INFLUENCE OF LIQUID NITROGEN COOLING ON BRAZILIAN SPLITTING CHARACTERISTIC OF COAL AND SANDSTONE

by

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The use of liquid nitrogen fracturing can effectively improve the permeability of unconventional natural gas reservoirs. In order to explore the impact of liquid nitrogen cooling on the tensile failure behavior of coal and sandstone, a series of physical and Brazilian splitting tests were conducted on coal and sandstone. Compared with the control group, the velocity, tensile strength, and splitting modulus reduction of coal were 24.7%, 19.7%, and 52.4%, respectively, and the corresponding reductions for sandstone were 5.5%, 14.7%, and 15.4%. Energy analysis and failure characteristics demonstrated that liquid nitrogen cooling promoted widespread distribution of internal damage in coal and sandstone, and the degree of internal structure damage determined the complexity of the failure mode. The greater the internal damage, the more branch cracks occurred during failure, and the greater the path tortuosity and degree of fragmentation.

Key words: *liquid nitrogen cooling, tensilestrength, coal and sandstone, applied energy, crack path*

Introduction

Compared with traditional hydraulic fracturing, liquid nitrogen fracturing can achieve better reservoir transformation effect, with strong reservoir adaptability, less environmental impact, saving a lot of water resources, and wider applicability [1, 2]. The liquid nitrogen fracking technology for enhanced oil and gas recovery has achieved success in the oil and gas field [3, 4]. In order to further improve the engineering application of this technology, it is essential to study the intrinsic permeability mechanism of the liquid nitrogen thermal-pressure effect on reservoirs. Currently, laboratory studies are mainly conducted in the following areas: firstly, the deteriorating effect of low temperature freezing of rocks by liquid nitrogen on rock mechanical properties, investigating the influence law of low temperature liquid nitrogen on mechanical parameters such as rock modulus of elasticity, Poisson's ratio, compressive strength, and fracture toughness [5-7]. Secondly, the modified characteristics of rock micro-structure under the influence of low temperature liquid nitrogen, qualitatively studying the initiation and extension of microcracks at the micro level, and quantitatively exploring the variation law of pore struc-

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ture size distribution of rocks at the micro level [8, 9]. Thirdly, numerical simulation of heat and mass transfer and cracking rules in the liquid nitrogen fracturing reservoir, mainly analyzing the spatiotemporal evolution law of rock temperature and ice-water phase change [10, 11].

Therefore, liquid nitrogen fracturing is expected to become a key technology for reservoir transformation. In order to further explore the transformation law of liquid nitrogen stimulation on unconventional natural reservoirs, this article explores the influence law of liquid nitrogen freezing on the tensile failure characteristics of coal and sandstone, studies its deteriorating effect on the ultrasonic wave velocity, tensile strength, and splitting modulus of coal and sandstone, and based on energy perspective, investigates the characteristics of energy before and after liquid nitrogen freezing with respect to load level changes, discusses the inherent causes of failure and damage characteristics. The research results can provide scientific guidance for the exploitation of unconventional natural gas under the conditions of liquid nitrogen fracturing.

Material preparation and methods

This article uses coal samples from the Pingdingshan Coal Mine in China and sandstone samples from Xuzhou, Jiangsu Province. After the samples are transported to the laboratory, they are processed into standard Brazilian splitting test samples with a diameter of 50 mm and a thickness of 25 mm, as shown in fig. 1, using equipment. The processing errors of all samples are within the tolerance range recommended by the international society for rock mechanics (ISRM). In order to ensure the homogeneity of the samples, samples with similar wave velocities are selected as experimental objects to minimize experimental errors. Both coal and sandstone are divided into control groups and experimental groups, with two samples in each group. No treatment is performed on the control group, while the experimental group is frozen in liquid nitrogen for one hour and then allowed to return to room temperature in a sealed bag (to reduce the influence of moisture). The wave velocity and mass before and after the cooling are measured three times and the average is taken. Using a universal testing machine, the Brazilian splitting test is performed on all samples using displacement loading at a speed of 0.05 mm/min. Finally, photographs of the fractured coal and sandstone are taken to observe the characteristics of the crack propagation path.

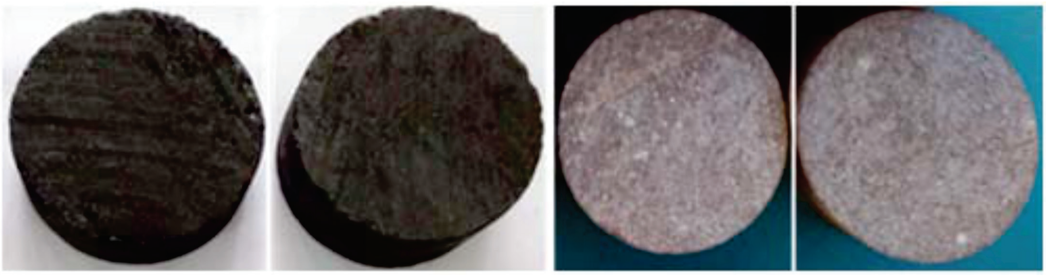

Figure 1. Coal and sandstone samples

Changes in physical and tensile strength

The magnitude of the wave velocity mainly depends on the size of the internal pore volume of the rock. The more pores there are, the greater the energy consumption when the sound wave penetrates, the longer the time required for penetration, and the smaller the wave velocity. As can be seen from fig. 2, the wave velocities of coal and sandstone have different degrees of reduction before and after liquid nitrogen cooling, with reductions of 24.7% and 5.5%, respectively. This indicates that liquid nitrogen cooling can promote the development of internal pore and crack systems in rock and coal matrix. However, under the same temperature difference, the degree of damage exhibited by coal and sandstone is significantly different for two main reasons: First, the temperature stress caused by liquid nitrogen is far greater than the tensile strength of coal and slightly greater than the tensile strength of sandstone. Obviously, the difficulty of fracturing the coal matrix is lower. Second, coal is more heterogeneous, and the initial crack or pore size is larger than that of sandstone. Under the same conditions, the crack tip in coal is more prone to expansion. In addition, the mass of coal and sandstone (immediately weighed after liquid nitrogen cooling) increases by 5.9% and 1.7%, respectively before and after liquid nitrogen cooling. After excluding the factor of condensation of air moisture, it shows that the mass of liquid nitrogen entering the coal matrix is large, and after being taken out, the liquid nitrogen expands and gasifies inside the coal matrix, which can promote the secondary development of cracks. The fracture sound generated in the coal when taken out from the liquid nitrogen confirms this. In contrast, sandstone does not exhibit this phenomenon. This is another factor inducing a high degree of damage in coal body.

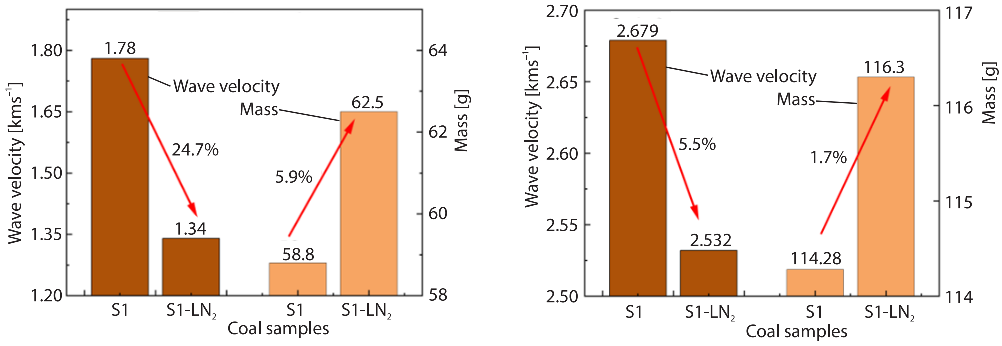

Figure 2. Wave velocity and mass of coal and sandstone

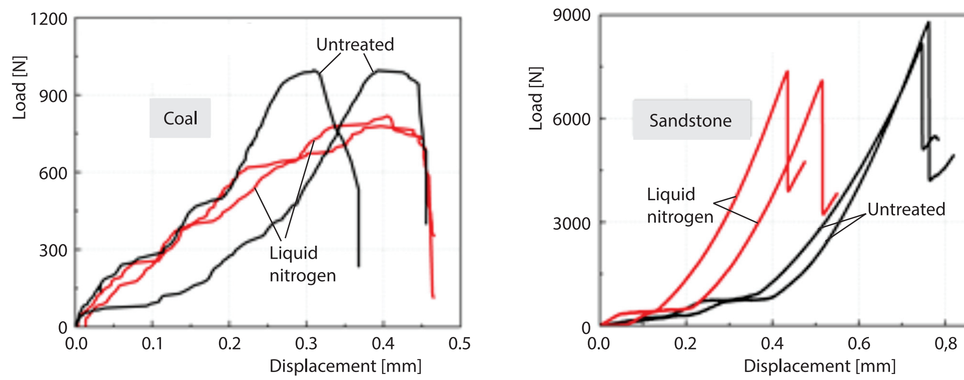

Figure 3. Load-displacement curves of coal and sandstone

From the load-displacement curves, fig. 3, it can be found that coal and sandstone exhibit different forms of deformation before and after liquid nitrogen cooling. For coal, the tortuosity of the curve after liquid nitrogen cooling is significantly increased. This indicates that the development of internal cracks in coal during the loading process is sudden, resulting in fluctuating changes in the bearing capacity of coal samples. The main reason is the influence of liquid nitrogen damage, which promotes the formation of macroscopic cracks by gathering nucleation of damage zones during loading process, leading to a gradual loss of bearing capacity. Especially near the peak, the formation of the macroscopic fracture surface of the coal body is more active and the yield is obvious, and the displacement corresponding to the peak load has increased. For sandstone, there is no obvious change in the shape of the curve.

Figure 4 shows that the average tensile strength of coal and sandstone before liquid nitrogen cooling is approximately 0.5 MPa and 4.3 MPa, respectively, with the latter being eight times higher than the former. This also explains the significant decrease in the velocity of coal and rock. After liquid nitrogen cooling, the average tensile strength of coal and sandstone is approximately 0.405 MPa and 3.68 MPa, respectively, with decreases of about 20% and 15%, respectively. To study the changes in the splitting modulus before and after liquid nitrogen cooling, the load is divided by the area of the loading surface to obtain stress, and the displacement is divided by the diameter to obtain strain. The load-displacement curve is transformed into a stress-strain curve, and the slope represents the splitting modulus. By calculation, the changes in splitting modulus of coal and sandstone before and after liquid nitrogen cooling are shown in fig, 4. It can be observed that after liquid nitrogen coolingcooling, the splitting modulus of coal decreases by as much as 52.4%, while that of sandstone decreases by 15.4%. In conclusion, liquid nitrogen cooling can effectively reduce the mechanical properties of coal and sandstone, and promote the development of internal fractures.

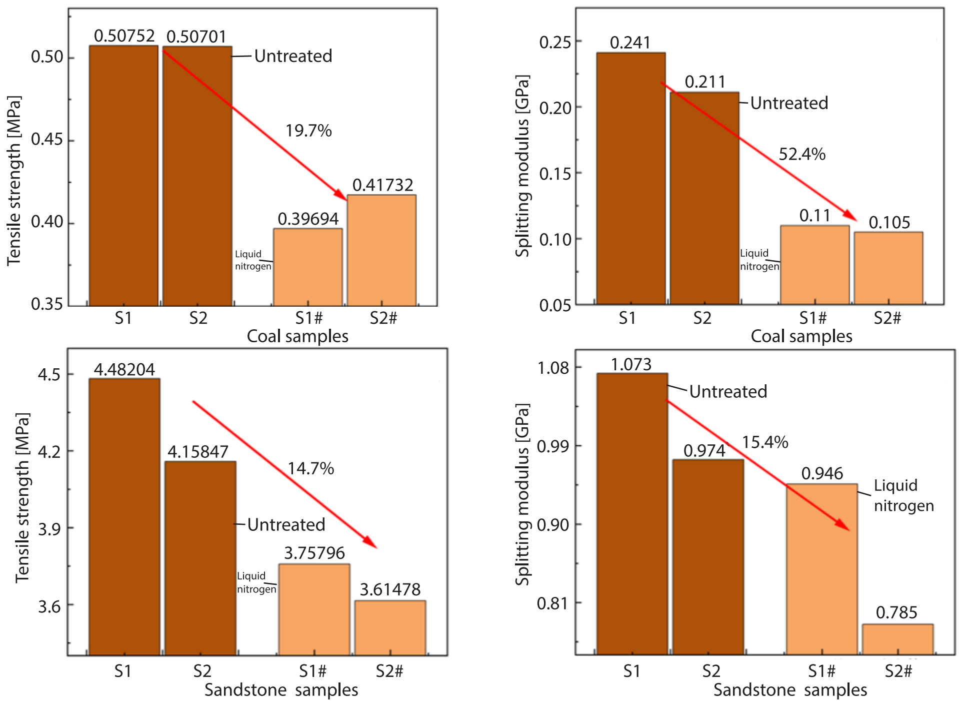

Figure 4. Tensile strength and splitting modulus of coal and sandstone

Applied energy evolution

During the loading process, as energy is continuously injected into the rock, internal energy accumulates. As cracks propagate and the rock sample undergoes failure, energy is consumed. Therefore, by integrating the load-displacement curve, the variation of energy during the loading process can be obtained. This energy is called applied energy [12]. Figure 5 shows the relationship between the applied energy of coal and sandstone under tensile conditions and the loading level. As the loading level increases, the applied energy gradually increases. After liquid nitrogen cooling, the applied energy of coal and sandstone exhibits two different trends. Before reaching 80% of the loading level, the applied energy of frozen coal decreases compared to the control group. However, beyond 80%, the applied energy increases, with an average increase of approximately 31.6%.

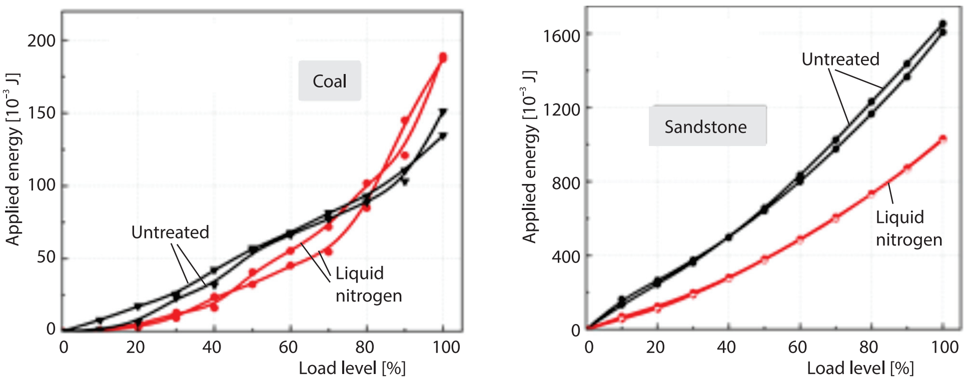

Figure 5. Applied energy of coal and sandstone

The main reason for this is that during the early stage of crack formation, the damaging effect of liquid nitrogen is utilized, resulting in lower overall energy consumption. However, as the coal sample approaches failure in the later stage, due to the influence of liquid nitrogen damage, the number of branch cracks increases and the energy consumed during the formation of multiple crack surfaces dramatically increases. Furthermore, after liquid nitrogen cooling, the applied energy of the sandstone is reduced throughout the entire loading process, with an average reduction of 58.5%. This is mainly due to the decrease in cohesion of the micro-structure under the freeze-thaw effect, resulting in the formation of microcracks. Therefore, the energy required during the process of crack propagation and the formation of crack surfaces is greatly reduced.

Failure mode

The tensile strength and energy-dissipating characteristics of rocks can be reflected in their failure patterns. Therefore, this section investigates the failure characteristics of coal and sandstone before and after liquid nitrogen cooling. Figure 6 shows the crack paths after the failure of coal and sandstone. In the Brazilian splitting test, it can be observed that all specimens exhibit tensile failure characteristics. In the control group specimens, the crack

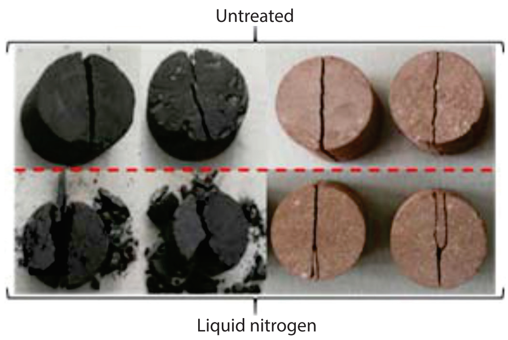

Figure 6. Splitting fracture path of coal and sandstone

paths consist of a single main crack without the generation of branch cracks. The main crack originates from the center point and extends through the specimen towards the loading point. After the cooling, the coal samples show an increase in branch cracks, an increase in crack tortuosity, and a higher degree of fragmentation, leading to a significant increase in applied energy in the later stage. Similarly, a branch crack forms in the sandstone. The results indicate that the failure mode primarily depends on the extent of internal damage within the sample. The wider the distribution of internal damage, the more complex the crack propagation paths during failure.

Conclusion

In this work, the tensile failure characteristics of coal and sandstone were investigated before and after liquid nitrogen cooling through Brazilian splitting tests. The results showed that both coal and sandstone exhibited varying levels of reduction in wave velocity after liquid nitrogen cooling, with coal experiencing a reduction of approximately 25%. In addition, the tensile strength of both coal and sandstone decreased by 19.7% and 14.7%, respectively, with a corresponding reduction in the splitting modulus, particularly in coal, where the reduction was as high as 52.4%. Energy analysis showed that the applied energy of coal samples first decreased and then sharply increased after liquid nitrogen cooling, with a final increase of 31.6%, while the overall applied energy of sandstone decreased by 58.5%. Furthermore, the failure characteristics demonstrated that liquid nitrogen cooling resulted in a wider distribution of internal damage within coal and sandstone, leading to an increase in branch cracks, crack tortuosity, and degree of fragmentation, particularly in coal samples.

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References

[1] Huang, Z. W., *et al*., A Review of Liquid Nitrogen Fracturing Technology, *Fuel*, *266* (2020), 4, ID117040

[2] Hong, C. Y., *et al*., Enhance Liquid Nitrogen Fracturing Performance on Hot Dry Rock by Cyclic Injection, *Petroleum Science*, *20* (2023), 2, pp. 951-972

[3] Mcdaniel, B. W., *et al*., Field Applications of Cryogenic Nitrogen as A Hydraulic Fracturing Fluid, *Proceedings-SPE Annual Technical Conference and Exhibition*, *50* (1998), 3, pp. 561-572

[4] Li, H., *et al*., A Fully Coupled Electromagnetic-Thermal-Mechanical Model for Coalbed Methane Extraction with Microwave Heating, *Journal of Natural Gas Science and Engineering*, *46* (2017), 10, pp. 830-844

[5] Hou, P., *et al*., Influence of Liquid Nitrogen Cooling State on Mechanical Properties and Fracture Characteristics of Coal, *Rock Mechanics and Rock Engineering*, *55* (2022a),7, pp. 3817-3836

[6] Hou, P., *et al*., Effect of Liquid Nitrogen Freeze-Thaw Cycle on Fracture Toughness and Release Rate of Saturated Sandstone, *Engineering Fracture Mechanics*, *258* (2021), 10, ID108066

[7] Su, S. J., *et al.*, A Fractal Perspective on Structural Damage and Fracture Characteristics of Coal Subjected to Liquid Nitrogen Cooling at Laboratory-Scale, *Fractals*, *30* (2022), 4, ID2250080

[8] Qin, L., *et al*., Changes in The Pore Structure of Lignite After Repeated Cycles of Liquid Nitrogen Freezing as Determined by Nitrogen Adsorption and Mercury Intrusion, *Fuel*, *267* (2020), 5, ID117214

[9] Su, S. J., *et al*., Experimental Study on Coal Permeability and Cracking Characteristics under LN2 Freeze-Thaw Cycles, *Journal of Natural Gas Science and Engineering*, *83* (2020), 11, ID103526

[10] Yan, M., *et al.*, Heat-Mass Transfer Coupling Effects in Water-Ice Phase Transformation of Water-Bearing Coal Frozen with Liquid Nitrogen, *Applied Thermal Engineering*, *215* (2022), 10, ID118902
[11] Zhang, S. K., *et al*., Thermal Characteristics Analysis with Local Thermal Non-Equilibrium Model During Liquid Nitrogen Jet Fracturing for HDR Reservoirs, *Applied Thermal Engineering*, *143* (2018), 10, pp. 482-492
[12] Lu, Y. Y., *et al.*, Influences of Super-Critical CO_2 Saturation on Tensile Characteristics and Failure Modes of Shales, *Energy*, *221* (2021), 4, ID119824

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