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Aspects of particulate dry deposition in the urban environment

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Abstract

Micro-scale deposition models, typically used for pipes, were adapted to outdoor situations and combined with computational fluid dynamics (CFD) calculations of flow conditions in order to study the fine structure of the deposition velocity on ground, walls, and roofs in an urban environment. Several deposition modeling techniques taken from the literature were used for the predictions. The urban geometry was represented by two different blocks of houses, which together with two wind directions gave four different cases to study. The calculations show large local variations of the deposition velocity resulting in a pattern similar to the variation of the friction velocity. This demonstrates the strong dependence of the deposition velocity on the friction velocity. Further alteration of the deposition velocity is caused by the variation of the micro-scale roughness and different surface temperatures. The results presented provide some guidance for where to look for hotspots of deposited material and also show that a representation of the deposition velocity in a city by only one or just a few values is a great simplification locally and could lead to serious mistakes.

Keywords: Dry deposition velocity; Deposition modeling techniques; Aerosol; Urbanized area; Hotspots

1. Introduction

Knowledge of the particulate dry deposition flux to outdoor surfaces in a city is needed for calculation of human exposure to aerosols. The particulate concentration followed by industrial release, vehicle emissions and from other human activities is influenced by the dry deposition. Walls of buildings and other surfaces may also be affected by the deposition and as a result be sooted and soiled. Release of hazardous aerosol or radioactive materials may cause a need for remediation of streets and walls of buildings, and the knowledge of the location of deposit would be valuable. Particles in cities have diameters in a wide range, ≈0.1–10 μm, often with a maximum around 2 μm [1]. Particle densities for soot-dominated particles are often around 1500 kg m^{-3} [2]. Biological hazardous aerosols have sizes between 1 and 10 μm [3] with densities around 1300 kg m^{-3} [4].

The method to calculate the dry deposition flux is normally based on the concept of the dry deposition velocity, v_d, with a corresponding deposition flux that equals v_d times the particle concentration. However, models and experiments for determining v_d of particulate fluxes onto typical surfaces in cities, e.g. walls of buildings and streets, are rare.

In the scientific literature, models for dry deposition of particles are presented especially for two areas, i.e. for pipe flows (often ventilation channels) and for air quality studies. The bases for deposition models for pipe flows normally is a diffusion equation which is integrated from the surface for smooth surfaces and from the micro-scale roughness height k_s (or some fraction of k_s) for rough surfaces [5]. k_s is defined as the mean height of the roughness elements. The parameter k_s often is some millimetres or less. The upper limit of integration is chosen to be outside the particle boundary layer. Deposition velocity will depend on k_s, friction velocity (in this context normally denoted by u_τ), particle size and density. Here, u_τ is defined as $\sqrt{(\tau/\rho)}$ where τ is the shear stress at the wall and ρ is the air density. Note, that u_τ is he same as u_* used in air quality studies.

The basis for deposition models for air quality models is also a diffusion equation, which is integrated from the surface through the canopy (normally vegetation) to a reference height above

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the canopy [6,7]. The result is formulated by using an aerodynamic resistance above the canopy and a surface resistance for the canopy. The aerodynamic resistance depends on reference height, canopy height (zero plane displacement), roughness height z_0, friction velocity u_* and atmospheric stability. The canopy resistance depend on the collection efficiency of the surface and is determined by various deposition processes; u_*, z_0, particle size and density and canopy type. Unlike the micro-scale roughness k_s, z_0 is not the mean height of the roughness elements, but instead about 10% of the roughness elements. Typical values of z_0 are 0.01 m (grass) to 1.0 m (forest, urban area). The canopy is treated as a unity and details within the canopy is not resolved. The parameter u_* is calculated from wind velocity above the canopy. Gravitational settling is also a part in both types of deposition models.

For *vertical surfaces* in ventilation channels there are three regimes of deposition determined by particle size, particle density, turbulence and surface roughness [5]: (i) for small particles (0–0.1 μm) there is a Brownian-turbulence diffusion regime with decreasing v_d for increasing particle size, (ii) for intermediate particle size there is a diffusion–impaction regime with increasing v_d for increasing particle size, and (iii) for the larger particles there is an inertia-moderated regime with slowly decreasing v_d for increasing particle size. Note, that for *horizontal surfaces* there will, in addition to the above mentioned regimes, be a gravity settling modification of v_d especially in the inertia-moderated regime.

Wells and Chamberlain [8] and Chamberlain et al. [9] made wind-tunnel experiments with smooth and rough surfaces, which show the three regimes for vertical surfaces described above. They found significantly larger v_d for the rough surfaces than for the smooth surfaces. Higher values of v_d were also measured to filter papers than to surfaces with widely spaced roughness elements. Liu and Agarwal [10] made experiments with similar results as Wells and Chamberlain [8] for smooth surfaces in pipes in the diffusion–impaction regime and the inertia-moderated regime. Sippola and Nazaroff [11] presented ventilation duct experiments for smooth and rough surfaces in the diffusion–impaction regime showing larger v_d for the rough surfaces (insulated ventilation ducts with micro-scale roughness height equal to 1.7 mm) than for the smooth surfaces (steel ducts) supporting the results of Chamberlain et al. [9].

Several papers present theoretical models for v_d in pipes (Friedlander and Johnstone [12], Davies [13], Wood [14], Fan and Ahmadi [15,16], Guha [17], Valentine and Smith [18], Zhao and Wu [19], Johansen [20]). In addition, Sippola and Nazaroff [5] have summarized the knowledge on particle deposition from turbulent flows in ventilation ducts. The main parameters influencing v_d is friction velocity, u_τ, particle size, particle density and micro-scale roughness height, k_s. Many of the existing models are applied to smooth (steel) surfaces, but the equations in some of the models can also be used for rough surfaces. For example, Gua presents result for both smooth and rough surfaces. The theory includes Brownian and turbulent diffusion, thermophoreses, turbophoreses, electrostatic forces, gravity and lift forces. For smooth surfaces existing models often agree relatively well between each other and with experimental data. However, for rough surfaces the agreement is worse. Therefore, Sippola and Nazaroff [11] derived a model in form of an interpolation formula based on their measured data.

Some authors have also reported experimental data of outdoor deposition. Offer and Goossens [21] and Erell and Tsoar [22] report wind-tunnel and field experiments on deposition of wind transported dust. They observed spatial variation especially in hilly terrain and where filter effects due to vegetation occurred. However, there was no determination of the spatial variation of flow parameters like u_τ and no correlation between flow parameters and deposition parameters were presented. Also, Simmons and Pocock [23] measured heavy metal particle flux to the surface in an urban area. They found that a large variability on a scale of 1 km could be explained by the release sources. On a smaller scale (<100 m) there was an additional variability of 90% (standard deviation divided by mean value), but the reason was not analyzed. The air flow conditions were not measured.

Although some experimental information on deposition is available, Monforti et al. [1] concludes that there exists "no experimental or deeper theoretical studies which focus on deposition on urban areas". They modeled particulate flux to cultural heritage sites in Florence Italy by using a multi-layer box model, but without resolving flow circulations in street canyons. The deposition velocity was calculated according to a procedure presented by Zhang et al. [7]. Calculated v_d for all suspended particles (weight maximum at 2 μm) ranged 0.05–0.8 cm s^{-1}, which seemed reasonable compared to observed range in urban areas (0.1–1 cm s^{-1}).

To account for the flow circulations, Benett [24] tries to formulate the effects of recirculation zones of a rough surface on the surface resistance by introducing a new term depending on the length scale for surface eddies. This term will increase the total resistance and can be used in deposition formulations using mean wind and roughness length z_0.

Gidhagen et al. [25] studied dispersion of ultra fine aerosols in a street canyon by coupling an aerosol model to a CFD model. The deposition model included Brownian diffusion, inertial impaction and gravitational settling, but could not be applied to smooth surfaces. They found that coagulation and deposition of ultra fine particles may reduce the concentration of particle concentration in the canyon by 30% at low wind speeds. However, no direct presentation of the particle deposition velocity was given.

Zhang et al. [7] has developed a dry deposition scheme for land areas, i.e. mainly for application over larger vegetated areas. The scheme includes turbulent transfer, Brownian diffusion, impaction, interception, gravitational settling and particle rebound. Their model also included the three regimes described above [5], together with the gravitational settling modification for horizontal surfaces. The model included 15 land use categories, one of which is urban, each with a predefined roughness length z_0 and radius of collectors. The model shows that the deposition velocity depends on surface type, friction velocity, particle density and particle size. The deposition velocity increases for rougher surfaces and higher u_τ. According to Fig. 1 in Zhang's paper a typical v_d is about 3 mm s^{-1} for 5 μm particles (2000 kgm^{-3}, 5 ms^{-1} at 20 m). However, the model is