A hybrid approach for the numerical simulation of flows in urban environment

Bence Hermann and Miklós Balogh

Budapest University of Technology and Economics

Dept. of Fluid Mechanics
Budapest University of Technology and Economics

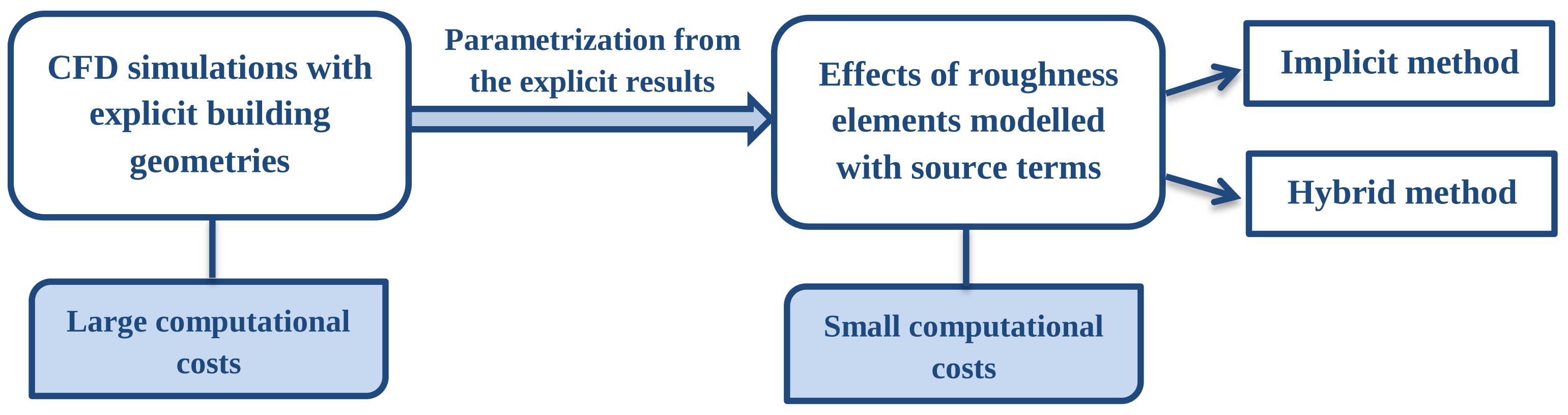
Abstract

Observing the nature of the air flows in urban environment is essential in the understanding of processes which have influence on urban climate and air quality. Numerical simulation is one way to achieve this. However, CFD simulations of atmospheric flows in these environments require huge amounts of computational capacity if the whole geometry is fully detailed. There are techniques to reduce this requirement, while still producing acceptable results. One of these is the hybrid method, which uses source terms in the transport equations to model the effects of the buildings implicitly. The geometry is explicitly modelled only around the target area of analysis. This method can drastically reduce the cell number, resulting in a much faster numerical simulation. The aim of this study is to create an OpenFOAM solver which is capable of handling this porosity drag force approach. The parameters of the source terms are calculated by performing a series of CFD calculations with different cuboid-shaped buildings using cyclic boundary conditions. A local drag coefficient can be obtained for each cell level between the ground and the top of the building, for each building geometry. This is the main parameter of the source terms. The final goal was to implement the hybrid model in OpenFOAM with the parametrized implicit approach, and it is compared to the results of explicit CFD simulations.

Key words: *porous drag-force approach, parametrization, RANS, OpenFOAM, height dependent drag coefficient*

Introduction

In this study the parametrization of an OpenFOAM RANS CFD solver is performed which is capable of utilizing the so-called hybrid method in the simulation of flows in urban environment. ”Hybrid” means that the effects of the buildings can be taken into account either explicitly by resolving the geometry, or implicitly by using source terms in the transport equations, depending on the region. The parametrization is performed based on the results of numerous CFD simulations with explicitly modelled building geometries.



CFD simulations with explicit building geometries

Parametrization from the explicit results

Effects of roughness elements modelled with source terms

Implicit method

Hybrid method

Large computational costs

Small computational costs

Figure 1: Role of explicit and implicit modelling methods in this study

Numerical simulations with explicit geometries

A series of RANS simulations were performed to parametrize the porous drag force approach. In each case the vertical distribution of the field variables around a surface-mounted cuboid was examined, which models one building of an infinite building array as seen on Figure 2. The cuboids were described using the building density $\lambda = \frac{L_{dx}L_{dy}}{L_xL_y}$ and building height H parameters.

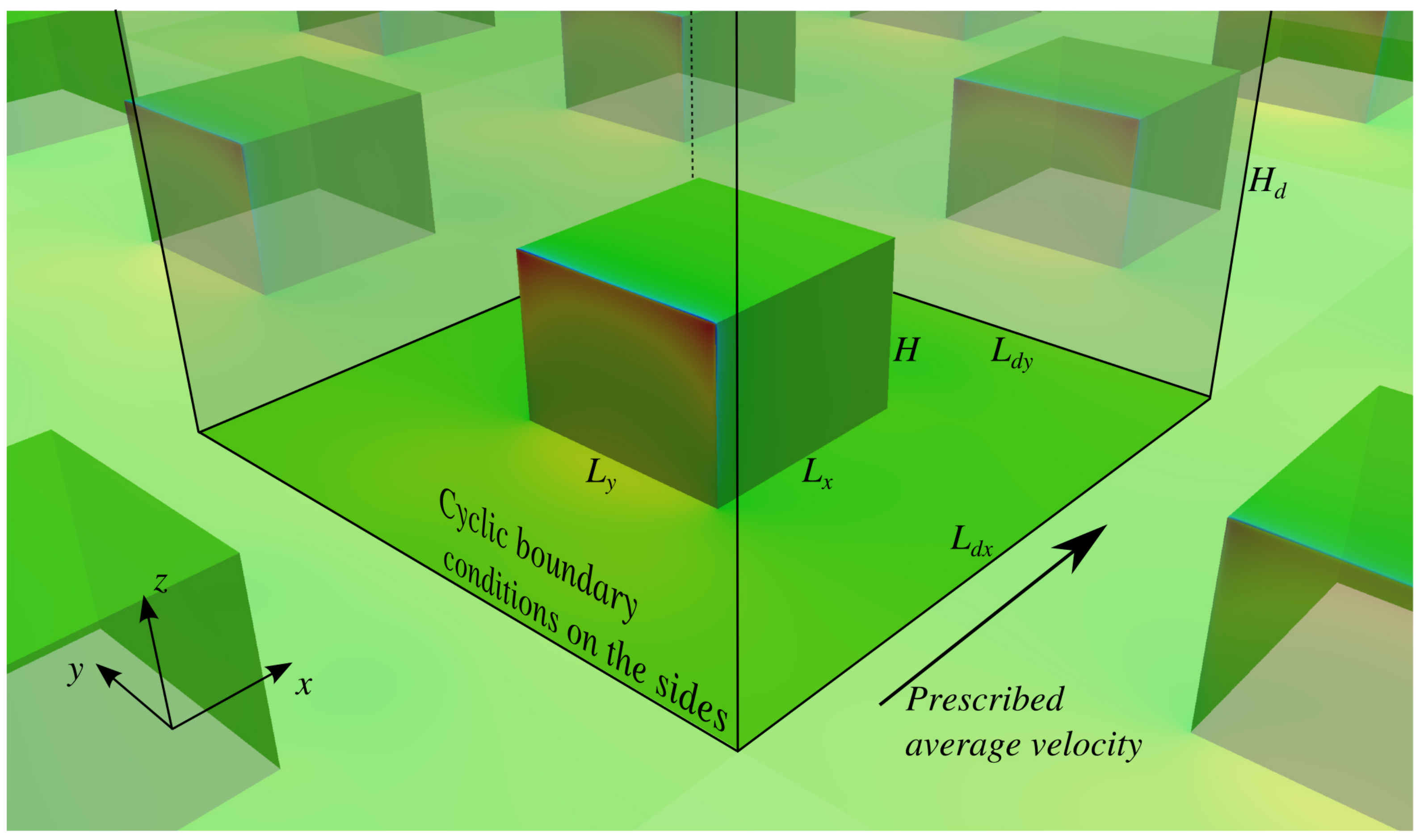


Figure 2: Geometrical model and boundary conditions

Properties for the CFD simulations:

- Incompressible, steady state flow
- Modified $k-\varepsilon$ turbulence model and rough wall functions proposed by Balogh (2014)
- Field variables initialized by averaging the profiles by Richards and Hoxey (1993)
- Explicit pressure gradient source term to keep the initial average velocity constant

Parametrization of the distributed drag force approach

The vertical distribution of the field variables was extracted from the results, which depended on λ and H aside from the vertical ground distance. Analytical expressions were fit to the obtained curves in two steps (see Figure 3). An individual profile was fit in each case for the different λ-H pairs, then the λ and H dependence of the profile's parameters was described with a second-order surface fitting method. The velocity, k and ε profiles were the following:

$$U(\widetilde{z}) = \begin{cases} A_{U1} \cdot tan\left(A_{U2}(\widetilde{z} - A_{U3})\right) + A_{U4} + A_{U5}\widetilde{z} = U_1(\widetilde{z}) & \text{if } \widetilde{z} = \frac{z}{H} < 1 \\ U_1(1) + A_{U6} \cdot ln(\widetilde{z}) = U_2(\widetilde{z}) & \text{elsewhere.} \end{cases} \tag{1}$$

A blending function was introduced to ensure the continuity of the derivative of $U(\widetilde{z})$:

$$U(\widetilde{z}) = (1 - f_b(\widetilde{z}))\,U_1(\widetilde{z}) + f_b(\widetilde{z})U_2(\widetilde{z}) \qquad \textit{where:} \qquad f_b = \frac{tanh(B(\widetilde{z}-1)) + 1}{2} \tag{2}$$

$$k(\widetilde{z}) = A_{k1}e^{-A_{k2}(\widetilde{z}-1)} - A_{k3}e^{A_{k4}(-\widetilde{z}-A_{k5})} \tag{3}$$

$$\varepsilon(\widetilde{z}) = (1 - f_b(\widetilde{z}))\left(\frac{A_{\varepsilon1}}{\widetilde{z}} - \frac{A_{\varepsilon2}}{\widetilde{z}-1} + A_{\varepsilon3}\widetilde{z} + A_{\varepsilon4}\right) + f_b(\widetilde{z})\left(\frac{A_{\varepsilon5}}{\widetilde{z} - A_{\varepsilon6}}\right) \tag{4}$$

The two-step surface fitting method for the A_{fvj} parameters:

$$A_{fvj} = A_{\lambda1}\lambda^2 + A_{\lambda2}\lambda + A_{\lambda3} \tag{5}$$

$$A_{\lambda i} = A_{H1}H^2 + A_{H2}H + A_{H3} \tag{6}$$

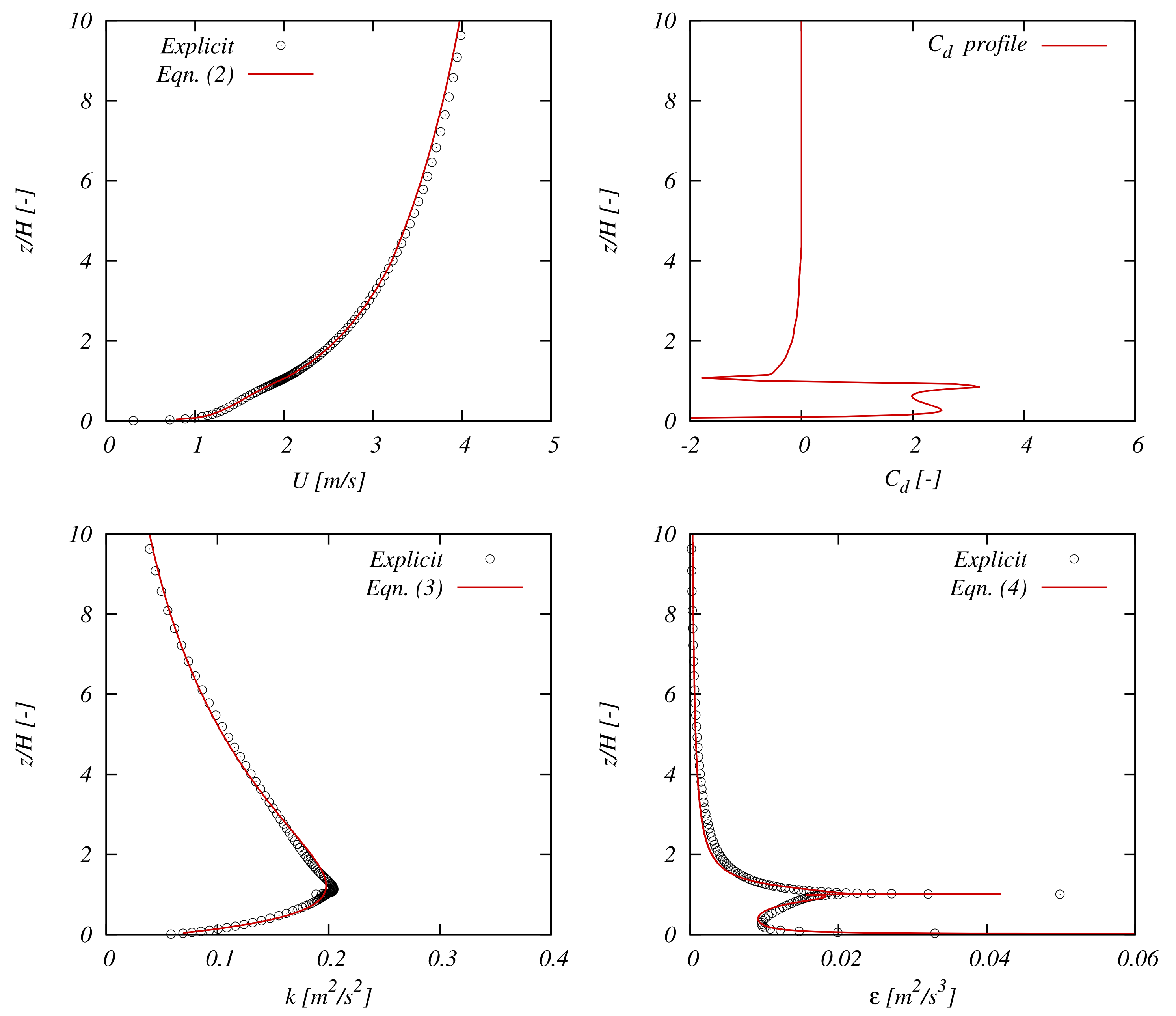
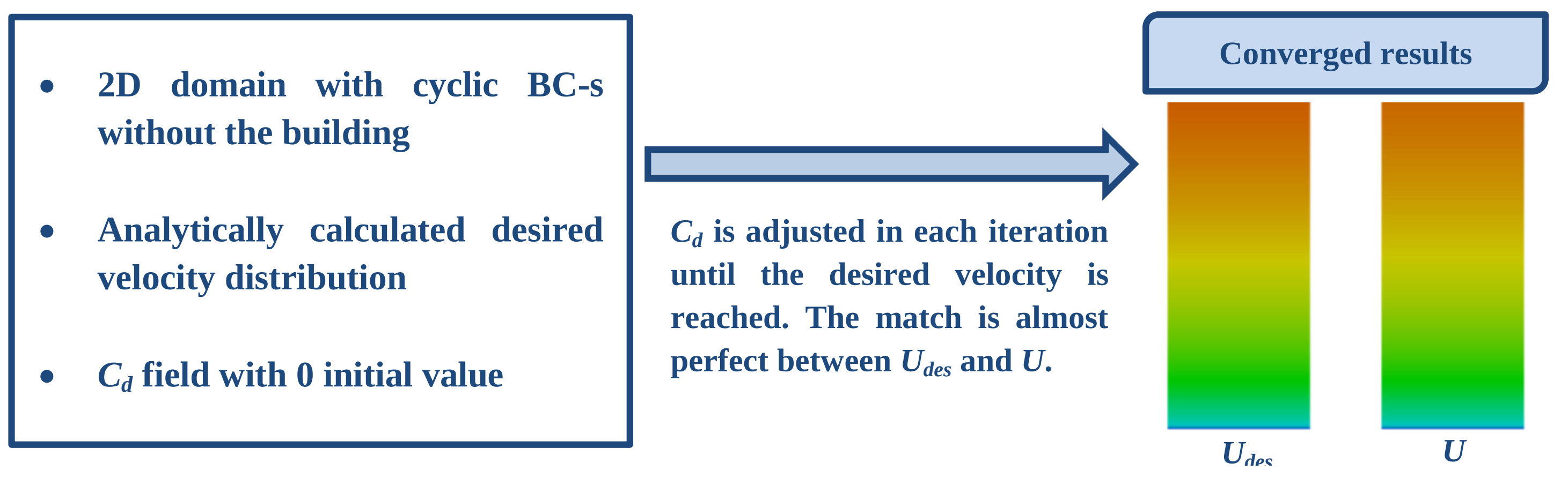


Figure 3: Field variable profiles

The source term below was added into the momentum equation to implement the building resistance implicitly into the new solver, where the vertical distribution of the sectional drag coefficient was obtained by an OpenFOAM solver written for this purpose as seen on Figure 4.

$$S_i(z) = \frac{1}{2}\rho C_d(z)A_fUu_i \tag{7}$$



- **2D domain with cyclic BC-s without the building**
- **Analytically calculated desired velocity distribution**
- ***C***

C_d is adjusted in each iteration until the desired velocity is reached. The match is almost perfect between U_{des} and U.

Converged results

Figure 4: Calculation method for the sectional drag coefficient

Conclusions

- An OpenFOAM solver capable of handling both explicit and implicit regions is developed
- Parametrization was based on the results of explicit CFD simulations
- Viable for numerous urban atmospheric CFD problems, e.g. calculating the forces acting on a certain building, pollutant dispersion in urban areas or planning of the location of wind turbines
- Varying building side ratios and flow directions will also be investigated
- Source terms will be implemented into the $k-\varepsilon$ equations to ensure good matching between the turbulence quantities, and validation will be performed against the MUST experimental data

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