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Visualization of flow patterns in a cell of redox flow battery by infrared thermography

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ABSTRACT

For redox flow batteries (RFBs), it is very important to flow electrolyte uniformly in the porous electrodes. Integrated segment methods have been studied to analyze in situ flow behavior in a cell of RFBs. However, the resolution of the contour plots obtained with these methods is very low at present since only several dozen segments can be used. Therefore, to visualize the flow patterns of electrolyte in the electrode, a model cell which consists of a single porous electrode and two clamping plates was constructed and tested. The experiments were performed by feeding hot working liquid to the cell after cooling the cell without discharging cooling water, and measuring the temperatures in the electrode by thermocouples and the temperature distribution of the outer surface of the clamping plate by infrared thermography (IRT). Time variations of temperatures of the outer surface of the clamping plate show similar trends with one in the electrode. Further, the temperature distributions measured by IRT were considerably changed when the inlet and outlet conditions were changed. This shows that the flow patterns of electrolyte in the electrode can be visualized by measuring the outer surface temperature distribution of the clamping plate by IRT.

1. Introduction

Redox flow batteries (RFBs) can charge or discharge electric energy by transporting electrons between two solutions containing different redox couples. Electric energy is stored in the battery itself for conventional batteries while it is stored in the solutions for RFBs. Therefore the capacity of the battery can be easily adjusted by the mass of the solutions for RFBs. Thus, RFBs are expected to be a safe, long-life and large-scale battery to store the energy from renewable energy sources, and have been reviewed by Ponce et al. [1], Weber et al. [2] and Arenas et al. [3].

A cell of RFBs consists of two electrodes separated by an ion exchange separator. Porous media such as carbon felt is used as electrode and electrolyte flows in the electrodes. Storing and releasing electricity are achieved by transporting electrons between positive and negative electrolyte through the ion exchange separator.

To improve the efficiency and lifetime of RFBs, it is very important to flow electrolyte in the electrodes uniformly. If electrolyte does not flow in the electrodes uniformly, especially there are stagnation areas in the electrodes, efficiency and lifetime of RFBs will be seriously deteriorated due to Ohmic and mass transport polarization and also the corrosion of electrodes caused by a partial increase in electric resistance in the electrodes. Therefore, it is essential to reveal the flow field of electrolyte in the porous electrodes. However, since the electrodes of a cell of RFBs are sandwiched by opaque plates, it is difficult to observe the flow patterns directly from outside of the cell.

The CFD (Computational Fluid Dynamics) is powerful tool to analyze the flow field in the cell of RFBs, and many studies have been done [4–8]. To analyze in situ flow behavior in a cell of RFBs experimentally, integrated segment methods using current collectors [9], micro potential probes [10], current collectors and potential probes [11], open circuit voltage [12], flexible integrated temperature and flow microsensors [13] and printed circuit boards [14] have been studied. With these methods, the in situ flow field in a cell of RFBs can be presented in contour plots. However, since only several dozen segments at most can be used for these methods, the resolution of the contour plots was very

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Abbreviations: CFD, Computational Fluid Dynamics; EPSS, electrode position supporting sheet; IRT, infrared thermography; PVC, PolyVinyl Chloride; RFB, redox flow battery

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Nomenclature

Symbols

t_c	temperature measured by thermocouple
t_g	temperature measured by IRT

low at present. Further, the area of a cell used in the experiments was very small (several cm^2 to 100 cm^2) and the results cannot be applied to real-scale RFBs in which the cell area is considerably larger than the experimental cell area.

Houser et al. [15,16] proposed a novel thermal visualization method by using heat sensitive liquid crystal sheet. They placed the liquid crystal sheet on a half-cell of an RFB which cell area was 9 cm^2 and observed it through a clear PVC plate. Cooled water (10 °C) was pumped through the cell for 10 min, and then hot water (35 °C) was pumped through the cell. Video files show that the flow of hot water in the cell can be visualized by the method.

On the other hand, observations of two-dimensional temperature distribution by using infrared thermography (IRT) have been performed [17–19]. The resolution of IRT is much higher than in the integrated segment methods. In these studies, thin metal foils (tens of μm) were used as the observation walls to eliminate the effect of the heat capacity of the wall. However, the electrodes of a cell of RFBs are sandwiched by clamping opaque plates and the thickness of the clamping plates should be several millimeters at least, since the large clamping force is required to prevent the leakage of electrolyte from the cell. Therefore, thin metal foil cannot be used as clamping plates for a cell of RFBs. However, it is expected that the temperature distribution on the outer surface of the clamping plate reflects the inside temperature of the electrode, even though the thickness of the clamping plate would be several millimeters and there should be an error caused by the heat capacity of clamping plate and the conductive heat transfer in lateral and thickness directions in the clamping plate. The thermal visualization method proposed by Houser et al. [15,16] used heat sensitive liquid crystal sheet with a temperature sensitive range of 25–30 °C. IRT has much greater temperature range than liquid crystal sheet. Therefore, in this study, to visualize the flow patterns in the electrode of a cell of an RFB, the temperature in the electrode and the outer surface temperature distribution of the clamping plate were simultaneously measured by thermocouples and IRT, respectively. The experiments were performed with a model cell in which a single electrode (carbon felt) was sandwiched by clamping plates and by feeding hot working liquid to the cell after cooling the cell.

2. Experimental apparatus and procedure

In this study, the visualization of flow patterns of electrolyte in a single electrode was attempted, therefore, a cell which consists of a single electrode sandwiched by clamping plates was constructed as a model cell instead of a pair of electrodes with ion exchange separator between them. A schematic diagram of the model cell and a snap shot of the experiment are shown in Figs. 1 and 2. Here, ion-exchanged water was used as a working liquid instead of electrolyte even though the properties such as viscosity and thermal conductivity of ion-exchanged water differ from the electrolyte, since the objective of this study is to try to visualize the flow patterns of the working liquid in the model cell by using IRT for the first step. The model cell was composed of a cell frame (2 mm-thick PVC plate) sandwiched with two packings (EPDM (ethylene propylene diene monomer rubber) 0.5 mm in thickness) to prevent leakage of the working liquid and two clamping plates (one was a 4 mm-thick stainless steel plate and the other was a 30 mm-thick acrylic plate). Ribs were welded on the outer surface of the stainless steel plate to prevent deformation and its outer surface was painted in black.

A schematic diagram of the cell frame is shown in Fig. 3. The middle parts of two packings and the cell frame were cut off to form a cell with a size of 170 mm in height and 400 mm in length. Two inlets (in1 and in2) and two outlets (out1 and out2) were placed at the bottom and the top of the cell, respectively. Here, each inlet and outlet was composed of four circular grooves with 3 mm pitch machined on the cell frame, and each groove had 1 mm-diameter. The position and number of inlets and outlets were not optimum one, since they were just used to vary the inlet and outlet conditions described later. An electrode (4 mm-thick carbon felt (AAF304ZS (void ratio is 95%)), Toyobo Co., Ltd) was set in the cell, and the flow paths (distributers) were placed at the bottom and the top of the electrode. The bottom distributer was used to spread working liquid fed from inlets in lateral direction, and the top one was used to direct working liquid to the outlets, respectively. Usually, to support the position of electrodes and preserve the ion exchange separator, an electrode position supporting sheet (EPSS) is inserted in the distributer. In this study, plapearl (Kawakami Sangyo Co., Ltd.) shown in Fig. 4 was used as an EPSS. Dimensions of the cell are shown in Fig. 5. Eight holes were opened to the acrylic plate to set calibrated K-type thermocouples with silicone plugs in the positions of the electrode shown from TC1 to TC8 in Fig. 5, and the positions were symmetric in horizontal and vertical directions.

The experimental procedure was as follows: two clamping plates (a stainless steel plate and an acrylic plate) were clamped with 16 pairs of bolts and nuts by a clamping force which can compress 4 mm-thick carbon felt to 3 mm in thickness. The cell was cooled sufficiently by feeding cool working liquid with a temperature of about 10 °C from the inlets by a pump. After that, hot working liquid with a temperature of

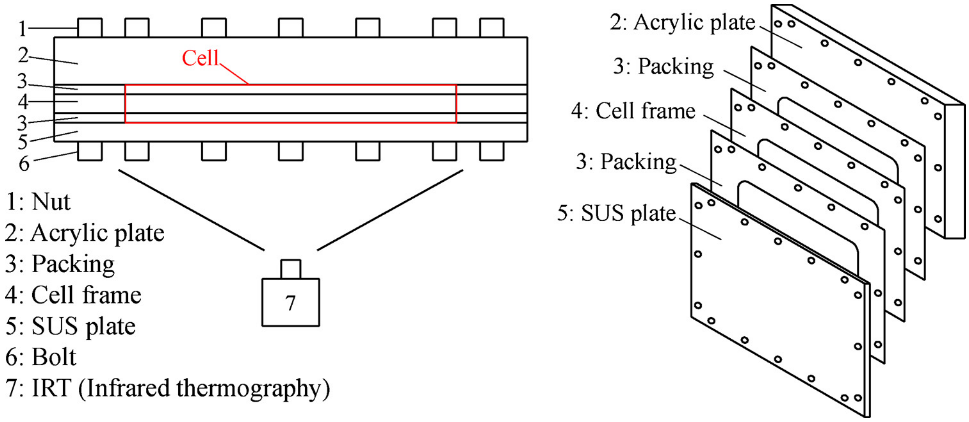

Fig. 1. Schematic diagram of the experimental apparatus.