Declaration

I hereby declare that the work presented in this Thesis titled *"Analysis of Lattice Boltzmann Method for Turbulent Flow Simulation on Multi-core GPU Architecture"* submitted to the Indian Institute of Technology Jodhpur in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the joint supervision of *Dr. B.Ravindra* and *Dr. Akshay Prakash.* The contents of this Thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.

Alankar Agarwal
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Certificate

This is to certify that the Thesis titled *"Analysis of Lattice Boltzmann Method for Turbulent Flow Simulation on Multi-core GPU Architecture"*, submitted by *Alankar Agarwal (P14BS001)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Ph.D.Thesis Supervisor

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Ph.D. Student

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List of Symbols

Symbol	Description
c	lattice speed
$\overline{C}_D$	mean drag coefficient
c_s	speed of sound
C_s	Smagorinsky constant
C_1, C_2, C_3	impeller clearance (cm)
d	diameter of square cylinder (mm)
D	impeller diameter (cm)
D_c	circular disk diameter (cm)
D_f	discrete delta function
D_s	shaft diameter (cm)
$\vec{e}_k$	particle velocity vector in the k^{th} direction
f_k	particle distribution function along direction k
f_k^{eq}	equilibrium distribution function along direction k
$f_k^{'}$	post-collision states of the particle distribution function along direction k
$f_k^{''}$	post-forcing particle distribution function along direction k
$\overline{f}_k$	filtered particle distribution function
$\overline{f}_k^{eq}$	filtered equilibrium distribution function
F_k	discrete force distribution function along direction k
$\vec{F}_b$	force vector on the boundary nodes
G	kernel function
H	height of the square duct (mm)
H_w	water level (cm)
k	spatial direction
k	turbulent kinetic energy (m^2/s^2)
i, j, k	indexing in x, y, and z direction, respectively
L	length of the square duct (mm)
L_{bf}	baffle length (cm)
L_{bl}	blade length (cm)
N	rotational speed of the impeller (rpm)
N_{bf}	number of baffles plate
N_{bl}	number of blades
n	width of mapping window
n_x, n_y, n_z	domain size in x, y, z dimension, respectively
r	radial location (cm)
Re	Reynolds number
$\overline{S}$	characteristic filtered rate of strain
S_{ij}	filtered strain rate tensor at grid location, i, j
T	diameter of the cylindrical tank (cm)
t_r	simulation run time (sec)
$\vec{u}$	macroscopic fluid velocity vector (m/s)
u_x, u_y, u_z	magnitude of velocity in x, y, and z direction, respectively (m/s)

Symbol	Description
$\vec{U}_b$	velocity vector on the lagrangian markers at boundary surface (m/s)
$\vec{U}_b^{uf}$	unforced velocity vector at boundary nodes (m/s)
$< u >$	mean streamwise velocity (m/s)
$< v >$	mean normal velocity (m/s)
$\vec{u}^{uf}$	unforced fluid velocity vector (m/s)
U_m	Mean velocity (m/s)
U_{rad}	radial velocity of fluid flow (m/s)
U_{tip}	tip velocity of impeller blades (m/s)
V_w	water volume (l)
W	width of the square duct (mm)
W_{bf}	baffle width (cm)
W_{bl}	blade width (cm)
w_k	weight factor along direction k
$\vec{x}$	position vector of Eulerian fluid nodes
$\vec{x}_b$	position vector of boundary nodes
x^*	streamwise distance from the downstream face of the cylinder (mm)
x	streamwise dimension (mm)
y	cross-stream dimension (mm)
y	spanwise dimension (mm)
Δ	filter width
$\Delta x, \Delta y, \Delta x$	size of the lattice/grid spacing in x, y, and z directions, respectively
Δt	time-step size
$\overline{\phi}$	spatial dependent uantity
ρ	density of fluid (kg/m^3)
τ	relaxation time parameter
τ_t	total Relaxation time
ν	kinematic viscosity of the fluid (m/s^2)
ν_{SGS}	eddy viscosity (m/s^2)
ν_t	total effective viscosity (m/s^2)
$\overline{\Pi}_{ij}$	non-equilibrium momentum flux tensor at grid location, i, j
$< \cdot >$	time-and spanwise-averaging

List of Abbreviation

Abbreviation	Full form
$2-D$	Two-Dimensional
$3-D$	Three-Dimensional
$4-D$	Four-Dimensional
BB	Bounce-Back
BBL	Bounce-Back on the Link
BTE	Boltzmann Transport Equation
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
$CUDA$	Compute Unified Device Architecture
D_2Q_7	Two-dimensional lattice structure with seven velocities
D_2Q_9	Two-dimensional lattice structure with nine velocities
D_3Q_{13}	Three-dimensional lattice structure with thirteen velocities
D_3Q_{15}	Three-dimensional lattice structure with fifteen velocities
D_3Q_{19}	Three-dimensional lattice structure with nineteen velocities
D_3Q_{27}	Three-dimensional lattice structure with twenty-seven velocities
D_mQ_n	Lattice structure of m-dimensional and n-directions
DNS	Direct Numerical Simulation
$ELBM$	Entropic Lattice Boltzmann Method
$FCHC$	Face-Centered Hyper Cubic
FD	Finite Difference
FE	Finite Element
FV	Finite Volume
FHP	Frisch, Hasslacher, and Pomeau
$GPCs$	Graphics Processing Cluster
$GPUs$	Graphics Processing UnitsS
ID	Index
IB	Immersed Boundary
$IB-LBM$	Immersed Boundary-Lattice Boltzmann Method
LBE	Lattice Boltzmann Equation
$LBGK$	Lattice Bhatnagar-Gross-Krook
LBM	Lattice Boltzmann Method
LDA	Laser Doppler Anemometry
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulation
$LGCA$	Lattice Gas Cellular Automata
$MLUPS$	Millions Lattice Updates Per Second
MRT	Multi-Relaxation Time
NS	Navier-Stokes
$PDEs$	Partial Differential Equations
$PE's$	Processing Elements
PIV	Particle Image Velocimetry
$QELBM$	Quasi-Equilibrium Lattice Boltzmann Method

RANS	Reynolds-Averaged Navier-Stokes
RMS	Root-Mean-Square
RPM	Revolution Per Minute
SGS	Subgrid-Scale
SG	Sliding Grid
IO	Inner-outer
SIMD	Single Instruction Multiple Data
SM	Sliding Mesh
SMs	Streaming Multiprocessors
SRT	Single-Relaxation Time
$SRT - LBM$	Single-Relaxation Time-Lattice Boltzmann Method
SST	Shear-Stress-Transport
TPCs	Texture Processing Clusters
TKE	Turbulent Kinetic Energy