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Numerical study of forced convective heat transfer around airships

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Abstract

Forced convective heat transfer is an important factor that affects the thermal characteristics of airships. In this paper, the steady state forced convective heat transfer around an ellipsoid is numerically investigated. The numerical simulation is carried out by commercial computational fluid dynamic (CFD) software over the extended *Re* range from 20 to 10^8 and the aspect ratio from 2 to 4. Based on the regression and optimization with software, a new piecewise correlation of the Nusselt number at constant wall temperature for ellipsoid is proposed, which is suitable for applications to airships and other ellipse shaped bodies such as elliptical balloons. The thermal characteristics of a stratospheric airship in midsummer located in the north hemisphere are numerical studied. The helium temperature predicated using the new correlation is compared to those predicted by correlations applicable for spheres and flat plates. The results show that the helium temperature obtained using the new correlation at noon is about 5.4 K lower than that using the correlation of spheres and about 2.1 K higher than that of flat plates.

Keywords: Airships; Ellipsoid; Forced convection heat transfer; Helium temperature; Balloon

1. Introduction

The research and development of airships started to thrive in the late 1990s because of the wide range of application demands for stratospheric airships in military, commercial, and scientific fields, such as ground surveillance (SantaPietro, 2012), Earth observation (Ilieva et al., 2014), intelligence and reconnaissance (Smith et al., 2011), missile defense (Androulakakis and Judy, 2013), aerial transportation (Bonnici et al., 2014), environmental monitoring (Hygounenc et al., 2004), planetary exploration (Kusagaya et al., 2006), and telecommunication relay (Schmidt et al., 2007).

The lift of airships is mainly from the density difference between the buoyancy gas and the ambient air, which differs from that of traditional aircraft. This unique feature makes airships have huge volume and be sensitive to the surrounding thermal environment. The accurate prediction of thermal characteristics is especially important and difficult for the design and research of airships, since the density and pressure of the buoyancy gas strongly depends on the temperature (Li et al., 2012). The forced convective heat transfer around the external surface of an airship is one of the most important factors that affect the thermal characteristics of the airship. For the external forced convection heat transfer of airships, there is no specific correlation available yet. Most of the researchers treated an airship as a simple geometry, such as a sphere, a flat plate or a cylinder (Kreith and Kreider, 1974; Rapert, 1987; Wu et al., 2015).

It is commonly seen that for calculating the forced convection heat transfer between the external surface of a balloon and the ambient air, the balloon was idealized as a sphere with the characteristic length of mean diameter of the balloon, since the geometry of a balloon could be simplified as a sphere (Kreith and Kreider, 1974; Carlson and

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Horn, 1983; Farley, 2005; Dai et al., 2012; Liu et al., 2014). Almost all the correlations developed by other authors for a sphere are limited to low Reynolds numbers ($Re < 10^5$). These correlations may provide adequate accuracy for small balloons or large balloons in some extent. For example, a balloon flying in stratosphere is not too large and the wind speed is low. However, generally speaking, low-*Re* correlations are not satisfactory because modern large balloons usually encounter the situations with the Reynolds number (*Re*) greater than 10^6 in station keeping in the stratosphere when the wind speed is high. A modern high altitude balloon may have a volume as large as 400,000 m^3, which is far away from the applicable range of the existing correlations (Rainwater and Smith, 2004; Wu et al., 2015). Therefore, it is necessary to propose a new correlation with wide applicable range for sphere and ellipse shaped aerostats, for which Dai et al. (2013) developed a correlation for spherical aerostats applicable to the *Re* from 20 to 10^8.

While in calculating the forced convective heat transfer over the external surface of an airship, which is an ellipse shaped, the correlations for spherical aerostats may lead to an over-estimation. Therefore, some of the researches treated an airship as a flat plane with the characteristic length equals to the long diameter of the airship in calculating the forced heat transfer (Rapert, 1987; Xia et al., 2010; Li et al., 2011). Apparently, this simplification may lead to noticeable uncertainties. For example, the convective heat transfer coefficient of an airship with an aspect ratio of 2.5 may be under-predicted by 25% at $Re = 10^5$.

Up to now, the study of forced convective heat transfer around a large ellipse is rare. In the past decades, several works devoted to understanding the physics of flows passing around particles of different shapes and correlating the drag force as a function of the *Re* and the particle shape were reported. Kishore and Gu (2011) numerically investigated the heat transfer phenomena of isothermal spheroid particles in an unbounded Newtonian fluid. The correlation for the average Nusselt number (*Nu*) of ellipsoids was proposed on the basis of the well-known correlation of Whitaker (1972) for the average *Nu* of spheres. This correlation is corresponding to *Re*, Prandtl number (*Pr*) and aspect ratio (*E*), which is the ratio of the diameter of the ellipsoid parallel to the flow to the diameter normal to the flow. The application range of the new correlation is $1 \leqslant Re \leqslant 200$; $1 \leqslant Pr \leqslant 1000$ and $0.4 \leqslant E \leqslant 4$. Richter and Nikrityuk (2012) numerically studied the forced convective heat transfer coefficient of isothermal ellipsoidal particles with air corresponding to *Re* from 10 up to 250. The correlation is based on the sphericity Φ and the crosswise sphericity $\Phi_{\perp}$, where Φ denotes the ratio of the particle surface area to the surface of the volume-equivalent sphere and $\Phi_{\perp}$ denotes the ratio between the projected area of the particle (in flow direction) and the cross-section area of the volume-equivalent sphere.

The above brief review indicates that it is necessary to obtain a forced convective heat transfer correlation for airships with high *Re* conditions. Aiming at this demand, the work of the present paper is to develop a correlation for the forced convection heat transfer around an isothermal ellipsoid that is applicable to airships, with the *Re* up to 10^8. Based on the data obtained from the CFD calculations, a new piecewise correlation of average *Nu* is proposed. The effects of the aspect ratio on the thermal characteristics of airships are investigated in detail.

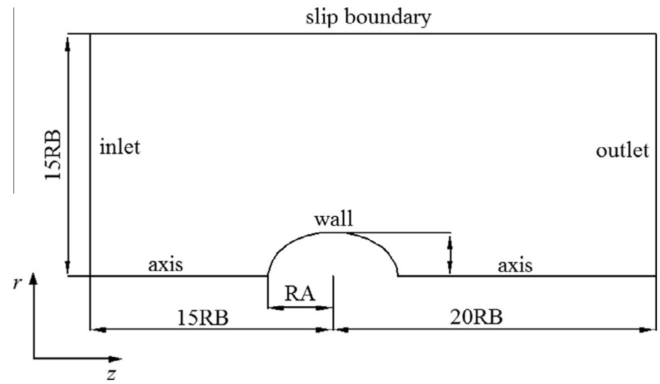

Fig. 1. Schematic of the computational domain and airship configuration.

2. Problem statement and governing equations

Compared to the local speed of sound, the magnitude of the cruising speed of an airship is much lower. Therefore, the 3-D incompressible flow of air over an airship can be simulated by considering the flow in a tubular domain with an ellipsoid placed symmetrically on the tube axis with slip boundary conditions. The long diameter ($2RA$) is parallel to the flow and the short diameter ($2RB$) of the airship is normal to the flow. The aspect ratio E is defined as RA/RB.

The surface temperature of the airship, T_w, is assumed to be constant at 270 K. The thermal physical properties of air (density, ρ; thermal conductivity, λ; heat capacity at constant pressure, c_p; and kinematic viscosity, υ) are assumed to be constant at the air temperature T_0, which is assumed to be 260 K in the calculations. The air flow over a stratospheric airship can be treated as axis symmetry since in the station keeping the airship is located in the stratosphere where the wind flows horizontally and the orientation of the airship is parallel to the wind velocity to reduce the drag force. Meanwhile, the difference of the air density and temperature between the top and bottom of the airship is negligible. Owing to the axis symmetry of the flow, the 2-D cylindrical coordinate can be used to model the 3-D flow. The computational domain and the configuration of the airship are illustrated in Fig. 1.

The phenomena of fluid flow and heat transfer are governed by the continuity, momentum and energy equations. The 2-D forms of the governing equations in cylindrical coordinate can be expressed as follows:

Continuity equation

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r} + \frac{\partial u_z}{\partial z} = 0 \tag{1}$$

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