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Visualization of Natural Convection Heat Transfer on a Single Sphere using the Electroplating System

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1. Introduction

The natural convection heat transfer on a single sphere is indispensable for many engineering applications such as spherical lamps, pebble bed reactor and so on [1].

The natural convective flows on outer sphere rise along surface. At top of sphere, the flows are lifted-up plume shape. For laminar flows, the local heat transfer shows maximum at the bottom of sphere and a monotonic decreases as flows approached to the top [2]. However, for sufficiently high Rayleigh numbers, the turbulent flows occur and drastically increase local Nusselt number at the top of sphere [3].

The laminar natural convection heat transfer on a single sphere has been studied experimentally and numerically by several researchers. However, relatively less study has been performed for turbulent flows as it requires large facilities to achieve high Rayleigh numbers. The flows, which occur transition, is hard to experiment because of unstable.

This study tried measurement of heat transfer and visualization external natural convection on a single sphere. The basic idea is that the plating patterns of copper on the sphere in mass transfer system will reveal the amount of heat transfer according to angular distance from the bottom.

2. Background

2.1 Overall heat transfer from a single sphere

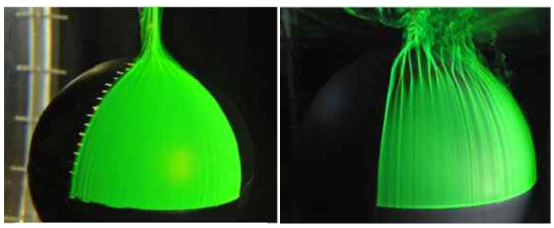
Kitamura et al. [1] performed experimental studies on natural convective heat transfer on spheres at $1.0\times10^9 < Ra_D < 4\times10^{10}$, and proposed natural convection heat transfer correlations for a single sphere. Amato and Tien [4] also performed experimental studies such as above and proposed the correlation at $3\times10^5 < Ra_D < 8\times10^8$. Churchill and Chu [5] reviewed experimental and numerical many investigations and presented a correlation in wide range $Ra_D < 10^{11}$ and $Pr > 0.7$. Jia and Gogos [6] performed numerical studies for on laminar natural convection in isothermal spheres for overall heat transfer and confirmed temperature profiles, and velocity profiles. Schütz [4] carried out experimental studies on natural convection mass transfer on spheres at $3\times10^5 < Ra_D < 8\times10^8$ and presented overall mass transfer correlation. Weber et al. [7] also performed experimental studies such as above and proposed the correlation at $4\times10^5 < Ra_D < 4\times10^{10}$. Table I shows correlation of investigators.

Table I: Natural convection heat and mass transfer correlations on a sphere

Authors	Correlations	Range
Kitamura [1]	$Nu_D = 0.2 Ra_D^{0.3}$	$1\times10^9 < Ra_D < 4\times10^{10}$
Amato and Tien [2]	$Nu_D = 2 + 0.5 Ra_D^{0.25}$	$3\times10^5 < Ra_D < 8\times10^8$
Churchill and Chu [5]	$Nu_D = 2 + \frac{0.589 Ra_D^{0.25}}{[1+(0.469/Pr)^{9/16}]^{4/9}}$	$Ra_D < 10^{11}$, $Pr > 0.7$
Schütz [4]	$Sh_D = 2 + 0.53 Ra_D^{0.256}$	$2\times10^8 < Ra_D < 10^{10}$
Weber [6]	$Sh_D = 2 + 0.59 Ra_D^{0.25}$	$10^7 < Ra_D < 10^{11}$

2.2 Visualizations

Kitamura et al. [1] investigated experimentally critical Rayleigh numbers of turbulent transition for natural convection from isothermal sphere at $4\times10^5 < Ra_D < 4\times10^{10}$. The natural convective flows were visualized from the heated spheres using dye and smoke. Fig. 1 (a), (b) are visualization results of laminar and turbulent flow for water at $Ra_D = 2.5\times10^8$, 6.6×10^9 respectively. The laminar boundary layer develops over the sphere and covers the whole surface when the Rayleigh numbers are less than critical. With increasing the Rayleigh numbers, the boundary layer concentrates locally to form streaks, and then, the streaks are lifted-up from of the sphere in turbulent region.



(a) $Ra_D=2.5\times10^8$ (Laminar) (b) $Ra_D=6.6\times10^9$(Turbulent)

Fig. 1. Visualizations of natural convective flow induced around spheres (Water) [1].

3. Experiments

3.1 Analogy concept

In this study mass transfer experiments were replaced heat transfer experiments using analogy concept. At the mass transfer system, measurements were made using the limiting current technique with a copper sulfate–cupric acid ($CuSO_4$–H_2SO_4) electroplating system [8]. In this system, the amount of copper ion plated at the cathode can be regarded as the amount of the heat transfer. This mean that the observation of the electroplating pattern will replace the local heat transfer patterns [9].

3.2 Test matrix and apparatus

Table II shows test matrix. Prandtl number was fixed 2,094. Diameter of sphere is 0.04 m, and this correspond to $Ra_D = 1.08\times10^{10}$ in turbulent region.

Table II: Test matrix

Pr	D (m)	Ra_D	Gr_D
2,094	0.04	1.08×10^{10}	5.15×10^{6}

Figure 2 shows a schematic of the test apparatus. A cathode was located in center of acrylic tank. An anode was located bottom. The electric potential is applied by the power supply (VüPOWER K1810) and the current is measured by the Multimeter (FLUKE-45).

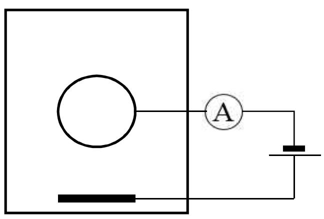


Fig. 2. A schematic of the test apparatus.

Figure 3 shows experiment equipment. The sphere of cathode diameter was 0.04 m. At the side of the sphere, a small hole was made nut form in order to fix the sphere using a bolt shape copper rod. This rod connect electric wire and sphere. The anode copper plate on the floor width and length is 0.08 m and 0.10 m.

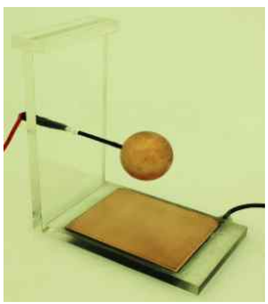


Fig. 3. The experiment equipment.

4. Results and Discussions

4.1 Comparison with correlation and test results

Figure 4 shows the comparison with existing correlations and an experiment result. Correlations have similar trend that Nu_D increase as Ra_D increasing. Test result has the most similar to Kitamura's correlation. Thus, the test result is reliable.

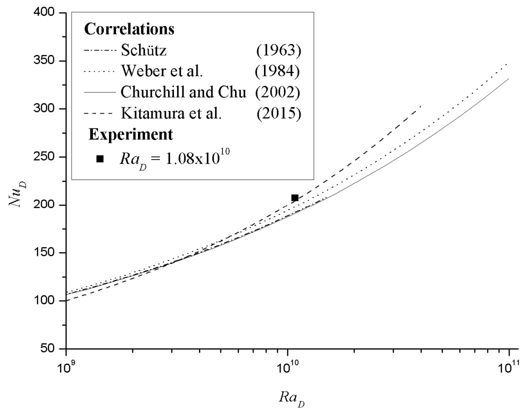
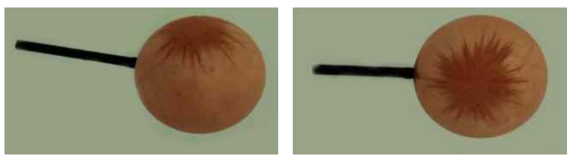


Fig. 4. Comparison with correlations and an experiment.

4.2 Visualization of heat transfer around single sphere

Figure 5 present the side and top view of plating pattern on the cathode. A copper plated thinly at the bottom of the sphere, and a copper plated thickly at the top of the sphere. The streak shape electroplating pattern was observed on top of the sphere. It may be explained that thin copper plating position at the bottom is the laminar flow region and thick one at the top is the turbulent flow region. For sufficiently large Rayleigh numbers, the flows will becoming unstable and transient to turbulent occur. So, electroplating patterns form will be changed probably because of transition instability.



(a) Side view (b) Top view

Fig. 5. Electroplating patterns.

5. Further study

The heat transfer measurements and electroplating pattern visualizations will be performed to compare with existing studies at several Ra_D. And the lifted-up points which transition occur will be measured and compared with existing test results. Transition instability would be confirmed through the results of repeated visualization.

6. Conclusion

This study simulated natural convection on a single sphere and performed a mass transfer experiment using heat and mass transfer analogy concept. Overall Nu_D was similar comparing with correlations. For visualization experiment, streak form plating pattern was observed. In this case, it seems that turbulence sets on the top of sphere and increases local heat transfer.

ACKNOWLEDEGEMENT

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