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Fluid flow and heat transfer of high-Rayleigh-number natural convection around heated spheres

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ABSTRACT

Experimental investigations were carried out on the natural convective flows of water and air induced around heated spheres. A keen interest was directed to high-Rayleigh-number flows that undergo turbulent transition. For the sake of this, spheres with different diameters, $d = 50$ to 1000 mm, were fabricated and tested, and this enabled the experiments in the wide and high ranges of Rayleigh numbers, $5 \times 10^6 < Ra_d < 4 \times 10^{10}$ for water and $4 \times 10^5 < Ra_d < 4 \times 10^9$ for air. In particular, the present maximum Rayleigh numbers are one or two decades higher than those of the prior experiments. The flows ascending along the heated spheres were first visualized to investigate the mechanisms of turbulent transition and the critical Rayleigh numbers. The results showed that the turbulent transition begins at the top of the sphere when the Rayleigh numbers are at around 3.0×10^8 for water and 3.5×10^8 for air. Then, the transition points move from the top to the side of the sphere with further increase in the Rayleigh numbers. The average Nusselt numbers from the spheres were subsequently measured and correlated with the Rayleigh numbers. The result showed that the present Nusselt numbers coincide fairly well with the prior laminar correlations in the range of the Rayleigh numbers less than the above critical. On the other hand, they showed a considerable deviation from the prior turbulent correlation when the Rayleigh numbers beyond the critical.

1. Introduction

Natural convective flows induced around heated or cooled spheres have been the subject of numerous analytical, computational and experimental investigations. This is not only because a sphere is one of the most fundamental geometry for the study of natural convection, but also because its heat transfer is indispensable for many engineering applications such as spherical tanks containing high or low temperature gases and liquids, spherical electric lamps, packed beds of spherical bodies for catalytic reactors or latent-heat-type thermal energy storage tanks and so on. These applications together with the simple geometry have motivated a considerable body of research on the natural convection around spheres. However, the main body of the previous studies have concerned with a laminar natural convection, while very little attention has been directed to a turbulent natural convection. This is mainly due to the reason that turbulent flows are difficult to attain experimentally, and that high-Rayleigh-number flows need a great deal of computational effort and skills.

However, to the best of the author's knowledge, several workers have carried out the experimental and numerical investigations on the high-Rayleigh-number natural convections. Among these investigations, the experimental studies that have dealt with the natural convections for the Rayleigh numbers higher than 10^7 are listed in Table 1, where types of experiment, measured quantities, test fluids, sizes of test spheres, ranges of Rayleigh numbers and proposed heat or mass transfer correlations are tabulated. In those experiments, the heat transfer experiment by Yamagata [1] may be the first and only work that has dealt the high-Rayleigh-number flows of air. He has measured the average Nusselt numbers from heated spheres to air in the range of Rayleigh numbers, $Ra_d = 66 - 5 \times 10^7$. However, his main concern was directed to the laminar natural convection rather than the turbulent natural convection, thus, he has not discussed the critical Rayleigh number for turbulent transition and also the turbulent heat transfer. Amato and Tien [5] have also carried out the heat transfer experiments using water as a test fluid. By the use of water and the test spheres of different diameters, 25.4 mm < d < 101.6 mm, the experiment covered the wide range of Rayleigh numbers, $3 \times 10^5 < Ra_d < 2 \times 10^9$. They have reported that the average Nusselt numbers, in particular, in the range of Rayleigh numbers,

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Table 1
Previous experiments on high-Rayleigh-number natural convections around spheres.

Worker(s)	Ref.	Year	Measurements	Test fluids	Diameter of test sphere d	Range of Ra_d or $(Gr_d \cdot Sc)$ number	Heat or mass transfer correlation
Yamagata	[1]	1943	Heat transfer, average Nusselt numbers	Air ($Pr = 0.71$)	40, 70, 100, 201 mm	$66 < Ra_d < 5.0 \times 10^7$	Not proposed
Van Der Burgh	[2]	1960	Mass transfer, melting solid KCl sphere in KCl aqueous solution	KCl solution	9.9, 24.7 mm	$9 \times 10^5 < Ra_d < 4 \times 10^7$	$Sh_d = 0.525{Ra_d}^{1/4}$
Schűtz	[3]	1963	Mass transfer, Local and average Sh_d numbers, Electrochemical method	$CuSO_4$ in H_2SO_4 aqueous solution ($Sc = 1800$)	9.5, 17.9, 24.9, 31.7, 39.8 mm	$2.3 \times 10^8 < (Gr_d \cdot Sc) < 1.5 \times 10^{10}$	$Sh_d = 2 + 0.59(Gr_d \cdot Sc)^{1/4}$
Kranse & Schenk	[4]	1965	Mass transfer, melting solid Benzene sphere in liquid Benzene	Benzene ($Pr = 8$)	50.5, 70.5 mm	$6.4 \times 10^8 < (Gr_d \cdot Sc) < 4.8 \times 10^9$	$Sh_d = 2 + 0.59(Gr_d \cdot Sc)^{1/4}$
Amato & Tien	[5]	1968	Heat transfer, average Nusselt numbers, velocity and temperature in boundary layer	Water ($Pr = 6$)	25.4, 50.8, 76.2, 101.6 mm	$3 \times 10^5 < Ra_d < 8 \times 10^8$	$Nu_d = 2 + 0.500{Ra_d}^{1/4}$
Mori et al.	[6]	1976	Mass transfer, melting solid KCl sphere in KCl aqueous solution	KCl solution ($Sc = 500–600$)	5, 15 mm	$1.6 \times 10^7 < (Gr_d \cdot Sc) < 4 \times 10^8$	$Sh_d = 0.507(Gr_d \cdot Sc)^{1/4}$

$3 \times 10^5 < Ra_d < 8 \times 10^8$, are proportional to (1/4) power of Rayleigh numbers. The correlation is considered to represent the laminar heat transfer. While, their Nusselt numbers for the higher Rayleigh numbers, $Ra_d > 8 \times 10^8$ show a considerable scatter. This has hampered the further discussions on the heat transfer by turbulent natural convection.

Meanwhile, several workers have dealt the mass transfer associated with natural convection melting of solid spheres in liquids. For example, Van Der Burgh [2] has submerged solid KCl spheres in a liquid KCl solution and measured the heat transfer rates from the mass of melt and the latent heat of fusion. Kranse and Schenk [4] and Mori and coworkers [6] have also conducted similar melting experiments by utilizing solid benzene or KCl spheres submerged in liquid benzene or KCl aqueous solution, respectively. They have reported that the average Sherwood numbers, Sh_d, of the spheres are also proportional to (1/4) power of $(Gr_d \cdot Sc)$, indicating that the mass is transferred by the laminar natural convection. Moreover, Schűtz [3] has measured the local and average Sherwood numbers from spheres with an electrochemical method. A $CuSO_4$ electrolyte dissolved in H_2SO_4 was utilized as a test fluid, and the Schmidt number, Sc, of the fluid was very large at around 1800. The measurements were carried out in the range, $2.3 \times 10^8 < (Gr_d \cdot Sc) < 1.5 \times 10^{10}$. He has reported that the local Sherwood numbers show a steep increase near the top of the sphere when $(Gr_d \cdot Sc)$ numbers are increased from 2.3×10^8 to 5.2×10^8, and also that the limiting current of the cathode there fluctuates randomly with time when $(Gr_d \cdot Sc) = 1.5 \times 10^9$. These results suggest the occurrence of turbulent transition over sphere. However, he has not discussed further on the turbulent transition and also on the turbulent mass transfer, because his average Sherwood numbers still follow the laminar correlation even at their maximum $(Gr_d \cdot Sc)$ number of 1.5×10^{10}.

Meanwhile, Churchill [7] has derived correlating equations for the average Nusselt numbers based on semi-analytical solutions for limiting cases of $Ra_d = 0$ and ∞, and also for boundary layer flows. He has shown that the proposed correlations are applicable to all Rayleigh and Prandtl numbers by comparing prior experimental data. In fact, his laminar correlation has well predicted the experimental Nusselt numbers for the flows of different Rayleigh and Prandtl numbers. On the other hand, his turbulent correlation has not been validated by the experiments, because no reliable experimental data has been available even at present. Moreover, we will need further discussions on the critical Grashof numbers for the turbulent transition, $Gr_d = 10^9$, because the number was merely inferred from the prior data for vertical plates and horizontal cylinders.

Furthermore, several workers have carried out the numerical computations on the laminar natural convection around spheres in a wide range of Rayleigh numbers. For instance, Jafapur and Yovanovich [8] have calculated average Nusselt numbers for the range of Rayleigh numbers, $0 < Ra_d < 10^8$ and Prandtl numbers, $0 < Pr < \infty$. Yang et al. [9] have also presented the average Nusselt numbers for the Grashof numbers, $10^5 < Gr_d < 10^9$ and the Prandtl numbers. $Pr = 0.02$, 0.7, 7 and 100. Their numerical Nusselt numbers coincide fairly well with those estimated from Churchill's laminar correlation. The result will validate Churchill's laminar correlation.

The above literature survey indicates that several subjects have remained unclear. The one of such subjects is the transition from laminar to turbulent flows over spheres. We have very little information on the mechanisms of transition as well as on the critical Rayleigh numbers. The other subject is the heat transfer, in particular, in the region of high Rayleigh numbers beyond critical. As was shown in Table 1, most of the previous workers have performed the mass transfer or melting experiments, while very few workers have carried out the heat transfer experiments. Yet, their maximum Rayleigh numbers remained low as, $Ra_d = 5 \times 10^7$ for air and $Ra_d = 8 \times 10^8$ for water. The numbers are considered insufficient to deal with the turbulent transition phenomena and to discuss the heat transfer by turbulent natural convection. These motivate the present experimental investigations. In order to realize the high-Rayleigh-number flows, the authors have fabricated and tested the spheres of different diameters from 50 mm to 1000 mm. Water and air at room-temperature were also adopted as a test fluid. These have enabled the experiments in the wide and high ranges of Rayleigh numbers, $4 \times 10^5 < Ra_d < 4 \times 10^9$ for air and $5 \times 10^6 < Ra_d < 4 \times 10^{10}$ for water. In particular, the maximum Rayleigh numbers are one or two decades larger than those of the prior experiments. The authors have first carried out intensive visualization experiments on the natural convective flows induced around the isothermally heated spheres. The visualizations are intended to obtain information on the turbulent transition phenomena and also on the critical Rayleigh numbers. The authors have subsequently performed the heat transfer experiments to obtain heat transfer correlations for the high-Rayleigh-number natural convection.

2. Experimental apparatus and measurements

A schematic of present test sphere is shown in Fig. 1 together with a photo of 1000 mm-diameter sphere. Test spheres having different diameters of 50, 100, 200, 300, 500 and 1000 mm were fabricated and utilized for the experiments. The test spheres were made of two aluminum hemispheres, 3 mm or 4 mm thick and the two hemispheres fit snugly together by means of round collars