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Micro–scale simulation of atmospheric emissions from power–plant stacks in the Po Valley

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ABSTRACT

The atmospheric dispersion of the NO_X plume that will be emitted from a new power–plant, at present under installation, was simulated at micro–scale with Micro–Swift–Spray (MSS) Model. The plant will be constructed in a residential urban area in the town of Modena (Po Valley, Northern Italy), where low wind speeds and thermal inversions are quite frequent. Simulation results point out a different behavior of urban canopy in influencing the 3D dispersion patterns among urban obstacles, according to atmospheric mixing conditions: in case of moderate wind events, urban canyon phenomena may occur with a consequent increasing of NO_X concentration gradients among buildings, while with low winds the near–field influence of the buildings emphasizes pollutant accumulation. The MSS simulated NO_X concentrations result always much lower than the regulatory limits for air quality. The comparison of simulation results with measured concentration data for NO_X shows the importance of micro–scale dispersion modeling to perform an accurate and reliable assessment of meteorological condition effects on pollutant distribution, and the ability of MSS in providing reliable simulations of atmospheric dispersion.

Keywords: *Micro–scale simulation, urban canopy, plant stacks, low wind, measured concentrations*

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1. Introduction

The reduction of pollutant emissions from combustion plants are firm commitments set by the European Commission. The European Commission promotes the "cogeneration" (EU, 2004), i.e. combined production of heat and electricity, because the self–production of electric power reduces the needs of electricity generation from conventional systems. However, the impact of a cogeneration plant on air quality depends on its emission performance but also on the dispersion of its stack emissions in the atmosphere.

In this case study, a new power plant, methane fuelled, consisting of a tri–generation unit and five auxiliary devices (conventional generators), will be installed in the General Hospital of a Northern Italy town (Modena, Central Po Valley, 34 m asl.).

The atmospheric impact at local scale of the stack emissions from this power plant have already been investigated by Ghermandi et al. (2014) which showed how the impact at ground resulted smaller for the emissions by the tri–generation unit than by the conventional boiler, also under meteorological conditions favoring pollutant accumulation in the atmosphere.

Main aim of the present work was to study the dispersion patterns of stack emissions at micro–scale in the urban area close to the General Hospital, where maximum concentration values for the emitted pollutants are expected and where atmospheric dispersion is strongly influenced by building location, distance and height.

The simulations were performed by the Micro–Swift–Spray (MSS) code (Moussafir et al., 2004; Tinarelli et al., 2012) featured in the ARIA INDUSTRY software package. This code includes the mass–consistent diagnostic 3D wind–field model Micro–Swift (Aria Technologies, 2010) and the Lagrangian Particle Dispersion model Micro–Spray (Arianet, 2010) implemented for micro–scale applications, able to simulate the airborne pollutant dispersion among buildings. The model considers non–homogeneous and non–stationary atmospheric turbulent conditions, plume rise effects (Anfossi et al., 1993) and stochastic velocity fluctuations (Thomson, 1987). Plume rise phenomena can be simulated by Micro–Spray in different atmospheric conditions by computing the buoyancy flux of each particle (i.e. plume parcel) according to the exhaust gas exit conditions and the atmospheric stability class. In presence of a ground surface–based thermal inversion layer, the partial penetration of the inversion is simulated through those plume particles that still retain high buoyancy when reaching the top of the inversion layer (Arianet, 2010).

MSS Model performances in approaching complex phenomena were widely tested in the literature and showed a good agreement with Computational Fluid Dynamics (CFD) models (Tinarelli et al., 2007; Tinarelli et al., 2008), with other diagnostic wind flow and Lagrangian particle dispersion models and with experimental data (Hanna et al., 2011).

The simulations were performed under two different atmospheric conditions during winter, the most critical season for air quality in the Po Valley (Ferrero et al., 2011): a low wind (i.e. wind speed <2 m/s) event (prevalent condition at the studied site) and a case of wind speed significantly above the average winter value.

The simulation was focused on NO_X dispersion, being the most critical pollutant for methane fuelled plants: the ground level concentrations of emitted NO_X obtained from the simulations were compared with air quality regulatory limits.

The reliability of MSS Model in simulating dispersion patterns in urban environment according to the daily evolution of atmospheric mixing conditions was evaluated by the correlation between simulated and measured concentration data.

2. Case Study

A new power plant will be installed at the General Hospital of Modena in order to supply its total energy demand. It will consist of six devices supplied by methane gas: a tri–generation unit powered by an internal combustion four–stroke engine, three conventional boilers, and two industrial steam generators. Stacks are all 10 m high except for the tri–generator (15 m). The plant design is oversized in order to fulfill the energy demand with safety criteria, and during ordinary operation only three devices will be active: the tri–generator, one boiler and one steam generator. Features and operating conditions of the plant were described by Ghermandi et al. (2014), who estimated the emitted exhaust gas flows from stacks on the basis of the hourly average planned fuel consumption in the monthly mean day. For a daily micro–scale simulation, spanning over a period of 24 hours, a specific hourly modulation of emission patterns for boilers and for steam generators was considered. For the tri–generator, which operates at steady–state conditions, the emission pattern was assumed to be constant throughout the day.

3. Model Setup and Data Set

MSS simulation was performed over a 500 m x 500 m horizontal domain, centered at plant position and divided into a regular grid of cells with size of 2 m x 2 m. This domain represents the urban area surrounding the General Hospital where the highest atmospheric impact from the future power plant is expected. The vertical domain is divided into a grid of 20 layers with variable thickness from the ground to 200 m (domain top): the first vertical layer is 2 m thick. The numbered points in Figure 1a show the plant stack locations in the micro–scale domain: boiler (1), steam generator (2), and tri–generator (3). Building geometry (Figure 1b) was drawn out from an urban elevation model provided as a polygon vector file (shapefile) (E.R., 2011) using a GIS software package.

Two days, January 14th and February 6th, were selected from the winter 2010 meteorological dataset in order to obtain simulations under widely differing meteorological conditions.

Both simulated and measured meteorological data were used in MSS simulations. Wind speed data were provided by the meteorological station of the Osservatorio Geofisico (University of Modena and Reggio Emilia) located in Modena near the sources. Meteorological simulated data comprise mesoscale vertical wind profiles and mixing height. These data have been provided by the Regional Environmental Agency (ARPA) using the diagnostic model CALMET (Deserti et al., 2001), which requires input meteorological ground measurements and radiosounding profiles of temperature and wind speed (Chandrasekar et al., 2003). Daily patterns for hourly wind speed and for mixing height in the two test days are plotted in Figure 2. In 2010, average winter values of wind speed and mixing height in Modena resulted of 1.7 m/s and 310 m, respectively.

January 14th is characterized by low winds (i.e. wind speed <2 m/s); mixing height pattern clearly shows that stable conditions occur early in the morning and at nightfall, while thermal convection prevails only in the middle of the day. Similar atmospheric conditions, in which stability occurs for most of the day, are unfavorable to pollutant dispersion and are fairly frequent during the winter in the Po Valley (Bigi et al., 2012). On the contrary, on February 6th, wind speed values are higher than the average measured value for the whole 2010 winter season and the irregular trend of the mixing height is due to clouds and rainy periods (daily precipitation is 8 mm). This day has been chosen in order to evaluate the dispersion patterns in conditions of moderate wind, which infrequently occur in the studied area.

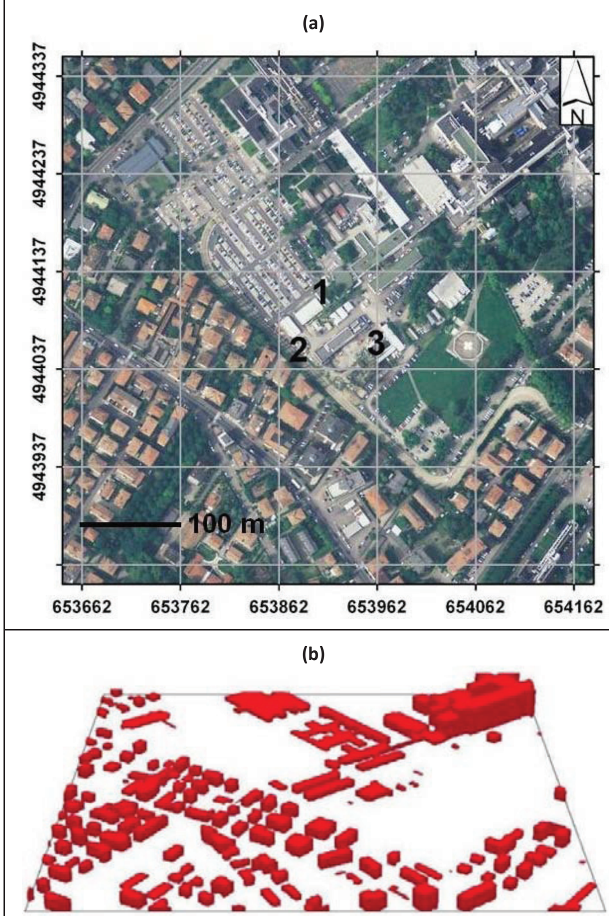

Figure 1. *The studied area in Modena: geographical map* ***(a)*** *and 3D block–shaped structure in MSS* ***(b)****.*

The MSS simulation time step has been set to one hour, consistently with the acquisition time step of meteorological input data.

The same operating conditions consistent with the plant design have been assumed for both simulations; therefore the NO_X emission rate from the plant is the same for the two days. Table 1 reports daily average for exhaust gas temperature and velocity at the exit of the three device stacks during the two test days.

4. Results

4.1. NO_X concentration maps and micro–scale stagnation effects

The maps of daily average NO_X concentration (i.e. the average of the 24 hourly runs of the MSS simulation) in the first atmospheric layer, obtained from the simulation of the emissions of all three future plant sources, for the two test days, are shown in Figure 3.