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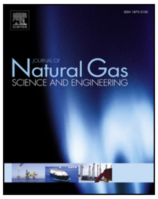

Experimental study of the effect of liquid nitrogen pretreatment on shale fracability

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ABSTRACT

When cryogenic liquid nitrogen (LN_2) comes into contact with deep reservoirs, it will bring about serious thermal damage to rock pore structure. Therefore, LN_2 pretreatment on reservoirs can contribute to further improving the stimulated reservoir volume (SRV) during large-scale hydraulic fracturing. To investigate the effect of LN_2 pretreatment on the SRV of shale reservoirs, a series of physical and mechanical experiments related to shale reservoir fracability were conducted. A quantitative fracability evaluation model suitable for different confining pressures was developed from the perspective of fracturing mechanisms. The changes in shale fracability due to LN_2 pretreatment were discussed in detail. The responses in P-wave velocities and $T2$ spectrum curves demonstrate that shale pore structure is subjected to serious damage after freeze-thaw cycles, and some micro-pores are aggregated to form micro-cracks or even macro-cracks. The decreases in tensile, compressive and shear strength and elastic modulus show that the mechanical properties of shales are deteriorated due to cryogenic damage effect. The changes in physical and mechanical properties of shales reveal respectively that LN_2 pretreatment can lead to a slight reduction in shale brittleness, a significant improvement in micro-crack development, a moderate decrease in stability of the bedding planes, a relative increase in the propagation ability of fractures. Based on the result of the analytic hierarchy process, it can be concluded that shale fracability is efficiently enhanced due to LN_2 pretreatment, especially under high confining pressure condition. Finally, the hydraulic fracturing experiments under tri-axial stress were carried out to further validate the feasibility of LN_2 pretreatment to improve the SRV of shale reservoirs. Compared with the experimental results without LN_2 pretreatment, it is found that the initiation pressure and initiation time decline by about 54% and 60% respectively. Both the size and complexity of the SRV of shales are enhanced obviously.

1. Introduction

Unconventional shale gas reservoirs possess extra-low porosity (usually $< 10\%$) and ultra-low permeability (usually < 0.1mD), which consequently results in the difficulties of obtaining industrial production rate before large-scale hydraulic fracturing treatment. Admittedly, horizontal wells combined with multistage hydraulic fracturing have become a crucial technology for the effective development of shale gas resources (Fisher et al., 2005; Mayerhofer et al., 2010; Wu et al., 2012). However, the SRV of shale reservoirs in China is usually limited compared with the successful development cases in America shale gas fields. This is mainly due to the unique geomechanical characteristics in China shale reservoirs such as low rock brittleness, undeveloped natural fractures and large horizontal stress difference, etc. (Zou et al., 2017). The obvious plastic and nonlinear deformation characteristics for deep shale reservoirs also yields a higher initiation pressure and lower SRV. Additionally, the multistage fracturing technology mainly adopts water-based fracturing fluid, which can bring about a series of crucial problems such as formation damage, water resources shortage, backflow difficulty and environmental pollution. In order to address the negative effects associated with hydraulic fracturing, putting forward a novel fracturing technology or method, which can not only improve the SRV, but also alleviate the ecological environment problems, becomes essential to efficiently and rationally exploit the shale gas resources.

Cryogenic liquid nitrogen (LN_2) ($-196\,^{\circ}$C at 1atm) coming into contact with rocks will induce serious damage to pore structure owing to the thermal shock and frost effect. Thus, LN_2 fracturing could have some promising application prospects in improving the SRV of

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unconventional oil and gas reservoirs. Some experimental studies (Cha et al., 2014; Wang et al., 2016; Zhang et al., 2016) have revealed that cryogenic waterless fracturing fluid, such as LN_2 and supercritical or liquid carbon dioxide, have the potential to achieve larger fracture networks. Limited mine applications (King, 1983; Grundmann et al., 1998; McDaniel et al., 1997; Gupta and Bobier., 1998) have also demonstrated that the initial production rate is effectively improved after cryogenic fracturing treatment. However, the obstacle that must be firstly addressed besides the equipment conditions is the transport of proppants in LN_2. This is because that the viscosity of LN_2 is too low to carry proppants into the fractures. Especially, when LN_2 is injected into the formation from the surface, based on the phase diagram analysis of nitrogen, it may transform into a supercritical fluid, which leads to a significant decrease in the viscosity of liquid nitrogen. Besides, the self-propping theory to coal (McDaniel et al., 1997) may be inappropriate for shale, because the rubblization process usually does not appear for shales in experimental studies. The accompanying turbulence effects by increasing the fluid velocity can only transport proppants from the wellbore to the perforations (Gupta and Bobier., 1998). Considering the limitations of fracturing with LN_2, LN_2 pretreatment combined with hydraulic fracturing or LN_2-hot fluid-water alternate injection fracturing may be a feasible technology that can simultaneously generate large fracture networks and effectively carry proppants into fractures. A similar theory (cryogenic fluid alternate hot steam injection) has been proposed to increase the permeability of formations (Halbert, 1971).

Some studies have been conducted to separately investigate the effect of cryogenic LN_2 pretreatment on the physical and mechanical properties of rocks (Inada and Yokota, 1984; Inada et al., 1997; Aoki et al., 1990; McDaniel et al., 1997; Hori and Morihirob, 1998; Yavuz et al., 2006; Li et al., 2012; Cai et al., 2014a,b; Han et al., 2018). All results reveal that after cooling-heating cycles, the inner structure of rocks is severely damaged and the strength of rocks is obviously weakened. The effect of LN_2 pretreatment on re-fracturing process has been studied (Zhao et al., 2016). The result shows that many thermal cracks perpendicular to the original fracture surfaces were induced under high thermal gradient. These thermal cracks can provide the weakened zones for hydraulic fracture reorientation. Although all experiments have indicated that cryogenic pretreatment can create a favorable condition for hydraulic fracturing, to the best knowledge of the authors, no research now is conducted to reveal the effect of LN_2 pretreatment on the formation of complex fracture networks in shale reservoirs, especially from the perspective of fracturing mechanisms.

The main purpose of this paper is to investigate the effect of LN_2 pretreatment on shale fracability, and discuss the feasibility of the cryogenic LN_2 pretreatment to improve the SRV of shale reservoirs. In Section 2, the influencing factors related to shale reservoir fracability and also influenced by LN_2 cooling were analyzed, then some new quantitative evaluation formulas for each potential factor were constructed. In Section 3, a series of experiments involving these potential influencing factors were performed with and without LN2 pretreatment, respectively. The changes in the physical and mechanical properties of shales due to cryogenic damage were analyzed in detail. In Section 4, a universal evaluation model for reservoir fracability was developed by integrating the physical and mechanical factors based on analytic hierarchy process, and the change in shale reservoir fracability was discussed. Tri-axial fracturing simulation experiments were performed to further validate the effect of cryogenic pretreatment on shale fracability. The meaningful conclusions were summarized in Section 5.

2. Analysis of factors influencing shale fracability

Fracability represents the intrinsic ability of the reservoir to generate the sufficient and complex fracture networks under the same engineering condition. Mine practices show that reservoirs with higher fracability is usually considered to be the better fracturing candidate (Chong et al., 2010; Zou et al., 2016a,b). At present, fracability index has been widely regarded as an integrated variable that can quantitatively characterize the ability of reservoirs to form complex fracture networks. Unfortunately, a universal model for evaluating the fracability index is not yet available. Some researchers initially adopted rock brittleness index to directly evaluate reservoir fracability (Jarvie et al., 2007; Bybee, 2009). However, the on-spot fracturing practices demonstrated that high brittleness layers did not necessarily generate complex fracture networks, i.e. those limestone or granite layers with very high brittleness may become the barriers that impede the further propagation of fractures. Therefore, the construction of a fracability evaluation model should not only consider positive influencing factors (such as rock brittleness, fractures development), but also contain negative effects related to energy dissipation such as clay content and fracture toughness. All potential influencing factors are not independent, but jointly characterize the fracability of shale reservoirs. Some evaluation models have been developed by comprehensively considering the geological, mechanical and physical factors (Sui et al., 2016; Wang et al., 2015; Jin et al., 2014; Fu et al., 2015). From the perspective of fracturing mechanism, only these factors seriously affected by LN_2 pretreatment are analyzed and incorporated into the universal fracability evaluation model in this paper.

2.1. Rock brittleness

Brittleness characterizes the mechanical response of rocks to the failure process under specific external loading conditions. Generally, brittleness represents the ability of rocks to form multi-dimensional complex fragments, it dominates the complexity of the fracture networks during fracturing process. At present, there are three main methods to evaluate rock brittleness index in petroleum industry, namely log data interpretation (Rickman et al., 2008), mineral content analysis (Jarvie et al., 2007; Gale and Holder, 2010) and rock mechanics experiments. The calculation of dynamic elastic parameters based on logging data to evaluate rock brittleness is a more common method in the field. Purely considering the mineralogical compositions of rocks, it is easy to neglect the influence of diagenesis and in-situ stress. Moreover, the mineral components of rocks are generally not influenced by external conditions (such as LN_2 pretreatment). The mechanics experiments are considered here to be a more reasonable method to evaluate rock brittleness. Rock mechanics methods usually include deformation/strength characteristics analysis (Hucka and Das, 1974; Altindag, 2010; Li et al., 2012) and energy dissipation analysis (Tarasov and Potvin, 2013; Hou et al., 2016; Xia et al., 2016; Zhang et al., 2017).

However, most mechanical evaluation models based on the stress-strain curve separately consider the pre-peak or post-peak deformation characteristics, and the entire failure process of rocks is neglected. In fact, the pre-peak deformation feature only represents a threshold of rock brittleness, and the post-peak failure behavior mainly determines the strength of brittleness. Brittleness characterizes the ability of rocks to resist inelastic deformation in the pre-peak region and self-sustain macroscopic failure in the post-peak region. Therefore, the evaluation of brittleness should consider the entire deformation and failure process of rocks. Essentially, the deformation and failure of rocks is a dynamic instability process involving the energy dissipation and release. For the whole loading process, the pre-peak dissipative energy reflects the ability of rocks to resist inelastic deformation, and the post-peak rupture energy characterizes the ability of rocks for self-sustaining failure. If the elastic energy accumulated in the loading process is sufficient to maintain the self-failure process of rocks, then the sudden release of excessive elastic energy will bring about the intact rock to break into fragments. Otherwise, the additional energy supplied by external loading system is required to support the failure of rocks, which indicates that rock brittleness is relatively low. Therefore, under tri-axial stress, a brittleness evaluation criterion based on energy balance can better reflect the difficulty of rock brittle failure and reveal the