Numerical simulation of pollutant dispersion over complex terrain using the RANS equations

R. Rossi¹,²

¹Dipartimento di Ingegneria Industriale, Università di Bologna, Viale Risorgimento 2, 40136 Bologna, Italy.
²Center for Turbulence Research, Stanford University, CA 94305, USA.

riccardo.rossi12@unibo.it

Abstract

The dispersion of a passive scalar emitted from a localized source is examined using the RANS equations to address the release of pollutants from a road tunnel and the interaction of the plume with the surrounding complex topography. The analysis is performed using a second-order accurate finite-volume discretization and refined turbulence models are employed to capture the flow features induced by the terrain topography, such as the strong anisotropy of turbulent scalar fluxes. The computations, based on monitored wind conditions in the area, highlight the effect of the complex terrain upon plume development and ground concentration downstream of the source.

1 Motivation and Objectives

The use of CFD models to predict the flow and dispersion over complex terrain is becoming increasingly popular thanks to advancements in turbulence modeling and computational resources (Rodrigo, 2010). CFD models based on the RANS equations are attractive as they have been found able to capture the relevant features of flows over complex topography and can be used to compute the wind flow and turbulent mixing within a distance of several kilometers. From this perspective, the actual benefit from the use of the RANS equations in large-scale simulations against well-established linear models for the wind flow and Gaussian air-quality models is still under assessment, but research work performed for realistic test cases had clarified that CFD models represent a valuable complementary tool along with reduced-order models and field-measurements (Palma et al., 2008).

In this paper the dispersion of a passive scalar emitted from a localized source is examined to address the release of pollutants from the portal of a road tunnel and the subsequent plume development across a complex terrain. The problem setup represents an actual case study where the simulations are performed to evaluate the interaction of the plume with densely populated zones located in the neighborhood of the tunnel portal. The main goal of the present study is to investigate the wind field and plume development as a function of statistically relevant local wind conditions in the area. Computed variations in the wind speed and direction in the region of interest and plume visualizations are employed to study the effect of the complex topography of the terrain on the pollutant release. The decay of the ground level concentration is also estimated to examine the interaction of the plume with the populated zones in the neighborhood of the portal and to address the onset of air-quality issues.

2 Overview of the site and wind data

The site examined in the present study, shown in Fig. 1, is located about 15 km to the NW of the city of Vicenza, in the north of Italy, where the road-tunnel “Malo” has been planned for construction.
A complex landscape is found in the area, formed by hills and mountains with a maximum height difference of about 600 m. The complexity of the landscape is clearly shown by the STL model of the terrain reconstructed from GIS data, also shown in Fig. 1. In the neighborhood of the south portal, major populated areas are found (zones A, B and C in the figure), thereby arising concerns towards excessive exposure to traffic induced pollution. Also shown in Fig. 1 is the position of the weather station employed to establish the prevailing wind conditions in the area.

The PDF of wind speed in Fig. 2 obtained from monitored data shows a skewed distribution towards low values of velocity magnitude (Weibull-type), in agreement with wind energy assessment studies reported in the literature (Justus et al., 1976). Short-span and long-span statistics in Fig. 2 are very consistent, even though the theoretical skewed shape of the distribution is better represented by the long-span dataset due to the larger amount of samples. The average wind speed, of about 1.3 m/s, is also consistent between the two dataset.

The analysis of the wind angle from the short-span dataset highlights two peaks in the PDF associated with the ESE and NNW wind sectors. Bimodal distributions of the wind angle were also observed by Fratianni et al. (2007) in the region of Piemonte, located to the west of the site examined in this study. The bimodal regime was attributed to the particular orography of the territory near the mountain range of the Alps, stretching approximately 1200 km from west to east in the north of Italy and located to the north-east of the tunnel site.

In Fig. 2, the direction of the axis between the two portals and the populated zones located near the tunnel is also shown and compared to the PDF of the wind angle. The point C is exposed to the highest frequency of wind blowing from the location of the portal, whereas the point A is found aligned with the secondary peak associated with the short-span statistics. The variability of the wind angle in the secondary PDF is estimated by fitting a normal distribution to measured data, from which a variance of about two wind sectors is estimated. Therefore, the zone B is also included in the analysis.

3 Methodology

The flow and dispersion over the complex terrain are examined by assuming neutral conditions for the atmospheric boundary layer and by approximating the release of pollutants with that of a passive...
Figure 2: Wind statistics from the weather station: top panel, wind speed; bottom panel, wind angle; the dashed vertical lines denote the direction of the axis between the tunnel portal and the monitoring points.

tracer. In such conditions, the RANS governing equations reduce to those for an incompressible fluid carrying a passive scalar:

\[ \frac{\partial U_i}{\partial x_i} = 0 \]  

\[ \frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} (U_j U_i) = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} (\overline{U_i U_j}) \]  

\[ \frac{\partial C}{\partial t} + \frac{\partial}{\partial x_j} (U_j C) = D \frac{\partial^2 C}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} (\overline{U_j C}) + q_s, \]  

where \( \rho \) is the fluid density, \( \nu \) is the kinematic viscosity of the fluid and \( D \) the scalar diffusivity.

The source \( q_s \) in the scalar transport equation is introduced to mimic the release from the tunnel portal. The unknown Reynolds stress tensor \( \overline{U_i U_j} \) in the momentum equation (2) is estimated by a Differential Reynolds Stress Model (DRSM), where a modeled transport equation is solved for each individual stress, while the turbulent scalar flux \( \overline{U_j C} \) in the scalar transport equation (3) is modeled using an algebraic formulation (Rossi, 2010):

\[ \overline{U_i C} = -D_{ij} \frac{\partial C}{\partial x_j}, \]  

where the tensorial turbulent diffusivity \( D_{ij} \) is employed to account for the scalar flux anisotropy. The algebraic model (4) has been found superior to the standard modeling strategy based on an isotropic diffusivity and thus assuming a linear relationship between scalar fluxes and the mean gradient, providing improved accuracy in predicting turbulent dispersion from concentrated sources in complex flow setup (Rossi et al., 2011).

The computational domain extends to about 12 kilometers around the release site; at the boundaries, the inflow profiles of wind velocity and wind turbulence based on the reference weather data are specified using the method of Richard & Hoxey (1993). The inflow profiles, shown in Fig. 3, are generated using the average wind speed \( U_{ref} = 1.3 \) m/s measured by the weather station at 10m from the ground. An hex-dominant finite-volume grid is employed for the discretization of the STL model shown in Fig. 1. The horizontal resolution of the grid is 50m while an average cell-height of 20m is employed at the ground to allow the use of modified wall-functions based on the characteristic roughness height of the terrain.
4 Results

Wind patterns established at the ground with the change in the incoming wind direction are presented in Fig. 4. For the NW and NNW wind directions, the wind blows in a quite regular fashion in the valley where the monitoring zones A, B and C are located. Nonetheless, the effect of the mountain range located to the north-west of the south-portal is such to make the flow at the source location deviating from the unperturbed wind conditions. As the incoming wind turns from the NW to the NNW sector, the flow is seen turning in the opposite direction, producing greater flow alignment between the portal and the monitoring zone C in the NW case. This is a consequence of the interaction of the flow in the valley with that descending from the hills located to the north of the portal. The two streams are separated by one of the highest peaks, reaching almost 500 m of altitude, where flow separation occurs at the downhill side of the landscape for both the NW and NNW wind directions.

Greater complexity of wind flow at the ground is seen in the area of the south-portal for the ENE and ESE directions of the incoming wind. In this case, flow patterns at the portal location are affected by the hills located to the east of the portal, reaching almost 300 m of altitude. Despite the average flow angle over the reference area of the portal is found almost aligned with that of the incoming wind, the structure of the flow is very much affected by the landscape. When the wind blows from the ENE direction, flow separation occurs at the downslope side of the hill, yielding a converging arrangement of the streamlines associated with the two separate flows moving around the hilltop and merging at the portal location. When the wind turns to the ESE sector, flow separation occurs in the southern part of the hills, leading to a diverging arrangement of the streamlines at the portal location, induced by the pressure minimum arising within the separated zone. In general, the ENE sector is characterized by increased flow separation due to the wind blowing perpendicular to the valley. The separated flow affects the monitoring zone A in particular, which is located downstream of the mountain range of highest altitude.

Computed values of wind direction and speed variations are reported in Fig. 5. The average variation of the wind angle at the south-portal for the five wind directions examined in the study,
normalized by the single sector width of $22.5^\circ$, is about 50%, with a maximum deviation for the NNW direction of the order of a wind sector and a minimum variation of about 13% corresponding to the ENE case. Each one of the three monitored zones shows a similar trend for the incoming wind directions NNW, NW, ESE and SSE, whereas more scattering can be observed for the ENE direction, as suggested by the analysis of wind patterns at the ground. In the ENE case, the zone A shows variations as high as two wind sectors due to the massive flow separation occurring when the wind blows from the ENE direction, whereas the average variation at zones B and C for the same incoming wind flow is about 33% and 13%, respectively. Significant variations are also shown by the point C for the NNW case, where the local wind rotation from unperturbed conditions is of about two sectors. If the ENE sector is not taken into account, the average variation of wind angle for the four remaining wind directions at all monitored zones is of the same order as that characterizing the portal location,
of about 50%.

The average wind speed at monitored zones is found lower than the incoming wind speed for all wind directions. At the source location, the average reduction is about 25%, with a maximum of the order of 35% which is seen for the ESE wind direction. When the wind blows from the NNW and NW sectors, similar variations are found for the zones A and C, located near the hills, whereas the zone B, located in a relatively flat region, shows variations similar to the source location for the same wind directions.

The iso-surface of scalar concentration $C/C_{\text{max}} = 1\%$, where $C_{\text{max}}$ is the maximum concentration at the source, is employed in Fig. 6 to examine the effect of the terrain on the plume development downstream of the portal. The plume size and trajectory are seen to change appreciably with the incoming flow angle due to the established wind field at the ground. For the NW and NNW wind directions, the width of the plume emitted by the south-portal is found similar, but the plume extend much farther along the terrain in the NNW case. Furthermore, because of the greater flow alignment observed in the analysis of the wind field, there is a stronger interaction of the plume with the monitoring zone C when the wind blows from the NW sector.

In the ENE and ESE cases, the downwind extent of the plume is found comparable but the plume width is strongly influenced by the wind patterns at the portal location. The diverging arrangement of the streamlines at the portal location observed for the ESE wind direction leads to a stronger spread near the source, where the plume width is found larger than in the case of the NW and NNW wind directions. A weak interaction of the plume with the zone A is observed in this case due to the separation between the portal and the monitored location as well as because of the hills located downstream of the source along the ESE direction. When the wind blows from the ENE direction, the opposite trend can be seen due to the converging structure of the streamline at the source, where the plume width is found significantly reduced, thereby preventing the interaction of the plume with the monitoring zone B.

The decay of maximum concentration at the ground along the plume trajectory is shown in Fig. 7. From the slope of the profiles associated with the NW and NNW wind directions, it can be noted that the initial decay rate of pollutants concentration downstream of the source is very similar, in agreement with the similar wind speed reduction observed from wind data at the source location. Similarly, the higher decay rate observed for the ESE and ENE wind directions can be attributed to the higher wind speed reduction predicted by the simulations in the region of the portal. Although, the highest reduction is found for the ESE wind direction, the converging structure of the streamlines...
observed when the wind blows from the ENE sector is such to increase the decay rate of the maximum concentration at the ground.

Figure 6: Iso-surface of scalar concentration $C/C_{\text{max}} = 1\%$: top left, NW wind; top right, NNW wind; bottom left, ENE wind; bottom right, ESE wind.

5 Summary and Future work

In this contribution the dispersion of a passive scalar emitted from a localized source has been examined using the RANS equations to address the release of pollutants from a tunnel portal and the interaction of the plume with the surrounding complex topography. The analysis represented an actual case study and demonstrates the capability of the methodology to provide useful information towards a better understanding flow and dispersion developing over a complex terrain. Future work will address the assessment of the accuracy of the present methodology as well as the evaluation of potential benefits against reduced-order models.
Figure 7: Decay of normalized scalar concentration $C/C_{\text{max}}$ at the ground.

References


