HYBRID LATTICE-BOLTZMANN SIMULATION OF CONVECTIVE FLOW IN A CHANNEL WITH EXTENDED SURFACES

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To my beloved parents and wife

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ABSTRACT

Laminar convective flow in a channel with extended surfaces mounted at the bottom wall is investigated by using two methods. First, by the usual double-population SRT lattice Boltzmann method (LBM) and second by a hybrid scheme in which the flow is solved by single population LBM and the thermal field by the finite-difference (FD) technique with considering an appropriate coupling among them. Here, the iterative method has been chosen in order to solve the discretized energy equation with finite-difference. The transient Reynolds number for the condition of this study was determined to be 600 and all simulations were conducted in the laminar range of Reynolds numbers. It is shown that for CFD problems in which the steady state solution is desired or for those with time consistency it is possible to save computation time of the simulation remarkably by employing the aforementioned hybrid scheme. For the case study of this work, the hybrid scheme resulted in reduction of 18 percent of total simulation time.

ABSTRAK

Aliran perolakan lamina di dalam saluran dengan permukaan lanjutan di dasar saluran dikaji dengan menggunakan dua kaedah. Pertama, dengan kaedah biasa iaitu double population SRT melalui kaedah Lattice Boltzmann (LBM) dan yang kedua adalah dengan menggunakan kaedah hibrid di mana medan aliran diselesaikan dengan menggunakan single-population LBM manakala medan haba diselesaikan dengan menggunakan teknik perbezaan terhingga (FD) dengan mempertimbangkan gandingan yang sesuai untuk mereka. Di sini, kaedah iteratif telah dipilih untuk menyelesaikan persamaan tenaga dengan menggunakan kaedah perbezaan terhingga. Nombor Reynolds sementara untuk keadaan kajian ini telah ditentukan pada 600 dan semua simulasi telah dijalankan di julat nombor Reynolds yang lamina. Ia menunjukkan bahawa untuk masalah CFD yang memerlukan penyelesaian keadaan tenang atau bagi mereka dengan memerlukan konsistensi masa, ia menunjukan penjimatkan masa pengiraan simulasi yang banyak dengan menggunakan skim hibrid tersebut. Bagi kajian kes ini, skim hibrid menghasilkan pengurangan 18 peratus daripada jumlah masa simulasi.

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LIST OF SYMBOLS

C_i	Discrete particle velocity in each discrete direction
C_s	Speed of sound
$D2Q9$	Two-dimension nine-velocity LBM
f	Distribution function in discrete Boltzmann equation
FD	Finite-difference method
FE	Finite-element method
FV	Finite-volume method
LBE	Lattice Boltzmann equation
LBM	Lattice Boltzmann method
LBM-FD	Hybrid scheme of LBM and FD
m	Physical molecular mass
Ma	Mach number
Re	Reynolds number
t	Time
u	Macroscopic flow velocity in the LBM
υ	Kinematic viscosity in the LBM
ρ	Dimensionless fluid density in the LBM
τ	Single relaxation time of Boltzmann equation

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CHAPTER 1

INTRODUCTION

1.1 Background

Conventional sources of energy have been depleting at an alarming rate, which makes future sustainable development of energy use very difficult. This concern led to a recent expansion of efforts to produce efficient heat transfer equipment and generated increasing needs for understanding of fluid flow. Thus, heat transfer enhancement technology plays an important role and it has been widely applied to many applications. Suitable heat transfer augmentation techniques can result in considerable technical advantages and savings of costs. Channels with extended surfaces, because of their effectiveness in heat transfer are suitable candidates for engineering applications [1-3].

Figure 1.1 shows a rectangular channel with extended surfaces (ES). The ES's can be applied with different sizes and shapes on the inner surface of the channel. The transverse turbulators such as ribs or grooves break the laminar sub-layer and create local wall turbulence due to flow separation and reattachment between successive ribs, which reduce the thermal resistance and significantly enhance the heat transfer [3-4].

Geometrical characteristics such as duct aspect ratio, ES height, ES angle-of-attack, ES shape, and relative arrangement of the ES's (in-line, staggered, etc.), play significant role in the rate of heat transfer [5]. By use of suitable ES geometry, a large amount of heat can be transferred between a wall and a fluid in the channel with less unit size and even with very small temperature difference. During the work, using ES's enhances not only the heat transfer, but also results in considerable pressure loss and pumping power as well.

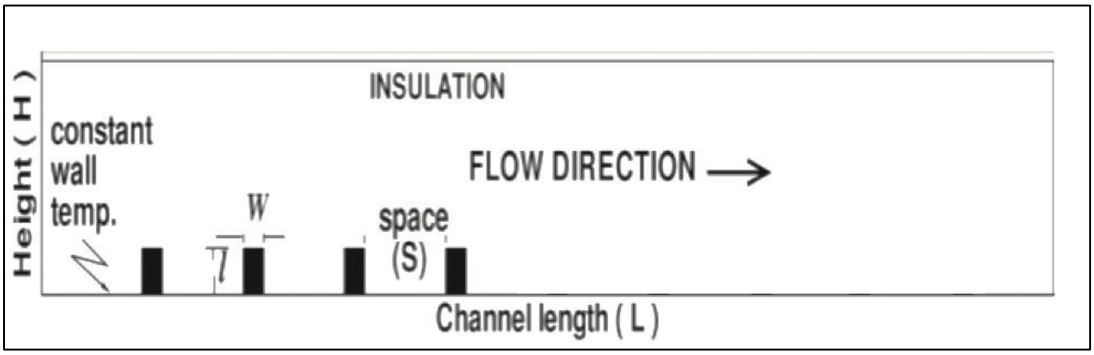

Figure 1.1 Two-dimensional channel with extended surfaces

Therefore, such channels are of interest for practical problems and here are taken as the case study to predict the behavior of the working fluid i.e., air, using three different CFD techniques, which are a mix of conventional, and the Lattice-Boltzmann (LBM) methods in order to determine the least computational time consuming one. LBM has been proven as a reliable CFD method but due to certain inherent limitations when it comes to simulation of coupled-variables problems e.g. fluid flow and temperature field, it has been suggested to employ the hybrid scheme of the LBM in which flow is solved by the LBM while the temperature gradient by a conventional CFD method e.g., finite-difference, and an appropriate coupling among them is implemented. Although this hybrid scheme is widely used but no literature address their required computational time compared with that problems that are solved by the LBM for the both variables i.e., velocity and temperature fields.

1.2 Problem statement and scope of the study

The laminar forced convective flow in a channel with inner extended surfaces on the lower wall is studied numerically. The industry requirements and demands for higher heat transfer devices have become very important factor in the design of engineering systems. In the field of heat exchanger performance, it is known that utilization of ES's can potentially lead to better heat transfer performance due to mixing of the fluid and increasing of heat transfer area [6]. Many investigations have been already performed in order to study heat transfer rate/enhancement in such geometries but here the focus is on the CFD method by a tradeoff between LBM-based CFD methods with considering their computational resources to have them compared. While researchers use hybrid scheme of the LBM it is of interest to compare its computational time compared with that of where both field are solved by the LBM say, LBM-LBM. If the computational time of the hybrid scheme i.e., LBM-FD, is bigger than LBM-LBM, finding a way to decrease the LBM-FD computational time is of interest since, by its implication we not only have been freed of the LBM limits (for coupled flows) but also have reduced the required computational time that makes the proposed method an asset.

The numerical simulation in this study is performed first by the usual LBM for both the velocity and temperature gradients along the channel (LBM-LBM) then while LBM is used again to simulate the velocity field, a conventional CFD technique i.e., finite difference (FD), is used to solve the unsteady advection-diffusion equation to obtain the temperature field (LBM-Unsteady-FD) and lastly, the flow is solved by the LBM while FD is used to solve the steady advection-diffusion equation (LBM-Steady-FD) and finally their required computational recourses are compared.

1.3 Application of the study

Due to limitations on solving fluid related problems analytically and importance of having prediction of the fluid's behavior for any practical use before build, computational fluid dynamics (CFD) places at the center of attention. Due to the vast usage of CFD in engineering problems, researches in the field have been always trying to propose new methods in order to have the simulations in less computation time and have a more accurate result. LBM was proposed about twenty years ago and due to its calculation that is done locally in the grid, it is a suitable method for parallel computing as it is of second order accuracy. Problems have been experienced that when it comes to simulation of coupled problems LBM cannot handle the problem for the second variable (dependent variable) i.e., here is temperature, because the range of the relaxation time (RT) for the second variable is imposed by the condition of the first variable i.e., here is velocity, as result although we can define the range of the RT in a way that locates in the valid range for Single Relaxation Time Lattice-Boltzmann scheme (SRT-LBM) but, the RT for the second variable is out of our control and may become invalid due to the condition of the first variable so, it is proposed to use the hybrid scheme of LBM where, the velocity field is handled by the usual SRT-LBM and the temperature field by a conventional CFD method that here finite-difference is chosen. Hence, by having a technique that comprises SRT-LBM and FD, it becomes possible to take advantage of the LBM model to handle the velocity the negatives sides of the SRT-LBM are eliminated by replacing an FD technique. If we could propose a hybrid scheme that also be capable to offers less computation time comparing with that of LBM-LBM, we have taken one step further in enhancement of current available CFD techniques that can handles the coupled problems more efficiently and requires less computational resources.

1.4 Objectives

The objectives of this study are as follows:

1. To obtain 2-D simulation for the channel by D2Q9-SRT-LBM for both the velocity field and temperature distribution.

2. To obtain 2-D simulation for the channel by D2Q9-SRT-LBM for the velocity field and finite-difference (FD) for unsteady advection-diffusion equation to acquire temperature distribution.

3. To obtain 2-D simulation for the channel by D2Q9-SRT-LBM for the velocity field and FD for steady-state advection-diffusion equation to acquire temperature distribution.

4. To compare the results and specifically computational time required for among the three above-mentioned simulation methods and determine the least time consuming one.

1.5 Thesis outlines

This thesis is divided into five chapters as follows:

Chapter 1 presents the problem statement, scope of this study, applications of the study and the objectives of the project.

Chapter 2 contains the literature review that is related to the fluid flow, heat transfer problems in rectangular channels and numerical studies with different CFD methods. This chapter covers the available literature on hybrid schemes of the Lattice-Boltzmann method in specific.

Chapter 3 provides the implementation methodology over each of the simulation methods concerns here i.e., 1- LBM-LBM, 2- LBM-unsteady-FD and 3- LBM-steady-FD.

Chapter 4 discusses the results obtained from each methods and compare them followed by Chapter 5 where the conclusions of this study are made.

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