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Focusing in a quadrupole acoustic channel

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ABSTRACT

We investigate analytically and numerically focusing of aerosol micron-and-submicron size particles in the incompressible laminar flow in a three-dimensional quadrupole acoustic channel of hyperbolic cross-section. The fluid–particle interaction of micron-size non-diffusive particles is described by a linear drag force. Considering motion of diffusive submicron particles, we account for their random displacements. Focusing efficiency is investigated for variety of flow and particle parameters, expressed in terms of dimensionless groups, namely acoustic strength parameter $\beta = 2p_s/\rho_f(\omega r_0)^2$, where p_s is the amplitude of pressure oscillations generated at channel walls, ω is the circular frequency of the oscillations, r_0 is the channel cross-sectional half-size, ρ_f is the fluid density; axial flow velocity parameter $\Pi_U = U/\omega r_0$, where U is the maximal velocity of the axial flow; and frequency parameter $\omega\tau$, where τ is Stokes relaxation time. It is shown that acoustic oscillations with frequency of about 1 kHz focus micron size particles on axial distance comparable to channel cross-sectional size. Submicron diffusive particles cannot be focused exactly at the channel axis owing to the adverse effect of Brownian motion leading to the diffusion broadening. It is shown that the achievable focusing width decreases with increasing the acoustic strength parameter.

1. Introduction

We propose a new principle of aerosol particle focusing into narrow particle beams, namely focusing by acoustic field in a narrow channel where the channel's cross-sectional size is much smaller than the acoustic wavelength.

Narrow particle beams are used in many applications to enhance transport efficiency, improve measurement resolution or deposit micropatterns precisely on a substrate. For example, particle beams are often used as inlets to single particle mass spectrometers to efficiently deliver particles to the analyzing region (see Huffman et al., 2005; Jayne et al., 2000; Kane & Johnston, 2000; Lee, Cho, & Lee, 2008; Liu, Ziemann, Kittelson, & McMurry, 1995a, 1995b; Nash, Baer, & Johnston, 2006; Slowik et al., 2004; Wexler & Johnston, 2001; Zhang et al., 2004). The narrow beams also help to ensure that particles pass through the most intense portion of the laser beam used to vaporize and ionize the particles (Wexler & Johnston, 2001). For similar reasons, particle beams are useful in cluster spectroscopy (Roth & Hospital, 1994; von Issendorff & Palmer, 1999). Particle beams are also used in material synthesis, whereby particles are deposited on substrates to produce ultrasmooth thin films by means of energetic cluster impact (Haberland, Insepov, & Moseler, 1995), to create three-dimensional microstructures (Akedo, Ichiki, Kikuchi, & Maeda, 1998), or for direct-write fabrication (Akhatov, Hoey, Swenson, & Schultz, 2008).

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The narrow beams can be used in health applications as a system that may increase the concentration of ambient particles. For purposes of particle concentration some centrifugal devices (Gordon, Gerber, Fang, & Chen, 1999) and virtual impact-type devices (Misra, Fine, Singh, & Sioutas, 2004; Sioutas, Koutrakis, Ferguson, & Burton, 1995) were previously considered.

Various principles of particle concentrating and focusing were described in the literature.

A major advance in microparticle electrodynamic focusing and concentration started when Paul and co-authors developed a mass spectrometer or quadrupole trap. Paul and Raether (1955) recognized that atomic ions could be stably focused by means of an ac field generated using the hyperbolic electrode configuration. This electrode design produces sinusoidally time-varying forces whose strengths are proportional to the distance from the channel axis. This leads to particle drifting motion towards the axis and their focusing there. Quadrupole electrodynamic focusing is inapplicable to large ($>$ 10 nm) charged particles.

Electrodynamic and electrostatic concentrating and focusing of ions and nanometer charged particles has become a major tool for studies involving single and multiple particle reactions and dynamics (see Davis, 1985; Hutchins, Holm, & Addison, 1991; Kane, Oktem, & Johnston, 2001; Loyalka, Tekasakul, Tompson, & Warder, 1995; Wuerker, Shelton, & Langmuir, 1959).

Aerodynamic focusing can be roughly divided into two broad categories. First, single shot focusing arises for particles with considerable inertia accelerated only once, most often through a jet (Akhatov et al., 2008; Dahneke & Friedlander, 1970; Fernández de la Mora & Riesco-Checa, 1988; Fuerstenau, Gomez, & Fernández de la Mora, 1994; Israel & Friedlander, 1967). Alternatively, multiple shot focusing occurs as a result of many acceleration and deceleration steps for particles that may have relatively little inertia (Fernández de la Mora, 2006; Liu et al., 1995a, 1995b; Maxey, 1987). Although each such step may concentrate the particles only slightly, their collective outcome is a highly concentrated or focused aerosol.

Multiple shot focusing takes place in spatially periodic flows occurring in periodic aerodynamic lens arrays (Liu et al., 1995a, 1995b, 2007; Wang, Kruis, & McMurry, 2005; Wang, Gidwani, Girshick, & McMurry, 2005; Wang & McMurry, 2006), where aerodynamic forces concentrate a range of micron and submicron size aerosol particles along the lens axis. However, flows in these lens arrays are inherently unstable because of early flow separation. As a result jets formed within them tend to become turbulent at relatively modest Reynolds numbers. This leads to particle mixing back into the flow resulting in a loss of particle delivery to the analyzing region (Eichler, de Juan, & Fernández de la Mora, 1998; Wexler & Johnston, 2001). Keeping eddies from forming in the flow is only possible at low lens Reynolds numbers, but this requirement is in conflict with particle focusing because optimal lens performance takes place at particle Stokes number equal to unity. The solution to the problem was found in reduction of the inlet pressure, which leads to the decrease of the Reynolds number.

The main challenge in focusing nanometer particles arises from their small inertia and high diffusivity (Liu et al., 1995a, 1995b; Wang, Kruis, et al., 2005; Wang, Gidwani, et al., 2005; Wang & McMurry, 2006). Employment of aerodynamic lenses and nozzles requires use very low pressures (below 300 Pa). Operating at very low pressure requires large pumping capacities (Wang, Kruis et al., 2005). Besides, lens arrays provide none control over beam broadening caused by particle diffusion resulting in poor focusing of nanometer particles.

The use of acoustic standing waves to concentrate initially homogeneously suspended aerosol or hydrosol particles in acoustic pressure nodal or antinodal planes was first visualized in Kundt wave tube and then described by Rayleigh (1945). Many subsequent works study and utilize this phenomenon. This was established that particles can be concentrated under the action of Stokes drag force and acoustic radiation force depending on their size and sound frequency (see Czyz, 1990; Dain, Fichman, Gutfinger, Pnueli, & Vainshtein, 1995; Danilov & Mironov, 2000; Duhin, 1960; Nigmatulin, 1990; Vainshtein, Fichman, Shuster, & Gutfinger, 1996; Whitworth & Coakley, 1992). The acoustic radiation force was also used to position and levitate particles (see Anderson, Cluff, Lemmon, & Putnam, 2005; Coakley, Bardsley, Grundy, Zamani, & Clarke, 1989; Danilov & Mironov, 1984; Doinikov, 1997a, 1997b; Fuchs, 1964; Gopinath & Mills, 1994; Hertz, 1995; Hinds, Mallove, & First, 1977; Kaduchak, Sinha, & Lizon, 2002; King, 1934; Nyborg, 1984). In those works the particle motion was studied in situations when undisturbed fluid was at rest.

Several works investigated the effect of acoustic radiation force on particle concentration and focusing in flowing fluids (Anderson, Buwig, Line, & Frankel, 2002; Goddard & Kaduchak 2005; Goddard, Martin, Graves, & Kaduchak, 2006; Lipkens, Costolo, & Rietman, 2008).

Goddard and Kaduchak (2005) and Goddard et al. (2006) were the first to acoustically focus particles in liquid flow in a capillary 5 mm tube. The authors used the ultrasound source ($f = 417$ kHz) attached to the tube external surface along the axial direction such that the opposed wall of the tube served as a reflector. Under these conditions, a standing wave was formed inside the tube with wavelength $\lambda = c/f$ smaller than the tube size ($\lambda < 2r_0$). This wave had only one pressure nodal line parallel to the tube axis where particles were focused.

Our goal is acoustic particle focusing in tubes of sizes similar to those used by Goddard and Kaduchak (2005) and Goddard et al. (2006) however in gas flows. This is stipulated by desirable application to production of narrow particle beams. For instance tubes in on-line single-particle analyzers have sizes of order of 10 mm. We note first that that several pressure nodal lines would appear in air filled tubes of such sizes because speed of sound in air is much lower than that in liquids. This would lead to particle concentrating along these lines. Kogan, Kaduchak, and Sinha (2004) and Marston and Thiessen (2004) have shown that the use of non-cylindrical tube shape and symmetry breaking allow particle focusing along only one line. Another issue is that high frequency ultrasound waves used by Goddard et al. being applied to particle focusing in gas-filled tube result in strong sound attenuation and dissipation (Krasilnikov & Krylov, 1984).

To reduce attenuation, in gas-related acoustic applications (coagulation, levitation) lower frequencies (1–20 kHz) were employed (see Brandt 1936; Caperan, Somers, Richter, & Fourcaudot, 1995; Ezekoye & Wibowo, 1999; Foster & Plaum, 1988;