

FLUIDIC STRUCTURES FOR MEMBRANELESS PARTICLE SEPARATION

[0001] Several different types of membraneless particle separation devices having a generally spiral or curved configuration have been described in co-pending patent applications. In general, such devices are 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. Some of these devices are also useful, depending on their configuration, to separate neutrally buoyant particles.

[0002] With reference to Figure 1, one example form of a separation device 20 is shown. This form shows an expanding spiral channel 22 with increasing radius of curvature. This geometry takes advantage of the rate of pressure change. Other configurations may also be used. In another form, the device may have a contracting spiral channel with a decreasing radius of curvature for the sidewalls. The radius of curvature and channel size may also be held substantially constant. In any case, the channel 22 evolves into two separate channels 24 and 26 (e.g. also referred to as channel #1 and channel #2 in Figure 1) to provide two outlet paths for the fluid.

[0003] These types of separation devices provide for particle separation in a variety of manners. For example, depending on the flow rate, the particle separation may be driven by the centrifugal force or the pressure that is created by flow fluid through the channel. In any event, it is the objective of such devices to achieve particle separation. In this regard, homogeneously distributed particles at the inlet are separated into a band, or populated in a portion of the fluid stream, and diverted at the outlet into a first portion or band including selected particulates and a second portion without such particulates resident therein. Designs and implementations of these types of devices for different environments and incorporating selected improvements are desired.

[0004] In one aspect of the presently described embodiments, the system comprises a plurality of individual curved particle separation devices stacked such that the devices are parallel to one another and an inlet coupler connected

to all inlets of the devices, the inlet couple being operative to facilitate input of fluid to all inlets of the plurality of individual curved particle separation devices.

[0005] In another aspect of the presently described embodiments, the curved particle separation devices are spiral devices.

[0006] In another aspect of the presently described embodiments, the curved particle separation devices comprise curved portions that span between 180 degrees and 360 degrees of angular distance along a diameter thereof.

[0007] In another aspect of the presently described embodiments, the system further comprises a feedback control system.

[0008] In another aspect of the presently described embodiments, the feedback control system is operative to control the system based on at least one of pressure, flow rate, bandwidth, viscosity, and temperature.

[0009] In another aspect of the presently described embodiments, the system further comprises at least a second plurality of stacked curved particle separation devices arranged in parallel with the plurality of stacked curved particle separation devices.

[0010] In another aspect of the presently described embodiments, the system comprises an inlet manifold, a plurality of separation channels facilitating fluid flow therein and arranged in a helical spiral configuration wherein the channels are parallel to one another and an output manifold.

[0011] In another aspect of the presently described embodiments, the output manifold includes a portion therein operative to split the fluid flow from each of the channels.

[0012] In another aspect of the presently described embodiments, the portion is a static collar portion.

[0013] In another aspect of the presently described embodiments, the portion is a substantially circular collar portion.

[0014] In another aspect of the presently described embodiments, the portion is comprised of curves to provide a continuously adjustable split of the fluid flow.

[0015] In another aspect of the presently described embodiments, the portion is comprised of discrete step segments to provide a step-wise adjustable split of the fluid flow.

[0016] In another aspect of the presently described embodiments, the plurality of separation channels is arranged in a first stage and a second stage.

[0017] In another aspect of the presently described embodiments, the first stage and second stage are separated by a fluid inverter.

[0018] In another aspect of the presently described embodiments, the system further comprises a feedback control system.

[0019] In another aspect of the presently described embodiments, the feedback control system is operative to control the system based on at least one of pressure, flow rate, bandwidth, viscosity, and temperature.

[0020] In another aspect of the presently described embodiments, the system further comprises an inlet main and an outlet main.

[0021] In another aspect of the presently described embodiments, the system further comprises a second device connected to the inlet and outlet mains.

[0022] FIGURE 1 is a representation of an example spiral particle separation device;

[0023] FIGURE 2 illustrates a form of the presently described embodiments;

[0024] FIGURE 3 illustrates a form of the presently described embodiments;

[0025] FIGURE 4 illustrates a form of the presently described embodiments;

[0026] FIGURE 5 illustrates a form of the presently described embodiments;

[0027] FIGURE 6 illustrates a form of the presently described embodiments;

[0028] FIGURE 7 illustrates a form of the presently described embodiments;

[0029] FIGURES 8(a)-8(d) illustrate a form of the presently described embodiments;

[0030] FIGURES 9(a)-9(b) illustrate a form of the presently described embodiments;

[0031] FIGURES 10(a) and 10(b) illustrate one form of the presently described embodiments;

[0032] FIGURES 11(a)-11(c) illustrate a form of the presently described embodiments;

[0033] FIGURES 12(a)-12(c) illustrate a form of the presently described embodiments

[0034] FIGURES 13(a)-13(b) illustrate a form of the presently described embodiments;

[0035] FIGURES 14(a)-14(c) illustrate a form of the presently described embodiments; and

[0036] FIGURE 15 illustrates a form of the presently described embodiments.

[0037] The presently described embodiments relate to various fluidic structures, implementations and selected fabrication techniques to realize construction of fluidic separation structures that are of a stacked and/or parallel configuration. These contemplated systems provide for efficient input of fluid to be processed, improved throughput, and, in some variations, adjustable and efficient treatment of output fluid.

[0038] It will be understood that variations of these devices may be realized based on dimensional scale and channel architecture. However, it is contemplated that the embodiments described herein will be highly scalable to span microscale (0 to 10 mL/min), miniscale (10-1000 mL/min), and macroscale (1-10 L/min) single-channel flow rates.

[0039] Planar embodiments utilizing convenient stacking techniques are contemplated. In this regard, circular arcs (that do not complete a spiral) in the range of 180 to 360 degrees allow for sequential stages of transverse flow pattern development, attainment of steady state flow velocity and time for several circulatory passes to sweep particles to a desired position in the fluid flow. Other planar embodiments described herein include helical spirals.

[0040] The presently contemplated embodiments may be fabricated from inexpensive materials such as PDMS for microscale, inexpensive plastics (such as acrylic, Lucite and polycarbonate) for miniscale and macroscale applications. Selected fabrication techniques for some of these embodiments are also described.

[0041] In addition, a parallel eight channel helical spiral embodiment provides for quick assembly and disassembly. Notable features of such a contemplated device include convenient inlet manifolds and outlet manifolds that include a bifurcating mechanism or splitter to split the fluid into particulate and effluent fluid streams. The contemplated embodiments also allow for a multiple stage device operative to output an extremely narrow band of particulates for further disposal or processing. Other parallel configuration embodiments and fabrication techniques therefor are contemplated. Also, a feedback and/or control system may be implemented with any of the presently described embodiments.

[0042] With reference now to Figure 2, a single planar spiral separation device 30 is illustrated. The device 30 has an inlet 32, at least one curved or spiral portion 34 and an outlet 36. This planar multi-spiral channel device 30, in one form, may be cut from plastic. The type of plastic may vary as a function of the specific application and the environment in which it is implemented. In one variation of the device 30, the center region of the device 30 near the inlet 32 may be removed to allow access for an inlet coupler to be described hereafter. The spirals portion 34 of the device may take a variety of forms. For example, the spiral portion 34 may be converging or diverging. As a further example, the outlet 36 and inlet 32 locations may be interchanged to suit the application, e.g. for increasing or decreasing centrifugal forces.

[0043] It should be appreciated that the fundamental operation of individual curved or spiral separation devices to separate particles in fluid, such as device 30 or other devices contemplated herein, is described in detail in selected portions of the above referenced patent applications (which are incorporated herein by reference). Therefore, such operation will not be described herein except to the extent that such description will enhance the description of the presently described embodiments.

[0044] With reference to Figure 3, a system 40 is representatively shown and comprises a plurality of devices 30 (shown in Figure 2) stacked in a parallel manner to allow for N-layers of parallel processing of fluid. Also

representatively shown in Figure 3 is an inlet coupler 42 -- which allows for input fluid to be provided to each device 30 within the entire stack from a common supply source. The inlet coupler 42 may take a variety of forms; however, in one example, the inlet coupler 42 is cylindrical and has perforations formed therein. The perforations correspond to inlets of the devices 30 stacked in the system 40. Outlet couplers of a similar configuration may also be implemented. Two outlet couplers 44 and 46 are representatively shown here, although the number of outlet couplers could vary based on the number of outlet paths or channels for each stacked device. The inlet coupler may be joined only with the top channel through an external AI plate, for example. Fluidic connection to all layers may be achieved by punching through all the top layers except for the bottom. At least two fluidic outlets, or outlet couplers such as those shown at 44 and 46, may be connected in the same manner on the top plate. All inlet and outlets connections may also be implemented on the bottom plate.

[0045] With reference to Figure 4, a system 50 comprises multiple planar curved arc segments 52 (e.g. fractional arc segments) that are vertically stacked as parallel channels to increase throughput. These planar curved arc segments do not complete a loop for any one segment 52, although the characteristics and functions of a spiral device will nonetheless apply to these segments 52 in this case. The arc segments or curved portions 52 comprise an inlet 54, curved or arc section 56 and an outlet 58. Also shown in Figure 4 is an inlet coupler 60 that, again, allows for an inlet of fluid from a common source to all of the separate arc segments shown. It should be appreciated that the inlet coupler may take a variety of forms. In one form, the inlet coupler is a cylinder and has perforations or a continuous slot corresponding to the inlet of each layer. Like the system 40 of Figure 3, the system 50 provides for increased throughput for fluid particle separation. At least one outlet coupler (not shown) may also be implemented. The outlet coupler(s) could resemble the inlet coupler of Figure 3 or 4, for example.

[0046] With reference to Figure 5, another planar curved structure 70 comprising stacked channels (not shown individually) is shown. The curved

structure 70 has an inlet 72 (which may include an inlet coupler), curved portions 74 and 76, and at least one outlet 78 or 79. As shown, there is an outlet 78 for selected particles such as particles of a particular size or density (e.g. buoyant particles). The outlet 78 is positioned midway around the curve between the curved portion 74 and curved portion 76. A second outlet 79 for selected particles of a second size or density (e.g. neutrally buoyant particles) is positioned at an end of the curve opposite the inlet 72. In general, these outlets 78 and 79 can be used to remove particles of varying sizes or densities from the fluid flow. As above, at least one outlet coupler may also be utilized.

[0047] With reference to Figure 6, a system 80 is shown. The system 80 comprises a plurality of devices 70, as shown in Figure 5, that are stacked in a configuration to allow for increased throughput by way of parallel processing. It should be appreciated that the system 80 may also comprise a single device 70 of increased width. Of course, as above, an inlet coupler and/or at least one outlet coupler may be implemented in the system.

[0048] With reference to Figure 7, a system 90 is illustrated. The system 90 represents a still further implementation of a plurality of systems 80 of Figure 6. This design may be advantageous as a function of the space requirements of the system and/or environment into which the presently described embodiments are implemented. Notably, as shown, the inlet for all of the curved separation device sections is at the center of the configuration of system 90. This allows for efficient processing of the input fluid and may be realized by use of an inlet coupler, such as an inlet coupler 42 (Figure 3) and inlet coupler 60 (Figure 4). Again, an outlet coupler, or couplers, may also be implemented.

[0049] With reference to Figures 8(a)-8(d), it will be appreciated that the stacked and/or parallel embodiments of Figures 3, 4, 5, 6 and 7 may be fabricated using a variety of different techniques. Figures 8(a)-8(d) show various cross sections of different embodiments of the presently described embodiments. These figures also provide description of fabrication details that may be used to form the presently described embodiments.

[0050] With reference to Figure 8(a), a cross-sectional view of a configuration 100 is illustrated. In this form, tubing 102 is disposed within chambers defined between endplates 106. The chambers are defined by plates 104 and spacers 108, as shown. In this configuration, the tubing 102 is controllably squeezed between the plates 104. To achieve the configuration 100, a variety of different assembly procedures may be used. Likewise, a variety of different materials may be used. However, in one form of the configuration of Figure 8(a) (and in corresponding example elements of Figures 8(b) –(d)), the end plates 106 are formed of aluminum, the tubing 102 is formed of Tygon material, and the spacers 108 and plates 104 are formed of plastic, such as Plexiglas.

[0051] In Figure 8(b), a similar structure 110 is provided except the tubing 102 is recessed within a cavity 114 formed in a plate 112 and stacked to increase throughput. The plates also are provided with alignment notches 116. Any suitable material may be used to form the plates 112, including a plastic material such as Plexiglas.

[0052] With reference to Figure 8(c), a system 120 is illustrated wherein tubing 102 is eliminated. In this case, sufficiently sealed cavities 124 are formed in a substrate 122 and form the fluid channels which are stacked to increase throughput. Also shown is a cap layer 128 to seal the top cavity 124. Like Figure 8(b), alignment notches 126 are also provided. The substrate 122 and cover plate 128 may be formed of any suitable material; however, in at least one form, these elements are formed of plastic material such as Plexiglas.

[0053] With reference to Figure 8(d), a system 130 comprises spiral tracks 132 defined by wall portions 134 and plates 136. The wall portions 134 and the plates 136 may take a variety of forms. But, in one form, these structures are formed of plastic. Essentially, the structure 134 is formed and then laminated on both sides to form the enclosed channels 132. Again, these parallel devices are stacked for improved support and throughput. As with Figure 8(a) – (c), both ends are supported by plates formed of, for example, aluminum.

[0054] Figures 9(a) - (b) illustrate a further embodiment of the presently described embodiments. As shown in Figure 9(a), a device 200 includes eight

parallel channels in a helical spiral arrangement. This embodiment provides for quick assembly and disassembly, as shown in the exploded view of Figure 9(b), the cross-sectional view of Figure 10(a) and the end cap and manifold structure of Figure 10(b).

[0055] In operation, fluid enters the device 200 through an inlet 202 and exits (separated) through outlet paths 204 and 206. An upper fluidic manifold 210 feeds the eight separate channels (such as channel 214) through the respective radially skewed slots on an end cap 212. A lower end cap 216 has slots corresponding to each channel as well as corresponding chutes 217. An outlet manifold 218 includes an inner ring 219 which acts as the bifurcator to split the fluid into particulate and effluent streams.

[0056] The helical spiral structure formed by the channels, such as channel 214, fits within an external protective sleeve 220. It will be appreciated that, in one form, the device 200 is tightened by counter rotating the top and bottom manifold and end cap structures. Tightening pushes the helical spirals against each other, thus preventing distortions to the individual flow cross sections and, therefore, allowing the use of thinner and less expensive materials and a further reduction in space. Each individual channel may optionally have individual flow control at inlet or outlet to stop the flow.

[0057] Although design is somewhat self-cleaning as it operates at velocities in the range of 0.1 to 10 m/s, parallel channels allow for redundancy when clogging develops in a channel as the other channels will take up the slack to continue operation. Optionally, a flow sensor can be incorporated within a feedback loop to adjust the flow rate in order to maintain a constant separation velocity. Additionally, other inline devices such as flash mixers may be integrated with the top manifold. The eight channels are shown to illustrate parallelization, but any number of channels may be used.

[0058] Depending on the source water quality, i.e. particulate concentration and size distribution, the spiral separator will collect all of the particulates into a band of different widths. In order to allow optimization of the efficiency of the

spiral concentrator in real time, it is desirable to have an adjustable stream splitter.

[0059] With reference now to Figures 10(a) and 10(b), an outlet manifold 218 having such a stream splitter is illustrated. The splitting mechanism can take a variety of forms as will be describe in connection with Figures 11 (a) – (c); however, in at least one form, the splitter will allow for the fluid to be split so that a portion 222 will exit the device on a first path as effluent and a portion 224 of the fluid will exit the device on a second path containing particles (e.g. a particle band).

[0060] The splitter is connected to the spiral separator device 200 such that it can be rotated on its central axis. For a device 200 with eight parallel channels, the splitter typically will rotate only about 45 degrees. The degree of radial change of the splitter wall can be optimized to the expected source water quality. For example, if the quality is expected to vary only slightly, a smaller change in radius is sufficient to capture the range of width change. If variations in water quality are larger, a larger change in radius may be necessary. When the adjustable splitter is operated manually, feedback from inline meters and other sensors may be used. Another manner of operating the splitter is to provide an automated feedback loop. In this way, optical sensors can be used at the exit portion of the channels to measure the bandwidth constantly and direct a server or motor to adjust the optimal splitter setting in real time. Similarly, flow sensors can also be used to monitor flow rate for feedback control of fluid velocity by adjusting pump speed and/or power.

[0061] With reference to Figures 11(a)-11(c), various forms of the output fluid manifold are shown. Figure 11 (a) shows a static splitter. In this form, the manifold 218 is provided with a substantially circular collar device 219 to act as a splitter. Collar devices with pre-set splits of 20:80, 30:70, through 80:20 may be used interchangeably. Figure 11(b) shows a continuously adjustable flow separator providing for non-linear control in custom curvature. In this form, the manifold 218' is provided with a portion 219' that includes strategically placed curved and straight portions to provide for the continuously adjustable flow.

Figure 11(c) shows a discrete stepwise adjustable flow separator design. In this form, the manifold 218" includes a portion 219" that is formed by discrete steps to provide discrete step-wise adjustable flow. In this form, the transition from one step to the next may be ratcheted.

[0062] The splitters, in any of these forms and others, are adjusted by turning the manifold of the device in a selected direction for a selected angular distance. This will move the splitting mechanism across the egress portion of the channel so that the split between the path 222 and the path 224 may be varied. Adjustments may be automated by a motor controlled by a computer.

[0063] Figures 12(a) and (b) show an extension of the embodiment in Figures 9(a)-11(c), wherein a modular eight channel two stage helical spiral embodiment is illustrated. A fluid inverter 316 is provided in the embodiment shown. The fluid inverter is comprised of circular plates 326 and 328, having slots therein corresponding to the spiral channels. The fluid inverter also includes passageways 330 connecting corresponding slots in the plates 326 and 328. In the example embodiment shown in Figures 12(a) and 12(b), a fluid inversion is initiated in the fluid flow so that any resident particle band flips from one side of the channel to the other side of the channel to provide a compaction of particles. This achieves a narrower band. In Figure 12(b), a first stage 314 is illustrated as well as a second spiral stage 315. To achieve the above noted flipping of the particle band, the spiral stage 315 is flipped upside down. The fluid inverter 316 is positioned between the stages.

[0064] To further explain the principles of the inversion process, reference is made to Figure 12(c). It will be appreciated that the embodiment of Figure 12 (c) differs in structure from the embodiment of Figures 12 (a) and (b) in that the spiral device is of a different configuration and an inverter structure, such as inverter 316, is not shown. Nonetheless, it will be appreciated by those of skill in the art that the inversion principles as explained in connection with this drawing can be applied to the inversion process of the inverter 316. As shown, a spiral device 350 includes an inlet 352, a first curved portion or stage 354 of the spiral channel, a transition 356, a second curved portion or stage 358 and

outlets 360, 362 and 364. In operation, the fluid is received at the inlet 352 and flows through the first stage 354 – with particles being separated and, in some forms, being focused in a particle band, on one side of the channel. As the fluid passed through the abrupt transition point 356, the band (or separated particles) flips to the opposite side of the channel. The second stage 358 then continues to compact the particles resulting in a more compact and even narrower band of particles.

[0065] With reference now to Figures 13 (a) and (b), a still further embodiment is shown. In Figures 13 (a) and (b), 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. It will be appreciated that this single channel helical structure resembles a hollow “slinky” type device with the shape of a coiled spring. This device may be fabricated in a variety of manners including in sections using injection molding techniques. The sections are then fused together using known processes before use. Another process for fabricating this device includes the use of extrusion molding techniques wherein the extruded plastic can be air-cooled or dipped in a liquid bath to solidify to its desired shape and structure. The helical coiling can be achieved by controlling the rotation of either the extrusion mandril or the cooling bath. A variety of different material can be used, including thermal plastics such as PVC with Shore “A” hardness, high density polyethylene, polypropylene, polystyrene, and polycarbonate.

[0066] As shown in Figure 13(b), a spiral device such as that shown in Figure 13(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.

[0067] With reference to Figures 14(a) through 14(c), a similar system having vertically stacked parallel channels is shown. However, the embodiment of Figure 14(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. Such a device may be fabricated by introducing rib structures on a web-fed Mylar-like plastic (or fluid impermeable) material. The rib structures may be formed using quick-set epoxy printing techniques.

[0068] As with the embodiment illustrated in Figures 13(a) and 13(b), the device 700, as shown in Figure 14(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.

[0069] With reference to Figure 14(c), it will be appreciated that the body 704 may be comprised of a single channel 1210, or a plurality of channels 1210 - 1224. Of course, any number or form of channels will suffice.

[0070] Moreover, it should be appreciated that any of the spiral or other devices described or contemplated herein may be disposed in a cascaded manner or in a parallel manner, as shown in Figures 13(a), 13(b), 14(a) and 14(b). Those actually shown are merely examples. Still further, any suitable material may be used to form the devices contemplated herein.

[0071] With reference now to Figure 15, an example feedback and control system 900 is illustrated. As shown, a separator 902 (which could take the form of any of the spiral or other separators contemplated by the presently described embodiments or others) receives input fluid 904 and processes it to achieve an effluent stream 906 and a particulate stream 908. As alluded to above, the system 900 may use various items of data, such as pressure, bandwidth, flow rate, temperature or viscosity – all of which may be measured using suitable sensors. The data is fed to a controller 910 that controls various actuators 920 that are operative to modify the performance of the device 902 in a desired manner.

Claims:

1. A particle separation system comprising:
 - a plurality of individual curved particle separation devices stacked such that the devices are parallel to one another;
 - an inlet coupler connected to all inlets of the devices, the inlet couple being operative to facilitate input of fluid to all inlets of the plurality of individual curved particle separation devices; and,
 - at least two outlet couplers connected to the corresponding outlets of the plurality of individual curved particle separation devices.
2. The system as set forth in claim 1 wherein the curved particle separation devices are spiral devices.
3. A particle separation system comprising:
 - an inlet manifold;
 - a plurality of separation channels facilitating fluid flow therein and arranged in a helical spiral configuration wherein the channels are parallel to one another; and,
 - an output manifold.
4. The system as set forth in claim 3 further comprising a feedback control system.