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Measurement in a wind tunnel of dry deposition velocities of submicron aerosol with associated turbulence onto rough and smooth urban surfaces

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A B S T R A C T

Dry deposition of a submicron aerosol is studied in a wind tunnel to measure dry deposition velocities onto horizontal and vertical urban surfaces of glass, cement facing and grass for several wind speeds and to measure the turbulence parameters associated with these deposition velocities. These deposition velocities are then compared to data of the literature and to the results of two models for dry deposition. The dry deposition velocity of the fluorescein aerosol increases with the intensity of the turbulence. This highlights the importance of the turbulent processes of impaction and interception in deposition. However, the ratio of dry deposition velocity to friction velocity depends on the surface type. It depends on the turbulence conditions in the boundary layer. These turbulent dry deposition processes thus vary in importance depending on the studied surface. Finally, settling represents a significant part of the deposition for low wind speeds and for smooth surfaces. This wind tunnel study permits the study of the deposition as a function of turbulent processes. It should be supplemented by *in situ* experiments to take into account all the physical processes involved under real conditions.

1. Introduction

In a polluted atmosphere or during transit of a plume containing stable or radioactive pollutants, and in the absence of rainfall events, dry deposition is the only transfer pathway from the air to the surface of particles and pollutants. At present, this dry deposition has been studied especially on natural surfaces representing the first link in the human food chain, but very little in the urban environment (Kelly, 1987; Fowler et al., 2009). However, a significant portion of the human population is concentrated in the urban environment, and in the case of passage of a radioactive plume, the quantity of radionuclides deposited by aerosols must be taken into account in estimating the dose rates received by the

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population (Kelly, 1987). Precise assessment of the transfer of pollutants by dry deposition of aerosols can thus be very important, and the lack of significant data for the urban environment is now acknowledged.

Dry deposition of aerosols depends on many factors: aerosol properties (diameter, density etc.), deposition surface variables (roughness, temperature, electrostatic properties etc.) and the meteorological variables (wind velocity, turbulence, relative humidity etc.) (Sehmel, 1980). Therefore aerosols do not deposit homogeneously in the urban environment. In the case of radioactive pollutants, this deposition must be studied for various surfaces, on a wall or street level, and not for an urban canopy, on a neighbourhood or city level, because the distribution of the deposits must be known precisely to assess the doses received by the residents. The dry deposition velocity is the coefficient used to quantify the transfer of aerosol particles by dry deposition in the environment. Most of the measurements of dry deposition velocities on urban surfaces in urban environments were conducted by Roed (1983, 1985, 1987) as a result of the fallout from nuclear tests and the Chernobyl accident, and by Pesava et al. (1999) and Maro et al. (2010) with a tracer aerosol generated *in situ*. However, these deposition velocities are not associated with precise measurements of turbulence or local meteorology. Presently, there are very few experimental data related to turbulent parameters for urban environments and surfaces. As a result there are significant uncertainties in the use of predictive models of deposition for this environment (Fowler et al., 2009).

Urban environments are complex and heterogeneous from the point of view of the turbulence and measurements under simple conditions should aid in understanding the deposition processes and quantifying deposition velocities on urban surfaces. The wind tunnel is an advantageous tool. It can be used as an initial approach to quantify dry deposition velocities as a function of a restricted number of controlled parameters and reproducible experiments can be conducted. Dry deposition has already been the subject of wind tunnel studies, on natural surfaces (Chamberlain, 1967) or on smooth and rough substrates (Liu & Agarwal, 1974; Horvath et al., 1996; Toprak et al., 1997; Dai et al., 2001), but rather for micron particles. However, the accumulation mode of the atmospheric aerosol ($0.1\ \mu m \leq d_p \leq 1\ \mu m$) is the mode that is the primary vector for chemical pollutants and radionuclides. It is the mode on which the surface distribution of the atmospheric aerosol is centred (Gründel & Porstendörfer, 2004; Van Dingenen et al., 2004; Papastefanou, 2008). Moreover, it transports these pollutants over large distances from a source to the urban environments, due to a relatively long residence time in the atmosphere (Jaenicke, 1988; Papastefanou, 2006). While the deposition of particles greater than a micrometre most often studied is strongly affected by inertial impaction and sedimentation, deposition of submicron aerosols, which is less studied, results from the contribution of several physical processes (Brownian diffusion, impaction, interception).

The main objective of this study is to quantify dry deposition velocities of a submicron aerosol on horizontal and vertical urban surfaces, for several wind speeds and under isothermal conditions in the wind tunnel. Various turbulent boundary layer conditions are thus encountered. These turbulence conditions associated with the dry deposition velocities are quantified by hot wire anemometer measurements and focus especially on determination of the friction velocities. Finally, the data from this study are compared to data in the literature and to analytically solved models developed for smooth surfaces (Lai & Nazaroff, 2000) and natural canopies (Zhang et al., 2001) which give deposition velocity estimations rapidly in the case of an accidental radioactive atmospheric release, and are intended to test and contribute to improve mechanistic models (Hussein et al., 2012; Piskunov, 2009).

2. Materials and methods

2.1. Wind tunnel and studied surfaces

The experiments were conducted in a recirculating wind tunnel of the IRPHE (University of Aix-Marseille, campus of Luminy, Marseille, France). The experimental test section was a glass channel with a stainless steel base 8650 mm long and a cross-section 280 mm high and 640 mm wide. Airflow speeds between 0.5 and 19 m s^{-1} could be generated.

Deposition was studied on horizontal conventional glass surfaces, cement facing and synthetic grass in the first experimental campaign (Fig. 1a), then on vertical conventional glass and cement facing surfaces in a second campaign (Fig. 1b). The commercial names of the materials and the roughness parameters of the cement facing (Flori et al., 2007) and synthetic grass are listed in Table 1. The roughness parameters of the cement facing measured by laser roughness measurements were the arithmetic mean deviation of the profile *Ra*, the standard deviation of the profile *Rq*, the valley depth of the profile *Rv* and the peak height of the profile *Rp*. The synthetic grass was composed of primary straight blades grouped into tufts, and thinner and shorter curly blades included in the canopy to make it denser. The parameters characterising the synthetic grass were determined by the authors for the primary straight blades and are the average canopy height h_c, the length of the straight blades l_b, the width of these blades w_b, the number of tufts per square metre n_t and the number of straight blades per square metre n_b. During the experiments on horizontal surfaces, the bottom of the test section was successively completely covered by each type of surface to develop the boundary layers and turbulence conditions characteristic of each surface. This configuration wanted to be a representative of the simplest urban condition: a boundary layer developed by a wind parallel to the surface (a ground, a wall, or a roof).

In the same way, a vertical wall of the test section was successively covered with conventional glass and cement facing, to measure deposition on a vertical wall. It should be noted that glass covered the walls in the form of a pavement of square plates 200 mm on a side, while the cement facing and synthetic grass covered the wind tunnel homogeneously and