Micro-Flow Channel Probe for Geological Environmental Diagnosis - New Integrated Device for *In-situ* Measurement of Diffusivity and Sorption Coefficient in Rock Matrix - 9294

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ABSTRACT

A micro-flow channel probe which enables *in-situ* migration experiments in a borehole was developed by the use of a micro-channel reactor technique. The feasibility of a prototype probe and its experimental procedure were confirmed in the field test carried out in the DH-5 borehole. The breakthrough curves of non-radioactive tracers, D_2O and K^+ were obtained in the fresh granite wall rock matrix. The diffusivity of D_2O was evaluated as 7E-12 m^2/s, and the distribution coefficient of K^+ was evaluated as 3 mL/g. These values were almost equal to results of laboratory experiments. All the experiments were carried out without any trouble, and no breakdown of sensitive units or clogging of the probe occurred. These results suggested the micro-flow channel probe could be a new tool which enables various *in-situ* experiments.

INTRODUCTION

In the site selection process of high-level radioactive waste, the natural barrier performance of the host rock is a key issue to confirm the isolation capability of the geologic disposal system at the candidate site. Although the migration properties of radionuclides are of great concern to evaluate the long-term safety, the data collected for the *in-situ* condition are quite limited; thus the use of such information is difficult particularly in the early stage of disposal site selection. We felt this difficulty is mainly due to the lack of a suitable measurement device which can be used in a simple and quick manner.

With the conventional method, an investigation tunnel and a long testing period are necessary for *in-situ* experiments to measure the tracer that has passed into bedrock [1]. “CHEMLAB” and “CHEMLAB2” are well-known tools for performing *in-situ* experiments using a borehole [2,3]. These probes have allowed various experiments by use of *in-situ* underground water, but they could not measure the borehole wall rock directly.

We developed a micro-channel reactor technique which can measure the migration properties such as diffusivity and sorption coefficient of injected tracer solutes using a rock plate [4,5]. Using this technique, we then developed a micro-flow channel probe that is able to carry out *in-situ* migration experiments in a short testing period. This paper describes the features of the micro-flow channel probe and outlines the feasibility test using the DH-5 borehole which the Japan Atomic Energy Agency has in Gifu Prefecture, Japan.

FEATURE OF MICRO-FLOW CHANNEL PROBE

Figure 1 shows an outline of the micro-flow channel probe. This probe has a 24.6m total length and 86mm maximum outer diameter. To insert it into the borehole, the shape is extremely long and slender. The probe is expected to function as a micro-chemical laboratory, and it has pressure resistance up to depths of 500m. The most innovative part of this probe is the micro-flow channel structure (length, 40mm; width, 6mm; depth, 0.2mm). After the micro-flow channel is pressed on the borehole wall, the tracer solution is introduced into the channel, and the migration characteristic of the rock is evaluated by measuring the concentration that changes slightly before and after contact with the rock.

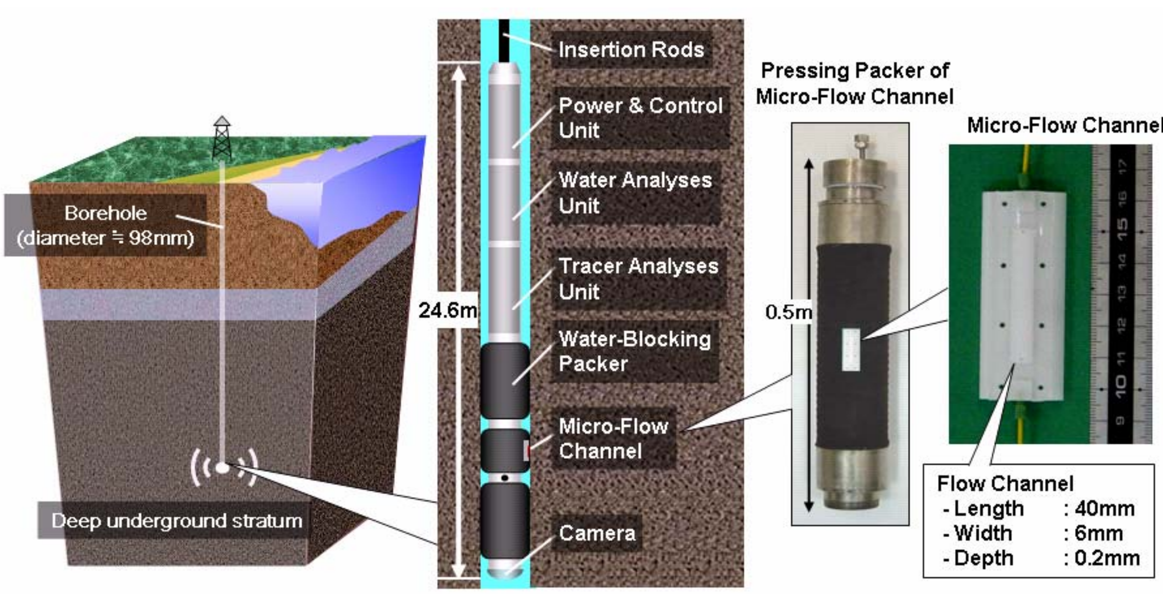


Fig. 1. Outline of micro-flow channel probe

Figure 2 summarizes features of the micro-flow channel probe. In this method, a breakthrough curve is obtained to evaluate the diffusivity and sorption coefficient in the rock matrix. Details of the measurement principle have already been reported [4,5]. Since the tracer concentration is measured in contact with the rock, the testing period could be shortened compared with the conventional method.

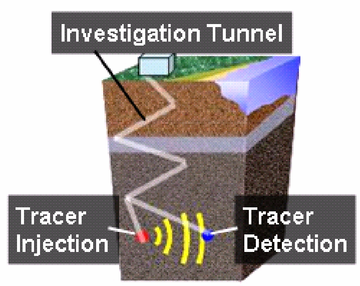
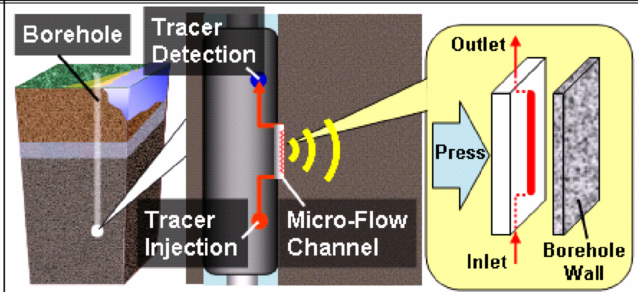
Item	Conventional Method (Investigation Tunnel)	This Study (Micro-Flow Channel Probe)
Schema		
Measuring Object	Tracer that penetrates rock	Tracer in contact with rock
Testing Period	> 1 year	≒ 1 month

Fig. 2. Features of the micro-flow channel probe

A measuring point in the borehole can be chosen while looking at images obtained by the camera installed in the probe. There is also a groundwater analyses sensor which can monitor pH, redox potential, dissolved oxygen concentration, and electric conductivity, etc. Water-blocking packers prevent water from entering the 2m-long section where the micro-flow channel is installed in the middle. The ground water in this section can be replaced while measuring the electric conductivity.

COMPONENT UNITS

The micro-flow channel probe is composed of five units, camera and packer unit, tracer analysis unit, water analysis unit, power and control unit, and control system. Features of each unit are described below.

Camera and Packer Unit

The camera and packer unit is 6m long and equipped with two CCD cameras, a pair of water-blocking packers, a micro-flow channel, a pressing packer, a protection sleeve, ground water sampling lines, a pressure gauge, and a thermometer. Both cameras are connected to the control system and able to inspect the borehole conditions in real time. One of the cameras is for downward viewing to check clearance of the borehole and the other is for side viewing to check the borehole surface condition.

The micro-flow channel is covered with an outer steel cylinder sleeve that protects the flow channel during insertion of the whole rod. When the probe reaches the target position, the sleeve is moved by water pressure and the micro-flow channel is exposed. Then the pressing packer is expanded by gas pressure and the channel is pressed onto the borehole wall surface.

Tracer Analysis Unit

The tracer analysis unit is divided into two subunits which are both 4m long. The units have tiny syringe pumps, valves, and pressure gauges in order to control the tracer solution flow. A spectrometry system is also included in order to analyze the tracer concentrations in real time. A non-radioactive multi-tracer solution which contains heavy water (D_2O: 30wt%), fluorescein sodium (uranine: 4ppm) and potassium chloride (KCl: 0.3mM), was used. The measurements of heavy water and fluorescein sodium were carried out with this spectrometry system which has an *in-situ* calibration system. The analyses of cation species including potassium were carried out after the experiment using a storage coil of a very long micro-tube (1.8mL) which stored the tracer concentration change with time. All devices have a maximum diameter of 74mm and are put in the pressure-resistance vessel (inner diameter, 76mm).

Water Analysis Unit

The water analysis unit can continuously monitor the groundwater properties such as pH, redox potential, dissolved oxygen concentration, electric conductivity, and temperature. Water samples are taken near the micro-flow channel. The hydraulic conductivity can also be evaluated by using the flow rate and the pump differential pressure which are measured by this unit.

Power and Control Unit

The power and control unit consists of the power supply circuits for the equipment in the probe, the control circuits for the analysis equipment, and the digital/analogue optical converter. All the control signals and measurement data are converted into digital optical data, and transferred to the ground control system via 16 optical fibers. This optical data transferring system avoids the noise generated by the electro-magnetic effect from electric machines around the borehole.

Control System

The software to control all the 26 different devices including four syringe pumps, five valves, four pressure gauges, and one spectrometer system equipped in the probe was developed and automatic operation can be achieved using LabVIEW systems (National Instruments). Almost all the data are displayed on one screen, except for the packer pressure.

PRE-INSERTION TEST

Since the micro-flow channel probe is extremely long, over 24m, the risk for it to become clogged while in the borehole was high. To avoid clogging of the probe, a pre-insertion test was carried out in a vertical condition. A 30m long stainless steel pipe was put into the upper part of the actual borehole which was constructed in a granite formation. The diameter of this pipe was 98mm and the bottom end was plugged by a flange. The inside of the pipe was filled with water, then procedures for the connection of units and insertion of the whole probe were established.

In the next step, a long dummy probe was inserted into the borehole in order to check for the safe insertion of such a long probe into the actual borehole. A weight sensor was attached on the probe to monitor the change of the weight due to contact with the borehole surface during insertion until the probe reached the target point of measurement. We chose the target depth in advance by checking drilled core samples taken from the borehole, particularly paying attention to cracks and scrapes on the borehole surface.

FIELD TEST

A field test was conducted to verify the performance of the micro-flow channel probe in the granite borehole. Figure 3 shows scenes from the field test using the DH-5 borehole which Japan Atomic Energy Agency has in Gifu Prefecture, Japan. The diameter of the DH-5 borehole is 98 mm, and the maximum depth is 502.3m. The stratum that is deeper than 30m consists of granite. In this field test, the measuring point was selected at 112m based on the observations of borehole CCD images and the drilled core samples.

(a) Facilities of field test (b) Insertion of probe

Fig. 3. Field test scenes

In the first step, a micro-flow channel probe was assembled and inserted carefully, using the weight sensor and CCD camera monitors. The probe and the nine cables were lowered into the borehole while being connected by the extension rods. The cables were bound to the rods by a tape at every 1m. After arriving at the target point, the micro-flow channel was exposed by opening the outer protection sleeve, and the actual attachment site on the fresh borehole wall was selected in a prudent manner using images from the side-viewing CCD camera. We confirmed it was possible to decide the measurement position through this operation. Then, the water-blocking packers blockaded the 2m-long section, and the groundwater was replaced ten times to recover the original groundwater property in the borehole.

In the process of pressing the micro-flow channel onto the borehole wall, first, the packer was pressed by water pressure of 0.3MPa to flush out the borehole wall. After the flushing, the packer was pressed again at 0.45MPa to seal the flow channel. It took about 90 min for the internal pressure of the flow channel to reach the same pressure as in the borehole. This indicated that the flow channel had been completely sealed up.

The tracer solution contained heavy water (D_2O: 30wt%), fluorescein sodium (uranine: 4ppm), and potassium chloride (KCl: 0.3mM). Heavy water and uranine were used as a non-adsorbent tracer, and K^+ was used as an adsorbent tracer. The solution was injected into the flow channel (capacity: 48μL) at a flow rate of 1μL/min for 900min.

Figure 4 shows the measurement point and typical breakthrough curves of D_2O and K^+. The cylindrical two-dimensional diffusion-advection analyses were adopted for the breakthrough curves to obtain the diffusivity and sorption coefficient in the rock matrix. The diffusivity of D_2O was evaluated as 7E-12 m^2/s, and the distribution coefficient of K^+ was evaluated as 3 mL/g using the D_2O diffusivity. These values were almost equal to values obtained in laboratory experiments.

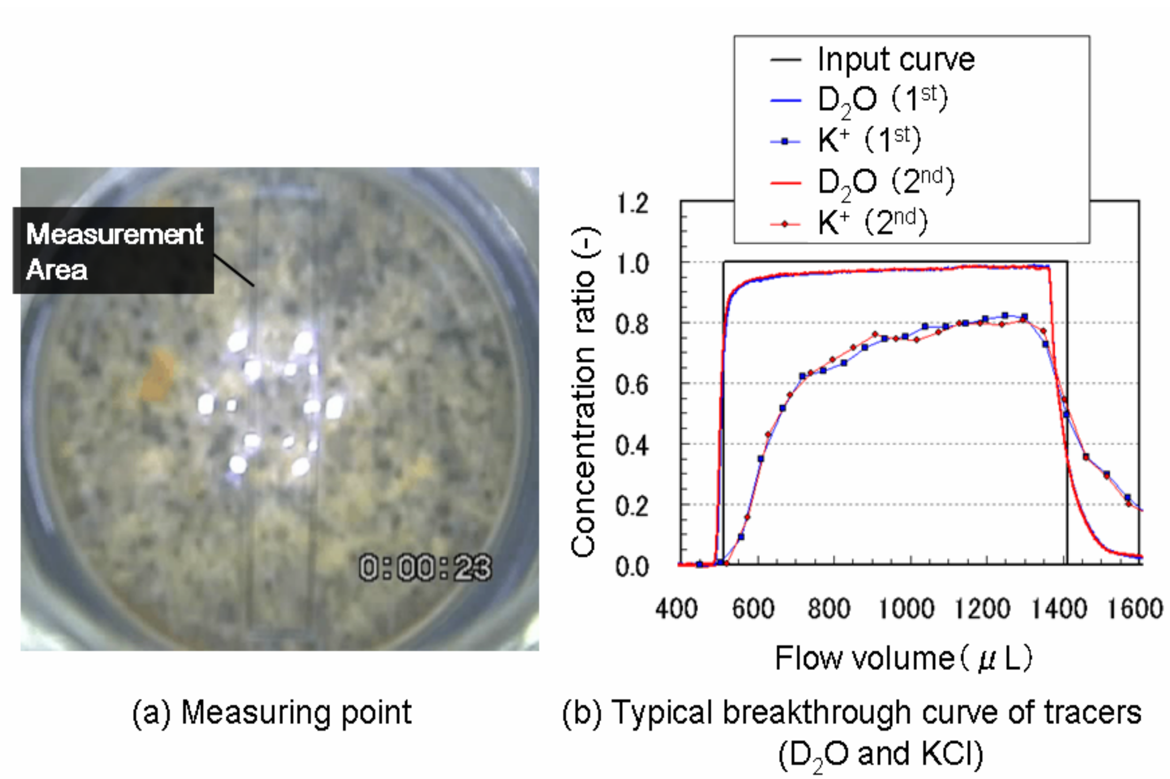


Fig. 4. A typical breakthrough curve obtained in the field test

The tracer injection test was carried out seven times at different flow rates and different places including four times with a hairline crack. The results indicated that the micro-flow channel probe could be applied as a new investigation tool for crack property.

The field test was started in the middle of November 2007 and completed at the end of January 2008 without any trouble; there were no breakdowns of sensitive units or any clogging of the probe. These results suggested the micro-flow channel probe could be applied to various *in-situ* experiments.

CONCLUSIONS

A micro-flow channel probe which enables direct *in-situ* migration experiments was developed. The probe employs a micro-channel reactor technique. A prototype probe, which was composed of five units(camera and packer unit, tracer analysis unit, water analysis unit, power and control unit, and control system) was manufactured. The field test was carried out to confirm the feasibility and the performance using an actual borehole. The breakthrough curves of D_2O and K^+ to evaluate the diffusivity and sorption coefficient in the rock matrix were obtained without any mechanical trouble. These results suggested the micro-flow channel probe is a good tool for performing *in-situ* experiments.

ACKNOWLEDGMENT

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