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A new Lagrangian method for modelling the buoyant plume rise

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HIGHLIGHTS

- The paper deals with the problem of the plume rise in the dispersion model.
- A new technique based on temperature difference is used for plume rise computation.
- Comparison of the model with experiments shows a satisfactory agreement.

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ABSTRACT

A new method for the buoyant plume rise computation is proposed. Following Alessandrini and Ferrero (Phys A 388:1375–1387, 2009) a scalar transported by the particles and representing the temperature difference between the plume and the environment air is introduced. As a consequence, no more particles than those inside the plume have to be released to simulate the entrainment of the background air temperature. A second scalar, the vertical plume velocity, is assigned to each particle. In this way the entrainment is properly simulated and the plume rise is calculated from the local property of the flow. The model has been tested against data from two laboratory experiments in neutral and stable stratified flows. The comparison shows a good agreement.

Then, we tested our new model against literature analytical formulae in a simple uniform neutral atmosphere, considering either the case of a single plume or the one of two plumes from adjacent stacks combining during the rising stage. Finally, a comparison of the model against an atmospheric tracer experiment (Bull Run), characterized by vertically non-homogeneous fields (wind velocity, temperature, velocity standard deviations and time scales), was performed. All the tests confirmed the satisfactory performance of the model.

1. Introduction

The computation of plume rise is one of the basic aspects for a correct estimation of the transport and dispersion of airborne pollutants and for the evaluation of ground level concentration.

A buoyant plume rises under the action of its initial momentum and buoyancy. It experiences a shear force at its perimeter, where momentum is transferred from the plume to the surrounding air, and ambient air is entrained into the plume. This phenomenon, entrainment, is responsible of the plume diameter increase, of the decrease of its mean velocity and of the average temperature difference between air and plume as well. In the first stage the plume also spreads under the action of the buoyancy-generated turbulence but progressively the effect of ambient turbulence becomes predominant. In a calm atmosphere, plumes rise almost vertically, whereas in windy situations they bend over. In this case, the velocity of any plume parcel is the vector composition of horizontal wind velocity and vertical plume velocity in the first stage and then approaches the horizontal wind velocity.

In the Eulerian dispersion models, the calculation of plume rise is based on the fluid dynamic equations, namely on the mass, momentum and energy conservation equations. A complete, exhaustive theory is not yet available. These equations are closed using the entrainment assumption proposed by Morton et al. (1956), which prescribes that the entrainment velocity, i.e. the rate at which ambient air is entrained into the plume, is proportional to the mean local rise velocity, i.e.:

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$$\frac{dR}{dt} = \beta\frac{dz}{dt} = u_e \tag{1}$$

where R is the plume radius, z the distance from the source, β is the dimensionless entrainment parameter and u_e the entrainment velocity; alternatively:

$$R = \beta z \tag{2}$$

which expresses the observed fact that the plume radius linearly increases with the distance from the source. The value of β has to be empirically established: although there are slightly different suggestions for it, the following values are generally accepted (Briggs, 1975; Hoult and Weil, 1972): $\beta = 0.6$ in the bent over buoyant plumes (in which the angle ϕ between the horizontal and the centreline $\phi \to 0$) and $\beta = 0.11$ for vertical buoyant plumes ($\phi \to 90^{\circ}$). The simple entrainment assumption (eq. (1) or 2) was generally used in semi-empirical analytical formulations (Briggs, 1975), whereas more complex three-dimensional expressions, which account at each plume position for the effect on the entrainment of the directions of both wind and plume, are inserted in the integral models (see, for instance:Ooms, 1972; Glendening et al., 1984). An example is the following:

$$u_e = \left[\beta\left|u_s - U_a\cos\left(\psi_p - \psi_a\right)\cos\left(\phi_p - \phi_a\right)\right| + \alpha\left|U_a\left[1 - \cos^2\left(\psi_p - \psi_a\right)\cos^2\left(\phi_p - \phi_a\right)\right]^{1/2}\right|\right] \tag{3}$$

in which: a, p refer to air and plume, respectively, U_a is the wind velocity, $\beta = 0.6$ and $\alpha = 0.11$ are the entrainment constants, ϕ and ψ are the angles that the x and z axes make with the wind (a) and plume (p) velocities.

In Lagrangian Particle Models (LPM) plume rise can be dynamically computed, i.e. each particle, at each time step, can respond to local conditions: wind speed and direction, ambient stability and turbulence (both the self-generated and ambient ones). This allows obtaining a high degree of resolution. Moreover, it allows simulating the interaction of a plume with a capping inversion layer and the mixture of different plumes in a "natural" way. However, the introduction of the plume rise computation in an LPM is not straightforward. In fact, the buoyant forces acting on the plume portions depend on the difference between their temperature and that of the background air. This can be computed only considering the entrainment phenomenon. To do that, these models should take into account all the fluid simultaneously, i.e. by filling the whole domain with a large amount of particles. This is practically impossible due to the huge amount of particles that it should be necessary to track in the computational domain. To overcome this problem three different "hybrid" techniques (i.e., that consider together Lagrangian and Eulerian properties) have been proposed (Webster and Thomson, 2002; Anfossi and Physick, 2005): particles emission occurs at the final plume height computed by analytical models (such as the Briggs, 1975; ones), an integral plume rise model is used at each time step for each particle and the derived velocities are added to the Lagrangian stochastic particles velocities (see, for instance, Anfossi et al., 1993) and a set of differential equations describing the time and space evolution of bulk plume quantities are solved at each time step (Webster and Thomson, 2002; Anfossi et al., 2010). An interesting method was proposed by van Dop (1992) in which a Langevin equation for the particle temperature is solved and the buoyancy of the particle is included in the Langevin equation for the particle velocity evolution. Though having advantages from the turbulence closure point of view, this approach has problems in the entrainment treatment.

In the present paper the method suggested by Alessandrini et al. (2012) and Alessandrini and Amicarelli (2012) for the buoyant plume rise computation is proposed again in a revised version and validated with further tests. It is based on the same idea described in recent papers related with chemical reactions in Lagrangian particle models (Alessandrini and Ferrero, 2009; Alessandrini et al., 2011) for simulating the ozone background concentration. A fictitious scalar transported by the particles, the temperature difference between the plume portions and the environment air temperature, is introduced. As a consequence no more particles than those inside the plume have to be released to simulate the entrainment of the background air temperature. In this way the entrainment is properly simulated and the plume rise is calculated from the local property of the flow. This new approach is wholly Lagrangian in the sense that the Eulerian grid is just used to compute the property of a portion of the plume from the particles contained in every cell. No equation of the bulk plume is solved on a fixed grid. Without considering the simplification of the model, this method has the advantage of being applicable also in those situations where the analytical equation for the vertical velocity is difficult to define, i.e. where several plumes, released by different stacks located close to each other, mix themselves together.

In the next Section the new plume rise model is presented. The third Section deals with the model validation in four situations: two water tank experiments (one in neutral and the other in stable conditions), an idealized neutral atmosphere (both single and two stacks cases) and, finally, an atmospheric tracer experiment, Bull Run (Hanna and Paine, 1987, 1989).

2. The new plume rise model

The new Lagrangian plume rise module was introduced in the Lagrangian stochastic particle model SPRAY (Tinarelli et al., 2000; Alessandrini et al., 2005a,b; Alessandrini and Ferrero, 2011). In the new module each particle carries two quantities that specify the difference between the temperature and the momentum of the plume air and the environment. To this aim we assign to any i-th emitted particle in the time interval Δt the "temperature mass" m_T, defined as follows:

$$m_{T_i} = \frac{\left[T_{p_{init}} - T_a(H_s)\right]|w_u|A\Delta t}{N_p} \tag{4}$$

where $T_{p_{init}}$ is the initial plume temperature, $T_a(H_S)$ is the environment air temperature at the stack height H_s, A is the stack exit section and N_P is the total number of particles released in the time interval Δt and w_u the plume exit velocity. Note that m_T does not have the dimension of a mass but can be considered a "mass" if the temperature difference plays the role of a density. Considering the domain divided in fixed regular cubic cells, the air-plume temperature difference for the generic cell, ΔT_c, is:

$$\Delta T_c(t_0) = \frac{\sum_i^M m_{T_i}(t_0)}{V_c}, \tag{5}$$

where M is the number of particles in the cell c and V_c is the cell volume.

In order to take into account the momentum flux we define the momentum mass m_{wi}, which is assigned to each particle. Also in this case, m_{wi} has not the dimension of a mass but it can be considered so when w_u plays the role of a density. At the beginning of the simulation we have: