Use of wind tunnel measurements for mathematical model comparison and validation

A. Corti[1], E. Canepa[2], D. Contini[1], M. Zanobini [1]
[1] *Department of Energy "Sergio Stecco" - University of Firenze, Via S. Marta 3, I-50139 Firenze (Italy)*
[2] *INFM - Department of Physics - University of Genova, Via Dodecaneso 33, I-16146 Genova (Italy)*

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1 Introduction

As far as airborne pollutant dispersion studies are concerned, wind tunnel measurements are essential for a complete model evaluation process (e.g., Schatzmann and Leitl, 1999) and very useful for developing and improving mathematical models, which up to now strongly rely on empirical parameters.

The boundary layer developed wind tunnel of CRIACIV (http://windlab.ing.unifi.it/) is equipped with a system that allows tracer mean concentrations in gaseous samples to be measured. This system, already used in model validation exercises (e.g., Canepa et al., 2000a; Corti et al., 2001), is based on a Flame Ionization Detector (FID), which allows 12 samples of gas, containing a known tracer, to be taken from different positions inside the tunnel and analyzed on-line.

The small scale model, used in this study, was characterized by one or two stacks with a maximum height of 50 m at full scale scenario and emissions represent buoyancy plumes by means of a less than air dense mixture. Different concentration measurements, like ground and vertical profiles, were carried out at different positions downwind the sources, in order to analyze the spatial distribution of the tracer.

Tracer wind tunnel measurements were compared against the well-known DIMULA, ISC3, SAFE_AIR and ADMS2 mathematical model outputs, using all their available options for the calculation of the dispersion σ-functions.

2 Description of the small scale model

After establishing the model scale (1:270) and the dimensions of the area interested by dispersion (about 1.3 km at full scale), an 'enhanced buoyancy scaling relationship' (Obasaju and Robins, 1998) was used instead of a complete scaling relationship. This allowed obtaining a sufficiently high flow speed in the working section, implying a better quality of the boundary layer flow.

The model parameters are referred to a realistic scenario of pollutant emissions from a waste thermal converter plant and are indicated both at small and full scale in Table 1. In order to simulate buoyancy emission conditions a gaseous mixture less dense than air has been used composed by helium (80% vol.) and ethylene (20% vol.), which represents a suitable organic tracer for the Flame Ionization Detector.

Among the four different experimental cases performed (see Corti et al., 2001), in this study we considered the case 3, a 50 m tall emitting stack with an identical second non-emitting stack downwind aligned with the flow, and the case 4, a single 33.8 m tall emitting stack (Figure 1). The case 3 and 4 were the simplest ones because of in such cases only one stack was emitting instead of two like in the case 1 and 2.

A neutral boundary-layer was developed using spires vortex generator (Irwin, 1981) at the tunnel inlet and roughness elements, with variable height from 10 to 50 mm (being the shorter near the model), covering the entire tunnel length. The height above the ground of the top of the completely developed boundary layer was about 0.60 m (at small scale) near the stacks with slowly increasing values at the end of the wind tunnel testing room.

Several wind profiles were measured with a single hot wire anemometer in order to characterize the flow inside the tunnel. Vertical wind profiles are well described by a power law, with exponential parameter p ranging from 0.06 to 0.14 depending on the distance from the source (origin of the reference system) along the wind tunnel testing room. Localized irregularities in the wind vertical profiles (Figure 2) may be present, partly due to particular confined turbulence conditions and partly to inherent experimental measurement uncertainty. Vertical turbulence intensity profiles at different distances from the source (Figure 2) show rather similar characteristics in the longitudinal direction, so that we can assume that the boundary layer is quite well developed.

The time interval for the acquisition of ethylene concentrations was about 4.5 minutes, suitable for the comparison at full scale scenario with hourly averaged pollutant concentrations obtained by means of simulation codes. A non-dimensional concentration field was obtained normalising the measured concentrations, C (expressed in $\mu g\ m^{-3}$), by means of:

$$\textit{Normalised concentration} = C\, U_{stack}\, A / Q$$

where, at full scale, $U_{stack} = 7.88\ m\ s^{-1}$ is the wind speed at the stack height, $A = 1.21\ m^2$ is the square of a reference length, assumed here the internal stack diameter, and $Q = 2.25\ g\ s^{-1}$ is the ethylene emission rate.

Table 1 Model parameter values at full and at small scale.

Parameter	Full scale value	Small scale value (1:270)
Stack height (case 3)	50 m	18.52 cm
Stack height (case 4)	33.8 m	12.5 cm
Internal stack diameter	1.1 m	4.1 mm
Distance between stacks (case 3)	11.2 m	4.1 cm
Ambient constant temperature	298.2 K	298.2 K
Emitted gas temperature	403.2 K	298.2 K
Emitted gas density	$0.863\ kg\ m^{-3}$	$0.360\ kg\ m^{-3}$
Density ratio ($\alpha = \rho_{gas}/\rho_{air}$)	0.740	0.309
Mean wind profile exponent (p)	0.11	0.11
Mean wind speed at the stack height (U_{stack})	$7.88\ m\ s^{-1}$	$1.21\ m\ s^{-1}$
Volumetric flow rate of emitted gas	$7.5\ Nm^3\ s^{-1}$	$2.16\ l\ min^{-1}$
Emitted gas vertical speed (V_{eff})	$11.6\ m\ s^{-1}$	$2.8\ m\ s^{-1}$
Boundary layer height	162 m	60 cm
Flux Reynolds number	2.52×10^7	1.43×10^4
Surface roughness (z_0)	0.01 m	0.05 mm

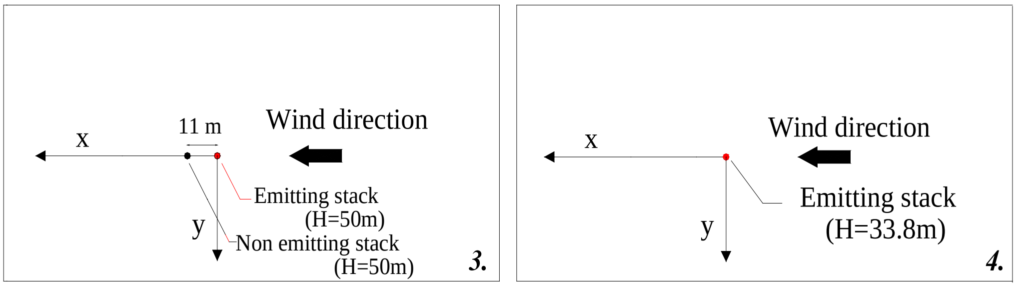

Figure 1 Small scale model configuration in the case 3 and 4.

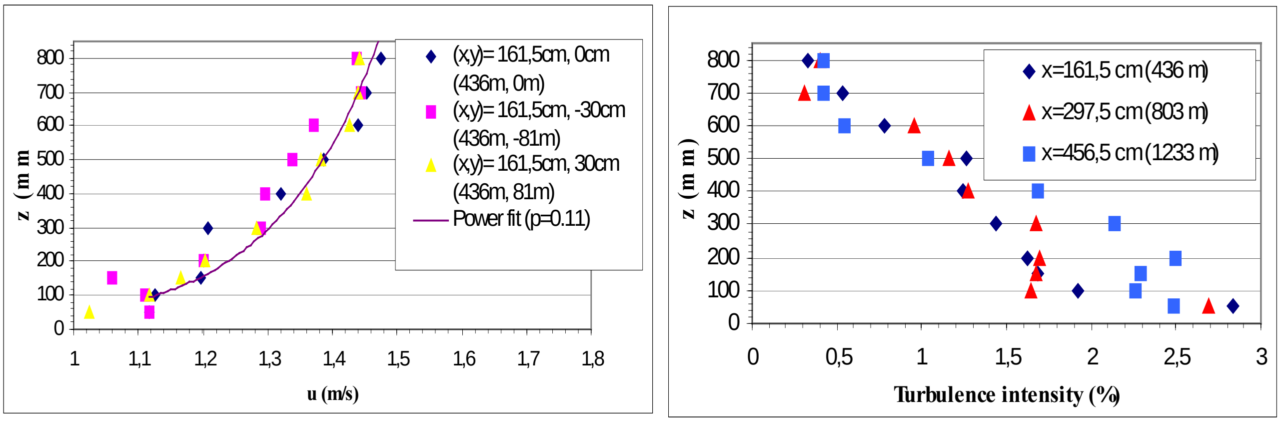

Figure 2 Small scale mean velocity and turbulence intensity profiles at different distances downwind from stacks (distances in brackets are at full scale).

3 Description of the mathematical models

DIMULA (Cirillo et al., 1986) is a Gaussian code characterized by three options to calculate dispersion σ-functions - ‘Briggs rural’ (Dr, in the following), ‘Briggs urban’ (Du) and ‘roughness option’ (Dz) - and Briggs formulas to calculate plume rise. This code allows calculation of ground level concentrations solely.

ISC3 (US EPA, 1995) is a Gaussian code widely employed for pollutant dispersion assessment and mentioned as a ‘preferred model’ in the US EPA recommendations. This code presents two different options to calculate dispersion σ-functions - ‘Briggs rural’ (Ir) and ‘Briggs urban’ (Iu) - and allows calculation of gradual plume rise by Briggs formulas.

The SAFE_AIR code (Canepa et al., 1999; Canepa et al., 2000b), used by the Liguria Region for air quality planning, is an evolution of the US EPA ‘alternative preferred model’ AVACTA II (Zannetti, 1986) and allows the treatment of non-homogeneous and non-stationary conditions in complex terrain. This model contains a meteorological preprocessor for the calculation of the 3D wind field and a pollutant dispersion simulator which makes use of both Gaussian plume segments and puffs. SAFE_AIR has four different options to calculate dispersion σ-functions: ‘Pasquill-Gifford-Turner’ (Sp), ‘Brookhaven’ (Sb), ‘Briggs rural’ (Sr) and ‘Briggs urban’ (Su).

ADMS2 (CERC, 1995) is a UK code characterized by a Gaussian scheme for stable and neutral atmospheric conditions, but a non-Gaussian one for unstable conditions, and allows the description of the planetary boundary layer by means of several physical parameters (A, in the following).

All these codes allow to simulate point, line and area sources in different atmospheric conditions and show particular sensibility with respect to the chosen option to calculate dispersion σ-functions.

4 Mathematical model validation exercise

In order to perform model validation and model inter-comparison we used some of the statistical indices described in Canepa and Builtjes (1999). Statistical indices (Table 2) were calculated referring to normalized concentrations relative to three ground longitudinal profiles (y = - 67.5 m, y = 0 m, y = 67.5 m at full scale) and three vertical ones (x = 420 m, x = 583 m, x = 1220 m at full scale). First, we used the ground level measured concentrations only, in order to evaluate model performances including DIMULA code, unable to calculate vertical concentrations. Then, both ground and vertical measured concentrations were considered, in order to set up a larger database for a more detailed validation test concerning ISC3, SAFE_AIR and ADMS2 codes.

Table 2 Case 3 (above) and case 4 (below): values of the statistical indices.

	ground concentrations						ground and vertical concentrations					
	FB	FS	FA2	MSE	NNR	NNR	FB	FS	FA2	MSE	NNR	NNR
ideal	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Dr	1.12	0.98	0.19	2.73	2.73	2.19	-	-	-	-	-	-
Du	0.56	0.94	0.42	1.15	1.42	0.61	-	-	-	-	-	-
Dz	1.45	0.86	0.00	6.14	6.14	7.62	-	-	-	-	-	-
Ir	1.34	1.10	0.04	4.84	4.84	3.98	0.55	-0.05	0.13	2.28	3.11	2.29
Iu	0.53	0.93	0.42	1.10	1.37	0.62	0.69	1.28	0.33	2.09	2.63	0.78
Sp	1.39	1.20	0.00	5.40	5.40	4.58	0.91	0.56	0.15	2.81	3.60	2.12
Sb	0.86	0.84	0.31	1.47	1.47	1.07	0.72	0.86	0.30	1.85	2.11	0.98
Sr	1.14	1.07	0.08	2.89	2.89	2.23	0.83	0.70	0.17	2.29	2.75	1.54
Su	0.73	0.98	0.31	1.67	2.11	0.94	0.91	1.40	0.26	3.24	4.01	1.08
A	1.52	1.37	0.00	7.86	7.86	5.99	0.77	0.20	0.09	2.93	4.71	9.15
Dr	0.99	0.84	0.34	2.27	2.35	1.34	-	-	-	-	-	-
Du	0.83	0.83	0.34	1.35	1.41	0.76	-	-	-	-	-	-
Dz	1.19	0.43	0.21	3.70	3.79	2.91	-	-	-	-	-	-
Ir	1.12	0.86	0.31	3.15	3.26	1.82	0.57	-0.10	0.44	1.48	1.86	1.08
Iu	0.79	0.75	0.48	1.18	1.23	0.67	0.80	0.95	0.38	1.43	1.55	0.79
Sp	1.11	0.94	0.17	2.79	2.79	1.79	0.75	0.34	0.36	1.38	1.51	0.97
Sb	0.79	0.74	0.38	1.18	1.18	0.89	0.62	0.61	0.58	0.81	0.84	0.54
Sr	0.94	0.87	0.38	1.83	1.84	1.25	0.70	0.50	0.52	1.07	1.11	0.67
Su	0.92	0.70	0.34	1.62	1.62	0.87	0.95	0.95	0.30	2.01	2.10	1.00
A	1.21	1.15	0.17	3.60	3.61	1.93	0.80	0.37	0.34	1.71	1.45	1.49

The FB values result always positive, showing the model tendency to underestimate on average measured data. Data dispersion around mean value is higher for experimental results than for simulated ones (except for Ir), as shown by FS index positive values. As far as case 3 is concerned, for ground concentrations the best results are given by Iu and Du, while for both ground and vertical concentrations by Iu and Sb (unfortunately it is not possible to perform a complete comparison because DIMULA is unable to calculate vertical concentrations). As far as case 4 is concerned, for ground concentrations the best results are given by Iu and Sb, while for both ground and vertical concentrations by Sb definitely. In despite of its detailed treatment of atmospheric turbulence and micrometeorology characteristics, ADMS2 doesn't give in these cases excellent results. We believe because it has been applied about a wind tunnel study, which doesn't allow to fully exploiting the ADMS2 peculiarity. Observing the values of FA2 and NNR, the only two indices strictly usable to compare simulations of different data sets (see Canepa and Builtjes, 1999), one can argue that model performances improve in case 4 with respect to case 3, in particular considering vertical concentrations as well. We believe because: i) case 4 is simpler than case 3 (there is not a second stack that, even if non emitting, could perturb the flux); ii) concentration profiles in case 4 are better developed than in case 3 in the wind tunnel sampling area due to the fact that the source in case 4 is lower than in case 3.

5 Conclusions

Ground and vertical measured concentration profiles, coming from wind tunnel experiments, were compared against the outputs of four different well known codes (DIMULA, ISC3, SAFE_AIR and ADMS2), in order to perform model validation and model inter-comparison. Results showed noticeable differences among the applied models, strongly dependent on the used σ–functions. The applied models underestimated on average experimental measurements. On the whole ISC3, using 'Briggs urban' σ-functions, and SAFE_AIR, using 'Brookhaven'σ-functions, gave the best results. In fact in this experimental case (flat terrain), it is not possible highlight the effects of the main difference between ISC3, which is a straight-line Gaussian model, and SAFE_AIR, which is a segmented Gaussian model.

We are aware that the used validation methodology is very simple because it does not take into account inherent uncertainty and it does not apply any techniques, like bootstrap resampling, to deduce the statistical significance of differences seen in model performance. In any case we believe this is a useful starting exercises. We finally emphasize the interesting study opportunities offered by wind tunnel small-scale simulations both in mathematical model development and validation.

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