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# Simulation of flow and heat transfer around a heated stationary circular cylinder by lattice gas automata

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ABSTRACT

A two-dimensional (2D) lattice gas automata model was developed to describe the behavior of flow and heat transfer around a heated stationary circular cylinder. To validate the feasibility of this model, heat transfer of a heated stationary circular cylinder, which is concentrically placed in a square enclosure, was simulated and compared with analytical results. Further investigations on flow and heat transfer past a heated stationary cylinder in a channel at Reynolds number of 100–200 were then carried out. The flow and heat characteristics were presented by streamlines and thermal nephograms. The dependences of drag coefficient and Nusselt number on the Reynolds number were further studied and compared to literature data. Simulation results of the heat transfer in the enclosure agree with the solution of the diffusive heat transfer equation. For the investigated Reynolds number range, time averaged drag coefficient decreases as Reynolds number increases, while Nusselt number increases with increasing Reynolds number. Reasonable agreements with previous investigations were achieved, demonstrating that the presented model provides an alternate method to simulate flow and heat transfer problems.

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## 1. Introduction

Problems involving hydrodynamic and/or heat and mass transfer associated with fluid structure interaction are of great interest to researchers from a wide range of fields due to its importance in a number of practical applications such as heat exchangers, gas turbine blades, electronic cooling, combustion systems, building aerodynamics, transport of aerosol particles, and coking process, etc. [1–8]. Reliable knowledge of the detailed structure of the flow field, drag, wake phenomenon, and heat transfer, etc., facilitate improved and efficient design of process equipments [9]. Generally, the flow and heat transfer around a cylinder is considered as a simple and useful model for interpreting these industrially important processes through predicting and understanding these phenomena. It provides useful insights into the underlying physical mechanism, which are of great significance for industrial processes and applications.

In the recent decades, numerous numerical studies have been conducted on flow and heat transfer around a stationary cylinder in a channel or in an enclosure, despite extensive discussions that have been performed by earlier experimental investigations [10–12]. Conventional computational fluid dynamics methods, such as finite element method and finite volume method, were widely used to simulate problems related to flow and heat transfer around cylinders by solving governing equations. The applications related to flow and heat transfer around a cylinder are listed in Table 1. However, one of the main issues of computational fluid dynamics is the handling of complex geometries and moving bodies. In the governing equations, the momentum and continuity equations and energy equation are decoupled and only one-way interaction from the governing equations is considered [13]. Moreover, these methods are very sensitive to the change of boundary conditions, which makes the convergence very difficult. Thus, much work still needs to be done in order to simulate more complicated configurations.

In contrast to conventional methods, lattice gas automata (LGA) and lattice Boltzmann method (LBM) have been widely used in scientific research and engineering applications over the past decades as novel substitutions for resolving problems involving hydrodynamic and thermal phenomena coupling with complex geometries, benefited from their flexibility and low computational cost. In these models, flow domain and time are discrete. Table 2 lists the applications of LGA/LBM to problems involving flow around cylinders. However, few work applied lattice gas automata or lattice Boltzmann method to heat transfer around cylinders. Yan et al. [14] applied thermal LBM to the heat transfer and flow past a rotating isothermal cylinder. Tang et al. [15] used lattice Boltzmann method to study the problems concerning forced convective flow and heat transfer between two parallel plates. Haeri and Shrimpton [16] proposed a new implicit fictitious domain method to simulate flow in complex geometries with heat transfer, and oscillating cylinders with convective heat transfer, flow around

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## Nomenclature

| | |
|---|---|
| $\mathbf{a}$ | Statistics level in x-direction |
| $\mathbf{b}$ | Statistics level in y-direction |
| $\mathbf{c}$ | Momentum at time *t*, lattice unit |
| $\mathbf{c}'$ | Momentum at $t+\Delta \mathrm{t}$, lattice unit |
| $c_d$ | Drag coefficient, dimensionless |
| $\mathbf{c}_i$ | Lattice velocities, $\mathbf{c}_i = \begin{cases} (\cos\frac{\pi}{3}i,\ \sin\frac{\pi}{3}i), & i=1,\ldots,6 \\ 0, & i=0 \end{cases}$, lattice unit |
| $e_i(t,\mathbf{r})$ | Energy state of the cell in *i* direction at time *t* and place $\mathbf{r}$, $e_i(t,\mathbf{r}) = \begin{cases} 1 & \textit{if cell is of high energy state} \\ 0 & \textit{if cell is of low energy state} \end{cases}$ |
| $D$ | Diameter of the cylinder, lattice unit |
| $\mathbf{e}_x$ | Unit vector in x direction |
| $\mathbf{F}$ | Force acting on the cylinder, $\mathbf{F} = \sum_p \frac{\Delta \mathbf{I}}{\Delta \mathrm{t}} = \sum_p \frac{\mathbf{c}-\mathbf{c}'}{\Delta \mathrm{t}}$, lattice unit |
| $g(\rho)$ | Galilean factor for FHP-II, $g(\rho) = \frac{7}{12}\frac{7-2\rho}{7-\rho}$, lattice unit |
| $H$ | Width of the channel, lattice unit |
| $\Delta \mathbf{I}$ | Momentum change, lattice unit |
| $i$ | Directions, i = 0,…, 6 for FHP-II |
| $\mathbf{n}$ | Direction vector |
| $Nu$ | Nusselt number, dimensionless |
| Pr | Prandtl number, $\mathrm{Pr} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}}$, dimensionless |
| $Pe$ | Peclet number for thermal diffusion, $Pe = \mathrm{Re} \bullet \mathrm{Pr}$, dimensionless |
| $\mathbf{r}$ | Position vector of a node |
| $r$ | Centrifugal distance, m |
| $r_{Lattice}$ | Centrifugal distance, lattice unit |
| $r'$ | Dimensionless space |
| $\Delta r'$ | Dimensionless space difference distance |
| $r_n^{'}$ | Dimensionless distance of point *n* |
| $R$ | Radius of the cylinder, lattice unit |
| $R_c$ | Radius of the infinite length cylinder, lattice unit |
| Re | Reynolds number, dimensionless |
| $t$ | Lattice time, lattice unit |
| $t'$ | Dimensionless time |
| $t^*$ | The reference evolution time, lattice unit |
| $\Delta t'$ | Dimensionless time difference distance |
| $T_c$ | Temperature of cylinder, K |
| $T_\infty$ | Temperature of fluid, K |
| $T$ | Dimensionless temperature |
| $\mathbf{u}$ | Macro velocity, lattice unit |
| $u$ | Local velocity, lattice unit |
| $u_{\max}$ | Maximum value of local velocity, lattice unit |
| $u_\infty$ | Fluid velocity at inlet, lattice unit |
| $\nu$ | Lattice viscosity for FHP-II, $\nu = \frac{1}{28}\frac{2401}{\rho(7-\rho)^3}\frac{49}{49-4\rho} - \frac{1}{8}$, lattice unit |
| $W$ | Length of the channel, lattice unit |
| $x$ | Position in x-direction, lattice unit |
| $x_{\max}$ | Length of the channel, lattice unit |
| $y$ | Position in y-direction, lattice unit |
| $y_{\max}$ | Width of the channel, lattice unit |

*Greek Symbols.*

| | |
|---|---|
| $\alpha$ | Thermal diffusivity, $m^2/s$ |
| $\alpha_{Lattice}$ | Thermal diffusivity in lattice gas system, lattice unit |
| $\beta$ | Energy state, $\beta = \begin{cases} 1 & \textit{if cell is of high energy state} \\ 0 & \textit{if cell is of low energy state} \end{cases}$ |
| $\rho$ | Density defined in lattice gas automata, lattice unit |
| $\theta$ | Value of angle |
| $\varepsilon$ | Proportionality coefficient of two systems |
| $\Omega_1$ | Cylinder domain |
| $\Omega_2$ | Fluid domain |

**Table 1**
Applications of conventional methods to problems involving flow and heat transfer around cylinders.

| Reference | Method | Research contents |
|---|---|---|
| Sharma et al. [6] | Semi-explicit finite volume method | Mixed convective flow and heat transfer around a square cylinder |
| Rashidi et al. [7] | Finite volume method | Flow and heat transfer characteristics around a cylinder with a porous layer |
| Lo and Su [13] | Embedding finite element method | Heat transfer of stationary cylinders in flow |
| Fragos et al. [42] | Galerkin finite element method | Two-dimensional turbulent flow over a surface-mounted obstacle |
| Richter and Nikrityuk [43] | Finite volume solver | Drag forces and heat transfer coefficients for spherical, cuboidal and ellipsoidal particles |
| Lee et al. [44] | Immersed boundary method | Flow over stationary and oscillating cylinders |
| Parnaudeau et al. [45] | Immersed boundary method | Flow over a circular cylinder |
| Zheng et al. [46] | Immersed boundary method | Mixed convection in a lid-driven cavity with an isothermal circular cylinder |
| Ren et al. [38] | Immersed boundary method with velocity and heat flux correction | Flow and heat transfer around cylinders |
| Mark et al. [47] | Immersed boundary method | Natural convection in a square cavity with and without a hot circular cylinder, and free air cooling of an electrically heated plate |
| Sarkar et al. [48] | SUPG based on finite element method | Flow and heat transfer of nanofluid past a square cylinder |
| Dhiman and Ghosh [49] | Finite volume solver | Flow and heat transfer past a trapezoidal bluff body |
| Jeon et al. [50] | Segregated finite element algorithm | Conjugate heat transfer around a circular cylinder involving heat source |
| Yoon et al. [51] | IB finite volume method | Laminar fluid flow and heat transfer past a circular cylinder near a moving wall |
| Chatterjee and Mondal [52] | Finite element method based on PISO algorithm | Heat transfer from square cylinders |

stationary cylinders, single cylinder with convective heat transfer, and convective heat transfer from a tube bank were studied separately. Zhang et al. [17] investigated radiation and natural convection combined heat transfer in a square enclosure with a heated circular cylinder. Nevertheless, for lattice Boltzmann method, microscopic detailed interactions among particles or between particles and walls cannot be obtained and the distribution functions of flow and energy are interdependent or, in other words, the coupling of flow with heat transfer needs more improvement. Once, researchers also developed thermal lattice gas automata models with poly-velocity such as 13-bit lattice gas automata [18,19] to deal with flow combined with thermal problems. The system is considered as discrete, and interaction between particles with different properties forms the flow and energy fields. Whereas, computational cost increases as more complicated space discretization and boundary conditions are defined for different particles. Thus, there is a need for a simpler but closer to physical nature and easier implementation method to solve the problems involving flow coupled with heat transfer.

The main purpose of this paper is to develop a single velocity thermal lattice gas automata model to investigate the process of flow and heat transfer around a heated stationary circular cylinder. In this model, fluid particles moving along meshes are of the same velocity and are distinguished by different energy state (high energy state and low energy state). Preliminary introduction can be found in reference [20]. Firstly, heat transfer of a concentric heated stationary circular cylinder was presented in a square enclosure saturated with fluid particles. The evolution process was compared with the results of analytical solution. Then further investigation on flow and heat transfer past a heated

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