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Influential parameters on ultrafine particle concentration downwind at waste-to-energy plants

Mauro Scungio [a], Giorgio Buonanno [a,b,*], Fausto Arpino [a], Giorgio Ficco [a]

[a] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via G. di Biasio 43, 03043 Cassino (FR), Italy
[b] Queensland University of Technology, 2 George Street, Brisbane, QLD 4000, Australia

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ABSTRACT

A numerical investigation on the parameters influencing the ultrafine particle concentrations downwind an incinerator plant has been carried out on a three-dimensional full scale model. The simulation was based on a modified version of the k–ε turbulence model in order to take into account the thermal buoyancy effect of the plume, and reproducing a stable and neutral atmospheric boundary layer by setting appropriate values of velocity, turbulent kinetic energy and turbulent dissipation rate. The ability of the model to reproduce and maintain a stable atmospheric boundary layer was evaluated by analyzing the turbulent characteristics of the flow along the domain. A parametric analysis made on the basis of different plant operational, environmental, and flue gas treatment parameters was carried out in order to evaluate the impact of incinerator plants on the background concentration of ultrafine particles. The evaluation was made at 5 km downwind the chimney in a breathable area, showing that the most significant impact is due to the flue gas treatment section, with a variation on the background concentration up to 370% for a plant hypothetically working without controls on ultrafine particles emission. Operational and environmental parameters determine variations of the concentrations ranging from 1.62% to 4.48% for the lowest and highest chimney, from 1.41% to 4.52% for the lowest and highest wind speed and from 2.48% to 4.5% for the lowest and highest flue gas velocity, respectively. In addition, plume rise evaluation was carried out as a function of wind speed and flue gas velocity from the chimney.

1. introduction

In waste management, incineration is a common practice for reducing waste volume and recovering its energy content in order to produce electricity and district heating. Nevertheless, incinerators have generated a strong debate in Western countries about their emission of ultrafine particles (UFPs from now on) (Maguhn et al., 2003). From a legislative point of view, air quality threshold limit values are only stated in terms of particle mass: PM_{10} and $PM_{2.5}$ (particulate matter collected by a selective inlet with a 50% cut-off efficiency at 10 μm of aerodynamic diameter and with a 50% cut-off efficiency at 2.5 μm of aerodynamic diameter, respectively). In addition, the Directive 2010/75/EU (2010) imposes different threshold limit values on the total dust emitted (total amount of particles emitted in terms of mass) at the stack of the plants, as type of fuel and total rated thermal input vary.

Monitoring UFPs is important for several reasons: the toxic nature of the particles due to the organic compounds on itself (Eiguren-Fernandez et al., 2010), the ability of UFPs to penetrate in the epithelial cells of the lower respiratory tract and accumulate in lymph nodes (Nel et al., 2006), the oxidative damage effects on DNA (Møller et al., 2008), and the potential association with paediatric asthma (Andersen et al., 2008) are some of the harmful effects on human health caused by exposure to nanoparticles. In addition, the International Agency for Research on Cancer (IARC), which is part of the World Health Organisation (WHO), has recently classified the particulate matter as carcinogenic to humans (Group 1) (Loomis et al., 2013).

According to the scientific literature in terms of anthropogenic emissions (Buonanno and Morawska, 2014b; Cass et al., 2000; UK Department for Environment, 1999; US Environmental Protection Agency, 2000), incinerators are supposed to emit a very low amount of particles if compared to fossil fuel power plants and vehicle emissions, since the Best Available Techniques (BAT) (European Commission, 2006) are used in the flue gas cleaning operations of modern plants. Actually, a small number of experimental campaigns focused on the evaluation of UFPs emission

* Corresponding author at: Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via G. di Biasio 43, 03043 Cassino (FR), Italy. Tel.: +39 0776 2993618.
E-mail address: buonanno@unicas.it (G. Buonanno).

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from incinerators (Buonanno et al., 2010a, 2009a, 2012, 2010b; Maguhn et al., 2003; Ragazzi et al., 2013), and numerical analysis on plume trajectory (König and Mokhtarzadeh-Dehghan, 2002) were carried out. Moreover, such analysis were often limited to the mass fraction of the aerosol emitted (Buonanno et al., 2011) or its dimensional and chemical characterisation, and only few papers report information on UFP stack concentration levels for plants with different emission control devices and plant operations (Cernuschi et al., 2012; Zeuthen et al., 2007).

In the present work, numerical investigation on UFPs number concentration at downwind side of incinerator plants is presented by solving the mass, momentum, turbulence and pollutant dispersion equations, as operational, flue gas treatment and environmental conditions vary, in neutral and stable atmospheric boundary layer condition.

2. Methods

2.1. Mathematical models

Dispersion of UFPs from incinerator chimney may be described by reproducing the turbulent and buoyant plume evolution in the atmospheric boundary layer. In this work, the commercial software Comsol Multiphisics® was used to solve the well-known standard version of the k-ε turbulence model, and the conservation equations for energy and species. In particular, the original equations of the k–ε turbulence model (Launder and Spalding, 1974) were modified in order to take into account the thermal buoyancy effect of the plume (De Lemos and Dórea, 2011):

$$\rho\frac{\partial k}{\partial t}+\rho\frac{\partial(U_i k)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+\mu_T\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-\varepsilon\rho+\rho\beta\frac{v_T}{\sigma_T}g\cdot\nabla T \quad (1)$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\frac{\partial(U_i \varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_1\frac{\varepsilon}{k}\mu_T\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-\rho C_2\frac{\varepsilon^2}{k}+C_1C_3\rho\beta\frac{v_T}{\sigma_T}g\cdot\nabla T \quad (2)$$

Eqs. (1) and (2) calculate the turbulent kinetic energy, k, and the turbulent dissipation rate, ε, respectively. The last terms of the right hand sides of Eqs. (1) and (2) were added in order to couple the velocity and temperature fields. In particular C_1, C_3 and σ_T are constants, ρ is the air density, β is defined as $1/T_{amb}$, where T_{amb} is the ambient air temperature, g is the gravity and ∇T is the temperature gradient. Detailed discussion about the original equations and the additional terms can be found in literature (De Lemos and Dórea, 2011; Launder and Spalding, 1974).

The UFPs dispersion was evaluated using an Eulerian approach, solving the following mass conservation equation for chemical species with a K-closure method (Moreira and Vilhena, 2010):

$$\frac{\partial c}{\partial t}+U\cdot\nabla c=(D+v_T)\nabla^2 c \quad (3)$$

in which c is the concentration, v_T is the eddy viscosity, and the molecular diffusion coefficient D is added to the eddy viscosity in order to take into account the turbulent diffusion of the particles. UFPs were modelled as a gas phase, imposing their diameter by the definition of a corresponding diffusion coefficient as reported by Baron and Willeke (2001). The relation between diffusion coefficient and particle diameter is:

$$D=\frac{kTC_C}{3\pi\eta d_p} \quad (4)$$

where D is the diffusion coefficient, k is the Boltzmann constant (1.38×10^{-23} N m K^{-1}), C_C is the Cunningham slip correction factor, defined as $C_C=1+\frac{\lambda}{d}\left[2.34+1.05\exp(-0.39\frac{d}{\lambda})\right]$ (Hinds, 1999), η is the air viscosity and d_p the particle diameter. Since a particle size of 100 nm was considered as emitted by the source, the corresponding diffusion coefficient, calculated from Eq. (4) is $D=6.8608\times10^{-10}$ m^2 s^{-1}. Particles of 100 nm were considered since this is the typical mode of UFPs size distribution from incinerator emission (Buonanno et al., 2009a; Maguhn et al., 2003). Buonanno et al. (2009b) found that particles emitted from combustion sources in rural environment (near highways) are only subjected to dilution process, showing that the mode does not change at different distances from the source. In the light of that, only the dilution process was considered in the present simulations, neglecting phenomena like aggregation, and condensation.

2.2. Computational models and boundary conditions

Fig. 1 reports the computational domain adopted for the present calculations, which is similar to that used by Hargreaves and Wright (2007) for a numerical reproduction of an atmospheric boundary layer with a k–ε turbulence model. The domain has a dimension of 5000 m in the y-direction (length), 35 D_s in the x direction (width) and 140 D_s in the z direction (height), where D_s is the stack diameter, which was set to 3 m.

The chimney is located at a distance of 40 D_s from the cross wind inlet, and is modelled as an adiabatic duct of 3 m of diameter and different heights: velocity, temperature and a UFP emission values were imposed on the chimney inlet. Assuming that, the flow at the chimney exit becomes fully developed, taking appropriate profiles of turbulence and velocity, leading to a more accurate reproduction of his structure, while the adiabatic condition imposed on the chimney walls makes the flue gas temperature constant along the duct. The temperature of the flue gas and the ambient air were set to 413.15 K and 298.15 K, respectively. No thermal flux (adiabatic condition) was set at the bottom of the domain, since neutral and stable atmosphere condition was considered. The background concentration of UFPs, assuming a rural environment, was set to 5.0×10^9 part m^{-3} as reported from Buonanno et al. (2009b), while different values of UFP emission were adopted and imposed on the chimney inlet. A typical neutral and stable atmospheric boundary layer (ABL) was reproduced by imposing at the cross wind inlet of the domain appropriate laws for vertical profiles of velocity, turbulent kinetic energy and dissipation rate. Since the main aim of the present work is to analyze the effect of the plant operational, environmental, and flue gas treatment parameters on the background concentration of UFPs, the ABL was considered only in neutral and stable condition, referring to a future development of the present study for the evaluation of different additional atmospheric stability classes. As regards the vertical profile for velocity, the following law was used (König and Mokhtarzadeh-Dehghan, 2002):

$$\frac{U}{U_{th}}=\ln(z/z_0)/\ln(z_{th}/z_0) \quad (5)$$

where z is the height from the ground, z_0 is a roughness length set to 0.3 m and z_{th} is the height at the chimney top level. For a neutral and stable boundary layer, Han et al. (2000) provided the following laws for turbulent kinetic energy (k) and dissipation rate (ε):

$$\left.\begin{aligned}k&=6\cdot u_*^2\\ \varepsilon&=\frac{u_*^3}{k\cdot z}\left(1.24+4.3\frac{z}{L}\right)\end{aligned}\right\}\ \text{for } z\leqslant 0.1\ \text{h} \quad (6)$$

$$\left.\begin{aligned}k&=6\cdot u_*^2\left(1-\frac{z}{h}\right)^{1.75}\\ \varepsilon&=\frac{u_*^3}{k\cdot z}\left(1.24+4.3\frac{z}{L}\right)\left(1-0.85\frac{z}{h}\right)^{1.5}\end{aligned}\right\}\ \text{for } z\geqslant 0.1\ \text{h} \quad (7)$$