Effects of Reynolds and Prandtl Numbers on Heat Transfer Around a Circular Cylinder by the Simplified Thermal Lattice Boltzmann Model

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Abstract. In this paper, the fluid flow and heat transfer around a circular cylinder are studied under various conditions (Reynolds number $10 \leq Re \leq 200$; Prandtl number, $0.1 \leq Pr \leq 2$). To solve the governing equations, we use the simplified thermal lattice Boltzmann model based on double-distribution function approach, and present a corresponding boundary treatment for both velocity and temperature fields. Extensive numerical results have been obtained to the flow and heat transfer behaviors. The vortices and temperature evolution processes indicate that the flow and temperature fields change synchronously, and the vortex shedding plays a determinant role in the heat transfer. Furthermore, the effects of Reynolds and Prandtl number on the flow and isothermal patterns and local and averaged Nusselt numbers are discussed in detail. Our simulations show that the local and averaged Nusselt numbers increase with the Reynolds and Prandtl numbers, irrespective of the flow regime. However, the minimum value of the local Nusselt number can shift from the rear point at the back of the cylinder with higher Prandtl number even in the steady flow regime, and the distribution of the local Nusselt number is almost monotonous from front stagnation point to rear stagnation point with lower Prandtl number in the unsteady flow regime.

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1   Introduction

The fluid flow and heat transfer over a bluff body, particularly a circular cylinder, is a longstanding interesting problem for both its considerable theoretical and practical significance. For such importance, extensive investigations have been conducted on the flow and heat transfer across a circular cylinder over the years. Previous research has mainly focused on flow characteristics such as the wake phenomena, drag coefficient, vortex shedding frequency [1–3], while much less attention has been devoted to heat transfer features. Karniadakis [4] presented limited results on Nusselt number for cylinder in air up to Reynolds number (Re) of 200 and found good agreement with the experimental results available in the literature. Lange et al. [5] investigated the effect of the temperature-dependent properties on heat transfer from a cylinder to the air in the range of Reynolds number as $Re \leq 200$. Similarly, Baranyi [6] studied momentum and heat transfer characteristics in the range of Reynolds number as $50 \leq Re \leq 180$. The heat transfer characteristics from a circular cylinder have been studied by Bharti et al. [7] for different Prandtl numbers. However, this work was investigated in the steady flow regime up to Reynolds number $Re = 45$. Furthermore, effects of the cylinder motion have also been investigated. For example, Bao et al. [8] and Liao and Lin [9] studied the convective heat transfer around a stream-wise or transversely oscillating cylinder; and Zu et al. [10] investigated the flow and heat transfer around a rotating circular cylinder. The natural convective has also been considered in the study by Liao and Lin [9]. It has been noticed that only limited numerical studies are available on heat transfer from a circular cylinder in the steady or unsteady flow regime, and most of these studies are restricted to the Prandtl number 0.71, corresponding to air. Different Prandtl numbers have been considered for a rotating cylinder in Ref. [10]; however, more detailed information (e.g., the local Nusselt number distribution around the cylinder surface) might be desirable.

In recent years, the lattice Boltzmann method (LBM) has emerged as an alternate and promising numerical scheme for simulating flow and other physical phenomena of fluid systems [11–14]. Unlike conventional CFD simulations which are mainly based on direct numerical approximations to the macroscopic Navier-Stokes (N-S) and energy equations, the basic idea of the LBM is to construct simplified kinetic models that incorporate the essential physics of microscopic or mesoscopic processes so that the macroscopic averaged properties can obey the desired macroscopic equations. The LBM has several computational advantages, such as a better representation of microscopic interactions, relative easiness in dealing with complex geometries, and outstanding efficiency with parallel computation [14]; and LBM has been widely used in scientific research and engineering applications, such as multiphase and multicomponent fluids [15, 16], reaction-diffusion systems [17], flow through porous media [18], compressible flows [19, 20], particulate flows [21], flexible body movement [22, 23], and other complex systems [24, 25].

To handle realistic thermal fluid flow, several thermal LBM models have developed and they can basically be classified into three categories: the multi-speed approach [26, 27], the hybrid approach [28], and the double distribution function approach [20, 29–32].