Visualization of Two Phase Natural Convection Flow in a Vertical Pipe using the Sulfuric Acid – Copper Sulfate Electroplating System

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1. Introduction

The passive containment cooling system (PCCS) driven by natural forces convection gain draws research interests after Fukushima NPP accident [1]. The PCCS was classified into three categories: Containment pressure suppression, Containment passive heat removal/pressure suppression systems and Passive containment spray. Among the types of containment passive heat removal/pressure suppression systems, the system composed of an internal heat exchanger and an external coolant tank is considered.

In a severe accident condition, the heat from the containment atmosphere is transferred to the outer surface of the heat exchanger by the convection and condensation of the mixture of steam and gases. On the other hand, the heat is transferred to external pool by single phase or two phase natural convection inside of heat exchanger pipes [2].

The study aimed at investigating the influence of the diameter (D) and height (H) of the heat exchanger pipes on the single phase and two phase natural convection heat transfer.

As the initial stage of the study, the two phase natural convection flow inside a vertical pipe is visualized. In order to achieve the aim with ample test rig, a sulfuric acid – cooper sulfate electroplating system was employed based on the analogy between heat and mass transfer. The reduction of hydrogen ion at the cathode surface at high potential was used to simulate the boiling phenomena.

2. Background

2.1 Natural convection in a vertical pipe

Single phase or two phase flows appear depending on the heat flux from the wall. The single phase natural convection inside a pipe is similar to the natural convection phenomena in flat plates when the influence of the curvature can be neglected. The flow depends on the channel height and diameter: The former determines the buoyancy and the latter determines the amount of fluid to be driven by buoyancy and the interaction between the boundary layers. However, for large L/S, boundary layers developing on opposing surfaces eventually merge to yield a fully developed condition. Thus, the L/S needs to be optimized [3].

The boiling process occurs when the temperature of the surface T_s, exceeds the saturation temperature T_{sat} corresponding to the liquid pressure. The process is characterized by the formation of vapor bubbles, which grow and subsequently detach from the surface. Vapor bubble growth and dynamics depend, in a complicated manner, on the excess temperature, the nature of the surface, and thermophysical properties of the fluid, such as its surface tension [4].

2.2 Sulfuric acid – copper sulfate electroplating system

Heat transfer systems and mass transfer systems are analogous, being mathematically similar under the same class of boundary and initial conditions. Table 1 shows the corresponding governing parameters. This implies that heat transfer experiments can be replaced by mass transfer experiments, and vice versa [5]. The sulfuric acid – copper sulfate (H_2SO_4-$CuSO_4$) electroplating system has been employed as the mass transfer system based on the analogy between heat and mass transfer systems.

Table 1: Dimensionless numbers for the analogous systems.

Heat transfer		Mass transfer	
Nusselt number	$\dfrac{h_h L}{k}$	Sherwood number	$\dfrac{h_m L}{D_m}$
Prandtl number	$\dfrac{\nu}{\alpha}$	Schmidt number	$\dfrac{\nu}{D_m}$
Rayleigh number	$\dfrac{g\beta\Delta T L^3}{\alpha\nu}$	Rayleigh number	$\dfrac{gL^3}{D_m\nu}\dfrac{\Delta\rho}{\rho}$

When electrical potential is applied to an acidified copper sulfate solution, copper ions from the anode move to the cathode due to the cupric ion density difference, convective motion, and the electric migration within the solution [6].

Figure 1 shows the limiting current density according to the applied voltage. Increasing the applied potential, the current increases for a while and a current plateau appears, which occurs as the transfer of the cupric ions

no more increases. At this limiting current situation, the concentration of copper ions at the cathode can be regarded as zero. Further increase of the potential leads the current increase with the appearance of gas bubbles at the cathode surface due to hydrogen reduction [7].
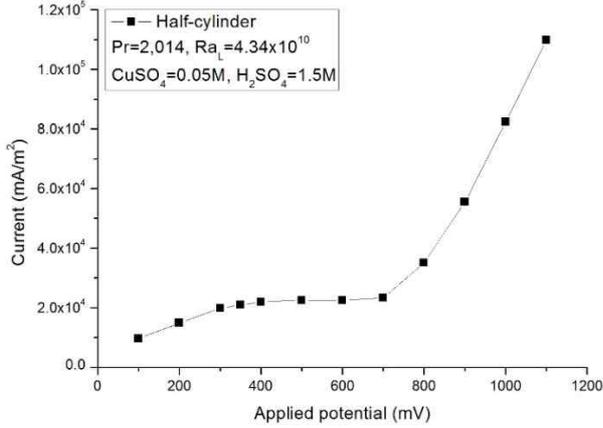

Fig. 1. Limiting current density curve.

The mass transfer rate is calculated at the region limiting current as the copper ions approaching zero. The following equation (1). Where, t_n is transference number for the given species, n is valence charge of the ion.

$$h_m = \frac{(1-t_n)I_{lim}}{nF(C_b - C_s)}. \tag{1}$$

Where, the terms of $(1-t_n)I_{lim}$ means that the amount of current due to copper ions. Then, it divided by n, the result can be converted into the number of copper ion. Finally, when it divided into Faraday constant, it means that it was the Mole number of a delivered copper ion per unit time and area.

$$h_m = \frac{(1-t_n)I_{lim}}{nF}. \tag{2}$$

3. Idea for two phase flow simulation

The basic idea of using the electroplating system for two phase flow simulation comes from the fact that the hydrogen generated at the extended applied potential can mimic the behavior of the bubble. The hydrogen bubble appeared at the applied potential of about 700mV. When the applied potential increases, the current increases steeply.
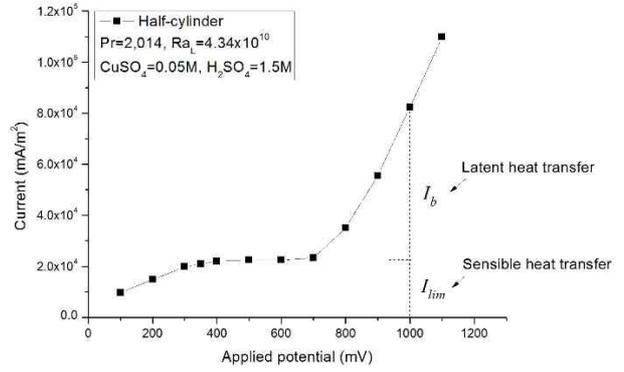

Fig. 2. Current density of latent and sensible heat transfer.

As shown in Fig. 2, the limiting current density denotes the sensible heat transfer and the current exceed the limiting current is used to reduce the hydrogen. Thus the amount of moles of hydrogen-molecule generated per unit time and area can be calculated as

$$\frac{I_b}{2F} \quad \left(\frac{H_2 Mole}{m^2 s} \right). \tag{3}$$

In order to generate the same volume of vapor, the required heat flux can be calculated as

$$\frac{I_b}{2F} \times 18g/mole \times 2247.63J/g. \tag{4}$$

4. Experiments

The apparatus and system circuit is depicted in Fig. 3. In order to visualize of bubble, the vertical pipe was cut in half and attached acryl plate. The diameter of the pipe and height was 0.04m and 0.08m respectively. Table 2 presents the properties of the acidified copper sulfate solution.
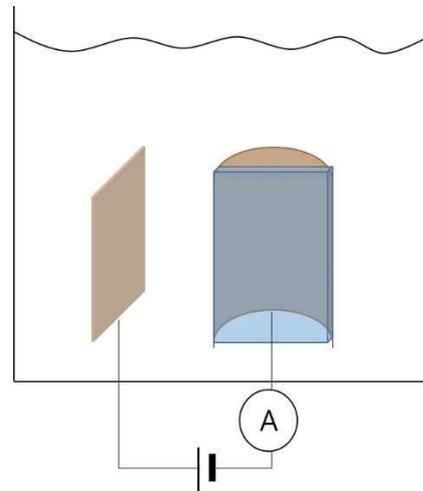

Fig. 3. The experiment system circuit.

Table 2: Properties.

ρ (Density)	1096.555 kg/m^3
μ (Viscosity)	0.0001253 kg/m·s
D (Diffusivity)	5.6×10^{-10} m^2/s
F (Faraday constant)	96368 Coulomb/mole
Pr	2014

(a) I=2.2×10^4 mA/m^2
q''=24.14J/m^{2}s

(b) I=2.3×10^4 mA/m^2
q''= 24.98 J/m^{2}s

(c) I=3.5×10^4 mA/m^2
q''=37.57 J/m^{2}s

(d) I=8.2×10^4 mA/m^2
q''= 88.16 J/m^{2}s

Fig. 5. Visualization of the natural convection mass transfer in vertical pipe varying the heat flux.

5. Results and Discussion

Figure 5 shows the hydrogen bubble generation according to the current density. The corresponding heat fluxes calculated by equation (4) are also presented. The bubbles do not appear as it lies in the limiting current 600mV. Fig. 5 (b), (c), (d) were for 700mV, 800mV, and 1000mV respectively.

6. Conclusions

This study tried to visualize the boiling heat transfer inside a vertical pipe using a cupric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system.
This seems to be successful so far. However further study has to be done to compare the result with real two phase flow situation. The surface tension and surface characteristics are to be tuned to simulate the real situation.

ACKNOWLEDGMENT

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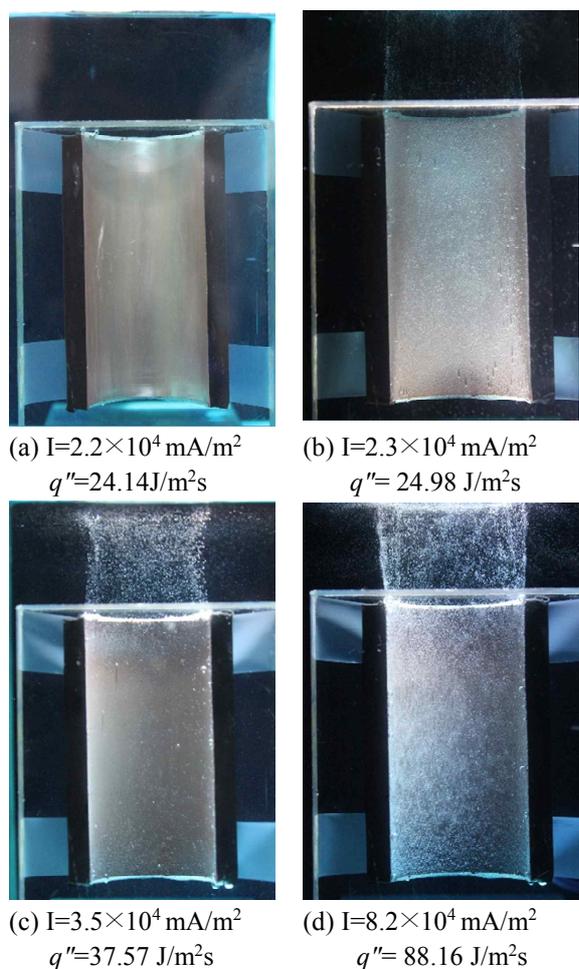[7] T. B. Draw et al., Advanced in Chemical Engineering, Academic Press, New York, London, 10, pp. 211-232, 1978.