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Recent Advances in Proppant Embedment and Fracture Conductivity after Hydraulic Fracturing

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Review Article

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Abstract

Studies on fracture conductivity and proppant distribution in fractures are frequently carried out with growing attention drew to stable production and maximizing conductivity. Laboratory inability to create formation conditions sets a major obstacle to learn several months or years' long-term conductivity. Proppant embedment is also studied in a number of researches, though by application of various simplified analytical models. A suggestion on studying proppant embedment would be taking factors like proppant crushing and rock creep into consideration to gain a more thorough understanding in interactions between proppants and formation. An integrated Discrete-Element-Method (DEM)/Computational-Fluid-Dynamics (CFD) numerical modeling method seems to be the most effective way to model proppant embedment and fracture conductivity after hydraulic fracturing.

Keywords: Proppant embedment; Fracture conductivity; Long-term; DEM-CFD

Introduction

In recent years, while commercial exploration of shale gas developed rapidly in North America, China accelerated process of shale gas exploration. At present, Fuling, Changning, Weiyuan and Yanchang had become four major shale gas production regions in China and produced more than 6 billion cubic meters gas each year, which made China rank the third in the world for its shale gas production. However, geologically complex and deeply buried formations cost the exploration of a single well 40-50% higher than that in America. This, together with the sharp decline in international oil prices, brings troubles like high exploration cost and long payback period. It is the bottleneck issue that China's shale industry is facing now. The key to stable production is to maintain long-term conductivity in fracture.

Currently long-term conductivity tests in laboratory are difficult and expensive. Though a relative long-term conductivity of sandstone can be obtained in a month or two, there're few laboratory researches on shale fracture conductivity of several months. Fracture conductivity test for a longer period (several months or years) can be limited by laboratory inability to create formation condition. Furthermore, the shale gas development program would not allow a long-term conductivity test for a period of months or years. In recent years, a number of laboratory researches and theoretical studies were carried out on this problem. However, these studies mainly focused on short-term conductivity tests of propped and self-propped fractures and theoretical analyses based on simplified models. Few researches were carried out on long-term conductivity of shale fracture. Researchers should focus on the new investigation method, DEM-CFD modeling method to make more reasonable attempts for future studies on proppant embedment and fracture conductivity.

Proppant Distribution in Shale Formations

Nagel, Zhu and Guo studied complex fracture propagation in shale fracturing by numerical simulation [1-3]. They found that the bulk of the tensile failure occurred along the plane of the created main hydraulic fracture and the bulk of shear failure occurred within the natural fracture system. Xu developed a novel shale fracture simulator and found that the proppant mostly stayed in two sides of the main hydraulic fractures in a near-wellbore region [4]. Sahai conducted a series of test to evaluate proppant transportation in complex fracture networks [5]. Results showed fracture conductivity sustained by proppants in complex fracture networks, mainly appears at primary hydraulic fractures and secondary hydraulic fractures around primary fractures.

Laboratory Studies on Short-Term Conductivity

According to API RP 61, Recommended Practices for Evaluating Short Term Proppant Pack Conductivity, fracture conductivity is obtained when its variation is less than 5%. Usually, the testing time is within 50 hours. Many researchers carried out laboratory studies on short-term fracture conductivity. Kassis found that a sparse monolayer of proppant appeared to be equally or more effective than a denser fairway distribution regardless of proppant type [6]. Zhang learned that poorly cemented natural fractures and the slippage of unpropped natural fractures improved fracture conductivity significantly [7]. Fredd reported that monolayer proppant pack in secondary fractures provided higher conductivity [8]. Alramahi and Sundberg showed that a systematic increase in monolayer pack embedment with decreasing Young's modulus was responsible for a sharp loss in fracture conductivity [9]. Studies mentioned here mainly focus on the proppant-related effects on conductivity with various factors like proppant size, strength, proppant size combination, pack layers and so on.

Laboratory Studies on Long-Term Conductivity

In recent years, scholars extended testing time to more than 50 hours and found that the fracture conductivity continued to reduce. Raysoni and Weaver found the permeability of pack decreased with increasing test duration at different temperatures [10,11]. Significant loss of permeability and proppant strength occured rapidly within the typical expectancy of a hydraulic fracture. Aven studied the effects of temperature and long-term dynamic flow on proppant diagenesis on Ohio sandstone slabs [12,13]. About 40% to 60% permeability loss was observed caused by diagenesis over a six-month period of testing at 350 °F. Though a relative long-term conductivity (one to six months) can be obtained in laboratory, it is rather difficult to operate experiments under formation pressure and temperature in a laboratory setup. It's also time-consuming and expensive to perform such a test.

Theoretical Analyses on Proppant Embedment

Li derived an analytical model to compute monolayer and multilayer proppant embedment under specified closing stress [14]. Neto and Kotousov developed a simple semi-analytical method for calculating the residual openings of fractures based on the Distributed Dislocation Technique and Terzaghi's classical consolidation model [15]. Deng first used Discrete Element Method to simulate proppant embedment in shale formation [16]. In this model shale was simulated by bonded particles, and the prediction of residual fracture apertures were carried out under different proppant sizes, shale moduli and closing stresses. However, this model needs to be improved in various aspects like fluid flow within the porous proppant pack. Zhang developed an integrated DEM-CFD modeling work flow to model proppant embedment and fracture conductivity [17]. Fracture conductivity after fracture closing was evaluated by modeling fluid flow through proppant pack by use of DEM coupled with CFD. Results showed that the fracture conductivity increased with the increase of proppant concentration or proppant size, and decreased with the increase of fracture-closing stress or degree of shale hydration. Shale-hydration effect was confirmed to be the main reason for the large amount of proppant embedment. With increasingly frequent application of DEM-CFD, it was believed that DEM-CFD was the most suitable computational method for modeling two-way solid–fluid interactions [18].

Conclusion

As stated above, various models have been adopted to predict fracture conductivity. However, these models considered proppants as rigid particles and could only be used to study proppant embedment and fracture conductivity in a short time. Factors like proppant crushing, rock visco-elastic-plasticity, coupled flow-stress-damage are not learned yet [19-21]. Thus, further work on long-term proppant embedment and proppant crushing needs to be done before taking a deeper look into interactions between proppants and shale. Conclusions drew from these earlier work can provide instructive sights into further researches on proppant embedment and long-term conductivity of complex shale fracture systems.

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