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School of Civil Engineering
FACULTY OF ENGINEERING

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Lattice Boltzmann method for indoor and urban flow

Dr M A I Khan
A.Khan@leeds.ac.uk

EPSRC
Engineering and Physical Sciences Research Council

NVIDIA

Outline

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- Background and Motivation
- Theoretical Background of Lattice Boltzmann Method (LBM)
- Discrete formulation of LBM
- LBM algorithm with D3Q19
- Fluid simulation with video game cards; LBM with GPUs using CUDA
- Results & Live Demo

Motivation for developing real-time or fast CFD

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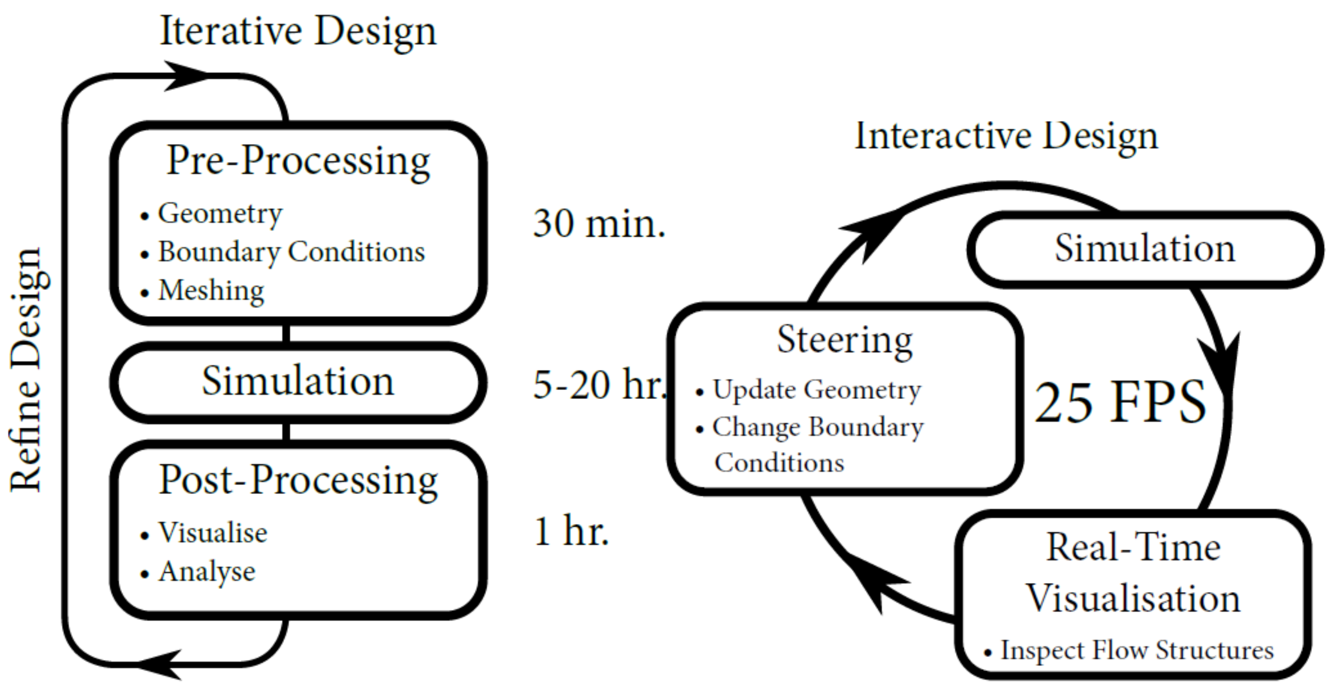

Traditional Design optimisation using CFD

Interactive Design optimisation using CFD

Indoor outdoor connection

- Naturally ventilated buildings are common worldwide and are advocated as part of sustainable and resilient infrastructure development
- However the relationship between external airflow and indoor air quality is still an area of much debate and challenging research.
- Even for simple building geometries, naturally induced airflow patterns can be highly complex.
- Since modelling outdoor and indoor air is a problem of scale/time, where large eddies dominate external flow but smaller eddies dominate inside buildings,
- Care needs to be taken when modelling these phenomena together.

Real-time CFD

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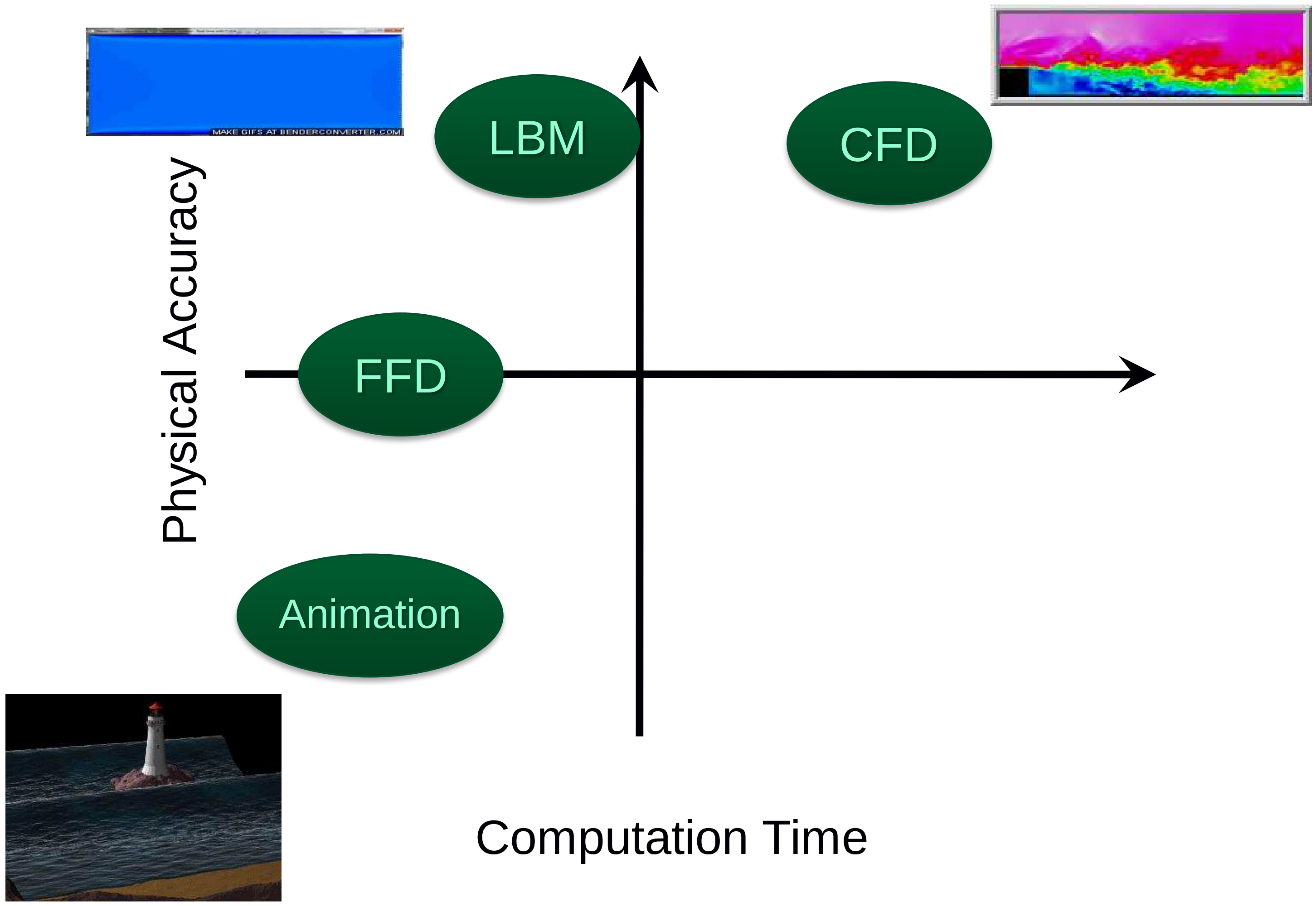
- Whilst the use of CFD-based simulation tools has led to significant insights into the role of spatio-temporal flow structures and its capability to transport or disperse heat, moisture and pollutants in general
- CFD has never been able to enter the realm of **<u>forecasting in the field of indoor environment.</u>**
- The main reason for this is that CFD-based tools which are currently available or in use require a substantial amount of computational resources and user time to get reasonably accurate results.
- The traditional CFD approach using finite-volume method (FVM) to capture the detail of urban flows and transient behaviour requires increasingly substantial computing resources.
- However, graphical processing units (GPUs) are becoming increasingly powerful with massively parallel capabilities, and therefore lend themselves to the airflow simulation process using a novel lattice Boltzmann method (LBM)

Why LBM


MAKE GIFS AT BENDERCONVERTER.COM
LBM
CFD
Physical Accuracy
FFD
Animation
Computation Time

Theoretical Background of Lattice Boltzmann Method (LBM)

Model classification for fluid flows

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Model type	Macroscopic	Mesoscopic	Microscopic
Characteristic model assumption	Interaction of molecules in the fluid neglected	Distribution of molecules in the fluid considered	Interaction of single molecules in the fluid considered
Examples: Models	Navier-Stokes, Euler, Stokes, Heat Equation	Liouville, Boltzmann, BGK-Boltzmann Eqn	Molecular dynamics (Newton's laws)
Examples: Observed quantities	Fluid velocity, pressure, density, temperature	Mean free path, mean molecular velocity, density	Molecular mass, velocity, extent and form
Examples: Numerical methods	Spectral, finite difference (FDM), volumes (FVM) and elements (FEM)	Monte Carlo, lattice Boltzmann, finite differences, volumes and elements	Molecular dynamics (MD)

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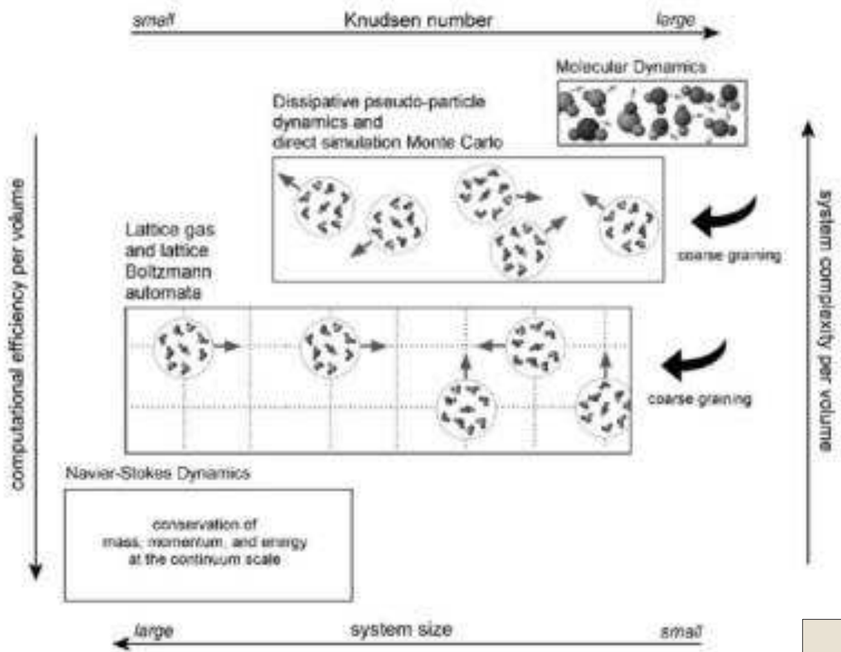
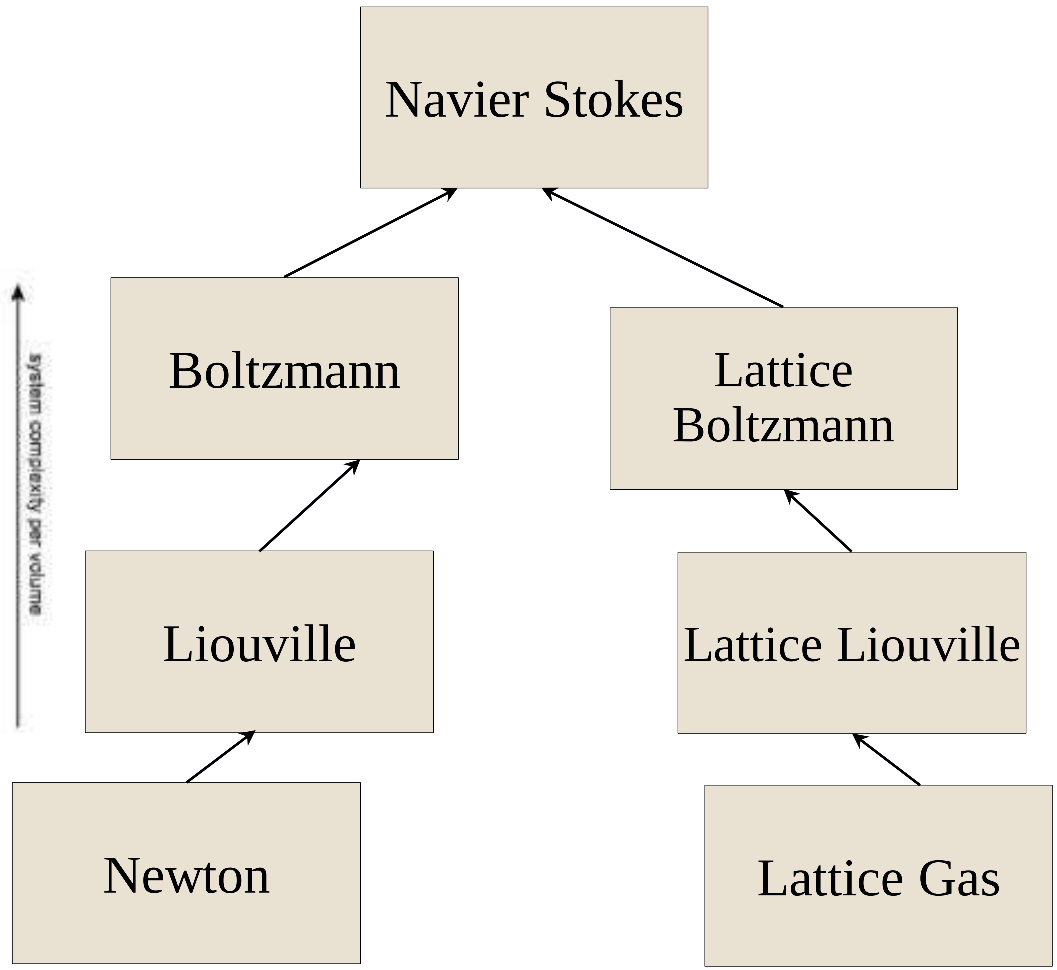
- Boltzmann equation
- $\frac{\partial f}{\partial t} + \boldsymbol{\xi} \cdot \frac{\partial f}{\partial \boldsymbol{x}} = C(f, f)$
- $f(\boldsymbol{x}, \boldsymbol{\xi}, t)$
- Here $\boldsymbol{\xi}$'s are the microscopic velocities

- Navier-Stokes equation
- $\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \boldsymbol{u} = -\boldsymbol{\nabla} p + \frac{1}{Re}(\Delta \boldsymbol{u})$
- $\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0$
- Here, $\boldsymbol{u}$ is the macroscopic or hydrodynamic velocity



Ref.: Raabe; Modelling Simul. Mater. Sci. Eng. 12 (2004) R13–R46)



Hierarchy of models (Succi 2001)

Computational procedure of LBGK scheme

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

Collide

$$f_i(\mathbf{x}, t+\delta_t) = f_i(\mathbf{x}, t) + \frac{1}{\tau}\left(f_i^{(eq)} - f_i\right)$$

Stream

$$f_i(\mathbf{x} + c\mathbf{e}_i\delta_t, t+\delta_t) = f_i(\mathbf{x}, t+\delta_t)$$

$$\rho = \sum_{i=0}^{q} f_i(\mathbf{x}, t) \qquad \rho\mathbf{u} = \sum_{i=0}^{q} c\mathbf{e}_i f_i(\mathbf{x}, t)$$

2nd order space and 1st order time accurate method

Playing Billiards with fictitious particles

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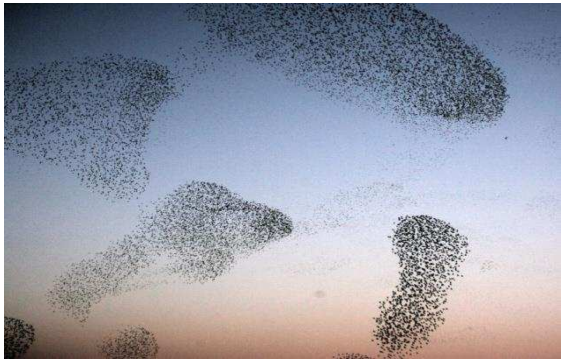
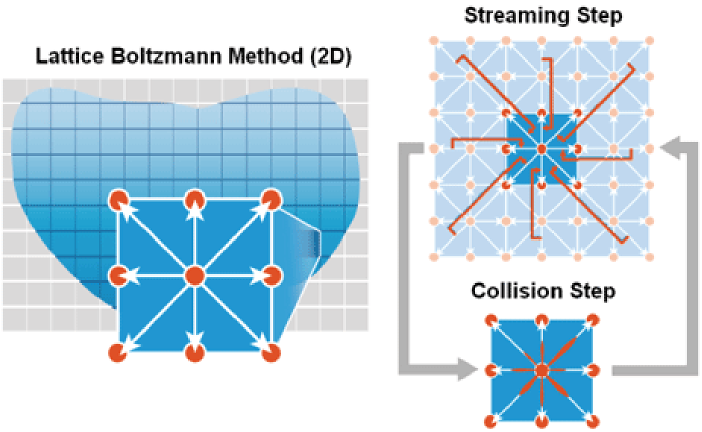
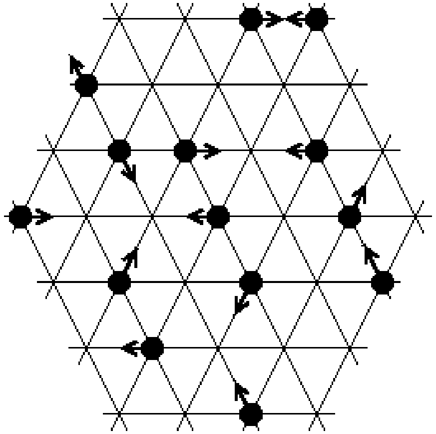
- Playing billiards on a discrete space-time lattice to simulate continuum fluid flow (bottom up approach)



- f_i's are the pseudo particles in LBM





Navier-Stokes vs Lattice Boltzmann

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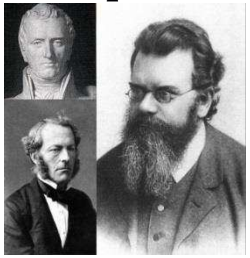
Conventional CFD

- CFD solves the conservation equations of macroscopic properties (i.e., mass, momentum, and energy) numerically
- Nonlinear advection
- Non-local parallel limited
- Boundary conditions difficult
- Geometry setup slow
- 3D time dependent flow expensive to solve
- Complex physics require complex models

Lattice Boltzmann

- LBM treats fluids as a fictitious collection of interacting mesoscopic (between micro and macro) particles
- Linear advection
- Local and parallel & SIMD
- BC easy for arbitrary geometry
- Geometry setup fast
- 3D time-dependent flow straightforward and fast
- Complex physics involve simple models



Claude-Louis Navier (1785-1836)
George Stokes (1819-1903)

Ludwig Boltzmann (1844-1906)

- LBM for 3D Turbulent and Thermal Flow

The D3Q19 Model

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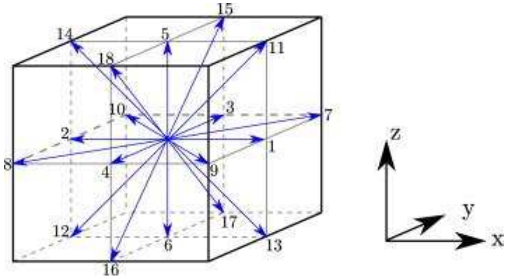
- It has a minimum number of velocities while maintaining good isotropy of the lattice
- The simulation of the velocity field is carried out on such a D3Q19 lattice;
- The complex collision operator is approximated by using the standard BGK scheme



- The distribution functions **f** , is close to a local equilibrium $\mathbf{f}^{(eq)}$ and relaxes toward this equilibrium with some characteristic time τ

Temperature coupled Model

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- To simulate thermal flows we use the coupled mode
- Here the velocity is simulated using D3Q19 lattice using BGK and the temperature is computed on a smaller D3Q6 lattice
- Boussinesq approximation is used to couple temperature and velocity via buoyancy force
- The evolution of temperature distribution function T_i on the lattice is given by

$$T_i\left(\mathbf{x} + c\mathbf{e}_i\delta_t, t + \delta_t\right) = T_i\left(\mathbf{x}, t + \delta_t\right)$$

$$T_i\left(\mathbf{x}, t + \delta_t\right) = T_i\left(\mathbf{x}, t\right) + \underbrace{\frac{1}{\tau_T}\left(T_i^{(eq)} - T_i\right)}_{\text{BGK Collision}} \text{ with } i \in \{1, \ldots, 6\}$$

Extending LBM to turbulent flows

Turbulent flow modelling

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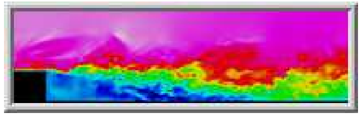
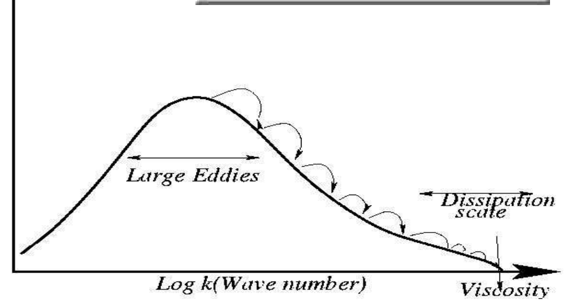
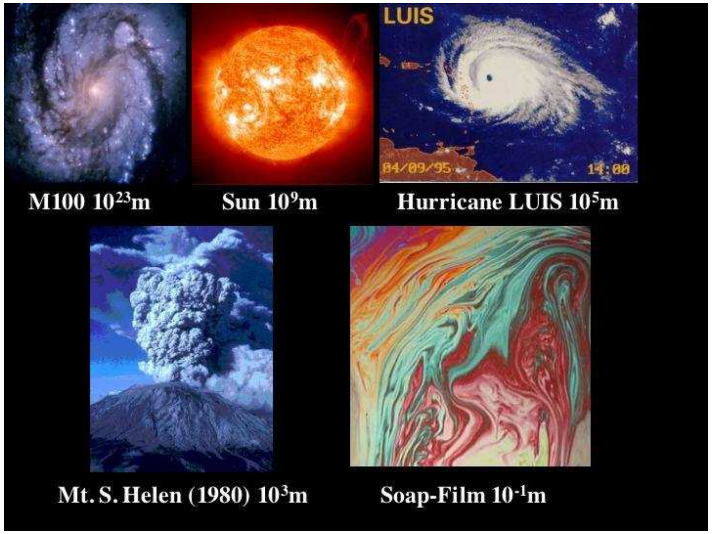
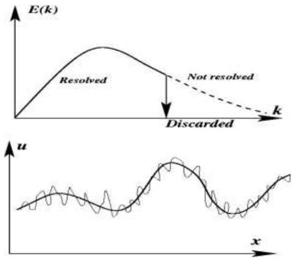
Big whorls have little whorls
That feed on their velocity,
And little whorls have lesser whorls
And so on to viscosity--- L F Richardson

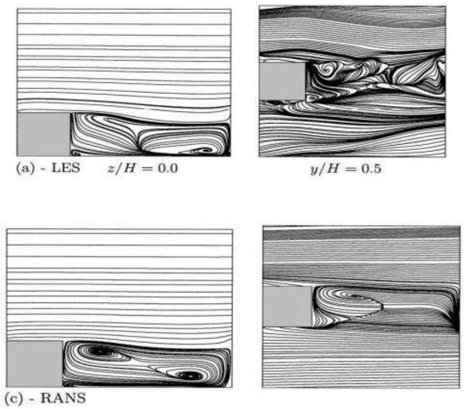




(N~Re$^{9/4}$)







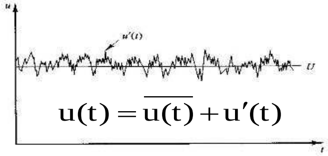
$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_i \bar{u}_j\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) + T_{ij}\right]$$

where $i = 1, 2, 3$

$$T_{ij} = \bar{u}_i \bar{u}_j - \overline{u_i u_j}$$

$$T_{ii} = 2\nu_T \bar{S}_{ij} \text{ where } \nu_T = C\bar{\Delta}^2 \left|\bar{S}\right|$$

$$\bar{u}(x) = \int_\Omega u(x')G(x, x')dx'$$



$$u(t) = \overline{u(t)} + u'(t)$$

Inclusion of Turbulence, LBM sub-grid model

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- To include the effect of turbulence without excessive increase of computational expense
- We use the simple Smagorinsky sub-grid model to include large Re flows

$$\nu_t = C\Delta^2 |\bar{S}|$$

- With the current model of single relaxation time τ, simulations becomes unstable at high Re hence the use of sub-grid modelling

$$\nu_{tot} = \nu + \nu_t$$

$$\tau_S = 3\nu_{tot} + \frac{1}{2} = 3\left(\nu + C\Delta^2|\bar{S}|\right) + \frac{1}{2}$$

- Stress tensor from LBM

$$|\bar{S}| = \frac{1}{6C\Delta^2}\left(\sqrt{\nu^2 + 18C\Delta^2\sqrt{\Pi_{\alpha\beta}\Pi_{\alpha\beta}}} - \nu\right)$$

$$\text{where } \Pi_{\alpha\beta} = \sum \mathbf{e}_{i\alpha}\mathbf{e}_{i\beta}\left(f_i - f_i^{(eq)}\right)$$

Graphics Processing Unit (GPU)

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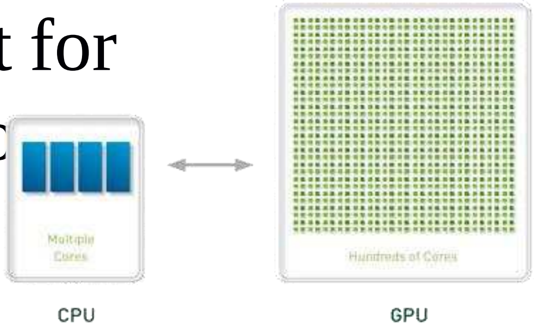
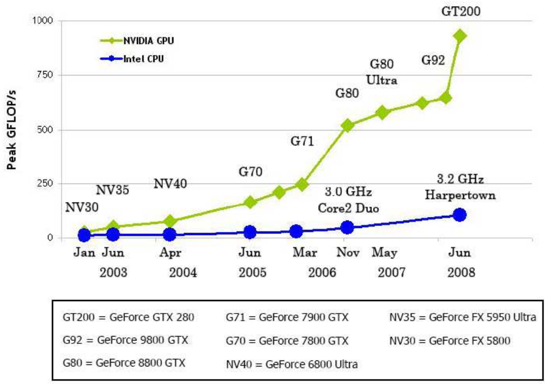
- The GPU is a computer component built for parallel computation originally for video games.
- GPU and CPU architectures are completely different.
- Thus GPU requires special programming (CUDA) techniques.
- GPUs are much faster than CPUs.
- GPU acceleration for LBM: 100x





LBM on a single GPU

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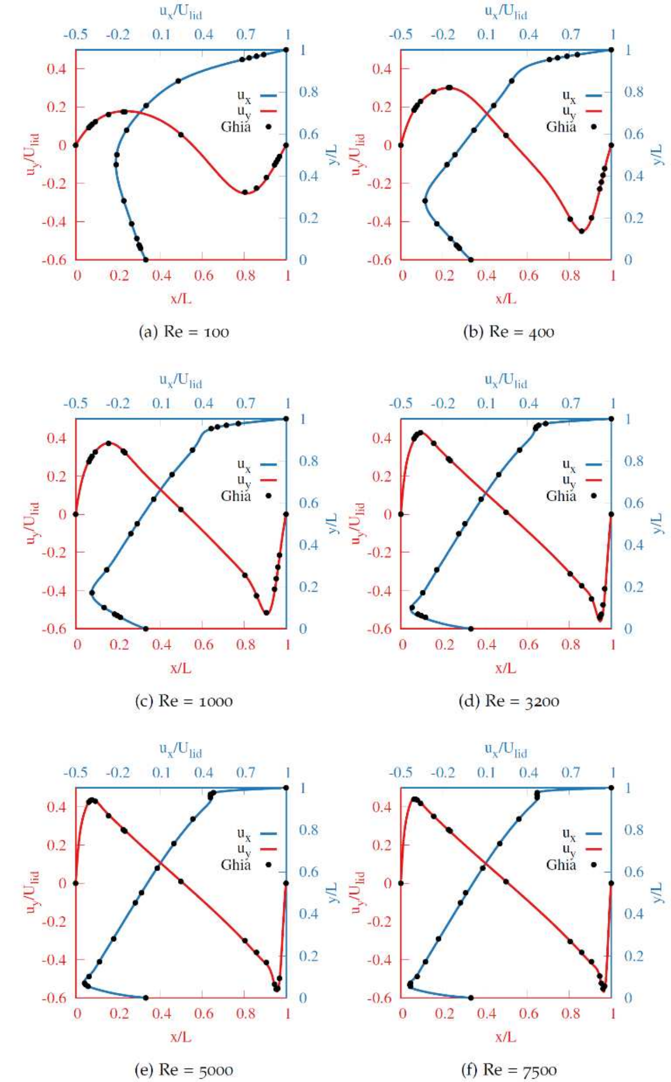
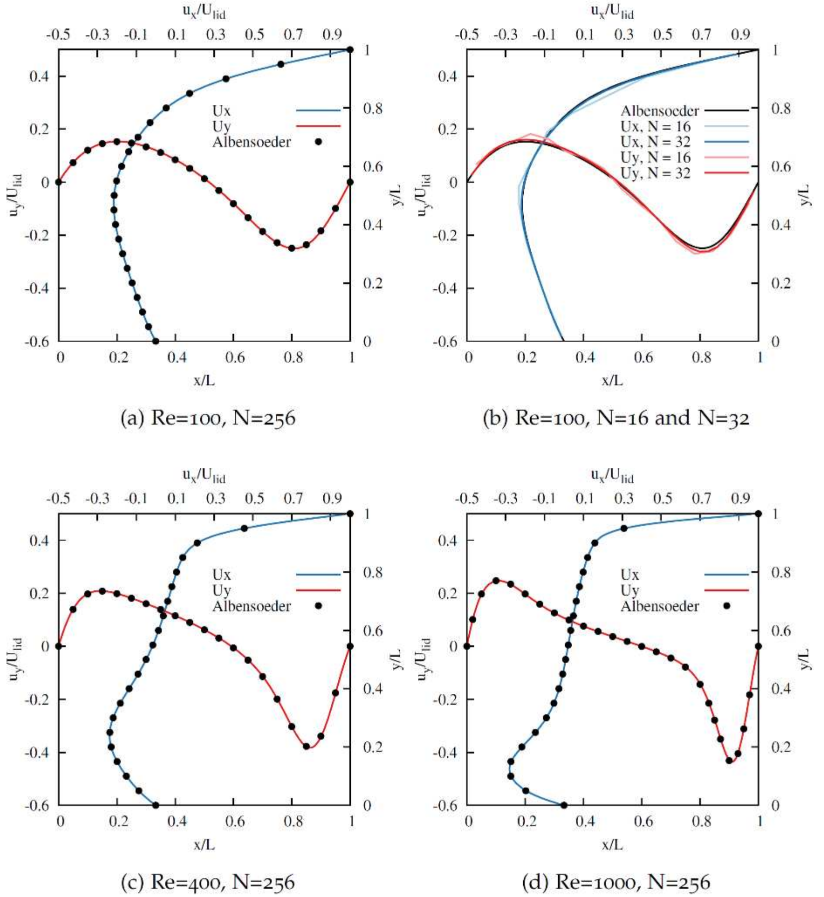


2D Cavity



3D Cavity

Validation against Tominaga et al. 2015

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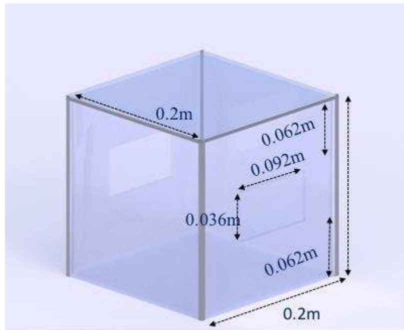
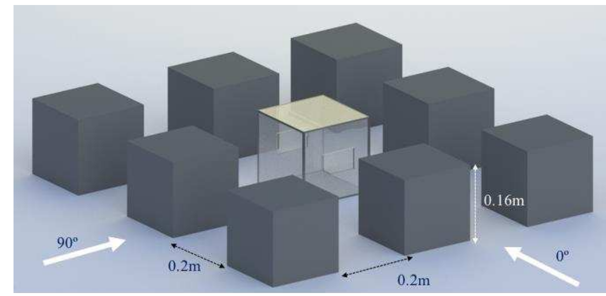
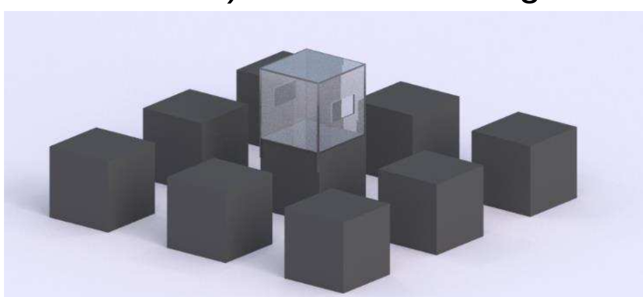


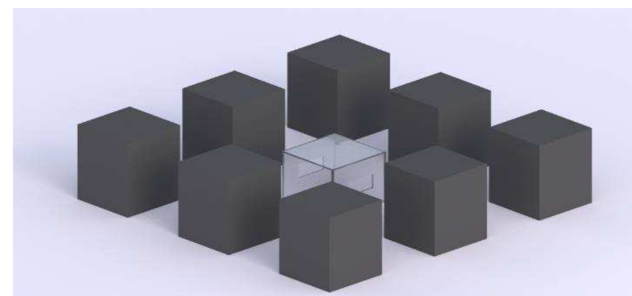
a) Isolated building



b) Array of equal sized buildings



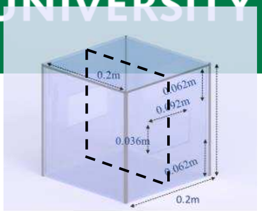
c) Array with **tall** central building

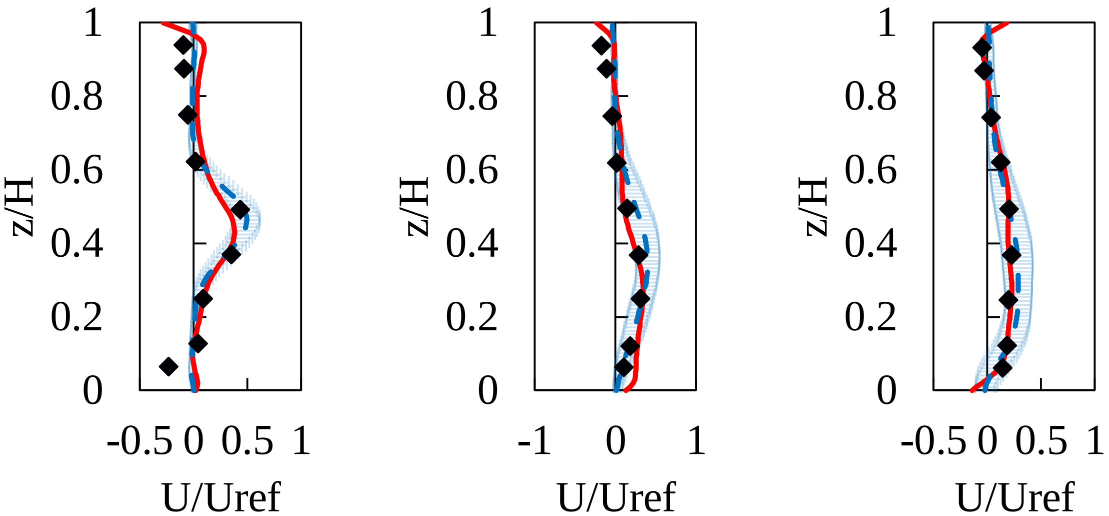


d) Array with **small** central building

For use in the urban environment, we conducted a validation study against a wind tunnel model of a cubical building with cross-flow ventilation in isolated and in an array format. Then we ran a parametric study to investigate the effect of having either a tall central building or a small central building.

Results – Isolated building

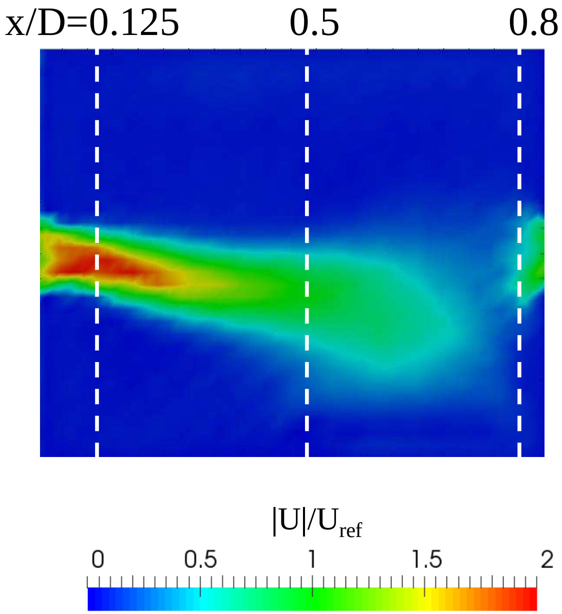




a) x/D=0.125

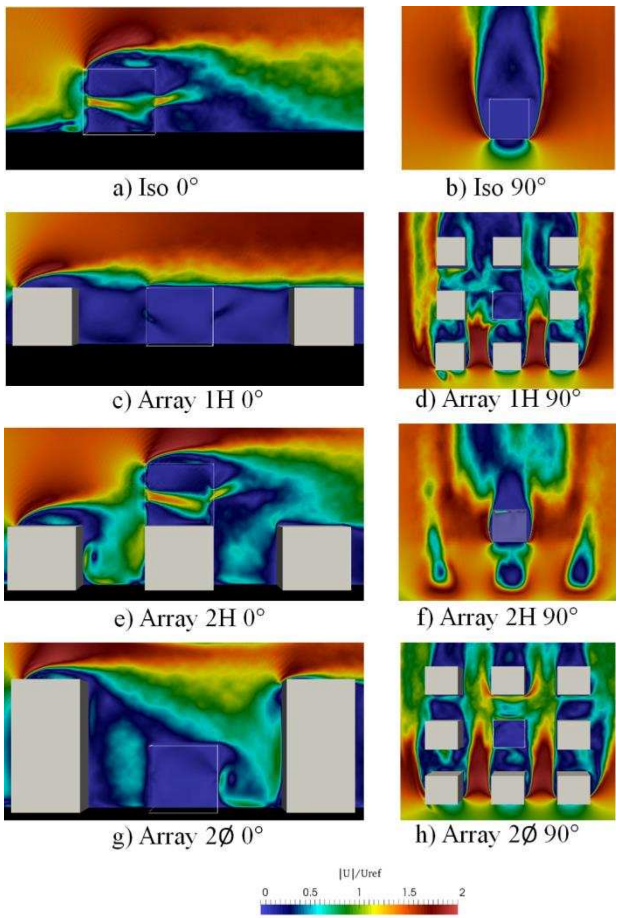
b) x/D=0.5

c) x/D=0.875



Fluent LBM Tominaga et al. 2015

d) Normalise velocity on centre-plane of isolated cube


a) Iso 0°
b) Iso 90°
c) Array 1H 0°
d) Array 1H 90°
e) Array 2H 0°
f) Array 2H 90°
g) Array 2Ø 0°
h) Array 2Ø 90°
|U|/Uref
0
0.5
1
1.5
2

Time to simulate 1 second of flow

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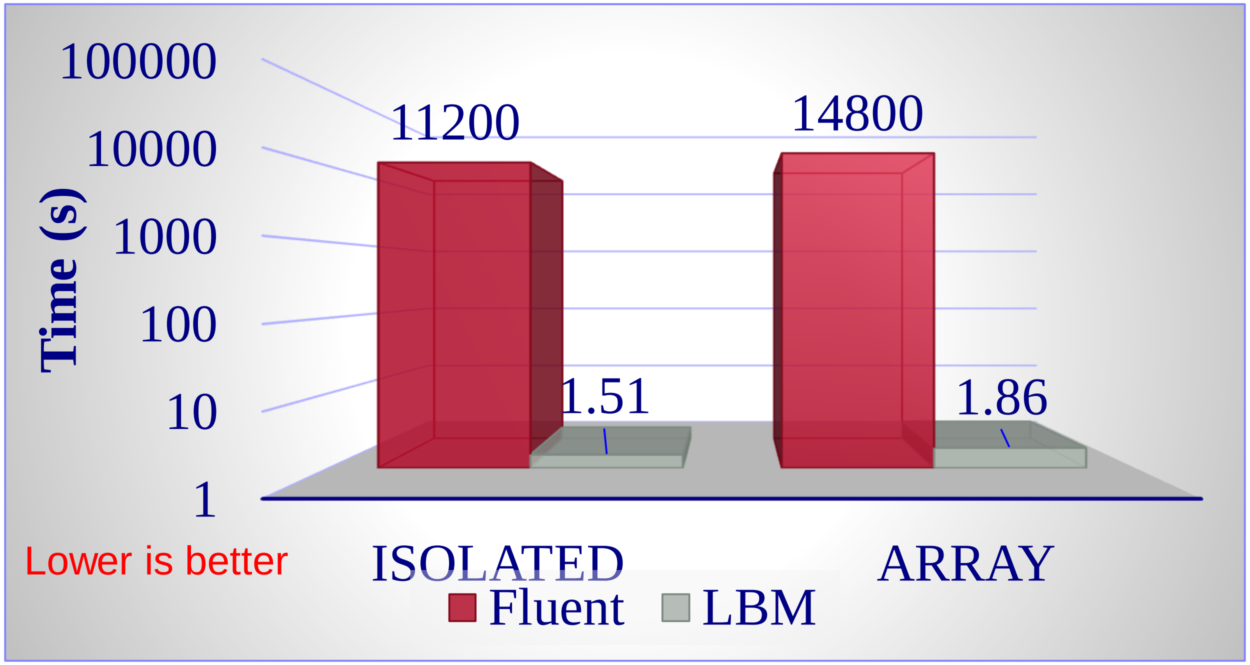

Fluent took 11200 seconds to simulate one second of flow for the isolated case and 14800 seconds for the array case. How long did it take the LBM code? 1.5s. That's almost 7500 times faster. And that's only on 1 graphics card.

Hospital Environment Control, Optimisation and Infection Risk Assessment (HECOIRA)

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Current EPSRC funded project

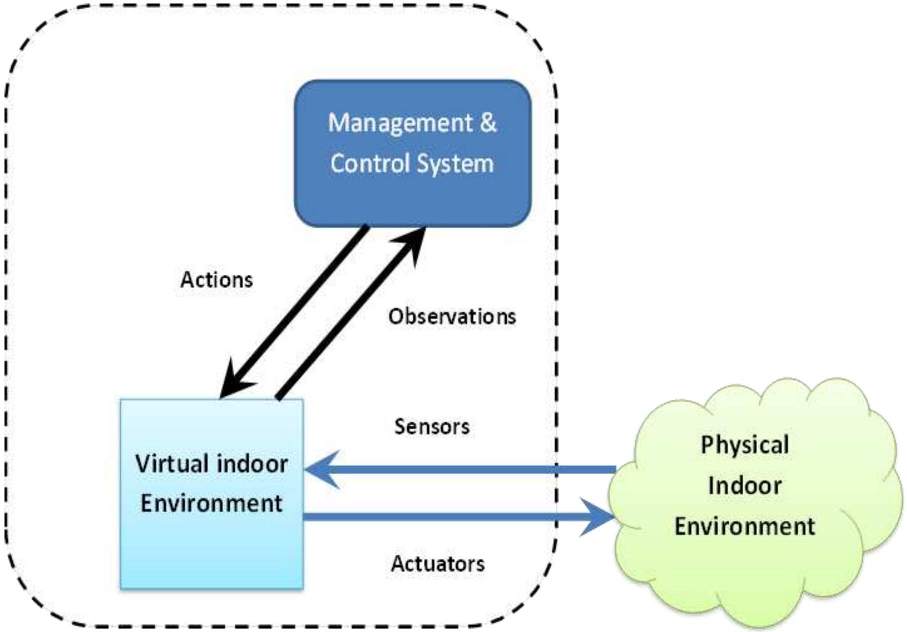

Figure Schematic diagram of symbiotic simulation –based control for indoor environment

Simulation based decision support & Control

Published works

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BUILD SIMUL (2015) 8: 405–414
DOI 10.1007/s12273-015-0232-9

Real-time flow simulation of indoor environments using lattice Boltzmann method

M. Amirul Islam Khan[1] (✉), Nicolas Delbosc[2], Catherine J. Noakes[1], Jonathan Summers[2]

1. School of Civil Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK
2. School of Mechanical Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK

ELSEVIER
Computers & Mathematics with Applications
Volume 67, Issue 2, February 2014, Pages 462-475

Optimized implementation of the Lattice Boltzmann Method on a graphics processing unit towards real-time fluid simulation

N. Delbosc [a], J.L. Summers [a], A.I. Khan [b], N. Kapur [a], C.J. Noakes [b]

Building and Environment 125 (2017) 273–284
Contents lists available at ScienceDirect
Building and Environment
journal homepage: www.elsevier.com/locate/buildenv

Modelling urban airflow and natural ventilation using a GPU-based lattice-Boltzmann method

Marco-Felipe King [a, *], Amirul Khan [a], Nicolas Delbosc [b], Hannah L. Gough [c], Christos Halios [c], Janet F. Barlow [c], Catherine J. Noakes [a]

[a] Institute for Public Health and Environmental Engineering, University of Leeds, Leeds, UK
[b] School of Mechanical Engineering, University of Leeds, Leeds, UK
[c] Department of Meteorology, University of Reading, Reading, UK

Ongoing work

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- Implement more accurate boundary conditions
- Implement Multiple relaxation model, hence more stable simulation even at higher Re with less lattice resolution
- Non-uniform lattice and curved boundaries
- Moving object with Immersed Boundary
- Multi-GPU implementation
- Coupling with DEM

Acknowledgements

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Thank You