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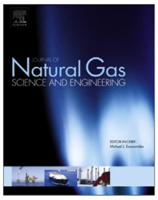

Numerical modeling of cryogenic fracturing process on laboratory-scale Niobrara shale samples

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ABSTRACT

Cryogenic fracturing is a new fracturing concept that uses cryogenic fluids as fracturing fluids. Its mechanism rests on the effect of a thermal shock (sharp thermal gradient) introduced by cryogen on the hot surface of reservoir rock. Fractures can then be initiated and propagated due to strong local tensile stress. The objective of this research is to simulate the cryogenic fracturing experiments on Niobrara shale samples. The experimental processes are simulated under different conditions and matched with the actual experiment results. The influences of different confining stress, injection pressure and failure criteria are identified by comparing results from modeling and experiments. The simulation tool developed can also predict the distribution of artificial fractured samples.

1. Introduction

Cryogenic fracturing is a new concept that looks to expand and improve on traditional hydraulic fracturing technology. The concept rests on the idea that a cryogenic fluid (such as liquid nitrogen) can induce fractures when brought into contact with a much warmer rock under downhole conditions. The rapid heat transfer, better known as a thermal shock, will cause the surface of the rock to shrink, relative to the inner warmer material of the rock and eventually fail in tension, inducing fractures orthogonal to the contact plane of the cryogen and the rock. Cryogenic fracturing technology could potentially increase the effects of fracturing and decrease the cost of fracturing resulting in more formations becoming economically viable.

The first cryogenic fracturing experiment was conducted by using gelled liquid carbon dioxide to stimulate tight gas sand formations instead of conventional fracturing fluids such as water or oil (King, 1983). All of the wells showed increased production rate after treatment. To further address the fracturing mechanism, McDaniel et al. (1998) conducted several laboratory liquid nitrogen submersion tests on coal samples to prove that cryogenic fracturing may have an advantageous effect on gas production from tight, low-rate coal-bed methane wells. They also applied cryogenic fracturing to 5 wells for field tests, which showed mixed results: three of them experienced increased production rate, one experienced equivalent production and one experienced decreased production. Among the three wells with increased production, two of them had long term increment in production. Grundmann et al. (1998) conducted later a cryogenic fracturing treatment in a Devonian shale well with liquid nitrogen. The well showed an 8% increment in the initial production rate when compared to a nearby offset well that underwent a traditional nitrogen gas fracturing treatment.

Thermally induced fracturing is one of the most important phenomenon during cryogenic fracturing. Although it is well established in rock mechanics, the focus of previous studies are mostly on high temperature rock failure, such as thermal spalling and thermal pressurization by pore fluid. Very few studies were conducted for rock failure at low temperature. The most simplified model for thermally induced fracturing during water injection is simply assume the fracturing pressure of the rock to be equal to the minimum stress with thermal effect (Detienne et al., 1998). Zoback (2007) presented a failure criterion for fracture initiation coupled with thermal effect as:

$$p_b = 3\sigma_{h\min} - \sigma_{H\max} - p_p - \sigma^{\Delta T} \qquad (1)$$

where:

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p_b is the formation break down pressure;
$\sigma_{h\min}$ is the minimum horizontal stress;
$\sigma_{H\max}$ is the maximum horizontal stress;

p_p is the pore pressure;

$\sigma^{\Delta T}$ is the thermo-elastic stress.

Luo and Bryant (2010) adapted this criterion and applied it to a research on CO_2 injection induced fractures. Zhou et al. (2010) studied the initiation, propagation and interaction of thermal failures within impermeable, hot and dry rocks due to the cooling of a main hydraulic fracture by long-term reservoir fluids circulation, combining thermo-elastic model (Jaeger et al., 2009) and stress intensity factor (Olson and Pollard, 1991).

The objective for this study is to model and evaluate the experimental cryogenic fracturing treatments on Niobrara shale samples. The fracturing process at low temperature of rock samples during cryogenic treatment are simulated and matched with experiment results. The simulation tool is capable of predicting the fracture distribution. In addition to previous studies, the influences of different confining stresses and injection pressure are identified. This study also provides valuable guidance to potential field applications of cryogenic fracturing technology.

1.1. Theoretical analysis

1.1.1. Heat transfer and fluid flow model

For an arbitrary control volume with arbitrary shape, the governing equation for mass and heat balance according to Fakcharoenphol et al. (2013) can be written in the form:

$$\frac{d}{dt}\int_{V_n} Q^{\kappa} dV_n = \int_{\Gamma_n} F^{\kappa}\cdot \vec{n}\, d\Gamma_n + \int_{V_n} q^{\kappa} dV_n \tag{2}$$

where:

$\kappa = 1, \ldots, NK$ (total number of components);
$n = 1, \ldots, NEL$ (total number of grid blocks);
V_n is an arbitrary subdomain of the system under study;
Γ_n is the closed surface by which the subdomain is bounded by;
Q is the quantity represents mass or energy per volume;
F is mass or heat flux;
q is sinks and sources;

$\vec{n}$ is a normal vector on surface element $d\Gamma_n$ pointing inward into V_n.

1.1.2. Thermoelastic model

Thermal stress is the stress change caused by temperature change within a solid material. It is the most important parameter when simulating the cryogenic fracturing process. The thermally induced stress can be integrated into the generalized stress-strain relation in a rock volume (Zoback, 2007), as shown below:

$$\begin{aligned}&\sigma_{kk} - B_i \times p_p - \frac{E}{(1-2\nu)}[\beta(T-T_0)]\\&= \frac{E}{(1+\nu)}\varepsilon_{kk} + \frac{E}{(1+\nu)(1-2\nu)}(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})\end{aligned} \tag{3}$$

Where:

σ is the normal stress;
ε is the strain;

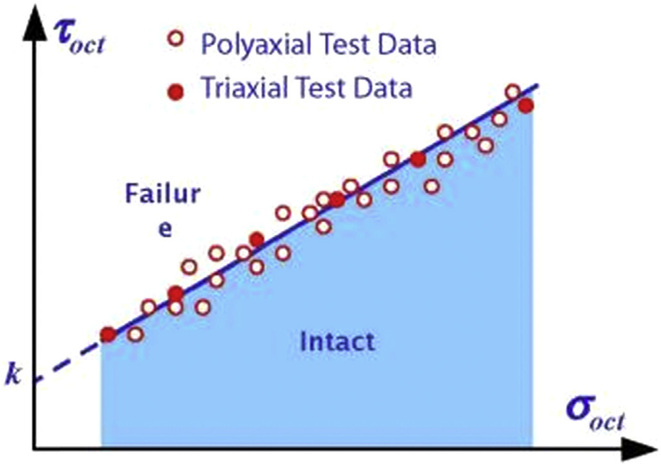

Fig. 1. Failure envelope of Mogi - Coulomb criterion by Aadnoy and Looyeh (2011).

Subscript kk is direction, which can be x, y and z;
B_i is the Biot number of the rock;
β is the linear thermal expansion of the rock;
E is the Young's modulus;
ν is the Poisson's ratio;
p_p is the pore pressure;
T is the current temperature;
T_0 is the reference or original temperature.

1.1.3. Rock failure criteria

A failure criterion is used to judge the condition of rock fracturing. It gives the maximum strength of rock under certain stress conditions. Once the stress exceeds the maximum strength given by the failure criterion, the rock will break, in other words, be fractured. The current failure model used in this simulating tool is the Mogi – Coulomb Failure Criterion, which is first introduced by Al-Ajmi and Zimmerman (2006) and widely used in rock mechanics. The Mogi – Coulomb Failure Criterion has the following

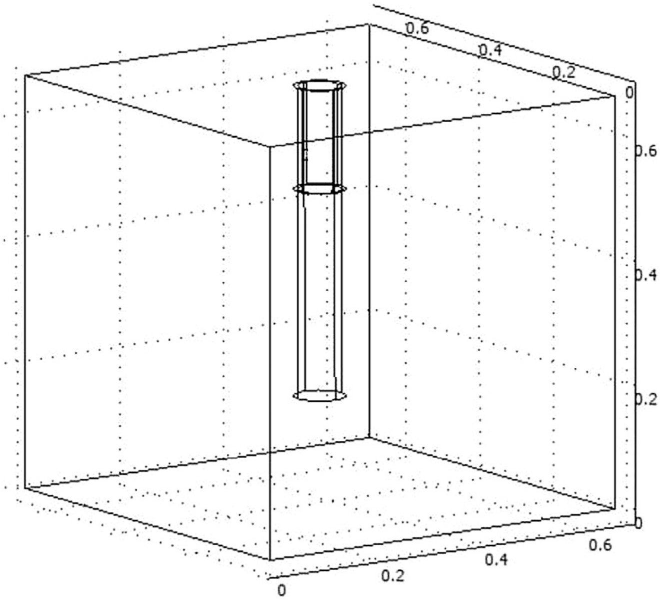

Fig. 2. Schematic drawing for modeling geometry.

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