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Visualization of natural convection heat transfer inside an inclined circular pipe

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ABSTRACT

Natural convection heat transfer inside an inclined pipe was visualized. Based on the analogy, mass transfer experiments were conducted instead of heat transfer ones using an electroplating system. The inclination (*θ*), diameter (*D*), and the length (*L*) of the pipe were varied 0° ~ 90°, 0.026 m ~ 0.063 m and 0.1 m ~ 0.3 m, respectively. The Ra_D ranged from 2.98×10^9 to 4.22×10^{10} and the *Sc* was 2094. The circumferential and axial flows interact with each other, which causes the complex internal flows inside the inclined pipe. The different copper plating patterns were appeared depending on the inclination (*θ*), diameter (*D*), and the length (*L*) and their influences on heat transfer inside the pipe were analyzed.

1. Introduction

Recently, studies on the natural convection inside a circular pipe have been carried out as the passive cooling system (PCS) of nuclear reactor and solar collectors have received the considerable attention [1,2]. Natural convection inside the pipe appears in many engineering applications, such as energy conversion and storage system, cooling of electronic systems and air cleaning system [1–10]. Most of the existing studies focus on the horizontal and vertical pipes and the studies on the inclined pipe are rare [1–3].

The heat transfer inside the inclined pipe is more complex than those for horizontal and vertical pipes. In the horizontal or the vertical pipe, a simple flow is formed either along the circumference or along the axis [6–10]. However, in the inclined pipe the circumferential flow and the axial flow interact and form a complex flow depending on the inclination (*θ*) of the pipe, which exerts a complex influence on the heat transfer. However, existing studies rarely dealt with the topic. In addition, most of the existing studies were conducted within limited range of $10^6 < Ra_D < 10^8$ and low *Pr* [1–5].

Fig. 1 shows the geometry and parameters of the inclined pipe. The internal flow of the inclined pipe is influenced by the parameters: inclination (*θ*), diameter (*D*), and length (*L*). The flows formed along the circumference and the axis vary according to the parameters of the pipe [1–3].

In this study, natural convection experiments were performed for the inclined pipe varying the inclination (*θ*), the diameter (*D*) and the length (*L*). The inclination (*θ*) was varied from 0° to 90°, the diameter (*D*) from 0.026 m to 0.063 m and the length (*L*) from 0.1 m to 0.3 m. The range of Ra_D was from 2.98×10^9 to 4.22×10^{10}. The *Sc*, which corresponds to *Pr* was 2094. The copper plating patterns appeared on the inner surface of the pipe after the experiments reveal the mass transfer i.e. heat transfer.

2. Theoretical backgrounds

2.1. Natural convection heat transfer inside a horizontal pipe

In the horizontal pipe, the internal flow is formed along the circumferential wall from the bottom ($\varphi = 0°$) toward the top ($\varphi = 180°$). The flow arrived at the top descend to the bottom. This is called as two D-shaped natural convective flows [1,2,6]. Since it is the main flow in the horizontal pipe, the heat transfer depends on the diameter (*D*).

Chae and Chung [6] carried out the mass transfer experiments on the natural convection in the horizontal pipe. The *Sc* was 2094, the length (*L*) was 0.09 m and the diameter (*D*) was varied from 0.02 m to 0.0259 m. The range of Ra_D was from 6.8×10^8 to 1.5×10^{12}. The measured local average mass transfer rates indicated that it was smallest at the top as the boundary layer formed along the circumferential wall is thickest at the top. Therefore, they confirmed that the two D-shaped natural convective flows are formed.

Sarac and Korkut [11] conducted the mass transfer experimental study on the natural convection inside the horizontal pipe. The *Sc* was varied from 1977 to 2282 and $Gr_D Sc$ was varied from 5.7×10^9 to 1.6×10^{11}. They proposed the correlation as follows:

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

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Nomenclature

C	Molar concentration [$mole/m^3$]
D	Diameter of pipe [m]
D_m	Mass diffusivity [m^2/s]
F	Faraday constant [94,485C/mol]
g	Gravitational acceleration [9.8 m/s^2]
Gr_D	Grashof number ($g\beta\Delta TD^3/\nu^2$)
h	Heat transfer coefficient [$W/m^2{\cdot}K$]
h_m	Mass transfer coefficient [m/s]
I_{lim}	Limiting current density [A/m^2]
k	Thermal conductivity [$W/m{\cdot}K$]
L	Length of pipe [m]
n	Number of electrons in charge transfer reaction
Nu_D	Nusselt number (hD/k)
Pr	Prandtl number (ν/α)
Ra_D	Rayleigh number ($g\beta\Delta TD^3/\alpha\nu$)
Sc	Schmidt number (ν/D_m)
Sh_D	Sherwood number (h_mD/D_m)
$t_{Cu}{}^{2+}$	Transference number of Cu^{2+}
T	Temperature [K]
U_x	Uncertainty of x

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Volume expansion coefficient [$1/K$]
γ	Dispersion coefficient
θ	Inclination [°]
θ_*	Angle of plating pattern [°]
μ	Viscosity [$kg/m{\cdot}s$]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]
φ	Angular position in the pipe [°]
ω	Orientation angle [°]

Elshazly et al. [7] performed the experiments to explore the effect of the orientation angle (ω) in the elliptic horizontal pipe. The orientation angle (ω) is the angle formed by the major axis of the ellipse and the horizontal. The length of the major axis was 0.5 m and the working fluid was air. They reported that the heat transfer improved according to orientation angle (ω). In addition, the heat transfer at each end of the pipe was higher than those at the middle of the pipe due to the in–flows of the fresh fluid at both ends of the pipe.

2.2. Natural convection heat transfer inside a vertical pipe

In the vertical pipe, the internal flow is formed along the axis from the entrance to the exit. The length (L) of the pipe influences the thickness of the boundary layer formed along the axial wall [8–10]. In addition, the interaction between the inner boundary layers varies according to the diameter (D) [9]. As a result, the natural convection in the vertical pipe depends on the length (L) and the diameter (D).

Roul and Nayak [8] investigated the effect of L/D (length per diameter) on the heat transfer in the vertical pipe. The L/D was varied from 10 to 18.89 and the working fluid was air. They confirmed that the heat transfer decreases in the exit when the L/D increases.

Ohk and Chung [9] carried out numerical and experimental studies

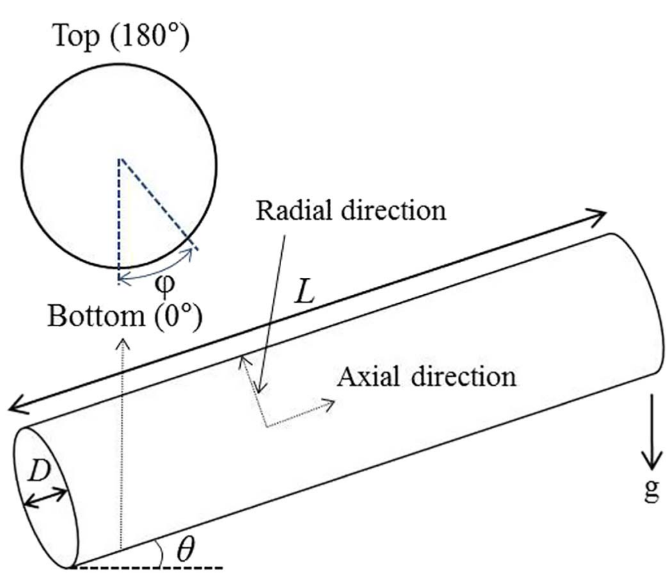

Fig. 1. Geometry and parameters of an inclined pipe.

to confirm the influence of the diameter (D), length (L) and Pr on the natural convection in the vertical pipe. The diameter (D) ranged from 0.003 m to 0.03 m, the length (L) from 0.2 m to 1.0 m and the Pr from 0.7 to 2014. At high Pr of 2014, the Ra_L value was varied from 6.85×10^{11} to 8.46×10^{13}. They verified that the different phenomena occurred as the interaction of the boundary layers varies according to the diameter (D), the length (L) and the Pr. At large diameter (D), short length (L) and high Pr, the boundary layers do not interact and the phenomena becomes similar to those on the vertical plates. Or only momentum boundary layers interact and duct flow effect appears. At small diameter (D), long length (L) and low Pr, chimney effect appears as both momentum and thermal boundary layers interact.

2.3. Natural convection heat transfer inside an inclined pipe

In the inclined pipe, there are the interactions between the circumferential flow and the axial flow [1]. This causes complex internal flow and affects heat transfer. With the increase of the inclination (θ), the vertical cross section varies from the circle toward the ellipse. This causes the increase of the heated length and the relative decrease of the detachments of the boundary layers. Hence, the heat transfer in the inclined pipe depends on inclination (θ), diameter (D), and length (L).

Hasobee and Salman [1] conducted the experimental study to verify the influence of the inclination (θ) on the natural convection in the inclined pipe. The working fluid was air. The diameter (D) was 4.8 cm and the length (L) was 50 cm. They reported that the heat transfer improves according to the increase of the inclination (θ) from 0° to 90° and moving of the position from the entrance to the exit.

Al-arabi et al. [3] performed the experiments for natural convection in the inclined pipe. They used air as the working fluid. The inclination (θ) from 0° to 75°, diameter (D) ranged from 13.5 mm to 19.7 mm and the length (L) from 197 mm to 565 mm. Elshazly et al. [4] investigated the effect of the inclination (θ) on heat transfer in the elliptic pipes with the Ra_D ranging from 2.6×10^6 to 3.6×10^7. The inclination (θ) was varied from 0° to 75°. Moawed and Ibrahim [5] additionally varied the axis ratio at the same experimental conditions with Elshazly et al. [4]. The range of Ra_D was from 2.6×10^6 to 3.6×10^7. *Al*-arabi et al. [3], Elshazly et al. [4] and Moawed and Ibrahim [5] reported the similar results with Hasobee and Salman [1].

Mohammed et al. [2] carried out the experiments to investigate the effect of the inclination (θ) on the local heat transfer. The diameter (D) was 59.3 mm, the length (L) was 1.2 m and the inclination (θ) was varied from 0° to 90°. The air was used for the working fluid. They confirmed that the heat transfer decreases as the flow proceeds from the entrance to the exit. However, they reported that the heat transfer

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