Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

The Natural Convection Heat Transfer inside Vertical Pipe: Characteristic of Pipe Flow according to the Boundary layer

Seung-Min Ohk and Bum-Jin Chung*
Department of Nuclear Engineering, Kyung Hee University
#1732 Deokyoung-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Korea
**Corresponding author: bjchung@khu.ac.kr*

1. Introduction

The Passive Cooling System (PCS) driven by natural forces drew research attention since Fukushima nuclear power plant accident [1]. The performance of the PCS affected by the geometries as the driving forces of natural convective flows depends on them. The natural convection heat transfer of the vertical pipe is influenced by the length and diameter of the pipe and material properties as well.

This study investigated the natural convection heat transfer inside of vertical pipe with emphasis on the phenomena regarding the boundary layer interaction. Numerical calculations were carried out using FLUENT 6.3 [2]. The length and diameter of the pipe were varied from 0.2 m to 1.0 m and from 0.003 m to 0.05 m, respectively which covered both laminar and turbulent flow conditions. They correspond to Gr_L of 3.8×10^8 - 4.2×10^{10}. Experiments were performed for the parts of the cases to explore the accuracy of calculation. Based on the analogy, heat transfer experiment is replaced by mass transfer experiment using sulfuric acid copper sulfate ($CuSO_4-H_2SO_4$) electroplating system [3].

2. Background theories

Natural convective flow is driven in the heated vertical pipe due to the buoyancy. Both temperature and velocity boundary layers develop along the pipe. In case of small length-to-diameter pipes, the boundary layers do not overlap, the heat transfer is similar to that on the vertical flat plate [4].

Le Fevre [5] suggested a natural convection heat transfer correlation (1) on a vertical plate for laminar condition and Fouad [6] suggested a correlation (2) for the turbulent condition.

$$Nu_L = 0.67(Gr_L Pr)^{0.25} \quad \text{at} \quad Gr_L < 10^9 \qquad (1)$$

$$Nu_L = 0.31(Gr_L Pr)^{0.28} \quad \text{at} \quad Gr_L > 10^9 \qquad (2)$$

In case of large length-to-diameter pipes, the boundary layers formed at the opposite walls merge into a single buoyant rising stream [7]. Flows are accelerated by chimney effect, and the heat transfer is enhanced as the flow rate increases [8].

3. Experiment and Numerical analyses

3.1 Experiment apparatus and test matrix

The experimental apparatus and circuit are shown in Fig. 1. The vertical cathode pipe with the anode rod at center is located in a top-opened acrylic tank. The test matrix is presented in Table I. the length (L) was varied from 0.2 m to 1.0 m for each diameter (D) is 0.005 m and 0.01 m.

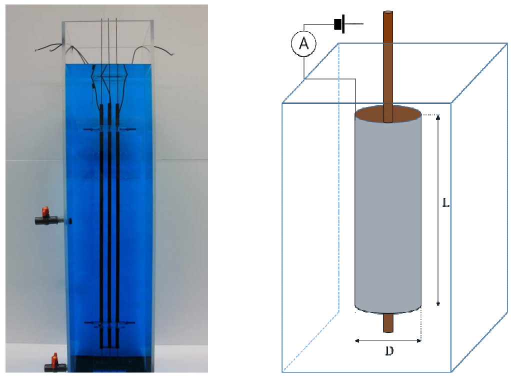


Fig. 1. Experimental apparatus and circuit.

Table I: Test matrix for experiment

Pr	***D*** **(10^{-3} m)**	***L*** **(m)**	***Gr_L***
2,014	5, 10	0.2−1.0	$3.8\times10^8 - 4.2\times10^{10}$

3.2 Experimental methodology

Mass transfer experiments are performed replacing heat transfer experiment based on analogy [9]. A sulfuric acid-copper sulfate ($CuSO_4-H_2SO_4$) electroplating system is employed as the mass transfer system. Detailed explanation can be found in Chung et al. [10, 11].

3.3 Numerical analysis

Figure 3 shows the simulation domain, indicating the flow region and boundary conditions. The bottom of domain is taken to be the pressure inlet and the top pressure outlet. The heated wall temperature is kept at the constant temperature of 400K.

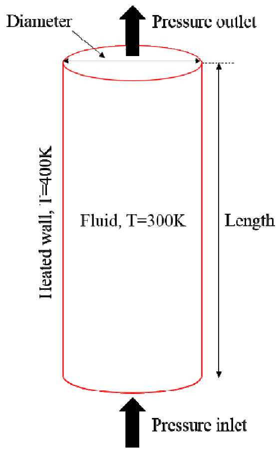


Fig. 2 simulation domain.

Table II presents the calculation test matrix: the diameter ranged from 0.003 m to 0.05 m, length from 0.2 m to 1.0 m and the Prandtl numbers 0.7, 1, 20, 2,014. The test matrix covers the range of experiments.

Table II: Test matrix for calculation

Pr	***D*** **(10^{-3} m)**	***L*** **(m)**	***Gr_L***
0.7, 20, 2,014	3, 5, 10, 30, 50	0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0	$3.8\times10^{8} - 4.2\times10^{10}$

The calculations are conducted laminar and turbulent conditions using FLUENT 6.3. The temperature difference between wall and bulk fluid is 100K. A second order upwind algorithm was used for laminar and turbulent flow conditions, where the SIMPLE algorithm was used to couple the pressure-velocity fields. For turbulent flow condition, Spalart-Allmaras one equation model was used with the basic properties supplied by FLUENT. The *y+* value was selected between 0.7 and 0.8 so that the calculation agrees with the experimental results.

3. Results and discussion

3.1 Validation between results and exist correlation

Fig. 3 shows the measured and calculated Nu_L with the predictions from natural convection heat transfer correlations. Calculations results agree with the experiments results within 8%.

For large diameter vertical pipes, where the thermal boundary layers are not expected to merge in the pipe, the local Nusselt numbers for laminar and turbulent flow condition agree with those on the vertical flat plates. For smaller diameter vertical pipes or lower Prandtl number cases, where thicker thermal boundary layers are expected, the calculated Nusselt numbers were lower than those of Le Fevre and Fouad.

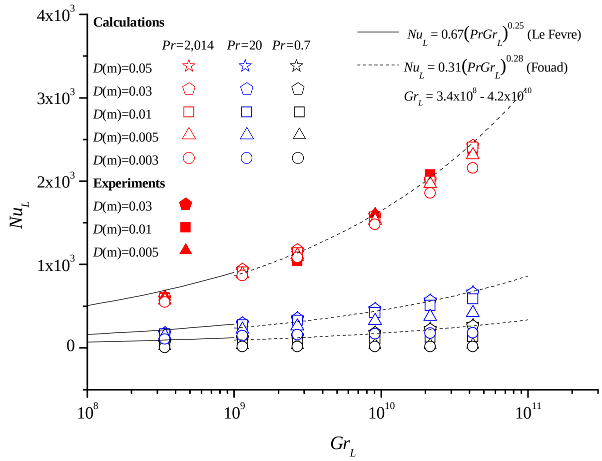
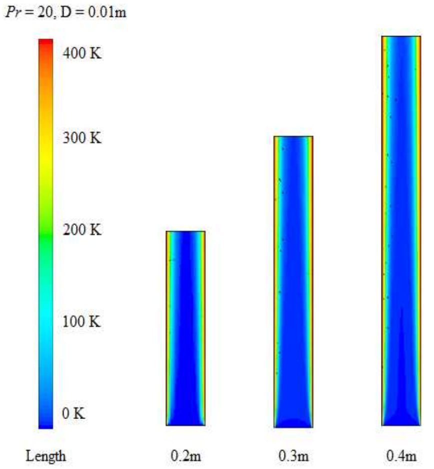


Fig. 3 Nu_L according to the Gr_L for all diameter and Prandtl number.

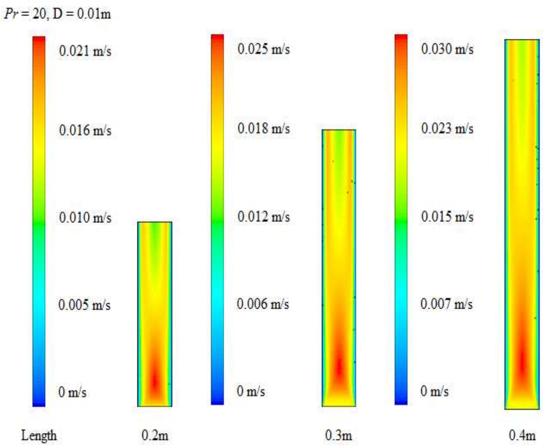
3.2 Velocity and temperature profiles

Figure 4 shows thermal and velocity contours. With the fixed diameter of 0.01 m and Prandtl number of 20, the length of the pipes are 0.2 m, 0.3 m, and 0.4 m. In Fig. 4(a), the thermal boundary layers are only developed in the vicinity of the inner wall of the pipes and the thermal boundary layers interferences are observed, which means that the behavior of the thermal boundary layers are similar to those on the vertical plate at the open channel flow condition. Fig. 4(b) shows the velocity contours. Near the inlets, the velocity peaks appear at the center. While at the exit, they appear near the walls. This means that the velocity profiles are similar to those of the forced convection near the inlet but similar to those of the natural convection near the exit. This behavior is enhanced as the length of the pipe increases. This phenomenon occurs due to the duct flow situation, where the mean velocity at each elevation should be constant regardless of the amount of buoyant driving forces. Thus the flow near inlet becomes like forced convection and that near exit becomes like natural convection.

Figure 5 shows thermal and velocity contours for Prandtl number of 0.7. With the reduced Prandtl number, thicker thermal boundary layers are expected and they merge inside a pipe as shown in Fig. 5(a) for 0.3 and 0.4m. The merged plumes are accelerated along the pipe and chimney like effect is appeared. Fig. 5(b) is completely different from Fig. 4(b). The velocity peaks appear near the exit.

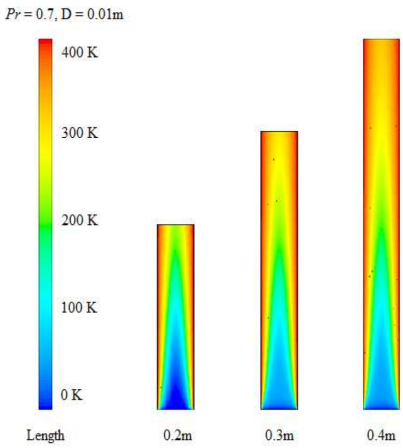


(a) Temperature.

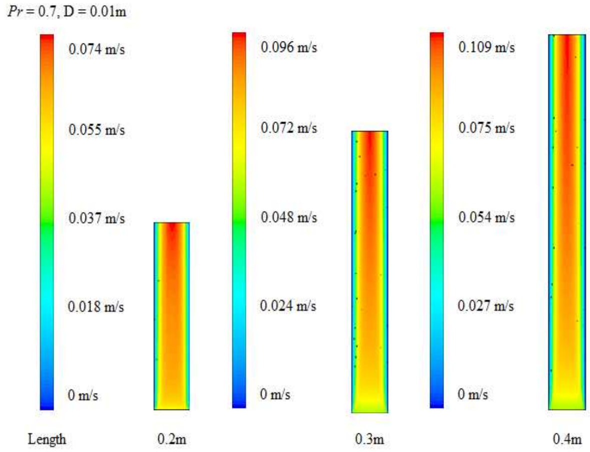


(b) Velocity.

Fig. 4. Temperature and velocity contours according to the length (D=0.01 m, *Pr*=20).



(a) Temperature contours (D=0.01m, *Pr*=0.7)



(b) Velocity contours

Fig. 5. Temperature and velocity contours according to the length (D=0.01 m, *Pr*=0.7).

4. Conclusions

The natural convection heat transfer inside a vertical pipe is studied experimentally and numerically. Experiments were carried out using sulfuric acid-copper sulfate (H_2SO_4-$CuSO_4$) based on the analogy concept between heat and mass transfer system. Numerical analysis was carried out using FLUENT 6.3.

It is concluded that the boundary layer interaction along the flow passage influences the heat transfer, which is affected by the length, diameter, and Prandtl number.

For the large diameter and high Prandtl number cases, where the thermal boundary layers do not interfered along the pipe, the heat transfer agreed with vertical flat plate for laminar and turbulent natural convection correlation within 8%. When the flow becomes steady-state, the forced convective flow appears in the bottom of the vertical pipe and natural convection flow appears near the exit. It is different behavior from the flow on the parallel vertical flat plates. Nevertheless, the heat transfer was not different greatly compared with those of vertical plate.

For the small diameter and low Prandtl number, the thermal boundary layers were overlapped at the center of the pipe. And then, the merged plumes are accelerated along the pipe and it seems the chimney like effect is occurred.

Further study is needed for the duct flow that acceleration flow behavior in natural convection.

ACKNOWLEDGEMENT

This study was supported by the Ministry of Science, ICT & Future Planning (MSIP) and was supported by

Nuclear Research & Development Program grant funded by the National Research Foundation (NRF) (Grant code : 2012M2A8A2025679)

REFERENCES

[1] Development and Conceptual Design for Passive Containment Cooling System, Ministry of Trade, Industry &Energy, Korea Institute Energy Technology Evaluation and Planning, 2014.

[2] Fluent User's Guide release 6.3 Fluent Incorporated, 2006.

[3] S. H. Ko, D. W. Moon, B. J. Chung, Applications of electroplating method for heat transfer studies using analogy concept, Nuclear Engineering and Technology, Vol. 38, No.3, April 2006.

[4] F. P. Incropera, D. P. Dewitt, Foundations of Heat and Mass Transfer 6th ed., John Wiley & Sons, INC, New York, pp. 586-589, 2011.

[5] E. J. Le Fevre, Laminar free convection from a vertical plane surface, Proceedings of the 9th International Congress of Applied Mechanics, Vol. 4, pp. 168-174.

[6] M. G. Fouad, N. Ibl, Natural convection mass transfer at vertical electrodes under turbulent flow conditions, Electrochimica Acta, Vol. 3, pp. 233-243, 1960.

[7] A. Bejan, Convection Heat Transfer, 3rd ed., John Wiley & Sons, INC, New York, pp. 197-200, 2013.

[8] C. K. Lim, B. J. Chung, Influence of a center anode in analogy experiments of long flow duct, International Journal of Heat and Mass Transfer, Vol. 46, pp. 174-180, 2014.

[9] E. J. Fenech, C. W. Tobias, Mass transfer by free convection at horizontal electrodes, Electrochimica Acta, Vol. 2, pp. 311-325, 1960.

[10] S. H. Ko, D. W. Moon, B. J. Chung, Applications of electroplating method for heat transfer studies using analogy concept, Nuclear Engineering and Technology, Vol. 38, pp. 251-258, 2006.

[11] B. J. Ko, W. J. Lee, B. J. Chung, Turbulent mixed convection heat transfer experiments in a vertical cylinder using analogy concept, Nuclear Engineering Design, Vol. 240, pp. 3967-3973, 2010.