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A wind-tunnel study of the effect of turbulence on PM_{10} deposition onto vegetation

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A B S T R A C T

The fraction of particles deposited from an airstream (deposition fraction) onto idealized substrates has been shown to be influenced by isotropic turbulence through increased deposition onto nonimpaction surfaces (Moran, S.M., Pardyjak, E.R., Veranth, J.M., 2013. Understanding the role of grid turbulence in enhancing PM10 deposition: scaling the Stokes number with R_λ. Physics of Fluids 25, 115103). Here, we extend this by considering deposition onto realistic vegetative surfaces. Results from wind-tunnel deposition experiments conducted using nonvolatile particles and various types of artificial vegetation under grid-generated isotropic turbulence conditions are presented and compared with the previous idealized experiments. The nonimpaction-surface fraction of the total deposition is shown to scale with the Reynolds number and a new effective area parameterization is developed to account for inertial deposition onto nonimpaction surfaces. A combined formulation of the turbulent Stokes number and the effective deposition area are used to collapse the data. The results show that laminar impaction models dramatically under predict deposition for a given classical Stokes number. The new parameterization shows improved performance for deposition onto vegetation with the coefficient of determination (r^2) increasing from 0.15 to 0.65 when accounting for turbulence and nonimpaction-surface deposition area.

1. Introduction

This paper describes work done to experimentally investigate the role of turbulence in enhancing particle deposition onto vegetation. The overall goal is to improve the parameterization of PM_{10} (i.e., particulate matter with an aerodynamic diameter less than or equal to 10 μm) deposition onto vegetation in atmospheric boundary-layer flows. This was accomplished by extending the previous idealized substrate particulate deposition work of Moran et al. (2013) to realistic vegetative elements.

Understanding the underlying physics of particle transport and deposition is critical to many areas of engineering, biology, and environmental science. Particle transport phenomenon is a complex area of physics involving aspects of fluid dynamics, heat and mass transfer, atmospheric chemistry, and micrometeorology. Many studies have been conducted to better understand the dry deposition processes of particles with length scales spanning many orders of magnitude from nano-scale to millimeter-scale (Wesely and Hicks, 2000). Many factors such as diffusion, surface roughness and adhesion, inertial impaction, gravitational settling, and re-emission characteristics determine the appropriate modeling approach to use.

Depending on particle characteristics (physical size, density, shape, etc), deposition surface characteristics, and atmospheric conditions, an individual solid particle traveling in the wind can either remain suspended or interact with and deposit onto a surface. The primary mechanisms for dry particle deposition are Brownian diffusion, interception, inertial impaction, and sedimentation (or gravitational settling) (Shao, 2000). Earlier work by Chamberlain (1967) experimentally determined the deposition velocities of several classes of particles ranging from 0.8 μm to 32 μm onto various surfaces in field and wind-tunnel studies. Further work by Aylor (1975); Slinn (1982) and Aylor and Ferrandino (1985) extended the work to a wider range of particle sizes and surface characteristics.

Focusing on inertial impaction physics, May and Clifford (1967) and Marple and Liu (1974) performed detailed

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laboratory experiments to determine the impaction deposition of aerosol particles. These laminar flow results have been subsequently incorporated into atmospheric particle deposition models (e.g., Raupach et al., 2001; Aylor and Flesch, 2001). A brief review of the literature indicates that while these mechanisms have been explained both theoretically and empirically, the specific role of atmospheric turbulence on inertial deposition onto vegetative surfaces remains a largely unexplained area (Petroff et al., 2008). Additionally turbophoresis, or particle migration towards walls due to gradients in the turbulence field, is thought to play an important role in deposition (Guha, 2008). Petroff et al. (2009) and Katul et al. (2010) have included turbophoresis parameterizations derived from pipe flow experiments into one-dimensional inertial impaction deposition models. The results of Katul et al. (2010) indicated, that for particles in the range of 0.1–10 μm in vegetative canopies the effect of turbophoresis on deposition was small.

Near-source vehicle generated fugitive dust modeling is an area that is especially sensitive to the details of inertial particle deposition parameterizations. One way to mitigate roadside dust emissions is to utilize vegetative windbreaks to enhance mixing, reduce flow velocity, and provide deposition surfaces. Several field experiments have demonstrated the impact that roadside windbreaks and vegetative canopies have on reducing fugitive dust (Veranth et al., 2003; Etyemezian et al., 2004; Pardyjak et al., 2008, 2013). These experiments also demonstrate that existing particle deposition parameterizations significantly under predict deposition (Veranth et al., 2003). In fact, in order to force the existing models to match experimental field data, vegetative elements must be reduced in size by multiple orders of magnitude (Amatul, 2007; Pardyjak et al., 2013). This mismatch between the experimental and modeled results indicates that typical inertial impaction deposition models do not contain all of the relevant physics and must be improved.

Most particle deposition models (e.g., Raupach et al., 2001) parameterize the deposition fraction (DF) as a function of the classical Stokes number (Seinfeld and Pandis, 2012)

$$Stk = \frac{D_p^2 \rho_p C_c u}{18 \mu L_c} \tag{1}$$

where D_p is the particle diameter, ρ_p the particle density, C_c the Cunningham correction factor, u the flow velocity, μ the dynamic viscosity of air, and L_c is a characteristic length scale of the deposition surface. Physically, for flow around an object with a characteristic length scale, L_c, the Stokes number is the ratio of the particle stopping distance to the object's characteristic length scale. It indicates the ability of a particle to continue moving with flow streamlines around an object. Interception may occur in cases where a particle follows a streamline of the flow whose distance from a surface is less than or equal to the radius of the particle. Inertial impaction or interception may also occur when the characteristic length scale of the obstacle is small enough to allow for even low inertia particles to deposit. In the experiments presented below impaction and interception are indistinguishable, and therefore, are combined and referred to collectively as impaction throughout the manuscript.

In turbulent flows, streamlines are highly unsteady leading to situations where particles may not follow streamlines or where particles experience increased likelihood of interception. Moran et al. (2013) hypothesized that free-stream turbulence is the missing physical parameter in existing deposition models. They performed a set of wind-tunnel experiments with and without grid-induced turbulence to isolate the role of turbulence on particle deposition. Using idealized square polymer substrates with the deposition faces oriented in all six principle directions, Moran et al. (2013) found that free-stream turbulence dramatically increases the particle deposition fraction onto surfaces regardless of orientation resulting in substantially higher deposition fractions at much lower Stokes numbers than commonly used models (e.g., May and Clifford, 1967).

The present work extends the work of Moran et al. (2013) from idealized substrates to realistic vegetative element geometry. The current experiments were designed to further test the hypothesis that particle deposition onto vegetation is enhanced by the presence and intensity of free-stream turbulence.

2. Experimental setup

2.1. Wind tunnel and turbulence

To measure particle deposition, a series of wind-tunnel deposition experiments were performed with grid-generated isotropic turbulence. The experimental methods are based on the procedures of Moran et al. (2013). The experiments comprised three separate components conducted at the same location within the tunnel. Aerosol quantification, turbulence measurement, and the deposition experiments were conducted individually after they were found to be repeatable. The experiments were conducted within the test section of a low-speed wind tunnel of length 2.44 m with a cross section of 1.22 m by 0.61 m at operating velocities of 4.9, 8.3, and 9.5 m s^{-1} (Fig. 1). To generate isotropic turbulence within the wind tunnel, an acrylic grid was placed at the beginning of the test section. The grid was the same 50% solidity grid with 2.54 cm bar thickness used in Moran et al. (2013) (see Fig. 2).

The core of these experiments is a mass-balance procedure using a fluorescent tracer solution with nonvolatile particles injected into the wind-tunnel free stream. The deposition experiments involved measuring vegetation area, quantifying aerosol size and concentration, measuring the turbulence statistics within the tunnel, rinsing the substrates after deposition, and carefully quantifying the fluorescence of the diluted wash solution.

2.2. Aerosol generation

The particle deposition experiments consisted of injecting fluorescent micro-particles into the tunnel free stream in the presence of grid generated turbulence. An Ultra-Sonic Humidifier (USH) (Model V5100NS, Kaz Inc., Hudson, NY) was used to aerosolize a solution of 80% H_2O, 20% Glycerol ($C_3H_8O_3$). This particular ratio was chosen by Moran et al. (2013) because the resulting particle size distribution was confined to the PM_{10} regime. The solution was mixed with powdered fluorescein sodium salt ($C_{20}H_{10}Na_2O_5$) (Sigma-Aldrich, St. Louis, MO) with a concentration of 0.5 mg mL^{-1}. As the solution was nebulized in the USH, the fluorescein, water, and glycerol mixture was aerosolized into particles with a mean diameter of ≈ 3.2 μm depending on the wind tunnel operating conditions (see Table 2).

The exact quantity of water in the aerosol is unknown because the relative humidity was not recorded during the experiments. However, a theoretical discussion of the effect of water within the solution may suffice. In our Stokes number calculations, the density is assumed to be 100% glycerol. The initial solution was 80% water and 20% glycerol and presumably some of the water does evaporate within the wind tunnel. Assuming that no water evaporates, the density of the water-glycerol mixture at room temperature is 1052 kg m^{-3}, assuming all of the water evaporates, the density is 1260 kg m^{-3}. This provides a range of potential particle density