STUDY ON HYDRAULIC FRACTURING USING SUPERCRITICAL CARBON DIOXIDE

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1. INTRODUCTION

Geological storage of carbon dioxide has been attracted to avoid emitting carbon dioxide to the atmosphere. In general, porous rock formation beneath low permeability formation (caprock) has been considered to be a target formation for carbon dioxide storage. However, an aquifer with anticlinal caprock near large-scale emission sources is very limited. Therefore, a development of a new method to increase the potential of carbon dioxide storage has been required, and a method to create fractured reservoir in low-permeability rock using hydraulic fracturing has been proposed by Ishida *et al* (2007).

When carbon dioxide injected into the deep formation, it will be in a supercritical state at the temperature of greater than 31.1°C and the pressure of greater than 7.38 MPa. Supercritical carbon dioxide has a low viscosity less than that of water. However, there are few studies on the fracture propagation behavior using supercritical carbon dioxide. Ishida *et al.*[2] show that fracturing fluids with low viscosity tend to generate wavelike cracks with many secondary branches. Igarashi[3] shows that permeability is most important factor on the fracture shape in unconsolidated sediment.

In this study, to create fracture system in low-permeability rocks by hydraulic fracturing, hydraulic fracturing experiments using supercritical carbon dioxide or water were conducted. To clarify the effects of viscosity and the flow rate of fracturing fluid and type of rock on the fracture propagation behavior were experimentally investigated.

2. EXPERIMENTAL SYSTEM

2.1 Outline of the system

Fig. 1 shows the schematic diagram of the experimental system for the hydraulic fracturing experiments. The experimental system mainly consists of a carbon dioxide supply system, a syringe pump, a preheater, a packer, a true triaxial compressive stress loading system and a data recording system. Carbon dioxide gas is supplied from a gas cylinder, and is converted to liquid-phase with the carbon dioxide supply system, and is filled in the syringe pump. The liquid-phase carbon dioxide is pumped at constant flow rate with the syringe pump, and is heated through the preheater to satisfy the temperature condition higher than 31.1°C, and is sent to the packer inserted into a borehole of a specimen.

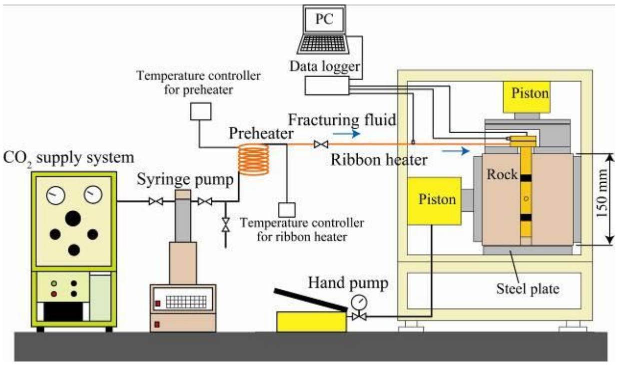

Fig. 1 Schematic diagram of experimental system.

2.2 Specimen

The hydraulic fracturing experiments were performed using 150 mm cubic of Inada granite and Ogino tuff that have low-permeability. The borehole was 20 mm in diameter, and was drilled in the center of the rock in a direction perpendicular to the rift plane or bedding plane of the rocks. The rift and bedding plane were determined by measuring P-wave velocities along each side. Horizontal compressive stress σ_H and σ_h ($\sigma_H > \sigma_h$) and vertical compressive stress σ_V ($\sigma_h > \sigma_V$) were applied with the true triaxial compressive stress loading system.

2.3 Packer system

Fig. 2 shows the cross-sectional view of the packer developed in this study. The washers made of urethane rubber were used as packer elements. The thermocouple and the pipe for pressure measurement were inserted through the upper joint to near the outlet of fracturing fluid. The pressure of the fracturing fluid was measured with two pressure transducer. One was directly attached to the packer, and the other was attached to the joint of tube. Accordingly, this packer enables accurate measurement of the temperature and pressure of the fracturing fluid near the outlet for fluid in the packer to make sure that the carbon dioxide is supercritical state.

3. EXPERIMENTAL CONDITION

3.1 Pressurization experiments

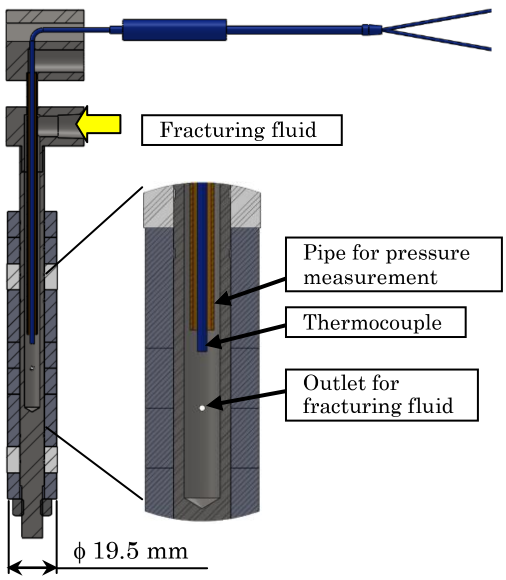

Fig. 2 Cross-sectional view of packer.

To investigate temperature change of carbon dioxide during the hydraulic fracturing experiments, the pressurization experiments were carried out. Carbon dioxide was pumped to the packer inserted into the steel pipe at the constant flow rate until the pressure reach 10 MPa. The steel pipe was inserted into the borehole of the specimen. The experiments were conducted fifth times by flow rate of 50 ml/min, once by 100 ml/min and second times by 150 ml/min, respectively.

3.2 Hydraulic fracturing experiments

Table 1 shows the experimental conditions for the hydraulic fracturing experiments. Carbon dioxide and water were used as the fracturing fluid to investigate the effect of the viscosity of the fracturing fluid, and they were pumped at the constant flow rates of mainly 10, 50 and 150 ml/min to investigate the effect of the flow rate of the fracturing fluid. The maximum horizontal compressive stress σ_H was 5 MPa, the minimum horizontal compressive stress σ_h was 3 MPa, and the vertical compressive stress σ_V was 1 MPa. In all experiments, a distance between packer elements was set to be 60 mm.

4. RESULTS AND DISUSSION

4.1 Results of pressurization experiments

Figs. 3 and 4 show the pressure and the temperature during the pressurization experiments obtained by the flow rate of 50 and 150 ml/min, respectively. Though the pressure measured at two measuring points were approximately same, that measured at the packer was slightly greater than that measured at the joint of the tube.

First, by opening the outlet valve of the syringe pump, the pressure rapidly increased up to approximately 4 MPa of the vapor pressure of carbon dioxide. Then, the pressure gradually increased up to 10 MPa by the supply of carbon dioxide. The temperature increased to the temperature of the carbon dioxide heated by the heaters. However, as shown in Fig. 3, the temperature decreased temporarily at the pressure of around 6 MPa. This result suggests that a phase-change of carbon dioxide occurred or an adiabatic expansion occurred, because it was observed that the packer elements were moved outward due to the pressure of the fluid. Then the temperature increased gradually over the critical temperature due to the adiabatic compression of carbon dioxide.

4.2 Results of hydraulic fracturing experiments

Figs. 5 and 6 show the pressure and the temperature during the hydraulic fracturing experiment using carbon dioxide or water at the flow rate of 50 ml/min for Inada granite. In a set of hydraulic fracturing experiments by carbon dioxide, it was observed that the temperature decreased temporarily and then increased similar to the results obtained by the pressurization experiments. After the fracture occurred, the temperature was

Table 1 Experimental conditions for hydraulic fracturing experiments.

Fracturing fluid	Specimen	Flow rate (ml/min)	Loading condition			
				σ_H (MPa)	σ_h (MPa)	σ_V (MPa)
CO_2	Inada granite	10	Triaxial	5	3	1
		50	Uniaxial	1		
			Biaxial	5	3	
		150	Triaxial	5	3	1
	Ogino tuff	10, 50, 100				
		150	Biaxial	5	3	
Water	Inada granite	50	Triaxial	5	3	1
	Ogino tuff					

to the atmosphere pressure. In two condition of the flow rate of 10 and 100 ml/min for Ogino tuff, the specimen did not fractured in this study. The pressure did not increase by the flow rate of 10 ml/min for Ogino tuff due to the leakage of carbon dioxide. The pressure increased, and the syringe pump was stopped by a pressure limiter by the flow rate of 100 ml/min for Ogino tuff. The fracture was created by the flow rate of 50 ml/min for Inada granite. However, breakdown pressure (P_b) was lower than the critical pressure of 7.38 MPa. As for the other conditions, the temperature and the pressure at the breakdown satisfied the critical point. Accordingly the fractures were created by supercritical carbon dioxide in these conditions.

To observe created fractures, the packer was inserted to the borehole again, and water mixed with red ink was injected slowly in the packer with a hand pump. Furthermore, the fractures on the specimen surfaces were traced with marker, and were scanned with a image scanner. The scanned images were traced manually on PC. To observe the inner fractures, the specimens were cut with a diamond cutter, and cut planes were evaluated by the similar procedure. In this way, perspective views of specimens were obtained.

Fig. 7 shows the perspective views of the fractures for the various conditions. By comparing the fractures created by supercritical carbon dioxide with those created by water, the effects of the fracturing fluid on the fracture propagation behavior were investigated. Single planer fractures were created by water, while widely branched fractures were created by supercritical carbon dioxide. Moreover secondary branched fractures were also observed for the fractures created by latter. Accordingly, supercritical carbon dioxide, which was low viscosity, tends to be affected by the local anisotropy of rock strength than water.

In this study, the borehole of the specimen is perpendicular to the rift plane or the bedding plane of rocks that have minimum P-wave velocities. According to the Kirsch equations, the fracture was expected to be propagated to the orientation of the maximum principal stress. The fracture created by water, the fracture was propagated approximately to

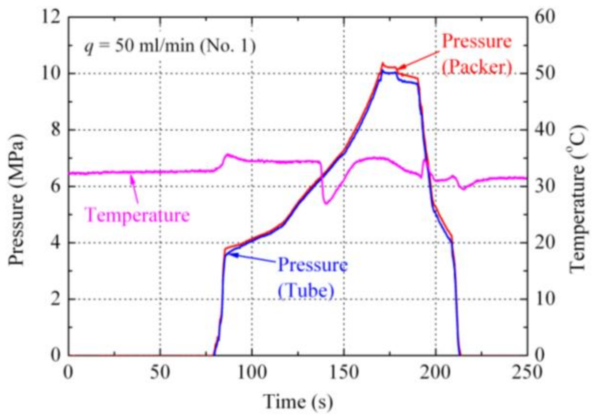

Fig. 3 Pressure and temperature during pressurization experiment (q = 50 ml/min).

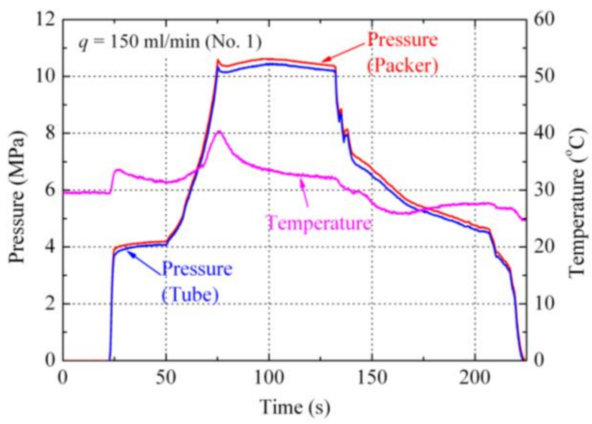

Fig. 4 Pressure and temperature during pressurization experiment (q = 150 ml/min).

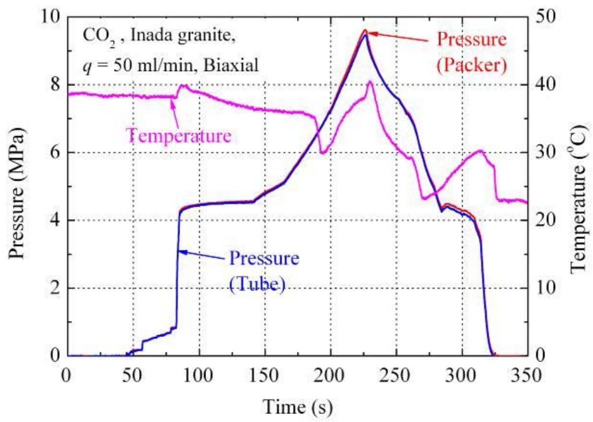

Fig. 5 Pressure and temperature during hydraulic fracturing experiment (CO_2, Inada granite, q = 50 ml/min, P_b = 9.62 MPa, T_b = 40.5°C).

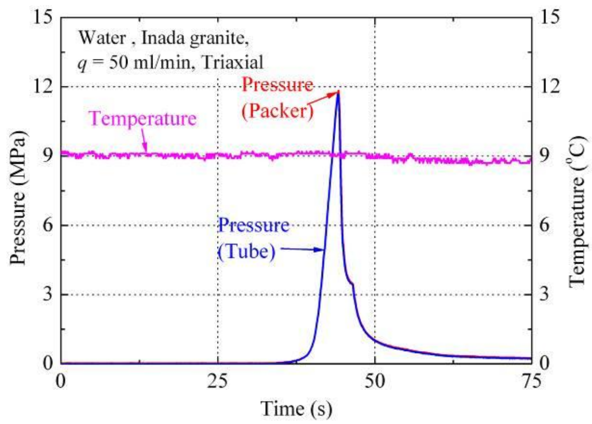

Fig. 6 Pressure and temperature during hydraulic fracturing experiment (water, Inada granite, q = 50 ml/min, P_b = 11.84 MPa, T_b = 9.1°C).

the orientation of the maximum principal stress. By contrast, the fractures created by supercritical carbon dioxide, which has low viscosity, were not only branched but also were propagated along the structurally weak plane like rift plane or bedding plane of rocks. There is a report[4)] that the fracture tends to propagate along rift plane at which microcracks are oriented, for coarse-grained rock such as granite. This tendency was observed on both granite and tuff in this study. Hence, the orientation of the fracture propagation is strongly affected by the viscosity of the fracturing fluid.

The influence of the flow rate of carbon dioxide on the fracture propagation could not be observed in this study. However, the observations of the fractures in this study were limited to the macroscopic fractures. Therefore, microscopic observations with a microscope should be conducted in the future.

Two types of rocks, Inada granite and Ogino tuff, were used as the specimens in this study. In both rocks, the branched fractures were created, and the fractures obtained for Inada granite were more finer. The reason can be considered that the microscopic anisotropy of rock strength of Inada granite, which is a crystalline rock, is greater than that of Ogino tuff. As a result, the orientation of the fracture propagation of the Inada granite becomes more complexity.

5. CONCLUSIONS

1) To enable accurate measurement of temperature and pressure of fracturing fluid, a packer with a thermocouple and a pressure transducer was developed.
2) Viscosity of supercritical carbon dioxide is considerably lower than water. As a result, orientation of fracture propagation by super critical carbon dioxide tends to be complex.
3) Influence of flow rate of carbon dioxide on fracture propagation could not be observed by microscopic observations. However, macroscopic observations of fractures should be conducted in the future.
4) Fractures created by supercritical carbon dioxide, which has low viscosity, tend to propagate along structurally weak plane like rift plane or bedding plane of rocks.
5) Fractures obtained for granite were finer than those obtained for tuff. The reason can be considered that microscopic anisotropy of rock strength of granite is greater than that of tuff.

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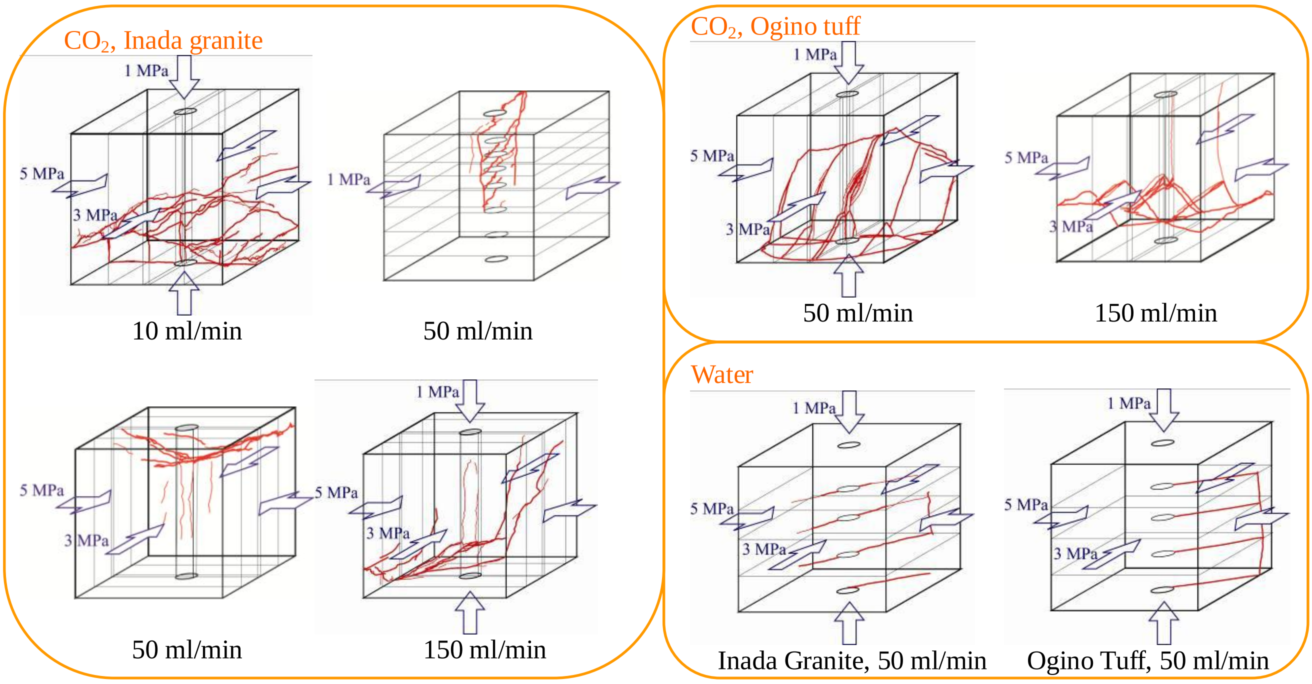

Fig. 7 Perspective views of fractures for various conditions.