Visualization of a Single-Phase Natural Circulation Loop using Mass Transfer Experiment

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1. Introduction

When an accident occurs in the nuclear power plant, the containment atmosphere needs to be cooled continuously. Fukushima accident in 2011 highlighted the necessity of the passive system when the external power was lost [1]. As the passive system can be driven by gravity without any AC power and active components such as pumps, it is reliable, simple, and cheap [2]. Natural circulation loop is one of promising passive cooling system. The loop was driven by the buoyancy force caused by the density difference between the heat source and heat sink. Many studies have been performed regarding the natural circulation loop [3-5]. However for high *Pr* fluid adopted in molten salt reactors and electronic device cooling systems, experimental studies have rarely been conducted [1].

In this study, the authors established the natural circulation loop for high *Pr* number fluid using the mass transfer system and investigated the derived condition such as flow development and patterns. The copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system based on analogy between heat and mass transfers were adopted as the mass transfer system. *Sc* was 2094, which corresponds to *Pr* in heat transfer systems. The PIV (Particle Image Velocimetry) was used to visualize and analyze the characteristics of natural circulation flow patterns.

2. Theoretical Background

2.1 Basic Phenomena of Natural Circulation

Natural circulation is driven by the buoyancy force caused by the density difference. The uniform directional circulation is generated when lighter fluid rises and denser fluid falls. In the loop, the flow rate is determined by the balance between buoyancy and friction. The force balance can be expressed as Eq. (1) and it can be simplified at steady-state condition to Eq. (2) [3].

$$\frac{L}{A}\frac{d\dot{m}}{dt} = g\beta\rho\oint TdZ - f\frac{L}{D}\frac{\dot{m}^2}{2\rho A^2} \qquad (1)$$

$$\Delta\rho g H = f\frac{L}{D}\frac{\rho\bar{u}^2}{2} + K\frac{\rho\bar{u}^2}{2} \qquad (2)$$

Where friction factor, f, gravitational acceleration (m/s^2), g, mass flux (kg/s), $\dot{m}$, time (s), t, average velocity of flow (m/s), $\bar{u}$, cross section (m^2), A, loop diameter (m), D, centerline elevation difference between the cooler and the heater (m), H, loss coefficient, K, total loop length (m), L, temperature (K), T, elevation (m), Z, thermal expansion coefficient (1/K), β, density (kg/m^3), ρ and kinematic viscosity (m^2/s), ν.

The key dimensional parameters affecting the flow characteristics of the loop, are *H*, *L* and *D*. Generally, the buoyancy force increases with *H*. The friction increases as *L* increased or *D* decreased. Also, *D* is related to the instability of the flow.

2.2 Existing Studies

Vijayan [4] reported the general trends of the steady state and stability behaviors of the single-phase natural circulation loops. He proposed a correlation for the steady state laminar flow in the loop with function of *Re* and Gr_m (*D*/*L*) as Eq. (3).

$$Re = 0.1768(Gr_m\frac{D}{L})^{0.5} \ (10^5 < Gr_m\frac{D}{L} < 5\times10^7) \qquad (3)$$

The correlation showed reasonable agreement with experimental data.

Vijayan *et al.* [5] studied effect of the loop diameter on the steady state and stability behaviors of the natural circulation loop. The straightforward way to enhance the flow rate is to reduce the friction by increasing loop diameter. And, the loop diameter also plays an important role on the stability behavior. The experiments were performed in four single channel uniform diameter loops of rectangular shape. The instability threshold was found to decrease with increased loop diameter. However, the unstable region shifts up with decreased loop diameter. They insisted that, small diameter loops are more stable than large diameter ones.

Shin *et al*. [1] studied on the flow characteristics of high *Pr* fluid in a rectangular natural circulation loop. A joint experimental and numerical analysis were performed. They reported a zigzag velocity profile appeared at the upward flow at the upper part of the heating section was proposed. Also, they observed a local natural convection due to the large temperature gradient near the wall.

3. Experimental setup

3.1 Experimental Methodology

The single-phase natural circulation loop was set up using mass transfer system based on analogy between heat and mass transfers. The *Sh* and the *Sc* in the mass transfer system correspond to the *Nu* and the *Pr* in heat transfer system, respectively.

The copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system was adopted as the mass transfer system. The experimental technique was first coined by Levich [6]. Selman *et al*. [7] established a set of material property relations at different conditions. Ko *et al*. [8] extensively used and expanded the experimental method to many applications.

When the electric potential is applied, cupric ions are generated at the anode, which increases the cupric ion concentration in the fluid near the anode and the reverse phenomenon occurs at the cathode. Thus necessary density difference in the fluid within the loop can be established. Here the cathode and anode simulates the cooler and heater, respectively.

3.2 Loop Design

It is important to design dimensional parameters for the loop to be drive steadily without instabilities. The authors designed the H, L, D and L_H prior to perform the experiment.

The force balance Eq. (2) has to be satisfied to drive the natural circulation loop. However, the $\Delta\rho$ and $\bar{u}$ are dependent variables. In order to design key geometrical parameters, the scale of the $\Delta\rho$ and $\bar{u}$ were estimated roughly, introducing several assumptions together with Eq. (2).

The $\Delta\rho$ can be calculated from concentration difference, ΔC between inlet and outlet of the cathode (or anode) pipe. However, the ΔC is also dependent variable. Considering the reduction of cupric ion at the cathode, which may restrict available experimental time, the initial concentration of the solution was determined as 0.1 M. And the authors assumed that the ΔC of the designed loop system can be regarded as 0.1 M. Because the initial concentration of the solution was 0.1 M and the highest current density can be determined just before the hydrogen evolution. And thus, the concentration of the cathode surface can be zero by the limiting current [8]. Hence, $\Delta C \sim 0.1$ M.

The $\bar{u}$ was predicted by the Eq. (4), where concentration difference (kmol/m^3), ΔC, current (A), I, flow rate (m^3/s), Q and the number of moles of copper ions that reduced by charge of 1 coulomb (5.18×10^{-9} kmol/s), a, respectively. Because all the electrons are participate in reduction reaction of the cupric ions. Hence, volumetric flow rate can be calculated knowing ΔC and I, where a is constant.

$$\Delta CQ = \alpha I \tag{4}$$

And finally, the $\bar{u}$ can be calculated with Q and A.

Using predicted scales of $\Delta\rho$ and $\bar{u}$, the scale of D in Eq. (2) was estimated with fixed value of L as appropriate length to perform experiment, 2.4 m. As a results, 0.004 m of D was selected to drive the loop in the present mass transfer system. The cathode and anode length was designed as lengthy as possible within L scale. The final designed dimension of the key parameters are listed in Table 1.

Table I: Key design parameters of the loop

H (m)	***L_H (m)***	***D (m)***	***L (m)***
0.5	0.5	0.004	2.4

3.3 Test Apparatus

Figure 1 shows the test apparatus and the PIV setup. The loop was made by assembling two copper pipes to circular glass tube. At the top of the loop, silicone tubes were attached for injection of the copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4). A power supply (PSW 160-21.6; GWINSTEK) and ammeter (Digital multimeter-15B+; FLUKE) were used.

PIV was used to measure instantaneous velocity and flow pattern in circular tube. PIV measurement regions are located (a) 0.03 m, (b) 0.1 m, (c) 0.2 m, (d) 0.4 m far from the outlet of the cathode. The laser was located on the side of the loop and the CCD (Charged Coupled Device) camera was located at the front side of the loop.

A continuous wave Nd;YVO4 laser (MGL-N-532-5W; DPSS) with a power of 5 W and a wave length of 532 nm was used. The thickness of laser sheet was 0.002 m. The tracer particles were hollow glass particles 10 μm in mean diameter and with a density of 1100 kg/m^3, the same as the density of working fluid. Particle containing images were captured by the CCD Camera (Phantom Lab111 6G Mono; Komi).

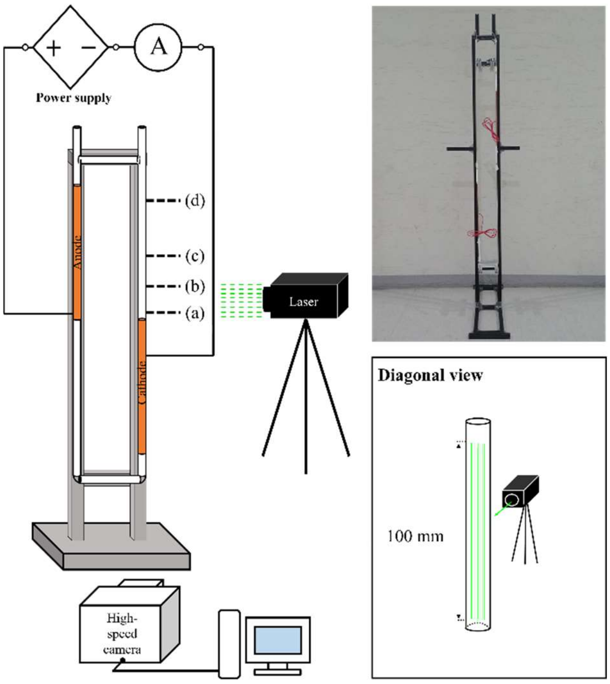

Fig. 1. Test apparatus and PIV setup.

3.4. Experimental Procedure

Once the working fluid was filled the loop entirely, the time was needed to reach quiescent state. After the quiescent state reached, a small potential was applied so that the small current density was applied, 1.59 A/m^2. And the current density was increased to 6.37 A/m^2, which was the maximum current density prior to evolution of the hydrogen at the cathode.

4. Results and Discussion

4.1. Validation of the steady state flow

In order to determine whether the steady-state condition is reached, an arbitrary position, (d) was chosen to monitor the flow velocities with the elapsed time. Fig. 2 shows the mean velocity according to the elapsed time. 600 seconds later from the initially imposed current density, 6.37 A/m^2, the mean velocity was 0.43 mm/s. And the mean velocity decreased with elapsed time and no outstanding change of current was measured from 3,960 to 10,200 second. And then, the mean velocity of the loop at (a-d) were averaged, 0.184 mm/s with standard deviation of 0.021 mm/s.

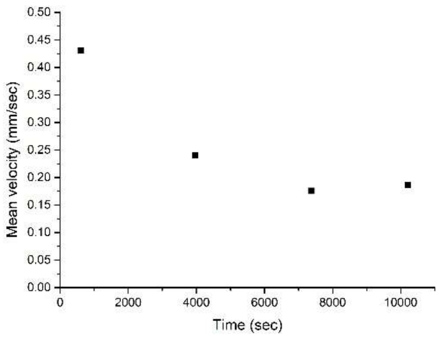

Fig. 2. Mean velocities according to the elapse time at (d).

The result was compared with the correlation, Eq. (3) which is developed for steady-state condition of the natural circulation loop in laminar condition as shown in the Fig. 3. The scale of Gr_m (D/L) at the present work is lower than the range of the correlation so that a trend line was extrapolated in dash line. The *Re* of the present work is well agreed with the correlation. Hence, it is clear that the natural circulation loop by the mass transfer experiment drives in steady state condition.

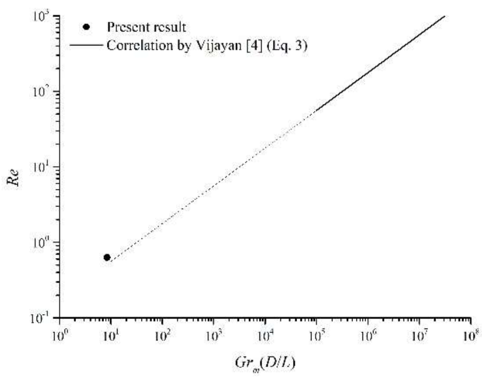

Fig. 3. Comparison of the present result with existing correlation.

4.2. Flow characteristics of the loop

Figure 4 represents the velocity profiles along the flow direction just after the cathode pipe. The typical natural convective flow patterns, where the velocity peaks appear near walls, were observed in Fig. 4(a) and (b), near the outlet region. Due to high *Sc* of the system, the concentration boundary layer was very thin and formed the double humped velocity profiles. However, as the flow traveled further, the forced convective velocity profiles were observed, where the velocity peak appears at the center as in Fig. 4(c) and (d). The locally lighter fluid of the wall region of the Fig. 4(a) and (b) gathered into the center region as the flow developed. Because the momentum boundary layer gradually developed along the adiabatic region from the outlet, the parabolic velocity profiles were observed. Similar phenomenon was founded in the existing study, which used high *Pr* working fluid over 20 as shown in Fig. 5 [1].

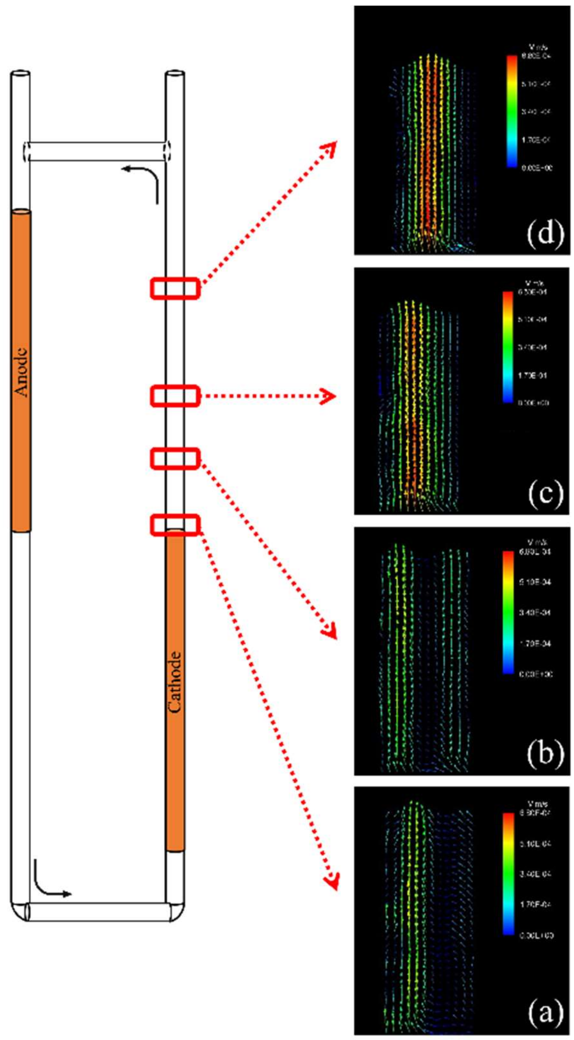

Fig. 4. Velocity profile at each observation points.

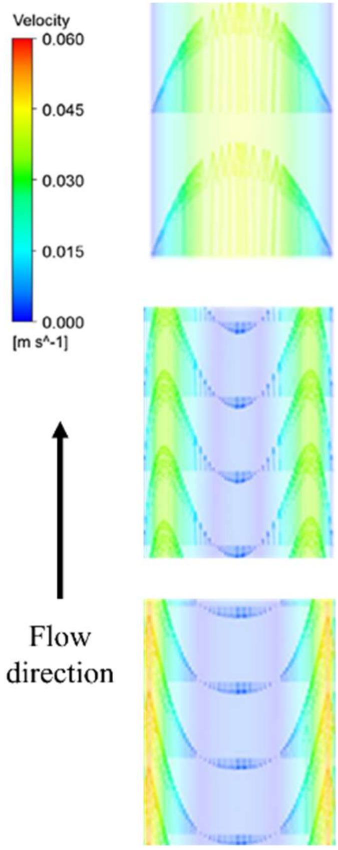

Fig. 5. Velocity profile of numerical result of Shin *et al* [1].

5. Conclusions

A natural circulation loop was set up based on mass transfer experimental method. Copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) solution was used as the working fluid. *Sc* was 2094, which corresponds to *Pr* in the heat transfer system. The flow patterns were visualized using PIV system.

The loop was designed by force balance equation in order to establish the steady state flow of the loop. The mean velocity of the loop was measured and compared with existing correlation for steady state condition. The result well agreed with the correlation.

Flow patterns in the loop according to the position showed different characteristics. The natural convective flow pattern near the cathode outlet changed into the forced convective flow pattern as flow traveled along the loop. It is concluded that the natural circulation loop was successfully realized in steady state condition using mass transfer experiment at high *Sc*.

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