NUMERICAL STUDY OF CONVECTIVE HEAT TRANSFER AND FLUID FLOW THROUGH POROUS MEDIA

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To my beloved parents, family and friends

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In the name of Allah, the Most Gracious and Most Merciful.

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ABSTRACT

Lattice Boltzmann method (LBM) is applied to predict the phenomenon of natural convection in a generalised isotropic porous media model filled in a square geometry by introducing a force term to the evolution equation and porosity to the density equilibrium distribution function. The temperature field is obtained by simulating a simplified thermal model which uses less velocity directions for the equilibrium distribution function and neglects the compression work done by the pressure and the viscous heat dissipation. The reliability of this model for natural convective heat transfer simulation is studied by comparing with results from other previous simulations at a porosity value, ε = 0.9999 which is close to unity resembling a square cavity condition. The model is then used for simulation at ε equal to 0.4, 0.6 and 0.9. The results obtained are discussed in terms of the Nusselt number, streamlines and isotherms. Comparison with previous works confirms the applicability of the model.

ABSTRAK

Kaedah Kekisi Boltzmann (LBM) diaplikasikan untuk menjangka fenomena perolakan semulajadi pada model umum untuk bahan poros yang bersifat isotropik dalam sebuah geometri berbentuk segiempat sama dengan memperkenalkan kesan daya dalam persamaan evolusi dan keporosan kepada fungsi keseimbangan ketumpatan. Medan suhu diperolehi dengan mensimulasi model terma yang telah dipermudahkan dengan menggunakan kurang arah halaju untuk fungsi peredaran keseimbangan dan mengabaikan kerja mampatan yang dilakukan oleh tekanan dan kehilangan haba kelikatan. Kebolehpercayaan model ini untuk pemindahan haba konvektif secara semulajadi dikaji dengan membandingkan kepada keputusan simulasi hasil kerja yang terdahulu pada nilai keporosan, ε = 0.9999 yang hampir kepada 1 yang menyerupai keadaan segiempat sama yang kosong. Seterusnya, model digunakan untuk simulasi pada ε bersamaan dengan 0.4, 0.6 dan 0.9. Keputusan yang diperolehi diboncangkan dari segi nombor Nusselt, garisan stream dan garisan isothermal. Perbandingan dengan hasil kerja terdahulu menunjukkan yang model ini memberikan keputusan yang memuaskan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

SYMBOLS

β	Bulk coefficient
$\mathbf{c}$	Micro velocity vector
D	Dimension
ε	porosity
$f(\mathbf{x},\mathbf{c},t)$	Density distribution function
f_i	Discretized density distribution function
f_i^{eq}	Discretized equilibrium density distribution function
$F_{f,g}$	External force
G	Boussinesq effect
g	Gravitional force
g_i	Discretized internal energy distribution function
g_i^{eq}	Discretized equilibrium internal energy distribution function
μ	dynamic viscosity
k	permeability
ρ	density
H or L	Characteristic length

Ω	Collision operator
q	local heat flux
R	ideal gas constant
t	time
τ	time relaxation
T	temperature
u	Velocity vector
ν	kinematic viscosity
w	Weight coefficient
x	Space vector
χ	thermal diffusivity

Abbreviations

LBM	Lattice Boltzmann method
BGK	Bhatnagar-Gross-Krook
LBE	Lattice Boltzmann equation
PDE	Partial Differential Equation
D2Q9	nine-velocity direction model
D2Q4	four-velocity direction model
LB	Lattice Boltzmann
FEM	Finite Element Method
FDM	Finite Difference Method

Non-dimensional parameter

Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
Da	Darcy number

CHAPTER 1

INTRODUCTION

1.1 Background

Convective heat transfer is mode of energy transfer between a solid surface and the adjacent fluid in motion. It involves the combined effects of conduction and fluid motion. Convective heat transfer is known as forced convection if the fluid is forced to flow over the surface by external means. If the fluid motion is initiated by buoyancy forces as a result of density differences due to variation of temperature in the fluid, it is known as natural convection (Cengel, 2003).

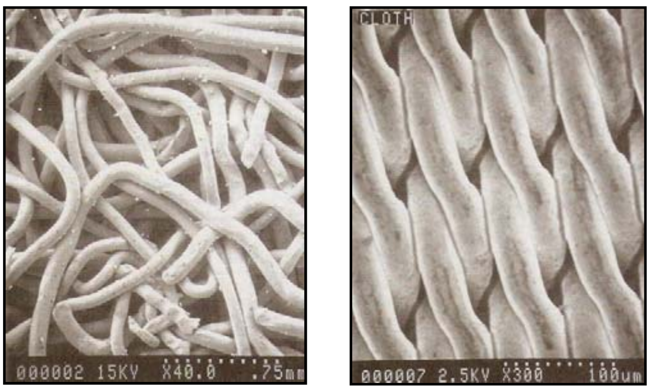

Figure 1.1 Examples of porous media structure (Kaviany, 1992)

Porous media is a medium that is formed by many relatively closely packed particles or solid matrix with its void filled with fluids (Kaviany, 1992). The porosity of a medium is defined as the fraction of the total volume of the medium that is occupied by void space (Nield and Bejan, 1992).

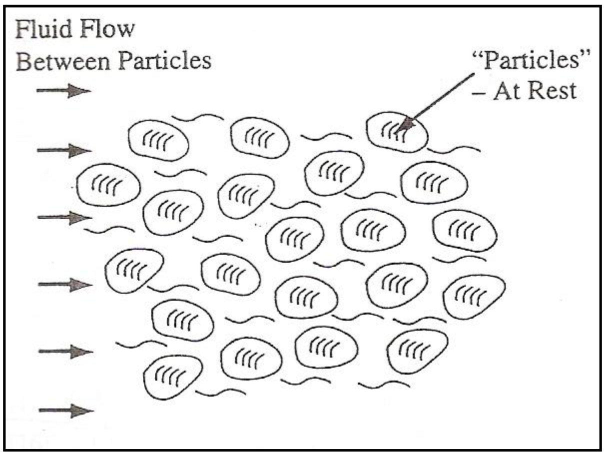

Figure 1.2 Flow in a porous medium (Oosthuizen and Naylor, 1999)

Convective heat transfer through porous media has received attention from many researchers. In particular, natural convective heat transfer through porous media has been studied extensively since the past several decades because of its importance in industry (Kakac et.al, 1990). Some of the applications include heat transfer through a layer of granular insulating material entirely filled with air and heat transfer from a pipe or cable buried in soil or in a bed of crushed stones saturated with flowing ground water (Oosthuizen and Naylor, 1999).

Before the development of high speed digital computers, experimental and theoretical methods have been used to solve problems related to fluid flow and heat transfer including convective heat transfer in porous media. However, with the existence of digital computers, numerical methods became more popular. When the problems are very complex, it is relatively easier to solve by using numerical methods. (Tannehill et.al, 1997).

1.2 Numerical Methods

The governing equations of fluid dynamics and heat transfer form the basis of numerical methods in fluid flow and heat transfer problems. The Navier Stokes equation coupled with energy equation only partially address the complexity of most fluids of interest in engineering applications. In addition to that, the equation is so complex that currently there is no analytical solution except for a small number of special cases. The most reliable information pertaining to a physical process of fluid dynamics is usually given by an actual experiment using full scale equipments. However, in most cases, such experiment would be very costly and often impossible to conduct (Azwadi, 2007).

With the recent computer technology, the Navier-stokes equation is able to be solved numerically. In order to simulate fluid flows on a computer, continuity equation, Navier-Stokes equation coupled with energy equation need to be solved with acceptable accuracy. Researchers and engineers need to discretize the problem by using a specific method before they can solve the problem. The numerical simulation begins with creating a computational grid. Grid is the arrangement of these discrete points throughout the flow field (Anderson, 1995). Depending on the method used for the numerical calculation, the flow variables are either calculated at the node points of the grid or at some intermediate points.

Common numerical methods are finite difference, finite volume and finite element method. In recent years, researchers have also developed other methods apart from the three aforementioned methods. In this project, a relatively new method; Lattice Boltzmann Method (LBM) will be used.

1.3 Lattice Boltzmann Method

Lattice Boltzmann Method (LBM) is a relatively new approach that uses simple microscopic models to simulate complicated macroscopic behavior of transport phenomena. In other words, it describes the fluid at molecular level and models for the collision between molecules.

The core idea of the LBM is to develop simplified kinetic models that incorporate the essential physics of microscopic processes so that the macroscopic averaged properties comply with the desired macroscopic Navier-Stokes equations. The concept of particle distribution has been developed in the field of statistical mechanics to describe the kinetic theory of liquids and gases.

This single-particle distribution is then used in the lattice Boltzmann scheme. The degree of freedom used to define the particle distribution is reduced from the physical world to a computationally manageable number in the simulation while still maintaining fidelity with the continuum prescription of the physical world. The LBM was found to be as stable, accurate and computationally efficient as classical computational methods for simulation of a single phase, isothermal fluid flow (Azwadi, 2007). Simulations for thermal related problems such as natural convective heat transfer require additional thermal equilibrium distribution function apart from the initially stated particle distribution function. The application of this model also has been proven to be successful (He et.al, 1998).

1.4 The advantages of Lattice Boltzmann Method

There are a few advantages of Lattice Boltzmann Method (LBM) compared to the conventional numerical methods. Firstly, the algorithm is simple and thus can be implemented with a kernel of just a few hundred lines. Moreover, the algorithm can be modified to suit other relatively complex simulation.

Secondly, the LBM allows for an efficient parallelization of the simulations even on parallel machines with relatively slow interconnection networks. This is due to only interaction of each lattice node with its nearest neighboring nodes are involve at each iteration step.

Thirdly, the LBM can also be implemented to simulate multiphase flows. In classical numerical methods, for multiphase flow, the partial differential equations need to be written for each of the two phases. The implementation of such a model requires advanced software engineering techniques to track the position of this interface and to implement its dynamics. LBM eliminates this problem where the two phases can be represented by the same fluid model.

Fourthly, LBM has been proven to be successfully used in applications that involve interfacial dynamics and complex. Apart from that, the natural advantage of LBM compared to conventional numerical methods is that, no descretization of the macroscopic continuum equations need to be provided. Hence, the LBM does not need to consider explicitly the distribution of pressure on interfaces of refined grids since the implicity is included in the computational scheme.

Last but not least, since only one or two speeds and a few moving directions are used in LBM, the transformation related to the microscopic distribution function and macroscopic quantities is extremely simple and consists of no more than arithmetic calculations.

1.5 Comparison : LBM and other numerical methods

In the conventional fluid flow simulation and other physical modeling, the starting point is to discretize the partial differential equations (PDE). These PDEs are discretized either by finite differences, finite element or finite volume. Then, standard numerical methods are used to solve the resulting of ordinary differential equations.

In Lattice Boltzmann Method (LBM), the particle velocity distribution function is discretized instead of hydrodynamic variables. The derivation of the corresponding macroscopic equation requires multi-scale analysis (Gladrow, 2000).

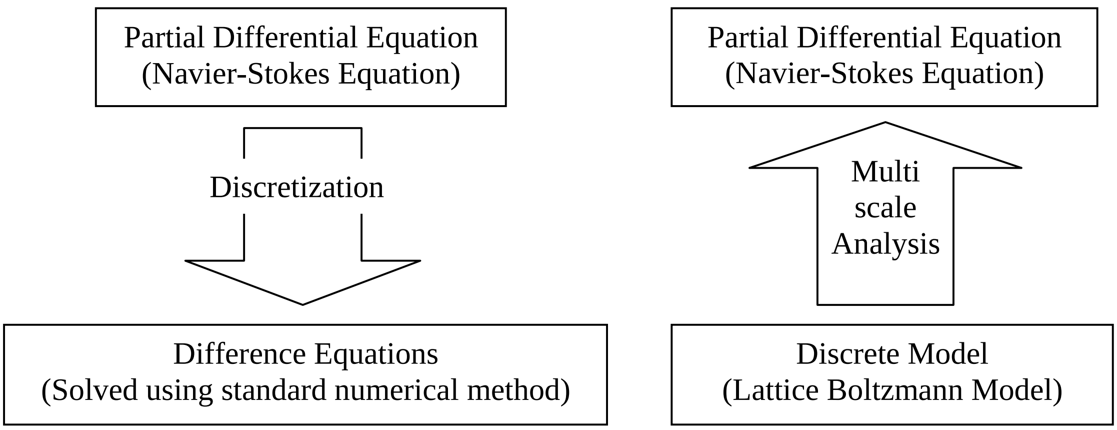

Figure 1.3 Classical numerical methods versus LBM

1.6 Natural convection through porous media - LBM

A benchmark solution for natural convection in square geometry has been developed nearly three decades ago (Davis, 1983). Due to industrial demand for numerical solutions, the problem has been till now progressively extended to porous media.

Darcy's equation was earlier used by researchers to study natural convection in porous media. However, previous results indicate that the equation is only applicable at low velocity condition (Darcy, 1856). For higher velocity condition, modifications to the equation are required which includes consideration of non-linear drag due to the solid matrix (Forchheimer, 1901) and viscous stresses by the solid boundary (Brinkman, 1947). These two factors may not affect the study in low velocity but it must be considered for high velocity studies. The combination of these two equations is known as Brinkman-Forchheimer equation. The behaviour of this non-Darcian condition is shown in physical experiment (Prasad et.al, 1985). Due to lack of generality in the model to be used for a medium with variable porosity, a generalised model was then developed (Nithiarasu et.al, 1997).

Mesoscopic approach for fluid flows have been extensively used with the advancement of lattice Boltzmann method (Shen and Doolen, 1997). Since then, studies of incompressible flows through porous media have been done by using the proposed generalised model (Guo and Zhao, 2002). The model was created by introducing a force term to the evolution equation and porosity to the density equilibrium distribution function (Guo et.al, 2002). Simulations for thermal related problem such as natural convective heat transfer require additional thermal equilibrium distribution function (He et.al, 1998). A simplified model can be used by neglecting the compression work done by the pressure and the viscous heat dissipation (Peng et.al, 2003). Such simulations have also been done for porous media (Seta et.al, 2006) which also yield comparatively good results. Other study showed that for certain limited conditions, the thermal equilibrium distribution function calculation can actually be further simplified by using less velocity directions for the equilibrium distribution function without reducing the accuracy in computation (Azwadi and Tanahashi, 2006).

1.7 Statement of identified problem

Lattice Boltzmann Method (LBM) have been used to simulate natural convection in porous media by using nine velocity directions model (D2Q9) for both velocity and temperature field. However, no attempt have been made to use a simplified model (D2Q4) to simulate the temperature field although previous research have shown that the calculation effort can be reduced by using simplified model (D2Q4) for temperature field (Azwadi and Tanahashi, 2006). Therefore, in this study, the temperature field will be simulated by D2Q4 model.

1.8 Objectives of the Project

In this study, a simplified version of thermal model will be used to simulate natural convective heat transfer in porous media. It uses less velocity directions for the equilibrium distribution function. The objective of this study is to demonstrate the ability of this new model to produce the same result with conventional thermal model.

1.9 Scope of the Project

This master project will be limited to:

a) steady state incompressible fluid flow
b) rectangular enclosure with differentially heated walls
c) isotropic porous media
d) non-Darcy region