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Survival of aerosol particles in a puff with spatially inhomogeneous size spectrum

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ABSTRACT

Aerosol particles released from emission sources undergo various atmospheric and aerosol processes before they become a part of the background aerosols. Coagulation and dispersion, the two important processes that governs evolution of particle characteristics in a puff with an inhomogeneous size distribution of particles in space is considered in this study. This specific case consists of an initial Gaussian aerosol packet in which larger particles are preferentially segregated to farther distances from the centre of the packet. The coagulation-dispersion equation is solved using Jaffe approximation technique for obtaining essential results such as survival fraction, that is, fraction of particles surviving due to the simultaneous action of coagulation and dispersion. Analytical results are developed for the temporal variations of the number concentration, mean size and the standard deviation. The asymptotic results yield the final characteristics of the spectra of the particles which form a part of the background aerosols. These quantities are useful for defining the "effective aerosol source terms" in the general dynamic equations for background aerosols, long-range transport of aerosols, and geo-engineering applications. The results are further discussed.

1. Introduction

In the vicinity of aerosol emission sources, very high number concentration of aerosol particles are encountered that leads to rapid self-coagulation of source particles while they disperse in the environment. Emitted source particles grow in size due to self-coagulation and eventually survive due to the joint action of coagulation and dispersion. The fraction of source particles that form a part of ambient aerosols in the atmosphere is termed as survival fraction, which depends on number concentration, size of the puff/plume, coagulation coefficient, and diffusion constant. The use of survival fraction of aerosol particles has a conceptual advantage in defining the source terms in the dynamic equations for background aerosols in the presence of localized sources. For example, the survival fraction as a source modifier function will reduce the computational burden of aerosol dynamics model without adding complexity to the simplified linear model neglecting self-coagulation for the particle growth equation in the lower troposphere (Lushnikov, Zagaynov, & Lyubovtseva, 2017). Also, the survival fraction concept is useful in defining exact source term for geo-engineering applications (Anand & Mayya, 2013; Stuart et al., 2013), and establishing parameterization scheme for sub-grid scale aerosol dynamics in the long-range aerosol transport model (Pierce, Theodoritsi, Adams, & Pandis, 2009).

Analytical expressions to estimate survival fraction, effective number of particles survives in a puff and plume that undergoes

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simultaneous coagulation and diffusion/dispersion, are obtained by solving the coagulation-dispersion equation (Anand & Mayya, 2009, 2011; Turco & Yu, 1997, 1999). In these studies, survival fraction is obtained for various initial conditions on particle size, and model parameters such as coagulation kernel and release mechanisms (instantaneous or continuous), assuming that the initial particle size distribution is unvarying in space. However, this may not generally be the case, and depending upon generation and ejection mechanisms, spatial segregation of particles may arise. The spatial inhomogeneity of aerosol size spectrum is generated due to various reasons such as small-scale turbulent fluctuations on rates of particle formation (Housiadas, Drossinos, & Lazaridis, 2004), physical processes like coagulation (Kasper, 1984) and emission processes, etc. For example, particles formed in detonations, cracker bursts or fireworks during festive seasons (Joshi, Khan, Anand, & Sapra, 2016; Zhao, Yu, Yin, Liu, & He, 2014) could be spatially segregated. Similarly, one can argue that in particles dispersed through sprays or stacks, larger particles are likely to be ejected farther. Also, spatial separation and clustering of cloud droplets is well known in the context of vortices in turbulent flows (Fung & Vassilicos, 2003; Ravichandran, Deepu, & Govindarajan, 2017). In order to draw attention to this aspect and to illustrate the approach, we consider a specific case of particle size segregation in a spatial packet and obtain survival fraction of aerosol particles during the course of their evolution due to coagulation and dispersion. This work advances the important task of estimating particle incorporation from localized sources into atmospheric background discussed in earlier publications (Anand & Mayya, 2009, 2011).

2. Problem formulation

In the present study, we consider specific cases of particle release scenario like cracker burst/fireworks during festive seasons (Joshi et al., 2016; Zhao et al., 2014) or aerosol plume releases from industrial stacks, which are important sources of air pollution. In these release conditions, polydisperse aerosol particles are initially ejected with either equal amount of energy from the burst or constant velocity from the stack. This initial dispersion of precursor particles leads to size segregated spatial inhomogeneity of particles as demonstrated below.

If particles of diameter d_p (corresponding volume, u) with fractal dimension d_f are flung with initial velocity v_0 (in the case of stack releases), they would stop at radial distance, $r = v_0\tau = \frac{mC_c}{3\pi\mu d_p}$, where, τ is the relaxation time, m is particle mass, C_c is Cunningham slip correction factor, and μ is fluid viscosity. Then, the relationship between stopping distance and particle size is given by, $u \propto r^{\frac{d_f}{d_f-1}}$ in the continuum regime and $u \propto r^{\frac{d_f}{d_f-2}}$ in the free-molecular regime. Although the exponent could vary widely depending upon the fractal dimension, for compact particles ($d_f = 3$), the value of exponent will be about 1.5 and 3 respectively. Also, it is possible that other models of burst releases, say, using equal energy partitioning assumption could lead to relationship such as $u \propto r^{\frac{2d_f}{d_f-2}}$, which will give rise to a broader range of exponents. In any case, all the models uniformly predict that larger particles will be flung father away from the centre. In view of this fact, we chose a value of 2, which turns out be mathematically convenient for the purpose of illustrating a case study of size segregated particle coagulation. One may then write, $u = \beta r^2$, where, β is a constant, defined as the ratio of characteristic particle volume (u_c) to the square of spatial extension of the packet (b_0^2). This relationship shows that the bigger size particles are scattered to farther distances from the centre of the spherical cloud due to larger mass and stopping distances.

Combining this initial correlation between particle size and space with Gaussian distribution of number concentration in space, the varying initial monodisperse size distribution is written as,

$$n(u, r,0) = \frac{N_a}{\pi^{3/2}b_0^3} exp[-r^2/b_0^2]\delta[u - \beta r^2] \tag{1}$$

where, $n(u, r, t)$ is the number of particles with volumes lying between u and $u + du$ per unit volume of fluid at position r and time t, N_a is the total number of particles in the puff and b_0 is the initial puff width. Fig. 1 shows the plot of particle size distribution expressed in

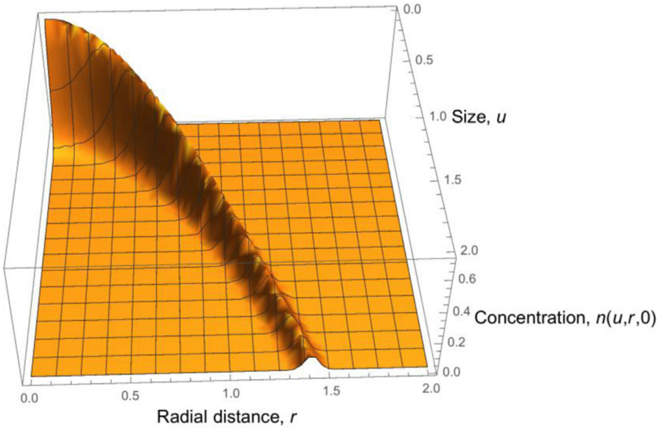

Fig. 1. Monodisperse size spectrum, heterogeneous in space r.