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Lattice Boltzmann method simulation of backward-facing step on convective heat transfer with field synergy principle

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Abstract

The lattice Boltzmann method (LBM) is applied to simulate the two-dimensional incompressible steady low Reynolds number backward-facing step flows. In order to restrict the approach to the two-dimensional flow, the largest Reynolds number chosen was $Re = 200$. To increase the uniformity of the radial temperature profile for fluid flow in channel and consequently to enhance the heat transfer, the inserted square blockage is used and investigated numerically. In addition, the field synergy principle is also applied to demonstrate that an interruption within fluid results in decreased intersection angle between the velocity and temperature gradient. The numerical results of velocity and temperature field agree well with the available experimental and numerical results.

Keywords: Lattice Boltzmann method; Backward-facing step; Heat transfer; Field synergy principle

1. Introduction

The kinetic nature of the lattice Boltzmann method (LBM) as a relatively new numerical scheme has achieved considerable success in simulating fluid flows and associated transport phenomena in the pass ten years [1]. Unlike conventional numerical schemes based on discretizations of macroscopic continuum equation, the LBM is based on microscopic models and mesoscopic kinetic equation. These algorithms are based on the idea of trying to model a fluid by simulating a discretized one-particle phase space distribution function similar to the one described by the traditional Boltzmann equation. It treats the fluid on a statistical level and simulates the movement and interaction of single particle or ensemble-average particle density distribution function by solving a velocity discrete Boltzmann equation. The fundamental 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 obey the desired macroscopic equations.

The lattice Boltzmann equation as a numerical scheme was first proposed by McNamara and Zanetti [2]. It neglects individual particle motion and results in smooth macroscopic behavior. Higuera and co-workers [3,4] introduced a linearized collision operator to simplify the scheme and statistical noise is completely eliminated in both models. A particularly simple linearized version of the collision operator makes use of a relaxation time towards an equilibrium value using a single relaxation time parameter. The relaxation term is known as the Bhatnagar–Gross–Krook (BGK) collision operator [5]. This model is called the lattice Boltzmann BGK model. Use of this collision operator makes the computations much faster. Due to the extreme simplicity, the lattice BGK (LBGK) equation [6] has become the most popular lattice Boltzmann model.

The channel flow over a backward-facing step is often used to evaluate the accuracy of various numerical schemes. The main character is a recirculation region just downstream of the step. At the enlargement, the flow

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Nomenclature

c	lattice streaming speed
c_p	specific heat capacity
c_s	sound of speed
ER	channel expansion ratio, H/h
f_α	density distribution function
f_α^{eq}	equilibrium distribution function for f_α
g_α	energy distribution function
g_α^{eq}	equilibrium distribution function for g_α
H	channel width downstream of step
h	step height
Int	integral, $\mathrm{Int} = \int_\Omega \rho c_p(\vec{V} \cdot \nabla T)\, \mathrm{d}x\, \mathrm{d}y$
k	thermal conductivity
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
Pe	Pelect number, $Pr * Re$
Pr	Prandtl number
p	pressure
Re	Reynolds number
T	temperature
T^*	dimensionless temperature $T - T_\mathrm{w}/T_\mathrm{in} - T_\mathrm{w}$
U	maximum velocity in the inlet
$\vec{V}$	velocity vector
w	inserted square blockage width
X_R	reattachment location

Greek symbols

τ_υ	relaxation time for f_α
τ_c	relaxation time for g_α
ε	internal energy
χ	diffusivity
Ω	integral area
ρ	density
υ	kinematic viscosity
δ	small parameter
δx	lattice spacing
δt	time step
θ	intersection angle between the velocity and temperature gradient

Subscripts

in	inlet
m	mean
w	wall

velocity is suddenly reduced and as a consequence the pressure is increased. Fluid particles near the lower wall are unable to negotiate the sudden "drop", causing the formation of a recirculation bubble just downstream of the sudden enlargement. As a result, the prediction of such quantities as the reattachment length (length of the recirculation bubble downstream of the step) tends to compare poorly with experimental data.

The length of the recirculation region is a function of the geometry (expansion ratio), the fluid momentum (Reynolds number) as well as the flow regime (laminar or turbulent). Also there are three important parameters which exert a great influence on the fluid mechanics and heat transfer in the backward-facing step, i.e. Reynolds number Re, channel expansion ER, and Prandtl number Pr. Such a flow pattern has a large number of practical engineering applications, including airfoils, electrical device, diffuser, and combustors. Kondoh et al. [7] used traditional CFD method to simulate laminar heat transfer in a separating and reattaching flow, and the numerical results agree very well with the experiment data of Aung [8] and Hall and Pletcher [9].

Based on an analog between heat convection and heat conduction, Guo and co-workers [10,11] studied the mechanism of convective heat transfer from a second look and proposed novel approaches of enhancing convective heat transfer under the parabolic fluid flow structure. The convection term can be transformed into the form of dot product of velocity and temperature gradient, and integrated the energy equation over the thermal boundary layer. These novel approaches involve improving the uniformity of velocity and temperature profiles as well as reducing the included angle between dimensionless velocity and temperature gradient vectors. Tao and co-workers [12,13] called this concept the field synergy principle and extended from parabolic to elliptic fluid flow and other transport phenomenon. The field synergy theorem was also applied to analyze the thermal performance of our cases.

The objective of this paper is to investigate the velocity and temperature field of this unique recirculation flow and compare the predictions with available experimental and numerical results.

2. Numerical method

2.1. Lattice Boltzmann hydrodynamics model

The nine-velocity LBM model on the 2D square lattice in Fig. 1, denoted as D2Q9 model, is used in the current

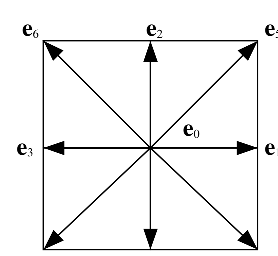

Fig. 1. The nine-velocity LBM model on the 2-D square lattice.