ELSEVIER

Chemical Engineering Science 61 (2006) 2212–2229

Chemical Engineering Science

www.elsevier.com/locate/ces

A measuring system for the time variation of size and charge of a single spherical particle and its applications

Yoji Nakajima*

Division of Materials Science and Engineering, Graduate School of Engineering, Hokkaido University, Sapporo, 060, Japan

Received 31 March 2004; received in revised form 21 September 2004; accepted 4 October 2004
Available online 21 June 2005

Abstract

A single charged particle is trapped in a simple quadrupole electrode assembly and oscillated by means of a controlled electric field. A laser Doppler velocimeter (LDV) of the fringe mode is used for detecting the amplitude and phase lag of the particle oscillation with respect to the driving ac field. A unique method for the LDV signal processing is presented that takes the advantage of the sinusoidal oscillation of the particle at a known frequency. Superimposed to the ac drive, a dc drive is added for highly accurate measurements of particle size and charge. This enables us also to discriminate the polarity of charge without Bragg cells.

In this paper, the basic principle of the method of the size and the charge measurements is explained and the accuracy of the measurements is demonstrated experimentally. The errors in the size and charge measurements, respectively, are less than 1% and 3% with a confidence coefficient of 99%. Since this apparatus repeats the measurements every 0.3 s for a single particle, the errors can be reduced to 0.1% and 0.3% when the measured values over a period of 30 s, or over 100 data are averaged.

As some areas of its applications, experimental data are presented on the Rayleigh instability of evaporating charged droplets. It is shown that there are three types of Rayleigh fission. One of the types seemed to show occurrence of air breakdown around a micron sized spherical particle, which has not been reported so far. However experiments in highly insulating gas (SF_6) revealed that it was not the case but a type of Rayleigh fission. Nevertheless the experimental results gave important information on the charge limit of spherical solid particle due to electric breakdown in air at normal room conditions.

Some cares to ensure the advantages of the present method are presented, and possible improvements of the apparatus are also suggested for future use.

Keywords: Charged droplet; Charged particle; Charge measurement; Size measurement; LDV; Electrodynamic trapping; Rayleigh fission

1. Introduction

Measurement of time variations in particle size and charge properties often yields novel information. For instance, evaporation characteristics of small droplets (Taflin et al., 1988; Shulman et al., 1997; Widman et al., 1998), uptake dynamics of HCl by a single sulfuric acid microdroplet (Schwell et al., 2000), the Rayleigh instability of charged droplets (Duft et al., 2002; Taflin et al., 1989), chemical reaction rate constant of droplets (Ward et al., 1987) have been studied from the measurement of the time variation in size of a single droplet. For these purposes, the electrodynamic balances (EDB) have been used to trap and to levitate a single aerosol particle freely in a gaseous medium. In the experiments cited above, bihyperboloidal electrodes (Wuerker et al., 1959) with complex design and construction were used, so that the electric field formed by the electrodes could be readily calculable. However, such bihyperboloidal electrodes are rather costly to construct, and moreover, the electrode configuration restricts the scattered light collection angle for the optical receiver within a rather narrow limit.

Instead, simpler forms of electrodes have been accepted for EDBs. Richardson et al. (1989) used a cylindrical and two hemispherical cap electrodes to measure the Rayleigh

* Tel.: +81 1170 66591; fax: +81 11 7069593.
E-mail address: yoji@eng.hokudai.ac.jp.

0009-2509/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2005.05.004

instability of charged droplets. Davis and Bridges (1994) examined the cause of charged droplet fission prior to reaching the Rayleigh instability limit by using two different sets of double ring electrodes. Bhanti and Ray (1998) used a similar type of EDB to Richardson's for the measurement of instantaneous chemical reaction rate constant in a droplet. Zhu et al. (2002) measured mass transfer from an oscillating small droplet using an octopole double ring electrode configuration. In the present system, a more facile electrode configuration, namely two parallel rod electrodes located in the central plane of a pair of parallel plate electrodes, is adopted for forming a quasi-quadrupole ac electric field, which can trap charged particles at the central portion of the electric field. The parallel plate electrodes also provide a uniform ac electric field to oscillate the charged particle.

In the experiments cited above, the droplet size was measured by using two elaborate optical methods based on the Mie light scattering theory. One is now called the phase function method (Bartholdi et al., 1980) and the other is called the optical resonance method (Ashkin and Dziedzic, 1981). Both the methods, in particular the latter, offer very accurate size measurement if the refractive index of the droplet is known precisely. But both the methods require very complicated and time-consuming computations. For several decades, hydrodynamic approaches for measuring the sizes of cloud droplets and smoke particles have been developed. Wells and Gerke (1919) utilized photographs of particle oscillation in an ac field for the first time, though they had to assume the charge of the droplet. Using a laser Doppler velocimeter, Mazumder and Kirsch (1977) and Renninger et al. (1981) proposed a novel method, in which the phase lag of the motion of particle relative to the oscillating driving force was related to the relaxation time or aerodynamic size of the particle. This system is now known as the E-SPART (electrical single particle aerodynamic relaxation time) analyzer.

In the present measuring system, a quasi-quadrupole electrode system mentioned above is incorporated in the measurement volume of a laser Doppler velocimeter of the fringe mode. The basic idea of the system is similar to that of the E-SPART analyzer, but the equipment is extremely simplified; it uses neither conventional LDV signal demodulator nor Bragg cells. Nevertheless the polarity of droplet charge can be discriminated if necessary, and further, the accuracy of the size and charge measurements is comparable to that attained by EDBs owing to the special method of LDV signal analysis and also to the repeated measurements for a single particle. In this paper, the unique features in the basic principle of the measuring system are elucidated and accuracy of the size and charge measurements is demonstrated.

This measuring system has been developed for the experiment of droplet agglomeration enhanced by electrostatic force and particle vibration (Nakajima and Sato, 2003). To exemplify other applications, some experimental results on the Rayleigh instability are presented, which show the complexity of the Rayleigh disruption of charged droplets. An attempt to clarify the charge limit for a spherical solid particle sustainable in normal air follows. Then a semi-empirical equation relating the particle diameter and the charge limit for negatively charged particles is proposed on the basis of Townsend theory. Although the theory of Townsend is not applicable to positively charged particles, an experiment in argon gas showed that the difference due to the polarity was not very significant, and the prediction may be usable for both positively and negatively charged particles.

2. Theoretical descriptions of the measuring system

2.1. Trapping electrodes

Wuerker et al. (1959) analyzed and examined the stability of charged particle motion in an exact bihyperboloidal electrode configuration to clarify the basis of electrodynamic trapping of charged particles. Here the simplicity of the trapping system is demonstrated because we might presume that a very sophisticated electrode configuration would be necessary for the trapping system.

In this experiment, a simplified electrode configuration as shown in Fig. 1 was used to trap and to levitate a charged particle at the center of the measurement volume of LDV. It consisted of a pair of parallel plates and two rods with two insulated spherical electrodes for each rod. An ac voltage was applied to the rods to form a quasi-quadrupole ac electric field, which electrodynamically trapped charged particles as in the quadrupole mass spectrum analyzers. The plate electrodes behaved like mirrors making the electric images of the rod electrodes. For analyzing the electric field distribution, the electric image method modified by the charge simulation method was used. Fig. 2 shows the equipotential and electric force lines thus obtained. As shown in the center of Fig. 2, a saddle point in the x–z plane is formed along the centerline of the electrode system. The electric field around the saddle point is described below.

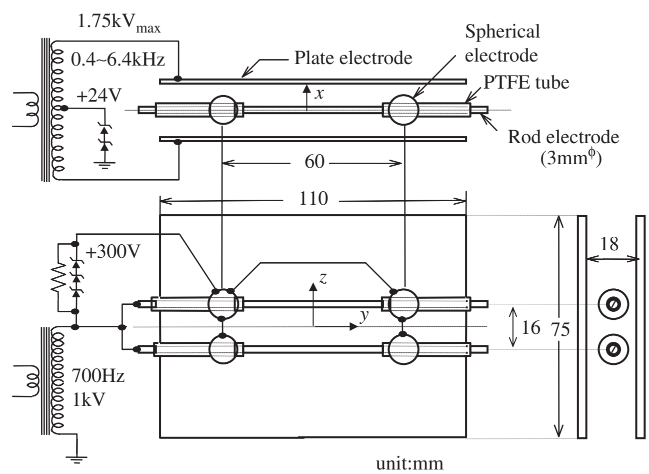

Fig. 1. Quadrupole electrode assembly for trapping charged particle (for negatively charged particles, polarity of diodes should be reversed).