FLOW AND DISPERSAL SIMULATIONS OF THE MOCK URBAN SETTING TEST

Joachim Eichhorn[1] and Márton Balczó[2]

[1]Johannes Gutenberg University, Mainz, Germany
[2]Budapest University of Technology and Economics, Budapest, Hungary

Abstract: An improved version of the microscale flow model MISKAM (Eichhorn and Kniffka, 2007) has been used to simulate three-dimensional wind and turbulence fields for the Mock Urban Setting Test (MUST). The model has been evaluated following the procedures defined in the German guideline for obstacle resolving microscale models.
In an earlier study in the framework of COST Action 732 (Goricsán et al., 2007) version 5.01 of MISKAM has already been used to compute flow fields for the MUST set-up. Some deviations between computed and observed wind profiles of the vertical velocity component had been found in the wake of the obstacles. The current study addresses the question whether or not recent improvements of the code will also lead to an improved model performance as far as the MUST case is concerned. MISKAM 6 (3rd beta version) now uses refined advection schemes for the transport of momentum and turbulence quantities, both formerly solved by a simple upstream scheme.
Preceding the discussion of flow simulations for the MUST set-up, a short summary of the evaluation results according to the German guideline will be given. The last part of the study introduces results of dispersal simulations and comparisons to the MUST wind tunnel data sets. The simulations have been carried out either using the upstream algorithm or the MPDATA scheme with up to 2 corrective steps to reduce numerical diffusion.

Key words: *MISKAM, numerical modelling, advection schemes, dispersal simulation, MUST.*

1. INTRODUCTION

During the past few years, the numerical flow and dispersal model MISKAM[1] has gained a high level of acceptance by environmental agencies, consulting engineers and meteorologists as well as research institutes. Mainly due to the code being compact and fast, allowing MISKAM to be run on standard personal computers, the model has proved its applicability to problems in urban planning by various independent institutions.

Since the PC version of MISKAM originates in the 90s, in parts the model code has still been accounting for resource limitations of former personal computers, e.g. expensive memory and slow processors. One result of these limitations was the adoption of upstream advection schemes for both momentum and scalars like turbulence kinetic energy. The upstream scheme is known to be stable and fast but also to suffer from severe numerical diffusion. Therefore, a logical step forward in the development of MISKAM was the implementation of refined advection schemes.

In a previous paper (Eichhorn and Kniffka, 2007) the 2nd beta version of MISKAM 6 has been evaluated according to VDI guideline 3783/9 (VDI, 2005) distinctly designated for the evaluation of microscale flow models. Some minor bug fixes have been applied since then. Therefore, a summary of the latest evaluation results will be given in section 3 of the current study.

2. THE MODEL MISKAM

Basic Equations and Closure

MISKAM computes flow fields by solving the complete three-dimensional equations of motion, adopting the Boussinesq approximations to eliminate sound waves. The continuity equation is replaced by the non-divergence condition for the flow field, thus ensuring mass conservation. This simplification, however, requires the additional solution of an elliptic differential equation for pressure perturbations. To solve the prognostic system along with the diagnostic pressure equation the model uses the splitting method by Patrinos and Kistler (1977). Turbulence closure is carried out by a standard k-ε-model but replacing the production rates of turbulence kinetic energy and dissipation following suggestions of Kato and Launder (1993) and Lopez (2002).

Once a steady-state flow and turbulence field has been computed, the advection-diffusion equation for inert pollutants can be solved to obtain three-dimensional mass concentration distributions. Sources of different types (point, line, area sources) may be arbitrarily spread over the model domain. Sedimentation and dry deposition can be accounted for by specifying appropriate values for sedimentation and deposition velocities, respectively.

Numerical Methods

The model equations are solved numerically on a Cartesian grid of Arakawa-C type. While for the diffusion equations an ADI procedure is applied, MISKAM 6 introduces different approaches to handle the advection terms: Momentum advection is solved either by a simple upstream scheme or by the predictor-corrector method suggested by MacCormack (1969). For the advection of scalars (turbulence kinetic energy, turbulent dissipation, pollutants) the MPDATA algorithm (Smolarkiewicz and Grabowski, 1989) has been implemented. The number of corrective steps

---

1 German acronym for '**Mi**kro**sk**aliges Strömungs- und **A**usbreitungs**m**odell' (microscale flow and dispersal model)

to reduce numerical diffusion can be set to 0, which corresponds to uncorrected upstream differencing, 1 or 2. Two corrective steps are recommended for the simulation of pollutant dispersal emitted from point sources. For turbulence quantities, however, only one step is allowed to keep the computational requirements manageable.

A simple but robust red-black SOR scheme is used to solve the pressure equation. The time step is continuously adjusted to fulfil the CFL criterion.

3. EVALUATION ACCORDING TO VDI 3783/9

The evaluation procedure, consisting of a set of consistency checks as well as comparisons of model results and wind tunnel data for some basic test cases, has been described in detail by Eichhorn and Kniffka (2007) together with its results for the 2nd beta version of MISKAM 6. In the meantime, further corrections have been applied to the code, necessitating a repetition of the evaluation. Table 1 assorts the hit rates for the wind tunnel comparisons as obtained from the current 3rd beta version and, in brackets, for the previous version.

Surprisingly, the corrected model version does not give improved evaluation results for all cases. An inspection of the near field in some cases even shows a deterioration of the hit rate below the thresholds as required by the guideline. The reasons for this behaviour still have to be reinvestigated, but they are presumably to be found within the turbulence closure in grid cells adjacent to buildings.

Table 1. Evaluation of MISKAM 6 beta3; hit rates q for Cartesian wind components u, v and w for comparisons to wind tunnel data. See guideline (VDI, 2005) for a specification of test cases and Eichhorn and Kniffka (2007) for details. Values in brackets refer to MISKAM 6 beta 2.

Test case	c1	c3	c4	c5	c6
Obstacle type, flow direction	Beam, 270°	Cube, 270°	Cube, 225°	Cuboid, 270°	Array of Cuboids, 270°
D (allowed normalised deviation)	0.25	0.25	0.25	0.25	0.25
W (allowed absolute deviation)	0.06	0.06	0.07	0.10	0.10
$q_{required}$ (%)	66	66	66	66	66
q_u (%)	84 (86)	94 (94)	84 (84)	80 (77)	92 (92)
q_v (%)	./.	99 (98)	76 (76)	90 (90)	68 (68)
q_w (%)	93 (96)	95 (93)	80 (81)	88 (87)	81 (81)

4. SIMULATION RESULTS FOR THE MOCK URBAN SETTING TEST

A detailed numerical exercise based on the Mock Urban Setting Test (MUST) data set was performed by participants of the COST Action 732. The Mock Urban Setting Test was a full-scale measurement campaign on an arrangement of 40-feet containers in Utah as described by Yee and Biltoft, 2004. Wind tunnel tests of the same arrangement were carried out in Hamburg (Leitl et al., 2007). The numerical models compared in COST 732 also involved MISKAM 5.01 (Goricsán et al., 2007). In this study, simulations are repeated using MISKAM 6 beta3 on the same computational grid to see if model improvements described in the previous section contribute to better simulation results.

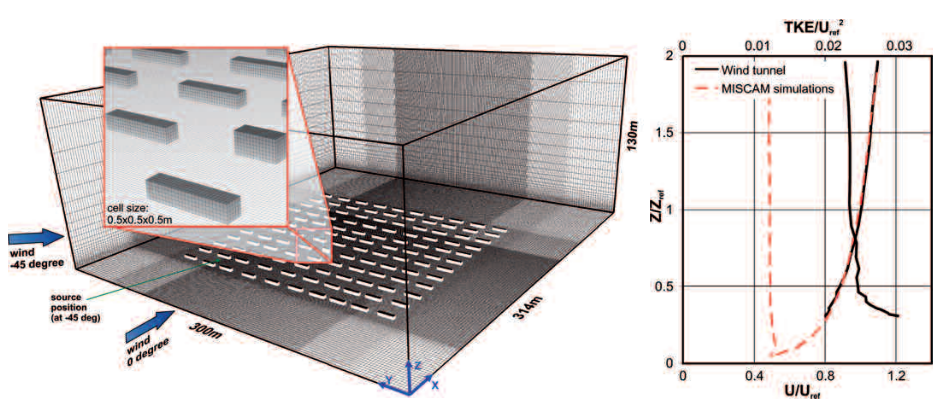

Figure 1. Computational domain and grid with wind directions (left); inlet boundary conditions used in the MUST case (right).

The computational domain and the grid are shown in Figure 1. Grid resolution of the full scale rectilinear grid was 0.5 m in each direction, resulting in 5 million grid cells in the whole domain. Flow fields were simulated using

McCormack scheme for momentum advection and MPDATA scheme for the advection of turbulence quantities at 0° and -45° wind direction. In the latter case also the dispersion from a ground source was calculated using either the simple upstream scheme or the MPDATA algorithm with two corrective steps. The logarithmic velocity inlet boundary condition agreed well with those measured in wind tunnel, but turbulent kinetic energy that is automatically generated by the model to the given roughness length of 0.01 m (wind tunnel profile: 0.017 m), was significantly lower than the measured one. Reference speed was 1 m/s at z_{ref} = 7.29 m. On the surfaces no-slip conditions, on the other boundaries no-flux conditions were applied as it is usual in MISKAM by default. The roughness length z_0 on the surface was set to 0.02 m.

Flow field at 0°

Flow field results of the simulation were compared to vertical profiles of the U and W velocity components. Position of the profiles can be seen in Figure 2. Note that most containers are 2.54 m high which corresponds to z/z_{ref} = 0.35.

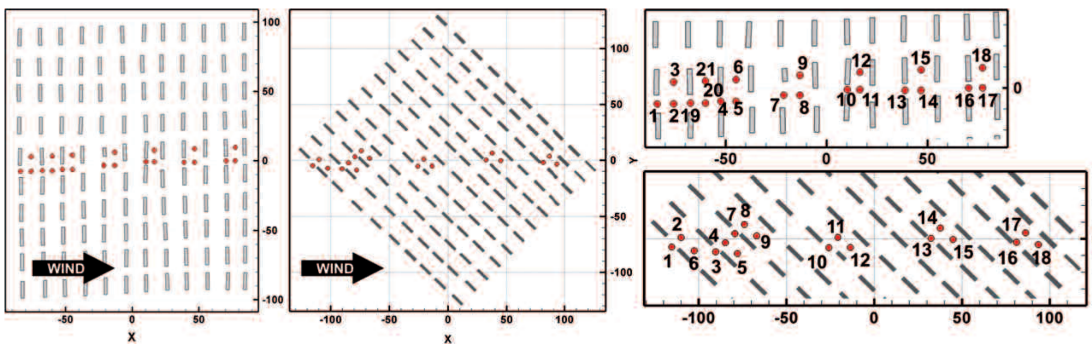

Figure 2. Vertical profile positions for 0° and -45° flow case.

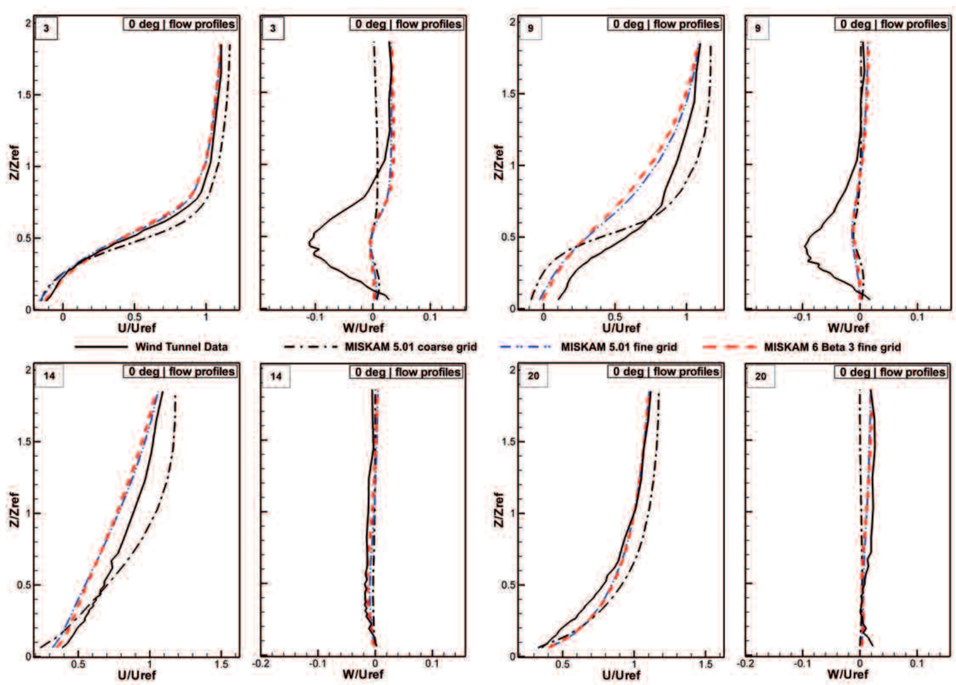

Figure 3. Typical vertical profiles behind obstacles (3, 9) and in longitudinal streets (14, 20) at 0°.

In Figures 3 and 4 also earlier results with a coarse grid of 1 m resolution (Goricsán et al., 2007) are shown for comparison.

Longitudinal component U:

- Profiles of U are almost similar to the wind tunnel measurements, in many cases slightly underestimating them.
- No remarkable differences can be found between MISKAM 5.01 and MISKAM 6 beta3 results in case of the fine grid.

Vertical component W:

- Because flow separation above the containers is not resolved properly by MISKAM, a known issue of the *k*-*ε*-model, the downward flow observed between obstacles, which is induced by the separation bubble, does not appear in the simulation profiles. Longer separation bubbles, as observed in MISKAM simulations also lead to smaller vertical velocities. (see Eichhorn, 2004)
- In longitudinal streets, the flow is almost undisturbed; simulated and wind tunnel profiles both give zero vertical velocity.

The finer grid (0.5 m resolution) gives a better over-all agreement of all wind components than the coarse grid.

Flow field at -45°

Similar conclusion can be made for the -45° case (Fig. 4).

- The flow direction did not allow any distinction between profiles like at 0°, but it can be stated that profiles far behind showed lower U velocities compared to the measurement than those in the first obstacle rows. Lower values for the component U are particularly typical in lower heights.
- In contrast to the measurements, the simulated vertical component is near zero, especially in the regions far downwind.
- MISKAM 5.01 and MISKAM 6 beta3 results differed from each other notably in some cases, showing the effect of the new scheme applied.

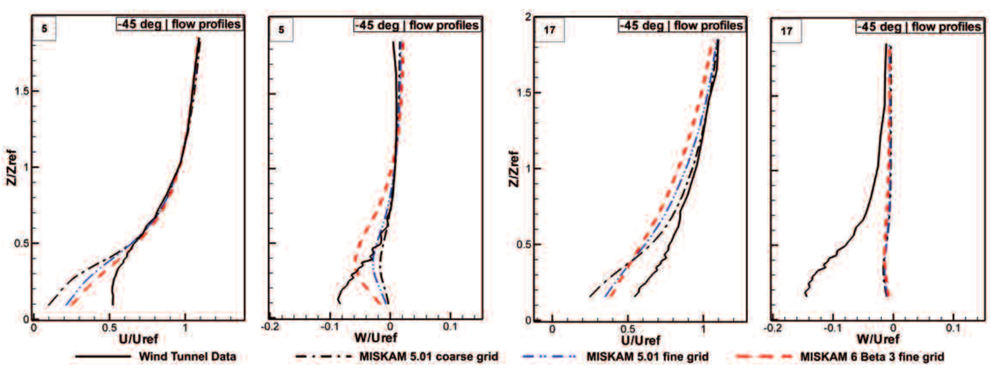

Figure 4. Typical vertical profiles in the second row (5) and in a rear row (17) at -45°.

Concentration field at -45°

Normalized concentrations C^* shown in the following are defined as:

$$C^* = \frac{C \bullet u_{ref} \bullet H^2}{Q} \qquad (1)$$

with C - measured or simulated concentration, u_{ref} - inlet velocity taken at container height H and Q - source strength.

Concentration fields near the surface show a direction change of the plume due to the channelling effect of the obstacle arrangement (Figure 5). The direction of the plume is different in MISKAM 5.01 and MISKAM 6 beta3 simulations; the latter giving a better agreement with the measured plume position. The same holds true for mass concentrations near the source, where MISKAM 5.01 overestimated the values as compared to the measurements.

Both MISKAM versions predict longer and thinner plumes than measured. This can be explained by the underestimation of turbulent kinetic energy of the incoming flow (see profiles in Fig. 1) that decreases dispersion perpendicular to the main flow direction. In part, the higher numerical diffusion of the upstream scheme reverses this effect, causing the plume to spread a bit wider, thus giving a slightly better agreement with the measurement than the more ambitious Smolarkiewicz correction. This can be seen explicitly at low concentrations near the plume boundaries.

Statistical analysis of the measured and simulated concentrations in the wind tunnel measurement points (Fig. 6) confirms the observations above. MISKAM 6 beta3 gives a very good approximation of the measured concentrations with a slight overestimation and a high R^2 of 0.92 and 0.84, compared with 50% overestimation and R^2 = 0.58 and 0.5 at the 5.01 version. The effect of the Smolarkiewicz correction steps is visible mainly at small concentrations (below 10^{-2}) and does not influence the overall picture.

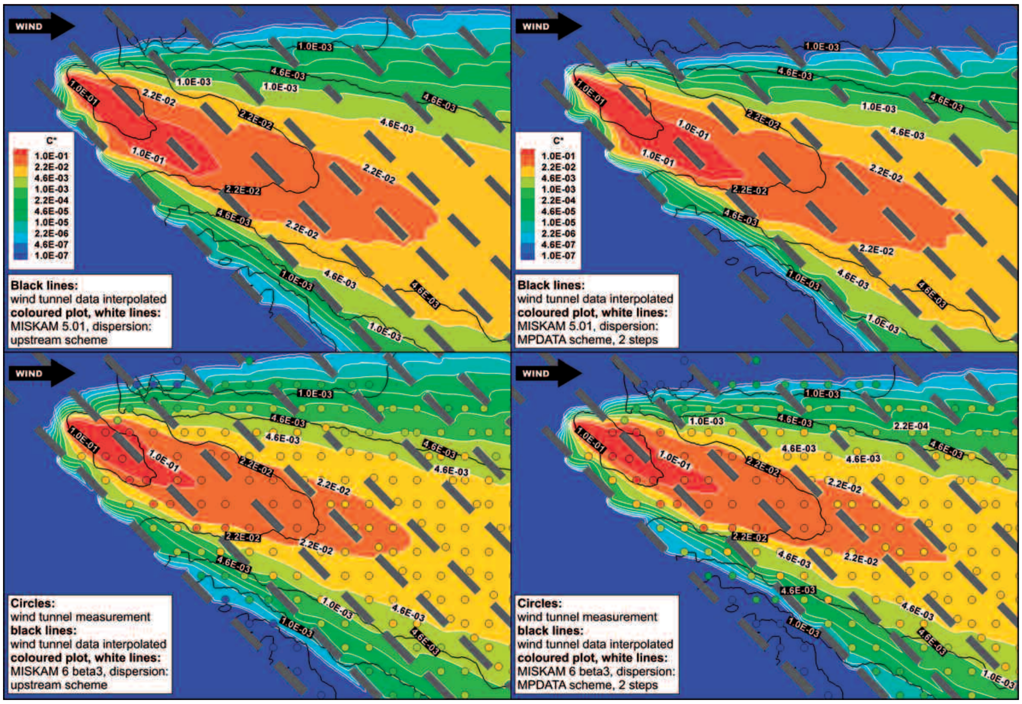

Figure 5. Comparison of concentration distribution in the -45° case in 1.28 m height obtained from MISKAM 5.01 (top) as well as MISKAM 6 beta3 (bottom) with upstream scheme (left) and with Smolarkiewicz correction (right). Note the exponential distribution of the contour levels.

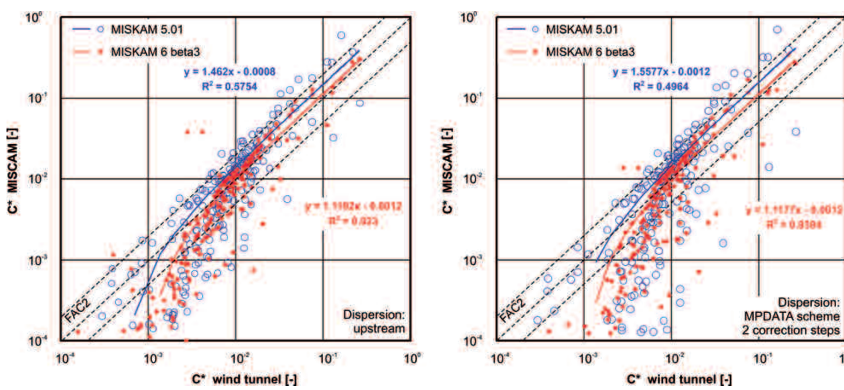

Figure 6. Comparison of measured and simulated concentrations at -45°. Left: dispersion calculation with upstream scheme; right: with MPDATA, 2 correction steps.

5. CONCLUSION

The refined advection schemes have no remarkable effects on the precision of results of the grid parallel (0°) flow case. In contrary, for the -45° case the use of the McCormack / MPDATA schemes significantly affected the wind field and subsequently the dispersion. Since the k-ε turbulence model does not allow MISKAM to resolve in detail all flow structures, some deviations from the wind tunnel measurements, as can be observed in the vertical velocity profiles, still remain and, together with the results of the evaluation procedure, give rise to a further revision of the turbulence model.

As far as the dispersal simulation is concerned, MISKAM 6 brought a considerable performance improvement compared to the previous version.

Acknowledgements: *The MUST data set has been provided by the Defence Threat Reduction Agency (DTRA) / Dugway Proving Ground (DPG) for use in COST732.*
Márton Balczó would like to thank Dr. István Goricsán for providing the MISKAM computational grids and student Károly Czáder for his help in the data processing.
Joachim Eichhorn wishes to express his gratitude to Dr. Matthias Ketzel (University of Aarhus, Roskilde, Denmark) for pointing out a coding error in MISKAM 6.

REFERENCES

Eichhorn, J., 2004: Application of a new evaluation guideline for microscale flow models. *9th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Garmisch-Partenkirchen, Germany, June 1-4.

Eichhorn, J. and A. Kniffka, 2007: An Improved Version of the Microscale Flow Model MISKAM - Evaluation According to VDI Guideline 3783/9. *11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Cambridge, United Kingdom, July 2-5.

Goricsán, I., M. Balczó, K. Czáder, A. Rákai and C. Tonkó, 2007: Simulation Of Flow In An Idealised City Using Various CFD Codes. *11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Cambridge, United Kingdom, July 2-5.

Kato, M. and B.E. Launder, 1993: The modelling of turbulent flow around stationary and vibrating square cylinders. Ninth *Symposium on 'Turbulent Shear Flows'*, Kyoto, Japan.

Leitl, B., Bezpalcova, K. and F. Harms, 2007: Wind tunnel modelling of the MUST experiment. *11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Cambridge, UK, July 2-5.

López, S.D., 2002: Numerische Modellierung turbulenter Umströmungen von Gebäuden. PhD thesis, University of Bremen, Germany.

MacCormack, R.W., 1969: The effect of viscosity in hypervelocity impact cratering, *AIAA Paper*, 69-354.

Patrinos, A.N.A. and A.L. Kistler, 1977: A numerical study of the Chicago lake breeze. *Boundary-Layer Meteorol.*, **12**, 93-123.

Smolarkiewicz, P.K. and W.W. Grabowski, 1989: The multidimensional positive definite advection transport algorithm: Nonoscillatory option. *J. Compu. Physics*, **86**, 355-375.

VDI, 2005: VDI 3783, Bl. 9: Umweltmeteorologie - Prognostische mikroskalige Windfeldmodelle - Evaluierung für Gebäude- und Hindernisumströmung. Beuth-Verlag, Berlin, Germany.

Yee, E. and C.A. Biltoft, 2004: Concentration fluctuation measurements in a plume dispersing through a regular array of obstacles. *Boundary-Layer Meteorol.,* **111**, 363-415.