Realization of thermocline for thermal energy storage system study using a copper-sulfate electroplating system

Min-Ju Kim, Jeong-Won Han and Bum-Jin Chung[*]
Department of Nuclear Engineering, Kyung Hee University
#1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Republic of Korea
[*]*Corresponding author: bjchung@khu.ac.kr*

1. Introduction

With the increase in renewable penetration, the undispatchable and intermittent characteristic of renewables has raised concerns about electric grid stability. For this reason, the research on energy storage has been performed vigorously [1,2].

Nuclear Power Plants (NPPs) play a base load supplier role in the electric grid. It is not easy to control the power in response to renewable energy variation. Recently, thermal energy storage (TES) system on NPPs has been considered to add flexibility of NPPs [2].

The packed bed type of TES uses the solid fillers in a storage tank. It charges or discharges thermal energy through heat exchange between the heat transfer fluid (HTF) and solid filler. During the operation of the thermocline type TES, the thermocline is formed, which is a temperature gradient zone caused by thermal stratification [3,4].

The present study is aiming at developing an experimental procedure to simulate the thermocline packed bed TES by utilizing the mass transfer experimental technique, which does not allow temperature gradient (mass concentration gradient) within the bulk fluid. We simulated the temperature distribution of thermocline TES system at the discharging mode.

2. Theoretical background

2.1 General thermal behavior of packed bed TES

Figure 1 shows the schematic diagram of the packed bed thermocline TES. The charging of thermal energy is performed through the flow of hot HTF from the top to the bottom. The discharging of thermal energy is performed through the reversed flow direction of the cold HTF. Due to the very slow fluid velocity, thermal stratification occurs during the operation and forms the thermocline, which is more pronounced when highly buoyant and poor conductivity HTF is employed. The extent of thermal stratification affects the performance of the TES because the thickness of thermocline determines the amount of usable thermal energy, i.e. thermal efficiency of the TES [3].
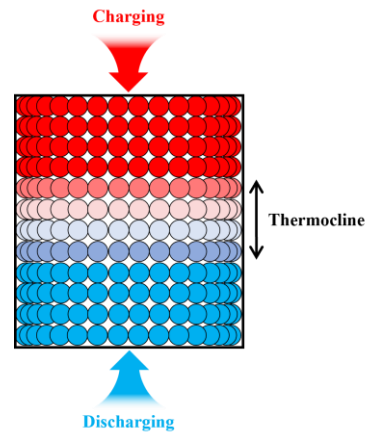

Fig. 1. Schematic diagram of packed bed thermocline TES.

2.2 Electroplating system in mass transfer

Heat transfer experiments can be replaced by mass transfer experiments based on the heat and mass transfer analogy. This analogy concept stands on the basis of the identical mathematical class of the governing equations for the two systems [5].

The copper-sulfate ($CuSO_4$-H_2SO_4) electroplating system was frequently adopted as the mass transfer system. The transfer of the cupric ions from the anode to cathode and the reduction of them at the cathode surface corresponds to heat transfer. The amount of cupric ions reduced at the cathode can be measured simply by the electric current measurement. This electroplating system has been adopted as an alternative experimental method for heat transfer experiment in existing studies [6–8].

The position of the anode and its distance from the cathode affect the measurement because a high concentration gradient of cupric ions is formed around the anode during the redox reaction [9]. Thus, in conventional mass transfer experiment, the anode is located away from the cathode to maintain the stable concentrations during the experiments. The anode should not induce concentration gradient within the fluid but act as the cupric ion provider, which were consumed at the cathode, to maintain the constant bulk concentration. However, in the thermocline TES simulation, the concentration gradient should be induced. The present study aims at maintaining the concentration gradient deliberately by maximizing the anode influence to simulate the temperature gradient in the thermocline TES.

3. Test setup

3.1 Test apparatus and test condition

Figure 2 shows the schematic diagram of the test apparatus. 0.05 M and 1.5 M of $CuSO_4$-H_2SO_4 working fluid is pushed from the bottom to the top by a pump, which corresponds to the discharging direction of the TES system. To implement the low flow velocity, bypass line was used. The copper anode is located just below the copper cathodes to supply high cupric ion concentration fluid to the test section. The high density of cupric ion near the anode simulates the cold temperature fluid in the TES system. The cathodes in the test section were arranged at uniform intervals to represent the height of the TES tank and electrically connected in parallel.
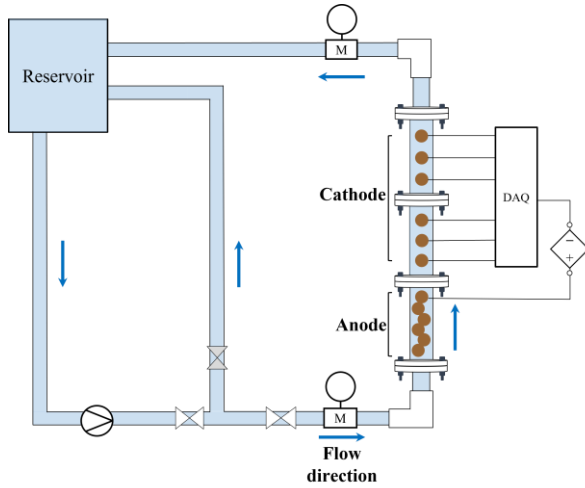

Fig. 2. Schematic diagram of test apparatus.

The diameter of the acryl duct is 0.03 m and the copper sphere is 0.025 m. The height of the test section is 0.4 m. The fluid velocity is about 0.01 m/s which is generally used in the TES system to prevent the degradation of concentration gradient region by fluid mixing.

4. Results and discussion

4.1 Anode influence on electric current in electroplating system

Figure 3 shows the variation of the measured electric current according to the height. With increasing height, the current decreased. As the abundant cupric ions generated at the anode came up from the bottom, the redox reaction occurred more actively in the cathode close to the anode. As the working fluid flowed up, the cupric ion concentration decreased because some cupric ions had already reacted at the previous cathode. The electric currents measured at the top cathodes are almost 0.
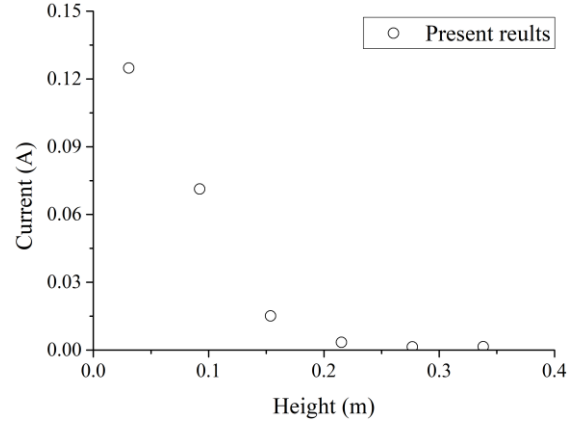

Fig. 3. Variation of measured current according to the height.

Figure 4 shows the local bulk concentration of the reacted cupric ion. For the local bulk concentration calculation from the measured current, the test section was virtually divided into uniform local volume including each cathode copper sphere. The local bulk concentration was calculated by Eq. (4.1). The local bulk concentration decreased with the height increase, which was similar to the temperature gradient in the thermocline TES system at discharging mode.

$$Local\ bulk\ concentration = \frac{\int I\ dt}{F \times n \times Local\ volume}, \quad (4.1)$$

where I is the measured current (C/s), F is the faraday constant (96,485 C/mol), and n is the number of electron in charge transfer reaction (2).
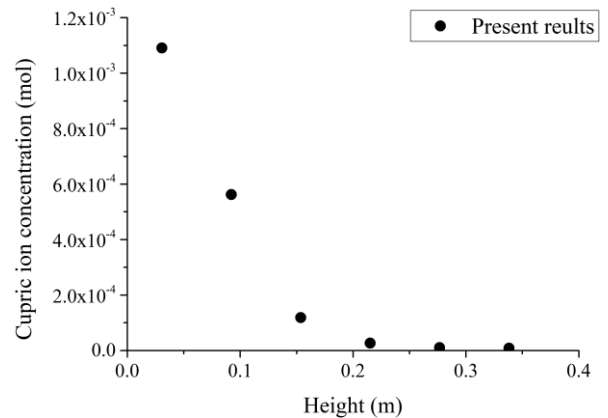

Fig. 4. Variation of local bulk concentration of cupric ion.

5. Conclusions

The thermocline in TES system was realized by copper-sulfate electroplating system. The formation of concentration gradient zone which is corresponding to the thermocline was confirmed by the anode influence.

The present study is a basic stage for development of an alternative experimental method for thermocline TES system experiment. Further study needs to be

performed under more sophisticated experimental conditions. The authors expect that through the further study, this will be utilized as the alternative experimental method for thermocline TES system.

ACKNOWLEDEGEMENT

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