# INVESTIGATION OF FLOW AROUND BLUFF BODY USING LATTICE BOLTZMANN METHOD

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## SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical.

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## STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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**Dedicated to my parents, my lovely family, Noor Atiqah Md Din, Siti Zuulaika Rejal, and Noor Safiah Suhaimi**

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## ABSTRACT

Flow around a bluff body, a square cylinder, has extensive significance in engineering. The main objective in this thesis was to investigate a flow around bluff body using a Lattice Boltzmann Method. To achieve this objective, various values of Reynolds numbers have been a parameter to see the flow characteristic around bluff body in the channel with geometry mesh. There are two types of square cylinder condition for this case study which is single square cylinder and double square cylinder side by side. For both condition, square cylinder have been place in channel. The simulation for both cases was studied under isothermal lattice Boltzmann method condition in which we investigated computationally in a two-dimensional configuration using a fluid dynamics program. The different Reynolds numbers has given the different flow characteristic around the square cylinder. From the simulation, discussions have been made, and conclusion for this thesis has been obtained. Finally, for future investigation, the correlations obtained from this numerical result could be used to investigate the flow around bluff body.

## ABSTRAK

Aliran di sekeliling objek yang pegun, berbentuk silinder segi empat sama, mempunyai kaitan yang sangat mendalam di dalam kejuruteraan. Objektif utama tesis ini adalah untuk mengkaji aliran di sekeliling objek yang pegun menggunakan kaedah kekisi bersilang Boltzmann. Untuk mencapai objektif ini, pelbagai nilai nombor Reynold telah digunakan sebagai parameter untuk melihat ciri-ciri aliran di sekeliling silinder segi empat sama di dalam paip yang bergeometri. Terdapat 2 keadaan silinder segi empat sama di dalam kajian ini, di mana hanya satu silinder segi empat sama diletakkan di dalam paip, dan dua silinder segi empat sama disusun bersebelahan. Walaubagaimanapun, kedua-dua keadaan silinder segi empat sama ini diletakkan di dalam paip. Simulasi model dikaji dengan kaedah isothermal lattice boltzmann menggunakan program dinamik bendalir dua dimensi. Nombor Reynold yang berbeza menghasilkan cirri-ciri aliran yang berbeza di sekeliling silinder segi empat sama. Daripada simulasi yang dihasilkan, diskusi telah diadakan, dan kesimpulan telah dibuat. Kajian dan analisis parameter yang mempengaruhi aliran di sekeliling silinder segi empat sama didalam paip ini perlu diambil kira dan di hubungkaitkan untuk kajian di masa akan datang.

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### Symbols

| | |
|---|---|
| a | : Acceleration |
| **c** | : Micro velocity vector |
| $c_s$ | : speed of sound |
| $f(\mathbf{x},\mathbf{c},t)$ | : Density distribution function |
| $f_i$ | : Discretised density distribution function |
| $f_i^{eq}$ | : Discretised equilibrium density distribution function |
| $g$ | : Gravitational force |
| $h$ | : Channel height of inflow channel |
| H | : Channel height downstream |
| $t$ | : Time |
| $u$ | : Horizontal velocity |
| **u** | : Velocity vector |
| U | : Channel inlet velocity |
| $v$ | : Vertical velocity |
| V | : Volume |
| **x** | : Space vector |
| $\rho$ | : Density |
| $\tau$ | : Time relaxations |

## LIST OF ABBREVIATIONS

BGK : Bhatnagar Gross Krook

CFD : Computational fluid dynamic

D2Q9 : Two dimensional nine velocities model

LB : Lattice Boltzmann

LBE : Lattice Boltzmann equation

LBM : Lattice Boltzmann method

LGA : Lattice gas approach

MD : Molecular dynamic

2-D : Two dimensional

## Non-dimensional parameters

*Re* : Reynold number

# CHAPTER 1

# INTRODUCTION

## 1.1 PROJECT BACKGROUND

Understanding the science of fluid dynamics is crucial in many branches of engineering. It is also broad, interdisciplinary field that touches almost every aspect of our daily lives. Fluid dynamics involving aerospace, automotive, chemical processing, power generation, heating, ventilation, air conditioning, biomedical, oil and gas, marine and many others.

Nowadays, there is a lot of research and investigation about the flow dynamics behavior. With the recent advances in computing power today's microprocessor, numerical investigation and solutions of flow problems can be brought to the desktop. Because fluid related problems arising in science and engineering are extremely complex by nature, the use of a computer is necessary to determine the fluid motion of a particular problem.

There are many type of computational method in order to solve fluid flow problem and it is becomes a very important tools to researcher. According to fluid flow phenomenon, the computational fluid dynamics (CFD) is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. In order to that, Lattice Boltzmann method (LBM) is introduced which is one class of computational fluid dynamics method for fluid simulation.

## 1.2 LATTICE BOLTZMANN METHODS

Lattice Boltzmann methods (LBM) is a class of computational fluid dynamics (CFD) methods for fluid simulation. Instead of solving the Navier–Stokes equations, the discrete Boltzmann equation is solved to simulate the flow of a Newtonian fluid with collision models such as Bhatnagar-Gross-Krook (BGK). By simulating the interaction of a limited number of particles the viscous flow behavior emerges automatically from the intrinsic particle streaming and collision processes.

LBM is a relatively new simulation technique for complex fluid systems and has attracted interest from researchers in computational physics. Unlike the traditional CFD methods, which solve the conservation equations of macroscopic properties (i.e., mass, momentum, and energy) numerically, LBM models the fluid consisting of fictive particles, and such particles perform consecutive propagation and collision processes over a discrete lattice mesh. Due to its particulate nature and local dynamics, LBM has several advantages over other conventional CFD methods, especially in dealing with complex boundaries, incorporating of microscopic interactions, and parallelization of the algorithm.

The primary goal of Lattice Boltzmann method (LBM) is to build a bridge between the microscopic and macroscopic dynamics rather than to dealt with macroscopic dynamics directly. In other words, the goal is to derive macroscopic equations from microscopic dynamics by means of statistics rather than to solve macroscopic equation.

## 1.3 OBJECTIVE

The objective of this project is to simulate a 2-Dimensional droplet motion on incline surface using Lattice Boltzmann method (LBM) algorithm. From this, we can see the fluid flows and what phenomenon happened.

## 1.4 SCOPES

In order to achieve the objectives notified earlier, there was some scopes have been recognized. First scope is to understand about Lattice Boltzmann method (LBM). Understanding the LBM is the most important thing as to solve this problem, this method is the main priority. Second scope for this project is to simulate the flow phenomenon using CFD programming. Simulation is important as it will be use to investigate the flow around bluff body.

## 1.5 PROBLEM STATEMENT

i. First, the Lattice Boltzmann method involving an equation and variables or parameter that is seldom used.

ii. Finally, programming or coding of software will be used on producing these simulations have to be performed repeatedly.

## 1.6 FRAMEWORK

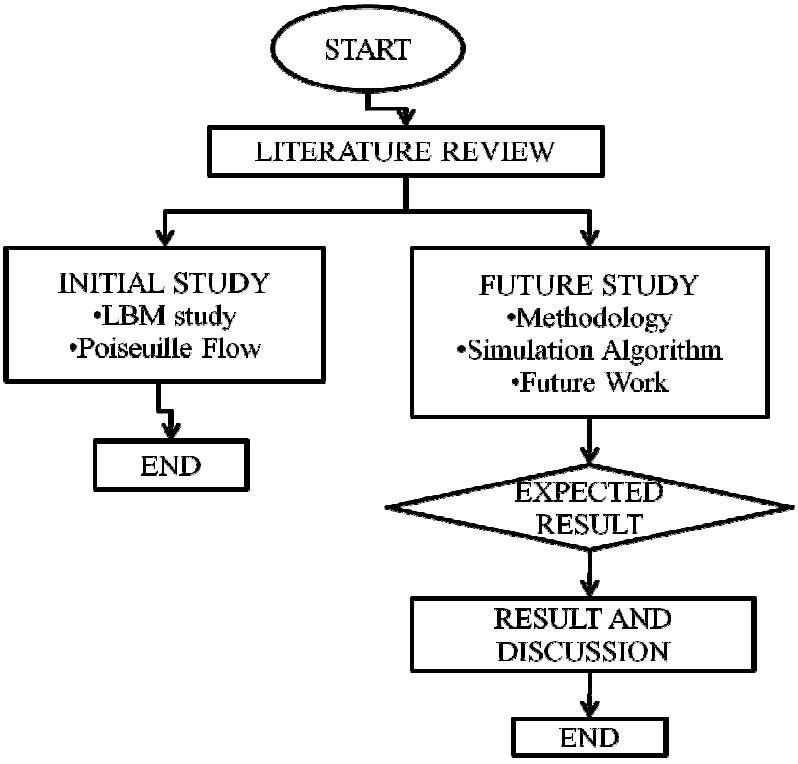


Figure 1.1: Framework

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 LATTICE BOLTZMANN METHOD (LBM)

The Lattice Boltzmann method (LBM) is considerably as an alternative approach to the well known finite difference, finite element, and finite volume techniques for solving the Navier-Stokes equation. Although as a new comer in numerical scheme, the Lattice Boltzmann approach has found recent successes in a host of fluid dynamical problems, including flows in porous media, magneto hydrodynamics, immiscible fluids and turbulence. LB scheme is a scheme evolved from the improvement of lattice gas automata and inherits some features from its precursor, the LGA. The first LB model was a floating-point version of its LGA counterpart each particle in the LGA model (represented by a single bit Boolean integer) was replaced by a single particle distribution function in the LB model (represented by floating point number).The lattice structure and the evolution rule remained the same. One important improvement to enhance the computational efficiency has been made for the LB method: the implementation of the BGK approximation (single relaxation time approximation). The uniform lattice structure was unchanged.

The starting point in the Lattice Boltzmann scheme is by tracking the evolution of the single particle distribution $f_\alpha$. The concept of particle distribution has already well developed in the field of statistical mechanics while discussing the kinetics theory of gases and liquids. The definition implies that the probable number of particles in a system that

travel freely, without collisions, for distances (mean free path) long compared to their sizes. Once the distribution functions are obtained, the hydrodynamics equations can be derived.

Although LBM approach treats gases and liquids as system consisting of individual particles, the primary goal of this approach is to build a bridge between the microscopic and macroscopic dynamics, rather than to deal with macroscopic dynamics directly. In other words, the goal is to derive macroscopic equations from microscopic dynamics by means of statistic, rather than to solve macroscopic equations.

The LBM has a number of advantages over other conventional CFD methods. The algorithm is simple and can be implemented with a kernel of just a few hundred lines. The algorithm can also be easily modified to allow for the application of other, more complex simulation components. For example the LBM can be extended to describe the evolution of binary fluid, or extended to allow for more complex boundary conditions. Thus the LBM is an ideal tool in fluid simulation. General concept of Lattice Boltzmann Method can be identified from Figure 2.1 (Azwadi, 2007).

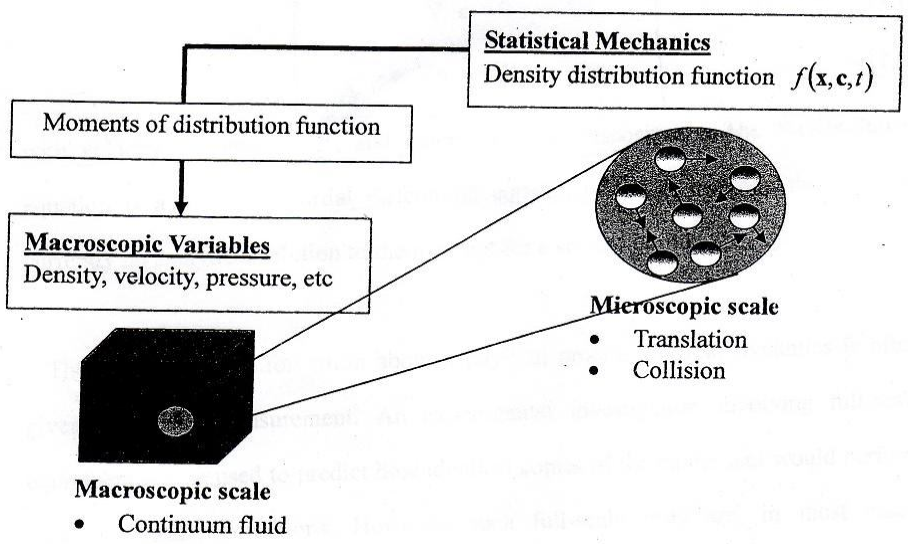


Figure 2.1: General concept of Lattice Boltzmann method (Azwadi, 2007)

## 2.2 NUMERICAL OF LATTICE BOTLZMANN METHOD

In the Lattice-Boltzmann method, space is divided into a regular lattice and real numbers at each lattice site represent the single-particle distribution function at that site, which is equal to the expected number of identical particles in each of the available particle states *i*. In the simplest model, each particle state *i* is defined by a particle velocity, which is limited to a discrete set of allowed velocities. During each discrete time step of the simulation, particles move, or hop, to the nearest lattice site along their direction of motion, where they "collide" with other particles that arrive at the same site. The outcome of the collision is determined by solving the kinetic Boltzmann equation for the new particle-distribution function at that site and the particle distribution function is updated.

The outcome of collisions is very simply approximated by assuming that the moment of the interacting particles will be redistributed at some constant rate toward an equilibrium distribution $f_i^{eq}$. This simplification is called the single-time-relaxation approximation. In mathematical terms, the time evolution of the single-particle distribution is given by:

$$f_i(\mathbf{x} + \mathbf{c}_i \Delta t, t + \Delta t) = f_i(\mathbf{x}, t) - \frac{1}{\tau}\left[f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t)\right] \tag{2.1}$$

Where $f_i^{eq}$ is the density distribution function along the $i$ direction at lattice site $x$, $\Delta t$ the time step and $\boldsymbol{c}_i$ is the particle velocity in the $i$ direction. The second term on the right-hand side is the simplified collision operator $\Omega i$. The rate of change toward equilibrium is $1/\tau$, the inverse of the relaxation time, and is chosen to produce the desired value of the fluid viscosity. The equilibrium function $f_i^{eq}$ can be written as:

$$f_i^{eq} = \frac{n}{(2\pi RT)^{D/2}} \exp\left\{-\frac{(\mathbf{c}-\mathbf{v})^2}{2RT}\right\} \tag{2.2}$$

The macroscopic density *n* and velocity vector *u* are calculated by the conservation laws,

$$n = \sum_i f_i$$
$$n\mathbf{u} = \sum_i \mathbf{c}_i f_i \tag{2.3}$$

For single phase flow, pressure can be calculated from $p = c_s^2 n$ with the speed of sound $c_s = 1/\sqrt{3}$. To obtain the Navier-Stokes equations, the equilibrium distribution functional form must be carefully chosen. In the 9-speed square lattice, a suitable equilibrium distribution function has been proposed with Maxwell-Boltzmann equilibrium distribution function

$$f_i^{eq} = \rho\omega_i\left[1 + 3(\mathbf{c}_i \cdot \mathbf{u}) + \frac{9}{2}(\mathbf{c}_i \cdot \mathbf{u})^2 - \frac{3}{2}\mathbf{u}^2\right] \tag{2.4}$$

$$\omega_1 = 4/9, \omega_{2\sim5} = 1/9, \omega_{6\sim9} = 1/36 \tag{2.5}$$

In the limit of long wavelengths, the LBE recovers the following quasi-incompressible NSEs by the Chapman–Enskog expansion

$$\frac{1}{\rho_0 c_s^2}\frac{\partial p}{\partial t} + \nabla \cdot u = 0 \tag{2.6}$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho_0}\nabla p + \upsilon\nabla^2 u \tag{2.7}$$

Where $\rho_0$ is the constant average density in the system and the kinematics viscosity is

$$\upsilon = \frac{2\tau - 1}{6} \tag{2.8}$$

If, in addition, a low Mach number assumption is invoked as the nearly incompressible limit is approached, equations $\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{u}) = 0$ will approximate the incompressible Navier-Stokes equations with error of the order of $M^2$. Here, the primed quantities denote fluctuations. It should be pointed out that using the artificial compressibility to simulate incompressible Navier-Stokes equations has been proposed by Chorin and others. One of the main differences between the lattice Boltzmann method and previous artificial-compressible methods is that a different set of primitive variables is used in each approach. In addition, all terms in LBM, including convection terms and dissipation terms, are solved through relaxation to equilibrium (via the collision operator),whereas in the artificial-compressible methods, some explicit finite difference schemes must be employed for these terms.

## 2.3 COMPUTATIONAL FLUID DYNAMICS (CFD)

Nowadays, there's a lot of CFD software can be identified in every research involving fluid problem. In solving these entire problem, CFD has evolved from a mathematical curiosity to become a method or essential tool in solving the Navier-Stokes equation and the continuity equation or an equation derived from them. In other words, CFD is the science of determining a numerical solution to the governing equations of fluid flow while advancing the solution through space or time to obtain a numerical description of the complete flow field of interest.

In simulating fluid flow using CFD software on a computer, it would be necessary to solve Navier-Stokes equation with infinite accuracy. In reality, numerical researchers

must choose a method to discredits the problem. Some of the general numerical methods used in CFD are described here.

The setting up of a numerical simulation begins with creating a computational grid. The flow variable are calculated at the node points of this grid and, in some methods, at some intermediate points as well. The spacing between grid points has to be fine enough to attain a high enough degree of accuracy. The are advantages, however, to keep the number of grid points small since more grids points means more computer memory is required and a greater time is needed to perform each iteration of the calculation. The simplest computational grid is a rectangular lattice with fixed spacing between node points in each dimension. There are a range of methods that use unstructured grids where the density of the node points is not constant and is higher in the regions where more accuracy is required. Unstructured meshes often end up being connected in a triangular or tetrahedral fashion because these shapes fill space well and they require a minimum number of vertices. Some methods even use adaptive meshes where node points are created and destroyed as flow features move through the computational domain. This keeps the total number of nodes to a minimum, while still providing the required resolution for certain flow features.

It is extremely easy to implement Lattice Boltzmann applications in regular geometries. The following Matlab scripts are only one or two pages long. Furthermore, they are self-consistent and merely use the basic matrix formalism of Matlab. They do not invoke external routines such as linear algebra packages or differential equation solvers. And yet, complex flows are simulated with high accuracy.

## 2.4 MOLECULAR DYNAMICS

One obviously way to simulate a fluid flow on a computer is to model the individual molecules which make up the fluid which so called the molecular dynamics (MD) approach. MD approach is based on Newton's second law or the equation of motion**, F = ma**. From the knowledge of the force on each atom, it is possible to determine the acceleration of each atom in the system. Integration of the equations of the motion then

yields a trajectory that describes the positions, velocities and accelerations of the particles as they vary with time. The method is deterministic; once the position and velocities of each atom are known, the state of the system can be predicted at any time in the future or the past. However, this can be restrictively time consuming when considering even a very small volume of fluid. Even when a gas is being considered where there are fewer molecules and a larger time step can be used, because of the longer mean free path of the molecules, the number of molecules that can be considered is severely limited.

## 2.5 LATTICE GAS APPROACH

Another approach which has proved less popular is the lattice gas approach (LGA). This approach can be considered as a simplified version of MD approach where groups of fluid 'particle' are considered instead of a large number of individual particles. The LGA model is based on a square lattice (HPP model) or triangular lattice (FHP model) whose nodes can be occupied by the particles. Thus space is discretised, and in particle it is also finite. Impulsions are also distributed in a discrete fashion where all particles have the same mass (equal to one unit) and equal absolute velocity, i.e. they will fly from one lattice node to its nearest neighbor in one unit of time (thus time is also discrete). Furthermore, an exclusion principle is imposed on the particles implies that no two particles may sit simultaneously on the same node if their direction is identical.

The time evolution of the LGA consists of a collision step and a propagation step. In the collision step, particles can change their velocities' direction due to collisions and in the propagation step, particles move in the direction of their velocities to the new sites where they will collide again. The collision rules are chosen in order to conserve both mass and momentum. The detailed nature of the microscopic interactions does not affect the form of the equations but only the values of the coefficients (such as the viscosity) appearing in them.

To summarize, LGA are inherently simple; their discrete nature makes them straight forward to implement by computer and they lend themselves to agent based approaches