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Particle segregation in aerosol flow

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ABSTRACT

It is shown how the uniformity of a polydisperse aerosol can be assessed by means of a segregation index, defined in terms of the mean and the mean square of $n(D_p; \vec{r})dD_p$, the number concentration of particles with diameter in the range $(D_p, D_p + dD_p)$ in a volume element centered at \vec{r} . The segregation index is zero for a uniform aerosol and attains positive values for any other situation, in such a manner that the larger the value of the index, the worse the aerosol uniformity. As an illustrative example, numerical calculations have been performed for a polydisperse aerosol undergoing simultaneous diffusion and electrostatic dispersion in a laminar flow tube. In this case, the segregation index, zero at the tube entrance (uniform aerosol), increases steadily as the aerosol approaches the tube outlet. Some practical implications for aerosol sampling from a duct are discussed.

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1. Introduction

An ideally homogeneous aerosol can be thought of as a collection of suspended particles whose number concentration, morphology (size, shape), and chemical composition are independent of the spatial location considered. Any sample taken from this system is fully representative of the aerosol, but this ideal situation is never encountered in practice.

In general, real aerosols are segregated with respect to concentration, morphology and/or chemical composition (i.e. any or all of these properties vary from place to place). In these conditions, withdrawing a fully representative sample is not possible. It seems obvious, from a qualitative point of view, that the larger the extent of segregation within the system, the less representative will be the sample. It is thus important to quantify the degree of particle segregation (or lack of uniformity) in specific cases of practical interest. However, experimental measurement of the spatial distribution of chemical composition, size, shape and number concentration of aerosol particles is beyond our present technical capabilities. We must content ourselves with performing numerical calculations, e.g. solving the general dynamic equation (Friedlander, 2000), in order to obtain quantitative estimations of the degree of particle segregation in a system.

The purpose of the present work is to quantify the extent or degree of segregation of aerosols. To simplify the treatment, it will be assumed that all the particles have the same chemical composition and also the same shape, so that the only variables needed are particle size and number concentration. A definition of the degree of segregation will be introduced, and numerical examples of the evolution of an increasingly segregating aerosol will be presented for the specific case of particles undergoing diffusion and electrostatic dispersion in a laminar flow tube. Finally, an example of the effect of the aerosol homogeneity on sampling representativeness will be discussed.

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2. Quantification of aerosol uniformity

A polydisperse aerosol is uniformly distributed within a region if its particle size distribution is constant, independent of location, in that region. Let $n(D_p; \vec{r})dD_p$ be the number concentration of particles with diameter in the range between D_p and $D_p + dD_p$ in a volume element centered at position \vec{r} . Uniformity in a volume V means that, in the volume V , n is independent of \vec{r} and that n is a constant for each particle size interval $(D_p, D_p + dD_p)$.

It may happen that the aerosol is uniform along a specific spatial direction, but not along others. Consider for instance an aerosol flowing in a circular tube; from symmetry considerations, the steady-state size-dependent particle number concentration depends only on the radial and axial coordinates, $n = n(D_p; r, x)$. In other words, the aerosol is uniform within any differential ring of width Δr and thickness Δx but, in general, is not uniform along the r, x directions. The specific form of the function $n(D_p; r, x)$ can, in principle, be calculated by using the general dynamic equation (Friedlander, 2000), which accounts for all the changes undergone by $n(D_p; r, x)$ due to a variety of phenomena, such as nucleation, coagulation, diffusion losses, electrical effects, etc. Consider now the simple case in which the particles are unipolarly charged and their concentration is high enough for mutual repulsion (space-charge) to be important; further, let us assume that (i) the mean number of charges per particle is small, so that image force effects need not be considered (Scheibel & Porstendörfer, 1984; Yu & Chandra, 1978); (ii) the particles are large enough so that their diffusivity is negligible but, at the same time, (iii) not too large so that inertial effects are also insignificant; and (iv) there is no condensing vapor in the system. In this case, because coagulation between particles carrying charges of the same sign is negligible, the only mechanism by which $n(D_p; r, x)$ can change is mutual electrostatic repulsion (also known as electrostatic dispersion). It is well known that if the aerosol is radially uniform at the tube entrance, it remains radially uniform all along the tube (see for instance, Yu, 1977), that is, the concentration profile simplifies to $n(D_p; x)$. In this specific case, thus, the aerosol is uniform along the r, θ directions.

In order to quantify the homogeneity of the aerosol, a parameter, which may be termed the *degree of segregation*, can be defined in terms of the mean and the mean square of $n(D_p; \vec{r})$:

$$S(D_p; \vec{r}) = \frac{\langle n^2 \rangle}{\langle n \rangle^2} - 1. \quad (1)$$

The meaning of this expression is better understood using the example of an aerosol flowing in a tube. In this case, the mean ($k = 1$) and the mean square ($k = 2$) of n in a differential section at a distance x from the tube entrance are given by

$$\langle n^k \rangle = \frac{\int_0^R r u_x(r) n^k(D_p, r, x) dr}{\int_0^R r u_x(r) dr}, \quad (2)$$

where u_x is the axial component of the gas flow velocity (the other two velocity components are assumed to be zero), and R is the tube radius. If the aerosol is uniform at the tube entrance, so that

$$n(D_p; r, 0) = n_0(D_p), \quad 0 \leq r < R, \quad (3)$$

where R is the tube radius, then $\langle n^k \rangle = n_0^k$, and $S(D_p; 0) = 0$. Thus, $S = 0$ means uniformity (perfect mixing) or, equivalently, zero segregation. Downstream of the tube entrance, the changes in the distribution $n(D_p; r, x)$ due to the mechanisms mentioned above (coagulation, diffusion, space charge, etc.) lead to non-zero, positive values for the degree of segregation: $S(D_p; x > 0) > 0$. The larger the value of S , the worse the homogeneity of the aerosol. Increasing values of S quantifies the deterioration of the aerosol uniformity as it flows downstream.

The degree of segregation, as defined by (1), is a function of particle size. This fact may complicate the comparison among aerosols having different particle size distributions. Such a direct comparison between different aerosols may be done if a *global degree of segregation*, involving the whole particle size distribution, is used instead:

$$S_G(\vec{r}) = \frac{\int_0^\infty S(D_p; \vec{r}) dD_p}{\int_0^\infty dD_p}. \quad (4)$$

For an aerosol flowing in a tube and having a uniform concentration at the tube entrance, the global degree of segregation is also zero at $x = 0$, and attains non-zero, positive values for $x > 0$. (Note: The use of 0 and ∞ in the integration limits in (3) and (4) is a formal way of expressing that the integrals must be extended to the whole particle size distribution; in practice, the integration limits are finite numbers, say $D_{p,min}$ and $D_{p,max}$, so that the integral in the denominator of (4) is also a finite number.)

3. Application to unipolarly charged diffusive particles in a laminar flow tube

In the remaining part of this paper, the above ideas will be applied to the specific case of an aerosol undergoing simultaneous diffusion and electrostatic dispersion in a laminar flow tube.

Using the dimensionless variables

$$x^* = x/L; \quad r^* = r/R; \quad n^* = n/n_{T0}; \quad n_T^* = n_T/n_{T0}; \quad u_x^* = u_x/\bar{u}_x; \quad E_r^* = \varepsilon_0 E_r / e R n_{T0}; \quad \beta = DL/\bar{u}_x R^2; \quad V_s = e n_{T0} LZ / \varepsilon_0 \bar{u}_x, \quad (5)$$

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