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Evaluation of a model for vehicle induced turbulence for urban wind simulation

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SUMMARY:
Pollution caused by road traffic in cities is a major problem, and Computational Fluid Dynamics (CFD) have become an established tool for its investigation. Wind tunnel and in-situ measurements showed, that the moving cars themselves generate turbulence, which influences the flow patterns and pollution dispersion. Hence, this effect, called Vehicle Induced Turbulence (VIT), must be considered in the numerical procedure in certain situations. We present a system of additional source terms for the Reynolds Averaged Navier Stokes equations (RANS) to model VIT. Comparison with wind tunnel measurements shows that this approach correctly reproduces the changes in TKE in a street canyon with perpendicular winds. The method only requires the definition of additional fluid volumes along the streets and takes the direction of vehicle velocity into account. It can be easily transferred to two-way traffic and roads in real urban environments and gives also for these results that are in good agreement with measured results.

Keywords: Traffic produced turbulence, Urban wind simulation, Computational wind engineering

1. INTRODUCTION

Pollution caused by road traffic is a major problem, especially in densely built-up areas along busy roads. Pollution dispersion has been successfully investigated using Computational Fluid Dynamics (CFD) (Di Sabatino et al., 2013). But moving vehicles not only emit pollutants, they also contribute to the air movement that disperses the pollutants, as they generate turbulence, called vehicle induced turbulence (VIT) or traffic produced turbulence (TPT). Wind tunnel and in-situ studies showed, that VIT depends namely on the number of lanes, vehicle density, and one- or two-way traffic, (Kastner-Klein et al., 2001; Vachon et al., 2002), and becomes predominant at low wind speeds (Di Sabatino et al., 2013). Since situations with high pollutant loads also occur when wind speeds are low, it is important to take this effect into account in wind simulations.

Several approaches to incorporate VIT have been developed (Di Sabatino et al., 2013). Approaches with cars modelled as moving obstacles or with stationary cars and moving walls (Solazzo et al., 2008) are, however, limited to rather simple rectangular geometries. Other authors have modeled VIT using extra source terms to the RANS equations in certain regions of the computational domain, without considering individual vehicles. In (Di Sabatino et al., 2003) a parametrization of an additional turbulence production term has been derived for different traffic densities. In (Hataya et al., 2006) a set of additional source terms for all equations, i.e. for momentum, turbulent kinetic energy and dissipation, has been proposed, which was also used in (Zhao et al., 2021), where cars are explicitly modelled obstacles.

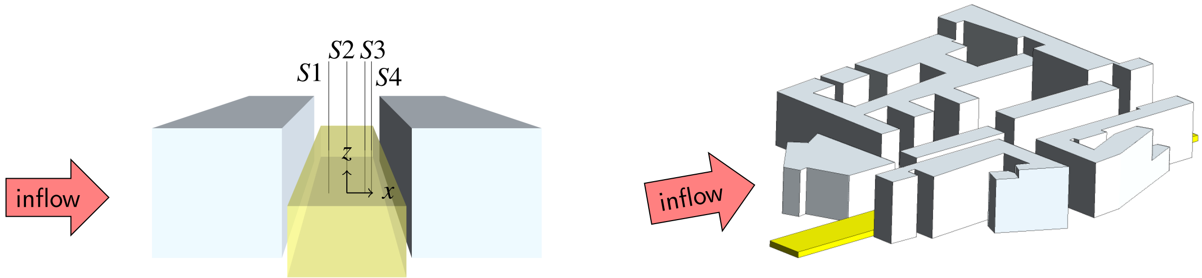

Figure 1. Left: Street Canyon with vertical lines S1 to S4 in the cross-section $y = 0$. Right: Complex of buildings of Stoeckach. The additional volume (yellow) models the lane, where the source terms are added.

In this study, we define, based on these approaches, source terms that are suitable to account for the effects of VIT in RANS simulations. We validate our modeling by comparing it with published wind tunnel data of a street canyon and apply it to simulate two-way traffic as well as larger urban areas.

2. THE VIT MODEL

To model the effects of VIT, additional source terms F_i, $i = 1, \dots, 3$, F_k, and F_ε are added to the momentum equations in Cartesian coordinates and the transport equations for turbulent kinetic energy k as well as turbulence dissipation rate ε, respectively. We use source terms F_i and F_ε similar to those of (Hataya et al., 2006), and F_k according to (Di Sabatino et al., 2003):

$$F_i = -\frac{C_f A_i}{2V_{\text{lane}}} |\mathbf{U} - \mathbf{U}_{\text{car}}| \ (u_i - u_{\text{car},i}) , \quad F_k = \frac{\rho C_f A}{2V_{\text{lane}}} |\mathbf{U} - \mathbf{U}_{\text{car}}|^3, \quad \text{and} \quad F_\varepsilon = \rho \ \frac{\varepsilon}{k} \ \frac{k^{3/2}}{l_{\text{lane}}} \ C_\varepsilon .$$

ρ denotes the density, $\mathbf{U} = (u_1, u_2, u_3)$ and $\mathbf{U}_{\text{car}} = (u_{\text{car},1}, u_{\text{car},2}, u_{\text{car},3})$ are the velocity vector and the vehicle velocity vector in Cartesian coordinates with $|\mathbf{U}| = \sqrt{\mathbf{U}^2}$. A is the front area of a car and A_i the effective area in relation to the respective direction. The volume V_{lane} with length l_{lane} is the space occupied by one vehicle on the lane (including the distance between two vehicles), so that the traffic density is taken into account here. C_f represents the sectional drag coefficient of automobiles, and C_ε is the ratio of l_{lane} to turbulence length scale in the canopy layer.

3. NUMERICAL SETUP

The first application scenario is a street canyon consisting of two parallel building blocks of dimensions $10H \times H \times H$ with distance H between the buildings, see Fig. 1. In a separate volume with width $0.8H$, height $H/2$ and length $12H$ between the two buildings, the additional source terms are taken into account. The second scenario is an urban environment, some buildings of the Stoeckach district in Stuttgart, Germany, see Fig. 1. VIT is taken into account for one main road, which has an angle of 20° to the prevalent wind direction, in a fluid volume with height 3 m. Symmetry boundary conditions are used at the top and lateral sides of the computational domain, the inlet profiles are specified according to a power law and pressure outlet boundary conditions are used on the opposite side. The computations were carried out with a second order upwind scheme, SIMPLE pressure coupling and standard k-ε-turbulence model using the enhanced wall treatment of ANSYS FLUENT.

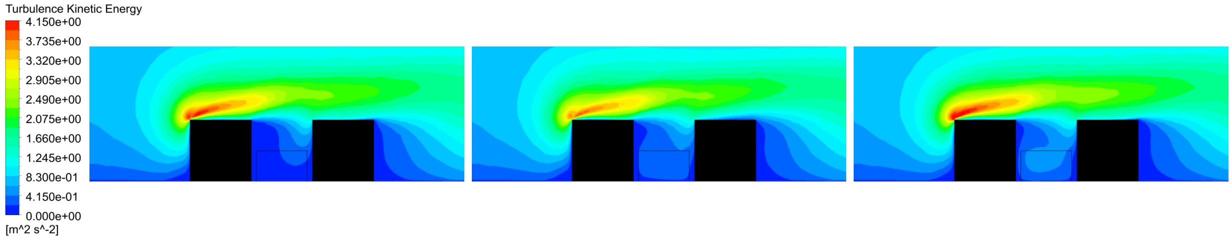

Figure 2. TKE in the cross-section $y = 0$: without VIT (left), with VIT (middle) and two-way traffic (right) with $C_f = 0.2$ and wind velocity at the inlet 4,7 m/s at height H. One-way traffic is in positive y-direction and two-way traffic (in positive y-direction for $x > 0$, in negative y-direction for $x < 0$).

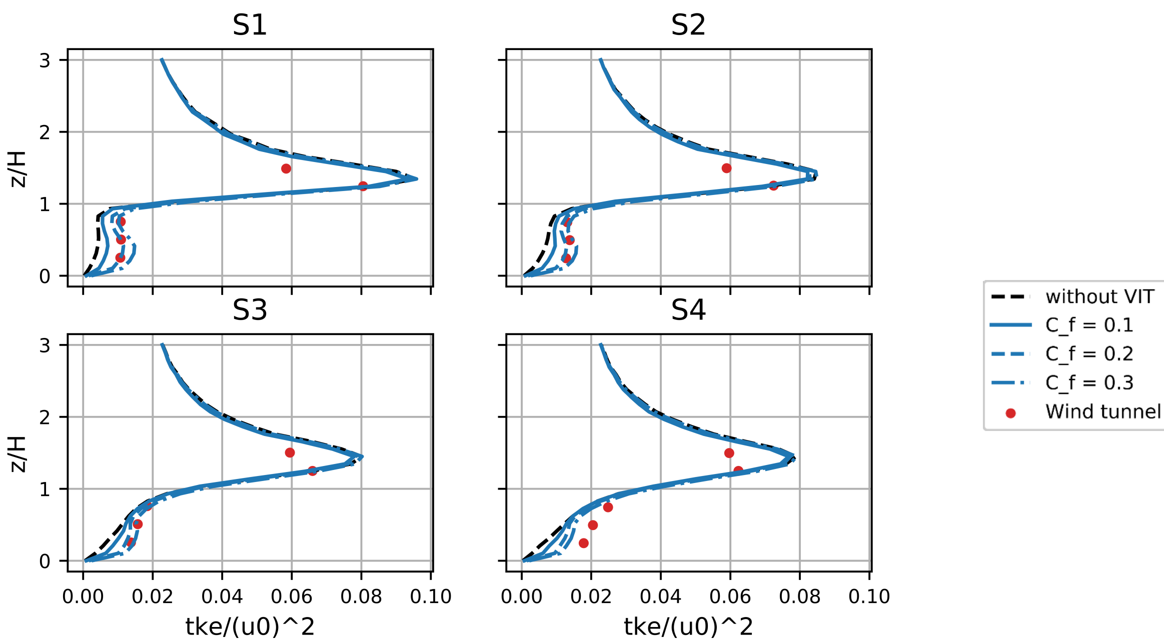

Figure 3. Simulated and measured TKE along the vertical lines S1 to S4 for different values of C_f.

4. RESULTS

First, the method is applied to the street canyon. Fig. 2 shows the increase of TKE in the street canyon, when VIT is taken into account, and the further increase for two-way traffic. For a more detailed analysis, the results are compared to wind tunnel results by Kastner-Klein (see Solazzo et al., 2008). Along four vertical lines S1: $x = -0,208H$, S2: $x = 0$, S3: $x = 0,208H$, and S4: $x = 0,375H$ in the cross-section $y = 0$, see Fig. 1, normalized values of TKE are plotted for different values of C_f in Fig. 3. The the typical peak above roof level ($H/z = 1$) is noticeable. The expected increase of TKE is observed in the lower part of the canyon when VIT is included. The fundamental behavior, that TKE decreases from the lee side to the wind side, is correctly reproduced, even if the absolute values for S4 are too small.

Second, the method has been applied to the real urban neighborhood in Fig. 1. The results for one-way traffic with vehicle velocity of 50 km/h and wind velocity at the inflow plane of 3 m/s at height 10 m in Fig. 4 show the elevation of TKE above the lane, when VIT is taken into account,

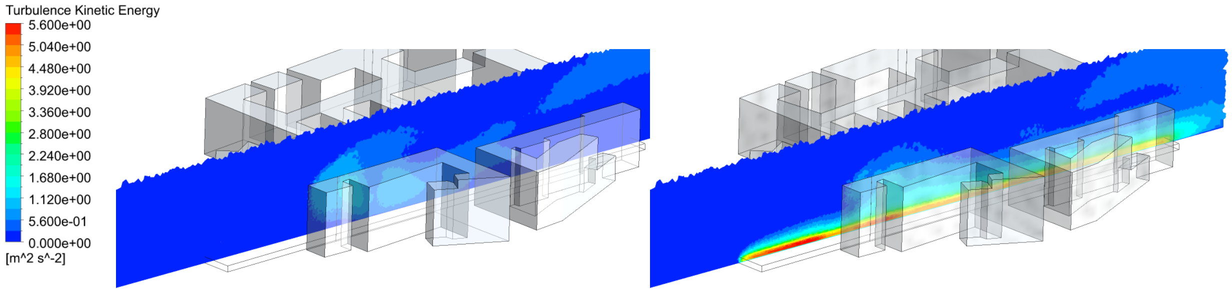

Figure 4. TKE on a vertical cross-section through the Stoeckach quarter parallel to the main road. Left: without, right with consideration of VIT.

in accordance with observations (Vachon et al., 2002).

5. CONCLUSION

A VIT model, based on additional source terms for momentum, turbulent kinetic energy and dissipation, has been presented. These source terms are added to the RANS equations in specific fluid volumes that model the lanes, taking into account the direction of traffic. So it is possible to model real road urban settings and two-way traffic. The results show good agreement with published wind tunnel data for the case of a street canyon with perpendicular winds, and also provide the results expected from published investigations for two-way traffic and a real urban environment. The model can be easily integrated into the simulation of pollutant dispersion.

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REFERENCES

Di Sabatino, S., Buccolieri, R., and Salizzoni, P., 2013. Recent advancements in numerical modelling of flow and dispersion in urban areas: A short review. International Journal of Environment and Pollution 52, 172–191.

Di Sabatino, S., Kastner-Klein, P., Berkowicz, R., Britter, R., and Fedorovich, E., 2003. The Modelling of Turbulence from Traffic in Urban Dispersion Models – Part I. Environmental Fluid Mechanics 3, 129–143.

Hataya, N., Mochida, A., Iwata, T., Tabata, Y., Yoshino, H., and Tominaga, Y., 2006. Development of the simulation method for thermal environment and pollutant diffusion in street canyons with subgrid scale obstacles. Proceedings of 4th International Symposium on Computational Wind Engineering (CWE2006), Yokohama.

Kastner-Klein, P., Fedorovich, E., and Rotach, M., 2001. A wind tunnel study of organised and turbulent air motions in urban street canyons. Journal of Wind Engineering and Industrial Aerodynamics 89, 849–861.

Solazzo, E., Cai, X., and Vardoulakis, S., 2008. Modelling wind flow and vehicle-induced turbulence in urban streets. Atmospheric Environment 42, 4918–4931.

Vachon, G., Louka, P., Rosant, J.-M., Mestayer, P., and Sini, J.-F., 2002. Measurements of Traffic-Induced Turbulence within a Street Canyon during the Nantes'99 Experiment. Water, Air, & Soil Pollution: Focus 2, 127–140.

Zhao, Y., Jiang, C., and Song, X., 2021. Numerical evaluation of turbulence induced by wind and traffic, and its impact on pollutant dispersion in street canyons. Sustainable Cities and Society 74, 103142.