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Review article

A new approach for modeling dry deposition velocity of particles

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ABSTRACT

The dry deposition process is recognized as an important pathway among the various removal processes of pollutants in the atmosphere. In this field, there are several models reported in the literature useful to predict the dry deposition velocity of particles of different diameters but many of them are not capable of representing dry deposition phenomena for several categories of pollutants and deposition surfaces. Moreover, their applications is valid for specific conditions and if the data in that application meet all of the assumptions required of the data used to define the model. In this paper a new dry deposition velocity model based on an electrical analogy schema is proposed to overcome the above issues. The dry deposition velocity is evaluated by assuming that the resistances that affect the particle flux in the Quasi-Laminar Sub-layers can be combined to take into account local features of the mutual influence of inertial impact processes and the turbulent one. Comparisons with the experimental data from literature indicate that the proposed model allows to capture with good agreement the main dry deposition phenomena for the examined environmental conditions and deposition surfaces to be determined. The proposed approach could be easily implemented within atmospheric dispersion modeling codes and efficiently addressing different deposition surfaces for several particle pollution.

1. Introduction

The dry deposition process, which controls the transfer of pollutants from the atmosphere to the surface, is of interest to several disciplines, such as industrial emissions, natural dust, trace metals, chemicals, etc. In the nuclear field, if event of a severe accident and the release of radionuclides in the atmosphere occurs, certain key challenges arise, such as characterizing the specific types of release as well as studying the dispersion and deposition phenomena useful for defining effective mitigation measures and actions to protect the population.

As highlighted in ATMES (Atmospheric Transport Model Evaluation Study) report (Klug et al., 1992), the greatest number of uncertainties in numerical evaluations of pollutant transport and dispersion in air are introduced by the parameterizations both of the source term and deposition velocities.

There is no single accepted theoretical description of the dry deposition phenomena due to the complexity of the fluid-dynamic processes that influence the deposition flux and the lack of a complete experimental set of data covering all scenarios of interest that limits the understanding of certain key aspects occurring in the process.

Various experimental campaigns, performed in different international laboratories, resulted in the evaluation of the dry deposition velocities for different types of pollutants and deposition surfaces. Nevertheless, there is a difficulty in generalizing this phenomenon because the velocity values differ by four orders of magnitude for gases and three orders of magnitude for particles (Sehmel, 1980; Pryor et al., 2007; Guha, 2008; Petroff et al., 2008). These issues limit the possibility of studying the dry deposition process using a single modeling approach. In fact, the models proposed in literature are not capable of representing dry deposition phenomena for several categories of pollutants and deposition surfaces because their applications is valid for specific conditions and if the data in that application meet all of the assumptions required of the data used to define the model.

In this field, some studies, performed at the Department of Energy, Information Engineering and Models Mathematicians (DEIM) of the University of Palermo, Italy, were focused on identifying of a approach capable of representing dry deposition phenomena for several categories of pollutants and deposition surfaces. Based on the study, a new scheme for the parameterization of the dry deposition velocity of particles is proposed. The primary goal is to develop a model that can be easily implemented within atmospheric dispersion modeling codes and is capable of efficiently addressing different deposition surfaces.

This study involved comparisons with experimental data reported in literature for different particle deposition scenarios. The results indicate that the proposed approach can determine, with good agreement, the main aspects of the phenomena involved in dry deposition processes for the studied environmental conditions and deposition surfaces.

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2. Dry deposition process

The dry deposition process refers to all phenomena of meteorological, chemical and biological nature that influence a flux of gas and particle pollutants interacting with a ground surface without involving the water in the atmosphere.

In this field, the knowledge regarding the dry deposition of particles is far from complete due to the complex dependence of deposition on particle size, density, terrain, vegetation, meteorological conditions and chemical species.

The primary phenomena that are considered to affect the process can be described as follows:

- transport due to atmospheric turbulence in the low layer of the Planetary Boundary Layer (PBL), which is called the Surface Layer (SL). It is independent of the physical and chemical nature of the pollutant and depends only on the atmospheric turbulence level (i.e. turbulent movements of air);
- diffusion in the thin layer of air, which overlooks the air-ground interface (named the Quasi-Laminar Sublayer, QLS), where the molecular diffusion for gas, Brownian motion and turbulent diffusion for particles and gravity for heavier particles becomes dominant;
- transfer to the ground (e.g. interception, impaction, and rebound), which exhibits a pronounced dependence on the surface type with which the pollutant interacts.

The Brownian diffusion and eddy turbulence effects make a significant contribution to the total dry deposition velocity for particles in the size range from 0.01 μm to approximately a few micrometers. It is assumed to dominate the diffusion processes in the quasi-laminar sublayer surface. For particles of intermediate diameter d_p (in the range of approximately 0.1–1 μm), the process strongly depends on atmospheric conditions, surface characteristics, and particle size.

Above this range, the deposition is dominated by other phenomena, such as the inertial impaction characterized by the following interaction mechanisms (Petroff et al., 2008):

- Inertial impaction. If the particle inertia is too large, then the particle, transported by the flow towards an obstacle, cannot follow the flow deviation (particles may not be able to follow it due to inertia) and can consequently collide with the obstacle and remain on the surface.
- Turbulent impaction. In this mechanism, the particle has a sufficiently high velocity such that turbulent eddies can result in a transverse "free fight velocity". Thus, particles possess sufficient momentum to reach the surface (Epstein, 1997; Almohammed and Breuer, 2016; Kor and Kharrat, 2016).

3. Short review of the dry deposition models for gas and particle

A key concept to studying the dry deposition process is the deposition velocity v_d (m s^{-1}) (i.e. the deposition velocity at a given height z), which can link the pollutant vertical flux to the concentration measured at quota z (m) to the ground reference level as follows:

$$v_d = \frac{F}{C(z)} \tag{1}$$

where F ($gm^{-2}s^{-1}$) is the pollutant flux removed per unit area; and $C(z)$ (gm^{-3}) is the pollutant concentration at quota z.

By considering that the reciprocal of v_d is the overall resistance to the mass transfer, the influence of the various phenomena on the deposition velocity can be expressed in terms of an electrical analogy. Based on the analogy of electrical circuits, the resistance to the deposition can be configured as resistances in circuits in parallel and series to describe the transfer factor between the air and the surface.

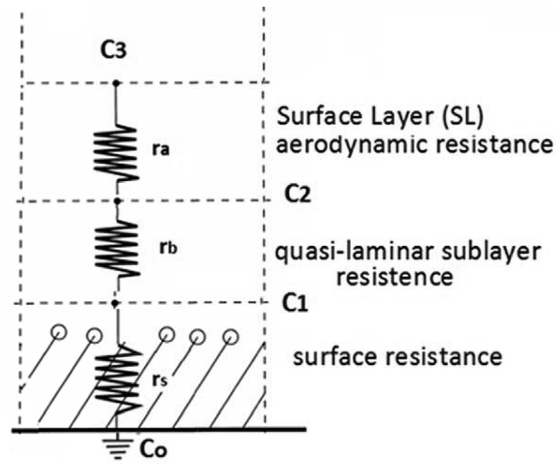

Fig. 1. Electrical analogy for the dry deposition of gaseous pollutants.

For a gaseous pollutant collection, it is possible to schematize the process, as indicated in Fig. 1; hence, we can express the relationship as follows:

$$\left|F\right| = \frac{C_3 - C_2}{r_a} = \frac{C_2 - C_1}{r_b} = \frac{C_1 - C_0}{r_s} \tag{2}$$

where r_a is the aerodynamic resistance considering the turbulence phenomenon in SL; r_b is the quasi-laminar sublayer resistance related to the diffusion phenomenon for gas and collisions due to the Brownian motion for particles; and r_s is the surface resistance, which depends on the nature of the receptor ground.

Based on the previous equation, the following relationship can be derived:

$$C_3 = (r_a + r_b + r_s)\,|F| \tag{3}$$

Accordingly, the dry deposition velocity formulation for gas can be given as follows:

$$v_d = \frac{1}{r_a + r_b + r_s} \tag{4}$$

Different studies have been reported in the literature (Wesely et al., 1985; Giorgi, 1986; Padro et al., 1991; Erisman et al., 1994; Padro, 1996; Wesely et al., 2001; Zhang et al., 2003; Kor and Kharrat, 2016) to evaluate parameters r_a and r_b. The calculation of the gas surface resistance r_s depends on the primary pathways for uptake, such as diffusion through the leaf stomata and uptake through the leaf cuticular membrane. A revised parameterization, which includes a realistic treatment of the cuticle and ground resistance in winter (low temperature and snow-covered surfaces) as well the handling of seasonally-dependent input parameters, has been reported in (Zhang et al., 2003).

For particle pollutants in the SL region, the turbulence acts on the particles' motion similar to that on gas; however, the process is also influenced by gravity, so relationship Eq. (2) should be modified. In the quasi-laminar sublayer, as mentioned above, the deposition process is particularly influenced from the Brownian motion and the gravity due to heavier particles.

The resistances r_a, r_b and r_s are considered to be in parallel to a second pathway-gravitational settling, which can be defined as the reciprocal of the settling velocity (Slinn and Slinn, 1980; Hicks et al., 1985, 1987; Hanna et al., 1991; Seinfeld and Pandis, 1998).

Seinfeld and Pandis (1998) derived a dry deposition flux relationship based on the assumption that $r_s = 0$, which can be expressed by equating the vertical fluxes in two layers over a surface to the total resistance as follows: