

IN-LINE AIR BUBBLE SUSPENSION APPARATUS FOR ANGIOGRAPHY INJECTOR FLUID PATHS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/705,250 filed on 18 June 2020, the disclosure of which is incorporated by reference in its entirety.

BACKGROUND OF THE DISCLOSURE

Field of the Disclosure

[0002] The present disclosure relates generally to fluid injector systems and associated fluid path elements for high pressure injection of medical fluids. More specifically, the present disclosure describes a fluid delivery system having at least one air bubble suspension apparatus. Other embodiments relate to features of air bubble suspension apparatuses suitable for use in fluid injection procedures.

Description of Related Art

[0003] In many medical diagnostic and therapeutic procedures, a medical practitioner, such as a physician, injects a patient with one or more medical fluids. A number of injector-actuated syringes and powered fluid injectors for pressurized injection of medical fluids, such as a contrast solution (often referred to simply as “contrast”), a flushing agent, such as saline or Ringer’s lactate, and other medical fluids, have been developed for use in procedures such as cardiovascular angiography (CV), computed tomography (CT), ultrasound, magnetic resonance imaging (MRI), positron emission tomography (PET), and other imaging procedures. In general, these fluid injectors are designed to deliver a preset amount of fluid at a preset pressure and/or flow rate.

[0004] Typically, fluid injectors have at least one drive member, such as a piston, that connects to the syringe, for example via connection with a plunger or an engagement feature on a proximal end wall of the syringe. The syringe may include a rigid barrel with the syringe plunger being slidably disposed within the barrel. The drive members drive the plungers in a proximal and/or distal direction relative to a longitudinal axis of the barrel to draw fluid into or deliver the fluid from the syringe barrel. In certain applications, such as angiography, the medical fluids are injected directly into the arterial system at fluid pressures up to 1200 psi.

[0005] During certain injection procedures at these high fluid pressures with fluid being administered directly to the cardiac system, it is imperative that no air be co-injected with the medical fluid as patient harm may result. Thus, new methods and devices are necessary to

prevent injection of inadvertent air during a high-pressure fluid injection procedure. Further, at pressures of up to 1200 psi during some CV injections, air in the fluid path compresses; however, if the injection is stopped upon air detection, the air volume may expand rapidly due to release of pressure. In addition, release of system compliance upon cessation of injection may result in continued fluid flow as the compliance volume is released in the absence of the fluid pressure. Thus, high pressure fluid injection systems must address for these phenomena when preventing inadvertent air injection.

SUMMARY OF THE DISCLOSURE

[0006] In view of the foregoing, there exists a need for devices, systems, and methods for preventing air from being delivered to a patient during an injection procedure. Embodiments of the present disclosure are directed to an apparatus for suspending air bubbles in a fluid path of a fluid injector system. The apparatus includes a housing, an internal chamber having a curved interior wall defined within the housing, an inlet fluid pathway in fluid communication with the internal chamber, the inlet fluid pathway extending into the chamber at a tangent to the curved interior wall, and an outlet fluid pathway in fluid communication with the internal chamber, the outlet fluid pathway spaced from the inlet fluid pathway such that fluid flowing into the internal chamber via the inlet fluid pathway is directed away from the outlet fluid pathway. The internal chamber is configured to create an internal fluid vortex in an injection fluid entering the internal chamber from the inlet fluid pathway, and wherein the internal fluid vortex at least temporarily suspends one or more air bubbles in the fluid in the internal vortex and delays the passage of the one or more air bubbles to the outlet fluid pathway.

[0007] In some embodiments, the outlet fluid pathway extends from the internal chamber in a direction perpendicular to a flow path of fluid within the internal chamber.

[0008] In some embodiments, at least a portion of the outlet fluid pathway has a cross-sectional area greater than a cross-sectional area of the inlet fluid pathway to reduce fluid velocity in the outlet fluid pathway relative to fluid velocity in the inlet fluid pathway.

[0009] In some embodiments, the outlet fluid pathway extends substantially parallel to the inlet fluid pathway. In some embodiments, the internal chamber is at least partly spherical or hemispherical.

[0010] In some embodiments, the apparatus further includes a recess extending radially outward from the internal chamber.

[0011] In some embodiments, the apparatus further includes a valve in fluid communication with the internal chamber for draining air accumulated in the internal chamber.

[0012] In some embodiments, the housing includes a first housing section including the inlet fluid pathway and the outlet fluid pathway, and a second housing section including at least a portion of the internal chamber. One of the first housing section and the second housing section includes a flange for receiving the other of the first housing section and second housing section.

[0013] In some embodiments, the housing includes at least one strengthening rib extending radially outward from the outlet fluid pathway.

[0014] In some embodiments, the apparatus further includes a screen disposed in the outlet fluid pathway such that fluid flowing out of the internal chamber passes through the screen.

[0015] In some embodiments, the housing includes a light-transmissible material configured to illuminate air bubbles in the internal chamber.

[0016] In some embodiments, the housing includes a connector arm configured for attachment to an injector housing of the fluid injector system.

[0017] In some embodiments, the apparatus further includes an adjustable valve for changing a cross-sectional area of at least one of the inlet fluid pathway and outlet fluid pathway.

[0018] Other embodiment of the present disclosure are directed to an apparatus for suspending air bubbles in a fluid path of a fluid injector system. The apparatus includes a housing defining an internal chamber, an inlet fluid pathway in fluid communication with the internal chamber, an outlet fluid pathway in fluid communication with the internal chamber; and an extension tube in fluid communication with the inlet fluid pathway and extending into the internal chamber. The extension tube includes a tip spaced apart from the outlet fluid pathway such that fluid flowing into the internal chamber via the extension tube is directed away from the outlet fluid pathway.

[0019] In some embodiments, the apparatus further includes a screen dividing the internal chamber into an inlet portion and an outlet portion. The screen includes at least one aperture providing fluid communication between the inlet portion and the outlet portion. Fluid flowing into the internal chamber from the extension tube must flow through the at least one aperture of the screen to reach the outlet fluid pathway.

[0020] In some embodiments, a first portion of the screen adjacent to the tip of the extension tube is impermeable to fluid, and a second portion of the screen adjacent to the outlet fluid pathway includes the at least one aperture. In some embodiments, the screen includes a funnel defining the at least one aperture, the funnel tapering from a maximum cross-sectional area adjacent the inlet portion of the internal chamber to a minimum diameter extending into the outlet portion of the internal chamber.

[0021] In some embodiments, the screen includes a hood at least partially obstructing the at least one aperture such that fluid must flow around the hood to flow through the at least one aperture. In some embodiments, the screen includes mesh. In some embodiments, the at least one aperture includes two or more apertures arranged in an arc.

[0022] In some embodiments, the housing includes a first housing section including a flange configured to receive the screen, and a second housing section received within the flange of the first housing section to capture the screen between the first housing section and the second housing section.

[0023] In some embodiments, the inlet fluid pathway tapers from a smaller cross-sectional area to a larger cross-sectional area in a direction of fluid flow through the inlet fluid pathway to reduce flow velocity of fluid flowing through the inlet fluid pathway.

[0024] In some embodiments, the extension tube extends parallel to an inner wall of the internal chamber. In some embodiments, the outlet fluid pathway extends at an acute angle relative to the inlet fluid pathway.

[0025] In some embodiments, the housing includes a light-transmissible material configured to illuminate air bubbles in the internal chamber.

[0026] In some embodiments the housing includes a connector arm configured for attachment to an injector housing of the fluid injector system.

[0027] In some embodiments, the apparatus further includes an adjustable valve for changing a cross-sectional area of at least one of the inlet fluid pathway and outlet fluid pathway.

[0028] Other embodiments of the present disclosure are directed to a fluid injector system including at least one fluid reservoir configured for injecting medical fluid and at least one bubble suspension apparatus in fluid communication with the at least one fluid reservoir. The at least one bubble suspension apparatus includes a housing defining an internal chamber, an inlet fluid pathway in fluid communication with the internal chamber, and an outlet fluid pathway in fluid communication with the internal chamber, the outlet fluid pathway spaced from the inlet fluid pathway such that fluid flowing into the internal chamber via the inlet fluid pathway is directed away from the outlet fluid pathway. The fluid injector system further includes at least one air detector configured to detect one or more air bubbles in a fluid path connecting the at least one fluid reservoir to the at least one bubble suspension apparatus, and at least one shutoff valve downstream of the at least one bubble suspension apparatus and configured to move from an open position to a closed position in response to the air detector detecting the one or more air bubbles in the fluid path. The internal chamber is configured to

create an internal fluid vortex in an injection fluid entering the internal chamber from the inlet fluid pathway, and wherein the internal fluid vortex at least temporarily suspends one or more air bubbles in the fluid in the internal vortex and delays the passage of the one or more air bubbles to the outlet fluid pathway. Features of the various embodiments of the bubble suspension apparatus suitable for use with fluid injector systems are described herein.

[0029] In some embodiments, the bubble suspension apparatus is movable between an injection position in which the outlet fluid pathway extends substantially vertically downward from the internal chamber such that buoyancy of air bubbles in the internal chamber further induces the one or more air bubbles to remain suspended in the internal fluid vortex in the internal chamber, and a priming position in which the outlet fluid pathway extends substantially vertically upward from the chamber such that the buoyancy of air bubbles in the internal chamber induces the air bubbles to flow from the internal fluid vortex through the outlet fluid pathway.

[0030] In some embodiments, the system further including an adjustable valve for changing a cross-sectional area of at least one of the inlet fluid pathway and the outlet fluid pathway.

[0031] Further aspects or examples of the present disclosure are described in the following numbered clauses:

[0032] Clause 1. An apparatus for suspending air bubbles in a fluid path of a fluid injector system, the apparatus comprising: a housing; an internal chamber having a curved interior wall defined within the housing; an inlet fluid pathway in fluid communication with the internal chamber, the inlet fluid pathway extending into the chamber at a tangent to the curved interior wall; and an outlet fluid pathway in fluid communication with the internal chamber, the outlet fluid pathway spaced from the inlet fluid pathway such that fluid flowing into the internal chamber via the inlet fluid pathway is directed away from the outlet fluid pathway, wherein the internal chamber is configured to create an internal fluid vortex in an injection fluid entering the internal chamber from the inlet fluid pathway, and wherein the internal fluid vortex at least temporarily suspends one or more air bubbles in the fluid in the internal vortex and delays the passage of the one or more air bubbles to the outlet fluid pathway.

[0033] Clause 2. The apparatus according to clause 1, wherein the outlet fluid pathway extends from the internal chamber in a direction perpendicular to a flow path of fluid within the internal chamber.

[0034] Clause 3. The apparatus according to clause 1 or 2, wherein at least a portion of the outlet fluid pathway has a cross-sectional area greater than a cross-sectional area of the inlet

fluid pathway to reduce fluid velocity in the outlet fluid pathway relative to fluid velocity in the inlet fluid pathway.

[0035] Clause 4. The apparatus according to any of clauses 1-3, wherein the outlet fluid pathway extends substantially parallel to the inlet fluid pathway.

[0036] Clause 5. The apparatus according to any of clauses 1-4, wherein the internal chamber is at least partly spherical or hemispherical.

[0037] Clause 6. The apparatus according to any of clauses 1-5, further comprising a recess extending radially outward from the internal chamber.

[0038] Clause 7. The apparatus according to any of clauses 1-6, further comprising a valve in fluid communication with the internal chamber for draining air accumulated in the internal chamber.

[0039] Clause 8. The apparatus according to any of clauses 1-7, wherein the housing comprises: a first housing section comprising the inlet fluid pathway and the outlet fluid pathway; and a second housing section comprising at least a portion of the internal chamber, wherein one of the first housing section and the second housing section comprises a flange for receiving the other of the first housing section and the second housing section.

[0040] Clause 9. The apparatus according to any of clauses 1-8, wherein the housing comprises at least one strengthening rib extending radially outward from the outlet fluid pathway.

[0041] Clause 10. The apparatus according to any of clauses 1-9, further comprising a screen disposed in the outlet fluid pathway such that fluid flowing out of the internal chamber passes through the screen.

[0042] Clause 11. The apparatus according to any of clauses 1-10, wherein the housing comprises a light-transmissible material configured to illuminate air bubbles in the internal chamber.

[0043] Clause 12. The apparatus according to any of clauses 1-11, wherein the housing comprises a connector arm configured for attachment to an injector housing of the fluid injector system.

[0044] Clause 13. The apparatus according to any of clauses 1-12, further comprising an adjustable valve for changing a cross-sectional area of at least one of the inlet fluid pathway and the outlet fluid pathway.

[0045] Clause 14. An apparatus for suspending air bubbles in a fluid path of a fluid injector system, the apparatus comprising: a housing defining an internal chamber; an inlet fluid pathway in fluid communication with the internal chamber; an outlet fluid pathway in fluid

communication with the internal chamber; and an extension tube in fluid communication with the inlet fluid pathway and extending into the internal chamber, the extension tube comprising a tip spaced apart from the outlet fluid pathway such that fluid flowing into the internal chamber via the extension tube is directed away from the outlet fluid pathway.

[0046] Clause 15. The apparatus according to clause 14, further comprising a screen dividing the internal chamber into an inlet portion and an outlet portion, wherein the screen comprises at least one aperture providing fluid communication between the inlet portion and the outlet portion, and wherein fluid flowing into the internal chamber from the extension tube must flow through the at least one aperture of the screen to reach the outlet fluid pathway.

[0047] Clause 16. The apparatus according to clause 14 or 15, wherein a first portion of the screen adjacent to the tip of the extension tube is impermeable to fluid, and wherein a second portion of the screen adjacent to the outlet fluid pathway comprises the at least one aperture.

[0048] Clause 17. The apparatus according to any of clauses 14-16, wherein the screen comprises a funnel defining the at least one aperture, the funnel tapering from a maximum cross-sectional area adjacent the inlet portion of the internal chamber to a minimum diameter extending into the outlet portion of the internal chamber.

[0049] Clause 18. The apparatus according to any of clauses 14-17, wherein the screen comprises a hood at least partially obstructing the at least one aperture such that fluid must flow around the hood to flow through the at least one aperture.

[0050] Clause 19. The apparatus according to any of clauses 14-18, wherein the screen comprises mesh.

[0051] Clause 20. The apparatus according to any of clauses 14-19, wherein the at least one aperture comprises two or more apertures arranged in an arc.

[0052] Clause 21. The apparatus according to any of clauses 14-20, wherein the housing comprises: a first housing section comprising a flange configured to receive the screen; and a second housing section received within the flange of the first housing section to capture the screen between the first housing section and the second housing section.

[0053] Clause 22. The apparatus according to any of clauses 14-21, wherein the inlet fluid pathway tapers from a smaller cross-sectional area to a larger cross-sectional area in a direction of fluid flow through the inlet fluid pathway to reduce flow velocity of fluid flowing through the inlet fluid pathway.

[0054] Clause 23. The apparatus according to any of clauses 14-22, wherein the extension tube extends parallel to an inner wall of the internal chamber.

[0055] Clause 24. The apparatus according to any of clauses 14-23, wherein the outlet fluid pathway extends at an acute angle relative to the inlet fluid pathway.

[0056] Clause 25. The apparatus according to any of clauses 14-24, wherein the housing comprises a light-transmissible material configured to illuminate air bubbles in the internal chamber.

[0057] Clause 26. The apparatus according to any of clauses 14-25, wherein the housing comprises a connector arm configured for attachment to an injector housing of the fluid injector system.

[0058] Clause 27. The apparatus according to any of clauses 14-26, further comprising an adjustable valve for changing a cross-sectional area of at least one of the inlet fluid pathway and the outlet fluid pathway.

[0059] Clause 28. A fluid injector system comprising: at least one fluid reservoir configured for injecting medical fluid; at least one bubble suspension apparatus in fluid communication with the at least one fluid reservoir; the at least one bubble suspension apparatus comprising: a housing defining an internal chamber; an inlet fluid pathway in fluid communication with the internal chamber; and an outlet fluid pathway in fluid communication with the internal chamber, the outlet fluid pathway spaced from the inlet fluid pathway such that fluid flowing into the internal chamber via the inlet fluid pathway is directed away from the outlet fluid pathway; at least one air detector configured to detect one or more air bubbles in a fluid path connecting the at least one fluid reservoir to the at least one bubble suspension apparatus; and at least one shutoff valve downstream of the at least one bubble suspension apparatus and configured to move from an open position to a closed position in response to the air detector detecting the one or more air bubbles in the fluid path, wherein the internal chamber is configured to create an internal fluid vortex in an injection fluid entering the internal chamber from the inlet fluid pathway, and wherein the internal fluid vortex at least temporarily suspends one or more air bubbles in the fluid in the internal vortex and delays the passage of the one or more air bubbles to the outlet fluid pathway.

[0060] Clause 29. The fluid injector system according to clause 28, wherein the bubble suspension apparatus is movable between: an injection position in which the outlet fluid pathway extends substantially vertically downward from the internal chamber such that buoyancy of air bubbles in the internal chamber further induces the one or more air bubbles to remain suspended in the internal fluid vortex in the internal chamber; and a priming position in which the outlet fluid pathway extends substantially vertically upward from the chamber

such that the buoyancy of air bubbles in the internal chamber induces the air bubbles to flow from the internal fluid vortex through the outlet fluid pathway.

[0061] Clause 30. The fluid injector system according to clause 28 or 29, wherein the internal chamber comprises at least one curved interior wall, wherein the inlet fluid pathway extends into the internal chamber at a tangent to the curved interior wall.

[0062] Clause 31. The fluid injector system according to any of clauses 28-30, wherein the outlet fluid pathway extends from the internal chamber in a direction substantially perpendicular to a flow path of fluid in the internal fluid vortex within the internal chamber.

[0063] Clause 32. The fluid injector system according to any of clauses 28-31, wherein at least a portion of the outlet fluid pathway has a cross-sectional area greater than a cross-sectional area of the inlet fluid pathway to reduce fluid velocity in the outlet fluid pathway relative to fluid velocity in the inlet fluid pathway.

[0064] Clause 33. The fluid injector system according to any of clauses 28-32, wherein the outlet fluid pathway extends substantially parallel to the inlet fluid pathway.

[0065] Clause 34. The fluid injector system according to any of clauses 28-33, wherein the internal chamber is at least partially spherical or hemispherical.

[0066] Clause 35. The fluid injector system according to any of clauses 28-34, wherein the bubble suspension apparatus further comprises a recess extending radially outward from the internal chamber in a direction substantially opposite the outlet fluid pathway.

[0067] Clause 36. The fluid injector system according to any of clauses 28-35, further comprising a valve on the recess and in fluid communication with the internal chamber for draining air accumulated in the recess.

[0068] Clause 37. The fluid injector system according to any of clauses 28-36, wherein the housing of the bubble suspension apparatus comprises: a first housing section comprising at least one of the inlet fluid pathway and the outlet fluid pathway; and a second housing section comprising at least a portion of the internal chamber, wherein one of the first housing section and the second housing section comprises a flange for receiving the other of the first housing section and the second housing section.

[0069] Clause 38. The fluid injector system according to any of clauses 28-37, wherein the housing of the bubble suspension apparatus comprises at least one strengthening rib extending radially outward from outlet fluid pathway.

[0070] Clause 39. The fluid injector system according to any of clauses 28-38, wherein the bubble suspension apparatus further comprises a screen disposed proximal to the outlet fluid pathway such that fluid flowing out of the internal chamber passes through the screen.

[0071] Clause 40. The fluid injector system according to any of clauses 28-39, wherein one or more of the one or more air bubbles temporarily adhere to a surface of the screen as the fluid passes through the screen.

[0072] Clause 41. The fluid injector system according to any of clauses 28-40, wherein the screen comprises a hydrophilic coating on at least a portion of a surface of the screen.

[0073] Clause 42. The fluid injector system according to any of clauses 28-41, wherein the bubble suspension apparatus further comprises an extension tube in fluid communication with the inlet fluid pathway and extending into the internal chamber, the extension tube comprising a tip spaced apart from the outlet fluid pathway such that fluid flowing into the internal chamber via the extension tube is directed away from the outlet fluid pathway.

[0074] Clause 43. The fluid injector system according to any of clauses 28-42, wherein the screen divides the internal chamber into an inlet portion and an outlet portion, wherein the screen comprises at least one aperture providing fluid communication between the inlet portion and the outlet portion, and wherein fluid flowing into the internal chamber from the inlet fluid pathway must flow through the at least one aperture of the screen to reach the outlet fluid pathway.

[0075] Clause 44. The fluid injector system according to any of clauses 28-43, wherein a first portion of the screen adjacent to the tip of the extension tube is impermeable to fluid, and wherein a second portion of the screen adjacent to the outlet fluid pathway comprises the at least one aperture.

[0076] Clause 45. The fluid injector system according to any of clauses 28-44, wherein the screen comprises a funnel defining the at least one aperture, the funnel tapering from a maximum cross-sectional area adjacent the inlet portion of the internal chamber to a minimum diameter extending into the outlet portion of the internal chamber.

[0077] Clause 46. The fluid injector system according to any of clauses 28-45, wherein the screen comprises a hood at least partially obstructing the at least one aperture such that fluid must flow around the hood to flow through the at least one aperture.

[0078] Clause 47. The fluid injector system according to any of clauses 28-46, wherein the screen comprises mesh.

[0079] Clause 48. The fluid injector system according to any of clauses 28-47, wherein the at least one aperture comprises two or more apertures arranged in an arc.

[0080] Clause 49. The fluid injector system according to any of clauses 28-48, wherein the bubble suspension apparatus delays passage of the one or more air bubbles to the outlet fluid pathway by at least 100 milliseconds.

[0081] Clause 50. The fluid injector system according to any of clauses 28-49, wherein the housing comprises: a first housing section comprising a flange configured to receive the screen; a second housing section received within the flange of the first housing section to capture the screen between the first housing section and the second housing section.

[0082] Clause 51. The fluid injector system according to any of clauses 28-50, wherein the inlet fluid pathway tapers from a smaller cross-sectional area to a larger cross-sectional area in a direction of fluid flow through the inlet fluid pathway to reduce flow velocity of fluid flowing through the inlet fluid pathway.

[0083] Clause 52. The fluid injector system according to any of clauses 28-51, wherein the extension tube extends parallel to an inner wall of the internal chamber.

[0084] Clause 53. The fluid injector system according to any of clauses 28-52, wherein the outlet fluid pathway extends at an acute angle relative to the inlet fluid pathway.

[0085] Clause 54. The fluid injector system according to any of clauses 28-53, wherein the housing of the bubble suspension apparatus comprises a light-transmissible material configured to illuminate air bubbles in the internal chamber.

[0086] Clause 55. The fluid injector system according to any of clauses 28-54, wherein the housing of the bubble suspension apparatus comprises a connector arm configured for attachment to an injector housing of the fluid injector system.

[0087] Clause 56. The fluid injector system according to any of clauses 28-55, further comprising an adjustable valve for changing a cross-sectional area of at least one of the inlet fluid pathway and the outlet fluid pathway.

[0088] Further details and advantages of the various examples described in detail herein will become clear upon reviewing the following detailed description of the various examples in conjunction with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0089] **FIG. 1** is a perspective view of a fluid injector system according to an embodiment of the present disclosure;

[0090] **FIG. 2** is a schematic view of a fluid injector system in accordance with an embodiment of the present disclosure;

[0091] **FIG. 3** is a perspective view of an air bubble suspension apparatus according to an embodiment of the present disclosure;

[0092] **FIG. 4** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 3** in an injection position;

[0093] **FIG. 5** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 3** in a priming position;

[0094] **FIG. 6** is a cross-sectional side view of the air bubble suspension apparatus according to an embodiment of the present disclosure;

[0095] **FIG. 7** is a perspective view of an air bubble suspension apparatus according to an embodiment of the present disclosure;

[0096] **FIG. 8** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 7** in an injection position;

[0097] **FIG. 9** is a perspective view of an air bubble suspension apparatus according to an embodiment of the present disclosure;

[0098] **FIG. 10** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 9** at a first time interval of an injection protocol;

[0099] **FIG. 11** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 9** at a second time interval of an injection protocol;

[00100] **FIG. 12** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 9** at a third time interval of an injection protocol;

[00101] **FIG. 13** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 9** at a fourth time interval of an injection protocol;

[00102] **FIG. 14** is a cross-sectional side view of the air bubble suspension apparatus of **FIG. 9** in a priming position;

[00103] **FIG. 15** is a cross-sectional side view of an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00104] **FIG. 16** is a perspective view of the air bubble suspension apparatus of **FIG. 15**;

[00105] **FIG. 17** is a cross-sectional side view of an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00106] **FIG. 18** is an exploded perspective view of the air bubble suspension apparatus of **FIG. 17**;

[00107] **FIG. 19** is a perspective view of a screen for an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00108] **FIG. 20** is a perspective view of a screen for an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00109] **FIG. 21** is a perspective view of a screen for an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00110] FIG. 22 is a perspective view of a screen for an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00111] FIG. 23 is a perspective view of a screen for an air bubble suspension apparatus according to an embodiment of the present disclosure;

[00112] FIG. 24 is a front view of a screen for an air bubble suspension apparatus according to an embodiment of the present disclosure; and

[00113] FIG. 25 is a perspective view of an air bubble suspension apparatus according to an embodiment of the present disclosure.

[00114] Referring to the drawings in which like reference characters refer to like parts throughout the several views thereof, the present disclosure is generally directed to an in-line air bubble suspension apparatus for use with a fluid injector system.

DETAILED DESCRIPTION

[00115] For purposes of the description hereinafter, the terms “upper”, “lower”, “right”, “left”, “vertical”, “horizontal”, “top”, “bottom”, “lateral”, “longitudinal”, and derivatives thereof shall relate to the disclosure as it is oriented in the drawing figures. Spatial or directional terms, such as “left”, “right”, “inner”, “outer”, “above”, “below”, and the like, are not to be considered as limiting as the invention can assume various alternative orientations.

[00116] As used herein, the singular form of “a”, “an”, and “the” include plural referents unless the context clearly dictates otherwise. All numbers used in the specification and claims are to be understood as being modified in all instances by the term “about”. The terms “approximately”, “about”, and “substantially” mean a range of plus or minus ten percent of the stated value.

[00117] As used herein, the term “at least one of” is synonymous with “one or more of”. For example, the phrase “at least one of A, B, and C” means any one of A, B, and C, or any combination of any two or more of A, B, and C. For example, “at least one of A, B, and C” includes one or more of A alone; or one or more of B alone; or one or more of C alone; or one or more of A and one or more of B; or one or more of A and one or more of C; or one or more of B and one or more of C; or one or more of all of A, B, and C. Similarly, as used herein, the term “at least two of” is synonymous with “two or more of”. For example, the phrase “at least two of D, E, and F” means any combination of any two or more of D, E, and F. For example, “at least two of D, E, and F” includes one or more of D and one or more of E; or one or more of D and one or more of F; or one or more of E and one or more of F; or one or more of all of D, E, and F.

[00118] It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification, are simply exemplary examples of the disclosure. Hence, specific dimensions and other physical characteristics related to the examples disclosed herein are not to be considered as limiting.

[00119] When used in relation to a component of a fluid delivery system such as a fluid reservoir, a syringe, an air suspension apparatus, or a fluid line, the term “distal” refers to a portion of said component nearest to a patient. When used in relation to a component of an injector system such as a fluid reservoir, a syringe, an air suspension apparatus, or a fluid line, the term “proximal” refers to a portion of said component nearest to the injector of the injector system (i.e. the portion of said component farthest from the patient). When used in relation to a component of a fluid delivery system such as a fluid reservoir, a syringe, an air suspension apparatus, or a fluid line, the term “upstream” refers to a direction away from the patient and towards the injector of the injector system. For example, if a first component is referred to as being “upstream” of a second component, the first component is located nearer to the injector than the second component is to the injector. When used in relation to a component of a fluid delivery system such as a fluid reservoir, a syringe, an air suspension apparatus, or a fluid line, the term “downstream” refers to a direction towards the patient and away from the injector of the fluid delivery system. For example, if a first component is referred to as being “downstream” of a second component, the first component is located nearer to the patient than the second component is to the patient.

[00120] As used herein, the terms “capacitance” and “impedance” are used interchangeably to refer to a volumetric expansion of injector components, such as fluid reservoirs, syringes, fluid lines, and/or other components of a fluid delivery system as a result of pressurized fluids with such components and/or uptake of mechanical slack by force applied to components. Capacitance and impedance may be due to high injection pressures, which may be on the order of 1,200 psi in some angiographic procedures, and may result in a volume of fluid held within a portion of a component in excess of the desired quantity selected for the injection procedure or the resting volume of the component. Additionally, capacitance of various components can, if not properly accounted for, adversely affect the accuracy of pressure sensors of the injector system because the volumetric expansion of components can cause an artificial drop in measured pressure of those components.

[00121] The terms “first”, “second”, and the like are not intended to refer to any particular order or chronology, but refer to different conditions, properties, or elements. All documents referred to herein are “incorporated by reference” in their entirety. The term “at least” is

synonymous with “greater than or equal to”. The term “not greater than” is synonymous with “less than or equal to”.

[00122] It is to be understood that the disclosure may assume alternative variations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification, are simply exemplary aspects of the disclosure. Hence, specific dimensions and other physical characteristics related to the examples disclosed herein are not to be considered as limiting.

[00123] While the systems and apparatuses described herein are with reference to an angiography (CV) injection system, other pressurized injection protocols, such as computed tomography (CT), ultrasound, positron emission tomography (PET), and magnetic resonance imaging (MRI) may also incorporate the various embodiments described herein for preventing injection of air.

[00124] Referring to the drawings in which like reference characters refer to like parts throughout the several views thereof, the present disclosure is generally directed to fluid injector systems and bubble suspension apparatuses for delaying movement of one or more air bubbles through a fluid line towards a patient and preventing the delivery of the one or more air bubbles that may inadvertently occur during an injection procedure.

[00125] Referring first to **FIG. 1**, an embodiment of a dual syringe angiography injector system **2000** is illustrated. The angiography injector system **2000** is configured for injection of two medical fluids through a first fluid path **210A** for a medical fluid, such as an imaging contrast media for an angiography injection procedure, and a second fluid path **210B** for a flushing fluid, such as saline or Ringer’s lactate. The dual syringe angiography injector system **2000** may include an injector housing **12** having two syringe ports **15** configured to engage two syringes **10A**, **10B**. In some embodiments, the syringes **10A**, **10B** may be retained within corresponding pressure jackets **17A**, **17B** for example to prevent pressure-induced swelling and potential bursting of the syringes **10A**, **10B**.

[00126] The fluid injector system **2000** may further include at least one graphical user interface (GUI) **11** through which an operator can view and control the status of an injection procedure. The GUI **11** may be in operative communication with a controller **900** (see **FIG. 2**) which sends and receives commands between the GUI **11** and fluid injector system **2000**. The GUI **11** may be provided on the injector housing **12** or may be mounted remotely from the injector housing **12**.

[00127] The dual syringe angiography injector system **2000** may further include at least one upstream air detector **200** associated with fluid paths **210A,B** for detecting one or more air bubbles within an air detection tubing region **250** of the first fluid path **210A** and the second fluid path **210B**. The air detection tubing region **250**, for example, may be associated with a proximal or upstream portion of the first fluid path **210A** and the second fluid path **210B**. In some embodiments, the at least one air detector **200** may be a single module having at least one sensor operatively associated with each of the first fluid path **210A** and the second fluid path **210B**. In some embodiments, the at least one air detector **200** may include at least two distinct modules, each module operatively associated with one of the first fluid path **210A** and the second fluid path **210B**. The at least one air detector **200** may be in operative communication with the controller **900** (see **FIG. 2**) such that the controller **900** may receive signals from the at least one air detector **200** indicating the detection of one or more air bubbles in one or both of the first fluid path **210A** and/or the second fluid path **210B**. Once the signal(s) are received, controller **900** may send a signal or command to the fluid injector **2000** to stop a fluid injection procedure, for example, by closing one or more shut-off valves (see **FIG. 2**, **215A**, **215B** and/or **390**) downstream of the at least one air detector **200** to prevent the detected air bubble from being injected into the patient. The at least one air detector **200** may include an ultrasonic sensor, and optical sensor, or other suitable sensor arrangement, configured to detect the one or more air bubbles within the fluid path.

[00128] With continued reference to **FIG. 1**, the dual syringe angiography injector system **2000** may further include bulk fluid containers **19A** and **19B** for filling and refilling the respective syringes **10A**, **10B** with imaging contrast media and flushing fluid, respectively. The bulk fluid containers **19A** and **19B** may be in selective fluid communication with the syringes **10A**, **10B** via respective bulk fluid paths **216A** and **216B** and bulk fluid valves **215A** and **215B**.

[00129] Further details and examples of suitable nonlimiting powered injector systems, including syringes, pressure jackets and pressure jacket retention mechanisms, tubing, shut-off valves, controllers, and air detectors, are described in U.S. Patent Nos. 5,383,858; 7,553,294; 7,666,169; 8,945,051; 10,022,493; and 10,507,319, and International PCT Application Nos. PCT/US2013/061275; PCT/US2018/034613; PCT/US2020/049885; PCT/US2021/035273; and PCT/US2021/029963, the disclosures of which are hereby incorporated by reference in their entireties. While the fluid injection system **2000** is described herein in the context of a dual syringe angiography (CV) injector, it is to be understood that the fluid injector system

2000 may be adapted for single- and multiple-syringe configurations of any injection procedure (e.g. CT, PET, MRI, ultrasound, etc.)

[00130] Referring now to **FIG. 2**, a schematic diagram of the fluid injector system **2000** shown in **FIG. 1** is illustrated. The injector system **2000** includes a piston **13A**, **13B** respectively associated with each of the syringes **10A**, **10B** and their corresponding pressure jackets **17A**, **17B** (see **FIG. 1**). Each of the pistons **13A**, **13B** is configured to drive a respective plunger **14A**, **14B** within a barrel of the respective syringe **10A**, **10B**. The controller **900** is operatively associated with the injector system **2000**, for example to activate the pistons **13A**, **13B** to reciprocally move the plungers **14A**, **14B** within the syringes **10A**, **10B** and thereby execute and halt an injection procedure. In particular, the controller **900** may include at least one processor programmed or configured to actuate the pistons **13A**, **13B** and various other components of the injector system **2000**, such as one or more shut-off valves, as described herein, to take in and deliver medical fluids according to a programmed protocol for an injection procedure. Controller **900** may include computer readable media, such as memory, on which one or more injection protocols may be stored for execution by at least one processor.

[00131] The controller **900** may be programmed or configured to execute a filling operation during which the piston **13A**, **13B** associated with each syringe **10A**, **10B** is withdrawn toward a proximal end of the syringe **10A**, **10B** to draw injection fluid **F** (e.g. imaging contrast media and flushing fluid) into the syringe **10A**, **10B** from the bulk fluid containers **19A**, **19B**. During such filling operation, the controller **900** may be programmed or configured to selectively actuate the bulk fluid valves **215A** and **215B** to establish fluid communication between the respective syringes **10A**, **10B** and the bulk fluid containers **19A**, **19B** via the bulk fluid paths **216A** and **216B** to control filling of the syringes **10A**, **10B** with the appropriate injection fluid **F**. Upon completion of the filling operation, and optionally a priming operation to remove any air from the syringes **10A**, **10B** and various embodiments of the bubble suspension apparatuses described herein (for example by priming any such air back into the bulk fluid containers **19A**, **19B** or through a priming tube), controller **900** may be programmed or configured to selectively actuate bulk fluid valves **215A** and **215B** to block fluid communication between the respective syringes **10A**, **10B** and bulk fluid containers **19A**, **19B** via bulk fluid paths **216A** and **216B**.

[00132] After the filling operation and priming operation, the controller **900** may be programmed or configured to execute a delivery operation during which the piston **13A**, **13B** associated with one or both of the syringes **10A**, **10B** is moved toward a distal end of the syringe to inject injection fluid **F** into the first fluid path **210A** and the second fluid path **210B**. The controller **900** may be programmed or configured to selectively actuate the bulk fluid valves

215A and **215B** to establish fluid communication between the syringes **10A**, **10B** and the patient, via the fluid paths **210A**, **210B**. The first fluid path **210A** and the second fluid path **210B** ultimately merge into a patient fluid line **210C** in fluid communication with the vasculature of the patient. According to various embodiments, the first fluid path **210A** and the second fluid path **210B** may merge at a fluid mixing connector that provides turbulent mixing of the first fluid and the second fluid, such as a fluid mixing connector described in International PCT Application Nos. PCT/US2021/019507 and PCT/US2014/026324, the disclosures of which are incorporated herein by reference.

[00133] The controller **900** may be in operative communication with the at least one air detector **200** such that the controller **900** may stop actuation of the pistons **13A**, **13B** in response to the air detector **200** detecting the presence of one or more air bubbles in at least one of the first fluid path **210A** and/or the second fluid path **210B**. The controller **900** may further be in operative communication with at least one downstream automated shutoff valve **390** such that the controller **900** may actuate the at least one downstream shutoff valve **390** to stop fluid flow through the at least one downstream shutoff valve **390** and into the patient vascular system. The at least one downstream shutoff valve **390** may be actuated by the controller **900** between various positions such an open position in which medical fluid may flow to the patient, a closed position in which fluid flow to the patient is prevented, and a hemodynamic monitoring position in which the vasculature of the patient is in fluid communication with a pressure transducer and isolated from the syringes **10A**, **10B**. In some embodiments, the downstream shutoff valve **390** may be a stopcock, pinch valve or the like. In certain embodiments, the downstream shutoff valves **390** may be associated with each of the fluid paths **210A** and **210B** and may be located before the first fluid path **210A** and the second fluid path **210B** merge into a patient fluid line **210C**. Suitable examples of pinch valves and pinch valve/fluid path configurations are described in International PCT Application No. PCT/US2021/029963. During a normal delivery operation, the controller **900** may be programmed or configured to move the downstream shutoff valve **390** to the open position to establish fluid communication between the patient and the fluid paths **210A**, **210B**. The controller **900** may be programmed or configured to move the downstream shutoff valve **390** to the closed position in response to air being detected by the at least one air detector **200**. Movement of pistons **13A**, **13B** may also be stopped in response to air being detected by the at least one air detector **200**. In the stop position, the downstream shutoff valve **390** fluidly isolates the patient from the fluid paths **210A**, **210B**, thereby preventing air from being injected into the patient.

[00134] With continued reference to **FIG. 2**, in some embodiments, each of the first fluid path **210A** and the second fluid path **210B** may include an air bubble suspension apparatus **300** configured to at least temporarily suspend or delay one or more air bubbles flowing through the fluid paths **210A**, **210B**. Each air bubble suspension apparatus **300** may be provided in line with the associated fluid paths **210A**, **210B** between the at least one air detector **200** and the downstream shutoff valve **390**, such that all fluid flow through the fluid paths **210A**, **210B** must pass through at least one air bubble suspension apparatus **300** in order to reach the patient.

[00135] In some embodiments, the controller **900** may be programmed or configured to move the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** to the closed position in response to one or more air bubbles being detected by the at least one air detector **200** along with concomitant stopping of pistons **13A**, **13B**. In the absence of the air bubble suspension apparatuses **300**, the one or more air bubbles detected by the at least one air detector **200** may travel through the fluid paths **210A**, **210B** at a sufficient velocity to flow past the bulk fluid valves **215A**, **215B** and the downstream shutoff valve **390** before the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** reach the closed position. For example, during a high pressure (e.g., 1200 psi) CV injection procedure, it may take from 60 milliseconds to 90 milliseconds, for example in one embodiment approximately 80 milliseconds, for the injector system **2000** to stop an injection procedure after an air bubble flows into the detection region of the at least one air detector **200**. The time required to stop the injection procedure may include: a time required for the at least one air detector **200** to communicate to the controller **900** that an air bubble has been detected, a time required for the controller **900** to communication with the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390**, and the time required for the bulk fluid valves **215A**, **215B** and/or the shutoff valve **390** to move from the open position to the closed position. At the high injection pressures (e.g. 1200 psi) typical of CV injection procedures, an air bubble may move from 2.8 mL to 3.6 mL of the volume of the fluid path **210A**, **210B** over the 60 milliseconds to 90 milliseconds between detection of the air bubble and closure of the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390**. For example, at approximately 1200 psi, an air bubble may travel a distance corresponding to 3.2 mL over 80 milliseconds at a flow rate of 30 mL/sec in a tubing with a 0.072 inch ID. The distance equivalence of 3.2 mL volume for such an embodiment may be approximately 4 feet of tubing length travelled during 80 milliseconds. Thus, even with a rapid response time of the at least one air detector **200**, the controller **900**, and the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390**, an air bubble may travel a significant distance, potentially into the patient, before the bulk fluid valves **215A**,

215B and/or the downstream shutoff valve **390** can be closed. Further, due to the compressibility of a gas compared to a liquid, the air bubble volume may be significantly reduced under the high injection pressures. Only halting fluid flow by stopping pistons **13A**, **13B** releases pressure on the system allowing the air bubble to expand in volume. The increased volume may move the air bubble down the fluid path past the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** before such valves are closed.

[00136] Embodiments of the air bubble suspension apparatuses **300** of the present disclosure are configured to at least temporarily delay the flow of air bubbles in the fluid paths **210A**, **210B** such that the controller **900** has sufficient time to move the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** to the closed position prior to the air bubbles reaching the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390**. As noted herein, during a high pressure (e.g., 1200 psi) CV injection procedure, it may take from 60 milliseconds to 90 milliseconds, for example in one embodiment approximately 80 milliseconds, for the system **2000** to close the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** in response to the at least one air detector **200** detecting an air bubble in the fluid paths **210A**, **210B**. Embodiments of the air bubble suspension apparatuses **300** may be configured to delay the flow of air bubbles by at least 60 milliseconds to 90 milliseconds, for example in one embodiment at least 80 milliseconds, so that the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** can be moved to the closed position before the air bubble can reach the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390**. As such, the air bubble cannot flow downstream of the bulk fluid valves **215A**, **215B** and/or the downstream shutoff valve **390** and into the patient. In some embodiments, the controller **900** is programmed or configured to move one or both of the bulk fluid valves **215A**, **215B** to the closed position in response to the at least one air detector **200** detecting an air bubble in the fluid paths **210A**, **210B**. In some embodiments, the controller **900** is programmed or configured to move the downstream shutoff valve **390** to the closed position in response to the at least one air detector **200** detecting an air bubble in the fluid paths **210A**, **210B**. In some embodiments, the controller **900** is programmed or configured to move one or both of the bulk fluid valves **215A**, **215B** and the downstream shutoff valve **390** to the closed position in response to the at least one air detector **200** detecting an air bubble in the fluid paths **210A**, **210B**.

[00137] Referring to **FIGS. 3-25**, features of various embodiments of the air bubble suspension apparatus **300** are shown according to the present disclosure. In general, embodiments of the air bubble suspension apparatus **300** includes a housing **310** defining an internal chamber **320**. The internal chamber **320** is in fluid communication with an inlet fluid

pathway **312** and an outlet fluid pathway **314**. The inlet fluid pathway **312** and the outlet fluid pathway **314** may be configured for fluid communication with associated fluid paths **210A**, **210B** of the fluid injector system **2000**. The at least one air bubble suspension apparatus **300** may be connected to the associated fluid path **210A**, **210B** such that injection fluid injected from the associated syringe **10A**, **10B** flows into the inlet fluid pathway **312**, through the interior chamber **320**, and out of the outlet fluid pathway **314**. The air bubble suspension apparatus **300** is located in each of the fluid paths **210A**, **210B** downstream of the at least one air detector **200** and upstream of the downstream shutoff valve **390** and, in some embodiments, upstream of the bulk fluid valves **215A**, **215B**. In this manner, the air bubble is at least temporarily suspended in the air bubble suspension apparatus **300** for a length of time to allow moving of the downstream shutoff valve **390** and/or the bulk fluid valves **215A**, **215B** to the closed position and stopping the injection procedure. In some embodiments, the air bubble suspension apparatus **300** may be configured to delay passage of the one or more air bubbles from the inlet fluid pathway **312** to the outlet fluid pathway **314** by at least 100 milliseconds.

[00138] The inlet fluid pathway **312** may be oriented relative to the internal chamber **320** such that fluid flow into the internal chamber **320** creates an internal fluid vortex in the injection fluid entering the internal chamber **320**. In some embodiments, the inlet fluid pathway **312** may be oriented such that injection fluid from the inlet fluid pathway **312** enters the internal chamber **320** substantially tangent to a curved or hemispherical interior wall **322** of the internal chamber **320**, thereby inducing the injection fluid to flow along the interior wall **322** to generate the fluid vortex. The internal fluid vortex induces one or more air bubbles that may be present in the injection fluid to be temporarily retained in the fluid vortex in the internal chamber **320**, thereby at least temporarily delaying passage of the one or more air bubbles to the outlet fluid pathway **314** and out of the air bubble suspension apparatus **300**. The internal fluid vortex may define a generally circular or otherwise continuous flow path along the curved or hemispherical interior wall **322** of the internal chamber **320** which causes the one or more air bubbles to be temporarily suspended in the injection fluid in the fluid vortex. In addition, the fluid vortex may induce the one or more air bubbles to coalesce into a smaller number of larger air bubbles, for example by collision and coalescence of small air bubbles. The curved or hemispherical interior wall **322** may minimize shear forces on the one or more air bubbles and thus, prevent the air bubble from shearing into smaller air bubbles in the vortex.

[00139] In various embodiments, the internal chamber **320** may have a volume (i.e. a fluid capacity) sufficient to delay a bubble of up to 0.5 milliliters (mL). In such embodiments, the internal chamber **320** may have a volume (i.e. a fluid capacity) of between 2 mL and 10 mL,

in some embodiments between 2.8 mL to 3.6 mL, in some embodiments approximately 3.2 mL, and in some embodiments approximately 5.4 mL. In the embodiment shown in **FIGS. 3-6**, the internal chamber **320** may have a volume (i.e. a fluid capacity) of approximately 6.77 mL for delaying a bubble of up to approximately 0.5 mL. In the embodiment shown in **FIGS. 7-8**, the internal chamber **320** may have a volume (i.e. a fluid capacity) of approximately 7.00 mL for delaying a bubble of up to approximately 0.5 mL. In some embodiments, the volume of the internal chamber **320** may be increased accordingly in order to delay bubbles having a greater volume than 0.5 mL.

[00140] With continued reference to the various embodiments shown in **FIGS. 3-25**, the outlet fluid pathway **314** may be oriented relative to the internal chamber **320** to prevent the one or more air bubbles suspended in the internal fluid vortex from readily flowing toward the outlet fluid pathway **314**. For example, the outlet fluid pathway **314** may be oriented such that the fluid flow path defined by the fluid vortex is directed away from the outlet fluid pathway **314**, or such that fluid flowing within the internal chamber **320** must change direction in order to enter the outlet fluid pathway **314** (see, e.g., **FIG. 14**). In some embodiments, the outlet fluid pathway **314** may extend substantially perpendicular from the interior wall **322** of the internal chamber **320** such that fluid flow in the fluid vortex passes transversely across an opening **315** of the outlet fluid pathway **314** (see, e.g., **FIG. 4**). The outlet fluid pathway **314** may be arranged such that, in an injection position of the air bubble suspension apparatus **300**, the outlet fluid pathway **314** extends at least partially downward from the internal chamber **320**. As air is buoyant relative to the injection fluid in the internal chamber **320**, any air bubbles present in the internal chamber **320** are induced by its relative buoyancy to float or migrate towards the top of the internal chamber **320** away from the outlet fluid pathway **314**. In addition, with such a configuration for the air bubble suspension apparatus **300**, the air bubble suspension apparatus **300** may be moved (e.g., rotated) from the injection position to a priming position in which the outlet fluid pathway **314** extends at least partially upward from the internal chamber **320** (see, **FIG. 5**). In the priming position, during a priming process to remove air from the fluid line prior to initiation of a fluid injection procedure, the air bubbles present in the internal chamber **320** are induced to float toward the outlet fluid pathway **314** so that under the influence of the priming fluid flow the air bubbles can be purged through the outlet fluid pathway **314** from a distal end of the associated fluid path **210A**, **210B**.

[00141] With particular reference to **FIGS. 3-5**, an embodiment of the air bubble suspension apparatus **300** is shown. The housing **310** may be formed of a first housing section **302** and a second housing section **304**. Forming the housing **310** from multiple sections may facilitate

manufacture via an injection molding process to form the various features of the air bubble suspension apparatus 300. The air bubble suspension apparatus 300 may be made of any suitable medical grade material, such as a medical grade polymeric material that is capable of withstanding the high fluid pressures within the air bubble suspension apparatus 300. The first housing section 302 may include at least one of the inlet fluid pathway 312 and the outlet fluid pathway 314. In the embodiment shown in FIGS. 3-5, the first housing section 302 includes both the inlet fluid pathway 312 and the outlet fluid pathway 314. The inlet fluid pathway 312 and the outlet fluid pathway 314 may extend substantially parallel to one another. The internal chamber 320 may be defined by the first housing section 302 and the second housing section 304. In the embodiment shown in FIGS. 3-5, each of the first housing section 302 and the second housing section 304 partially define the internal chamber 320. As shown in FIGS. 4 and 5, the first housing section 302 includes a flange 306 configured to receive an end feature 308, for example a lip, of the second housing section 304. In some embodiments, the flange 306 may be provided on the second housing section 304 and the end feature 308 may be provided on the first housing section 302. The first housing section 302 and the second housing section 304 may be joined via an adhesive, laser welding, ultrasonic welding, or the like. The housing 310 may include one or more strengthening ribs 324, 325 located at various positions to provide support against the high fluid pressure within the housing 310. In some angiography (CV) procedures, fluid pressure may be up to approximately 1200 psi. In some embodiments, a plurality of strengthening ribs 324 may extend radially from at least a portion of the inlet fluid pathway 312, the first housing section 302, the second housing section 304, and the outlet fluid pathway 314. In some embodiments, at least one strengthening rib 325 may extend parallel with the inlet fluid pathway 312 and/or the outlet fluid pathway 314. In certain embodiments, connector arm 360 may additionally act as a strengthening feature for inlet fluid pathway 314.

[00142] With continued reference to FIGS. 3-5, the internal chamber 320 may have a curved, hemispherical interior wall 322 to induce the injection fluid entering in the internal chamber 320 to flow in the internal fluid vortex, identified in FIG. 4 by vortex flow path B. In some embodiments, the interior wall 322 of the internal chamber 320 defined by the second housing section 304 may be substantially hemispherical or domed. As shown in FIG. 4, which illustrates the air bubble suspension apparatus 300 is shown in the injection position, the fluid inlet pathway 312 may extend into the internal chamber 320 substantially tangent to the interior wall 322 to create the internal fluid vortex. The fluid inlet pathway 312 may have an opening 313 into the internal chamber 320 such that injection fluid flowing into the internal chamber 320 in the direction A merges with the injection fluid in the internal chamber 320 flowing in

the fluid vortex flow path **B**. The injection fluid flowing into the internal chamber **320** from the fluid inlet pathway **312** thus enters the internal fluid vortex in substantially the same direction as the vortex flow path **B** to sustain the fluid vortex. The fluid vortex flow path **B** thus flows continuously within the internal chamber **320** so long as injection fluid continues to be introduced into the internal chamber **320** from the fluid inlet pathway **312**. The interior wall **322** may be shaped to induce recirculation of the injection fluid into the vortex flow path **B**.

[00143] With continued reference to **FIG. 4**, the outlet fluid pathway **314** may extend from the internal chamber **320** substantially perpendicular to the interior wall **322** and the fluid vortex flow path **B**, such that the fluid vortex flow path **B** flows transversely across an opening **315** of the outlet fluid pathway **314**. As such, at least some of the injection fluid in the fluid vortex flow path **B** flows past the opening **315** and back toward the opening **313** of the fluid inlet pathway **312** to sustain the fluid vortex.

[00144] With continued reference to **FIG. 4**, the internal fluid vortex may suspend one or more air bubbles **400** in the internal chamber **320** during an injection procedure executed by the fluid injector system **2000**. As injection fluid is introduced into the internal chamber **320** via the inlet fluid pathway **312**, any air bubbles **400** present in the incoming injection fluid migrate toward a low pressure region **LP** formed by the internal fluid vortex at a center of the fluid vortex flow path **B**. The injection fluid flowing in the fluid vortex flow path **B** form a boundary that at least temporarily suspends the one or more air bubbles **400** within the low pressure region and at least temporarily delays passage of the one or more air bubbles **400** toward the outlet fluid pathway **314**. The one or more air bubbles **400** suspended in the low pressure region **LP** may coalesce to form one or more larger air bubbles **402**. The interior wall **322** may be shaped to induce recirculation of the injection fluid into the vortex flow path **B**, and to induce the one or more air bubbles **400** into a tighter formation within the vortex flow path **B**. Even so, during the course of the injection the one or more larger air bubbles **402** may be sheared or shredded by fluid forces into smaller bubbles **404** that can migrate outside of vortex flow path **B**.

[00145] With continued reference to **FIG. 4**, in the injection position, the housing **310** is oriented such that the outlet fluid pathway **314** extends substantially vertically downward from the internal chamber **320**. As such, a flow direction **C** of injection fluid flowing out of the internal chamber **320** is substantially aligned with a direction of gravity **G**. As air is buoyant relative to the injection fluid, buoyancy of air bubbles **400**, **402** in the internal chamber **320** induces the one or more air bubbles **400**, **402** to tend to rise opposite the direction of gravity **G** toward an upper region of the internal chamber **320**, and therefore the air bubbles **400**, **402** tend

to remain suspended in the internal fluid vortex in the internal chamber **320** for a longer period of time. Further, even the sheared air bubbles **404** which cross the boundary formed by the fluid vortex flow path **B** are induced by buoyancy to tend to flow opposite the direction of gravity **G** and thus are further delayed from moving through the outlet fluid pathway **314**.

[00146] In some embodiments, at least a portion of the outlet fluid pathway **314** may have a cross-sectional diameter **Do** greater than a cross-sectional diameter **Di** of the inlet fluid pathway **312**. The greater diameter **Do** of the outlet fluid pathway **314** may reduce flow velocity at the outlet fluid pathway **314** of fluid exiting the internal chamber **320**. The reduced flow velocity consequently reduces the drag forces on the bubbles **404** outside the boundary formed by the fluid vortex flow path **B**, such that the buoyancy of the bubbles **404** may tend to overcome the drag forces inducing the bubbles **404** toward the outlet fluid pathway **314**. As a result, the bubbles **404** may be at least temporarily delayed from flowing out of outlet fluid pathway **314**.

[00147] With continued reference to **FIG. 4**, in some embodiments, the diameter **Di** of the inlet fluid pathway **312** may be selected to control the flow velocity of the injection fluid, including air bubbles **400** contained therein, into the internal chamber **320**. In particular, reducing the diameter **Di** increases the flow velocity. The diameter **Di** of the inlet fluid pathway **312** may be selected to produce a relatively high flow velocity, which has the effect of shredding the one or more air bubbles **400**. In some embodiments, the diameter **Di** of the inlet fluid pathway **312** may be approximately 3.7 mm (0.145 inches).

[00148] Referring again to **FIG. 5**, the air bubble suspension apparatus **300** is shown in the priming position for performing a priming or purging operation in which fluid is injected to prime/purge the air bubble suspension apparatus **300** and the associated fluid paths **210A**, **210B** prior to an injection procedure to remove any air from the air bubble suspension apparatus **300** and the associated fluid paths **210A**, **210B**. In the priming position, the housing **310** is oriented such that the inlet fluid pathway **312** and the outlet fluid pathway **314** extend substantially vertically upward from the internal chamber **320**. As such, the flow direction **A** of injection fluid flowing into the internal chamber **320** through inlet fluid pathway **312** is substantially in line with the direction of gravity **G**. The diameter **Di** of the inlet fluid pathway **312** may be sufficiently small that fluid flow velocity in the inlet fluid pathway **312** can carry the air bubbles **400** against the direction of buoyancy of the air bubbles **400**. That is, the flow velocity through the diameter **Di** generates sufficient drag force on the one or more bubbles **400** to overcome the force of the buoyant nature of the air bubbles **400** and drags the into the internal chamber **329**. As a result, the one or more bubbles **400** are transported by the injection fluid into the internal chamber **320**.

[00149] In the priming position, the outlet fluid pathway **314** also extends substantially vertically upward from the internal chamber **320**, such that the flow direction **C** of injection fluid flowing out of the internal chamber **320** is substantially opposite the direction of gravity **G**. Buoyancy of the air bubbles **400** in the internal chamber **320** induces the air bubbles **400**, **402** to float upward from the internal fluid vortex through the outlet fluid pathway **314**, working in concert with the drag associated with the fluid flow and thereby purging the air bubble suspension apparatus **300** of air bubbles **400**.

[00150] With continued reference to **FIGS. 3-5** the air bubble suspension apparatus **300** may include a connector arm **360** extending from the housing **300**. The connector arm **360** may be configured for connection to the injector housing **12** or other feature associated with the flow path or injector (see **FIGS. 1-2**). In particular, the connector arm **360** may be configured to interface with an actuator in communication with the controller **900** (see **FIG. 2**) of the fluid injector system **2000**. The controller **900** may be programmed or configured to rotate the air bubble suspension apparatus **300** between the injection position and the priming position via the connector arm **360** according to an injection protocol. Alternatively, the connector arm **360** may be configured to attach to the fluid injector system in either the injection or priming position and may be configured for a user to manually rotate the air bubble suspension apparatus **300** between the injection position and the priming position via the connector arm **360**, for example in response to a prompt by the system on a GUI, to prepare the fluid injector for a fluid injection procedure.

[00151] Referring now to **FIG. 6**, an embodiment of the air bubble suspension apparatus **300** is shown. The embodiment of the air bubble suspension apparatus shown in **FIG. 6** may be substantially similar to the embodiment shown in **FIGS. 3-5**, and only the differences therebetween will be discussed below. The embodiment of the air bubble suspension apparatus **300** shown in **FIG. 6** may include an air purging valve **350** on the housing **310** in fluid communication with the internal chamber **320**. The air purging valve **350** may particularly be disposed in fluid communication with the uppermost region of the internal chamber **320**. The air purging valve **350** may be used to drain air accumulated in the internal chamber **320**, particularly after completion of an injection procedure when using a multi-patient setup for conducting multiple sequential injection sequences using a multi-patient disposable set and a single patient disposable set. The air purging valve **350** may be set to a closed position during performance of the injection procedure such that any air bubbles **400**, **402** present in the injection fluid are suspended in the internal chamber **320** in the same manner described in

connection with **FIGS. 3-5**. Upon completion of an injection procedure and before initiation of a subsequent injection procedure, the internal fluid vortex and the vortex flow path **B** (shown in **FIG. 4**) dissipate due to the absence of fluid flow into the internal chamber **320**. As such, the vortex flow path **B** (shown in **FIG. 4**) no longer presents a flow boundary to the one or more coalesced air bubbles **402** suspended in the internal chamber **320**. The one or more coalesced air bubbles **402** may thus buoyantly float to the uppermost region of the internal chamber **320** adjacent the air purging valve **350**. The air purging valve **350** may be moved to an open position, either manually by an operator or automatically by the controller **900** such that the one or more coalesced air bubbles **402** may flow out of the internal chamber **320** via the air purging valve **350**, for example with a low fluid flow into the chamber to replace the volume of the purged air with fluid. In some embodiments, an outlet of the air purging valve **350** may be connected to a vacuum source, such as a hand syringe (not shown), to assist in removing the one or more coalesced air bubbles **402** from the internal chamber **320**. After the one or more coalesced air bubbles **402** are removed from the internal chamber **320**, the air purging valve **350** may be returned to the closed position in preparation for a subsequent injection procedure. Air purging valve **350** may be a stopcock, pinch valve, or the like.

[00152] With continued reference to **FIG. 6**, some embodiments the air bubble suspension apparatus **300** may include an adjustable valve **352** associated with the inlet fluid pathway **312** and/or an adjustable valve **354** associated with the outlet fluid pathway **314**. The adjustable valve **352** may be configured to change a cross-sectional area of the inlet fluid pathway **312**, and the adjustable valve **354** may be configured to change a cross-sectional area of the outlet fluid pathway **314**. Reducing the cross-sectional area of the inlet fluid pathway **312** and/or the outlet fluid pathway **314** increases flow velocity, whereas increasing the cross-sectional area of the inlet fluid pathway **312** and/or the outlet fluid pathway **314** reduces flow velocity. In some embodiments, it may be desirable to increase the cross-sectional area of the inlet fluid pathway **312**, thereby reducing flow velocity through the inlet fluid pathway **312**, as the reduced flow velocity may be less likely to dislodge air bubbles adhered to surfaces of the inlet fluid pathway **312**. In some embodiments, it may be desirable to increase the cross-sectional area of the outlet fluid pathway **314**, thereby reducing flow velocity through the outlet fluid pathway **314**, as the reduced flow velocity may be less likely to carry air bubbles from the fluid vortex **402** through the outlet fluid pathway **314**. The adjustable valves **352**, **354** may be stopcocks, pinch valves, or the like.

[00153] Referring now to **FIGS. 7-8**, an embodiment of the air bubble suspension apparatus **300** is shown. The embodiment of the air bubble suspension apparatus **300** shown in **FIGS. 7-**

8 may be substantially similar to the embodiments shown in **FIGS. 3-6**, and only the differences will be discussed below. The embodiment of the air bubble suspension apparatus 300 shown in **FIGS. 7-8** may include a recess 326 defined in the interior wall 322 and extending radially outward from an upper most region of the internal chamber 320 substantially opposite the outlet fluid pathway 314. The recess 326 may receive and retain one or more air bubbles 408. The recess 326 may be particularly adapted to receive and retain one or more air bubbles 408 in the form of microbubbles generated by outgassing of a medical fluid. In some embodiments, an air purge valve 350 such as described in connection with **FIG. 6** may be disposed on recess 326 such that the one or more air bubbles 408 accumulated in the recess 326 can be drained from the recess 326.

[00154] Referring now to **FIGS. 9-14**, an embodiment of the air bubble suspension apparatus 300 is shown. The embodiment of the air bubble suspension apparatus 300 shown in **FIGS. 9-14** may include several common features and components with the embodiments shown in **FIGS. 3-8**, and any elements not specifically described in connection with **FIGS. 9-14** are understood to be substantially similar to like elements of the embodiments of **FIGS. 3-8**. In the embodiment of the air bubble suspension apparatus 300 shown in **FIGS. 9-14**, the housing 310 includes a screen 328 dividing the internal chamber 320 into an inlet portion 332 and an outlet portion 334. Various embodiments of screen 328 are described herein in relation to **FIGS. 19-24**. The screen 328 may be disposed proximal to the outlet fluid pathway 314. The screen 328 may include at least one aperture 340 providing fluid communication between the inlet portion 332 and the outlet portion 334. Injection fluid flowing into the internal chamber 320 from the inlet fluid pathway 312 must subsequently flow through the at least one aperture 340 of the screen 328 to reach the outlet fluid pathway 314. In some embodiments, the screen 328 may include at least one funnel shaped aperture 342 defining the at least one aperture 340. The funnel 342 may taper from a maximum cross-sectional area adjacent the inlet portion 332 of the internal chamber 320 to a minimum diameter extending into the outlet portion 334 of the internal chamber 320. In some embodiments, at least a portion of the screen 328 may have a hydrophilic coating that induces air bubbles in the injection fluid to adhere to screen 328, and at least temporarily delaying the flow of such air bubbles toward outlet fluid pathway 314.

[00155] With continued reference to **FIGS. 9-14**, the air bubble suspension apparatus 300 may further include an extension tube 370 in fluid communication with and extending from the inlet fluid pathway 312 into the internal chamber 320. The extension tube 370 may include a tip 372 spaced apart from and past the flow axis of the outlet fluid pathway 314 such that the

injection fluid flowing into the internal chamber 320 via the extension tube 370 is directed away from the outlet fluid pathway 314. In some embodiments, the extension tube 370 may extend past the at least one aperture 340 in the screen 328 causing injection fluid flowing into the internal chamber 320 from the inlet fluid pathway 312 to flow into the vortex flow path B prior to reaching the at least one aperture 340. The inlet portion 332 of the internal chamber 320 may be at least partially hemispherical or domed where the vortex flow path B flows along the interior wall 322 of the internal chamber 320.

[00156] With continued reference to FIGS. 9-14, the inlet fluid pathway 312 and the extension tube 370 may be oriented at an acute angle relative to the outlet fluid pathway 314 such that injection fluid entering the internal chamber 320 from the extension tube 370 is directed away from the opening 315 of the outlet fluid pathway 314.

[00157] With reference to FIGS. 10-13, a sequence showing an embodiment of a bubble suspension effect within the internal chamber 320 during performance of an injection procedure is shown. Referring first to FIG. 10, injection fluid may flow in the direction A through the inlet fluid pathway 312 and the extension tube 370 into the internal chamber 320. One or more air bubbles 400 may be transported with the injection fluid into the internal chamber 320. The orientation of the extension tube 370 directs the injection fluid and the one or more bubbles 400 into the vortex flow path B. In addition, the buoyancy of the one or more bubbles 400 relative to the injection fluid inhibits flow of the one or more air bubbles through the at least one aperture 340 in the screen 328 toward the outlet fluid pathway 314.

[00158] Referring now to FIG. 11, as the injection fluid flows in the vortex flow path B, the one or more air bubbles 400 may migrate towards the low pressure region LP at the center of the vortex flow path B, thereby becoming at least temporarily suspended within the internal chamber 320. Further, the one or more air bubbles 400 may coalesce into one or more larger volume coalesced air bubbles 402 within the low pressure region LP, while injection fluid and additional air bubbles 400 continue to enter the internal chamber 320 via the extension tube 370 (see FIG. 12).

[00159] FIG. 13 shows the air bubble suspension apparatus 300 after fluid flow into the internal chamber 320 has stopped, for example after completion of the injection procedure. With no new injection fluid being introduced into the internal chamber 320 to sustain the internal fluid vortex, the vortex flow path B (shown in FIGS. 9-12) dissipates and no longer presents a flow boundary to the one or more coalesced air bubbles 402 suspended in the internal chamber 320. The one or more coalesced air bubbles 402 may thus float to the uppermost

region of the internal chamber 320 due to buoyancy of the one or more coalesced air bubbles 402 relative to the injection fluid. In some embodiments, the air bubble suspension apparatus 300 may include an air purging valve 350 (substantially as described herein in connection with FIG. 6) in fluid communication with the uppermost region of the internal chamber 320 to facilitate removal of the one or more coalesced air bubbles 402 from the internal chamber 320 for example between two injection procedures when a multi-patient injection sequence is used.

[00160] With continued reference to FIGS. 9-14, the air bubble suspension apparatus 300 may be rotated approximately 180° from the injection position shown in FIGS. 10-13 to the priming position shown in FIG. 14. In the injection position, the outlet fluid pathway 314 extends substantially vertically downward from the internal chamber 320. As such, a flow direction C of injection fluid flowing out of the internal chamber 320 is substantially aligned with a direction of gravity G. As air is buoyant relative to the injection fluid, buoyancy of air bubbles 400, 402 in the internal chamber 320 induces the one or more air bubbles 400, 402 to tend to float opposite the direction of gravity G toward an upper region of the internal chamber 320, and therefore the air bubbles 400, 402 tend to remain suspended in the internal fluid vortex in the internal chamber 320. Further, even air bubbles which cross the boundary formed by the fluid vortex flow path B are induced to flow opposite the direction of gravity G and through the screen 328 and thus are further delayed from reaching the outlet fluid pathway 314.

[00161] In the priming position, shown in FIG. 14, the outlet fluid pathway 314 extends substantially vertically upward from the internal chamber 320 such that the flow direction C of injection fluid flowing out of the internal chamber 320 is substantially opposite the direction of gravity G. Buoyancy of air bubbles 400, 402 in the internal chamber 320 induces the air bubbles 400, 402 to flow from the chamber 320 through the outlet fluid pathway 314, thereby purging the air bubble suspension apparatus 300 of air.

[00162] With reference to FIG. 9, the air bubble suspension apparatus 300 may include a connector arm 360 extending from the housing 300. The connector arm 360 may be configured for connection to the injector housing 12 or other feature associated with the flow path or injector system 2000 (see FIGS. 1-2). In particular, the connector arm 360 may be configured to interface with an actuator in communication with the controller 900 (see FIG. 2) of the fluid injector system 2000. The controller 900 may be programmed or configured to rotate the air bubble suspension apparatus 300 between the injection position and the priming position via the connector arm 360 according to an injection protocol. Alternatively, the connector arm 360 may be configured to attach to the fluid injector system in either the injection or priming

position and may be configured for a user to manually rotate the air bubble suspension apparatus 300 between the injection position and the priming position via the connector arm 360, for example in response to a prompt by the system on a GUI 11, to prepare the fluid injector for a fluid injection procedure.

[00163] Referring now to FIGS. 15 and 16, an embodiment of the air bubble suspension apparatus 300 is shown. The embodiment of the air bubble suspension apparatus 300 shown in FIGS. 15 and 16 may include many common features and components with various embodiments shown in FIGS. 3-13, and any elements not specifically described in connection with FIGS. 15 and 16 are understood to be substantially similar to like elements of any of the embodiments of FIGS. 3-13. In the embodiment of the air bubble suspension apparatus 300 shown in FIGS. 15 and 16, the housing 310 may be formed on the first housing section 302 and the second housing section 304, of which the first housing section 302 includes the inlet fluid pathway 312, extension tube 370, and the outlet fluid pathway 314. The inlet fluid pathway 312 may extend at an acute angle relative to the outlet fluid pathway 314. The second housing section 304 may be hemispherical or domed such that the vortex flow path B flows along the interior wall 322 of the internal chamber 320 in a circular or otherwise continuous manner. The first housing section 302 may include a flange 306 configured to receive an end feature 308, for example a lip, of the second housing section 304. In some embodiments, the flange 306 may be provided on the second housing section 304 and the end feature 308 may be provided on the first housing section 302. The first housing section 302 and the second housing section 304 may be joined via an adhesive, laser welding, ultrasonic welding, or the like.

[00164] With continued reference to FIGS. 15 and 16, the extension tube 370 may extend past the opening 315 of the outlet fluid pathway 314 such that injection fluid flowing into the internal chamber 320 is directed into the vortex flow path B away from the outlet fluid pathway 314. As with the embodiments shown in FIGS. 3-13, the vortex flow path B creates a boundary that at least temporarily delays passage of one or more air bubbles 400 suspended in the internal chamber 320 to the outlet fluid pathway 314. In some embodiments, the opening 315 of the outlet fluid pathway 314 may be positioned relative to the extension tube 370, for example underneath the extension tube 370, such that the extension tube 370 creates a flow obstruction to fluid and/or air bubbles 400 flowing toward the outlet fluid pathway 314.

[00165] In certain embodiments, the inner diameter of the inlet fluid pathway 312 may be tapered such that a proximal cross-sectional area A_p of the upstream inlet fluid pathway 312 is smaller than a distal cross-sectional area A_d of the downstream inlet fluid pathway 312. In

some embodiments, the proximal cross-sectional area **A_p** may be substantially circular, and the distal cross-sectional area **A_d** may be substantially elliptical or oval. In some embodiments, by increasing the downstream cross-sectional area **A_d** relative to the upstream cross-sectional area **A_p**, the fluid flow velocity (for example between approximately 0.1 mL/second and 30 mL/second) in the inlet fluid pathway **312** may slow, allowing air bubbles **410** in the inlet fluid pathway **312** to adhere to a sidewall **317** of the larger cross-sectional area **A_d**, for example by surface tension. The reduced fluid flow velocity in the inlet fluid pathway **312** resulting from the enlarged distal cross-sectional area **A_d** may not be sufficient to immediately dislodge the adhered air bubbles **410** from the sidewall **317**. That is, the adhesion force of the air bubbles **410** to the sidewall **317** may be greater than the force exerted on the air bubbles **410** by the injection fluid flowing through the distal cross-sectional area **A_d**. As such, the air bubbles **410** are at least temporarily delayed in flowing into the internal chamber **320** and thus delayed flowing out fluid outlet pathway **314**. In some embodiments, the enlarged distal cross-sectional area **A_d** of the fluid inlet pathway **312** may allow injection fluid to flow around the air bubbles **410** adhered to the sidewall **317**, rather than flowing into and potentially dislodging the air bubbles **410** adhered to the sidewall **317**. In some embodiments, the enlarged distal cross-sectional area **A_d** of the fluid inlet pathway **312** may allow the air bubbles **410** to adhere to the sidewall **317** at least partially outside the primary flow path of the injection fluid through the fluid inlet pathway **312**. In some embodiments, the inner surface of fluid inlet pathway **312** may be configured to attract and adhere air bubbles, such as by a surface treatment applied to the sidewall **317**. Such features regarding different cross-sectional areas of the fluid inlet pathway **312** are also applicable to other embodiments of the air bubble suspension apparatus **300** described herein.

[00166] With continued reference to **FIGS. 15** and **16**, the air bubble suspension apparatus **300** may be rotated approximately 180° from the injection position shown in **FIG. 15** to the priming position, analogous to **FIGS. 5** or **14**. In the injection position, the outlet fluid pathway **314** extends substantially vertically downward from the internal chamber **320**. As such, a flow direction **C** of injection fluid flowing out of the internal chamber **320** is substantially aligned with a direction of gravity **G**. As air is buoyant relative to the injection fluid, buoyancy of air bubbles **400**, **402** in the internal chamber **320** induces the one or more air bubbles **400**, **402** to tend to float opposite the direction of gravity **G** toward an upper region of the internal chamber **320**, and therefore the air bubbles **400**, **402** remain suspended in the internal fluid vortex in the internal chamber **320**. Further, even air bubbles which cross the boundary formed by the fluid

vortex flow path **B** are induced to flow opposite the direction of gravity **G** and through the screen **328** and thus are further delayed from reaching the outlet fluid pathway **314**.

[00167] In the priming position, the outlet fluid pathway **314** extends substantially vertically upward from the internal chamber **320** such that the flow direction **C** of injection fluid flowing out of the internal chamber **320** is substantially opposite the direction of gravity **G**. Buoyancy of air bubbles **400**, **402** in the internal chamber **320** induces the air bubbles **400**, **402** to flow from the chamber **320** through the outlet fluid pathway **314**, thereby purging the air bubble suspension apparatus **300** of air.

[00168] With continued reference to **FIGS. 15** and **16**, the air bubble suspension apparatus **300** may include a connector arm **360** extending from the housing **300**. The connector arm **360** may be configured for connection to the injector housing **12** or other feature associated with the flow path or injector system **2000** (see **FIGS. 1-2**). In particular, the connector arm **360** may be configured to interface with an actuator in communication with the controller **900** (see **FIG. 2**) of the fluid injector system **2000**. The controller **900** may be programmed or configured to rotate the air bubble suspension apparatus **300** between the injection position and the priming position via the connector arm **360** according to an injection protocol. Alternatively, the connector arm **360** may be configured to attach to the fluid injector system in either the injection or priming position and may be configured for a user to manually rotate the air bubble suspension apparatus **300** between the injection position and the priming position via the connector arm **360**, for example in response to a prompt by the system on a GUI **11**, to prepare the fluid injector for a fluid injection procedure.

[00169] Referring now to **FIGS. 17-18**, an embodiment of the air bubble suspension apparatus **300** is shown. The embodiment of the air bubble suspension apparatus **300** shown in **FIGS. 17-18** may include many common features and components with various embodiments shown in **FIGS. 3-16** and particularly **FIGS. 9-14**, and any elements not specifically described in connection with **FIGS. 17-18** are understood to be substantially similar to like elements of any of the embodiments of **FIGS. 3-16**. In the embodiment of the air bubble suspension apparatus **300** shown in **FIGS. 17-18**, the housing **310** may be formed by a first housing section **302** and a second housing section **304**, of which the first housing section **302** includes the inlet fluid pathway **312**, extension tube **370**, and the outlet fluid pathway **314**. The inlet fluid pathway **312** may extend at an acute angle relative to the outlet fluid pathway **314**. The second housing section **304** may be hemispherical or domed such that the fluid vortex flow path **B** flows along the interior wall **322** of the internal chamber **320** in a circular or otherwise

continuous manner. The first housing section **302** may include a flange **306** configured to receive an end feature **308**, for example a lip, of the second housing section **304**. In some embodiments, the flange **306** may be provided on the second housing section **304** and the end feature **308** may be provided on the first housing section **302**. The first housing section **302** and the second housing section **304** may be joined via an adhesive, laser welding, ultrasonic welding, or the like.

[00170] With continued reference to **FIGS. 17-18**, a screen **328** may be provided between the first housing section **302** and the second housing section **304**. In some embodiments, the screen **328** may be received within the flange **306** such that the end feature **308** retains the screen **328** in position between the first housing section **302** and the second housing section **304**. The screen **328** may divide the internal chamber **320** into an inlet portion **332** and an outlet portion **334**. The screen **328** may include at least one aperture **340** (as shown in **FIGS. 19-24**) providing fluid communication between the inlet portion **332** and the outlet portion **334**. Injection fluid flowing into the internal chamber **320** from the inlet fluid pathway **312** must subsequently flow through the at least one aperture **340** of the screen **328** to reach the outlet portion **334** and outlet fluid pathway **314**. In some embodiments, the screen **328** may have a hydrophilic coating that induces air bubbles **400** in the injection fluid to adhere to the screen **328**, for example, by increasing surface tension or adhesion therebetween, and thereby at least temporarily further delaying the flow of such adhered air bubbles **400** toward the outlet fluid pathway **314**. The extension tube **370** may be positioned within the internal chamber **320** such that injection fluid entering the internal chamber is directed toward the vortex flow path **B** and away from the one or more apertures **340** of the screen **328**. For example, the one or more apertures **340** of screen **328** may be located on a portion of screen **328** proximal to the distal outlet of extension tube **370**.

[00171] Referring now to **FIGS. 19-24** various embodiments of the screen **328** are shown which are suitable for use in embodiments of the air bubble suspension apparatuses **300** described herein in connection with **FIGS. 9-13** and **17-18**. Referring to **FIG. 19**, screen **328** may include a plurality of apertures **340** distributed substantially uniformly over screen **328**.

[00172] Referring next to **FIGS. 20-24**, the screen **328** may include a solid portion **380** impermeable to fluid and air, and one or more apertures **340** located outside of the solid portion **380**, for example located on portion of screen **328** proximal to the distal outlet of extension tube **370** when assembled. The screen **328** may be positioned in the air bubble suspension apparatus **300** such that the solid portion **380** is adjacent the extension tube **370**. Injection fluid

entering the internal chamber 320 via the extension tube 370 must therefore enter the vortex flow path **B** and circulate within the internal chamber 320 at least once prior to reaching the one or more apertures 340. In the embodiment shown in **FIG. 20**, the solid portion 380 occupies approximately one half of the screen 328 and the one or more apertures 340 occupy approximately one half of the screen 328. In the embodiment shown in **FIG. 21**, the solid portion 380 occupies a larger proportion of the screen 328 than the one or more apertures 340. In some embodiments, the one or more apertures 340 may be arranged in any pattern such as a grid, arc, or line. In some embodiments, the one or more apertures 340 may be non-uniformly distributed over the screen 328.

[00173] In the embodiment shown in **FIG. 22**, the screen 328 includes a single aperture 340 offset from a centerline **CL** of the screen 328. The solid portion 380 occupies the remainder of the screen 328. Offsetting the aperture 340 from the centerline **CL** of the screen 328 may force air bubbles in the internal chamber 320 (see **FIGS. 17-18**) to change direction in order to reach and pass through the aperture 340, thereby further delaying the flow of air bubbles out of the air bubble suspension apparatuses 300.

[00174] Referring next to **FIG. 23**, the screen 328 may include at least one funnel 342 defining the at least one aperture 340. The funnel 342 may taper from a maximum cross-sectional area adjacent the inlet portion 332 of the internal chamber 320 to a minimum diameter extending into the outlet portion 334 of the internal chamber 320 (see **FIGS. 9-14** and **17-18**).

[00175] Referring next to **FIG. 24**, in some embodiments of screen 328 each of the one or more apertures 340 may be partially obstructed by a hood 344. Each hood 344 may extend from the screen 328 into the inlet portion 332 of the internal chamber 320 (see **FIGS. 17-18**), and against the fluid flow direction such that fluid and any associated air bubbles in the inlet portion 332 must flow around the hood 344 to pass through the associated aperture 340. In some embodiments, the hoods 344 may be configured such that air bubbles adhere to the hoods 344, for example via surface tension, to delay flow of air bubbles out of the inlet portion 332.

[00176] In all of the embodiments of the screen 328 shown in **FIGS. 19-24**, the screen 328 may have a hydrophilic coating that induces air bubbles in the injection fluid to adhere to the screen 328, and thereby at least temporarily delaying the flow of such air bubbles toward the outlet fluid pathway 314. In various embodiments, other surfaces of the internal chamber 320 may be at least partially coated with a hydrophilic coating. Further, any portion of the screen 328 or the various features thereof may be configured such that air bubbles adhere to the screen 328, for example via surface tension, to delay flow of the air bubbles through the one or more

apertures **340**. In some embodiments, the screen **328** may be a mesh, for example made from a material that readily adheres air bubbles to the surface thereof.

[00177] According to certain embodiments, the change in fluid pressure across the screen **328** may be substantially zero, so that there is no significant change in fluid velocity at the screen **328** that may dislodge any air bubbles adhered to the screen **328**. Instead, the injection fluid may freely flow through other apertures **340** or pathways in the screen instead of dislodging any air bubbles adhered to the screen **328**. For example, the volume of inlet portion **332** (see **FIGS. 17-18**) upstream of the screen **328** may be substantially the same as the volume of outlet portion **334** (see **FIGS. 17-18**) immediately downstream of the screen **328** so that there is no significant change in fluid pressure due to flow path restriction.

[00178] It should be understood that features of the various embodiments of the screen **328** shown in the embodiments of **FIGS. 19-24** may be combined with one another and still fall within the scope of the present disclosure.

[00179] Referring now to **FIG. 25**, various embodiments of the air bubble suspension apparatus **300** may include a generally cylindrical housing **310** from which the inlet fluid pathway **312** and the outlet fluid pathway **314** extend. The inlet fluid pathway **312** and the outlet fluid pathway **314** may be in fluid communication with opposing ends of the internal chamber **320**. As injection fluid is introduced into the internal chamber **320** via the inlet fluid pathway **312** in a direction substantially tangential to the arc of the cylindrical housing **310**, an internal fluid vortex is generated in the form of a spiral or helical vortex flow path **B** flowing along the interior wall **322** of the internal chamber **320**. One or more air bubbles **400** carried by the injection fluid migrate towards the low pressure region **LP** at the center of the vortex flow path **B**. The injection fluid in the vortex flow path **B** forms a boundary at least temporarily preventing the one or more air bubbles **400** from flowing to the outlet fluid pathway **314**. The length of the spiral or helical vortex flow path **B** may be proportional to the height of the housing **310**. Therefore, the height of the housing **310** may be proportional to the time for which flow of the air bubbles **400** is delayed within the internal chamber **320**. Thus, increasing the cylindrical height of housing **310** may result in an increased suspension time of the one or more air bubbles **400** in the helical vortex flow path **B**.

[00180] With continued reference to **FIG. 25**, the air bubble suspension apparatus **300** may be rotated from the injection position to the priming position by the controller **900** (see **FIG. 2**) or manually by a user. In the injection position shown in **FIG. 25**, the air bubble suspension apparatus **300** may be oriented such that the outlet fluid pathway **314** is positioned below the

inlet fluid pathway **312**. As such, buoyancy of one or more air bubbles **400** within the internal chamber **320** causes the one or more air bubbles **400** to float upward in the internal chamber **320**, against the direction of gravity **G** and the direction of vortex flow path **B** and away from the outlet fluid path **314**.

[00181] In the priming position, the air bubble suspension apparatus **300** may be oriented such that the outlet fluid pathway **314** is positioned above the inlet fluid pathway **312** for example by rotation of the air bubble suspension apparatus **300** by approximately 180° around a lateral axis. As such, buoyancy of one or more air bubbles **400** within the internal chamber **320** causes the one or more air bubbles **400** to float upward in the internal chamber **120** toward the outlet fluid path **314**, thereby purging the internal chamber **320** of air under flow of the priming fluid.

[00182] The air bubble suspension apparatus **300** may include a connector arm **360** extending from the housing **300**. The connector arm **360** may be configured for connection to the injector housing **12** or other feature associated with the flow path or injector system **2000** (see **FIGS. 1-2**). In particular, the connector arm **360** may be configured to interface with an actuator in communication with the controller **900** (see **FIG. 2**) of the fluid injector system **2000**. The controller **900** may be programmed or configured to rotate the air bubble suspension apparatus **300** between the injection position and the priming position via the connector arm **360** according to an injection protocol. Alternatively, the connector arm **360** may be configured to attach to the fluid injector system in either the injection or priming position and may be configured for a user to manually rotate the air bubble suspension apparatus **300** between the injection position and the priming position via the connector arm **360**, for example in response to a prompt by the system on a GUI **11**, to prepare the fluid injector for an injection procedure.

[00183] In some embodiments, the distal surface of housing **300** may include a protrusion **384** extending upward into the internal chamber **320**. The protrusion **384** may be approximately domed, conical, and/or a Gaussian surface. The protrusion **384** may extend any height within the internal chamber **320**. In some embodiments, the protrusion **384** may extend up to half of a height of the internal chamber **320**. The protrusion **384** may be configured to obstruct the flow of the one or more air bubbles **400** toward the opening **315** of the outlet fluid pathway **314** by extending into the low pressure region **LP** of the fluid vortex and preventing one or more air bubbles **400** in the low pressure region **LP** from moving downward past the protrusion **384** towards the outlet fluid pathway **314**. The protrusion **384** therefore further suspends the one or

more air bubbles **400** in the internal chamber **320** in tandem with the bubble suspension provided by the fluid vortex.

[00184] In some embodiments, the housing **300** may include a domed or conical recess **326** extending from a proximal surface of the internal chamber **320**, similar in function to the recess **326** of **FIGS. 7-8**. The recess **326** may receive and retain one or more air bubbles **400** floating upward in the internal chamber **320** under the influence of buoyancy to remove the one or more air bubbles **400** from the vortex flow path **B**. The recess **326** may also be adapted to receive and retain one or more air bubbles in the form of microbubbles generated by outgassing of a medical fluid. In some embodiments, an air purge valve **350** as described in connection with **FIG. 6** may be disposed on the housing **300** in fluid communication with the recess **326** such that the one or more air bubbles **400** accumulated in the recess **326** can be removed from the recess **326** as described herein.

[00185] In all embodiments of the air bubble suspension apparatus **300** described herein, the housing **310** may be at least partially constructed of a transparent or semi-transparent light-transmissible material, such as polycarbonate, that may act as a light tube. By directing a light source to the housing **310**, the one or more bubbles **400, 402, 404, 406, 408** can be illuminated such that the operator can more easily discern the presence of air bubbles in the air bubble suspension apparatus **300**.

[00186] It should be understood that features of the various embodiments of the air bubble suspension apparatus **300** shown in the embodiments of **FIGS. 3-25** may be combined with one another and still fall within the scope of the present disclosure.

[00187] While various examples of the present disclosure were provided in the foregoing description, those skilled in the art may make modifications and alterations to these examples without departing from the scope and spirit of the disclosure. For example, it is to be understood that features of various embodiments described herein may be adapted to other embodiments described herein. Accordingly, the foregoing description is intended to be illustrative rather than restrictive. The disclosure described hereinabove is defined by the appended claims, and all changes to the disclosure that fall within the meaning and the range of equivalency of the claims are to be embraced within their scope.