Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2017

Visualization of Natural Convection Heat Transfer in an Inclined Circular Pipe

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1. Introduction

As the passive cooling system (PCS) of nuclear reactor has received the considerable attention recently, the studies on natural convection heat transfer in an inclined circular pipe are being gradually carried out [1, 2]. However, the analysis of the results is insufficient although the internal flow formed by interaction of boundary layers is complex unlike the external flow of the pipe. Also most of the studies were conducted for a narrow range of $10^6<Ra_D<10^8$ and low *Pr* [1-5].

Figure 1 shows the geometry and parameters of the inclined pipe. In the case of natural convection in the inclined pipe, the boundary layers formed in the radial and the axial direction vary depending on the inclination (θ), diameter (D), and length (L) of the pipe [1-3]. And their interaction results in complex of flow in the pipe [1]. Thus, the internal flow formed by the interaction of the boundary layers needs to be defined. Also, the effects of each parameter and *Pr* on the internal flow should be verified.

In this study, the visualization and the measurements of heat transfer were performed to explore the natural convection flow in the inclined pipe. The study was conducted varying the inclination (θ), the diameter (D) and the length (L). The inclination (θ) is varied from 0° to 90°, the diameter (D) from 0.026m to 0.063 m and the length (L) from 0.1 m to 0.3 m. The range of Ra_D is $2.98 \times 10^9 \leq Ra_D \leq 4.22 \times 10^{10}$. Based on the analogy between heat and mass transfer, the mass transfer experiments are performed using a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system.

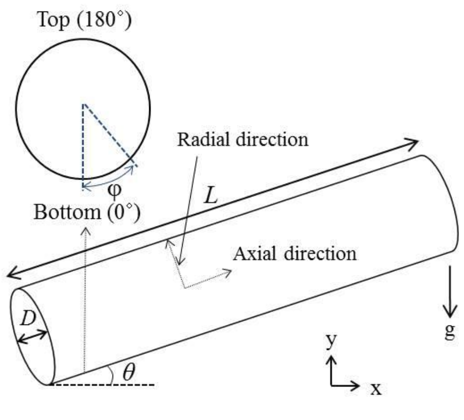


Fig. 1. Geometry and parameters of an inclined pipe.

2. Theoretical background

2.1 Natural convection heat transfer inside a horizontal and vertical pipe

In the horizontal circular pipe, the boundary layer is formed from the bottom (φ = 0°) toward the top (φ = 90°) along the inner wall. The plumes reached the top descend to the bottom. As a result, a symmetrical D-shaped circumferential flow is formed [1, 2, 6].

Chae and Chung [6] carried out the mass transfer experimental studies about the natural convection in a horizontal pipe for $6.8\times10^8<Ra_D<1.5\times10^{12}$. The measured local average mass transfer rates indicated that two D-shaped natural convective flows developed from the bottom to the top in the horizontal pipe.

Sarac and Korkut [7] performed the experimental studies for the heat transfer in the horizontal pipe in the range of $5.7\times10^9<Ra_D<1.6\times10^{11}$. They proposed the correlation for the inside natural convection as follows:

$$Sh_D = 0.703(Gr_D Sc)^{1/4} \quad (1)$$

In the vertical circular pipe, the axial flow occurs along the inner wall of the pipe from entrance to exit. The thickness of boundary layer formed in the axial direction is influenced by length (L) [8-10].

Roul and Nayak [8] investigated the effect of heat flux and *L/D* (length per diameter) on heat transfer in the vertical pipe. They confirmed that the heat transfer reduces in the exit as *L/D* increase.

2.2 Natural convection heat transfer inside an inclined pipe

For the inclined pipe, there are complex phenomenon due to the interaction between the circumferential flow in the horizontal pipe and the axial flow in the vertical pipe [1]. Depending on the variation of inclination (θ), the vertical cross section transforms from the circle toward the ellipse, which changes the heat transfer and the flow in pipe.

Hasobee and Salman [1] conducted the experimental studies to confirm the influence of inclination (θ) on the natural convection heat transfer in the pipe. They reported that the heat transfer increases according to moving of inclination (θ) from the 0° to 90° and the position from the entrance to the exit. Al-arabi *et al.* [7] carried out the experiments for heat transfer in the pipe. They reported similar results with Hasobee and Salman [1].

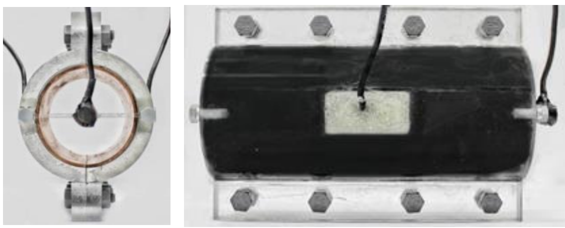
3. Experiments

3.1 Analogy concept

Heat and mass transfer are analogous; the mathematical expressions between two systems are the same. Thus, the heat transfer problems can be solved using the mass transfer experiments [11]. At the mass transfer system, the measurements were made using the limiting current technique with a copper sulfate–cupric acid ($CuSO_4$–H_2SO_4) electroplating 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 test matrix

The test apparatus are shown in Fig. 2. To facilitate the process of identifying the patterns inside the pipe, the copper cathode was composed of two halves of the pipe. The copper anode rod was located at the center using the anode fixing device. Also, an angle adjustor which allows to freely adjusting the inclination (θ) from 0° to 90° was constructed.



(a) Front view (b) Side view

Fig. 2. Photographs of the apparatus.

Table I shows the test matrix for the experiments. *Sc* corresponding to *Pr* was 2,094. In the test of length (L) effect, the diameter (D) was fixed at 0.063 m and length (L) was varied from 0.1 m to 0.3 m. And in the test of diameter (D) effect, the length (L) was fastened at 0.2 m and diameter (D) was changed from 0.026 m to 0.063 m, which correspond to Ra_D ranging from 2.98×10^9 to 4.22×10^{10}. The inclination (θ) was changed from 0° to 90° for all diameters (D) and lengths (L).

Table I: Test matrix for the experiments.

Sc	L(m)	D(m)	Ra_D	θ(°)
2,094	0.1	0.063	$4.22{\times}10^{10}$	0°, 5°, 15°, 30°, 45°, 60°, 90°
	0.2	0.026	$2.98{\times}10^{10}$	
		0.038	$9.43{\times}10^{10}$	
		0.063	$4.22{\times}10^{10}$	
	0.3	0.063	$4.22{\times}10^{10}$	

4. Results and Discussions

4.1 Comparison with existing studies for horizontal pipe

In order to verify the experimental results of this study, they were compared with the existing studies for horizontal pipe (Fig. 3). It is because there were no comparable correlations and data for the natural convection heat transfer in the inclined circular pipe. The results of this study agreed with Sarac and Korkut [7] correlation within 11 % error. When the diameter (D) is equal to 0.063 m, Nu_D's according to the length (L) have 1.96 % error, and they are very similar.

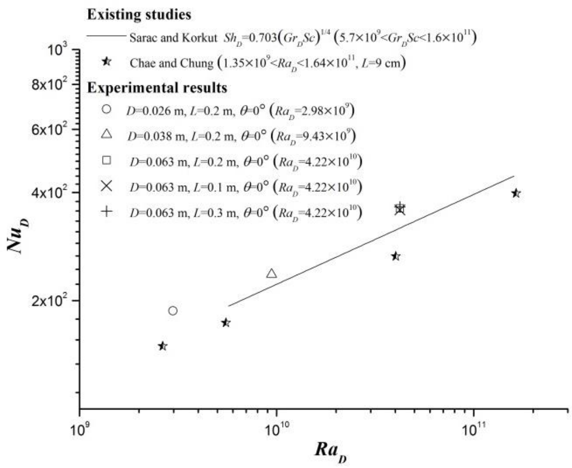


Fig. 3. Comparison of the experiment data with the results of existing studies.

4.2 Influences of inclination, diameter and length

Figure 4 presents the mass transfer coefficients (h_m) according to all the inclination (θ), the diameter (D) and the length (L). Based on the analogy between mass and heat transfer, the mass transfer coefficient (h_m) corresponds to the heat transfer coefficient (h_h).

The mass transfer coefficients (h_m) decrease according to increase of the inclination (θ). Also, the axis ratio of an elliptical vertical cross section increases. It means increase of heated length. When the heated length increases, the thickness of the boundary layer at the top increases and the heat transfer reduces.

In the inclined pipe, the boundary layers in axial direction are formed at both the bottom and the top. The boundary layer formed at the bottom is detached to the top of the pipe (Fig. 5). The degree of detachment at the bottom varies with increasing of inclination (θ). At the top, the acceleration of the flow velocity reduces as the number of the detached plumes decreases according to the increase of the inclination (θ). As the results, when the inclination (θ) increases, the interacted phenomena between the boundary layers of the circumferential direction and the axial direction cause the decrease of the heat transfer.

For the decrease of the diameter (D), the mass transfer coefficients (h_m) increase. The heat transfer increases because the thickness of the boundary layer becomes thin with the decrease of heated length. The mass transfer coefficients (h_m) decrease when the length (L) increases. This is because the area where the leading edges take place in the boundary layer decreases when the length (L) increases.

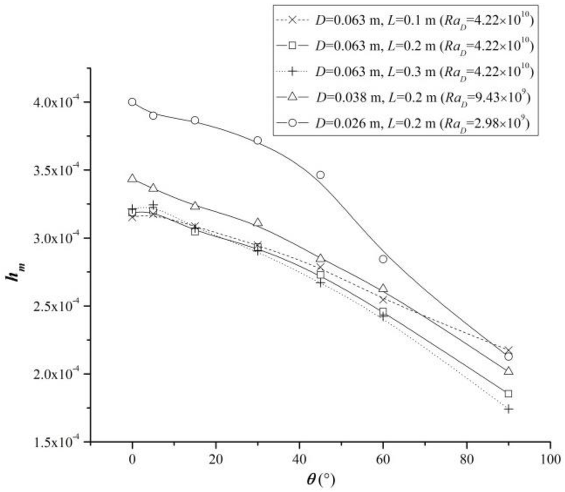
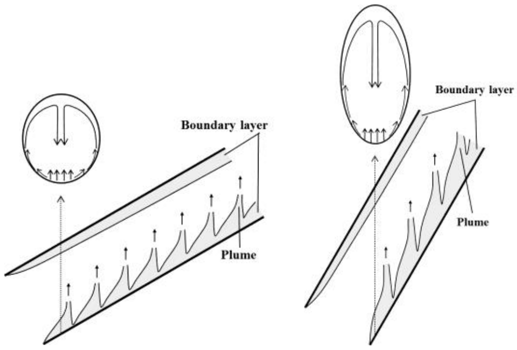


Fig. 4. Effect of inclination (θ) on the variation of *hm*.



(a) θ=30° (b) θ=60°

Fig. 5. Sketch of the vertical and the axial cross section for the inclined pipe.

4.3. Visualization of natural convection heat transfer and flow

Through the results of plating patterns, this study confirmed the internal flow and detachment of boundary layers. There are two types of pattern on cathode; dot pattern, dot and line pattern.

The plating patterns become light due to a lack of the heat exchange with the fresh fluid. That is the meaning of the reduction of heat transfer. If the boundary layer detaches, the detachment points appear in bright spot and they are the dot patterns. After the detachment occurs, a new thermal boundary layer is formed until it becomes thick just before the detachment occurs. Thus, the line patterns are formed and they are the same as newly grown boundary layer.

Near the bottom, there is only a dot pattern as the fluid remains stagnant and it rises vertically from the bottom. But in the other area, dot patterns and dot and line patterns are observed as the boundary layer is formed along the circumferential direction (Fig. 6).

Figure 7 presents the result of the visualization depending on the inclination (θ) of the pipe. In the horizontal pipe, there is only a circumferential flow along the vertical cross section. The patterns head to the vertical direction shown as Fig. 7(a). Thus, the criteria for the angle of patterns (θ*) is y-axis of the vertical cross section. The angle of patterns (θ*) equals to the inclination (θ) at θ=0°. Even at the different inclination (θ), the angle of the patterns (θ*) and the angle of the pipe (θ) were expected to be equal. However, in Fig. 7(b), (c) and (d), the angle of patterns (θ*) is larger than the inclination (θ) according to the increase of inclination (θ). It is thought that the axial flow becomes stronger than the circumferential flow according to increasing of inclination (θ). Other observed features are the same as the horizontal pipe.

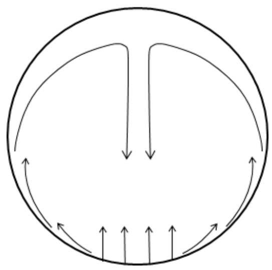
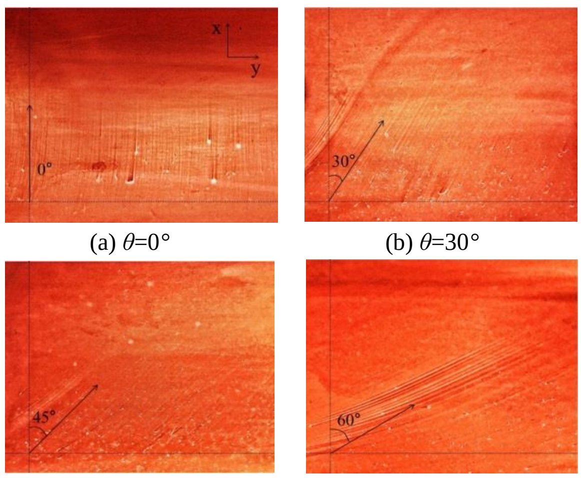


Fig. 6. Sketch of the vertical cross section for the circumferential flow at θ = 0°.



(a) θ=0° (b) θ=30°
(c) θ=45° (d) θ=60°

Fig. 7. The visualization results of the inclination (θ).

5. Conclusion

The visualization and measurements of heat transfer were performed to explore the natural convective flow in the inclined circular pipe. This work was conducted varying the inclination (*θ*), the diameter (*D*) and the length (*L*). The experimental results are compared with the existing studies for the horizontal pipe and agreed well with Sarac and Korkut [7].

The heat transfer reduces as the increase of the inclination (*θ*). The reason is that when the heated length of circumferential direction increases, the thickness of boundary layer at the top increases. Another reason is that the acceleration of the flow velocity in the axial direction reduces as the number of the detached plumes decreases.

According to the increase of the diameter (*D*) and length (*L*), the heat transfer reduces. That's why the thickness of the boundary layer becomes thin with the decrease of heated length and the region of leading edge occupying the boundary layer reduces.

As the results of the visualization, the detachment of the boundary layer and the internal flow were verified. The detachment patterns appeared as the weak parts of the plating. Based on this, the internal flow rising vertically in the bottom and flowing along the circumferential direction in the other area was confirmed. Also, it was verified that the influence of the flow formed in each direction is changed according to varying of inclination (*θ*).

This study analyzed the influences of the parameters as well as confirmed the detachment of the boundary layer and internal flow through the visualizations. Based on all of the results, sketch of the flow in the inclined pipe presented.

ACKNOWLEDEGEMENT

This work was supported by “Human Resources Program in Energy Technology” of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20164030200990)

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