Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 52 (2013) 2199–2203

Advances in Space Research
(a COSPAR publication)

www.elsevier.com/locate/asr

Numerical study of forced convective heat transfer around a spherical aerostat

Qiumin Dai, Xiande Fang *, Yu Xu

Department of Man, Machine and Environment Engineering, College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing 210016, PR China

Received 5 January 2013; received in revised form 29 August 2013; accepted 2 September 2013
Available online 10 September 2013

Abstract

Forced convective heat transfer is one of the major factors that dominate the thermal behaviors of aerostats. Due to the large physical size, the convection around an aerostat has high Reynolds numbers. The existing forced convective heat transfer correlations are limited to the Reynolds number lower than 10^5, which are not appropriate for aerostat applications. Therefore, it is necessary to obtain a convective heat transfer correlation applicable to spherical aerostats at high Reynolds numbers. In this paper, steady convective heat transfer from an isothermal spherical aerostat is numerically investigated. The numerical simulation is carried out by commercial computational fluid dynamic software with the Reynolds number from 20 to 10^8. The average Nusselt numbers are obtained and compared with those of available in literature. Based on regression and optimization with software, a new piecewise correlation of Nusselt number is proposed. The verification shows that the new correlation is reliable.

Keywords: Spherical aerostat; Forced convection; Heat transfer; Nusselt number; High Reynolds number

1. Introduction

Aerostats are light-than-air vehicles. They can be used as the platform for ground surveillance, environment guide and telecommunication. The low cost and long duration operation of aerostats have attracted growing interests.

In the past decades, investigations have been carried out on the thermal characteristics of aerostats. It is widely accepted that convective heat transfer is one of the major factors that dominate the thermal behaviors of aerostats. In the research of forced convective heat transfer of an aerostat, most of the researchers treated an aerostat as a simple geometry, such as sphere, cylinder or flat plate. Kreith and Kreider (1974) established a simple model to predict the thermal behaviors of aerostats. The forced convective heat transfer equation in their model was limited to a low Reynolds number range, which might cause remarkable error for large scale aerostats. Therefore, Carlson and Horn (1983) modified the coefficient of forced convective heat transfer with a correction factor. Farley (2005) selected a different equation, but it was still not suitable for high Reynolds number conditions. Cheng et al. (2010) employed an empirical correlation of cylinder. Dai et al. (2011) and Xia et al. (2010) chose a semi-empirical correlation of flat plate to describe the forced convective heat transfer around balloons.

Up to now, the study of spherical convective heat transfer at high Reynolds numbers is rare. Numerical and semi-empirical correlations of convective heat transfer related to spheres were mainly focused on low Reynolds number conditions. However, the Reynolds number for aerostats may easily increase to the magnitude of over 10^7, far beyond the applicable range of the existing forced convective heat transfer correlations. Therefore, it is necessary to obtain a convective heat transfer correlation for spheres with high Reynolds numbers.

* Corresponding author. Tel./fax: +86 25 8489 6381.
E-mail addresses: daiqiumin913@126.com (Q. Dai), xd_fang@nuaa.edu.cn (X. Fang), xuyu-121@163.com (Y. Xu).

0273-1177/$36.00
http://dx.doi.org/10.1016/j.asr.2013.09.004

This paper is to develop a heat transfer coefficient correlation of forced convection around isothermal spheres that is applicable to spherical aerostats, with the Reynolds number up to 10^8. Based on the data obtained from the computational fluid dynamic (CFD) calculations using commercial CFD software, a new piecewise correlation of average Nusselt numbers is proposed. The new correlation is verified with the available experimental data.

2. Problem statement and mathematical formulation

The 3-D flow of the incompressible fluid of air with a uniform velocity U_0, temperature T_0 and pressure p_0 over a spherical aerostat of radius R is simulated by considering the flow in a tubular domain with a sphere placed symmetrically on the tube axis with slip boundary conditions. The surface of the sphere is assumed to be at a constant temperature of T_w. The thermal physical properties of air (density, ρ; thermal conductivity, λ; heat capacity, c_p; and kinematic viscosity, v) are assumed to be at the air temperature T_0, which is assumed to be 260 K in the calculations. 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 sphere are illustrated in Fig. 1.

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

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

momentum equation

$$u_z\frac{\partial u_z}{\partial z}+u_r\frac{\partial u_z}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\upsilon\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_z}{\partial r}+\frac{\partial^2 u_z}{\partial z^2}\right) \tag{2}$$

$$u_z\frac{\partial u_r}{\partial z}+u_r\frac{\partial u_r}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\upsilon\left(\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}+\frac{\partial^2 u_r}{\partial z^2}-\frac{u_r^2}{r^2}\right) \tag{3}$$

energy equation

$$\rho q+\lambda\left(\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}\right)-p\left(\frac{1}{r}\frac{\partial(ru_r)}{\partial r}+\frac{\partial u_z}{\partial z}\right)+S=0 \tag{4}$$

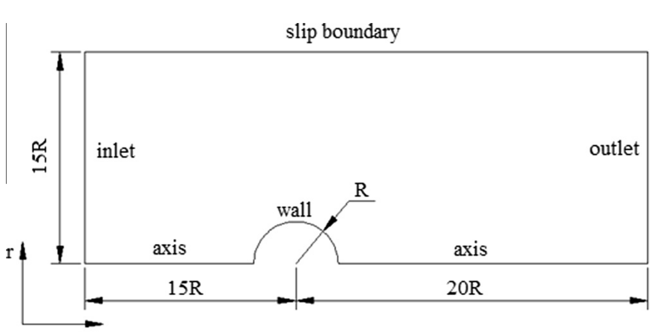

Fig. 1. Computational domain and sphere configuration.

where u_z and u_r are the velocity components, p is the pressure, T is the temperature of the fluid, q is the heat flux, and S is the generalized source term.

The boundary conditions can be stated as:for the inlet $u_z=U_0,u_r=0,T=T_0,p=p_0$, for the outlet $\frac{\partial u_z}{\partial z}=0,\frac{\partial u_r}{\partial z}=0,\frac{\partial T}{\partial z}=0,\frac{\partial p}{\partial z}=0$, for the slip boundary $\frac{\partial u_z}{\partial r}=0,u_r=0,\frac{\partial T}{\partial r}=0,\frac{\partial p}{\partial r}=0$, for the axis $\frac{\partial u_z}{\partial r}=0,u_r=0,\frac{\partial T}{\partial r}=0,\frac{\partial P}{\partial r}=0$, and for the sphere wall $u_z=0,u_r=0,T=T_w,\frac{\partial p}{\partial n_s}=0$,where n_s denotes the unit normal vector on s, the surface of sphere.

The governing equations together with the boundary conditions provide the theoretical framework for studying the momentum and heat transfer characteristics of isothermal spheres. The numerical solutions of the governing equations with the boundary conditions yield the velocity, pressure and temperature fields. These, in turn, can be used to evaluate the global characteristics such as the pressure coefficient and the Nusselt number. The pressure coefficient is defined as the ratio of the static pressure to dynamic pressure on the surface of the sphere and is calculated by the following expression:

$$C_p=2\left(\frac{p_\theta-p_0}{\rho U_0^2}\right) \tag{5}$$

where p_θ is the surface pressure at an angular position of θ.

The local Nusselt number on the surface of the isothermal sphere is evaluated by

$$Nu_\theta=-\frac{2R}{T_w-T_0}\frac{\partial T}{\partial n_s} \tag{6}$$

The local Nusselt number can be averaged over the whole sphere to obtain the surface mean Nusselt number

$$Nu=\frac{1}{2}\int_0^\pi Nu_\theta\sin\theta\mathrm{d}\theta \tag{7}$$

The mean Nusselt number can be used to estimate the rate of the convective heat transfer around the sphere with constant wall temperature.

3. Numerical method

3.1. Grid generation

The computational domain is meshed using the structured grid generated by the pre-processor Gambit. The computational domain is divided into two separate sub-domains. The first sub-domain is very dense and covers the region around the sphere. The second sub-domain is relatively coarse and covers the remaining flow. The grid density of the first sub-domain can be determined by the dimensionless parameter y^+. It is calculated by the following expression:

$$y^+=\frac{yu^*}{v} \tag{8}$$

where y is the distance to the nearest wall, u^* is the friction velocity, and v is the kinematic viscosity.