ON THE RELATIVE IMPORTANCE OF VEGETATION TERMS IN COMPUTATIONAL FLUID DYNAMICS ON FLOW AND DISPERSION IN THE URBAN ENVIRONMENT

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Abstract: The relative importance of vegetation terms was analysed for flow and dispersion in an urban street canyon with avenue-trees. To this end, simulations with three k-ε turbulence models and different approaches to model vegetation were performed. The different approaches resulted in rather slight differences in mean flow velocities, turbulence kinetic energies and dissipation rates, but in more pronounced differences in pollutant concentrations.

Key words: *Pollutant Dispersion, Street Canyon, Avenue-Trees, Computational Fluid Dynamics, k-ε Turbulence Models, Vegetation Terms*

INTRODUCTION

Vegetation is ubiquitous in the urban environment. It exists in form of urban forests, parks, gardens, grouped and single trees or shrubs, façade and roof greening, and as avenue-trees in street canyons. Their implications on the urban microclimate and micrometeorology are manifold and complex (e.g. Oke, 1989; Mochida and Lun, 2008). With respect to city ventilation and air quality, it is known that avenue-trees in urban street canyons can result in lower wind velocities and increased traffic pollutant concentrations at the pedestrian level (e.g. Gromke and Ruck, 2012). The latter points out the importance of reliable modelling approaches for vegetation in Computational Fluid Dynamics (CFD) simulations of flow and pollutant dispersion in the urban environment.

The present study investigated the implications of extra sink and source terms to represent vegetation in the Reynolds-averaged Navier-Stokes (RANS) equations for momentum, turbulence kinetic energy and dissipation. CFD simulations of flow and pollutant dispersion in an urban street canyon with avenue-trees were performed by employing different combinations of the extra sink and source terms. Furthermore, the numerical simulations are compared to wind tunnel data by Gromke and Ruck (2009) to qualitatively assess their reliability. However, this aspect is not elaborated in detail here, since the main purpose of this study is to assess the relative importance of the vegetation module constituting terms.

COMPUTATIONAL DOMAIN AND NUMERICAL SETTINGS

The computational domain was made to mimic the wind tunnel setup of an isolated street canyon with a central row of avenue-tress which was used to study flow and pollutant dispersion (Gromke and Ruck, 2009; CODASC, 2008), see Figure 1. A total of ~1.1 million hexahedral cells was used to discretize the domain with a structured grid. Inside the street canyon and at the building walls cubical cells of edge length $H/24$ (with H the building height) were employed. From the building walls facing away from the street canyon, the grid was coarsened with stretching factors < 1.15. The distance from the domain inlet to the windward building was 6.8 H and from the leeward building to the domain outlet was 15.2 H, fulfilling the recommendations provided by the COST Action 732 (Franke et al., 2007; Franke et al., 2011) and in the AIJ guidelines for CFD pedestrian wind environment studies (Tominaga et al., 2008). At the inlet a power law velocity profile according to that in the wind tunnel was assigned and the vertical profiles of turbulence kinetic energy and dissipation were chosen according to Richards and Hoxey (1993). The outlet was specified as pressure outlet and all other domain boundaries and the building walls were defined as walls with roughness length $z_0 = 0$ where standard wall functions were employed. Traffic emissions were modelled by momentum-free volume sources of line-like structure spanning along the street canyon length and covering the first cell above ground.

The CFD code ANSYS Fluent V12.1.4 (ANSYS Inc., 2009) was used. Steady-state RANS simulations were performed with three variants of the k-ε turbulence model, the standard, the renormalized group (RNG) and the realizable model. Second order discretization schemes were chosen throughout except for gradients where the least squares cell based scheme was employed. For pressure velocity coupling the SIMPLE algorithm was used. The turbulent Schmidt number Sc_t for species transport was taken to 0.7.

VEGETATION TERMS

The principal ways how vegetation affects air flow were summarized by Wilson and Shaw (1977). Momentum is extracted by the aerodynamic resistance of the plant parts, and wake turbulence is generated by the conversion of mean kinetic energy into turbulence kinetic energy and by the breakdown of larger scale turbulent motions into smaller scale motions. The latter is associated with a short-circuiting of the eddy cascade which results also in an enhanced dissipation. Additionally, there is a buoyant contribution to turbulence arising from temperature differences between plant parts and air.

In order to account for the vegetation effects on air flow, except that of the buoyant contribution, terms are added to the transport equations of momentum (Equation 1), turbulence kinetic energy (Equation 2) and dissipation (Equation 3) on computational cells which contain vegetation according to

$$-\frac{1}{2}\rho\, C_d\; LAD\, U_i\, \boldsymbol{U} \tag{1}$$

$$\rho\, C_d\; LAD\left(\beta_p \boldsymbol{U}^3 - \;\beta_d \boldsymbol{U}\, k\right) \tag{2}$$

$$\rho\, C_d\; LAD\,\frac{\varepsilon}{k}\left(C_{\varepsilon 4}\beta_p \boldsymbol{U}^3 - \;C_{\varepsilon 5}\beta_d \boldsymbol{U}\, k\right) \tag{3}$$

where ρ is the density of air, C_d is the leaf drag coefficient, LAD is the leaf area density, U_i is the velocity component of direction i, $\boldsymbol{U}$ the velocity magnitude, β_p is the fraction of mean kinetic energy that is converted into wake turbulence kinetic energy ($\beta_p = 0\ldots1$), β_d is a coefficient that accounts for short-circuiting of the eddy cascade, k is the turbulence kinetic energy, and $C_{\varepsilon 4}$ and $C_{\varepsilon 5}$ are empirical coefficients. The coefficients are summarized in Table 1, where C_d and LAD were dictated by the aerodynamic resistance of the tree model from the wind tunnel experiment (Gromke and Ruck, 2009) and the remaining values are the same as commonly employed in canopy flow studies (e.g. Katul et al., 2004).

Table 1. Coefficients in the vegetation terms

C_d (-)	LAD ($m^2\ m^{-3}$)	β_p (-)	β_p (-)	$C_{\varepsilon 4}$ (-)	$C_{\varepsilon 5}$ (-)
0.2	1250	1.0	5.1	0.9	0.9

For the study of the relative importance of vegetation terms, simulations were performed with either the extra terms in the momentum equations only, or with the complete set of terms in all transport equations. This was motivated since in previous studies often the extra terms in the momentum equations only were employed. Note that the extra terms in the transport equations of turbulence kinetic energy and dissipation consist of both a source and sink contribution. This is to account for the enhanced production of turbulence, i.e. wake turbulence, which due to its smaller length scales compared to shear turbulence is subjected to faster dissipation so that the vegetation acts as a net sink for turbulence kinetic energy (Green, 1992; Green et al., 1995; Sanz, 2003).

WIND TUNNEL EXPERIMENT

The CFD simulations are compared with wind tunnel measurements of flow velocities and pollutant concentrations in an isolated urban street canyon with a central row of avenue-trees (Gromke and Ruck, 2009; CODASC, 2008). To this end, normalized vertical velocities U_3/U_H (with U_H the undisturbed approach flow velocity at building height H) in a vertical plane at $x_2/H = 0.5$ in the street canyon and normalized pollutant concentrations c^+ along a vertical line at $x_1/H = -0.46$ and $x_2/H = 0.0$ close to the leeward wall of the windward building were employed (Figure 1). It is noted that in this region around the center of the street canyon the flow and dispersion processes are dominated by a canyon vortex (e.g. Gromke et al., 2008). The experiment Reynolds number based on H and U_H was $Re_H = 37.000$.

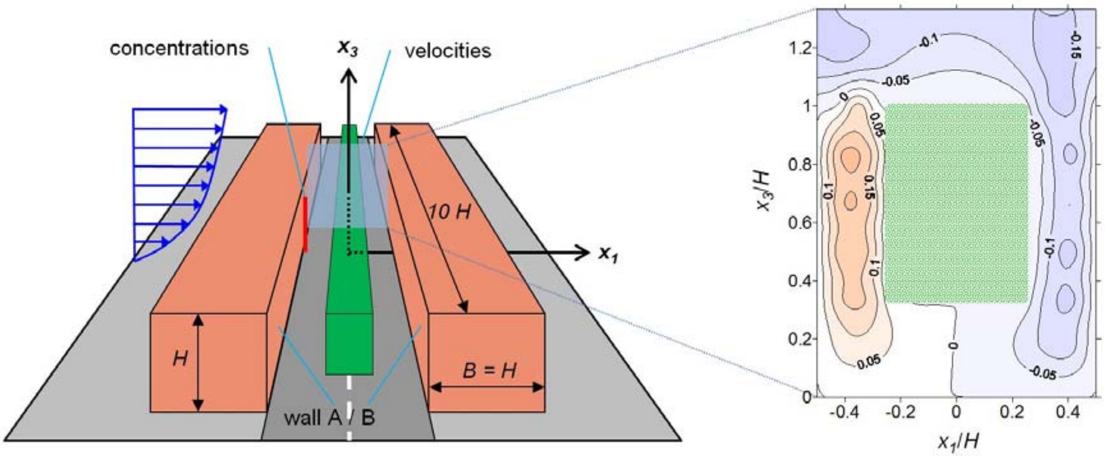

Figure 1. Isolated street canyon model with avenue-trees (left), and normalized vertical velocities U_3/U_H from wind tunnel measurements (right).

RESULTS

<u>Wind Velocities</u>

Figure 2 depicts the simulated normalized vertical wind velocities U_3/U_H in the vertical plane as indicated in Figure 1 with the extra terms in the momentum equations only (Equation 1). The vegetation zone is indicated by the dashed line. Figure 3 shows the normalized differences between simulations with the full set of vegetation terms (Equation 1-3) and the extra terms in the momentum equations only according to

$$\frac{\left|U_{3(mom,tke,diss)}\right| - \left|U_{3(mom)}\right|}{U_H} = \frac{\Delta U_3}{U_H} \tag{4}$$

For all k-ε turbulence models, overall increases in the vertical velocities are observed when the full set is employed. The increases are most prominent in the downward streaming part of the canyon vortex in front of wall B. Contrary to the regions between the building walls and the avenue-tree, velocity decreases dominate within the vegetation region. The general patterns of velocity differences are similar for all models where the strongest increases are found for the realizable k-ε model. The differences are largely smaller than 3% of U_H which drives the flow inside the street canyon.

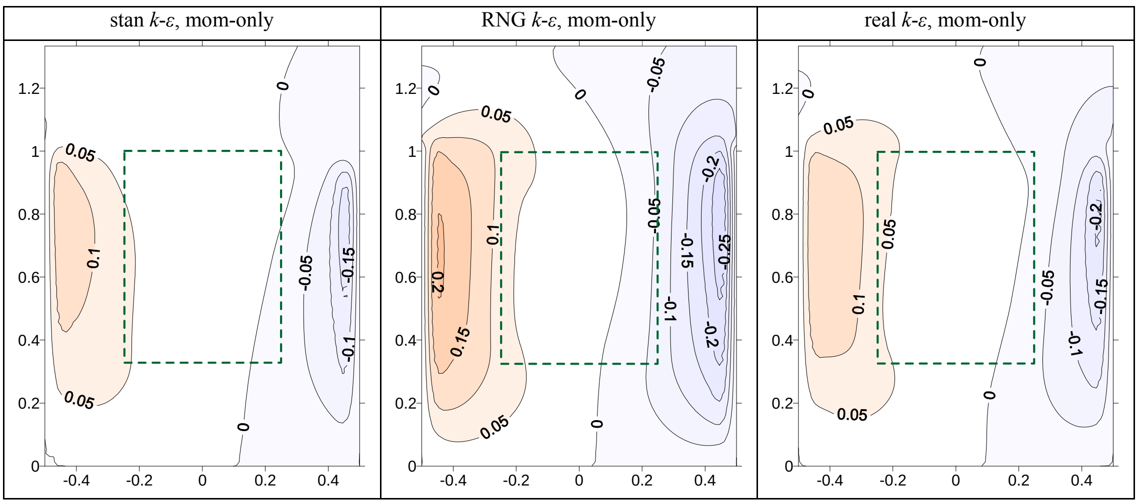

Figure 2. Simulated normalized vertical velocities U_3/U_H in the vertical plane at $x_2/H = 0.5$ (Figure 1) with the extra terms in the momentum equations only (Equation 1).

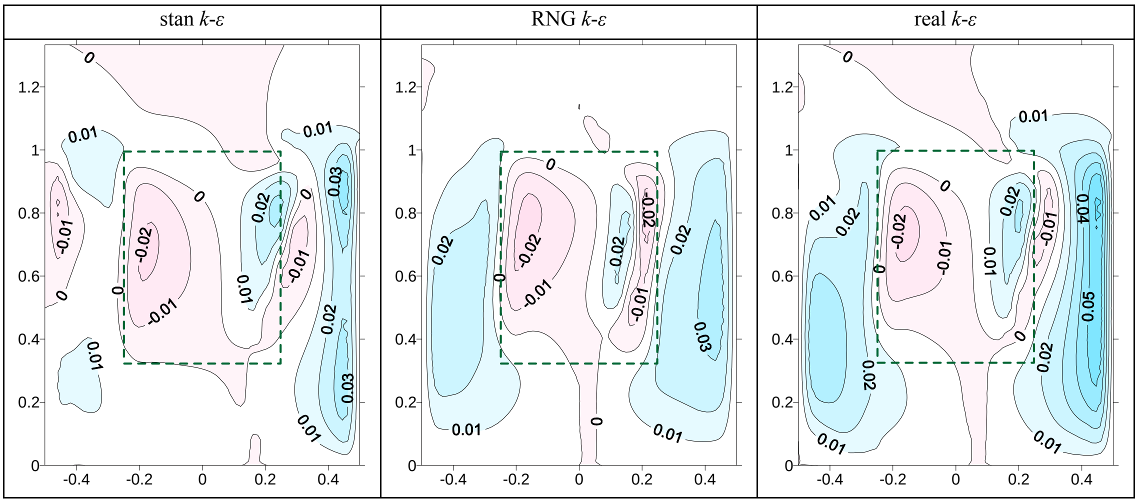

Figure 3. Normalized differences $\Delta U_3/U_H$ (Equation 4) between simulations with the full set of vegetation terms (Equation 1-3) and the extra terms in the momentum equations only (Equation 1).

A comparison with the wind tunnel velocity measurements (Figure 1) reveals the best agreement for the simulation with the RNG k-ε turbulence model. The relative differences in the flow rate of the upward flowing part of the canyon vortex in the gap between the leeward wall A and the vegetation zone are -32.7%, 1.5% and -21.2% for the standard, the RNG and the realizable model, respectively. For that reason the analyses and discussions in the remainder of this article focus on the RNG k-ε model results.

Turbulence Kinetic Energy

The normalized turbulence kinetic energies k/U_H^2 for the RNG k-ε turbulence model simulations are shown in Figure 4. Decreased values are found for the simulations with the full set of vegetation terms within the entire vegetation region where the contours of turbulence kinetic energy resemble the shape of the tree crown. The lower values indicate the net loss of turbulence kinetic energy due to the short-circuiting of the wake turbulence and its accelerated dissipation (Green, 1992; Green et al., 1995). Maximum differences between the two simulations are observed in the top of the vegetation zone with the center at its right corner. The same observations are made with the standard and realizable k-ε turbulence models (not shown here). The differences in the turbulence kinetic energies are attributed to shear layer at the interface between the street canyon top and the lower roof level with its high content of turbulence kinetic energy. The turbulence kinetic energy of the shear layer is mixed into the canyon vortex and is finally entrained into the street canyon in front of wall B. Since the wind velocity in the vegetation zone is low but the transport of turbulence kinetic energy into that zone is strong, the extra term (Equation 2) becomes finally a sink contribution and causes the peak in turbulence kinetic energy differences.

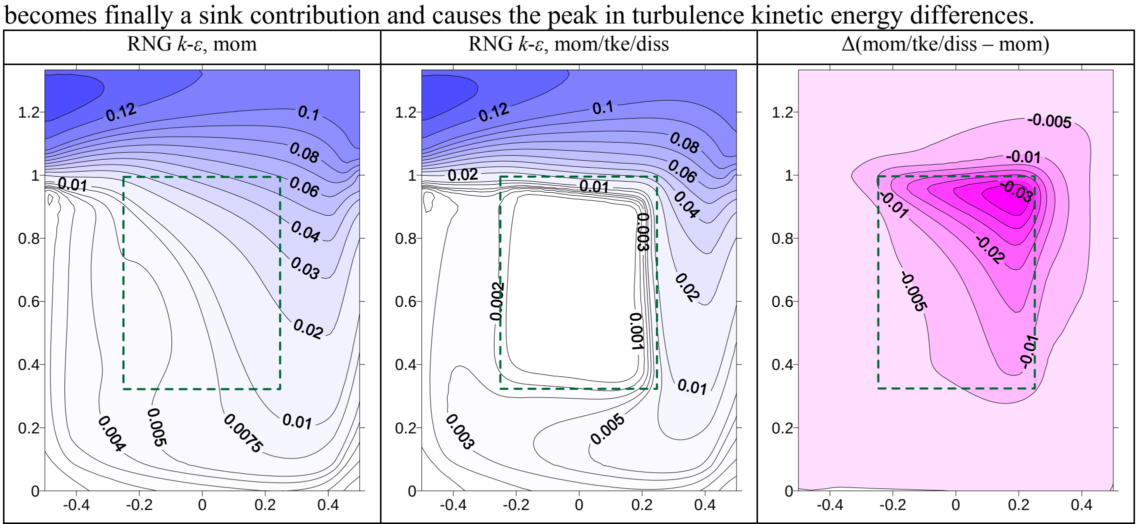

Figure 4. Normalized turbulence kinetic energy k/U_H^2 for the RNG k-ε turbulence model simulations.

Dissipation Rate

Figure 5 shows the normalized dissipation rates $\varepsilon\ H/U_H^3$ as obtained with the RNG k-ε turbulence model simulations. The general patterns of dissipation rates and their differences conform with those found for the turbulence kinetic energy in Figure 4. Comparable patterns of dissipation rates are also observed for the standard and realizable k-ε turbulence model simulations (not shown here). The dissipation rate in the vegetation zone with the full set of vegetation terms is reduced. The pronounced differences in the top right corner of the vegetation zone are a direct consequence of the balance of the source and sink contribution in Equation 3 and the same argument as for the turbulence kinetic energy holds.

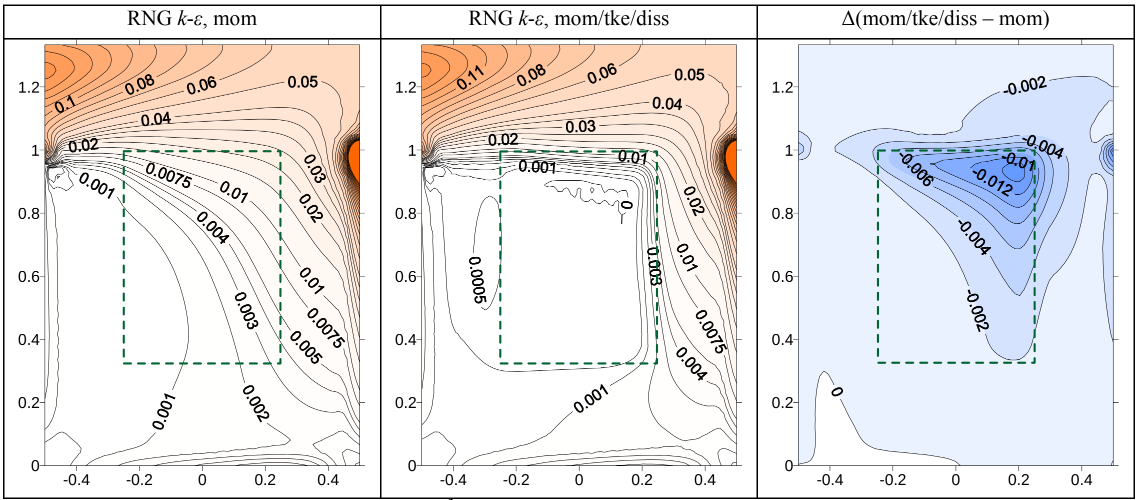

Figure 5. Normalized dissipation rates $\varepsilon\ H/U_H^3$ for the RNG k-ε turbulence model simulations.

Pollutant Concentrations

Figure 6 shows the normalized pollutant concentrations c^+ along a vertical line close to the wall A (Figure 1) which were calculated according to normalizing formula for line sources (e.g. Gromke and Ruck, 2012). Whereas for the standard k-ε model the full set of vegetation terms resulted in higher concentrations, the opposite is true for the RNG and realizable model. The differences are smallest for the RNG k-ε turbulence model. The mean relative differences between the simulations with the full set of vegetation terms and the extra terms in the momentum equations only, are 26.2%, -7.0% and -27.9% for the standard, the RNG and the realizable k-ε model, respectively. The outperformance of the RNG k-ε model with a turbulent Schmidt number $Sc_t = 0.7$ compared to the standard and realizable model is clearly visible. This is in accordance with the vertical velocities where also the RNG k-ε model was found to provide the closest agreement with the wind tunnel data, see Figures 1, 2.

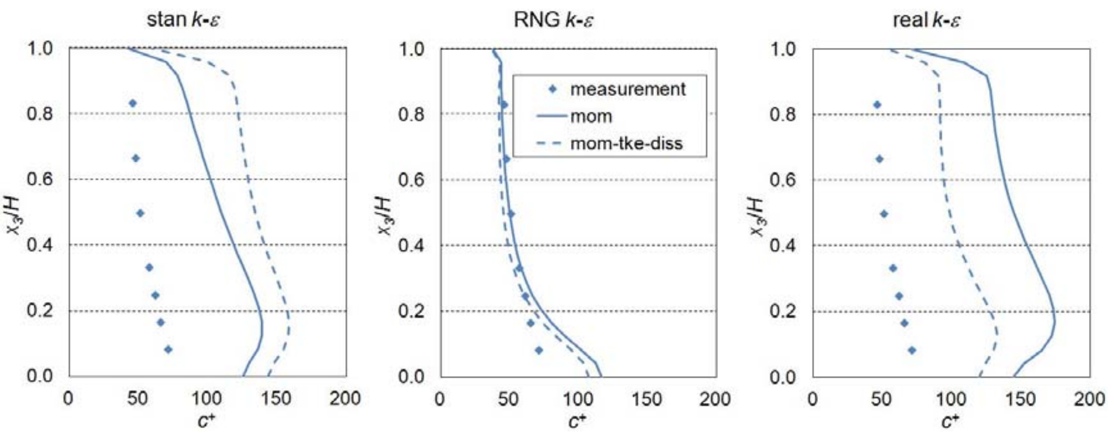

Figure 6. Normalized pollutant concentrations c^+ close to the wall A (Figure 1).

SUMMARY AND CONCLUSION

CFD simulations of flow and pollutant dispersion in an urban street canyon with avenue-trees were performed. The standard, the RNG and the realizable k-ε turbulence model with different sets of vegetation terms were employed, namely with (i) extra terms for drag in the momentum equations (Equation 1), and with (ii) additionally extra terms for production and destruction of turbulence kinetic energy and dissipation in the corresponding transport equations (Equations 1, 2, 3). The full set of vegetation terms resulted in overall higher vertical flow velocities except in the vegetation zone (Figures 2, 3). The differences between the two sets were largely limited to below 3% of the undisturbed approach flow velocity U_H. In terms of turbulence kinetic energy and dissipation, the full set of extra terms resulted in lower values in particular in the top right corner of the vegetation zone (Figure 4, 5). For the pollutant concentrations, no clear tendency could be observed (Figure 6). Higher concentrations were found for the standard k-ε model simulations when the full set of vegetation terms was employed (in average 26.2%), whereas lower concentrations were found for the RNG and realizable k-ε model (in average -7.0% and -27.9%, respectively). In summary, the results suggest that the additional extra vegetation terms (i.e. Equations 2, 3) do not have a pronounced impact on mean velocities and turbulence quantities, but have a stronger impact on the pollutant concentrations. Finally, the RNG k-ε turbulence model was found to outperform the standard and the realizable k-ε model both in terms of flow velocities and pollutant concentrations. Although the intercomparison of the k-ε models and their assessment against wind tunnel data was not the focus of this study, it is an important finding as it suggests the RNG k-ε turbulence model for the investigation of flow and dispersion in urban street canyons.

ACKNOWLEDGEMENTS

This research was supported by a Marie Curie Intra European Fellowship within the 7th European Community Framework Programme.

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