

## PARTICLE ANALYSIS IN AN ACOUSTIC CYTOMETER

### CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Serial No. 61/008,422, filed December 19, 2007, U.S. Patent Application Serial No. 12/283,461, filed September 11, 2008, and U.S. Patent Application Serial No. 12/283,491, filed September 11, 2008, the entire contents of each of these patent applications are incorporated by reference herein.

### TECHNICAL FIELD

[0002] The following inventions relate generally to the field of particle analysis. The inventions also relate generally to cytometers and acoustics.

### BACKGROUND

[0003] It was realized early in the development of flow cytometry that the angular dependence of the light scattering intensity from a particle contains a wealth of information related to a particle's intrinsic and extrinsic properties. For example, Mullaney, et al. experimentally demonstrated the use of forward light scatter, from about 0.5 degrees to about 2 degrees for cell size estimation. In the same time period, it was also realized that cell orientation relative to the incident light beam can introduce artifacts that affect population resolution and instrument sensitivity for particles that do not possess axial symmetry parallel to the flow direction. Loken et al. showed that nonspherical particles in the form of fixed chicken erythrocytes yield a bimodal scattering distribution that is related to rim-on or face-on illumination of the disk-cell structure. Particle orientation dependent scattering effects due to asymmetries that are apparent in the complex geometrical shape of sperm cells have also been demonstrated. Several researchers have suggested passive solutions to orienting particles by shaping the sample nozzle to introduce asymmetries into the velocity flow field of the hydrodynamic sheath system. It has been shown that the most critical aspect in efficient X and Y sperm discrimination in flow cytometric sorting is the orientation of the sperm in the optical scattering plane. Recently, novel nozzle geometries have demonstrated proper orientation of up to 60% of the sperm heads in the optical scattering plane at analysis rates near 2000 particles/s dramatically affecting the sorting efficiency. Other researchers have addressed particle asymmetries by collecting data over a large array of scattering angles using scanning flow

cytometry (SFC) at the cost of lower particle analysis rates (approximately 400 particles/s). Systems have demonstrated continuous angular scattering data spanning 70 degrees but the data is taken relative to an arbitrary particle orientation that results in large variations of the collected angular spectra for asymmetric particles.

[0004] One of the earliest large-scale demonstrations of separating biological cells using acoustic forces was done by Doblhoff, et al. In that system, acoustic radiation pressure was used for selective retention of viable hybridoma cells for the purpose of removing nonviable cells and smaller cellular debris from a 20 liter bioreactor. That system was based on a multi-planar transducer design and demonstrated viable cell retention rates as high as 99.5% with varying results for cellular debris rejection. Early systems required high power input, typically in excess of 15W, thus necessitating a cooling unit for the drive transducers. More recently, Feke and coworkers developed a novel particle separation strategy that relies on both acoustic radiation pressure and secondary acoustic forces. A high-porosity polyester mesh (pore size two orders of magnitude greater than particle size) in an acoustic standing wave served as a collection matrix whereby particles at nodal locations were trapped within the mesh and secondary acoustic forces formed particle agglomerates and created an attractive force at the mesh surface. In a similar demonstration of retention of hybridoma cells, retention efficiencies of about 95% were achieved with negligible effects on cell viability. This system achieved high cell densities of approximately  $1.5 \times 10^8$  cells/mL with only hundreds of mWatts of input power.

## SUMMARY

[0005] An embodiment of the present invention comprises an apparatus that acoustically manipulates a particle and stops flow of the particle. This apparatus preferably comprises a capillary for flowing a fluid containing the particle therein, an acoustic signal producing transducer acoustically manipulating the particle, and a stop flow device. The stop flow device is preferably a pump or one or more valves. This embodiment can comprise a particle sorter, a particle fractionator, and/or a flow cytometer. This embodiment can further comprise an analyzer to analyze the particle and/or an imager.

[0006] One embodiment of the present invention comprises a method for acoustically manipulating one or more particles. This embodiment preferably includes flowing a fluid containing particles therein, applying acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles, stopping the fluid, and reviewing at least one of the particles. In this embodiment of the present invention reviewing at least one of the particles can

include analyzing at least one of the particles, and/or sorting at least one of the particles. The particles can also be flowed through a flow cytometer.

[0007] Another embodiment of the present invention comprises an apparatus that acoustically manipulates a particle and reverses flow of the particle. This apparatus preferably includes a capillary for flowing a fluid containing the particle therein, an acoustic signal producing transducer acoustically manipulating the particle, and a reverse flow device. The reverse flow device preferably comprises a pump and/or one or more valves. The apparatus of this embodiment can further comprise an analyzer for analyzing the particle and/or an imager. The apparatus of this embodiment can optionally comprise a sorter, a fractionator, and/or a flow cytometer.

[0008] Another embodiment of the present invention comprises a method for acoustically manipulating one or more particles. This embodiment includes flowing a fluid containing particles therein, applying acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles, reversing the direction of flow, and reviewing at least one of the particles that were reversed in the flow. In this embodiment, reviewing the particles can comprise analyzing at least one of the particles and/or sorting at least one of the particles. This embodiment can also include flowing the fluid through a flow cytometer.

[0009] Yet another embodiment of the present invention comprises an apparatus that acoustically aligns and orients a particle in a flow stream. This apparatus preferably comprises a capillary for flowing a fluid containing the particle therein, an acoustic signal producing transducer acoustically manipulating, aligning and orienting the particle, and a particle analyzer. The apparatus of this embodiment preferably comprise a flow cytometer, a particle fractionator, and/or a particle sorter where the sorter sorts the particle based on size. The apparatus can optionally include an imager. The acoustic signal producing transducer of this embodiment preferably aligns the particles in either a polar direction about a flow axis or aligns the particle in a direction of flow. The particle of this embodiment can be a red blood cell, a platelet or a sperm.

[0010] Yet another embodiment of the present invention comprises a method for acoustically aligning and orienting particles in a flow stream of a particle analyzer comprising flowing particles through the flow stream, subjecting the particles to an acoustic radiation pressure, acoustically aligning the particles in the flow stream of the particle analyzer, and acoustically orienting the particles in the flow stream of the particle analyzer. In this embodiment, the particle analyzer can be a flow cytometer. This method can also include a non-axisymmetric field wherein the particles are asymmetric. Further, this embodiment optionally

comprises selecting a predetermined orientation of the particles, where the orientation is within an optical scattering plane. This embodiment can comprise distinguishing between different types of particles based upon particle asymmetries. This embodiment can further comprise yielding repeatable orientations of particle clusters or sorting particles. The sorting of the particles can include pre-analysis in-line separating of particles based on size. In addition, this embodiment can align the particles in a polar direction about a flow axis or align the particles in a direction of flow. Still further, this embodiment can optionally comprise fractionating the particles. In this embodiment, the particle can be a red blood cell, a platelet or a sperm.

[0011] One embodiment of the present invention comprises an apparatus that analyzes a particle. The apparatus of this embodiment preferably comprises a capillary for flowing a fluid containing the particle therein, a radial acoustic signal producing transducer that acoustically orients non-axial symmetric particles in said capillary, a transport device that transports said particles through an interrogation point, and a particle analyzer. In this embodiment, the radial acoustic signal producing transducer preferably aligns the particle in the capillary and concentrates the particle in the capillary. The radial acoustic signal producing transducer can also create an acoustic field that aligns the particle. This embodiment can also optionally include a hydrodynamic sheath that aligns the particle. The apparatus of this embodiment can further comprise an imager.

[0012] Another embodiment of the present invention comprises a method for analyzing particles in a particle analyzer. This method preferably comprises flowing particles in a flow stream, applying a radial acoustic radiation pressure to the flow stream, acoustically orienting non-axial symmetric particles in the flow stream, transporting the particles through an interrogation point, and analyzing the particles. This embodiment can also include aligning the particles in a flow stream with either an acoustic field or a hydrodynamic focus. This method also preferably comprises concentrating the particles in the flow stream.

[0013] Another embodiment of the present invention comprises an apparatus that analyzes a particle in a fluid. The apparatus of this embodiment preferably comprises a capillary for flowing a fluid containing the particle therein, an acoustic signal producing transducer that acoustically maintains particle focus in said capillary regardless of flow rate, and a particle analyzer for analyzing the particle. This apparatus can further comprise a stop flow device and/or a reverse flow device. The apparatus of this embodiment also preferably comprises an imager.

[0014] Still another embodiment of the present invention comprises a method of analyzing one or more particles in a flow stream. This embodiment preferably comprises

labeling the particles with a lanthanide, flowing the particles in the flow stream, applying acoustic radiation pressure to the flow stream to maintain particle focus regardless of flow rate, and analyzing the particles with the lanthanide. This embodiment can also include stopping and/or reversing the flow stream.

**[0015]** Still another embodiment of the present invention comprises an apparatus that sorts particles by size. This apparatus preferably comprises a capillary for flowing a fluid containing the particles therein, and a radial acoustic signal producing transducer acoustically sorting and separating the particles in said capillary by size. This embodiment can further comprise a flow cytometer and/or a particle analyzer and/or an imager. The apparatus also preferably comprises a particle sorter.

**[0016]** A further embodiment of the present invention comprises a method for sorting particles by size. This method preferably comprises flowing particles in the flow stream, applying radial acoustic radiation pressure to the flow stream, and acoustically sorting and separating the particles by size. This method also preferably comprises transporting larger particles of the separated particles into a flow cytometer and analyzing the larger particles. The transporting step of this embodiment preferably transports the larger dependent particles to a central axis of the flow stream. This embodiment also preferably comprises in-line sorting.

**[0016a]** In one aspect of the present invention, there is provided an apparatus, comprising: a capillary for flowing a fluid containing a particle therein; an acoustic signal producing transducer for acoustically manipulating the particle; and a stop flow device.

**[0016b]** In another aspect of the present invention, there is provided an apparatus, comprising: a capillary for flowing a fluid containing a particle therein; an acoustic signal producing transducer for acoustically manipulating the particle; and a reverse flow device.

**[0016c]** In another aspect of the present invention, there is provided an apparatus comprising: a capillary for flowing a fluid containing a particle therein; an acoustic signal producing transducer for acoustically orienting the particle; and a particle analyzer.

[0016d] In another aspect of the present invention, there is provided an apparatus, comprising: a capillary for flowing a fluid containing a particle therein; a radial acoustic signal producing transducer for acoustically orienting asymmetric particles in a radial acoustic field within said capillary; a transport device for transporting said particles through an interrogation point; and a particle analyzer.

[0016e] In another aspect of the present invention, there is provided a method for acoustically manipulating one or more particles, the method comprising: flowing a fluid containing one or more particles therein; directing acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles; stopping the fluid; and reviewing at least one of the particles.

[0016f] In another aspect of the present invention, there is provided a method for acoustically manipulating one or more particles, the method comprising: flowing a fluid containing one or more particles therein; directing acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles; reversing the direction of flow of said fluid; and reviewing at least one of the particles that were reversed in the flow.

[0016g] In another aspect of the present invention, there is provided a method for acoustically orienting particles in a flow stream of a particle analyzer, the method comprising: flowing particles through a flow stream; directing acoustic radiation pressure to the particles; and acoustically orienting the particles in the flow stream of the particle analyzer.

[0016h] In another aspect of the present invention, there is provided a method for analyzing particles in a particle analyzer, the method comprising: flowing one or more particles in a flow stream; directing radial acoustic radiation pressure to the flow stream; acoustically orienting asymmetric particles in the flow stream; transporting each particle through an interrogation point; and analyzing each of the particles.

[0016i] In another aspect of the present invention, there is provided a method of analyzing one or more particles in a flow stream, comprising: labeling one or more particles with a lanthanide; flowing the particles in a flow stream; directing radial acoustic radiation pressure to the flow stream to align the particles along the direction of the flow stream; and analyzing at least a portion of the particles labeled with the lanthanide.

[0016j] In another aspect of the present invention, there is provided a method for separating particles by size, the method comprising: flowing particles in a flow stream; applying radial acoustic radiation pressure to the flow stream; and acoustically separating the particles by size by applying radial acoustic pressure, wherein smaller particles are substantially unaffected by the radiation pressure.

[0016k] In another aspect of the present invention, there is provided a method for separating particles by size, the method comprising: flowing particles in a flow stream; applying radial acoustic radiation pressure to the flow stream; and acoustically separating the particles by size by applying radial acoustic pressure, and transporting larger particles into a flow cytometer, wherein smaller particles comprise cellular debris.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

[0017] The accompanying drawings, which are incorporated into and form a part of the specification, illustrate one or more embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating one or more preferred embodiments of the invention and are not to be construed as limiting the invention.

### **In the drawings:**

[0018] **Fig. 1** is an embodiment of the present invention illustrating a line drive capillary where particles are acoustically focused to the central axis of the capillary;

[0019] **Fig. 2A** is a density plot of acoustic force potential in the cross section of a circular capillary driven by a line source according to one embodiment of the present invention;

[0020] **Fig. 2B** illustrates an induced particle rotation to lie in a stable force equilibrium plane according to one embodiment of the present invention;

[0021] **Fig. 3** is an embodiment of the present invention illustrating a line driven acoustic fractionator where large particles are transported to the capillary axis while smaller particles remain unaffected by the acoustic field;

[0022] **Figs. 4A and 4B** illustrate particles flowing through a capillary in a random orientation when the acoustic field is off and then particles aligned coincident with the capillary axis upon excitation of the acoustic field according to one embodiment of the present invention;

[0023] **Figs. 5A-5C** illustrate selective fractionation of particles that are approximately 1  $\mu\text{m}$  and approximately 10  $\mu\text{m}$  in a line drive capillary according to one embodiment of the present invention;

[0024] Fig. 6 is an embodiment of the present invention illustrating a sample input into a flow cytometer where the sample is concentrated reducing its volume and thus reducing the analysis time in flow cytometry applications.

#### **DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS**

[0025] As used herein "a" means one or more.

[0026] As used herein "capillary" means a flow channel or chamber having a shape selected from rectangular, elliptical, oblate circular, round, octagonal, heptagonal, hexagonal, pentagonal, and triangular.

[0027] In one embodiment of the present invention, acoustic radiation pressure preferably focuses particles to the center of a capillary. This embodiment enables fundamental changes in the way single cells or particles can be either analyzed or processed in a flow stream. This sample delivery embodiment expands the analysis capabilities of flow cytometry by improved analysis or preanalysis or both of sample preparation and purification.

[0028] A non-limiting embodiment of an acoustic particle focusing device is illustrated in Fig. 1. This device preferably comprises acoustically driven capillary 10 where an acoustic particle trap oriented parallel to the flow direction comprises line source 12 and fluid 18 with particles/cells 16. This embodiment may enable removal of high-velocity sheath flow associated with hydrodynamic focusing and allows extended particle transit times within the optical interrogation region while maintaining a high particle analysis rate due to an inherent in-line particle concentration effect. Additionally acoustic focusing of the particle stream provides the ability to stop and reverse the flow direction without defocusing the particle stream while maintaining particle registration. The increased particle transit times provide an opportunity for high-sensitivity optical measurements that use low-power light sources and less sensitive optical components. Control of flow direction and rate allows for reanalysis of targets of high significance may thereby minimize uncertainties in the scattering data associated with system level fluctuations.

[0029] An additional property of an acoustically driven flow chamber is a non-axisymmetric force field may be created within the flow stream. Force asymmetries within the flow chamber orient nonspherical cells or particles such that consistent scattering signatures, that are typically not possible with standard hydrodynamic flow systems, may be produced by positioning asymmetric particles in a predetermined orientation within the optical scattering plane. In this embodiment, optical scattering data associated with specific particle orientation can, for example, distinguish between different types of bacteria based upon particle asymmetries and improve analysis and sorting of irregular cell types such as RBC's and sperm cells. The asymmetric force field may also yields repeatable orientations of particle clusters that are formed from the coalescence of multiple microspheres or cells such as, for example 'dumbbell' shapes from agglutination of two particles. Discrimination of particle clusters can be made easier by pulse shape analysis and angular scattering interpretation due to the unique induced orientation of the cluster relative to the scattering plane for example, the induced orientation may be cause the central axis of the 'dumbbell' to be parallel to the flow axis.

[0030] An acoustically line-driven capillary embodiment of the present invention may bring new modes of particle and cell analysis to the detection system of a flow cytometer, and may be employed in particle or cell separations for in-line sample preparation. A primary advantage of acoustic radiation pressure is that it can be used in fairly large chambers with high volume throughput. The acoustic field acts similarly on most biological particles and is thus inherently nonspecific whereby most biological particles are transported to the same spatial location. The magnitude of the field, however, is highly size dependant and makes acoustic radiation pressure an excellent candidate in applications that require high throughput, pre-analysis in-line separating of particles based upon size e.g. sperm from vaginal cells in forensic analysis, virus from bacteria or intact cells from cellular debris. In the description above, a line-driven capillary with a cylindrical geometry may be used as the acoustic focusing device, but general geometry (square, rectangular, elliptical, oblate circular, etc.) devices that employ acoustic radiation pressure to position the particles can be used in applications of particle separation, debris rejection, particle alignment, and sample purification.

### **Acoustic Radiation Pressure**

[0031] The force on a particle resulting from acoustic radiation pressure depends upon frequency of excitation, pressure amplitude within the medium, and the density/compressibility contrast between the particle and the host medium. Within an acoustic standing wave, it is a time-averaged drift force which transports the particles to a nodal or an anti-nodal position. The

expression for the acoustic radiation force potential  $U$  on a spherical particle in an acoustic standing wave is given by:

$$U = \frac{4}{3} \pi a^3 \left[ \left( \beta_o \frac{\langle p^2 \rangle}{2} \right) f_1 - \frac{3}{2} \left( \frac{\rho_o \langle v^2 \rangle}{2} \right) f_2 \right]$$

[0032] Here,  $a$  is the particle radius,  $\beta_o$  is the compressibility of the surrounding fluid, and  $\rho_o$  is the density of the surrounding fluid. The pressure and velocity of the acoustic field in the absence of the particle are described by  $p$  and  $v$ , respectively, and the brackets correspond to a time-averaged quantity. The terms  $f_1$  and  $f_2$  are the contrast terms that determine how the mechanical properties of the particle differ from the background medium. They are given by:

$$f_1 = 1 - \frac{\beta_p}{\beta_o}$$

$$f_2 = \frac{2(\rho_p - \rho_o)}{(2\rho_p - \rho_o)}$$

[0033] The subscript  $p$  corresponds to intrinsic properties of the particle. The force  $F$  acting on a particle is related to the gradient of the force potential by:

$$\mathbf{F} = -\nabla U$$

[0034] Particles are preferably localized at positions where the potential  $U$  displays a minimum. For a circular cross section capillary, a potential minimum is coincident with the axis of the capillary forming the particle trap in Fig. 1 when driven in a dipole type mode. Other modes exist and are advantageous for spatial positioning of particles in locations other than the axis of the capillary for selected applications.

### Acoustic Line-Driven Capillary

[0035] Forces resulting from acoustic radiation pressure are preferably an effective means to localize particles in an arrangement similar to hydrodynamic focusing without the need for sheath fluids. The line-driven capillary of the present invention may be effective in sheath replacement. A capillary with a source aperture larger than a line contact can yield similar results. This embodiment has demonstrated acoustically driven capillaries with source apertures that have an extended contact length along the circumference of the capillary that spans more than about 45 degrees. It may be constructed from a capillary that is driven by a piezoceramic source in contact with its outer wall. Vibration of the structure creates a localized pressure node along the central axis where an axial particle trap is formed. A diagram of this device is given in

Fig. 1. Particles in a dilute suspension enter the device from the top and experience a radial force that transports them to the pressure node as they flow through the system. In an embodiment of the present invention, the particles contained in a sample are simultaneously concentrated and aligned in single file as they are then transported through the interrogation laser. The particles are transported through the interrogation laser via various transport devices, including but not limited to, a pump and/or one or more valves.

[0036] Implementation of acoustic particle focusing preferably allows new flow cytometry techniques and methods to evolve due to fundamental changes in the way particles are positioned within the sample cell. Concentric flow streams with different flow velocities are not required as with conventional hydrodynamically sheath-focused systems. Acoustically focused sample streams can be stopped, slowed, reversed or any combination thereof without degrading alignment of the particle stream within the flow chamber. The increased residence time within the acoustic field produces a stream of particles whose focus is actually improved. Additionally, the flow can be reversed with no adverse effect on particle alignment within the flow chamber allowing rare targets to be repeat analyzed or stopped for extended analysis such as spectral decomposition of the scattered/fluorescence signature.

[0037] One of the unique flow capabilities of the present invention may be the ability to select the sample delivery rate. By slowing cell/particle transit times which may be, for example approximately 20 - 100 times slower than conventional systems, higher sensitivity optical measurements and measurements of photonic events that require longer interrogation times such as luminescence are possible.

#### **Particle Orientation in a Standing Acoustic Wave Field**

[0038] A known orientation of a particle as it passes through the interrogation region enables light scatter measurements or fluorescence measurements, or both that provide significant insight into cellular structure and intrinsic optical properties. The removal of several degrees of rotational freedom proves an invaluable tool to flow cytometry by increasing the value of current light scatter measurements by calibrating them to a specific orientation of a cell/particle and allowing reasonable consideration of new scatter angles as measured parameters. The acoustic line-driven capillary of the present invention and other methods to introduce acoustic radiation pressure into the flow cell are active means to rotate and align particles in both the direction of flow and in polar directions about the flow axis to yield angular calibrated scattering data for particles that are non-spherical. The force experienced by a particle in an acoustically driven tube is typically non-axisymmetric within the cross section of the flow

plane. The acoustic force distribution is dipolar in nature for particle focusing to the tube axis yielding force reflection symmetries within the plane. Calculations of the acoustic force potential  $U$  for a particle in a line driven tube in a dipole type mode as one example of this method are shown in Fig. 2(a) where the acoustic force  $F_u$  can be obtained by:

$$\mathbf{F} = -\nabla U$$

Where the flow direction is into the page. The in-plane force potential possesses reflection symmetry about two planes that intersect the central axis. The first plane of symmetry intersects central axis 20 and line drive 22 and the second plane of symmetry lies perpendicular to the first. Though two symmetry planes exist within the displayed two-dimensional acoustic force potential, only one results in stable equilibrium 24 location with respect to particle rotation. All regular particles will rapidly rotate into stable equilibrium 24 under small perturbations within the flow field as shown in Fig. 2(b).

[0039] Incorporating a third dimension into the force field calculation (axial component) yields an additional restriction in the rotational freedom of a particle induced by the acoustic force field. Calculations show that rod shaped particles (particles with two equal minor axes and one major axis) typically align their major axis with the axis of the capillary. Particles with bilateral symmetry, e.g. red blood cells, typically align one major axis parallel to the flow axis and the other major axis parallel to the stable symmetry plane denoted by the white dotted line in Fig. 2(a).

### Acoustic Separation of Cells and Cellular Debris

[0040] For particle transport to occur in an acoustically driven chamber according to one embodiment of the present invention, the acoustic force must be large enough to overcome the Brownian motion of the particles within the suspending medium. The magnitude of the acoustic radiation pressure force experienced by a particle is directly proportional to the particle volume, drive level of the acoustic field, mechanical properties of the medium and particle, and the spatial gradient of the acoustic field. For this reason, (due to a cubic relationship of particle radius) larger particles can be transported in an acoustic field at lower pressure amplitudes and excitation frequencies (smaller gradients) than smaller particles. This is typically true for particles that have a greater relative difference in their mechanical properties relative to the background medium as well.

[0041] One aspect of one embodiment of an acoustic separation system of the present invention is that it can operate clog-free (no filter) with almost zero pressure drop across the unit.

Due to the size dependence inherent in the acoustic radiation force and thermal particle motion, an embodiment of the present invention can separate samples at the front end of a flow stream based upon particle size and mechanical contrast. Acoustic forces are used to purify samples by concentrating analytes of interest at a specified location for selective collection leaving background debris unaffected. Such a system reduces analysis time for samples with high particulate backgrounds on a flow cytometer by greatly reducing the particle count and increasing data quality. For instance, Bossuyt showed that cellular debris within whole blood samples prepared by selected lysis methods can yield scattering events that account for up to 80% of all events in CD45 cell counting on a flow cytometer. Macey noted that certain whole blood lysis methods for preparing lymphocytes for flow cytometry analysis can result in poor forward and side scatter resolution due to the presence of residual cell fragments. In one embodiment of the present invention, an in-line purification device, such as a line-driven capillary located just prior to the sample inlet of a flow cytometer as shown in Fig. 3, is used to transport large particles of interest 30, which may be, for example, lymphocytes, to central axis 32 of the sample stream while smaller particles 34 such as cellular debris and proteins contained within the lysate remain unaffected. This is especially true for cellular debris with less mechanical contrast than the particles of interest. The central core of the sample stream is then fed into the flow cytometer and the remaining lysate is discarded eliminating a large particulate concentration from the sample. It should be noted that this method of sample preparation can be used as a sample purification step for any type of particle/cellular analysis where the reduction of background particulate count is advantageous.

### **Particle Orientation in a Standing Acoustic Wave Field**

#### **EXAMPLE 1:**

[0042] To demonstrate the effects of the acoustic field to induce deterministic particle orientation, experiments using particles with aspect ratios greater than unity were conducted with a line driven capillary. In one example, the capillary was made of glass and had an inner diameter of approximately 500  $\mu\text{m}$  and an outer diameter of approximately 1000  $\mu\text{m}$ . An acoustic source was attached to the outer surface of the capillary, parallel with the axis of the capillary and operated at approximately 1.78 MHz and approximately 10  $V_{pp}$ . A suspension of circular cylindrical carbon fibers in deionized water was transported down the tube with a syringe pump. The particles were then imaged through a microscope. The fibers had a minor axial dimension of approximately 8  $\mu\text{m}$  with varying greater major axis dimensions.

[0043] Fig. 4A illustrates the sample as it flowed from left to right through the capillary. Fibers were seen in random orientations as they were entrained in the fluid and transported through the system when no acoustic field was present. Upon acoustic excitation of the capillary, the fibers were transported and rotated to align coincident and parallel with the axis of the capillary, see Fig. 4B. The alignment shown here was due to the acoustic radiation pressure force aligning the major axis of the particles along the axis of the capillary.

#### **Field-Based Particle Size Selection for In-Line Sample Purification and Separation/Concentration**

[0044] By varying the drive voltage and/or the frequency of excitation of the acoustic source in an acoustically driven capillary, a binary fractionation of particles by size can be achieved. This effect is a result of the reduced acoustic force felt by the smaller particles due to the cubic dependence of the acoustic force on particle radius. In application, the larger particles contained within the central core of the capillary are fed into a smaller, coaxial capillary discarding the concentric flow field containing small particulates. The purified sample can be taken for further sample preparation steps or fed real-time into a flow cytometer or other means of analysis. Depending upon the application, the fluid outside the central core may also be considered a valuable sample to be collected and used for analysis.

#### **EXAMPLE 2:**

[0045] Results from preliminary experiments demonstrating the size selection capability as a function of drive level are illustrated in Figs. 5A-5C. In this example, an acoustically driven capillary was oscillated at approximately 1.78 MHz. A suspension of latex microspheres containing approximately 1  $\mu\text{m}$  diameter fluorescent spheres and approximately 10  $\mu\text{m}$  diameter non-fluorescent spheres are pumped through the driven capillary. The volume fraction of particles was approximately  $2.5 \times 10^{-5}$ . The capillary is defined by an inner diameter of approximately 500  $\mu\text{m}$  and outer diameter of approximately 1000  $\mu\text{m}$ .

[0046] Fig. 5A is a photograph taken through a fluorescence microscope where the approximately 10  $\mu\text{m}$  particles are viewed as large circular inclusions and the approximately 1  $\mu\text{m}$  particles are viewed as a grainy background. The fluorescence signal from the approximately 1  $\mu\text{m}$  particles is too low to be observed under the operating conditions of the experiment. Under low acoustic drive level of approximately 7  $V_{pp}$  (Fig. 5B), the approximately 10  $\mu\text{m}$  particles rapidly transported to the axis of the capillary. The approximately 1  $\mu\text{m}$  particles remained randomly distributed. Doubling the drive voltage to approximately 16  $V_{pp}$  resulted in

efficient transport of both sized particles to the central axis of the capillary, see Fig. 5C. The bright line along the axis of the cylinder was a result of the large, local increase in fluorescence due to the concentration of the approximately 1  $\mu\text{m}$  fluorescent particles at that location.

**Acoustic focusing/ orientation such as the effects of reflection symmetry on optical scatter parameters in an acoustically focused flow chamber**

[0047] An embodiment of the present invention addresses angular scattering associated with particles that are aligned in the optical scattering plane as a result of acoustic radiation pressure. The replacement of hydrodynamic sheath flow with acoustically driven particle alignment in a flow cell preferably leads to improved light scatter data and yields new parameters that are dependent upon particle geometry and orientation. In addition to the importance of particle orientation of asymmetric biological particles such as, for example, RBC's, sperm cells, and bacteria in flow cytometry analysis, complex geometries that are formed from the coalescence of multiple microspheres or cells for example, 'dumb bell' shapes from agglutination of two particles also benefit from particle orientation. Particle clusters are preferably more easily discriminated by having their orientation fixed in the scattering plane. Orienting microsphere 'doublets' to yield repeatable and unique scattering signatures due to how they transit the scattering plane will provide a means to isolate their contribution in optical scattering data for either data rejection or data acceptance by utilizing the solution of the inverse scattering problem for contacting spheres. The application of acoustically oriented particles in a flow stream is also applicable to the field of imaging where viewing selected orientations of particles is valuable in determining cellular morphology, localization of cellular constituents, or other particle/cellular characteristics.

**Enhanced detection capabilities under slow-flow, stop-flow, and reverse-flow conditions in acoustically focused flow chambers**

[0048] Another embodiment of the present invention further addresses the effects of slow-flow, stop-flow, reverse-flow, and increased analysis times in flow cytometry detection that result from replacing sheath flow with acoustic particle alignment. In the first instance, the ability to stop and reverse the flow direction of the sample stream allows for particles to be reanalyzed. The flow is stopped and/or reversed using various stop flow and reverse flow devices, including but not limited to, a pump or one or more valves. Peak spread (increased CV's) and data points that are outliers in the analysis plane are system dependent quantities that are a function of laser stability, quality of particle alignment, electronic noise, detector noise,

robustness of the assay (on/off rates, etc.), etc. By analyzing a particle of significance more than once, the data quality can be improved, particularly in the case of transient artifacts, and the statistical uncertainties in rare event analysis can be minimized.

**Acoustic field-based particle size selection for in-line sample purification and particle isolation.**

[0049] While acoustic focusing is useful for particle or cell analysis by replacing sheath flow in the detection system, yet another embodiment of the present invention extends the application of acoustic forces in acoustically driven capillaries to particle and/or cell separations for upstream, in-line sample conditioning in flow cytometry systems or general sample preparation and purification. Fig. 6 illustrates utilizing the present invention to acoustically size fractionate and concentrate samples by particle size and/or mechanical contrast relative to the background medium in real-time at the inlet of a flow cytometer before the analysis stage. Direct fractionation based upon particle size/mechanical properties alleviates the need for labor intensive sample preparation steps that include centrifugation and filtering. For flow cytometry applications, this is useful in reducing the background associated with cellular debris, proteins, and other molecular components in whole blood assays, and in particular, nowash assays that include cellular lysis. A sample preparation including a cellular debris rejection step prior to sample delivery into the flow cytometer can greatly reduce artifacts associated with scatter/fluorescence from the debris.

[0050] Although the invention has been described in detail with particular reference to these preferred embodiments, other embodiments can achieve the same results. Variations and modifications of the present invention will be obvious to those skilled in the art and it is intended to cover all such modifications and equivalents. The entire disclosures of all references, applications, patents, and publications cited above and/or in the attachments, and of the corresponding application(s), are hereby incorporated by reference.

What is Claimed:

1. An apparatus, comprising:

a capillary for flowing a fluid containing a particle therein;

an acoustic signal producing transducer for acoustically manipulating the particle;  
and

a stop flow device.

2. The apparatus of claim 1, further comprising an analyzer configured to analyze the particle flowing through the capillary.

3. The apparatus of claim 1, further comprising a particle sorter configured to sort the particle flowing through the capillary.

4. The apparatus of claim 1, further comprising a particle fractionator configured to fractionate the particle flowing through the capillary.

5. The apparatus of claim 1, further comprising a flow cytometer configured to analyze the particle flowing through the capillary.

6. The apparatus of claim 1, further comprising an imager configured to image the particle flowing through the capillary.

7. The apparatus of claim 1, wherein said stop flow device comprises a pump.

8. The apparatus of claim 1, wherein said stop flow device comprises one or more valves.

9. An apparatus, comprising:

a capillary for flowing a fluid containing a particle therein;

an acoustic signal producing transducer for acoustically manipulating the particle;  
and

a reverse flow device.

10. The apparatus of claim 9, further comprising an analyzer configured for analyzing the particle flowing through the capillary.

11. The apparatus of claim 9, further comprising a sorter configured to sort the particle flowing through the capillary.
12. The apparatus of claim 9, further comprising a fractionator configured to fractionate the particle flowing through the capillary.
13. The apparatus of claim 9, further comprising a flow cytometer configured to analyze the particle flowing through the capillary.
14. The apparatus of claim 9, further comprising an imager configured to image the particle flowing through the capillary.
15. The apparatus of claim 9, wherein said reverse flow device comprises a pump.
16. The apparatus of claim 9, wherein said reverse flow device comprises one or more valves.
17. An apparatus comprising:
  - a capillary for flowing a fluid containing a particle therein;
  - an acoustic signal producing transducer for acoustically orienting the particle; and
  - a particle analyzer.
18. The apparatus of claim 17, wherein said apparatus comprises a flow cytometer.
19. The apparatus of claim 17, further comprising a particle sorter configured to sort the particle flowing through the capillary.
20. The apparatus of claim 19, wherein said sorter separates the particle based on size prior to analysis.

21. The apparatus of claim 17, wherein said acoustic signal producing transducer aligns the particle in a polar direction about a flow axis.
22. The apparatus of claim 17, wherein said acoustic signal producing transducer aligns the particle in a direction of flow.
23. The apparatus of claim 17, comprising a particle fractionator configured to fractionate the particle flowing through the capillary.

24. The apparatus of claim 17, wherein the particle is a red blood cell or a platelet.
25. The apparatus of claim 17, wherein the particle is a sperm.
26. The apparatus of claim 17, further comprising an imager configured to image the particle flowing through the capillary.
27. An apparatus, comprising:
  - a capillary for flowing a fluid containing a particle therein;
  - a radial acoustic signal producing transducer for acoustically orienting asymmetric particles in a radial acoustic field within said capillary;
  - a transport device for transporting said particles through an interrogation point;  
and
  - a particle analyzer.
28. The apparatus of claim 27, wherein said radial acoustic signal producing transducer aligns the particle in said capillary.
29. The apparatus of claim 27, wherein said radial acoustic signal producing transducer concentrates the particle in said capillary.
30. The apparatus of claim 27, wherein said radial acoustic signal producing transducer creates an acoustic field that aligns the particle.
31. The apparatus of claim 27, comprising a hydrodynamic sheath that aligns the particle.
32. The apparatus of claim 27, further comprising an imager configured to image the particle flowing through the capillary.
33. A method for acoustically manipulating one or more particles, the method comprising:

flowing a fluid containing one or more particles therein

directing acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles;

stopping the fluid; and

reviewing at least one of the particles.

34. The method of claim 33, wherein reviewing comprises analyzing at least one of the particles.

35. The method of claim 33, wherein reviewing comprises sorting at least one of the particles.

36. The method of claim 33, further comprising flowing the fluid through a flow cytometer.

37. A method for acoustically manipulating one or more particles, the method comprising:

flowing a fluid containing one or more particles therein;

directing acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles;

reversing the direction of flow of said fluid; and

reviewing at least one of the particles that were reversed in the flow.

38. The method of claim 37, wherein reviewing comprises analyzing at least one of the particles.

39. The method of claim 37, wherein reviewing comprises sorting at least one of the particles

40. The method of claim 37, comprising

flowing the fluid through a flow cytometer after directing acoustic radiation pressure to the fluid and acoustically manipulating the one or more particles .

41. A method for acoustically orienting particles in a flow stream of a particle analyzer, the method comprising:
- flowing particles through a flow stream;
  - directing acoustic radiation pressure to the particles; and
  - acoustically orienting the particles in the flow stream of the particle analyzer.
42. The method of claim 41, wherein the particle analyzer is a flow cytometer.
43. The method of claim 41, wherein the acoustic radiation pressure is asymmetric.
44. The method of claim 41 wherein the particles are asymmetric.
45. The method of claim 41, further comprising selecting a predetermined orientation of the particles.
46. The method of claim 45, wherein the orientation is within an optical scattering plane.
47. The method of claim 41, further comprising distinguishing between different types of particles based upon particle asymmetries.
48. The method of claim 41, further comprising yielding repeatable orientations of particle clusters.
49. The method of claim 41, further comprising sorting the particles after directing acoustic radiation pressure to the particles .
50. The method of claim 49, wherein the sorting comprises pre-analysis in-line separating of particles based on size.
51. The method of claim 41, comprising aligning the particles in a polar direction about a flow axis.

52. The method of claim 41, comprising the particles aligning in a direction of flow.

53. The method of claim 41, further comprising fractionating the particles after acoustically orienting the particles in the flow stream of the particle analyzer .

54. The method of claim 41, wherein the particle is a red blood cell or a platelet.

55. The method of claim 41, wherein the particle is a sperm.

56. A method for analyzing particles in a particle analyzer, the method comprising:

flowing one or more particles in a flow stream;

directing radial acoustic radiation pressure to the flow stream;

acoustically orienting asymmetric particles in the flow stream;

transporting each particle through an interrogation point; and

analyzing each of the particles.

57. The method of claim 56, further comprising aligning the particles in the flow stream after directing radial acoustic radiation pressure to the flow stream .

58. The method of claim 57, wherein aligning is with an acoustic field.

59. The method of claim 57, wherein aligning is with a hydrodynamic focus.

60. The method of claim 56, further comprising

concentrating the particles in the flow stream after acoustically orienting asymmetric particles in the flow stream .

61. A method of analyzing one or more particles in a flow stream, comprising:

labeling one or more particles with a lanthanide;

flowing the particles in a flow stream;

directing radial acoustic radiation pressure to the flow stream to align the particles along the direction of the flow stream; and

analyzing at least a portion of the particles labeled with the lanthanide.

62. The method of claim 61, further comprising stopping the flow stream.

63. The method of claim 61, further comprising reversing the flow stream.

64. A method for separating particles by size, the method comprising:

flowing particles in a flow stream;

applying radial acoustic radiation pressure to the flow stream; and

acoustically separating the particles by size by applying radial acoustic pressure, wherein smaller particles are substantially unaffected by the radiation pressure.

65. The method of claim 64, further comprising transporting larger particles of the separated particles into a flow cytometer.

66. The method of claim 64, further comprising analyzing the larger particles.

67. The method of claim 64, wherein the transporting step transports the larger particles to a central axis of the flow stream.

68. The method of claim 64, further comprising in-line separating the particles after directing radial acoustic radiation pressure to the flow stream .

69. A method for separating particles by size, the method comprising:

flowing particles in a flow stream;

applying radial acoustic radiation pressure to the flow stream; and

acoustically separating the particles by size by applying radial acoustic pressure, and transporting larger particles into a flow cytometer, wherein smaller particles comprise cellular debris.