ARTICLE IN PRESS

Computers and Mathematics with Applications ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa

Three dimensional lattice Boltzmann simulation of steady and transient finned natural convection problems with evaluation of different forcing and conjugate heat transfer schemes

Gholamreza Imani *

Department of Mechanical Engineering, Persian Gulf University, 7516913798, Bushehr, Iran

A R T I C L E I N F O

Article history:
Received 2 September 2016
Received in revised form 22 May 2017
Accepted 16 June 2017
Available online xxxx

Keywords:
Thermal lattice Boltzmann method
Three-dimensional finned natural convection
Steady and transient simulations
Differentially heated cubical enclosure
Evaluation of the different forcing and conjugate heat transfer schemes

A B S T R A C T

In the present paper, for the first time, the lattice Boltzmann (LB) simulation of the three-dimensional steady and transient natural convection problem in a differentially heated cubical enclosure with a conducting fin on its hot wall is performed. As such, two main variants associated with the thermal lattice Boltzmann simulation of the finned natural convection problems namely, three popular forcing and two widely used conjugate heat transfer schemes are assessed for the Rayleigh numbers 10^3, 10^4, and 10^5. The results of the different forcing and conjugate heat transfer schemes are compared against each other and against those of the conventional methods to find the most computationally efficient schemes.

1. Introduction

Three-dimensional (3D) natural convection heat transfer in differentially heated cubical enclosures with conducting fins attached to their active walls has many industrial applications including energy storage systems, thermal control of electronic devices, cooling of radioactive waste containers, and ventilation of rooms, to name a few. In these applications, rectangular parallelepiped fins are widely used to augment heat transfer because of their simplicity and lower cost.

All the above-mentioned industrial applications of the natural convection heat transfer are associated with 3D phenomena. However, less effort in the literature has been devoted to the 3D numerical simulation of those problems, and majority of available studies including most recently published works have invoked 2D geometries [1–7]. Noteworthy is the fact that invoking the 2D geometries puts limits on using wide ranges of the fin geometries, thereby obstructing the way of full numerical exploration of heat transfer enhancement possibilities which could be achieved by the fins [8].

From those studies in the literature which considered the 3D problems, da Silva and Gosselin [9] used the finite element method to numerically simulate the thermal performance of an internally finned 3D cubical enclosure, to find ranges of parameters where the amount of heat transfer enhancement was affected by the fin geometry. Fredrick and Moraga [8] employed the finite volume method to perform a numerical simulation of the laminar 3D natural convection of air in a cubical enclosure with a conducting rectangular parallelepiped fin on the hot wall. As another research, Fredrick [2] used the finite volume method to conduct a 3D numerical simulation of the natural convection problem in a cubical enclosure with a vertical rectangular parallelepiped fin attached to the hot wall.

* Fax: +98 77 33440376.
E-mail addresses: g.r.imani@pgu.ac.ir, gholamrezaimn@gmail.com.

http://dx.doi.org/10.1016/j.camwa.2017.06.024

Nomenclature

f_i	Density distribution function
f_i^{eq}	Equilibrium distribution function of f_i
g_i	Fluid internal energy distribution function
g_i^{eq}	Equilibrium distribution function of g_i
g_{si}	Solid internal energy distribution function
g_{si}^{eq}	Equilibrium distribution function of g_{si}
H	Cubical enclosure side (m)
k_f	Fluid thermal conductivity ($^{W}/_{mk}$)
k_s	Solid thermal conductivity ($^{W}/_{mk}$)
$\overline{Nu}$	Average Nusselt number
Pr	Prandtl number
R	Gas constant ($\frac{kJ}{kg\,K}$)
Ra	Rayleigh number (defined by Eq. (10))
T_c	Temperature of the cold wall of the enclosure (K)
T_f	Fluid temperature (K)
T_h	Temperature of the hot wall of the enclosure (K)
T_o	Average temperature in the enclosure (K), $T_o = (T_c + T_h)/2$
T_s	Solid temperature (K)
$\mathbf{V} = (u, v, w)$	Velocity vector ($^{m}/_{s}$)
x, y, z	Cartesian coordinates (m)
x^*, y^*, z^*	Non-dimensional coordinates, $(x^*, y^*, z^*) = (x, y, z)/H$

Greek symbols

α	Thermal diffusivity ($^{m^2}/_{s}$)
δx	Lattice step (m)
δt	Time step (s)
ε	Internal energy density, $\varepsilon = {}^3/_2RT$, ($\frac{kJ}{kg}$)
λ	Solid–fluid thermal conductivity ratio, $\frac{k_s}{k_f}$
ν_f	Fluid kinematic viscosity ($^{m^2}/_{s}$)
ρ	Fluid density ($^{kg}/_{m^3}$)
$(\rho c_p)_f$	Fluid volumetric heat capacity ($^{J}/_{K\,m^3}$)
$(\rho c_p)_s$	Solid volumetric heat capacity ($^{J}/_{Km^3}$)
τ_v	Fluid hydrodynamic non-dimensional relaxation time
τ_g	Fluid energy non-dimensional relaxation time
τ_{gs}	Solid non-dimensional energy relaxation time

Subscripts

f	Fluid phase
s	Solid phase

It should be mentioned that this lack of the 3D studies in the literature could be attributed to the high computational cost associated with the 3D numerical simulations of the finned natural convection problems. This high computational cost, itself is linked not only to complex geometries of those problems but also to non-linear and coupled nature of the governing equations as well as to complexity of conjugate thermal boundary conditions at solid–fluid conjugate boundaries.

Nonetheless, the conventional numerical methods were used in all of the above-mentioned researches. However, during the last two decades, the lattice Boltzmann method (LBM) has become a robust numerical tool for fluid flow and heat transfer simulations [10–13]. This is because of its inherent features including but not limited to linear nature of the convection term, ease of coding, ease of parallelization of the computational code, and pure local collision operator [10]. Even though the early thermal lattice Boltzmann schemes such as multi-speed, suffered from severe numerical instability [11], a two-distribution function model proposed by He et al. [11], significantly improved the numerical stability of the thermal lattice Boltzmann models. Based on the proposed model by He et al. [11], a simplified 3D thermal lattice Boltzmann model was presented by Peng et al. [12], in which, the compression work and viscous heat dissipation were neglected for incompressible flows.