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Interactions between fine combustion droplets

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Abstract

Interactions between fine combustion droplets were directly observed using microscopic flow visualization and high speed photography. The observations revealed "attracting–revolving–repulsing" interactions between the droplets. Force analyses showed that the traditionally considered interparticle forces, including drag, gravitation, the Coulomb force and the van der Waals force, cannot explain these interactions. However, the induced dipoles on the droplets due to the non-uniform distribution of surface charges on the fine droplets have important influence on such interactions. Therefore, the inter-dipole forces must be taken into account in the interaction force analysis as well as the Coulomb force between the net charges. The inter-dipole force includes components in the radial and azimuthal directions and is inversely proportional to r^4. This force causes the particles to revolve and repel each other at small distance. The combined effects of the inter-dipole force and the traditionally considered forces give a complete explanation for the particle interactions.

Keywords: Fine combustion droplets; Particle interaction; Coagulation; Interparticle force; Inter-dipole force

1. Introduction

Inhalable particulate matter has become a much more serious atmospheric pollutant with most coming from combustion processes in power plants, industrial machines and vehicles. The rapid progress in the study of particulate control has led to interest on very fine particles. Particles with sizes less than 2.5 μm (PM2.5) can enter and remain in the human lungs while particles smaller than 1 μm (PM1) can penetrate the deeper alveolar regions, causing chronic lung damage. Unfortunately, the capture efficiencies of these fine particles by cyclones, electrostatic precipitators (ESPs) and filters are all relatively low. The most important way to improve the capturing efficiency is to promote coagulation or aggregation of fine particle into larger particles. Therefore, increasing efforts have been focused on particle interaction or aggregation mechanisms for submicron combustion particles, including solid soot precursors and coagulated droplets produced in combustion process.

The interactions and aggregation of fine particles are also important phenomena in many other areas, such as colloid sciences, water treatment, electrophotography, semiconductor processing, and pharmaceuticals. These researches covered solid particles or liquid droplets in air or liquid/water medium. The word particle is used extensively herein including solid particles and liquid droplets.

The modelling of the coagulation of fine particles has been studied for many years after the first attempt by Smoluchowski [1], who gave a basic equation for the change rate of the number concentration of aggregates of certain sizes. The equation has formed the core of almost all subsequent research into coagulation modelling, so subsequent developments can be considered as specific modifications of the original equation. Thomas et al. [2] gave a detailed review of recent coagulation modelling work. In Thomas's review, the collision efficiency, α, and the collision frequency, β, were identified as two core parameters in the of coagulation rate model. The collision efficiency and collision frequency are modeled differently for

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different conditions depending on the interparticle forces, intensity of fluid mixing, particle concentration and size distribution, particle shapes, particle surface chemistry in continuous medium and many other factors. Many simulations have investigated the influence of these various factors on the coagulation rate, along with the investigations of the effect of gravity, convection, interparticle forces, size heterogeneities and so on [2–9]. Experimental studies on the coagulation of fine particles have mostly focused on polystyrene Latex or amorphous silica suspensions in water or other liquid solutions [4,7,8,10,11]. Most of the experimental work have measured changes in the particle concentrations in the solutions using laser techniques and Coulter counters. Only Folkersma et al. [4,11] reported visual observations of perikinetic coagulation in a polystyrene Latex suspension with about 2 μm particles, but they did not analyze the interparticle forces.

Calculations and experimental studies of Brownian coagulation resulted in a coagulation zone diagram for a particle diameter of 3 μm, considering various interparticle forces, such as the van der Waals force, electrical forces and hydrodynamics. The coagulation and non-coagulation zones were divided by a graphical plane based on surface potential and ionic strength [6,7]. The results show that for some conditions the coagulation rate is very low as to zero, but is much higher for other conditions.

The analysis of particle interactions in aerosols of fine particles mixed with air has also long been of interest in various fields [12–15]. Because of the low viscosity of air, the particle interactions are much more rapid in air than in liquids. Therefore, visual observations of the particle interactions are much more difficult and have not been reported to our knowledge. In air-particle systems, the interparticle forces become more important, while the influences of particle and solution chemistry become negligible. The macroscopic flow and the coagulation are both affected by the interparticle forces.

The interaction forces between particles include the long-range forces, such as electrostatic and van der Waals forces, and contact forces, for example the capillary force, solid bridging or mechanical interlocking forces. There have been many studies

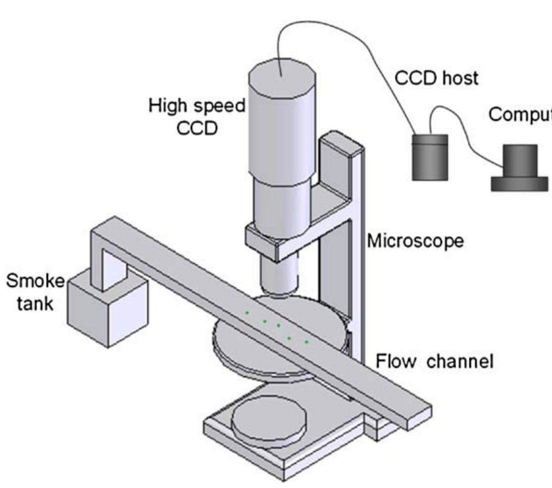

Fig. 1. Experimental Setup.

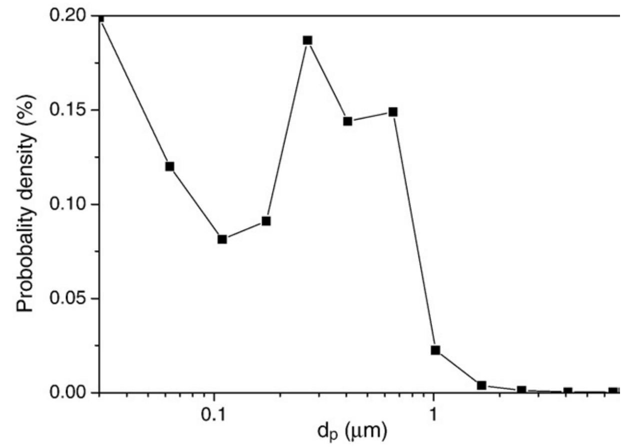

Fig. 2. Droplet size distribution.

of the particle interaction forces in the literature [12,13,16–20]. However, direct microscopic observations of the interactions between fine particles are needed to accurately analyze the forces.

In this research, microscopic flow visualization and high speed photography were utilized to observe the dynamical interactions between fine combustion droplets in air. The aim is to investigate the mechanisms governing the particle interactions and to analyze the interaction forces acting between fine droplets based on the kinematic observations.

2. Experimental setup and droplet parameters

Fig. 1 shows the experimental setup. A rectangular channel made of optical glass was mounted on a microscope platform under the objective, with the fine combustion droplets flowing slowly in air through the channel. A high speed CCD camera was attached to the microscope eyepiece. The aerosol flow was magnified by the microscope and then captured by the high speed camera linked to a computer. The flows were also observed on the monitor. This microscopic high speed PIV/PTV system has been described in detail in a previous paper [21]. The PIV/PTV system was able to measure the velocities and diameters of the fine droplets. For convenience, the fine combustion droplets were from burning cigarettes burning naturally in the tank with the smoke flowing from the tank. The microscopic observation shows that cigarettes burning smoke prevailingly composed by oil-like droplets. A camera speed of 125 fps was used. The observed area is 750 μm × 700 μm. The smoke droplet velocities measured by the microscopic high speed PIV/PTV system were mostly in the range of 50–250 μm/s. The number concentration of the droplets measured by the imaging method was about 360 /mm^3.

Folkersma et al. [4,11] used a microscope and a regular speed CCD camera in their observations of particle interactions in water, since the particle interactions in liquids are relatively slow compared to the interactions in air. In addition, the magnifying effects of the microscope made the high speed camera indispensable in the current experiments.

Particle diameters and surface charge distributions are the most important parameters controlling the interactions of fine