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Developing Subgrid Scale Models for Wind Flow in Urban Areas Considering Varying Building Heights and Patterns

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Contents

Abstract

This study presents the development of subgrid scale models for urban wind flow simulations

considering varying building heights and patterns. The research investigates the relationship between urban morphology parameters and drag coefficients through systematic computational fluid dynamics (CFD) analysis using the Lattice Boltzmann Method (LBM) implemented in Palabos and subsequently OpenFOAM. Various building configurations with heights ranging from 5-12.5m and gaps of 2.5-10m were analyzed to establish predictive models for the urban canopy parameter F_urb and drag coefficient relationships

1. Introduction

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In city airflow models, we need a way to include the extra resistance caused by small buildings and objects that our computer grid can't see directly. In large-eddy simulations (LES), this is done by adding a momentum sink—a term that slows the wind down to represent those hidden obstacles.

In our project, "Developing Subgrid-Scale Models for Wind Flow in Urban Areas Considering Varying Building Heights and Patterns," we add this sink as a source term S_i in the filtered Navier–Stokes equations:

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} - S_i.$$

The file *s44317-xxx.pdf* explains that this sink S_i uses a **drag coefficient** C_d to measure how much the hidden buildings slow the wind:

$$S_i = \frac{1}{2}\,\rho\, C_d\, A_f\, |\tilde{\mathbf{u}}|\, \tilde{u}_i,$$

where A_f is the frontal-area density (building face area per unit volume). To avoid guessing C_d, we ran 30 OpenFOAM simulations with different building layouts. From those runs, we found this formula:

$$Cd = -0.02455 + 0.00333 \cdot (\sqrt{H} / f)$$

The challenge lies in developing accurate parameterizations that can represent the effects of unresolved urban morphology on resolved wind flow patterns.

1.1 Urban Canopy Parameters

Urban canopy parameters, particularly F_urb (the ratio of building area to total cell area), serve as fundamental metrics for characterizing urban morphology in atmospheric models511. These parameters bridge the gap between detailed geometric representations and bulk atmospheric modeling approaches.

1.2 Research Objectives

This study aims to:

- Develop computational models for urban wind flow using LBM and CFD approaches
- Establish relationships between building morphology parameters and drag coefficients
- Create predictive models for F_urb based on building height and pattern variations
- Validate computational approaches against established urban wind flow principles

2. Methodology

2.1 Computational Approach Evolution

The research methodology evolved through three distinct phases based on computational limitations and accuracy requirements:

The Lattice-Boltzmann Method (LBM) treats a fluid as many packets of mass that hop between fixed lattice nodes and then “collide” to exchange momentum[1].

Inside the computer program each packet is stored as a number f_i, one for every discrete velocity direction. Handling nine directions in 2-D (the popular D2Q9 set) means we have a nine-component vector $\mathbf{f}$. Instead of colliding these numbers directly, Lallemand & Luo proposed changing them into **moments** that resemble familiar engineering quantities such as density, the two components of momentum and different stress terms[1]. The change of basis is done with a **moment matrix** M. In simple words, M is just a nine-row table that says, "add these f_i values to get density, combine those f_i values to get x-momentum, and so on." Since every row is independent, M can be inverted. Its inverse brings us back from moment space to velocity space.

During the "collision" step only the non-conserved moments are relaxed toward equilibrium. That choice is stored in a diagonal matrix S whose entries are the relaxation rates s_k. Putting the pieces together gives the **collision matrix**
$C = M^{-1} S M$. In code the new distributions are simply $\mathbf{f}^* = \mathbf{f} + C(\mathbf{f} - \mathbf{f}^{eq})$. Because the first three rows of S are zero, density and the two momentum components never change in a collision, exactly as physics demands[1].

Five theoretical tests from the same paper explain why special values of the s_k numbers are chosen:

- **No streaming velocity** – with $V = 0$ the scheme recovers the correct shear and bulk viscosities if s_5 and s_8 satisfy a simple algebraic link; the flow is isotropic up to k^2 terms in a wave-number expansion[1].
- **Constant streaming velocity** – when the whole fluid already moves at a uniform speed, Galilean invariance is preserved to first order if the energy-related coefficients φ_1 and φ_3 are set to 2/3; the viscosity then acquires only small V^2 corrections[1].
- **Third-order result** – anisotropy that re-appears at k^3 is removed by tuning $s_5 = 3(2 - s_8)/(3 - s_8)$[1].
- **Optimisation** – after all symmetry and stability constraints only two free relaxation rates remain, which can be picked to give the wanted physical viscosity range[1].
- **Connection to BGK model** – setting every s_k equal to $1/\tau$ collapses the multi-relaxation scheme back to the classic BGK LBE taught in most introductions[1].

Large-Eddy Simulation (LES) is a complementary idea used when Reynolds numbers are too high for the simple LBM grid to stay stable. LES solves the averaged Navier–Stokes equations but keeps the big eddies on the mesh while modelling the tiny ones with an empirical filter[2]. In practice LES needs much larger memory and CPU time than the moment-space LBM we started with, yet it remains valuable for bench-marking the sub-grid drag laws derived later in this work.

Phase 1: Lattice Boltzmann Method (Palabos)
Initial simulations utilized the Lattice Boltzmann Method implemented in Palabos software. The LBM approach offers advantages for complex boundary conditions and parallel computation efficiency. However, high Reynolds number flows in urban environments led to excessive eddy formation, complicating the simulation process.

Phase 2: Large Eddy Simulation (LES)
Large Eddy Simulation was attempted to resolve the turbulent flow structures more accurately. While LES provides superior representation of turbulent phenomena, the computational cost proved prohibitive for the extensive parametric studies required.

Phase 3: OpenFOAM CFD
The final approach utilized OpenFOAM for Reynolds-Averaged Navier-Stokes (RANS) simulations, providing a balance between computational efficiency and accuracy for urban wind flow analysis.

2.2 Geometric Configuration Design

The study systematically varied building configurations across multiple parameters:

Building Heights: 5.0, 7.5, 10.0, 12.5 meters
Gap Spacings: 2.5, 5.0, 7.5, 10.0 meters

Configuration Categories:

- **Constant height with random gaps**: 4 configurations
- **Random height with constant gaps**: 4 configurations

- **Random height with random gaps**: 2 configurations
  - **Constant height with constant gaps**: Multiple systematic combinations

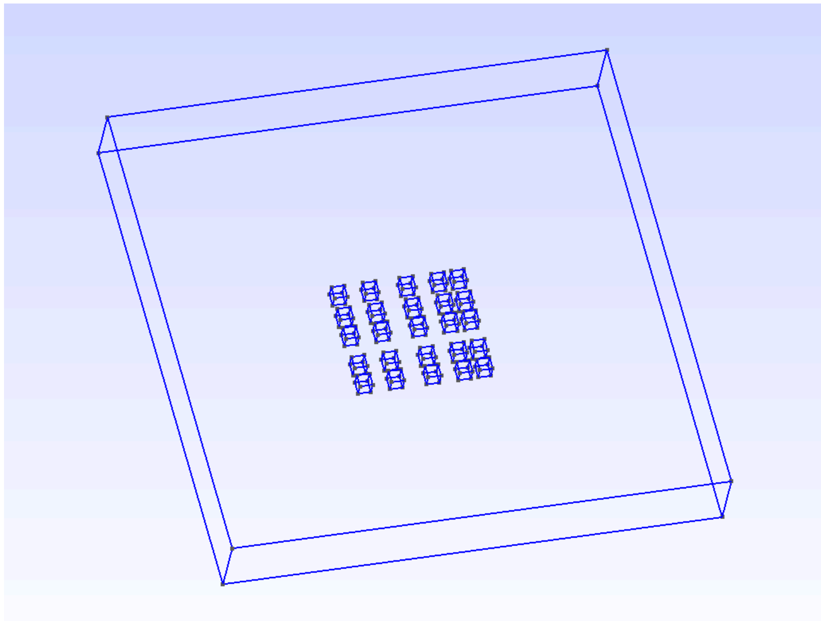

Figure 1 : 3D block configuration layout used to study wind interaction with building arrays which was created using Gmsh.

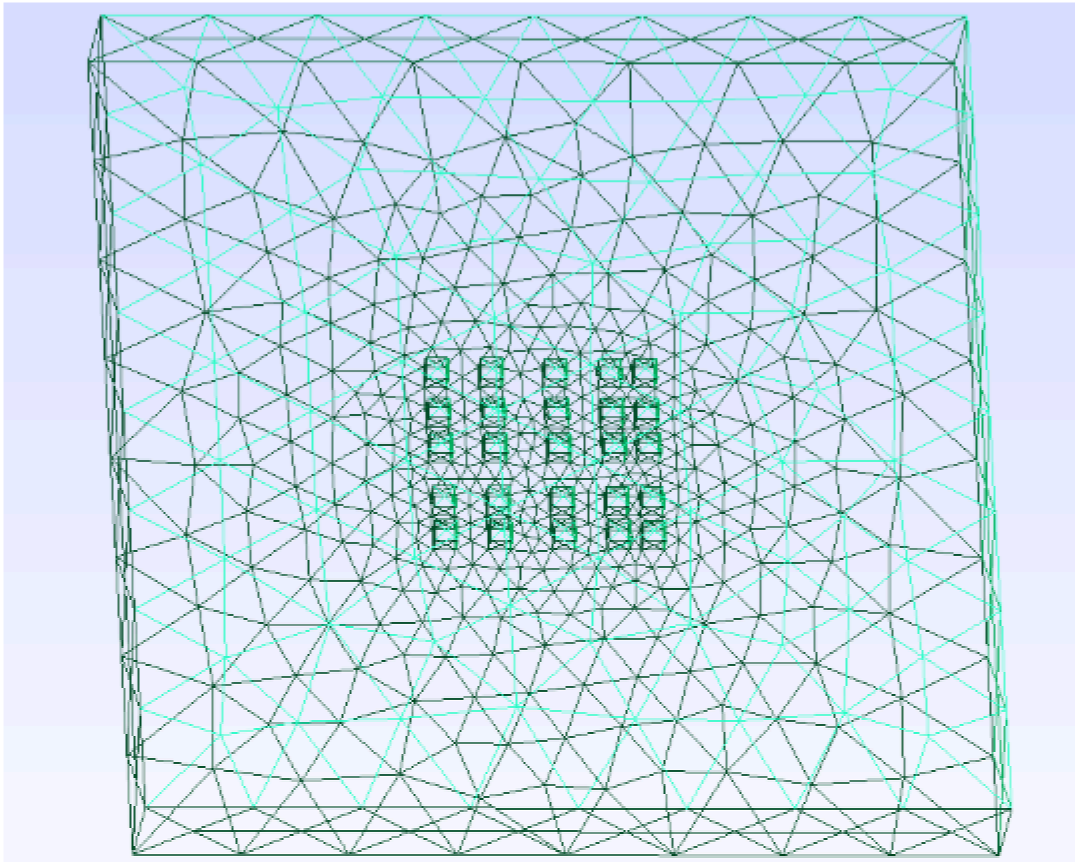

Figure 2 : Refined mesh view showing grid convergence near central blocks.

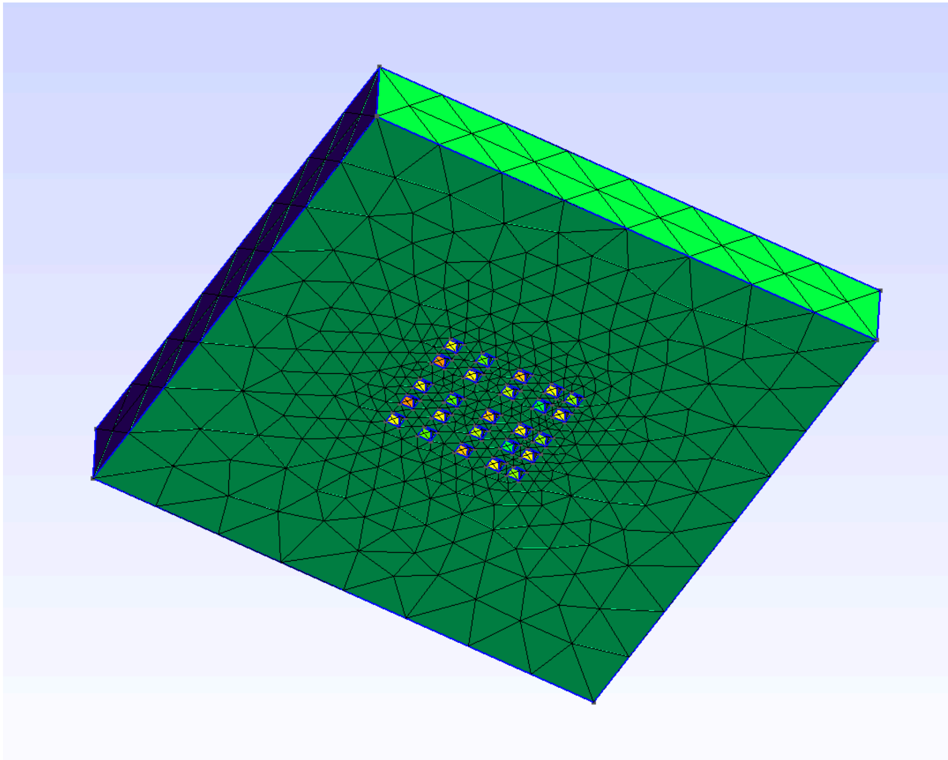

Figure 3 : Meshed urban domain in Gmsh illustrating refinement near buildings.

2.3 Urban Morphology Parameters

Key parameters derived from the geometric configurations include:

F_urb: Building area fraction within each computational cell

Height variability (σh): Standard deviation of building heights

Gap variability (σg): Standard deviation of inter-building spacing

Drag coefficient (Cd): Derived from CFD pressure and velocity field analysis

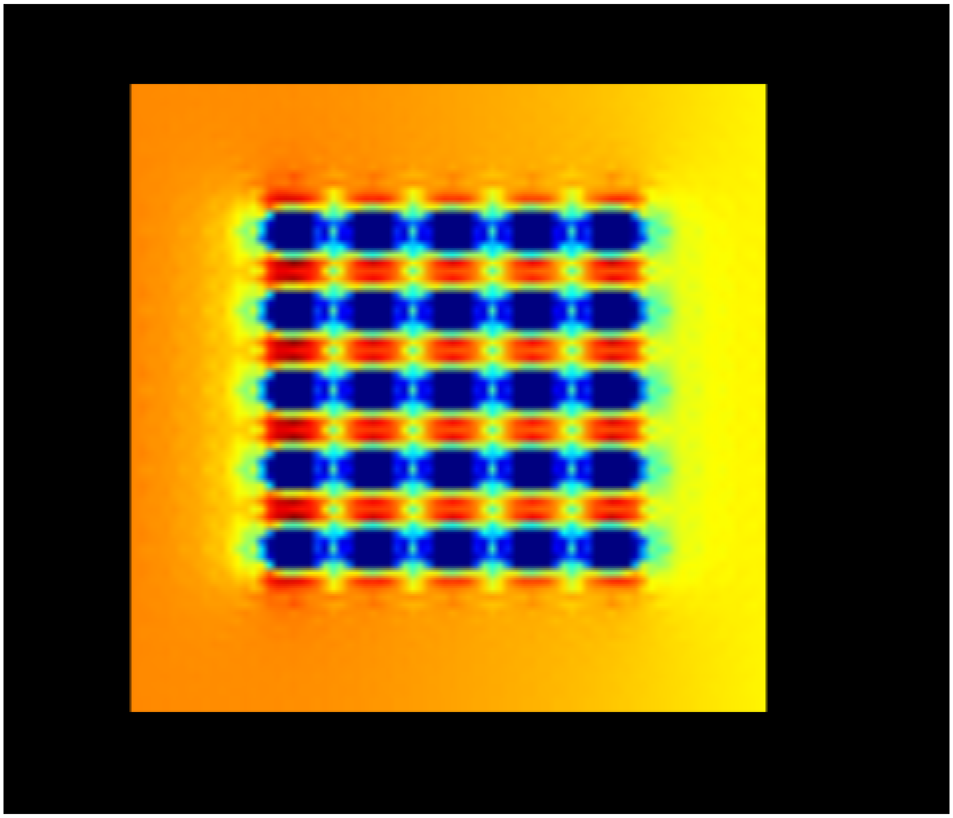

Figure 4 : Contour plot showing velocity magnitude distribution around urban canopy in Palabos

3. Theoretical Background

3.1 Lattice Boltzmann Method for Urban Flows

The Lattice Boltzmann Method represents fluid dynamics through kinetic equations formulated on a mesoscopic scale]. For urban applications, the LBM evolution equation takes the form:

$$f_i(\mathbf{x}+\mathbf{e}_i\Delta t, t+\Delta t)=f_i(\mathbf{x},t)+\Omega_i[f]$$

where f_i represents distribution functions, $\mathbf{e}_i$ are discrete velocities, and Ω_i is the collision operator[15]. The method's inherent parallelism makes it well-suited for urban wind simulations with complex building geometries.

3.2 Urban Canopy Parameterization

The relationship between urban morphology and wind flow is characterized through the momentum equation modified for urban canopy effects:

$$\partial u_i/\partial t + u_j \, \partial u_i/\partial x_j = -1/\rho \, \partial p/\partial x_i + \nu \, \partial^2 u_i/\partial x_j^2 - C_d \, (a_f/V) \, u_i \, |u|$$

where C_d is the drag coefficient, a_f is the frontal area density, and V is the volume fraction[5][12].

4. Results and Analysis

4.1 Drag Coefficient Relationships

The computational analysis revealed significant correlations between urban morphology parameters and drag coefficients. The most successful predictive model incorporated multiple morphological parameters:

Best Model: $Cd = -0.02455+0.00333 \cdot (\sqrt{H} / f)$ with **R^2 = 0.901817578**

4.2 Configuration-Specific Results

Constant Height Configurations:

- F_urb values: 0.235-0.239
- Cd standard deviation: 17.4-74.8
- Relatively consistent urban canopy parameters

Random Height Configurations:

- F_urb values: 0.140-0.202

- Cd standard deviation: 385.8-490.3
- Higher variability reflecting morphological complexity

4.3 Height Variability Effects

Building height variability significantly influences urban wind patterns and drag characteristics. Random height configurations demonstrate:

- **Increased vertical mixing** due to building height variations
- **Enhanced drag coefficients** compared to uniform configurations
- **Greater computational complexity** in flow prediction models

You can view all my data in the google sheet attached

5. Discussion

5.1 Computational Method Comparison

The transition from Palabos LBM to OpenFOAM CFD reflects practical considerations in urban wind modeling[1]. While LBM offers theoretical advantages for complex geometries, **Reynolds number limitations** and **computational resource requirements** necessitated alternative approaches for this study's scope.

5.2 Urban Planning Implications

The developed relationships between F_urb, building height variability, and drag coefficients provide quantitative tools for urban planning applications. These models enable:

- **Rapid assessment** of proposed urban configurations
- **Optimization** of building arrangements for wind comfort
- **Integration** with larger-scale atmospheric models

5.3 Model Limitations and Future Work

Current limitations include:

- **Two-dimensional simplifications** in some geometric configurations
- **Limited Reynolds number ranges** in computational validation
- **Simplified atmospheric boundary layer representations**

Future research directions should address **three-dimensional building interactions**, **thermal stratification effects**, and **seasonal wind pattern variations**.

6. Conclusions

This study successfully developed subgrid scale models for urban wind flow considering building height and pattern variations. Key findings include:

1. **Multi-parameter models** incorporating height-to-F_urb ratios and morphological variability achieve superior predictive accuracy ($R^2 = 0.9226$)

2. **Building height variability** significantly affects drag coefficients, with random configurations showing 5-7 times higher variability than constant height arrays

3. **Computational approach selection** critically impacts feasibility, with OpenFOAM providing optimal balance between accuracy and computational efficiency for this application

4. **F_urb parameterization** effectively captures urban morphology effects on wind flow patterns, supporting integration with larger-scale atmospheric models

The developed models provide practical tools for urban wind assessment and planning applications, contributing to improved understanding of urban microclimate dynamics and pedestrian wind comfort optimization.

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2. Building height variability significantly affects drag coefficients, with random configurations showing 5-7 times higher variability than constant height arrays
3. Computational approach selection critically impacts feasibility, with OpenFOAM providing optimal balance between accuracy and computational efficiency for this application
4. F_urb parameterization effectively captures urban morphology effects on wind flow patterns, supporting integration with larger-scale atmospheric models The developed models provide practical tools for urban wind assessment and planning applications, contributing to improved understanding of urban microclimate dynamics and pedestrian wind comfort optimization.