Aerosol Science and Technology

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uast20

Continuously Converging Multistage Focusing Lenses to Concentrate Aerosols at High Reynolds Numbers

Guillermo Vidal-de-Miguel [a] & Juan Fernandez de la Mora [b]

[a] SEADM, Parque Tecnológico de Boecillo, Valladolid, Spain

[b] Department of Mechanical Engineering, Yale University, New Haven, Connecticut, USA

Available online: 20 Sep 2011

To cite this article: Guillermo Vidal-de-Miguel & Juan Fernandez de la Mora (2012): Continuously Converging Multistage Focusing Lenses to Concentrate Aerosols at High Reynolds Numbers, Aerosol Science and Technology, 46:3, 287-296

To link to this article: http://dx.doi.org/10.1080/02786826.2011.621906

Aerosol Science and Technology, 46:287–296, 2011

ISSN: 0278-6826 print / 1521-7388 online
DOI: 10.1080/02786826.2011.621906

Continuously Converging Multistage Focusing Lenses to Concentrate Aerosols at High Reynolds Numbers

Guillermo Vidal-de-Miguel[1] and Juan Fernandez de la Mora[2]
[1]*SEADM, Parque Tecnológico de Boecillo, Valladolid, Spain*
[2]*Department of Mechanical Engineering, Yale University, New Haven, Connecticut, USA*

All known multi-stage aerodynamic lenses able to focus sharply a wide range of particle sizes include decelerating regions where the flow becomes turbulent at Reynolds numbers *Re* typically of 100 or less. Here, we propose a design for a focusing concentrator operating laminarly at *Re* of many thousands. The particles are accelerated by the gas through a continuously converging ladder of smooth contractions, each designed such that: (1) the flow remains laminar at substantial *Re*; (2) a certain band of particle sizes is focused in each contraction, without substantial defocusing of larger particle focused in 1 or several preceding contractions; (3) the form, length, and ratio of entry to exit diameter of each contraction, as well as the number of consecutive contractions are chosen such that all particles within a given relatively wide range of sizes are focused at the end of the ladder of contractions into a relatively narrow focal region. The focusing virtual impactor formed by coupling this device to a perforated surface could provide a powerful particle concentrator.

1. INTRODUCTION

It is often desirable to sample and concentrate particles suspended in a gas for further analysis or detection. Unlike a liquid or a low speed gas flow where the fluid density is relatively constant, the flow of particles suspended in a gas can be rendered highly compressible by inertial effects (Robinson 1956; Michael 1968; Fernández de la Mora and Rosner 1981, 1982). As a result, the number of particles per unit volume n at a given location in the flow may be substantially higher than its initial value n_0 at a reference point upstream. The concentration factor defined as

$$C = n/n_0 \qquad [1]$$

may therefore be much larger than unity, a situation of great practical interest to increase the sensitivity of instruments used for particle detection or analysis. Indeed, since the volumetric sampling flow rate q of such instruments is generally fixed, their sensitivity is increased by a factor C if the particles are concentrated by that factor before being sampled. Under practical situations involving detection or analysis of ambient particles, many aerosol instruments sample flows typically of 1 L/min, sometimes considerably more. If one's goal is to concentrate ambient particles by a factor of 1000 *prior to* detecting them, the concentrating device needs to handle flow rates of thousands of L/min, typically associated to very high Re. For a jet of velocity U formed by a nozzle of diameter D, Re is defined in terms of the fluid's kinematic viscosity ν as:

$$Re = DU/\nu \qquad [2]$$

Substantial concentration factors have been achieved in 2 types of inertial devices based on aerodynamic focusing and virtual impaction, respectively.

Virtual impactors are common instruments (Chen et al. 1986) that can be used as particle concentrators (Romay et al. 2002). They involve a jet of gas carrying particles, forced to impact against a virtual wall (an imaginary interface separating the jet from another fluid stream). This second fluid stream is most commonly a confined region of slow moving gas, often a cavity, but it could also be a second relatively strong jet (Willeke and Pavlik 1978, 1979). This virtual wall ideally deflects the majority of the impinging gas jet, but is penetrated by some of the suspended particles. In principle, none of the jet gas but some of the particles could be admitted into the cavity region, in which case C would be infinite. In practice, the virtual wall is most often fluid-dynamically unstable and it is conventionally stabilized in virtual impactors by accepting steadily a finite flow rate q of gas into the cavity of slow moving gas. The required minor to major flow ratio q/Q is typically larger than 3%, so that the maximum value of C achievable for particles transferred with high efficiency is generally less than 30. Note that this circumstance not only limits the concentrating ability of virtual impactors. It also reduces considerably their resolving power with respect to that of conventional wall impactors. The

Received 20 April 2011; accepted 2 August 2011.
Address correspondence to Guillermo Vidal-de-Miguel, SEADM, Parque Tecnologico de Boecillo 205, Valladolid, Boecillo 47151, Spain. E-mail: guillermo.vidal@seadm.com

reason is that impactors normally capture large particles and not small particles, yet, virtual impactors capture also at least a fraction *q/Q* of the small particles. Concentration factors much larger than 30 are achievable by connecting a set of N virtual impactors in series, where the limiting concentration factor C_1 of a single virtual impactor is raised to the power N of the number of stages: $C_N = C_1{}^N$. This approach has been demonstrated by Romay et al. (2002) for $N = 2$, to achieve $C > 100$ at high *Re*. Their instrument is limited in the largest particle size it can handle by particle losses on the flow lines leading from the first to the second virtual impactor stage.

Aerodynamic focusing is one of the most effective schemes known to concentrate aerosol particles (Fernández de la Mora and Riesco-Chueca 1988), and will be used here in combination with virtual impaction. The pioneering ideas leading to the notion of aerodynamic particle focusing are because of Israel and Friedlander (1967), with extensions by Dahneke and Friedlander (1970), Cheng and Dahneke (1979), Dahneke (1978), Dahneke and Cheng (1979), Dahneke et al. (1982), Sinha et al. (1982), and Sinha and Friedlander (1986). This early work is further described by Sinha et al. (1983), with later extensions summarized by Fernández de la Mora (1996), Piseri et al. (2004), and Fernández de la Mora (2006). In the pioneering work by the groups of Friedlander and Dahneke, the primary concern was to separate aerosol particles from the gas carrying them in order to introduce the particles into a vacuum system for further analysis, most often by mass spectrometry. The aerosol was introduced in the vacuum region of the mass spectrometer, where the gas expands producing a supersonic jet where gas and particles were separated. The width of the particle beam obtained was not substantially smaller than the diameter of the sonic nozzle, so that the term focusing did not mean that $C >> 1$. However, a critical source pressure was identified at which the particles kept approximately their initial concentration (or decreased it moderately), while the concentration of gas molecules diminished greatly. The term focusing could nonetheless be used in the sense that, as shown by Friedlander and colleagues, at pressures below that critical conditions, the particles in the beam did cross from one side of the symmetry axis to the other. Note in this respect that n is particle concentration, not gas concentration. The particle phase needs to be compressible, but the fluid phase may be either compressible or incompressible. The notion of particle phase compressibility is discussed by Robinson (1956), Michael (1968), Fernandez de la Mora and Rosner, and many others.

The first demonstration of focusing in the specific sense of interest to this study ($C >> 1$) was given by Fernández de la Mora and Riesco-Chueca (1988). (1) They showed that focusing can occur also in subsonic and low speed flows, and may arise as a true singularity, with C tending to infinity. C is however limited by so-called geometric aberration, due to the fact that the point at which particles of a given size cross the axis of symmetry varies slightly as a function of their initial distance to the axis of symmetry. (2) They demonstrated practical situations with $C > 1000$. (3) They showed that the slowly converging nozzles used previously could not focus particles as small as nozzles with more rapidly converging walls (including wedges with half angles $\alpha > \pi/2$). (4) They introduced the concept of the critical focusing Stokes number S_{crit}, above which particles initially near the axis would cross the axis, noting that subcritical particles do not cross the axis, critical particles cross it at infinity, and supercritical particles cross it at finite distances from the nozzle. Figure 1 shows schematically the Stokes number dependence of the focusing distance, $f(S)$, where S is defined conventionally as (Friedlander 1977)

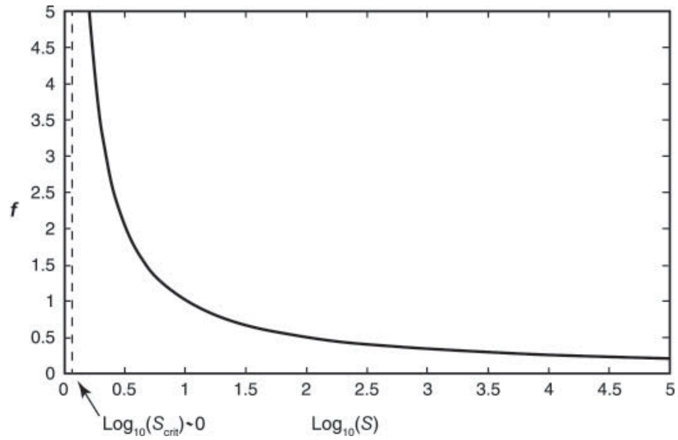

FIG. 1. Schematic dependence $f(S)$ of the focal distance f (normalized with the nozzle throat diameter) on the Stokes number S for particles accelerated through a focusing *contraction* with $d >> 1$.

$$S = \tau U/D, \quad [3]$$

based on jet speed U, nozzle diameter D, and the stopping time τ of a particle. τ is defined as the time required to reduce the speed of the particle by a factor of e (Euler's number) when flying through gas at rest in the absence of external forces. In this context, it is also useful to define the aerodynamic size of a particle as the diameter of a spherical particle whose resistance to motion in the gas is linear with its velocity relative to the gas, and whose density is 1 g/cm^3 and stopping time τ is the same as for the real particle.

The contributions of Fernández de la Mora and Riesco-Chueca (1988) were primarily theoretical, with additional numerical examples restricted to 2-dimensional flows. However, the general validity of their picture has been confirmed by experiments with axisymmetric nozzles (Rao et al. 1993; Fuerstenau et al. 1994). Easily fabricated thin-plate orifice nozzles ($\alpha = \pi/2$) have subsequently been most often used for aerodynamic focusing. However, Middha and Wexler (2003) have confirmed the advantage of even larger convergence cone angles, while both these authors and Piseri et al. (2004) have contributed improved geometries capable of focusing particles with unusually small Stokes numbers.

Aerodynamic lenses. While useful to concentrate sharply particles within a narrow S, these early studies did not solve the problem of concentrating simultaneously a wide range of particle sizes, which is the concern of the present study. An important step in that direction came from 2 independent lines of work, based on many (rather than just 1) acceleration and deceleration steps. This scheme will be referred to as *multiple shot focusing*. As shown by Robinson (1956), one suitably designed stage of acceleration and deceleration leads to a net concentration factor $C_1 > 1$. For small S, C_1 differs only slightly from unity. But a sequence of N such steps in series produces a concentration factor $C = C_1{}^N$, leading at sufficiently large N to a highly concentrated or "focused" aerosol, even at modest S values. This behavior was first seen in some striking calculations by Maxey (1987) involving spatially periodic flows, which have inspired a number of subsequent fluid dynamical investigations (i.e., Gañán-Calvo and Lasheras 1991; Tio et al. 1993a, 1993b; Martin and Meiburg 1994; Rubin et al. 1995, among many others). This rich line of theoretical work has had no observable effect on practical aerosol concentrators. Multiple shot focusing was first brought to practice in general as well as introduced conceptually in the aerosol literature by Liu et al. (1993) (Liu et al. 1993; 1995a, 1995b), without connection to Maxey's precedent. These authors used primarily sharp edge orifice nozzles, and introduced the widely accepted terminology *aerodynamic lens* to refer to each individual nozzle followed by a deceleration region. Their work has had considerable impact on the important problem originally addressed by Friedlander and Dahneke: determining the chemical composition of suspended particles after introducing them into a vacuum. These configurations imply a relatively rapid lateral expansion of a gas accompanied by a relatively slow lateral expansion of the aerosol particles. Though the flow through focusing lenses is typically subsonic, only the nozzle connecting to the downstream vacuum is supersonic when the downstream pressure is low enough. Highly supersonic jets are indeed unavoidable when introducing an aerosol initially at atmospheric pressure into a vacuum. But they are undesirable in applications such as those pursued here, where the process of particle concentration tends to take place close to the original pressure of the gas-particle suspension (often atmospheric pressure). For present purposes, the main advantage of multiple shot focusing with approximately periodic nozzles is the considerably wider range of S values that can be focused (typically from S below 0.1 up to above 1), and the higher concentration factor C generally achievable, compared with what is possible with single shot focusing.

The multiple shot approach is in principle not restricted to the formation of aerosol beams for introduction into a vacuum. However, in practice, it is not readily extended to applications involving atmospheric pressures and high gas flow rates. The reason is that the flow configurations so far employed or proposed lead to transition to turbulence and make the focusing devices inoperative at relatively low Re. For instance, according to Eichler et al. (1998; Figure 2), the focusing performance

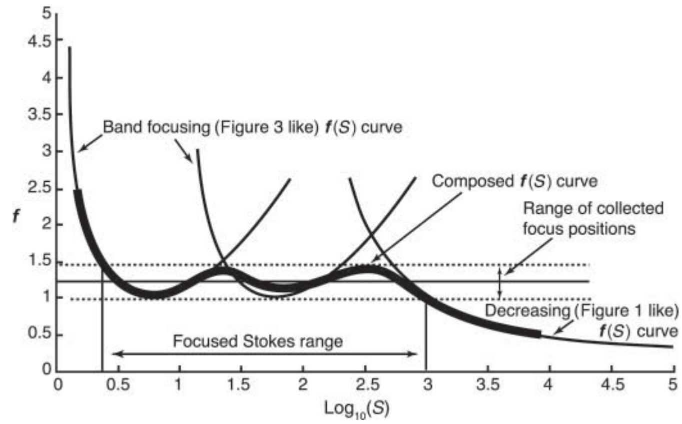

FIG. 2. Schematic of the $f(S)$ curve for particles accelerated first through a *contraction* with $d >> 1$, and then through 2 additional *contractions* having d values comparable to unity.

of the nozzle geometry most commonly used in aerodynamic lenses (a sharp edge orifice) degrades rapidly at Re above 70. The different types of focusing lenses lead all to detachment and reattachment of the streamlines (Liu et al. 1995a, 1995b), with corresponding flow fields becoming unstable at relatively low Re. This restriction is generally compatible with particle beam forming applications, but can be readily seen to be inadequate for most atmospheric pressure applications. For instance, for air at ambient conditions, with a nozzle diameter $D = 1$ mm, the flow rate at Re = 70 is $Q = 0.05$ L/min.

Focusing virtual impactors. Some remarks are pertinent here on solutions previously proposed to match a receiving tube or *collector* and an incoming jet in an aerosol concentrator. The aerodynamic configuration in the collector region needs to be sufficiently stable to enable safe passage of the smallest particles in the range of interest into the steady region of the collector cavity. Both virtual impactors and the various skimmer designs used for introducing focused aerosol beams into a final vacuum stage have the same configuration of a jet impinging on a plate or a cone with an aligned orifice. This type of configuration is typically unstable and, unless some means to stabilize the flow are implemented, produces a net oscillatory penetration of gas jet into the cavity. As previously discussed, the instability is solved via a relatively high suction through the collector orifice that limits the achievable concentration factor C. If the accelerating nozzle concentrates the particles into a region of diameter d_f substantially smaller than the nozzle throat diameter D, the collector orifice diameter d_c can be made comparable to d_f. The characteristic length of the virtual wall is therefore reduced by the factor d_c/D. In addition, as the edge of the collecting orifice is closer to the stagnated region, the radial component of the local velocity (neighboring the collector orifice) is also reduced by another d_c/D factor. The combination of these 2 factors reduces the local flow Re in the region of the sampling orifice by a potentially large factor $(d_c/D)^2$ and, what is more, permits reducing the minor to major flow rate required to stabilize the virtual wall and consequently increasing the achieved concentration ratio. For instance, if a beam of aerosol particles could be focused through a collection orifice having $d_c/D = 0.1$, the concentration factor C that could be achieved would be 100 times higher than that of a conventional virtual impactor if one assumes that the minor flow velocity in the virtual wall is equal in both the classic virtual impactor and the focused virtual impactor. But one could expect even better results because the minor flow velocity would presumably be much lower since the local Re of the virtual wall would also be 100 times lower. The advantages in this respect of a focusing virtual impactor have been noted by Fuerstenau et al. (1994). Unfortunately, the potential advantage noted by Fuerstenau et al. (1994) is restricted to single shot focusing, which can by its very nature concentrate only a relatively modest range of particle sizes. It could via multiple shot focusing be turned into a particle concentrator of wide size range, but only at flow rates too small to meet our present objectives.

2. DESIGN CONSIDERATIONS FOR CONTINUOUSLY CONVERGING MULTISTAGE AERODYNAMIC LENSES

Given the state of the art just discussed, 1 of 4 goals is to develop a focusing device concentrating highly a wide range of particle sizes (wide S range) and operating at high flow rates (high Re). The requirement of focusing a broad range of particle sizes demands the use of more than 1 focusing nozzle. But the turbulent transition problem characteristic of all prior focusing lenses (at all but relatively small values of Re) requires the development of a new aerodynamic configuration avoiding entirely flow detachment. This is not possible in the periodic or quasiperiodic acceleration–deceleration schemes of Maxey (1987) or Liu et al. (1993), since the converging accelerating region in each period must be necessarily followed by a diverging decelerating region, which is always unstable at high Re. The new scheme must therefore focus the broad particle size range of interest in a continuously converging geometry. A single convergence can focus sharply only a narrow range of particle sizes, so the new proposed configuration relies on a *ladder of contractions*, each of which focuses a progressively smaller range of particle sizes, without defocusing appreciably the larger particles previously concentrated.

Some clarifications with regard to the definition of focal distance used in this text are pertinent here to avoid confusion with prior art. Below S_{crit}, particles passing through a focusing nozzle do not cross the axis, but the beam can be still narrowed. Particles trajectories travel approximately parallel to the main flow while their distance to the axis diminishes asymptotically. This circumstance is indeed broadly used in focusing lenses to concentrate particles. But the distance required for the beam to reach a small diameter is typically high (several times the nozzle diameter), and those elongated beams would be difficult to stabilize in a high Re device, even using a single lens, because the jet becomes turbulent after a few nozzle diameters. For the application pursued here, we shall focus the beam of particles at a moderate distance from the nozzle. For $S > S_{\text{crit}}$, the beam of particles first converges toward a focal region and then diverges taking approximately the shape of a sand clock constriction. A perfect focus would mean that every particle having the same S crosses the axis at the same axial distance. Yet, aberration effects spread the trajectories. Rather than a singular point, the focus is here defined as the smallest section of the sand clock like constriction. For greater precision, the focal distance $f(S)$ is defined as the distance between the focal section of the particle beam and a reference position that can be chosen arbitrarily, for instance the throat of the nozzle. Note that for $S = S_{\text{crit}}$ the focal distance tends to infinity and for $S < S_{\text{crit}}$, the focal distance (as defined here) simply does not exist.

Smooth focusing contractions. A sectional view of a smooth focusing contraction acting as the elementary step in this *ladder* is shown in Figure 3a, and will subsequently be referred to as a *contraction*.

Although this configuration is not restricted to axisymmetric situations, the flow in the *contraction* of Figure 3a comes from a circular section of diameter d_i and ends in a circular section with a smaller diameter d_{i+1}. The contraction is therefore characterized by its shape, length, and the diameter ratio d:

$$d = d_i/d_{i+1}. \qquad [4]$$

The continuously converging geometry described in Figure 3a, with controlled inflexions and moderate radii of curvature, should be designed to prevent boundary layer separation. Note

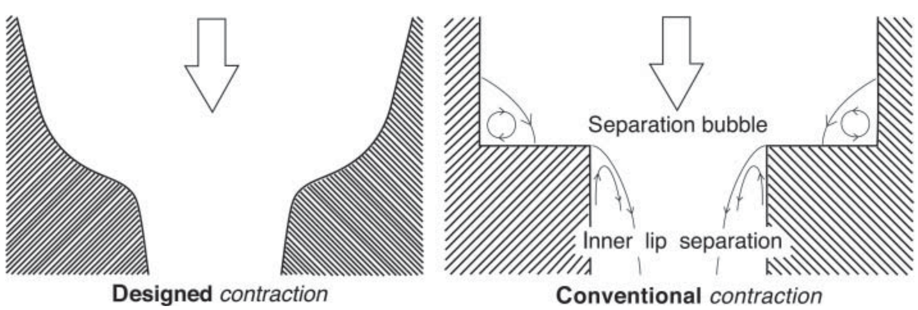

FIG. 3. Section of an individual focusing *contraction*. Right: conventional contraction subject to the appearance of a separation bubble at the outer corner, and flow separation at the inner lip. Left: well designed *contraction* avoiding these 2 problems.

the need to sidestep 2 types of instabilities characteristic of contractions, most readily visualized when sharp steps are involved (Figure 3b). First, the flow tends to separate on the outer corner where the wall first ceases to be cylindrical and begins to converge radially. This problem is associated to the instability of the decelerating (actually stagnating) boundary layer forming as the corner is approached axially from upstream. The result is a recirculation region at the corner, with vortices that can be periodically swept by the flow. Such vortices tend to form not only in stepped geometries but also in improperly designed smooth shaped contractions typical of the inlet region of wind tunnels. So-called Göertler vortex instabilities (Saric 1994) can also induce the instability of the flow in highly convex regions. This region has to be smooth enough to prevent bubble recirculation and Göertler vortex formation. The second problem is even more serious, and is associated to the singularity of the fluid velocity formed at the end of the step, when the wall ceases to be radial and turns again into an axial direction. The flow then simply separates, and another recirculating region forms between the separated jet and the wall. When this second step is rounded off slightly, the sharp turn forced into the flow creates a region of relatively high velocity, whereby the flow needs to decelerate downstream from the corner, leading similarly to boundary layer separation. This problem eventually disappears as the corner curvature is decreased, and the wall geometry is suitably designed downstream from it.

In order to promote focusing effects, it is desirable to make the geometry of the *contraction* as abrupt as possible. On the other hand, a stable aerodynamic configuration calls for smooth geometries. A *contraction* must therefore be abrupt enough to produce focusing effects with relatively low Stokes numbers, but smooth enough to avoid Göertler vortex formation and flow detachments downstream of the rounded corner region producing high velocities zones.

The *contractions* needed for present purposes have an unconventional $f(S)$ dependence. As other conventional focusing lenses, they also have a critical S, S_{crit}, at which the focal distance tends to infinity. In a conventional focusing lens, characterized by $d >> 1$, the focal distance f decreases monotonically with increasing S (Figure 1). In contrast, for the alternative *contractions* of interest to this study, where d is of order 2 to 3, $f(S)$ exhibits a characteristic minimum at a certain $S_m > S_{\text{crit}}$. Figure 4 has been constructed by integrating the particle trajectories using the Stokes drag law and a potential flow for a simplified abrupt contraction having $d = 3$ (note that the results of Figure 4 can only be interpreted qualitatively since such an abrupt geometry is usually incompatible with a potential flow).

The qualitative interpretation of this result is that there is a certain *band* of S values, centered at S_m, which is well tuned to the contraction, and is focused effectively at a moderate focal distance. Substantially larger or smaller S values focus much less efficiently, as indicated by their large focal distances. We shall subsequently refer to these lenses as *narrow band* or *band* lenses. Their novelty does not reside in their inefficient focusing

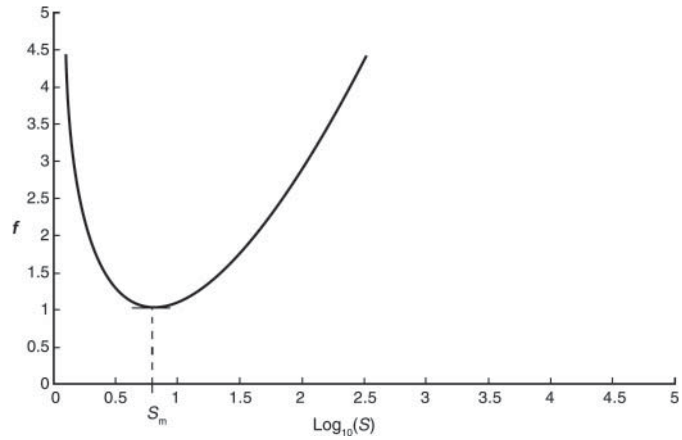

FIG. 4. Schematic of an $f(S)$ curve for particles accelerated through a focusing *contraction* in which d is comparable to unity.

of small particles (small S), but on their inefficient focusing also of large particles ($S >> 1$). A second important feature of band lenses follows from the minimum arising in the $f(S)$ curve, which makes the focal point relatively independent of S in the vicinity of S_m. This effect is crucial for the design of a series of wide range focusing contractions, and deserves some discussion.

Note first that the *band focusing* phenomenon is favored by values of d of order unity (around 2 and 3). In a conventional aerodynamic lens, where $d >> 1$, 2 undesirable things tend to happen. First, particles with $S >> S_{\text{crit}}$ have a long convergence path over which they can accelerate to relatively high radial speeds, in spite of their high inertia (sluggishness). Consequently, their trajectories cross the axis at a focal point, and tend to open up radially downstream from it, landing at the end of the process closer to the wall of the aerodynamic lens than they were initially. This is the overfocusing or defocusing phenomenon discussed by Liu et al. for S larger than a certain value $S_{\max}$. As a result, a succession of lenses is useful only to concentrate particles for which $S < S_{\max}$. This overfocusing effect is evidently moderated or even eliminated when d ceases to be large, since particles with high S have no time to acquire sufficient radial speeds. The second important difference between conventional lenses and *band* lenses is analogous to the first, but involves the particle velocity in the axial direction. At $d >> 1$, axial flow velocities right before the contraction are very small (the initial axial velocity to nozzle velocity ratio is proportional to $1/d^2$), so that large particles tend to spend plenty of time in the contraction region, which favors overfocusing. However, when d is of order unity, the large particles have a substantial initial axial velocity, and can cross the contraction region in a relatively short time. In other words, the large particles are *entrained* through the contraction by their initial axial velocity without any significant focusing or defocusing. The net result of this *entrainment* effect is that large particles are not defocused in a contraction suitable to sharply focus smaller particles. This high axial velocity could cause big particles to impact the walls of the contraction when the flow path becomes narrower, but as we shall discuss later, this effect can be minimized in a ladder of contractions by narrowing the beam of particles in a previous contraction working at $S < S_{crit}$.

The fact that lenses with a moderate contraction ratio d do not defocus particles with high S values, and may even focus them slightly, has been previously reported in the case of moderately corrugated periodic nozzles (Fernandez de la Mora 2006). This periodic geometry, however, contains unstable divergent regions and cannot operate at the high *Re* of interest here.

2.1. Composite Focusing Nozzles for High *Re* and Wide Stokes Range

Wide particle size range focusing at high *Re* as proposed here is based on a series of *contractions*, each of which focuses sharply the *band* of particle sizes which is designed to concentrate, without appreciably defocusing the various *bands* of progressively larger particles previously focused by prior *contractions*. In a general situation, contractions could be subjected to important particle losses by inertial impaction when the walls are narrowed, but this can be avoided by focusing particles in two stages within the ladder of contractions. Particles are first slightly prefocused in 1 contraction at $S < S_{crit}$ and enter the subsequent contraction where they are sharply focused at higher S. Once focused, particles cross the rest of subsequent contractions without defocusing or impacting the walls. Obviously, particles entering the first focusing stage cannot by prefocused. To avoid particle losses, the first focusing stage has to be of the type $d >> 1$. Avoiding overfocusing and wall losses is a necessary condition for success; but it is not sufficient. In addition, all particles within a wide size range must have closely matched focal points. The strategy to achieve this goal is discussed next.

Figure 5 illustrates qualitatively the $f(S)$ response of 2 successive *contractions*. The one most upstream has relatively large d and entry diameter. It therefore focuses particles with a relatively large S, and is characterized by the monotonically decreasing (Figure 1 like) $f(S)$ curve shown to the right. The second contraction has a moderate d value, associated with the $f(S)$ curve characterized by the band focusing (Figure 4 like) shown to the left. The $f(S)$ curve resulting from coupling both contractions in series is represented qualitatively in Figure 5 as a hybrid of the other 2 curves. The $f(S)$ curve resulting from placing in series 3 *contractions* is similarly shown in Figure 2.

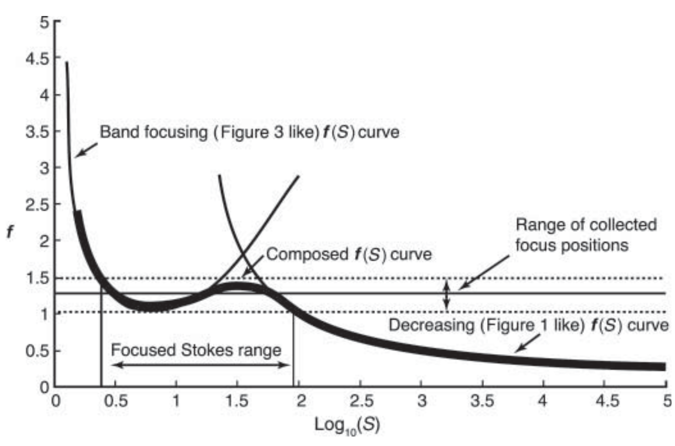

FIG. 5. Schematic of an $f(S)$ curve for particles accelerated first through a *contraction* with $d >> 1$, and then through a second *contraction* with d comparable to unity.

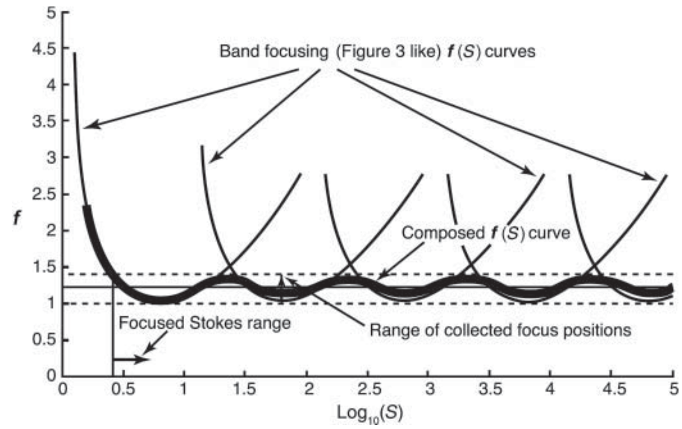

FIG. 6. Schematic of the $f(S)$ curve for a composite focusing nozzle formed by a sequence of N consecutive *contractions*.

The wavy pattern seen in Figures 2 and 5 permits having a broad range of S values focused within a relatively narrow axial region. Clearly, as illustrated in Figure 6, each additional *contraction* stage added would lead to a new wave in the composite $f(S)$ curve, further extending the range of Stokes numbers that could be narrowly concentrated at a common focus. Note that Figures 2, 5, and 6 are freehand drawings constructed to intuitively explain the behavior of succession of composite nozzles, so these results should be understood qualitatively.

Achieving a common focus is nontrivial because the composite desired custom $f(S)$ curve is affected by interactions between the various stages. But various iterations of fine tuning of the parameters d and the longitudinal distances characterizing the various *contractions* permits achieving the goal of minimizing the vertical amplitude of the waves (variation of focal distance), and controlling its mean position and the length of the wavy region (range of Stokes numbers focusable).

The composite focusing nozzle already described could be used without further additions to concentrate narrowly into a focal region the particles suspended in a large sampled flow rate of gas. These particles could then be interrogated optically, for instance to determine if they contain dangerous pathogens (Davitt et al. 2006; Kasparian et al. 2007). Alternatively, the focused particle beam could be impacted on a surface for various purposes. For instance, the beam could be used to write a narrow line, to alter this surface as a result of the spatially concentrated high-speed impact of relatively hard particles, or to cut the surface, etc. Higher particle velocities could be achieved without degrading the focus by extending longitudinally the final nearly cylindrical region of the last nozzle section, as in a gun, keeping

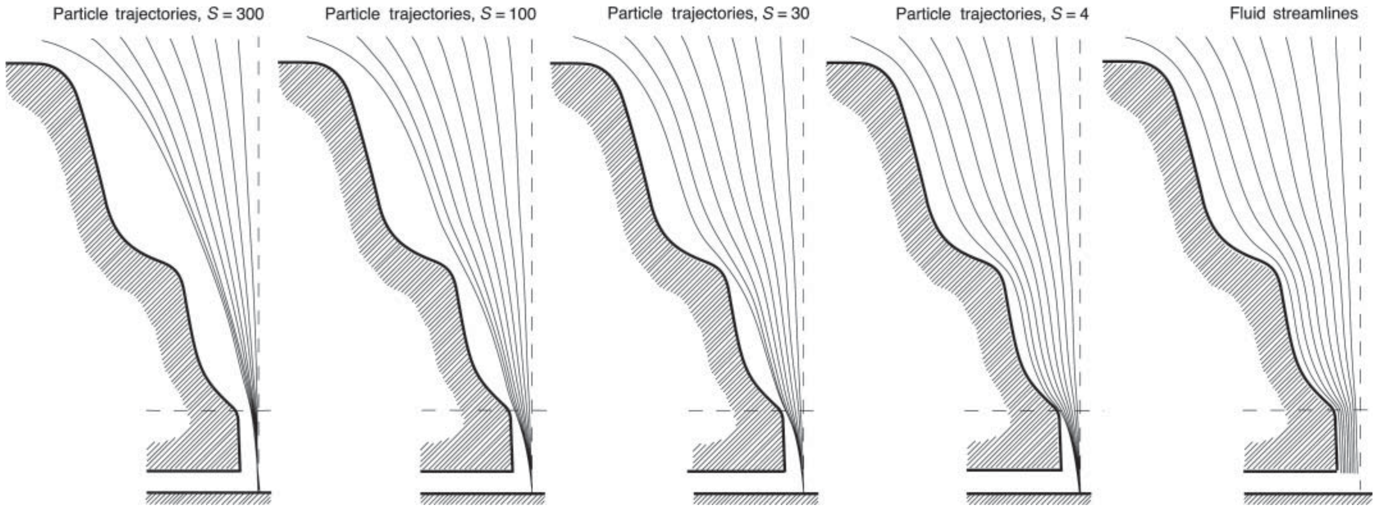

FIG. 7. Meridional section of a composite focusing nozzle formed by a series of 3 axisymmetric *contractions*, and capable of focusing a wide range of particle sizes in the same region at high *Re*. $S = 300$, 100, 30, 4, and streamlines, from right to left.

it slightly conical to provide acceleration to maintain the laminar flow. While a comparable result may be achieved by means of a single-shot focusing nozzle with particles of uniform size, the use of several *contractions* in series would permit focusing particles with a broader size distribution, which can generally be procured more economically.

Focusing virtual impactor for high Re, high C, and wide Stokes range. Coupling a composite focusing nozzle with a collector to make a focusing virtual impactor would bring together the advantages of permitting high flow rates (high *Re*), and high concentration factors (*C*) over a wide range of particle sizes. Figure 7 shows a half meridional section of an axisymmetric composite nozzle specially designed to maintain an almost fixed focal distance through a wide range of *S* facing an impaction plate. Streamlines and particle trajectories are also plotted respectively for $S = 4$, 30, 100, 300. Figure 8 represents the corresponding diameter of the focused beam D_m normalized with the nozzle exit throat diameter, at a fixed axial position, and as a function of *S*. In this case, with only 3 *contractions*, a range of almost 3 orders of magnitude in *S* is concentrated at a radius 20% of the nozzle throat radius.

Figure 9 includes the composite nozzle of Figure 7 facing a large collector piece with a centered inlet hole. In this case, the major flow would be deflected radially. A small portion of the jet flow (the minor flow) would be sampled through the centered hole in the collector, at a flow rate controlled downstream of this

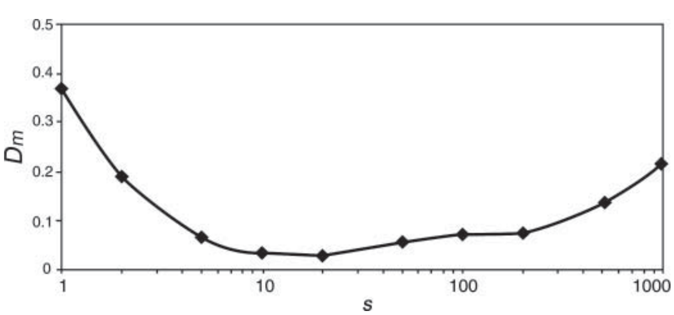

FIG. 8. Stokes number dependence of the diameter of the focused beam (normalized with the nozzle throat diameter) formed by the composite focusing nozzle of Figure 7 at a fixed axial position. This diameter has been computed for $Re = 7000$, and a realistic nonlinear aerodynamic drag law valid for particle *Re* below 800.

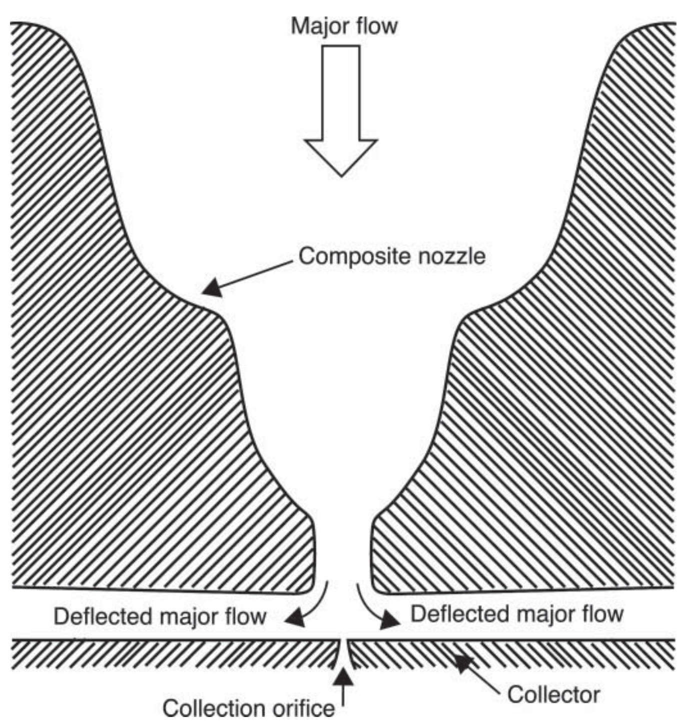

FIG. 9. Coupling of the composite focusing nozzle of FIG. 7 with a collector having a centered sampling orifice.

hole. Due to their high inertia (focused particles have S in the range from 2 to 1000, much higher than the impaction critical Stokes Numbers and that of conventional focusing lenses which are typically in the range S∼0.1), the particles having been focused toward the collecting orifice would be almost unaffected by the minor flow. Accordingly, those focused particles confined within a diameter smaller than the opening in the collector will penetrate through it. All the particles in a prescribed size range can in fact penetrate if the hole in the collector is made slightly larger than the width of the focused particle beam. For instance, according to Figure 8, any particle with Stokes ranging from 2 to 300 will enter a collector orifice 1/10 of the nozzle diameter.

Design strategy: designing the geometry of the focusing impactor of Figure 7 has comprised the following steps:

(1) First computations using stokes drag law and potential flow (incompressible and irrotational) to find particles trajectories. This very raw model permits iterating very quickly to set the longitudinal distances and the contraction factor of each stage that better produces a constant focal distance and minimizes wall loses. Evaluating the shape of the ripples of the $f(S)$ curves produced in this process one can quickly see if a contraction needs to be located more upstream or more downstream. For instance, if the focal distance corresponding to a given contraction is higher than its neighbors, one would accordingly reallocate that contraction more upstream. The optimum value of d can also be easily tuned by analyzing the amplitude of the wavy pattern of the $f(S)$ curves, the useful range of S and the amplitude of a wave associated to 1 contraction is decreased by decreasing the associated parameter d. Having an impaction plate located downstream the nozzle actually limits the domain where $f(S)$ can be calculated. Rather than optimizing the $f(S)$ curve shape, we have optimized the $D_m(S)$ curve shape. In first approximation, the value D_m grows linearly with the distance between the focal section and the impaction plate, and the qualitative considerations used to correct the shape of the nozzle can be as well discerned by analyzing the shape of the $D_m(S)$ curves. Particles whose inertia is expressed in 1 stage will also be affected in the more downstream stages. Tuning first the most downstream contractions and then the 1 more upstream allows meaningfully decoupling the design of the different stages.

(2) Once an outline of the shape of the nozzle including the impaction plate is computed, introducing a step to consider the stability of the flow is required. Here, computational fluid dynamics (CFD) plays a key role, and we are well aware that analyzing the proposed geometry is a complex task, especially when focusing calls for abrupt geometries that tend to be detached. The fluid domain is separated in 2 main regions. In a first region, the flow is attached and accelerated through the ladder of contractions, in the second region, the accelerated flow exits the nozzle to form a free jet that impinges against the impaction wall. The free jet exiting the nozzle is known for producing intense turbulence in its shear layer, but experimental studies also show that the axis of the jet remains laminar for a few nozzle diameters (as long as the flow arriving at this final section remains laminar). As particles of interest will be confined within the center of the jet, we have hypothesized that they will simply be unaffected by turbulence. The model utilized (Steady, axisimmetric, and incompressible Navier Stokes) is not converging in the highly turbulent free jet region at high Re, but having an approximated solution at least in the vicinity of the axis of the free jet is necessary to compute the particle trajectories. In order to produce this simplified solution at an affordable computational price, the numerical domain has been artificially split in 2 regions: an accelerating and attached region, and a detached and turbulent region. The attached flow in the accelerating region has been computed using steady, axisimmetric and incompressible Navier Stokes equations at increasing Re. The mesh was refined to assure capturing the boundary layer evolution. As primary stability criteria, the numerical stability of the solution has been used. Visual inspection of the boundary layer allowed assuring that the solution is free from flow separation and bubbles. Reaching numerical stability requires modifying the design of the nozzle. Again, trial and error method was used to redesign the geometry. The detached flow in the free jet region is calculated imposing an artificially low Re to force numerical convergence of the solution.

(3) After modifying the geometry, the $D_m(S)$ curve requires retuning. In this stage, as Re of the nozzle is known (because it is limited), the particle's Reynolds Number Re_p (based on the particle diameter and its drift velocity) can also be known as a function of S and the nozzle's Re. As a first approximation, the particle's Re^*_p based on the particle diameter and the fluid velocity through the nozzle gives an idea of the maximum Re_p that may be achieved.

$$Re_p^* = \sqrt{18S \cdot Re \cdot \frac{\rho}{\rho_p}} \qquad [5]$$

Where ρ/ρ_p is the gas to particle density ratio. For $Re = 7000$, $\rho/\rho_p = 10^{-3}$, and $S = 300$, yields $Re^*_p = 195$ which is below the sphere critical Re but far over the Stokes law region.

Particle trajectories are therefore computed using a non linear transitional aerodynamic drag law valid for spherical particle's having Re_p below 1000. The particle's drag coefficient C_D is computed using the approximated empirical expression:

$$C_D = \frac{24}{Re_p}\left(1 + 0.15 Re_p^{0.687}\right) \qquad [6]$$

Finally, iterating to reach smooth $D_m(S)$ curve while maintaining a "stable" configuration permits retuning the geometry similarly as done with the simpler model. The final focusing

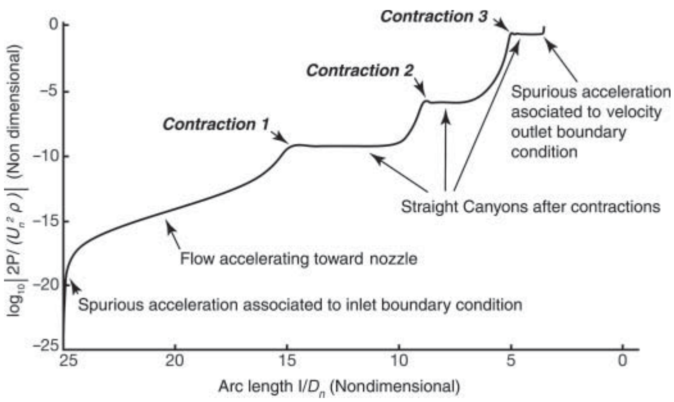

FIG. 10. Dimensionless pressure along the nozzle wall (arc length parameter), Log scale permits showing the acceleration produced in each contraction.

efficiency is evaluated by characterizing the diameter of the beam impacting the collector. These results are shown in Figure 8 for a Nozzle *Re* of 7000.

At $Re = 7000$, and a fluid velocity of 100 m/s, the dimensional diameter of the last contraction shown in Figure 7 is 1.05 mm, and the flow rate is 5.20 lpm. According to Figure 8, the particles focused within a beam diameter of 200 microns would range from 2 to 58 microns (for a density of 1000 Kg/m^3).

Because most commercial CFD packages are unreliable to predict the onset of turbulence (especially in the relevant limit of abrupt geometries), the proposed solution still requires experimental validation. Figure 10 illustrates the evolution of the pressure (more specifically the parameter $2P/(U_n^2 \cdot \rho)$ which is forced to be respectively 0 and –1 in the numerical domain inlet and outlet) along the wall of the nozzle.

Figure 10 shows first a smooth acceleration produced by the flow movement toward the nozzle; each contraction produces an abrupt acceleration followed by almost straight canyons with small adverse pressure gradients. Figure 10 also shows two spurious acceleration regions near the inlet and outlet numerical domain associated to the inlet and outlet boundary conditions. The spurious outlet acceleration is associated to an artificial acceleration of the boundary layer produced because a flat velocity profile is imposed at the nozzle exit. The effect of these spurious accelerations on the particles can be neglected as these spurious acceleration regions are sufficiently far from the contractions to assume that the important region (near the contractions and near the particle trajectories) remains unaffected. The proposed solution is numerically stable at $Re = 9 \cdot 10^4$. Though the stability of the flow is uncertain at such high *Re*, and especially if certain adverse pressure gradients appear, one can still reduce the *Re* in order to stabilize the flow. For instance, following our earlier study (Vidal and Fernandez de la Mora 2009); Spielman et al. (2009) have developed a growth tube followed by a lens for particle focusing and concentration using a set of two abrupt contractions working properly at *Re* as high as 700. In an original configuration comprising 1 single lens they efficiently focus particles ranging from 1 to 4 μm; in an improved configuration comprising two abrupt contractions they expand the range of concentrated particles up to 16 μm. Their experimental success with the two contractions shows the practical viability of the concepts presented here. One could worry that the adverse pressure gradients could spoil the performance of the focusing nozzle, but other devices working at very high *Re* such airfoils also work under adverse pressure gradients and turbulence appears only in the boundary layer before stalling. As the new nozzle would also work at relatively high *Re*, having a turbulent boundary layer would be affordable as long as the majority of the flow remains laminar.

More precise simulations (non stationary, compressible, 3D) could lead to better designs, perhaps able to work at higher velocities and *Re*. Indeed, sonic conditions would be most desirable to concentrate smaller particles, handle higher flow rates, and to prevent upstream traveling perturbations. Longitudinal and transversal instabilities could also be analyzed (Göertler instabilities have not been considered in the present design). Such an in-depth analysis, optimal design and the experimental validation shall be undertaken in the future.

3. CONCLUSIONS

A new aerosol focusing element consisting of a smooth contraction with contraction factor *d* around 3 has been proposed and studied numerically. These contractions remain aerodynamically stable at high *Re* and focus efficiently only a band of particles sizes. A smooth and continuously converging ladder of these contractions has the potential to focus a wide range of particle sizes in a common focal region and at high *Re*. Each contraction would concentrate a narrow band of particle sizes not defocusing the particles previously focused by upstream contractions. The conjunction of each contractions narrow band covers a wide range of particles sizes. This ladder of contractions has the potential to produce very high aerosol concentration factor if coupled to a virtual impactor having a small collection orifice to sample the focused particles beam. Designing this focusing device is a nontrivial task. Each contraction size and position must be selected such that all narrow bands cover together the entire wide range of particle sizes and are focused in the same focal region. Focusing calls for abrupt geometries wile stability calls for smooth geometries. A careful analysis of the fluid flow is required to approach the maximum focusing effects without spoiling the aerodynamic configuration.

An iterative design strategy allows matching the different contractions as well as designing abrupt-smooth balanced geometries that permit focusing while maintaining a laminar flow. As an example, a focusing ladder composed of three contractions and followed by an impaction plate was designed and numerically studied. Working at $Re = 7000$, this concentrator would focus particles ranging from $S = 3$ to 300 within a beam ten times smaller than the nozzle's diameter was designed in this study. The purpose of these calculations was to provide an initial view of the practical potential of the proposed geometries, and to illustrate the usefulness of the design rules proposed. Further experimental verification is still required.

REFERENCES

Chen, B. T., Yeh, H. C., and Cheng, Y. S. (1986). Performance of a Modified Virtual Impactor. *Aerosol Sci. Techn.*, 5(3):369–376.

Cheng, Y. S., and Dahneke, B. E. (1979). Properties of Continuum Source Particle Beam II. Beams Generated in Capillary Expansions. *J. Aerosol Sci.* 10:363–368.

Dahneke, B. (1978). Aerosol Beams, in *Recent Developments in Aerosol Science* (D. T. Shaw, ed.) John Wiley & Sons, New York, chapter 9.

Dahneke, B. E., and Cheng, Y. S. (1979). Properties of Continuum Source Particle Beam I. Calculation Methods and Results. *J. Aerosol Sci.*, 10:257–274.

Dahneke, B. E., and Friedlander, S. K. (1970). Velocity Characteristics of Beams of spherical Polystyrene Particles. *J. Aerosol Sci.*, 325–339.

Dahneke, B. E., Hoover, J., and Cheng, Y. S. (1982). *J. Coll. Interface Sci.*, 87:167.

Davitt, K., Song, Y. K., Patterson, W. R., Nurmikko, A. V., Pan, Y. L., and Chang, R. K. et al. (2006). Spectroscopic Sorting of Aerosols by a Compact Sensor Employing UV LEDs. *Aerosol Sci Tech.*, 40(12):1047–1051.

Eichler, T., de Juan, L., and Fernández de la Mora, J. (1998). Improvement of the Resolution of TSI's 3071 DMA via Redesigned Sheath Air and Aerosol Inlets. *Aerosol. Sci. Technol.,* 29(1):39–49.

Fernández de la Mora, J. (1996). Drastic Improvements on the Resolution of Aerosol Size Spectrometers via Aerodynamic Focusing: The Case of Variable-Pressure Impactors. *Chem. Eng. Commun.*, 151:101–124.

Fernandez de la Mora, J. (2006) Aerodynamic Focusing in Spatially Periodic Flows, *J. Aerosol Sci.*, 37(3):323–339.

Fernández de la Mora, J., and Riesco-Chueca, P. (1988). Aerodynamic Focusing of Particles in a Carrier Gas. *J. Fluid Mech*., 195:1–21.

Fernández de la Mora J., and Rosner D. E. (1981). Inertial Deposition of Particles Revisited and Extended: Eulerian Approach to a Traditionally Lagrangian Problem. *Phys.-Chem. Hydrodyn.*, 2:1–21.

Fernández de la Mora, J., and Rosner, D. E., (1982). Effects of Inertia on the Diffusional Deposition of Small Particles to Spheres and Cylinders at Low Reynolds Numbers. *J. Fluid Mech.*, 125:379–395.

Friedlander, S. K. (1977). *Smoke, Dust and Haze* (Section 4.6). Wiley, New York.

Fuerstenau, S., Gomez, A., and Fernandez de la Mora, J. (1994). Visualization of Aerodynamically Focused Aerosol Jets. *J. Aerosol Sci.*, 25:165–173.

Gañán-Calvo, A. M., and Lasheras, J. C. (1991). The Dynamics and Mixing of Small Spherical Particles in a Plane Free Shear Layer. *Phys. Fluids A,* 3:1207–1217.

Israel, G. W., and Friedlander, S. K. (1967). High Speed Beams of Small Particles. *J. Coll. Interface Sci.*, 24:330–333.

Kasparian, J, Boutou, V, Wolf, J. P., Pan, Y. L., and Chang, R. K. (2007). Single-Particle Laser-Induced-Fluorescence Spectra of Biological and Other Organic-Carbon Aerosols in the Atmosphere: Measurements at New Haven, Connecticut, and Las Cruces, New Mexico, G, Geoph. *Res. Atmos.*, D24S19:112(D24).

Liu, P., Ziemann, P. J, Kittelson, D. P., and McMurry, P. H. (1993). Aerodynamic Lenses for Producing Particle Beams of Controlled Dimensions and Divergence, in *Synthesis and Characterization of Ultrafine Particles*, J. Marijnissen, and S. Pratsinis eds. Delft University Press. pp. 119–135.

Liu, P., Ziemman, P. J., Kittelson, D. P., and McMurry, P. H. (1995a). Generating Particle Beams of Controlled Dimensions and divergence: I. Theory of particle Motion in Aerodynamic Lenses and Nozzle expansions. *Aerosol Sci. Tech.*, 22:293–313.

Liu, P., Ziemman, P. J., Kittelson, D. P., and McMurry, P. H. (1995b). Generating Particle Beams of Controlled Dimensions and divergence: I. Experimental Evaluation of particle Motion in Aerodynamic Lenses and Nozzle expansions. *Aerosol Sci. Tech.*, 22:293–313.

Martin, J. E., and Meiburg, E. (1994). The Accumulation and Dispersion of Heavy Particles in Forced Two-Dimensional Mixing Layers. Part 1: The Fundamental and Subharmonic Cases. *Phys. Fluids*, 6:1116.

Maxey, M. R. (1987). The Motion of Small Spherical-Particles in a Cellular-Flow Field. *Phys. Fluids*, 30:1915–1928.

McMurry, P. H., Kittleson, D. B., Ziemman, P. J., and Liu, P. (1993). Apparatus and Method for Shaping and Detecting a Particle Beam; U.S. Patent 5,270,542; Dec. 14, 1993.

Michael, D. H. (1968). The Steady Motion of a Sphere in a Dusty Gas. *J. Fluid Mech.*, 31:175–192.

Middha, P., and Wexler, A. S. (2003). Particle Focusing Characteristics of Sonic Jets. *Aerosol Sci. Tech.*, 37:907–915.

Piseri, P., Tafreshi, H. V., and Milani, P. (2004). Manipulation of Nanoparticles in Supersonic Beams for the Production of Nanostructured Materials. *Curr. Opin. Solid State Materials Sci.*, 8(3–4):195–202.

Rao, N., Navascues, J., and Fernandez de la Mora, J. (1993). Aerodynamic Focusing of Particles in Viscous Jets. *J. Aerosol Sci.*, 24:879–892.

Robinson, A. (1956). On the Motion of Small Particles in a Potential Field Flow, *Communications in Pure and Applied Mathematics.* 9: 69–84.

Romay, F. J., Roberts, D. L., Marple, V. A., Liu, B. Y. H., and Olson, B. (2002). A High Performance Aerosol Concentrator for Bioaerosol Agent Detection. *Aerosol Sci. Technol.*, 36:217–226.

Rubin, J., Jones, C. K. R. T., and Maxey, M. R. (1995). Settling and Asymptotic Motion of Aerosol Particles in a Cellular Flow Field. *J. Nonlinear Sci*., 5:337–358.

Saric, W. S. (1994). *Gortler Vortices: Mechanical and Aerospace Engineering*. Arizona State University, Tempe, Arizona, pp. 85287–6106.

Sinha, M. P.,, and Friedlander, S. K. (1986). Mass Distribution of Chemical Species in a Polydisperse Aerosol: Measurement of Sodium Chloride in Particles by Mass Spectrometry. *J. Colloid Interface Sci.*, 112:573–582.

Sinha, M. P., Griffin, C. E., Norris, D. D., Estes, T. J., Vilker, V. L., and Friedlander, S. K. (1982). Particle Analysis by Mass Spectrometry. *J. Coll. Interface Sci.*, 87:140–152.

Sinha, M. P., Giffin, C. E., Norris, D. D., and Friedlander, S. K. (1983). Particle Analyzing Method and Apparatus. US patent 4,383,171, May 10. 1983.

Spielman, S. R., Lewis, G. S., and Hering, S. V. (2009). A Growth Tube Lens for Particle Focusing and Concentration. Annual Meeting of the American Association for Aerosol Research, Paper 8F.03, October 27–30, 2009.

Tio, K.-K., Gañán-Calvo, A. M., and Lasheras, J. C. (1993a) The Dynamics of Small Heavy Rigid Spherical Particles in a Periodic Stuart Vortex Flow. *Phys. Fluids A*, 5:1679–1693.

Tio, K.-K., Liñán, A., Lasheras, J. C., and Gañán-Calvo, A. M. (1993b). On the Dynamics of Buoyant and Heavy Particles in a Periodic Stuart Vortex Flow. *J. Fluid Mech*., 254:671–699.

Vidal, G., and Fernandez de la Mora, J. (2009). Method and Apparatus to Sharply Focus Aerosol Particles at High Flow Rate and Over a Wide Range of Sizes: US patent application publication. No.: US 2009/030914, Dec, 17, 2009, based on Provisional Patent application No.: 61/131,878, filed on Jun. 13, 2008.

Willeke, K., and Pavlik, R. E. (1978). Size Classification of Fine Particles by Opposing Jets. *Environ. Sci. Technol.*, 12:563–566.

Willeke, K., and Pavlik, R. E. (1979). Secondary Effects in Particle-Size Classification by Opposing Jets. *J. Aerosol Sci.* 10:1.