On The 3D-Pollution Dispersion Over 2D-Hill Including Turbulence Modelling

Sládek I.[2/], Kozel K.[1/], Jaňour Z.[2/]

1/ U12101, Faculty of Mechanical Engineering, Czech Technical University in Prague.

2/ Institute of Thermo-mechanics, Academy of Sciences, Prague.

Abstract

The paper deals with a concentration-validation study performed on the mathematical/numerical model of atmospheric boundary layer flow. The mathematical model is based on the system of RANS equations closed by the two-equation $k-\varepsilon$ turbulence model together with wall functions. The finite volume method and the explicit Runge–Kutta time integration method are utilized for the numerics. The test–case is related to a neutral boundary layer 2D-flow over an isolated hill with a rough wall. 2D- and 3D- concentration results have been compared.

1 Mathematical formulation

The flow itself is assumed to be a turbulent, viscous, incompressible, stationary and indifferently stratified as well. The mathematical model is based on the RANS approach and the governing equations modified according to the method of artificial compressibility can be re-casted in the conservative and vector form

$$\vec{W}_t + \begin{pmatrix} u \\ u^2+\frac{p}{\varrho} \\ uv \\ uw \\ uC \end{pmatrix}_x + \begin{pmatrix} v \\ vu \\ v^2+\frac{p}{\varrho} \\ vw \\ vC \end{pmatrix}_y + \begin{pmatrix} w \\ wu \\ wv \\ w^2+\frac{p}{\varrho} \\ wC \end{pmatrix}_z = \begin{pmatrix} 0 \\ Ku_x \\ Kv_x \\ Kw_x \\ \tilde{K}C_x \end{pmatrix}_x + \begin{pmatrix} 0 \\ Ku_y \\ Kv_y \\ Kw_y \\ \tilde{K}C_y \end{pmatrix}_y + \begin{pmatrix} 0 \\ Ku_z \\ Kv_z \\ Kw_z \\ \tilde{K}C_z \end{pmatrix}_z \tag{1}$$

where $\vec{W} = (p/\beta^2, u, v, w, C)^T$ stands for the vector of unknown variables: the pressure p, the velocity vector $\vec{V} = (u, v, w)^T$, the passive pollutant concentration C (measured in $[kg/m^3]$) and the parameters K, $\tilde{K}$ refer to the turbulent diffusion coefficients and β is related to the artificial sound speed. The governing system (1) is closed by a conventional two-equation $k-\varepsilon$ turbulence model as briefly described in Sládek $et.al.$ (2008) [3].

2 Boundary conditions

The system (1) and $(k-\varepsilon)$ turbulence model is solved with the following boundary conditions, Castro (1981) [2]

Inlet: $u = \frac{u^*}{\kappa}\ln\left(\frac{z}{z_0}\right)$, $v=0$, $w=0$, $k = \frac{u^{*2}}{\sqrt{C_\mu}}\left(1-\frac{z}{D}\right)^2$, $\varepsilon = \frac{C_\mu^{3/4}\cdot k^{3/2}}{\kappa\cdot z}$; Outlet: homogeneous Neumann conditions for all quantities; Top: $u=U_0$, $v=0$, $\frac{\partial w}{\partial z}=0$, $\frac{\partial k}{\partial z}=0$, $\frac{\partial \varepsilon}{\partial z}=0$; Sides: symmetric conditions; Wall: standard wall functions are applied at ~ 50 wall-units from wall; where u^* is the friction velocity, $\kappa = 0.40$ denotes the von Karman constant, z_0 represents the roughness parameter.

3 Validation case

• The reference experimental data due to Khurshudyan (1981) [1] is also available in the ERCOFTAC database. Moreover, Castro (1996) [2] performed flow and pollution dispersion reference numerical study.

• The 2D-computational domain symmetric about hill summit is $9 \times 1.6\,m$ long x high and non-uniformly discretized by 400×80 cells. Two 3D-computational domains were tested starting at hill summit: (domain-1) $4.5 \times 0.11 \times 1.6\,m$ long×wide×high and discretized by $200 \times 11 \times 80$ cells and (domain-2) $4.5 \times 0.44 \times 1.6\,m$ long×wide×high and discretized by $200 \times 40 \times 80$ cells. The 2D flow-field was uniformly redistributed in the lateral $y-$direction for all 3D-computations. The free-stream air velocity $U_0 = 4\,m/s$ and boundary layer depth of $D = 1\,m$. The Reynolds number based on U_0 and hill height $H = 117\,mm$ is $Re \sim 3.1 \cdot 10^4$, Sládek $et.al.$ (2008) [3].

• The concentration input data: two different heights of a source in 2D/3D-runs have been assumed at the downwind side of the hill summit: $x_s = 3H$ and $z_s = 0.25H$, $0.5H$, both in the recirculation zone. A normalization of the concentration field is performed as $C \cdot U_0 H^2/Q$

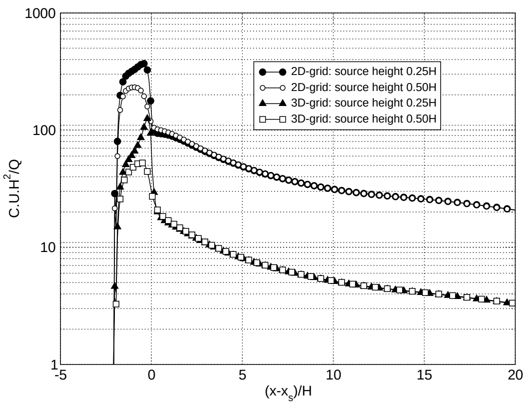

Fig 1: Ground-level-concentrations with source at heights $0.25H$ and $0.5H$ showing the effect of terrain amplification factor and pollutant plume decay in 2D-case (upper two profiles) versus 3D-case on domain-1 (lower two profiles).

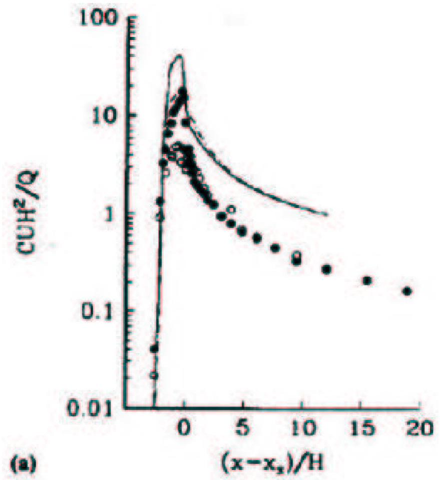

Fig 2: Castro's reference data (solid line) based on 3D-calculation from [2] pp.847: Profile of ground-level-concentrations profiles with source at heights $0.25H$ and $0.5H$, normalized as $C \cdot U_0 H^2/Q$.

4 Conclusion

Both 2D- and 3D-concentration simulations well captured the terrain amplification effect leading to a near ground upstream increase of the concentration level compared to source location x_s. It has been confirmed much slower 2D-pollutant plume downstream decay compared to 3D-case, see figure 1. A quantitative agreement can be found between our and the reference Castro's near-ground concentration predictions.

Acknowledgment: The presented work is supported by the Grant No. 1ET400760405.

References

[1] Khurshudyan L.H., Snyder W.H., Nekrasov I.V. (1981): Flow and dispersion of pollutants over two-dimensional hills, U.S. EPA, Report No. EPA-600/4-81-067.

[2] Castro I.P., Apsley P.P. (1996): Flow and dispersion over topography: A comparison between numerical and laboratory data for two-dimensional flows, Atmospheric Environment, Vol.31, No.6.

[3] Sládek I., Kozel K., Jaňour Z. (2008): On the 2D-validation study of turbulence $k - \varepsilon$ model including pollution dispersion, In: "Topical Problems Of Fluid Mechanics 2008", Institute of Thermo-mechanics, ISBN 978-80-87012-09-3, pp. 101–104, Prague.

5 Some numerical results

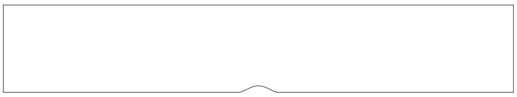

Fig 3: 2D-Computational domain $9.36\,m \times 1.6\,m$ for 2D-pressure-velocity field, discretized be 400x80 cells.

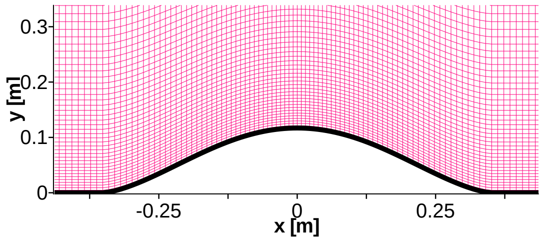

Fig 4: Zoom to non-uniform grid near hill.

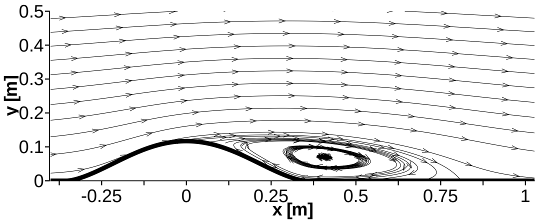

Fig 5: Zoom to separation zone behind hill, computed reattachment $x_r = 6.84H$, measured from experiment $x_r = 6.5H$.

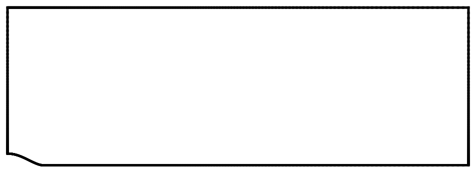

Fig 6: 2D-Computational domain $4.68\,m \times 1.6\,m$ for 2D-concentration field.

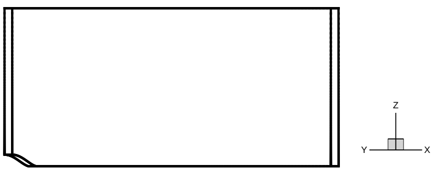

Fig 7: Rotated 3D-Computational domain-1 $4.68\,m \times 0.11\,m \times 1.6\,m$ for 3D-concentration field.

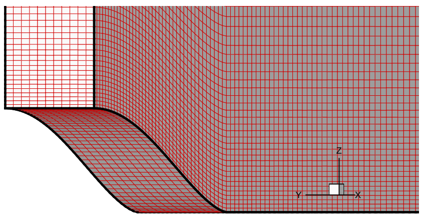

Fig 8: Zoom to 3D-computational domain-1 for 3D-concentration field discretized by 200x11x80 cells.

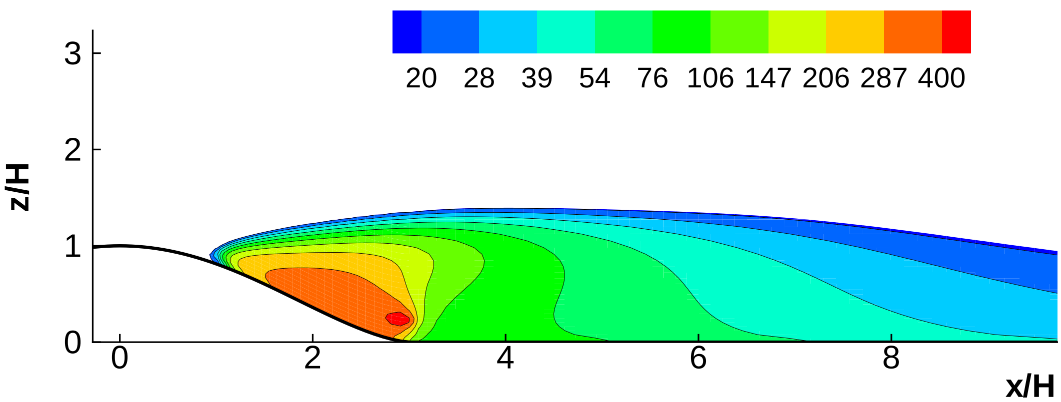

Fig 9: Computed contours of normalized 2D-concentration field $C \cdot U_0 H^2/Q$ with exponential scale for source height $0.25H$.

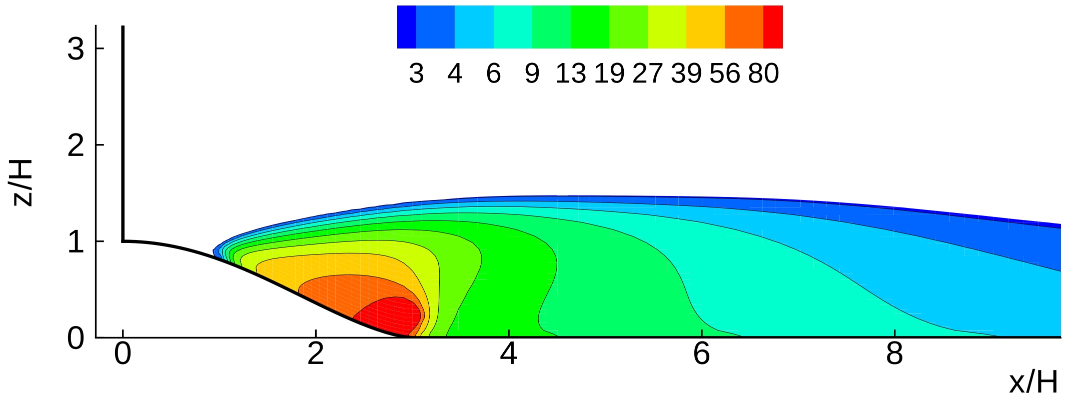

Fig 10: Computed contours of normalized 3D-concentration field $C \cdot U_0 H^2/Q$ with exponential scale for source height $0.25H$, middle XZ-plane at index J=6.

A much slower concentration plume decay is clearly visible when comparing both figures 9 and 10, especially the scales. The contours have practically the same shape, however both concentration fields differ from quantitative point of view.

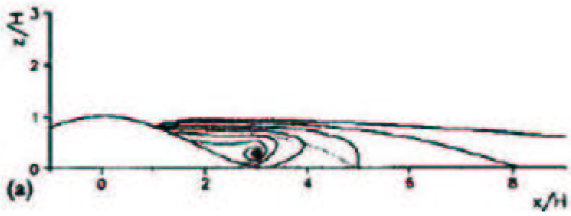

Fig 11: Reference data taken from [2] pp.847: Computed contours of normalized concentration field $C \cdot U_0 H^2/Q$ with exponential scale starting at value=1 (upper contour) for source height $0.25H$.

There is a quantitative matching between our computed 3D-concentration field and the reference Castro's data.