Natural convection flow separation on the inclined plate depending on inclination and *Pr*

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1. Introduction

Passive cooling systems (PCSs) are increasingly adopted considering NPP (Nuclear Power Plant) blackout condition, when the active devices such as the pump do not operate [1–2]. However, as to the natural convection, an in-depth study on simple geometries such as an upward facing inclined plate, has not been performed sufficiently. The natural convection on the inclined plate phenomena is very complicated, because of flow instability and flow separation due to buoyancy force not acting along the plate as the boundary layer develops [3–6].

In this study, we investigated the natural convection flow on the inclined plate. Natural convection heat transfers were measured and the visualizations by photograph and PIV (Particle Image Velocimetry) were performed. The study was conducted varying the inclination (θ) and *Pr*. Based on the analogy between heat and mass transfer, the mass transfer experiments are performed using a copper sulfate-sulfuric ($CuSO_4$-H_2SO_4) electroplating system. The flow separation was visualized by the plating pattern. And the flow development along the plate was visualized through the PIV.

2. Theoretical background

2.1 Natural convection on inclined plates

Natural convection on the inclined plate shows complex heat transfer characteristics depending on the inclination angle. First, the buoyant force is reduced due to the difference between the direction of flow and the direction of the gravitational force. Second, the orientation of the heated surface affects the flow development: upward-facing or downward-facing plates. In the upward-facing plate, the buoyant flow develops along the heated plate and the instability, caused by the hotter fluid locating below the ambient fluid, induces vortex and wave motions and at some distances the flow separates from the inclined plate [5].

2.2 Critical length

There is not a universal definition of the critical length. Vliet [7] and Al-Arabi and Sakr [8] used the term to define the transition to turbulent flow. Lloyd and Sparrow [4] and Chung and Choi [6] used it to define the location where instability occurs. And Fujii and Imura [5] used it to define the position of flow separation. They reported that the critical length varies with the inclination of plates.

2.3 Visualization

Kitamura *et al.* [9] performed the natural convection experiment varying the inclination of the plate for Gr_L ranging from 8.57×10^6 to 1.14×10^{13}. In the experiments, water at room temperature was used as the working fluid. The flow fields over the plates were visualized using dye. As shown in Fig. 1, in the horizontal plate (θ = 0°), flow separation point occurred at the center of the plate. In the inclination plate of the 15°, the location of flow separation moved to downstream.

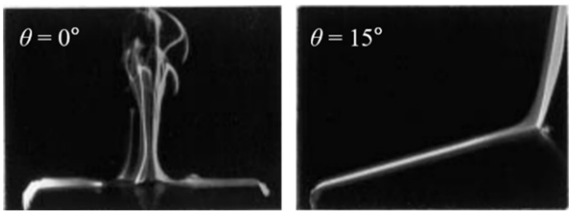

Fig. 1. Visualized flow field on horizontal and inclined plates [9].

3. Experimental set up

3.1 Mass transfer experiments based on analogy concept

Heat and mass transfers are analogous; the mathematical expressions between two systems are the same. Thus, the heat transfer problems can be solved using the mass transfer experiments and vice versa [10]. We adopted a copper sulfate-cupric acid ($CuSO_4$-H_2SO_4) electroplating system as the mass transfer system. In the electroplating system, the amount of plated copper corresponds to the amount of heat transfer. This means that the observation of the plating patterns will reveal the local heat transfer patterns.

3.2 Experimental apparatus and PIV experiments

Figure 2 represents the experimental circuit and the PIV arrangements. The experimental apparatus consisted of the cathode and anode electrodes immersed in an aqueous solution of copper sulfate-cupric acid in an acrylic tank. The cathode simulating the heated plate was placed on top of the acrylic triangular support. Anode which is large enough was located at the position not affecting the fluid flow.

In order to obtain the flow field on the active plate, the PIV was adopted. The laser is located on the side of the acrylic tank which imposes the continuous wave Nd;YVO_4 laser with a wavelength of 532 *nm* ; a power 6 *W* and the thickness of the light sheet is 0.002 *m*. The particle materials were hollow glass and 18 μm in mean diameter with a density of 1100 kg/m^3. The *x-y* streamwise velocity fields were captured by the CCD (Charge-Coupled Device) camera.

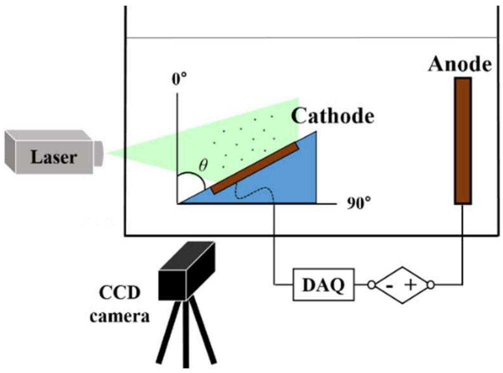

Fig. 2. Experimental circuit and PIV arrangements.

3.3 Test matrix

Table 1 shows the test matrix for natural convection on upward-facing inclined plates and PIV experiments. The width (*W*) of the plate was fixed at 0.05 *m* and the length (*L*) also fixed at 0.10 *m*. *Pr* was changed from 2094 to 8334. The inclination of the plate also varied from 0° (Vertical) to 90° (Horizontal).

Table I: Test matrix for natural convection on upward-facing inclined plates and PIV experiments.

***L* (*m*)**	***Gr*** Gr_L	***Pr* (Glycerol)**	***θ* (°)**
0.10	8.05×10^7	2094 (0 *M*)	0, 10, 20, 40, 60, 90
	3.57×10^7	4173 (1.5 *M*)	10, 40
	1.66×10^7	8334 (2.5 *M*)	

H_2SO_4 1.5 *M*, $CuSO_4$ 0.1 *M*

4. Results and discussion

4.1 Heat transfer on the inclined plates

Figure 3 compares the measured average Nu_L with the results of other studies. Closed symbols are the experimental results of this study, and open symbols are the experimental results of Lim and Chung [11]. Solid line denotes the laminar natural convection heat transfer correlation for the vertical plate by Le Fevre and Ede [12], Eq. (1). Dashed line denotes the laminar natural convection heat transfer correlation for the horizontal plate by McAdams [13], Eq. (2).

$$Nu_L = 0.67(Gr_L Pr)^{0.25} \quad (1)$$

$$Nu_L = 0.15(Gr_L Pr)^{1/3} \quad (2)$$

The experimental results of this study agreed well with the results of Lim and Chung [11] for all the inclinations. In the case of vertical plate, the measured average Nu_L of this study agreed with the heat transfer correlation within 4.63 % error. In the case of horizontal plate, the measured average Nu_L of this study agreed with the heat transfer correlation within 3.68 % error.

The average Nu_L increased with the increase of inclination from 0° to 90°, where the angle was measured from the vertical. As the inclination increased, the flow separation occurs near the leading edge and the introduction of fresh fluid increased.

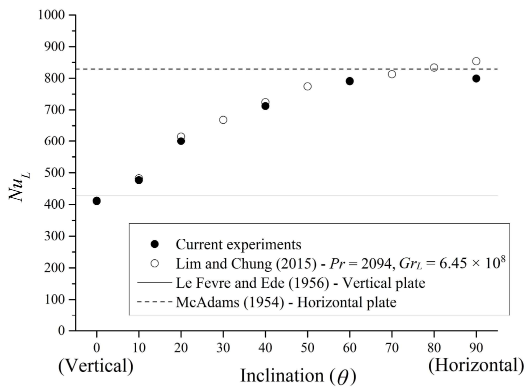

Fig. 3. Average Nu_L according to inclination.

4.2 Visualization of plating pattern

4.2.1 Influence on inclination of plate

Figure 4 shows the copper plating pattern appeared after experiments, according to the inclination of plate. The streak patterns are observed by the flow separation except for the 0° (Vertical). As the boundary layer develops, the fluid heated by the plate being located below, the flow instability occurs. Evenly spaced streak patterns are observed reflecting the three-dimensional flow structure incurred by the instability. Early and late detached flows are recorded by the copper depositions.

The early and late detached positions are marked in white lines and the average positions in red lines in Fig. 4. The locations of average lines gradually moved to downstream locations as the inclination decreased. As the inclination of plate increases, the buoyancy force caused by gravitation decreases as g $cos\theta$ and works more for transvers direction than for flow direction. Thus, the flow separation peels off at a shorter distance from the leading edge.

The critical length rapidly decreased at the inclination between 10° and 20°. It is in agreement with the observations of Lloyd and Sparrow [4] regarding the two different types of flow instabilities. The wave motion instability occurs for the inclination of less than 14°, and the vortex roll occurs for the inclination in excess of 17°.

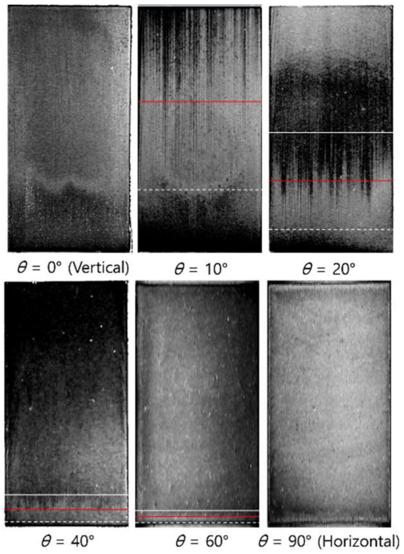

Fig. 4. Copper-plated patterns on the upward-facing plate (Pr = 2094).

Figure 5 compares the critical lengths for various inclinations from current experiments and previous studies. The solid line denotes the critical length correlation by Lim and Chung [11]. The average line of this study agreed with the critical length results of Lim and Chung [11] correlation and Vliet [7] to all the inclination except for Fujii and Imura [5]. This discrepancy seems to be caused by the different definitions of critical length.

$$L_c = 50.865 \times 1.041^{-\theta} \ (20° \leq \theta \leq 70°) \qquad (3)$$

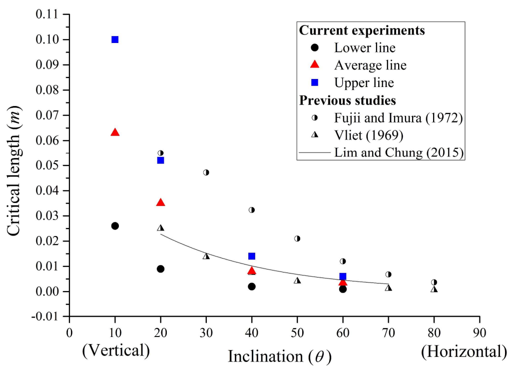

Fig. 5. Measured critical length for various inclination.

4.2.2 Influence on Pr

Figure 6 shows the copper plating patterns for the inclination 10° and 40° according to three different Pr's. The critical length increased as increasing the Pr for both 10° and 40°. The reduced thermal boundary layer thickness due to the increased Pr, delayed the flow separation as the relative volume of the low-density fluid was decreased. Fig. 7 indicated a graph of the variation of the critical length according to the Pr as shown in Fig. 6. The critical length increased as the Pr increased.

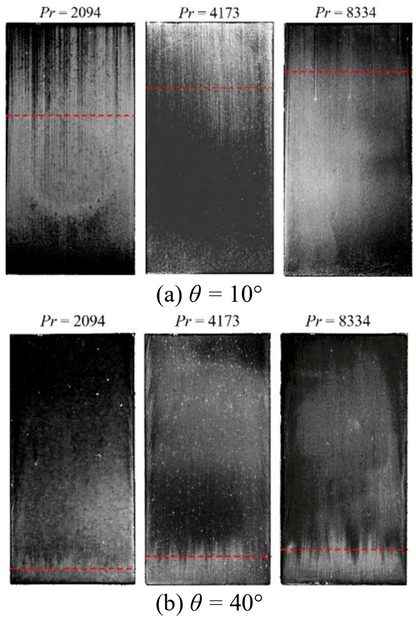

Fig. 6. Copper-plated patterns for various Pr (θ = 10°, 40°).

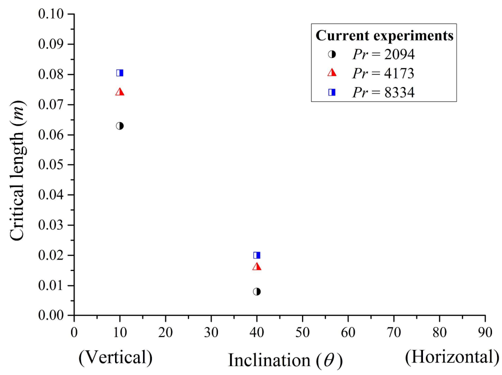

Fig. 7. Measured critical length for various Pr.

4.3 Visualized of flow fields

Figure 8 shows the vector flow field for variation of inclined plate obtained from PIV experiments. The length and color of arrows denote the magnitude of the velocity and the legend of velocity exists in the right-side. The 40° plate was analyzed, representatively.

The mainstream flows to the inclined plate direction and the maximum velocity occurs in the downstream region. The velocity in the ambient region is near the quiescent state. Although the flow separation was measured at 0.01 *m* away from the leading edge (marked with a black solid line) by the copper plating pattern, it was not clearly shown by PIV image.

The separated flow seems to be very narrow and swept by the mainstream. Hence, the regular flow separations along the inclined upward-facing plate were not observed unlike the theory of natural convection.

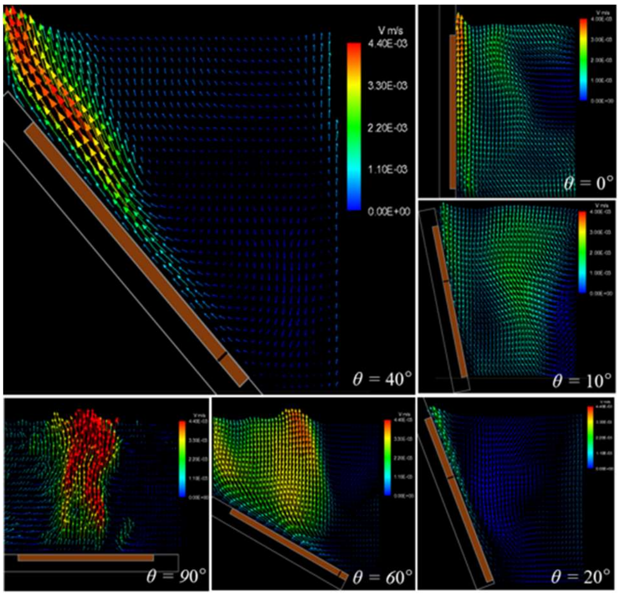

Fig. 8. Visualized flow fields on the inclined plates (Pr=2094).

5. Conclusion

The visualization and the measurements of heat transfer were performed to investigate the natural convection on the inclined plate. A copper sulfate-sulfuric acid (H_2SO_4-$CuSO_4$) electroplating system was used as the mass transfer system. The study was conducted varying the upward-facing inclination (θ) plate and the Pr.

The measured average Nu_L of the vertical and horizontal plates were agreed with the vertical and horizontal plate heat transfer correlations, respectively. The average Nu_L increased with the inclination from 0° to 90°. As the inclination increased, the flow separation occurs near the leading edge and the introduction of fresh fluid increased.

Copper plating patterns deposited on the cathodes successfully visualized the flow separations and streaks. The critical length decreased as increasing the inclination of the plate due to the instability acting more on the buoyancy force with the inclination.

The critical length increased according to the increase in Pr due to the decreased thermal boundary layer thickness.

The flow field on the plate was visualized through the PIV. Unlike the results of the copper plating pattern, the flow separation was not clearly observed for the various of inclination of the plate. This seems to be caused by the thin separated flow is quickly swept by the mainstream.

It was confirmed that the inclination of the plate and Pr were factors influencing the critical length variation. And this critical length was visualized by the copper plating pattern of the mass transfer experiment.

ACKNOWLEDGEMENT

This study was sponsored by the Ministry of Science and ICT and was supported by Nuclear Research & Development program grant funded by the National Research Foundation (NRF) (Grant code: 2017M2A8A4015283).

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