Final report

OTKA K 108936 “Flow and dispersion phenomena in urban environment”

1. SUMMARY

This multi-faceted project allowed our research group to improve both experimental and numerical methods for flow and dispersion modelling, mainly in urban areas. The results will be utilized in part directly (e.g. as a new dispersion model in the Hungarian emergency response system) or will serve the common good indirectly (e.g. better modelling tools will improve the quality of the environmental assessment of urban building projects).

Altogether, nine journal papers have been published (total IF: approx. 12.26), four PhD theses were successfully defended, each of them connected in part to the research plan of this project.

This report’s numbering follows the structure of the original research plan.

2.1 DEVELOPMENT OF MODELLING METHODS

2.1.1 Development of a boundary layer wind tunnel technique

As described in earlier progress reports, the refurbishment and upgrade of the Boundary Layer Wind tunnel (BLWT) was put on hold due to the difficulties to realize a closed laboratory necessary for the refurbishment. Despite our original expectations, applicable (non-OTKA) research grants to build the laboratory opened only in early 2016. Because of this, we moved the scientific work to our existing in-door wind tunnels. Spending on the BLWT was halted as well.

A proper time-resolved tracer concentration measurement equipment (Cambustion HFR 400) was purchased and used in the large horizontal Goettingen type wind tunnel for dispersion tests. (Subproject 2.2.2.)

During the last year of the project, we prepared the preliminary design of a new laboratory + wind tunnel. The new wind tunnel will be sufficiently large to model boundary layer flows on the scale of approximately 1:200. After studying a wide range of options and several foreign wind tunnels [1] an open-circuit suction type arrangement has been chosen (**Fig. 1**). The VEKOP 2.3.3-15 proposal for the new laboratory entitled “Establishment of an Atmospheric Flow Laboratory” gained NKFI approval and was recently filed for decision.

Figure 1. The new BLWT’s preliminary design.

2.1.2. Further improvement and validation of the drag-force approach in urban flow and dispersion models

Atmospheric flow simulations in engineering practice – such as simulations of pollutant dispersion, wind load on buildings, wind climate of urban areas – are fairly sensitive to the inlet boundary conditions. Before the implementation of the porous drag force approach, the OpenFOAM CFD toolbox had to be prepared for the simulation of atmospheric flows. Accordingly, the first objective of the work was to introduce suitable profiles for velocity and turbulent quantities, which do not only fit the measured vertical distributions, but also guarantee the overall consistency of the turbulence model. If the latter aspect is not verified, the inlet profiles deteriorate rapidly within the computational domain, leading to unrealistic wind profiles in the area of interest. Considering that, in general, the atmospheric boundary layer profiles might not satisfy the equations describing an unperturbed atmospheric boundary layer, turbulence models need to be corrected to guarantee the overall consistency of the approach. Former studies have addressed such a problem via the introduction of source terms in the transport equations of kinetic energy and turbulent dissipation rate, to guarantee consistency between the turbulence model and inlet profiles. In the present research, the formulation is further extended to improve the numerical stability of the approach as well as the realistic character of the produced profiles. This work was presented in the CWE2014 conference [2, 3] and it was published in the Journal of Wind Engineering and Industrial Aerodynamics [4].

The porosity drag force approach and a novel scale adaptive hybrid method are validated against up-scaled wind-tunnel measurements. The substance of the novel method is that the porous drag force approach is applied in the marginal regions for simulate the effects of the buildings and the vegetation, while the geometry of building blocks, or even some selected buildings can be considered explicitly via mesh refinement in the regions, where the flow features are important in the analysis point of view. A special meshing procedure is developed, which allows the separation of the regions with different surface coverage, furthermore provide continuous transition between the coarser mesh applied in marginal regions and the finest applied in the target area of the analysis. The local velocity results of the hybrid and explicit method is similar in the target area, however, the hybrid approach requires much less computational resources, namely one in five. The results are presented and discussed in a PhD thesis [5].

Implementation of the non-hydrostatic boundary layer model in OpenFOAM:

a) Parametrization for stable, neutral and unstable temperature stratification
b) Implementation of the non-hydrostatic boundary layer model (URANS, SAS)
c) Adjustment of the porous model

Tasks a) and b) were much easier to accomplish as originally expected. With regard to task a), a new solver was made available to the scientific community in the meantime, which made a customized parametrization unnecessary, and regarding b), existing turbulence models can be used with the named solver. Hence our work focussed on c).

The hybrid approach is further developed in order to complete the parametrization scheme, namely to derive closed form expressions for the vertical distributions of the model parameters, in the parameter space of the typical suburban regions. For this purpose, a series of CFD simulations were performed with explicitly resolved buildings with high resolution, which served as the basis of the parametrization scheme by providing the results which should be replicated by the implicit part of the hybrid approach. In the simulations, the rectangular computational domain contained only one square prism-shaped building with cyclic (periodic) boundary conditions on all four domain sides, which models an infinite building array inside the atmospheric boundary layer with the buildings located in a square configuration (see Figure 1). Based on the obtained data set, the parameters of the required source terms are determined as a function of the built-up density and the specific roof height of the suburban areas, using various optimization techniques. The resulted model is implemented in the openFoam CFD toolbox as a new solver extended with the corresponding turbulence model. The software is verified against the results obtained by explicit flow simulations at high resolution, and it is validated against measurements. This study is presented in the HARMO17 conference [6].

Validation of a bulk microphysical model of moisture transport into a pressure based CFD solver

While not mentioned originally in original research plan, the development of CFD modelling methods was extended on the integration and validation of a bulk microphysical model of moisture transport into a pressure based CFD solver, itself developed originally in OTKA T049573 (2007-2009) by Dr. Gergely Kristóf. This activity resulted in a journal paper and contributed to a successful PhD defense [7, 8].

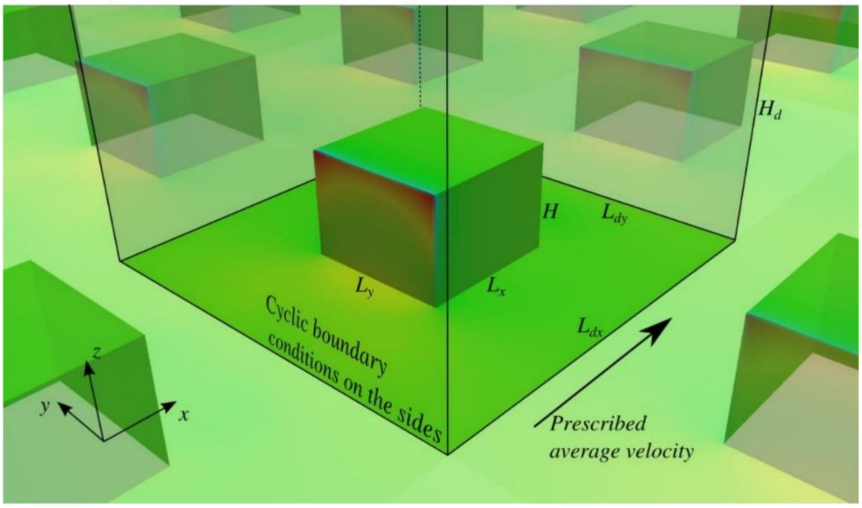

Figure 2. Schematic of the geometrical setup for the series of numerical simulations.

2.1.3. Numerical sensitivity evaluation and uncertainty estimation of obstacle resolving urban flow and dispersion models with the OpenFOAM open source CFD code and a wind tunnel validation test case Michelstadt

Anikó Rákai successfully finished and defended her PhD thesis, the second part of which included the results of the 1st year of this OTKA project [9].

2.2. STUDY ON WIND CONDITIONS AND DISPERSION AROUND URBAN BUILDING ARRANGEMENTS

2.2.1 Wind tunnel measurement of hazardous gas contaminant dispersion in semi-idealized urban settings

Ms Berbekár, spent some months at Hamburg University during her PhD studies at BME, working for the success of the COST Action ES1006 as well, and performing wind tunnel tests in the so called Michelstadt urban setup, and generating data sets for the validation of dispersion models. She successfully published several conference papers and a journal paper [10] with her supervisors in Germany, while being a PhD student at BME until her leave end of 2014.

2.2.2. Investigation of the pollutant dispersion around high-rise buildings

Measurement of far-field effects of building cluster wakes and analysis of the role of a single tall building was performed in our large Göttingen-type wind tunnel using the model of simple 2D street canyons. Velocity measurements were performed using a 2D hotwire system and results published in an international conference [11]. While preliminary conclusions can be drawn on the far field effect of a single tall building, further work would be necessary.

2.2.3 Influence of urban squares on ventilation and air quality

The wind tunnel measurements and CFD simulations addressing the flow and dispersion phenomena at urban squares performed by Mr Balczó resulted in a successful PhD defense. The importance, advantages and specifics of urban squares from the ventilation and air quality point of view is discussed in the thesis [12] and in papers [13]. Most importantly, flow structures on typical urban squares have been identified and summarized (**Fig. 3**).

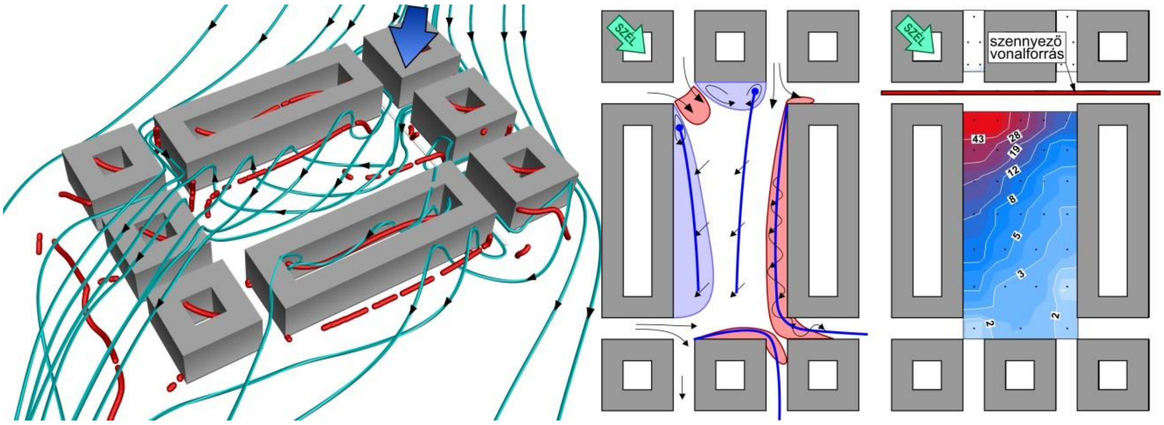

Figure 3. 3D flow features in an urban square at slanted flow direction (thick red lines: vortex cores), b: flow schematics of the square, light blue low speed zone, red: high speed zones thick blue lines: vortex cores. c) pollutant dispersion field in the square.

2.2.4. Measurement and quantification of near-field and far-field effects of building clusters on ventilation and air quality

An effective method has been developed for finding optimum building patterns via CFD modelling. In these models the urban canopy is approximated by an infinite 2D lattice of a given elementary building pattern, which also incorporates pollution sources. The surface mass transfer coefficients are computed for various wind directions and the non-dimensional form of the average value is used for characterizing ventilation intensity. The model does not require input data for boundary conditions, therefore the resulting ventilation intensity depends only on the geometrical configuration. Resultant velocity and turbulence profiles are found to be in close agreement with earlier models and wind tunnel measurements. The methodology of optimization is demonstrated on simple geometrical configurations and further results are shown for a more complex building arrangement characteristic of Central Europe. The research results are published in an international journal [14].

A co-operative investigation has been carried out with Eötvös Lóránd University for detecting new particle formation (NPF) events in urban area. The partner institution operates an on-line measuring system for monitoring the size distribution of particulate matter in the urban atmosphere. The diagnostic method is capable of detecting nucleation events. The research is aimed at the identification of the causes of nucleation on the bases of the comprehensive observation of the phenomenon. Our research team contributed by analyzing the near-field flow and dispersion process that way tracing back the "height of origin" of diagnostic samples in different wind conditions. The research results are published in a highly referenced international journal [15].

2.2.5 Input and output requirements, performance evaluation of emergency response tools for airborne hazard modelling

Our group members Ms. Berbekár and Ms. Rákai played an active role during the whole **COST ES1006 Action**, participating many of the meetings and performing CFD simulations and measurements for the Action.

The emergency response tool investigated is the Hungarian operational emergency-response tool used by our country's disaster management authorities. The otherwise sophisticated tool applies a very simple Gaussian dispersion model for industrial accidents.

After literature survey, a number of public mesoscale dispersion measurement data bases were processed. The data sets are converted into a comparable non-dimensional form. The point concentration statistics obeyed gamma distributions in every point. The spatial dependence of the mean value and the variance of the point concentration statistics were modelled by using maximum likelihood fits of phenomenologically parametrized 2D regression surfaces. The resulting statistical model can be used for predicting those dangerous areas around near ground sources in which the local concentration exceeds a given value with a given probability, provided that the time averages of source intensity, wind intensity, and wind direction are known. Comparisons with the results of the classical Gaussian model reviled that the classical approach is not conservative, because of grossly under predicting the lateral dispersion. The publication of the novel statistical model is in progress.

Literature

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