FLUIDIC DEVICE AND METHOD FOR SEPARATION OF NEUTRALLY BUOYANT PARTICLES

[0001] Conventional municipal water treatment (MWT) and other types of water purification systems include multi-stage filtration and sequential process steps for coagulation, flocculation, and sedimentation. A minimum of two stages of filtration typically include coarse 2-3 mm mesh filters at the inlet and 20-40μm multi-media filters for finishing, although many utilities have more intermediate filtration steps. Neutrally buoyant particles (e.g. particles having substantially the same density as water) can only be filtered or electro-chemically modified for sedimentation. Separation of these types of particles from water is very difficult. Moreover, such particles are typically TOC (total organic carbon) and contribute to major turbidity problems.

[0002] A spiral fluidic device useful for membrane-free filtration and separation has been developed. In general, such devices are very useful in connection with particles having density differences compared with water, thus creating centrifugal or buoyancy forces necessary for transverse migration through the channel for purposes of separation. However, neutrally buoyant particles present a special case and thus require additional fluidic considerations for separation. Heretofore, such additional considerations have not been fully explored.

BRIEF DESCRIPTION

[0003] In one aspect of the presently described embodiments, the system comprises an inlet to receive at least a portion of the fluid containing the neutrally buoyant particles, a spiral channel within which the fluid flows in a manner such that the neutrally buoyant particles flow in a tubular band offset from a center of the channel, a first outlet for the fluid within which the tubular band flows, and, a second outlet for the remaining fluid or effluent.

[0004] In another aspect of the presently described embodiments, the inlet is angled to facilitate earlier formation of the tubular band along an inner wall of the spiral channel using a Coanda effect where wall friction helps to attach impinging flow.

[0005] In another aspect of the presently described embodiments, the system further comprises a second spiral channel nested with the spiral channel such that the tubular band is narrowed as a result of flowing through the second spiral channel.

[0006] In another aspect of the presently described embodiments, the system further comprises a second inlet connected to the second outlet of the spiral channel to receive the remaining fluid, a second spiral channel within which the remaining fluid flows such that the remaining neutrally buoyant particles flow in a second tubular band offset from the center of the second channel, a third outlet for the fluid within which the second tubular band flows, and, a fourth outlet for more remaining fluid.

[0007] In another aspect of the presently described embodiments, the remaining neutrally buoyant particles are of a different size than the neutrally buoyant particles output through the first outlet.

[0008] In another aspect of the presently described embodiments, the system further comprises a second spiral channel within which at least another portion of the fluid flows.

[0009] In another aspect of the presently described embodiments, the system further comprises a recirculation channel between the first outlet and the inlet.

[0010] In another aspect of the presently described embodiments, the tubular band is formed as a function of at least one of fluid viscosity, average channel velocity, particle radius, fluid density, hydraulic diameter of channel, angular velocity, and differential velocity across particles.

[0011] In another aspect of the presently described embodiments, the tubular band is offset from the center of the channel as a function of a radius of curvature of the spiral channel.

[0012] In another aspect of the presently described embodiments, the spiral channel is a spiral wound structure.

[0013] In another aspect of the presently described embodiments, the spiral channel is a helical spiral structure.

[0014] In another aspect of the presently described embodiments, the method comprises receiving at least a portion of the fluid containing the neutrally buoyant particles at an inlet, establishing a flow of the fluid in a spiral channel wherein the neutrally buoyant particles flow in a tubular band through the spiral channel in an asymmetric manner, outputting the fluid within which the tubular band flows through a first outlet of the channel, and, outputting the remaining fluid through a second outlet of the spiral channel.

[0015] In another aspect of the presently described embodiments, the fluid is received at an angle to facilitate the formation of the tubular band along an inner wall of the spiral channel.

[0016] In another aspect of the presently described embodiments, the method further comprises establishing a second flow of the fluid through a second spiral channel nested with the spiral channel to narrow the tubular band.

[0017] In another aspect of the presently described embodiments, the method further comprises establishing a flow of the remaining fluid in a second spiral channel cascaded with the first spiral channel to separate neutrally buoyant particles of a different size than the neutrally buoyant particles output through the first outlet.

[0018] In another aspect of the presently described embodiments, the method further comprises establishing a flow of at least another portion of fluid in a second spiral channel.

[0019] In another aspect of the presently described embodiments, the method further comprises re-circulating in the system at least a portion of the fluid output through the first outlet.

[0020] In another aspect of the presently described embodiments, the flow of neutrally buoyant particles in a tubular band is adjustable as a function of fluid viscosity, average channel velocity, particle radius, fluid density, hydraulic diameter of the channel, angular velocity, and differential velocity across particles.

[0021] In another aspect of the presently described embodiments, the asymmetric manner of flow of the tubular band is a function of a radius of curvature of the spiral channel.

[0022] FIGURE 1 is a representation of a particle flowing through a channel and forces acting thereon;

[0023] FIGURES 2(a) and (b) illustrate a selected quantification of particle extraction;

[0024] FIGURES 3(a)-(f) illustrate an embodiment of a spiral device according to the presently described embodiments;

[0025] FIGURE 4 illustrates another embodiment according to the presently described embodiments;

[0026] FIGURE 5 illustrates still another embodiment according to the presently described embodiments;

[0027] FIGURES 6(a) and (b) illustrate still further embodiments according to the presently described embodiments;

[0028] FIGURES 7(a) and (b) illustrate still further embodiments according to the presently described embodiments; and,

[0029] FIGURE 8 illustrates a still further embodiment according to the presently described embodiments.

[0030] The presently described embodiments use a curved channel of a spiral device to introduce a centrifugal force upon neutrally buoyant particles (e.g., particles having substantially the same density as water,

or the fluid in which the particles reside) flowing in a fluid, e.g. water, to facilitate improved separation of such particles from the fluid. As these neutrally buoyant particles flow through the channel, a tubular pinch effect causes the particles to flow in a tubular band. The introduced centrifugal force perturbs the tubular band (e.g. forces the tubular band to flow in a manner offset from a center of the channel), resulting in an asymmetric inertial migration of the band toward the inner wall of the channel. This force balance allows for focusing and compaction of suspended particulates into a narrow band for extraction. The separation principle contemplated herein implements a balance of the centrifugal and fluidic forces to achieve asymmetric inertial equilibrium near the inner sidewall. Angled impingement of the inlet stream towards the inner wall also allow for earlier band formation due to a Coanda effect where wall friction is used to attach the impinging flow

[0031] The presently described embodiments relate to a membrane-free filtration technology that is capable of continuous flow and high throughput operation. The working principle relies primarily on purely fluidic flow in curved channel structures, eliminating the need for filter-interfaces or external force-fields. Balanced transverse force components concentrate and divert particle streams according to the designed size cut-off. This spiral flow filtration concept can address size and mass based separation of micro-particles, including biological agents. The design simplicity makes this device amenable both to inline integration with other downstream processes and to serve as stand-alone, high-throughput, macro-scale or fine micro-scale lab-on-chip applications.

[0032] With reference to Figure 1, a curved channel 10 (e.g. a curved portion of a spiral) having a particle 12 flowing there through is shown. As can be seen, asymmetric tubular pinch effects in the channel -- created by various forces -- are shown. The forces include a lift force F_W

from the inner wall, a Saffman force F_S, Magnus forces F_m and a centrifugal force F_{cf}. It should be appreciated that the centrifugal force F_{cf} is generated as a function of the radius of curvature of the channel. In this regard, this added centrifugal force F_{cf} induces the slow secondary flow or Dean vortex flow (shown by the dashed arrows) which perturbs the symmetry of the regular tubular pinch effect. Particles are concentrated in the inner equilibrium of the velocity contour (shown in the dashed ellipses).

[0033] More specifically, fluidic shear in straight channels is known to generate lateral forces which cause inertial migration of particulates. G. Segré and A. Silberberg, Nature, v. **189**, p. 209 (1961), G. Segré and A. Silberberg, J. Fluid Mech., v. **14**, p. 136 (1962), D. Leighton and A. Acrivos, Z. angew. Math. Phys., v. **36** p. 174 (1985), P. Cherukat, and J.B. McLaughlin, J. Fluid Mech., v. **263**, p. 1 (1994), P. G. Saffman, J. Fluid Mech., v. **22**, p. 385 (1965), S.I. Rubinow and J.B. Keller, J. Fluid Mech., v. **11**, p. 447 (1961), B. P. Ho and L. G. Leal, J. Fluid Mech., v. **65**, p. 365 (1974), P. Vasseur and R. G. Cox, J. Fluid Mech., v. **78**, p. 385 (1976), J. Feng, H. H. Hu and D. D. Joseph, J. Fluid Mech., v. **277**, p. 271 (1994), E. Ashmolov, J. Fluid Mech., v. **381**, p. 63 (1999), E. Ashmolov, Phys. Fluids, v. **14**, p. 15 (2002), J.–P. Matas, J. F. Morris and É. Guazzelli, J. Fluid Mech., v. **515**, p. 171 (2004), B. H. Yang, J. Wang, D. D. Joseph, H. H. Hu, T. –W. Pan and R. Glowinski, J. Fluid Mech., v. **540**, p. 109 (2005), E. E. Michaelides, J. Fluids Eng., v. **125**, p. 209, (2003), P. Cherukat and J. B. McLaughlin, Int. J. Multiphase Flow, v. **16**, p. 899 (1990), P. Cherukat, J. B. McLaughlin and A. L. Graham, Int. J. Multiphase Flow, v. **20**, p. 339 (1994).

[0034] G. Segré and A. Silberberg, Nature, v. **189**, p. 209 (1961), and G. Segré and A. Silberberg, J. Fluid Mech., v. **14**, p. 136 (1962), experimentally demonstrated a tubular pinch effect where neutrally buoyant particles migrate to form a symmetric band that is 0.6D wide,

where D is the channel diameter. In quadratic Poiseuille flow, three contributions have explained the lateral migration of a rigid sphere. The wall lift, F_W, acts to repel particulates from the wall due to lubrication. D. Leighton and A. Acrivos, Z. angew. Math. Phys., v. **36** p. 174 (1985), P. Cherukat, and J.B. McLaughlin, J. Fluid Mech., v. **263**, p. 1 (1994). The second contribution is the Saffman inertial lift, F_S, towards the wall due to shear slip,

[0035] (1) $$F_s = 6.46\eta V a R_e^{1/2}$$

[0036] where η, V, a, and Re are respectively, the fluid viscosity, average channel velocity, particle radius, and channel Reynold's number given by:

[0037] (2) $$R_e = \rho V D / \eta$$

[0038] with ρ and D being the fluid density and hydraulic diameter of the channel. [10, 14]. The third is the Magnus force, F_m, due to particle rotation towards the wall,

[0039] (3) $$Fm = \pi a^3 \rho \vec{\Omega} \times \vec{V}$$

[0040] where Ω_r is the angular velocity given by $\Delta V/r$ and ΔV is the differential velocity across the particle S.I. Rubinow and J.B. Keller, J. Fluid Mech., v. **11**, p. 447 (1961). F_w dominates near the wall and achieves equilibrium with the combined effects of F_s and F_m to confine particles in a band. G. Segré and A. Silberberg, J. Fluid Mech., v. **14**, p. 136 (1962), developed a reduced length parameter to scale this tubular pinch effect in a simple form,

[0041] (4) $$L = \left(\frac{\rho V l}{\eta}\right)\left(\frac{a}{d}\right)^3$$

[0042] where l is the actual channel length and d is the hydraulic channel radius. In curvilinear channel geometry, a centrifugal force, F_{cf},

modifies the symmetric tubular pinch effect. The fluid inertia from this force causes a secondary transverse flow or Dean vortex, P. Cherukat and J. B. McLaughlin, Int. J. Multiphase Flow, v. **16**, p. 899 (1990), P. Cherukat, J. B. McLaughlin and A. L. Graham, Int. J. Multiphase Flow, v. **20**, p. 339 (1994), S. A. Berger, L. Talbot and L. –S. Yao, Ann. Rev. Fluid Mech., v. **15**, p. 461 (1983), Yu. P. Gupalo, Yu. V. Martynov and Yu. S. Ryazantsev, Fluid Dyn., **12**, 109 (1977) which is a double recirculation as shown by the dot arrows in Fig. 1. The Dean number is a measure of the strength of this recirculation:

[0043] (5) $D_e = 2(d/R)^{1/2} R_e$

[0044] where R is the radius of curvature of the channel S. A. Berger, L. Talbot and L. –S. Yao, Ann. Rev. Fluid Mech., v. **15**, p. 461 (1983). Particles in mid-elevation migrate transversely outward with the Dean vortex, are repelled by the wall lift, and continue to loop back along the top and bottom walls towards the inside wall. The combined Saffman and Magnus forces are large in comparison to the viscous drag of the Dean vortex so particles are trapped in a force minimum located adjacent and closer to the inner wall.

[0045] So, it is apparent that the contemplated tubular band is formed as a function of at least one of fluid viscosity, average channel velocity, particle radius, fluid density, hydraulic diameter of channel, angular velocity, and differential velocity across particles. Moreover, as noted above, the tubular band is offset from the center of the channel as a function of a radius of curvature of the spiral channel. So, the configuration and operation of the system is a function of the factors contemplated, for example, by Equation 4. These factors or parameters are highly scalable and will vary as a matter of application in the range from micro-scale devices to macro-scale devices. Examples are provided herein; however, other implementations are contemplated.

[0046] Implementation of the methodology described herein results in a system whereby particles can be separated within a spiral channel and output in a manner so as to separate particles of selected sizes from an effluent stream. For example, with reference to Figure 2, a Coulter counter quantification of such particle extraction is illustrated. At 92 mm/s flow velocity, the concentration ratio of extracted particles in a particulate band 20, as shown in Figure 2(b), is 300 times that of the effluent 22 that is being output by the spiral channel 24. Experimentally, this calculates to a 99.1% efficiency of particle removal using the presently described embodiments.

[0047] Other advantages of the presently described embodiments include:

[0048] 1) Filtration capacity such as sample, volume, hydraulic retention times, filtration rate, cut-off particle size, and concentration factor can be adjusted by tailoring fluidic and dimensional parameters.

[0049] 2) Extension to size separation would merely involve tailoring of the flow parameters for a monotonic range of particle sizes and providing capture channels in sequential manner along the spiral channel.

[0050] 3) Ability to cascade several of these spiral structures, each tailored for a decreasing particle size range cut-off.

[0051] 4) Design simplicity making this device amenable both to inline integration with other downstream processes and to serve as a stand-alone application.

[0052] 5) Large dynamic size range in its filtration capacity makes it suited for both high-throughput macroscale and fine micro-scale lab-on-chip applications.

[0053] 6) Parallelization of modular units can be realized for higher throughput.

[0054] 7) This membrane-free device has the desirable combinations of high-throughput and low cost, making it inherently suited for preparative filtration in the range of micro-scale to macro-scale applications.

[0055] 8) Design technique is provided for a spiral structure for rapid fluidic separation of neutrally buoyant particles without a membrane.

[0056] 9) Double nested spiral channels can be implemented to compact band successively from both sides.

[0057] 10) Highly scalable implementation based on reduced length formula is realized.

[0058] 11) Flocculation and sedimentation steps can be eliminated in conventional water treatment.

[0059] 12) Contemplated structures may be used for other applications in water including: IC fab reclaim, cooling tower water, MBR (membrane bio reactor), pre-treatment for RO (reverse osmosis).

[0060] It should be appreciated that these advantages may be achieved in a variety of different embodiments. These embodiments will vary as a function of the parameters noted above which are controllable and/or configurable through channel design and operational parameters. Nonetheless, the described systems generally include an inlet to receive at least a portion of the fluid containing the neutrally buoyant particles, a spiral channel within which the fluid flows in a manner such that the neutrally buoyant particles flow in a tubular band offset from a center of the channel, a first outlet for the fluid within which the tubular band flows and a second outlet for the remaining fluid. So, in operation, the method includes receiving at least a portion of the fluid containing the neutrally buoyant particles at an inlet, establishing a flow of the fluid in a spiral channel wherein the neutrally buoyant particles flow in a tubular band through the spiral channel in an asymmetric manner, outputting the fluid within which the tubular band flows through a first outlet of the

channel and outputting the remaining fluid through a second outlet of the spiral channel.

[0061] In this regard, Figure 3(a) illustrates a spiral structure 30 that may be implemented in accordance with the presently described embodiments. This structure 30 is a double nested structure wherein a first spiral channel is nested with a second spiral channel. That is, the inlet 32 is connected to a spiral channel that spirals to the center of the structure 30 and then spirals back out to the outer periphery of the structure 30 – without interruption other than a change in direction. So, the outlet 34, having a first outlet portion 36 and a second outlet portion 38, is disposed on the outer periphery, as opposed to the center of the structure 30.

[0062] It should also be appreciated that the inlet could provide for an angled or inclined entry of fluid to the system to facilitate quicker formation of the tubular band along an inner wall of the spiral channel. This is the result of the Coanda effect where wall friction is used to attach the impinging flow. With reference to Figure 8, the channel 10 has an inlet 11 wherein the inlet stream is angled toward the inner wall by an angle θ. The tubular band 18 is thus formed earlier for egress out of the outlet 14. Of course, the second outlet 16 for the remaining fluid in which the band 18 does not flow is also shown. It should be understood that the inlet angle may be realized using any suitable mechanism or technique.

[0063] With reference back now to Figure 3(a) according to the presently described embodiments, the noted lateral forces across the spiral channel geometry transform a relatively homogeneous distribution of particles at the inlet 32 into an ordered band at the outlet 34. After spiral circulation, particles are collected at an inside outlet 36 and the effluent (water) are collected at an outside outlet 38.

[0064] Sequential images along the fluidic path are shown. Images are rotated and mirrored to match their flow directions for comparison. The bottom sides are toward the center of the spirals. The fluid runs left to right or bottom to top at the mean fluidic velocity of 92 *mm/s*. As shown, a dispersed particle suspension was introduced into an inlet (P#1) (Figure 3(b)) with an average flow velocity of 92 *mm/s*. After two spiral turns (P#2) (Figure 3(c)), the particles closest to the inner wall (lower boundary) have started to concentrate at 0.6w from the channel center where w is a half of the channel width. At the transitional point after 12 turns (P#3) (Figure 3(d)), particle concentration shows a band with a sharp edge on the inside and a more diffuse edge on the outside. It should be noted that this (P#3) (Figure 3(d)) is a transition point to change the flow from clockwise to counter-clockwise direction. This transition has beneficial effects on compacting the band of particles. After the transition point, the sharp edge of the band is switched to the outside and the continuing lateral force acts to mitigate against the dispersive effects of Brownian motion and diffusion. On the other hand, the diffuse outside edge of the band is switched to the inside and is now subjected to the compacting effect of the centrifugal and lift force induced effect. As a result, a sharp edge is developed as observed (P#4) (Figure 3(e)). The concentrated band of particles are diverted into the inside outlet (P#5, L= 34.2) (Figure 3(f)) whilst the effluent stream is routed into the outside outlet. Segré and Silberberg showed that the reduced length parameter for one order of concentration difference should be L>9 G. Segré and A. Silberberg, J. Fluid Mech., c. **14**, p. 136 (1962). The concentration difference between the collected samples is expected be about two orders of magnitude. The resultant band is less than 0.2D wide and could be further compacted.

[0065] Particle counting of collected samples after filtration confirm the results from the preceding observation. After the samples were

filtered with different flow rates, the collected samples were diluted to 50 times for coulter counting (Z2™ COULTER COUNTER®, Beckman Coulter, CA, USA). The concentration of particles from the outer outlet decreased as the flow velocity increased. As discussed previously, the efficiency of filtration depends on the corresponding length *L* that is a function of (particle velocity). Faster flow velocity improved filtration efficiency (particle capture efficiency) from 64.7% at 23 *mm/s* to 99.1% at 92 *mm/s*. The separation factor or ratio of concentrations of the particle and effluent outlets exceeds 300×, and can be further optimized. The important effect of the spiral geometry is to focus the particles into a narrow band through the asymmetric tubular pinch effect. This nested double spiral (Figure 3(a)) acts to sequentially compact each side of the band resulting in a sharper and narrower band than is predicted by the tubular pinch effect alone.

[0066] In another embodiment, Figure 4 illustrates the implementation of a spiral separator device according to the presently described embodiments within a purification system 400. As shown, the system includes a screen 402, a flash mixer 405, and a reduced coagulation tank 404. The spiral device 408 according to the presently described embodiments includes an inlet 410 as well as a first outlet 412 and a second outlet 414. Also shown in the system 400 is a recirculation channel or path 416 which is disposed between the inlet 410 and the coagulation tank 404.

[0067] In operation, fluid containing neutrally buoyant particles is received in the system and first filtered through the screen 402. The filtered water is then flash-mixed 405 before being introduced into the spiral device 408 through inlet 410. As the fluid flows in the spiral device 408, the tubular band of neutrally buoyant particles is maintained to flow in an asymmetric manner, relative to the center of the channel. This asymmetry allows for convenient separation of the fluid within which

the tubular band flows (which is output through outlet 412) and the remaining fluid (which is output through outlet 414). The concentrate stream is optionally re-circulated back, for example, to the reduced coagulation tank from outlet 412 to increase water recovery.

[0068] With reference now to Figure 5, a further embodiment to the presently described embodiments is shown. In this embodiment, a purification system 500 includes a two-stage spiral separation system to isolate particles of different sizes. In the example system shown, the particles are isolated in a 1 to 10 micrometer range. As shown, the system includes an input water source 502 connecting to a spiral separator 504 having an inlet 506, as well as a first outlet 508 and a second outlet 510. The second outlet 510 is connected to a second spiral separator 520 by way of an inlet 522. The spiral separator 520 includes a first outlet 524 and a second outlet 526 as shown.

[0069] In operation, the system 500 with the cascaded spiral stages facilitates a first separation of particles between those of greater than 10 micrometers being output from the first spiral separator in a waste stream and particles less than 10 micrometers being input to the second spiral separator 520 for further processing. The second spiral separator then separates particles greater than 1 micrometer and outputs fluid within which those particles reside by way of outlet 524. The remaining fluid or effluent is output through outlet 526. In this manner, the system 500 is able to isolate particles between 1 and 10 micrometers for various sampling processing. This concept can be extended by continued cascading of spiral structures with smaller size cut-offs to achieve fractionation of particles with decreasing size ranges.

[0070] With reference now to Figures 6 (a) and (b), a still further embodiment is shown. In Figure 6, a spiral device 600 according to the presently described embodiments is illustrated. In this embodiment, the spiral device 600 takes the form of a helical spiral. In this regard, the

spiral body portion of the device 604 is a helical spiral that has an inlet 606, a first outlet 608 and a second outlet 610. As shown in Figure 6(b), a spiral device such as that shown in Figure 6(a) can be disposed in a parallel arrangement to increase throughput of the system. As shown, spiral devices 600 are all connected to an input main 620 from a fluid manifold and the respective first outlets of the devices 600 are connected to a first outlet main 622. The second outlets of the devices 600 are connected to a second outlet main 624.

[0071] With reference to Figures 7(a) through 7(b), a similar system is shown. However, the embodiment of Figure 7(a) shows a spiral device 700 that is a spiral wound device. This device 700 includes a spirally wound body 704 having inlet 706, a first outlet 708 and a second outlet 710. As with the embodiment illustrated in Figures 6(a) and 6(b), the device 700, as shown in Figure 7(b), may be disposed in a system wherein a plurality of devices 700 are connected in parallel to a water inlet main 720 from a fluid manifold. Similarly, the first outlet lines for the devices are connected to a first outlet main 722. The second outlet lines of the devices 700 are connected to a second outlet main 724.

[0072] It should be appreciated that the spiral devices contemplated herein may take a variety of forms including the form of any of the spiral devices described in connection with co-pending and commonly assigned U.S. Application Serial No. 11/606,460, filed November 30, 2006, entitled "Particle Separation and Concentration System", which is incorporated herein in its entirety by this reference, provided that such devices are configured, dimensioned and operated to advantageously address neutrally buoyant particles within fluid. Of course, appropriate modifications would be made to such devices to accommodate the presently described embodiments. Moreover, it should be appreciated that any of the spiral devices described or contemplated herein may be disposed in a cascaded manner, as shown in Figure 5, or in a parallel

manner, as shown in Figures 6(a), 6(b), 7(a) and 7(b). Still further, any suitable material may be used to form the spiral devices contemplated herein.

Claims

1. A system for separation of neutrally buoyant particles from a fluid, the system comprising:

an inlet to receive at least a portion of the fluid containing the neutrally buoyant particles;

a spiral channel within which the fluid flows in a manner such that the neutrally buoyant particles flow in a tubular band offset from a center of the channel;

a first outlet for the fluid within which the tubular band flows; and,

a second outlet for the remaining fluid;

wherein the inlet is angled to facilitate earlier formation of the tubular band along an inner wall of the spiral channel.

2. The system as set forth in claim 1 further comprising a second spiral channel nested with the spiral channel such that the tubular band is narrowed as a result of flowing through the second spiral channel.

3. The system as set forth in claim 1 wherein the remaining neutrally buoyant particles are of a different size than the neutrally buoyant particles output through the first outlet.

4. The system as set forth in claim 1 further comprising a second spiral channel within which at least another portion of the fluid flows.

5. The system as set forth in claim 1 further comprising a recirculation channel between the first outlet and the inlet.

6. The system as set forth in claim 1 wherein the tubular band is formed as a function of at least one of fluid viscosity, average channel velocity, particle radius, fluid density, hydraulic diameter of channel, angular velocity, and differential velocity across particles.

7. The system as set forth in claim 1 wherein the tubular band is offset from the center of the channel as a function of a radius of curvature of the spiral channel.

8. The system as set forth in claim 1 wherein the spiral channel is a spiral wound structure.

9. The system as set forth in claim 1 wherein the spiral channel is a helical spiral structure.

10. A method for separating neutrally buoyant particles from a fluid, the method comprising:

receiving at least a portion of the fluid containing the neutrally buoyant particles at an inlet;

establishing a flow of the fluid in a spiral channel wherein the neutrally buoyant particles flow in a tubular band through the spiral channel in an asymmetric manner;

outputting the fluid within which the tubular band flows through a first outlet of the channel; and,

outputting the remaining fluid through a second outlet of the spiral channel;

wherein the fluid is received at an angle to facilitate the formation of the tubular band along an inner wall of the spiral channel.

11. The method as set forth in claim 10 further comprising establishing a second flow of the fluid through a second spiral channel nested with the spiral channel to narrow the tubular band.

12. The method as set forth in claim 11 further comprising establishing a flow of the remaining fluid in a second spiral channel cascaded with the first spiral channel to separate neutrally buoyant particles of a different size than the neutrally buoyant particles output through the first outlet.

13. The method as set forth in claim 10 further comprising establishing a flow of at least another portion of fluid in a second spiral channel.

14. The method as set forth in claim 10 further comprising re-circulating in the system at least a portion of the fluid output through the first outlet.

15. The method as set forth in claim 10 wherein the asymmetric manner of flow of the tubular band is a function of a radius of curvature of the spiral channel.