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Theoretical and numerical studies of cryogenic fracturing induced by thermal shock for reservoir stimulation

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A B S T R A C T

The phenomenon of cryogenic fracturing in rock via thermal shock is approached theoretically and numerically. This study first proposes a theoretical solution of the temperature and stress distribution in a finite plate based on the thermoelastic theory and then discusses the effect of several parameters, including the heat transfer coefficient, the thermal conductivity and the size of the specimen, on the temperature distribution and the associated thermal stress evolution in the plate-shaped model. In addition to predicting the stress and temperature distribution based on the theoretical solution, numerical modeling of the initiation and propagation of cryogenic fractures in a finite plate is used to further explain the effect of the heat transfer coefficient on the density of the newly formed fractures and the length of the fracture growth. The initiation and propagation of cryogenic fractures around a borehole filled with cold liquid and the effect of anisotropic stress on cryogenic fracturing are also studied via numerical modeling. The fracture mechanics are based on the time-dependent thermal loading (thermal shock) and on the concept of stress release and redistribution, with single- and multiple-fracture propagation starting from quenching-generated flaws at the surface at the beginning of thermal shock. Analysis of the best method for increasing the heat transfer coefficient further indicates that it is feasible to stimulate reservoirs with the cryogenic fracturing technique to create a strong thermal gradient that generates a considerable local tensile stress in the rocks surrounding the pre-existing main fractures or the borehole.

1. Introduction

Fractures are common features and have been observed in many materials for a long time. Some fractures can be observed by the naked eye, whereas others can be observed only with the help of instruments such as microscopes. Fractures often result in instability or collapse in many materials and structures, but they are sometimes helpful for industrial production. Hydraulic fracturing is beneficial for oil or gas extraction from low-permeability reservoirs[1] and the utilization of geothermal energy from hot, dry rock. Well stimulation by hydraulic fracturing is a process in which crack initiation and propagation is achieved by injecting fluid and proppant at a high rate and pressure into a reservoir. Although the use of hydraulic fracturing has drastically changed the expected production from unconventional resources, the serious reliance on water is associated with some disadvantages, such as formation damage and public scrutiny of fracturing fluids and chemicals. Therefore, waterless or reduced-water technologies have received more attention in recent years.

The purpose of hydraulic fracturing is to create fractures and significantly increase the accessible contact area between the reservoir and the borehole. In addition to hydraulic fracturing, temperature changes in the rock can also result in fractures. In the past several decades, a high-pressure water jet technology has been shown to successfully allow drilling into deeply buried hard rock to exploit geothermal energy.[2–4] In this method, a high heat flux is transferred from the impinging hot fluid jet to the rock, leading to high thermal stress in the rock due to the low thermal conductivity of rock. This thermal stress produces spalling fractures in the rock, which are mainly concentrated within a certain range from the rock surface and cannot extend deep into the rock. Fractures can be created by sudden temperature changes in materials, most often by subjecting a warm material to a cold fluid, which results in a thermal contraction of the surface and local tensile stress. Cracks form when the tensile stress exceeds the tensile strength of a material. The introduction of cold temperatures is much more conducive to forming cracks in rock than that high temperatures. This mechanism is beneficial for reservoir stimulation and the reduction or elimination of the use of water in hydraulic fracture engineering.

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Thermal shock has long been recognized as an important failure phenomenon in brittle solids due to sudden thermal transients, such as in ceramics with high-temperature quenching in cold water.[5,6] Finnie et al.[7] indicated that the rapid decrease in the temperature of the surface of a rock leads to tensile stresses that cause cracks to initiate and propagate into the rock. These authors also concluded that liquid nitrogen alone may be used in such a process, without prior heating and that it is possible to crack rock in this manner given sufficient time. Kim and Kemeny[8] experimentally studied the effects of rapid cooling and rapid unloading on rock damage and conducted thermal shock experiments consisting of slow heating up to a temperature of 100 °C followed by rapid cooling with a fan. Bažant et al.[9] reported that the cooling of rock in geothermal heat extraction from a hot, dry rock mass is sufficient to cause secondary cracks, which propagate from the crack walls orthogonally to the vertical plane of the main crack that was created by the hydraulic fracturing. Tran et al.[10] studied the potential of thermally induced tensile fracturing in a borehole in the Barnett shale, which has a low porosity and an ultralow permeability. Enayatpour and Patzek[11] numerically studied the thermal cracks in rock and suggested that the productivity of wells can be improved by injecting cold fluid into tight formations. Cha et al.[12] reported laboratory results for cryogenic fracturing in concrete and sandstone to study the feasibility of fracture stimulation by using cryogenic fluids to generate fractures in the rocks surrounding reservoir rocks. Cai et al.[13] indicated that the cooling of sandstone, marble, and shale samples with liquid nitrogen increased the degree of fracturing inside these rocks, especially the shale samples, consequently increasing the stimulation reservoir volume during the fracturing process.

The thermal stress caused by thermal shock depends on many material properties, including the elastic modulus, thermal expansion coefficient, tensile strength, thermal conductivity, and thermal diffusivity, and many parameters, including the heat transfer coefficient, specimen size, structure of the material (porosity) and duration of the thermal shock. For example, experimental experience suggests that porosity is detrimental to the cold-shock resistance of ceramics but is beneficial to hot-shock resistance,[14] which means that cold shocking is more suitable for tight shale than for high-porosity sandstone. However, current knowledge of the underlying mechanisms behind these phenomena appears to be quite limited. For example, Dahi Taleghani et al.[15] and Wang et al.[16] studied the effect of temperature on preexisting fractures and newly initiated fractures during hydraulic fracturing, Tarasovs and Ghassemi[17] and Than et al.[18] discussed the initiation and propagation of secondary cracks in rock and the associated crack widths and lengths. These studies address the boundary condition between the surface of the rock and the cold fluid by assuming that the temperature on the rock surface suddenly equals that of the cold fluid, i.e., the first thermal boundary condition. However, in reality, this contact is a heat convective boundary, and the temperature of the rock surface in contact with the cold fluid does not instantaneously to reach the temperature of the cold fluid; this period of time depends on the convective heat transfer coefficient between the fluid and the rock. Thus, the previous authors' models capture the initiation of thermal shock-induced cracking in rock under extreme conditions in which the convective heat transfer coefficient is infinite. Hasselman[19] derived a criterion of crack stability for a brittle solid uniformly cooled with triaxially constrained external boundaries that neglected the thermal conductivity of the material. Other parameters for anthropogenic materials and thermal shock environments have also been discussed,[20–24] and the results suggest that it is beneficial to couple the material properties and geometrical parameters in the thermal and stress fields to successfully predict the fracture behavior of brittle solids subjected to thermal shock. However, few studies have focused on the thermal shock of geomaterials such as rock. In low-permeability reservoirs, especially somewhat water-sensitive reservoirs such as Devonian shale,[25] cryogenic fracturing treatment is currently a potential method of well stimulation. Fracturing this type of formation with a cold fluid such as liquid nitrogen rather than warm gas could more efficiently prop open the resulting fractures. Longer fracture might form due to hydraulic effects along in the thermally induced fractures. These effects could significantly improve the surface area available for gas diffusion out of the shale.[25] However, the controls of cryogenic fracturing length in rock have not been clearly discussed before.

Cryogenic fracturing in practical reservoir stimulation is a complex process that includes thermal conduction/convection, deformation, fracture propagation, fluid flow even phase transition. The significant difference between cryogenic fracturing and conventional hydraulic fracturing is that cryogenic liquid could result in multiple fractures forming in the reservoir rock which is beneficial to oil and gas production. Therefore, it is important to study the fracture initiation and propagation of rock under thermal shock conditions. Of course, as indicated by Cha et al.,[26] other processes, such as phase transition induced pressure, also benefit fracture initiation and propagation. However, this study mainly focuses on the thermal shock process, including thermal/mechanical response and the fracturing process, to study the effect of sensitive factors on cryogenic fracturing. Therefore, the present paper revisits the classic problems of thermal shock in a plate and a plate with a circular hole via both theoretical and numerical models. The main feature that differentiates this work from most previous studies is that the material considered is rock; the theoretical model is capable of characterizing the thermal shock resistance of a rock, and the numerical model is capable of simulating the thermal fracture initiation and propagation processes during thermal shock. This paper begins by theoretically studying the transient temperature and stress distributions in homogeneous models with different thermal, mechanical and geometric parameters. Next, the cryogenic fracturing initiation and propagation induced by thermal shock in both a plate and a plate with a circular hole are addressed by assuming that the rock is a heterogeneous material.

2. Theoretical studies on a plate subjected to thermal shock

2.1. Temperature and thermal stress distribution

One of the most important issues for the cryogenic fracturing is the creation of secondary fractures around the main fracture. Therefore, we focused on the initiation and propagation of secondary fractures induced by cold shock around the main fracture at first. Consider a very long main fracture defined by the KGD (Khristianovic-Geerstma-de Klerk) model[27] shown in Fig. 1, in which cryogenic fluid is continually injected by a supplied source to maintain the opening width. When the tensile stress exceeds the tensile strength of the rock, a new crack, perpendicular to the main fracture, initiates at the main fracture boundary, as shown in Fig. 1. Such a problem can be simplified to study the cryogenic fracturing of a plane of a KGD fracture model, as shown in Fig. 2.

Previously, many experimental studies on the fracturing of brittle

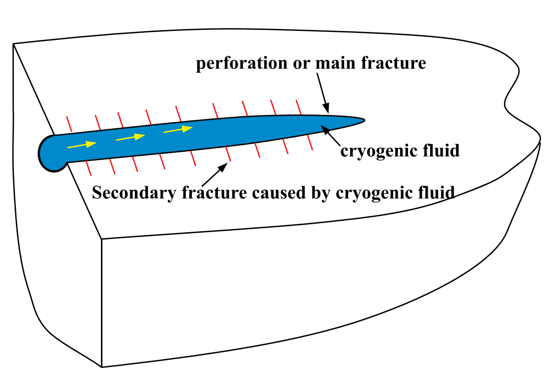

Fig. 1. Sketch of the application of cryogenic fracturing for reservoir stimulation.