing unconsolidated formations can be a valuable tool to overcome many uncertainties in the design of hydraulic fracturing and help the industry to optimize this process.

Several other significant works also supported the conclusion that a fracture in the weakly or unconsolidated formation is a zonal structure, rather than the planar structure normally expected in the hard rocks. For example, via image logging after the tests, Kry et. al. visually observed that the fracture created during the high pressure injection into the oilsands reservoir in Alberta, Canada was actually a zone that had a certain thickness and consisted of a multitude of microcracks [8]. These tensile microcracks did not connect with each other to form a macroscopic tensile fracture normally expected in hard rocks. Instead, they were permeated in and bridged by possibly dilated sands matrix. Based on this observation, Yuan (2008) derived a continuum-based fracture model and successfully history-matched a micro-frac test in the oilsands reservoir [9]. Through physical model tests, Khodaverdian et. al also postulated that fractures in the weak formations are either mobility-driven or formation damage-driven. In the latter, numerous shear cracks or fractures exist around a major tensile parting fracture. Together they form a fracture zone[10].

Even in its most basic form, hydraulic fracturing in unconsolidated sands is a complex process to model, as it involves the coupling of at least three processes: (i) the solid matrix deformation induced by the pore fluid pressure; (ii) the flow of fluid within the fractured zone and solid matrix; and (iii) the fractured zone initiation and propagation after formation failure. Thus, coupling of the solid matrix deformation and fluid flow is the key factor for modeling this complex process. In general, for modeling solid fracturing, the theoretical approach can be classified into the three categories of discrete models based on fracture mechanics, continuum models based on continuum mechanics, and statistical approaches [11]. For unconsolidated formations, a single planar fracture is very unlikely to occur, and the outcome is a fractured zone consisting of a network of interconnected tiny cracks. Thus, only continuum approaches are suitable in modeling this complex fracturing process. The hypothesis underlying continuum mechanics modeling approach is that the mechanical properties and ultimate strength of engineering materials depend, to a large degree, on micro-defects in their structure, and that under the presence of external effects such micro-defects may grow or nucleate. The presence of these micro-defects significantly affects the macroscopic elastic constants and strength of materials even when failure does not take place, and these effects may be described by one, or a set of internal variables [11, 12]. Thus, no real fractures really exist in the continuum mechanics modeling approach, and instead, the fracturing process is approximated by the change in the material behavior in macroscopic sense.

When coupling the continuum mechanics approach with fluid flow, the general hypothesis is that if an internal variable can be used as a state variable representing change in the mechanical properties of a fractured zone, then the same concept can be applied to the water mobility, which depends very much on the formation absolute permeability (k_a) and the relative permeability of water (k_{rw}). For the absolute permeability, there appears to be a general belief that absolute permeability of the porous media will increase as a result of fracturing or mechanical breakdown [13,14]. The relative permeability of water can be related to the water saturation (S_w) and oil saturation (S_o) if we assume that no free gas is involved at cold water injection at high injection pressure. Both the water saturation and the oil saturation change during the process of water injection, which finally results in the increase of the relative permeability of water. Thus, the increase of both absolute permeability and relative permeability of water contribute to the increase of formation water mobility during the hydraulic fracturing of unconsolidated oil sands reservoir. The flow model used in the numerical modeling should reflect these two factors properly.

The purpose of the paper is to present our modeling techniques in simulating the field scale hydraulic fracturing jobs in unconsolidated oil sands reservoir. We will follow the continuum mechanics and use elasto-plastic model with strain softening for simulating the sands matrix deformation. The intimate coupling between the deformation and fluid flow is considered via a porosity-saturation-dependent isotropic permeability model. All such theoretical approaches are tested by history matching of injection tests in the oilsands reservoirs.

2. GOVERNING EQUATIONS

The presence of a freely moving fluid in a porous medium modifies its mechanical response. Two mechanisms play a key role in this interaction between the interstitial fluid and the porous medium: (a) an increase of pore pressur
deformation in the porous me
of the porous medium cause
the fluid is prevented from