

(51) International Patent Classification:
C07C 1/20 (2006.01) B01J 10/00 (2006.01)(21) International Application Number:
PCT/US2011/052828(22) International Filing Date:
22 September 2011 (22.09.2011)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/385,392 22 September 2010 (22.09.2010) US
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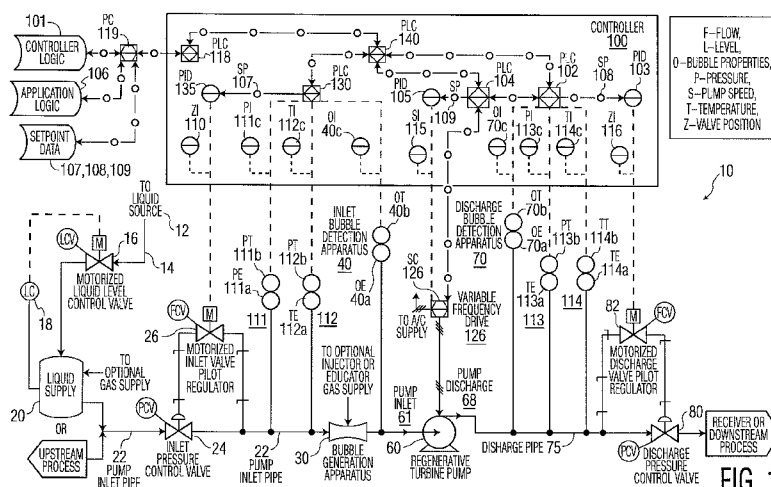
(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report (Rule 48.2(g))

(54) Title: CHEMICAL REACTOR SYSTEM AND METHODS TO CREATE PLASMA HOT SPOTS IN A PUMPED MEDIA



(57) Abstract: Methods and apparatus are disclosed to produce gas vapor bubbles in a liquid media and collapsing the bubble to create a plasma hot spot. Generated bubbles are introduced and collapsing the bubbles results in the partial or total conversion of the internal and boundary layer gas and liquid phase content of the bubble to plasma, ionized gas and ionized liquid. Consequently, a change or increase in the reactivity of the elements and compounds in the gas or liquid phases of the bubble and the surrounding liquid media occurs.

CHEMICAL REACTOR SYSTEM AND METHODS TO CREATE PLASMA HOT SPOTS IN A PUMPED MEDIA

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of the priority of United States Provisional Application Serial No. 61/385,392, filed September 22, 2010, and United States Provisional Application Serial No. 61/385,423, filed September 22, 2010, the entire disclosures of which are expressly incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to pump systems and controllers to create an automated, customizable, chemical reactor.

BACKGROUND OF THE INVENTION

Cavitation caused by ultrasonic and hydrodynamic equipment and techniques has been used for catalysis of many known and well defined endothermic reaction traditionally implemented with high temperature / high pressure processes for many years. The advantage of cavitation as a mechanism of chemical catalysis is the effect of high pressure and temperatures achieved in the domain of effect near the collapsed bubble, the rate of heating being sufficient to start and sustain reactions in aqueous and other solutions. Reactions catalyzed by these means are numerous and include hydrolysis, hydrogenation, transesterification, hydrodesulfurization, polymerizations, protonation, and others. The field of ultrasonic sonochemistry is well established and the techniques of sonication as a catalyst for reduction and oxidation chemistry and numerous organic and inorganic degradation and synthesis processes based on aspects and principles of sonochemistry have been in use in academia for experimentation and production of exotic chemical species for many years.

Implementation of hydrodynamic cavitation and sonochemistry for commercial or industrial scale resource processing, chemical synthesis, waste

recovery, recycling and remediation has arguably been curtailed by the nature of the mechanism used to catalyze reactions for these purposes - cavitation. While single bubble collapse as achieved in single bubble sonoluminescence has been demonstrated as a stable, controlled bubble collapse technique using the methods of ultrasonic cavitation, cavitation as applied in industrial processes almost invariably use multi-bubble cavitation as the catalytic mechanism. This technique, when used at high power levels on raw materials that are variable in composition, such as metal or mineral ores, mining influenced waste water, chemical process effluents, crude oil, waste biomass, surface or ground waters that have stratified and are compositionally variant based on location or depth or as a consequence of long detention, requires significant and continuous modification of process conditions to sustain economically feasible throughput rates. These types of changes to cavitation based mechanism are difficult as both ultrasonic and hydrodynamic cavitation require limited and specific conditions to achieve the high temperature and pressure collapse characteristics required to sustain productive rates of specific reaction catalysis.

Ultrasonic sonochemical processes are dependent on specific frequencies, or specific ultrasonic wave generation surface or horn travel distances or both. Once these variables are optimized in process, changes to reagent composition, ambient pressures, temperature, dissolved gases or other solvent or solute properties often immediately destabilize the bubble cloud formation and collapse, significantly halting or slowing reaction catalysis, rendering the continued application of the technique without process variable changes uneconomic. Adjustments to frequency and amplitude of the ultrasonic field directly affect the properties of the created and collapsing bubble, changing the resonant frequency. The changes to frequency or amplitude, ambient pressure, temperature or other solvent or solute properties may result in condition that, while producing cavitation, produce bubbles with properties of size, resonant frequency or collapse rate that are not optimal for the catalyzing the desired reactions or processing of the feedstock in its current condition. This limitation is due to the dependence of bubble properties on ultrasonic field frequency and amplitude. The bubble properties can be modulated through advanced process control of these process parameters, but only certain frequency and amplitude combinations are effective.

As a consequence, reactive closed loop control of processes based on this mechanism is limited in the scope of variation, detrimentally affecting the economics of processes using this mechanism of reaction catalysis.

There are many hydrodynamic cavitation implementation techniques using a variety of methods to manipulate the formation and collapse of bubbles through pressure and flow control. In addition, custom fittings and shaped orifices and other fixture based techniques for laminar and other unusual flow patterns, with and without closed loop control, have been in used to produce cavitation and catalyze compositional degradations and synthesis. Hydrodynamic cavitation techniques also suffer from restrictions due to optimal condition requirements similar to ultrasonic cavitation, where variation in composition, viscosities, dissolved or suspended solids content, dissolved gasses and other properties of the solvent or solute detrimentally affect the properties and formation of the clouds of bubbles and their subsequent collapse rates, shapes and characteristics.

Both ultrasonic and hydrodynamic cavitation also result in cavitation damage to process circuit elements as conditions for controlled cavitation often result in insipient or other undesirable cavitation effects at or on surfaces or system components, resulting in component wear, significantly affecting process economics.

SUMMARY OF THE INVENTION

The present invention provides a solution to the aforementioned limitations of both hydrodynamic and ultrasonic cavitation. Rather than causing bubble collapse through cavitation, methods and configurations are provided to produce bubbles in a controlled way directly and then, also in a directly controlled way, collapse those bubbles at a specific rate to a specific size. In addition, the bubbles collapse while entrained in fluid flow, preventing undesirable bubble collapse upon process component surfaces. As the formation and collapse of the bubbles occurs independent of optimal flow, pressure, temperature, viscosity, and other solvent and solute properties, and the bubble sizes and collapse rates are directly controlled and not a function of effective ultrasonic amplitudes or frequencies, or fixed pressure or flow established in specialized fittings, this mechanism of bubble collapse can be applied to catalyze reactions economically across a broad range of feedstock variability.

Methods and apparatus are provided to produce gas vapor bubbles in a liquid media and collapsing the bubble to create a plasma hot spot. Generated bubbles are introduced and collapsing the bubbles results in the partial or total conversion of the internal and boundary layer gas and liquid phase content of the bubble to plasma, ionized gas and ionized liquid. Consequently, a change or increase in the reactivity of the elements and compounds in the gas or liquid phases of the bubble and the surrounding liquid media occurs.

In one aspect, methods and apparatus are provided that use the properties of a collapsing gas vapor bubble in a liquid media as a catalyst for reactions between elements or compounds contained in the gas or liquid phases of the bubble, or as a catalyst for reactions between elements or compounds contained in the bubble and the elements or compounds present in the bubble containing liquid media.

In another aspect, methods and apparatus are provided to form gas vapor bubbles in a liquid media and to collapse them in isolation from each other using a controlled hydrodynamically generated pressure pulse of sufficient magnitude, both in rate of pressure increase and ultimate maximum pressure that the bubble vibrates, for example at its eigenfrequency, during collapse for a sufficient interval

of time to permit the formation of a plasma hot spot within the gas and liquid phases of the collapsing bubble.

In yet another aspect, a device is provided that permits concentrations of the gas and liquid phase constituents of the bubbles formed in a pumped media at a pump system inlet to be both directly and indirectly controlled, at the time of formation and during evolution through the various possible bubble sizes through to collapse as the bubbles pass from the pump inlet's low pressure zone through the pump at increasing pressure and out the discharge at a particular controlled maximum pressure.

In still another aspect, a pump system is provided based on a regenerative turbine pump with components arranged to allow controlled bubble production and introduction into the pump inlet and subsequent collapse of the bubbles entrained in the helical flow of the pump within the individual bucket chambers formed by the regenerative turbine pump impeller, wherein the bubbles are collapsed singly without the interfering effects of the collapse of adjacent bubbles.

In another aspect, methods and apparatus are provided for electric motor driven pump speed and pressure control. The pump control system dynamically calculates optimal pump speed and pump system pressures for one of the alternate apparatus configurations or applications, to start and sustain the formation in the pumped media of a specific number of gas vapor bubbles of a particular size and then subsequently collapse the same bubbles at a particular rate to a specific ultimate final bubble size.

The pump control system incorporates a controller that provides a speed setpoint signal to the pump motor drive and pressure setpoint signals used to operate pressure regulating valves controlling pump inlet, casing and discharge pressures.

The following description, with attached diagrams, provides details of the important aspects of the invention. Note, however, that the invention has other useful and novel aspects apart from those discussed. These additional aspects and advantages of the invention will become apparent when considering together the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a piping and instrumentation diagram depicting an exemplary implementation of the apparatus of the present invention including a pump system, subsystems, components and apparatus controller used to create gas vapor bubbles in a pumped liquid media and collapse them to plasma hot spots, in accordance with several aspect of the invention;

FIG. 2 is a piping and instrumentation diagram illustrating an alternate configuration of the bubble generation apparatus subsystem depicted in **FIG. 1**, utilizing a venturi;

FIG. 3 is a piping and instrumentation diagram illustrating another alternate configuration of the bubble generation apparatus subsystem depicted in **FIG. 1**, utilizing an eductor;

FIG. 4 is a piping and instrumentation diagram illustrating yet another alternate configuration of the bubble generation apparatus subsystem depicted in **FIG. 1**, utilizing an inline gas injection;

FIGS. 5a, 5b and 5c are cross-sectional views of the regenerative turbine pump shown in **FIG. 1**;

FIG. 6 is a flowchart showing examples of the controller's logic, including alternate operational sequences as required by the various functional configurations of the apparatus of the present invention, in accordance with several aspects of the invention;

FIG. 7 is a flowchart showing processing steps carried out by an application logic of the present invention;

FIG. 8 is a flowchart showing processing steps carried out by a bubble generation logic of the present invention; and

FIG. 9 is a flowchart showing processing steps carried out by a bubble collapse logic of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The apparatus of the present invention comprises several independent subsystems that can be configured as required by a particular application. The apparatus includes a regenerative turbine pump to effectively entrain and collapse bubbles. **FIG. 1** depicts an exemplary piping and instrumentation layout of the apparatus and its subsystems. In the alternate configurations, the apparatus generates a controlled linear stream of particularly sized bubbles in a pumped liquid media at the inlet, but outside of the casing, of a regenerative turbine pump and then rapidly collapse the bubbles, while entrained in the helical pumped media flow within the blade turbine of the impeller of the regenerative turbine pump so that a plasma hot spot is formed at the center of each collapsed bubble.

Referring to **FIG. 1**, an exemplary apparatus is generally indicated at **10**. **FIG. 1** shows a basic system overview but depending on the bubble generation apparatus used, the basic system may be modified. Proceeding from the apparatus inlet downstream through to the apparatus discharge, the liquid flow into the apparatus begins with an inlet pipe **14** connected between a liquid source **12** and a liquid supply **20** through motorized liquid level control valve **16** using level control **18**. The liquid supply **20** can supply a liquid that can be a single substance, mixture or solution and may be pressurized, heated or chilled. The liquid supply **20** delivery pressure at the pump inlet pipe **22** centerline is preferably equal to or greater than the net positive suction head required (NPSHr) by the regenerative turbine pump **60** at its expected maximum flow for the particular application, and is preferably greater than the expected maximum pressure required by the bubble generation apparatus **30**. The liquid supply delivery pressure can be provided from a tank or other storage medium, allowing connection of the device in a batch process. Alternately, the liquid supply **20** could be an effluent from an upstream process, allowing installation of the apparatus in a production line. The formation of bubbles in the fluid stream and the processing of the fluid stream depends on the initial solution. If the initial solution contains carbon dioxide, a venturi can be used to form bubbles in the fluid. If the initial solution does not contain carbon dioxide, carbon dioxide bubbles can be added to the solution for subsequent processing. Processing of the solution is undertaken

through a closed-loop feedback where process variables are adjusted as solution is processed to optimize processing as will be described.

When the regenerative turbine pump **60** is operating, the pumped liquid media will flow from the liquid supply **20**, through the pump inlet pipe **22**, then through an inlet pressure control valve **24** with a motorized inlet valve pilot regulator **26**. The controller **100** actuates the motorized inlet valve pilot regulator **26** as directed by controller logic **101** and application logic **106** in response to conditions in the pumped media at the pump inlet pipe **22**, such as pressure and temperature measured by inlet pressure and temperature sensors **111** and **112**, respectively. Pump inlet pressure sensor **111** may include pump pressure element **111a**, pump pressure transmitter **111b** and pump pressure indicator **111c**. Temperature sensor **112** may include temperature element **112a**, temperature transmitter **112b** and temperature indicator **112c**. The sensors comprise a detector element to measure and a transmitter to send the value. While the sensors are shown as discrete devices, the sensors could be a single device. Values sent from transmitters are shown to users on indicators, which can be local or remote gauges or computer graphical monitors. An example of a suitable commercially available pressure sensor/transmitter is Ashcroft Xmitr, 0-100 psi, 3". The primary control algorithms, operation and detection sequencing instructions and setpoints or setpoint algorithms, are stored in the controller, which can be a PC, Panel-PC, PLC (programmable logic controller) or some other specific purpose programmable HMI (human-machine interface) device or controller. An example of a suitable commercially available PLC is Allen-Bradley Micrologix 1400 Model 1766-L32BWAA. An example of a suitable commercially available PLC software with PID algorithms is RSLogix 500 Professional. An example of a suitable commercially available PC is HP Compaq dx2450.

The controller **100** calculates and adjusts the pumped liquid media pressure setpoint downstream of the inlet pressure control valve **24** by adjusting the inlet pressure control valve **24** using the motorized inlet valve pilot regulator **26**. These adjustments could be made using the inlet pipe **22** pumped media condition information gathered by the pump inlet pipe **22** sensors **40**, **111**, **112**, regulating pressure as required by the inlet bubble generation apparatus **30** and enabling sustained generation of bubbles of the required size and number for a particular

application. Inlet bubble detection apparatus **40** may include sensor element **40a**, transmitter **40b** and indicator **40c**.

Depending on the specific application and the nature of the pumped media, proper pressure control of the pumped media flowing through the pump inlet pipe **22** may include detection of other parameters of the pumped media's composition or condition, either apart from or in addition to temperature and pressure, such as flow rate, viscosity, two-phase void fraction, salinity, pH, total VOC (Volatile Organic Compound), BOD (Biological Oxygen Demand), or some other property or metric. When detection of conditions other than current pressure and temperature are used by the controller **100** to regulate apparatus inlet pressure, the controller logic **101** and application logic **106** may contain steps that detect and identify the additional sensors and evaluate the values therefrom in conjunction with the measured inlet pressure and temperature, calculating a new position setpoint for the motorized inlet valve pilot regulator **26**, which in turn adjusts the position of the inlet pressure control valve **24**, regulating the pressure in the pump inlet pipe **22** at the bubble generation apparatus **30**. In this way, changes in liquid supply temperature, pressure or other parameter values that occur during the operation of the apparatus, such as a level drop in a liquid supply **20** tank, turbulence in pump inlet pipe **22**, performance change in an upstream connected process, change in pressure of liquid supply **20**, or a change in the flow rate requirements of the downstream subsystems can be detected and compensated for using closed-loop control, maintaining pressure and flow as required by the bubble generation apparatus **30**.

Next, continuing with **FIG. 1**, the pumped media flows from the inlet pressure control valve **24** through the inlet bubble generation apparatus **30**. Bubbles are formed using one or more of at least three alternate possible configurations, although there are other possible effective methods of bubble production that could be adapted for use in the apparatus. It is expected that a useful configuration of the inlet bubble generation apparatus **30** will produce a steady, linear bubble stream in the range of approximately 100 to approximately 9,000 bubbles per second, as required by a particular application, with stable bubble diameters in the range of approximately 0.5 microns to approximately 1 mm, again as required by a particular application. Particular applications could

have different ranges of amounts and sizes of bubbles. Also, it is desirable for the bubble generation apparatus **30** to produce a linear stream of bubbles as opposed to uncontrolled clouds of bubbles produced by some types of bubblers and elements of cavitation reactors, even if the number and size of bubbles in the cloud are controlled. The following three configurations of the bubble generation apparatus **30**, while not representative of all possible alternatives as might be required by a particular application of the apparatus, provides for bubble production in sufficient number, size, and placement, and demonstrate some desirable features of potentially useful alternate bubble generation configurations. There are differences in performance features of the alternate configurations.

Referring now to **FIG. 2**, an alternate configuration of bubble generation apparatus **30** involves a modified apparatus generally indicated at **210**. This configuration uses a large bore venturi **270** installed inline before the inlet bubble detection apparatus **40**, if the system includes a bubble detection apparatus **40**, or in-line before the regenerative turbine pump **60**. In this configuration, the apparatus receives a liquid supply **20** that is sparged at a controlled rate by a compressor **250** with a feedstock gas supply or gas mix **252**, as regulated by the gas supply pressure controller **211**, which controls motorized gas pressure control valve **212**. Consequently the gas supply **252** is dissolved in the liquid supply **20** and the gas-saturated liquid is delivered to the inlet pipe **22** at or above standard pressure. Note that the addition of a gas to the liquid supply **20** may not be required for applications where the liquid supply contains volatile elements or compounds. In these cases the vapor pressure of the liquid might be sufficient for bubbles to form as they pass through the venturi **270** without the addition of an external gas to the liquid supply **20** solution. The liquid supply pressure is detected, transmitted and indicated by the liquid supply sparging gas sensor **254** which may include sensor element **254a**, transmitter **254b** and indicator **254c**. The liquid supply **20** pressure is read by the liquid supply sparging gas compressor speed control programmable logic controller (PLC) **256** and compared to the compressor speed setpoint **258** or the sparged liquid supply pressure setpoint. PLC **256** then retrieves the current compressor speed, recalculates a new compressor speed setpoint **258**, and transmits this together with the liquid supply **20** pressure as the process variable to the liquid supply sparging gas

compressor speed control proportional-integral-derivative controller (PID) **257**. PID **257** sends a ranged analog or digital signal to the compressor speed controller **259** that causes the controller to vary the power frequency delivered to the motor (not shown) of a compressor **250** so that it rotates at the compressor speed setpoint **258**.

As a result of this sparging action, the gas or gas mix supplied is dissolved into the liquid supply as a function of the solubility of the supplied gas **252** in the supplied liquid **20** at the pressure maintained in the liquid supply **20**. The saturated liquid is drawn across the venturi **270** by action of the regenerative turbine pump **60** resulting in a pressure drop in the venturi throat **272**, as controlled by the speed of regenerative turbine pump **60**, pump inlet pipe **22** or discharge pipe **75** pressure regulation, liquid supply pressure or some combination of thereof. As the gas-saturated pumped liquid media passes through the venturi throat **272**, some of the dissolved gas or gasses and some of the pumped liquid media vaporize. Consequently, bubbles are formed with elements or compounds contained in both the gas supply **252** and the liquid supply **20**. The specific gas vapor fractions in a bubble are calculated for a particular application using Bernoulli's equation, considering the dynamic dissolved gas and liquid vapor pressures, the differential pressure caused by the pressure drop across the venturi throat **272**, the velocity of the pumped media, the static operating pressure at the inlet of the bubble generation apparatus **30**, and any other property of the pumped media that can affect the gas vapor composition of the bubbles. This method enables automatic mixing of the dissolved gas and pumped media liquid gas vapor compounds in the bubbles. An example of a venturi for use in the present apparatus is the Venturi Tee made by LASCO Fittings, Inc., Brownsville, Tennessee.

Referring now to **FIG. 3**, a second alternate configuration of the bubble generation apparatus **30** includes a modified apparatus generally indicated at **310**. This configuration uses an eductor **370** installed inline in the pump inlet pipe **22** and outfitted an orifice **372** sized to govern the size and number of the generated bubbles. A gas supply **352** is maintained by a self-contained gas supply pressure controller **353**, and motorized gas pressure control valve **351**, at or above the maximum delivery pressure required by the eductor **370** for a particular

application. Pressure at the eductor orifice **372** is controlled by a motorized gas pressure control valve **374** installed between the gas supply **352** and the eductor **370**, regulating gas delivery pressure. The eductor gas supply pressure sensor **375**, which may include sensor element **375a**, transmitter **375b** and indicator **375c**, sends a ranged analog or digital signal representing the current regulated eductor gas delivery pressure to the eductor gas supply pressure control PLC **376**. PLC **376** reads this current pressure signal and transmits it as the process variable together with the eductor gas supply pressure setpoint **377** to the eductor gas supply pressure control PID **378**. PID **378** continuously recalculates and transmits a new analog or digital position signal to motorized gas pressure control valve **374** indicated by the motorized gas pressure control valve position indicator **379**, maintaining the eductor gas supply pressure setpoint **377**. Bubbles are created with a vapor content controlled directly by adjusting the internal diameter of orifice **372**, the pumped media liquid pressure and the eductor gas supply pressure setpoint **377**. This method is suited for applications where pump inlet pipe **22** or gas supply **352** pressures are low and enables indirect regulation of the gas and pumped liquid media vapor composition of the bubbles.

Continuing now with **FIG. 4**, another alternate configuration of the bubble generation apparatus **30** includes a modified apparatus generally indicated at **410**. This configuration uses a gas injection nozzle **470**, which is sized and shaped to produce bubbles based on flow rate and throughput of the system. The nozzle **470** is installed in the pump inlet pipe **22** line, pointed downstream and axially centered in the pump inlet pipe **22** before the inlet bubble detection apparatus **40** or the regenerative turbine pump **60**, optionally followed by a vortex fitting **472** such as, for example, a standard NIBCO vortex insertion feeder manufactured by NIBCO, Inc., from Elkhart, Indiana, or a Steinen Tan-Jet nozzle, manufactured by Wm. Steinen Mfg. Co., based in Parsippany, New Jersey, to assist bubble entrainment. In this arrangement, a gas supply **452** is connected to a compressor **450** which discharges the gas into a pressure regulated line. Inline gas injection nozzle pressure and compressor speed control PLC **476** reads the ranged analog or digital injector pressure signal from the inline gas injection nozzle pressure sensor **475** which may include element **475a**, transmitter **475b** and indicator **475c**. PLC **476** continuously retrieves the current inline gas injection nozzle pressure

setpoint **477** and recalculates a new pressure setpoint, transmitting a ranged analog or digital signal to the motorized gas pressure control valve **474** that regulates the injection nozzle pressure. If the inline gas injection nozzle pressure setpoint **477** cannot be achieved by the gas supply **452** pressure, as regulated by the gas supply pressure controller **453**, and motorized gas pressure control valve **412**, then PLC **476** starts the compressor **450**, and using the gas injection nozzle pressure **475** as the process variable, upwardly adjusts the inline gas injection nozzle compressor speed setpoint **458** until the inline gas injection nozzle pressure setpoint **477** is fractionally exceeded. Fine downward gas pressure adjustment can be accomplished by changing the pressure setpoint transmitted to the motorized gas pressure control valve **474**. Once PLC **476** calculates a pressure setpoint, it is transmitted to inline gas injection nozzle pressure control PID **478**, with injection nozzle pressure **475** as the process variable. PLC **476** relays the current compressor **450** motor (not shown) speed from the compressor speed controller **459** to inline gas injection nozzle compressor speed control PID **457** along with the current compressor speed setpoint **458**. This method enables bubble generation across a wide range of operating pressures, and direct control of bubble content, size and number by varying the inline gas injection nozzle pressure setpoint **477** or the inline gas injection nozzle **470** shape or size, in addition to the pump inlet pipe **422** pressure as regulated by the inlet pressure control valve **424**.

Referring back to **FIG. 1**, the pumped liquid media containing entrained bubbles passes through the optional inlet bubble detection apparatus **40**. In fixed or low flow applications, or with feedstock that is invariant in composition, it may be sufficient to monitor the bubble generation apparatus **30** operating conditions as reported by inlet pressure **111** and temperature **112** sensors, using a specific inlet bubble generation apparatus **30** configuration. Where such correlations are inadequate, or where bubble production parameter values must be more precisely controlled, additional analog or digital detection of the size and number of bubbles actually created may be required. In these applications, the controller **100** uses controller logic **101** that receives the analog or digital bubble production data signal output from the inlet bubble detection apparatus **40** and, in conjunction with other data from detection inlet sensors **111** and **112**, calculates new operational

parameter values, such as the pressure of the inlet bubble generating apparatus **30** as set by the inlet pressure control valve **24**, or the gas eductor (**FIG. 3, 370**) or injector (**FIG. 4, 470**) line pressure, as used in the alternate bubble generation apparatus **30** configurations, establishing closed-loop bubble production control. The controller logic **101** could be programmed using any suitable high or low-level computer programming language, and could be embodied as computer-executable instructions stored in a computer-readable medium, such as flash memory or other type of non-volatile memory. The inlet bubble detection apparatus **40** can be any one of a number of devices that are designed to produce a ranged analog or digital signal that corresponds to the number and sizes of bubbles present in a particular location in a two phase liquid media, such as an interferometric laser imaging sizer, a broadband sound velocimeter, Doppler Sonography or another acoustic technique for bubble sizing. Properties of the pumped media such as composition, opacity, inclusions, temperature, as well as the size and number of bubbles to be produced and the intended function of the invention will guide the selection of the appropriate inlet bubble detection apparatus **40** to be used in conjunction with a particular application.

Continuing with **FIG. 1**, the pumped liquid media containing the produced bubbles passes from the inlet bubble detection apparatus **40** and enters the regenerative turbine pump **60**. Next, the process water containing the entrained bubbles passes from the inlet bubble detection apparatus **40** and enters the regenerative turbine pump **60**. The turbine pump design with pump inlet, discharge, casing, channel layout, and connecting piping arrangements and low internal clearances enables the regenerative turbine pump to entrain gas bubbles in a helical flow of the pumped water within the pump casing's channel, preventing the bubbles from adhering to or forming on the internal surfaces of the pump or where the pumped bubble containing liquid media flows.

Referring now to **FIG. 5**, the bubbles and pumped liquid media pass through the pump inlet **61**, which preferably has a smooth, straight-walled bore with minimal change in internal diameter across the pumped media flow path and which preferably intersects the casing tangentially, so that turbulence within the pump inlet, and consequently disruption to bubble size and location in the flow path, is minimized. The pumped media then passes into the casing **62** of the

regenerative turbine pump **60** where the pumped liquid media is forced, by containment within the buckets **64** formed by impeller blade **65** within the pump casing's annular space, to flow in a helical pathway **66**. This occurs as the pumped liquid moves with the pump impeller **63** through the pump casing **62**. The pumped liquid media rotates about the axis of the direction of flow, causing an entrained bubble **67** to remain at the center of the flow path, preventing its adhesion to the pump casing's **62** internal surfaces and restraining it to a single impeller bucket **64**.

The rotational speed setpoint of the pump impeller **63**, determined during application design, and then subsequently maintained or adjusted as required by the controller **100** (see **FIG. 1**) during apparatus operation, is set so that the number of impeller buckets **64** that pass by the pump inlet **61** per second closely matches the number of flow entrained bubbles that pass through the pump inlet **61** per second. In addition, the pump speed setpoint and the regulated pump inlet and discharge pressure setpoints are those values that cause the pumped media flow rate to be such that the bubbles are moved singularly into the impeller buckets **64**, minimizing or eliminating the incidence of impeller buckets **64** that contain multiple bubbles or none during operation. Finally, the pump impeller **63** rotational speed and pump discharge **68** pressure are so adjusted and maintained during operation that the bubbles individually entrained in the pumped liquid media flow, and contained within individual impeller buckets **64**, are collapsed as the surrounding pumped liquid flows from the pump inlet **61** to the pump discharge **68** at cut-water **69** and the pressure within the bubble containing impeller buckets **64** increases from the pump inlet **61** pressure to the final regulated pump discharge **68** pressure. In this way the initial and final bubble sizes, rate of bubble collapse, and final collapsed bubble core temperature and pressure, and consequently the resulting changes in the pumped liquid media and bubble content properties, composition or reactivity, are directly and mechanically controlled. The actual rate of bubble collapse is determined by the difference between the initial and final bubble size and the rate of pressure rise within the pump casing **62**. Direct, automatic, mechanical control of these parameter values allows the apparatus function to be modulated, both initially and dynamically during operation for optimal performance of a particular application.

An example of a regenerative turbine pump for use in the present apparatus is the Regenerative Turbine Chemical Pump made by Roth Pump Company, Rock Island, Illinois. Roth regenerative turbine chemical duty pumps provide continuous, high pressure pumping of non-lubricating and corrosive liquids. These regenerative turbine pumps are provided with one piece, machined self-centering impellers for operation with a wide variety of chemicals with process heads up to 1400 ft. (427 m.), 600 psi (40 bar), TDH at 3500 rpm, NPSH from 3 to 14 ft. (0.91 to 4.2 m.), and temperatures to 450°F (232°C). Another example of a regenerative turbine pump for use with the present apparatus is Dynaflo Regeneration Turbine Pump made by Dynaflo Engineering, Middlesex, New Jersey. Another example of a regenerative turbine pump for use with the present apparatus is Model MT5003P3T6 made by Warrender, LTD., Wood Dale, Illinois.

Continuing downstream of the pump casing and referring to **FIG. 1** the pumped liquid media containing partially or totally collapsed bubbles passes out of the pump casing and through the pump discharge **68**. The pump discharge **68** preferably has a smooth, straight-walled bore with minimal change in internal diameter across the pumped media flow path and also preferably intersects the casing tangentially, so that turbulence is minimized.

Continuing with **FIG. 1**, the pumped liquid media passed through the optional discharge bubble detection apparatus **70** which may include sensor element **70a**, transmitter **70b** and indicator **70c**. As with inlet detection, the controller **100** can monitor conditions or properties of the pumped media in order to determine the correct speed setpoint **109** of the regenerative turbine pump **60** and the correct pressure setpoints **108** of discharge pressure control valve **80**. In applications where total collapse of produced bubbles is required, detection and measurement of the number and size of bubbles that remain in the pumped liquid media stream discharged from the regenerative turbine pump **60** can be used to recalculate a correction to the pump speed **109** or the discharge pressure **108** setpoints. In most applications it is expected that the rate of bubble collapse within the regenerative turbine pump **60** will increase as the maximum pump discharge pressure **108** setpoint, as controlled by the regenerative turbine pump **60** impeller (**FIG. 5C**) speed and regulated by the discharge pressure control valve **80**, is increased.

Once bubble generation is underway, the optional discharge bubble detection apparatus **70** is used to detect and measure any bubbles that remain in the pumped media flow downstream of the regenerative turbine pump **60**. If bubbles are detected in the discharge flow, where none should be present, or if bubbles larger than those that should be present are detected, then the discharge pressure setpoint can be increased.

An increase in regenerative turbine pump **60** discharge pressure can be accomplished in at least two ways. First, where the current discharge pressure setpoint, as regulated by the discharge pressure control valve **80**, is less than the shutoff, or maximum, pressure of the regenerative turbine pump **60** while operating at its current speed setpoint, then the discharge pressure control valve **80** is used to increase the discharge pressure setpoint. Second, where the current discharge pressure setpoint is equal to the maximum possible at the current regenerative turbine pump **60** speed setpoint, then the impeller **63** speed setpoint is increased. Consequently, the maximum possible discharge pressure setpoint is increased. Once the regenerative turbine pump **60** impeller **63** speed setpoint is increased, additional upward discharge pressure increase and regulation is accomplished by increasing the discharge pressure setpoint of the discharge pressure control valve **80**. In this way, the discharge pressure setpoint and the regenerative turbine pump **60** speed setpoint can be manipulated independently, allowing a particular application to achieve and sustain a particular discharge pressure setpoint, as required to collapse the generated bubbles, while at the same time varying the regenerative turbine pump impeller **63** speed setpoint. This enables the precise timing of the impeller buckets **64** (**FIG. 5A**) passing by the regenerative turbine pump **60** inlet to the number of bubbles output by the bubble generation apparatus **30**, enabling the aforementioned desired collapse of bubbles singularly in an isolated way at, for example, their eigenfrequencies.

Again, continuing with **FIG. 1**, the pumped liquid media now passes by the discharge pressure **113** and temperature sensors **114**, as well as any other detectors or sensors that are installed to measure the composition or condition of the pumped liquid media in the discharge pipe **75**. The discharge pressure and temperature sensors **113**, **114** may include sensor elements **113a**, **114a**, transmitters **113b**, **114b** and indicators **113c**, **114c**. Finally, the pumped liquid

media flows through the discharge pressure control valve **80** and out of the apparatus. The discharge pressure control valve **80** is configured for regulation of pumped liquid media pressure upstream of the discharge pressure control valve **80**, that is, pressure regulation occurs in the discharge pipe **75** between the regenerative turbine pump **60** and the discharge pressure control valve **80**. The inlet pressure control valve **24** regulates pump inlet pipe **22** pressure downstream of the inlet pressure control valve **24**. In this way, the pressure to collapse the generated bubbles required by a particular application is set and regulated by combined manipulation of the discharge pressure control valve **80** pressure setpoint **108** and the regenerative turbine pump **60** speed setpoint **109**. A receiving vessel or downstream process connection is provided after the discharge pressure control valve **80**.

The pumped liquid media and gas handling subsystems of the apparatus may be outfitted with relief, bypass or other unloader valves (not shown) and other safety devices and features as required by the nature of the particular application. Additionally, inlet and discharge isolation (not shown) and check valves (not shown) should be installed where required to prevent improper flow and to provide for apparatus isolation, testing and service.

Referring still to **FIG. 1**, the controller **100** provides both operation condition detection and control services for the apparatus. In its role as a pump motor control system, the controller **100** generates and transmits to the variable frequency drive **126** motor controller start, stop and other variable frequency drive function commands and the pump motor speed setpoint **109** signal. The variable frequency drive **126** is connected to and provides power for the regenerative turbine pump **60** motor, controlling the motor's rotational speed and consequently the coupled regenerative turbine pump **60** speed as directed by the motor speed control pilot signal received from the controller **100**. In addition to regenerative turbine pump **60** motor control, the controller **100** operates the motorized inlet valve pilot regulator **26** and motorized discharge valve pilot regulator **82**, varying the inlet pressure, as regulated by the inlet pressure control valve **24**, and the discharge pressure, as regulated by the discharge pressure control valve **80**. The controller **100** also monitors and can record apparatus subsystem parameter values received from the pump inlet pipe **22** and discharge pipe **75** sensors **40**, **70**,

111, 112, 113, 114 and recalculates setpoints related to the system's operation as required by a particular application.

The controller logic **101** stored and executed by the controller logic PLC **140** provides the controller **100** and the apparatus operational sequence and other functions. The controller logic **101** can be changed as required to include functions specific to a particular apparatus configuration. **FIG. 1** shows an exemplary set of detectors and controlling devices for implementing the operational methods explained herein. Other configurations of the apparatus are possible using other equipment, detectors and controllers not shown, or not using some of the shown apparatus subsystems or components. To accommodate possible physical configuration changes to the apparatus, the controller logic **101** - those programming instruction pertaining to the installed apparatus and controller **100** device identification, state detection, control and task distribution - can be altered such as by uploading the program to an external computer or device for storage, required modification and subsequent download back to controller logic PLC **140**. Alternately, separate instances of apparatus configuration specific controller logic **101** can be stored locally in the controller **100** or in an external computer or device, to be uploaded or executed as required by the controller logic PLC **140**. Additionally, it may be necessary to change the operational sequence of the apparatus for a particular application. Application logic **106** - such as the order of sensor or detector evaluation, the order of setpoint modification, the algorithms for setpoint modification, or algorithms used to identify and recover from operational fault states - may be stored in or accessible to and executed on the controller logic PLC **140**. As with controller logic **101**, a unique version of application logic **106** can be stored locally in the controller or on an external device or application logic **106** can be uploaded to an external device or computer, modified, and downloaded back to the controller logic PLC **140**. Inlet pressure setpoint **107** and discharge pressure setpoint **108** data that describe operational parameters such as pressure, temperature and bubble properties, and pump motor speed setpoint **109** data, are provided as individual values, independent or dependant values or value ranges or algorithms used to calculate values or value ranges, may be stored with or accessible to controller logic PLC **140** and can be uploaded and downloaded to an external device or computer. In each case,

where data or program code stored in or accessible to the controller logic PLC **140** is to be modified, rather than uploading, modifying and downloading existing setpoint data **107, 108, 109**, controller logic **101** or application logic **106** program code, it is also possible to access and modify this information on or accessible to the controller **100** directly using an external device or computer. In addition, an operator control panel (not shown) can be provided to allow manual control of the apparatus, manual entry of setpoint data **107, 108, 109**, manual manipulation of or interaction with controller logic **101** or application logic **106**, or manual control of invention subsystems or components directly, such as the pressure control valves **24, 80** or the variable frequency drive **126**.

The external link PLC **118** provides a direct connection and controller **100** interface to an external device or computer, direct access to the data and program code stored on or with the controller PLC **140** from an external device, and logic for automated or externally directed upload and download of reduction logic **106** and controller logic **101** and setpoint data **107, 108, 109**. Where the apparatus is part of a larger system, the controller logic **101** can incorporate steps to accept directives from and report operational parameter values and status to an external system, computer or device. In these cases, the external link PLC **118** can be configured and programmed to marshal this external communication and control between the external device or computer and the controller logic PLC **140**.

Note that **FIG. 1** depicts discrete PLCs in the controller **100**, such as one for external link **118** and one for controller logic **140**, as well as others such as inlet pressure control PLC **130**, discharge pressure control PLC **102** and pump motor speed control PLC **104**. These functions could be combined in a single PLC, a personal computer (PC) such as PC **119** or other similar device. In addition, while the external link PLC **118** and controller logic PLC **140**, as well as the other PLC's **130, 102, 104** and PID's including inlet pressure control PID **135**, discharge pressure control PID **103** and pump motor speed control PID **105**, are shown in **FIG. 1** to be incorporated into a single controller, devices performing these functions could be installed in separate locations as part of separate controllers – this alternate control component arrangement may be likely where the apparatus is incorporated into a larger overall process or system. Also, while controller logic **101** and application logic **106** are depicted in **FIG. 1** as residing in and executing

on the controller logic PLC **140**, it is possible that the controller logic **101** could reside in and execute on a different PLC, PC or other similar device than the one that stores and runs application logic **106**, and these separate PLC or alternate devices could also reside in separate controllers. Similar variation in component function distribution, grouping or placement is possible with the other sensor-transmitter-indicator devices such as **40, 70, 110, 111, 112, 113, 114, 135**, PLC **130, 102, 104** and PID **135, 103, 105** as well. The controller **100** component arrangements and functions rendered in **FIG. 1** are exemplary of stand-alone, self-contained operation and control of the apparatus, for use as depicted when the system is configured and connected upstream and downstream as shown, or as a design feature guide for different physical configurations of the invention or where the invention is incorporated as a single element or step in a multi-function or multi-step process. Consequently, in the discussion of the controller **100** component functions contained herein, it should be understood that where a particular PLC, PID or other device with specific functions is discussed, a PC, PLC or other functionally equivalent device could be substituted for the one described. Additionally, discrete functions performed by the described controller **100** component may be performed by another device along with other unrelated functions.

Individual subsystem controls and instrumentation may be grouped in the controller **100** by related function and may be monitored and controlled as a group by a discrete individual PLC, PC or other similar device. This permits discrete subsystem data storage and programming. In this way the addition, configuration change or removal of subsystems or subsystem components requires only the addition, change, reprogramming or deletion of those corresponding elements of the controller **100** directly responsible for the state detection or control of the affected subsystem or component.

Controller logic PLC **140** executes the controller logic **101** and application logic **106** program instructions that direct the operational sequence of the apparatus subsystems, as previously described, and responds to external computer or operator requests. PLC **140** also handles operational sequence interruptions and operational parameter value data requests generated by the subsystem controllers PLC **130**, PLC **102** and PLC **104**. PLC **140** may also be

used for handling and maintaining overall operational status information and requests for this information transmitted from the subsystem controllers and for relaying setpoint and subsystem status information between the apparatus subsystems as they request such data or status for their operation. Operational limit conditions, error states and other events then occur during operation that require the apparatus to change operational mode, halt, reset or communicate an operational or component status or alarm to an operator, external computer or device may also be handled by the controller logic PLC **140**.

The inlet pressure control PLC **130** receives from controller logic PLC **140**, initially and periodically as required, inlet pressure setpoint **107** data, as values, value ranges or as an algorithm used to calculate a setpoint value or value range using pump inlet pipe **22** sensor **40**, **111**, **112** data. The inlet pressure setpoint **107** data values specify, for a particular application, the required pressure and/or temperature of the pumped media and/or the required amount and/or size of bubbles that emit from the bubble generation apparatus **30**, or both. Additionally, inlet pressure setpoint **107** data may be provided for other properties of the pumped media at the pump inlet pipe **22** or of the generated bubbles. Inlet pressure control PLC **130** receives ranged analog or digital signal input from sensor transmitters whose elements are mounted at the bubble generation apparatus **30** inlet, such as the inlet pressure transmitter **111b** and the inlet temperature transmitter **112b**. Inlet pressure control PLC **130** is also connected to and receives a ranged analog or digital signal input from the inlet bubble detection apparatus **40**, which may be interpolated to represent the size and number of bubbles detected. Utilizing inlet pressure control application logic **106** and inlet pressure setpoint **107** data, inlet pressure control PLC **130** monitors pump inlet pipe **22** temperature, pressure, and other properties, as well as bubble number and size, and recalculates continuously during operation the required target inlet pressure setpoint **107**. During operation, the inlet pressure setpoint **107** required to maintain uniform, stable, continuous operation of the bubble generation apparatus **30**, as specified by a particular application, may vary due to pump inlet pipe **22** or discharge pipe **75** turbulence, pumped media flow rate or temperature change, pump speed change, discharge pressure change, or change in another property of the bubbles or pumped media. As these changes occur, the properties

of the generated bubbles may vary outside an application's specified range. Inlet pressure control PLC **130** can calculate a new inlet pressure setpoint **107** expected to mitigate the bubble property changes and restore bubble production to the application's specifications. This processing continues until interrupted by controller logic PLC **140**, which can provide new inlet pressure setpoint **107** data or direct inlet pressure control PLC **130** to set a specific inlet pressure setpoint **107** and stop processing. In addition, the controller **100** can provide panel mounted operators (not shown) and pump inlet pipe **22** sensor indicators - inlet pressure indicator PI **111c**, inlet temperature indicator TI **112c** - that enable manual control of the inlet pressure setpoint **107**. An inlet pressure setpoint **107** input via a panel operator may be processed by controller logic PLC **140** as setpoint data from an external device or computer would be and as a specific inlet pressure setpoint **107** with no additional processing by inlet pressure control PLC **130**.

Once an inlet pressure setpoint **107** is calculated by inlet pressure control PLC **130** it is transmitted together with the current inlet pressure process variable to inlet pressure control PID **135**. PID **135** continuously receives updated inlet pressure process variable and setpoint pressure values. PID **135** then calculates and transmits a ranged analog or digital signal corresponding to the position of the motorized inlet valve pilot regulator **26** required to set the inlet pressure control valve **24** to the inlet pressure setpoint **107**. If the motorized inlet valve pilot regulator **26** is equipped with its own controller, inlet pressure control PID **135** will transmit a ranged analog or digital signal representing the inlet pressure setpoint **107** to the motorized inlet pilot valve's controller, which will in turn calculate the required pilot valve position to set the inlet pressure control valve **24** to the inlet pressure setpoint **107**.

Alternately, controller logic PLC **140** can direct - either as part of its intrinsic logic or as commanded by an external computer or device or operator - inlet pressure control PLC **130** to use the analog or digital signal from the inlet bubble detection apparatus **40** as the inlet pressure control PID **135** process variable. Two sequential operational modes are employed to implement this control technique. First, inlet pressure control PLC **130**, using the aforementioned inlet pressure setpoint **107** handling techniques and in conjunction with inlet pressure control PID **135**, sets the inlet pressure so that the bubble generation apparatus **30**

is operating within application specifications for bubble number and size. Second, the interpolated analog or digital signal from the inlet bubble detection apparatus **40** corresponding to the optimal bubble properties is captured and used as the controlling setpoint in place of the inlet pressure setpoint **107**. This captured setpoint signal is continuously transmitted together with the signal from the inlet bubble detection apparatus **40**, which in this case is used as the process variable, to inlet pressure control PID **135**. PID **135** subsequently varies the position signal or pressure value transmitted to the motorized inlet valve pilot regulator **26**, and consequently the regulated pressure at the bubble generation apparatus **30** inlet, in response to changes in bubble properties. In this way, closed loop control of the inlet pressure required by the bubble generation apparatus **30** is continued in response to the inlet bubble detection apparatus **40** signal. Inlet pressure control PLC **130** can continue its control operation in this alternate mode or switch back to inlet pressure setpoint **107**, and detected inlet pressure process variable based control of inlet pressure control PID **135**.

Once the motorized inlet valve pilot regulator **26** position is set, the inlet pressure control valve **24** can maintain the set pressure without further pilot control adjustment. Consequently, in applications where repeated or continuous change in or adjustment of the inlet pressure setpoint **107** does not occur during normal operation, the inlet pressure control PID **135** can be omitted or replaced with a proportional-integral controller (PI) or other similar, simpler, proportional controller. It is understood, however, that in many applications, fine control of inlet pressure setpoint **107** variations will be required to sustain optimal apparatus operational parameter values.

Once bubbles are generated, they pass through the regenerative turbine pump **60** and are collapsed. Discharge pressure control PLC **102** and pump motor speed control PLC **104** both contribute to the process of pump discharge **68** and discharge pipe **75** pressure control. Discharge pressure control PLC **102** receives discharge pressure setpoint **108** data from controller logic PLC **140**, initially and periodically, similar to inlet pressure control PLC **130**, as values, ranges or algorithms to calculate the discharge pressure setpoint. Discharge pressure control PLC **102** receives and monitors ranged analog or digital signals from the discharge pipe **75** mounted sensors: discharge pressure sensor **113**; discharge

temperature sensor **114**, and discharge bubble detection apparatus **70**, as well as any other properties of the discharged process water that the apparatus might be additionally equipped to detect. Discharge pressure control PLC **102** continuously monitors the various aforementioned discharge pipe **75** process variables and recalculates the discharge pressure setpoint **108** required to collapse the bubbles at the rate and to the size required by the particular application. Similarly to bubble generation control, bubble collapse rate, final bubble size, or total bubble collapse control may require variable discharge pressure and pump rotation speed setpoints as operational parameters change. Discharge pressure control PLC **102** monitors discharge pipe process variables and continuously recalculates the discharge pressure setpoint **108** expected to mitigate any variance from bubble collapse specifications for an application.

Operation of the discharge pressure control valve **80**, through operation of the motorized discharge valve pilot regulator **82** by discharge pressure control PID **103**, as directed by pressure control PLC **102**, utilize signal types, signal processing, process variable selection - such as discharge pressure or discharge bubble detection apparatus **70** signal – and operational considerations and control techniques similar to the analogous pump inlet pipe **22** pressure control accomplished by inlet pressure control PLC **130** and PID **135**, motorized inlet valve pilot regulator **26** and inlet pressure control valve **24**. Remote control of the discharge pressure setpoint **108** by an external computer or device can be relayed through controller logic PLC **140** and discharge pressure control PLC **102**. Also, as is the case with manual pump inlet pipe **22** pressure control, manual discharge pipe **75** pressure control is possible using panel mounted operators (not shown) and the feedback from the panel mounted indicators including valve position indicator **110**, pressure indicator **111c**, temperature indicator **112c**, bubble indicators **40c** and **70c**, pump speed indicator **115**, speed indicator **218**, speed indicator **450**, discharge pressure indicator **113c**, discharge temperature indicator **114c** and valve position indicator **116**.

As hereinbefore set forth, the rotational speed setpoint **109** of the regenerative turbine pump **60** can be calculated by the controller **100** considering various factors. For example, the pump motor speed setpoint **109** must be high enough that the regenerative turbine pump **60**, when its impeller (**FIG. 2A, 63**) is

driven at the pump motor speed setpoint **109**, will output a minimum pressure equal to or greater than the calculated discharge pressure setpoint **108**. Subsequent to reaching the aforementioned minimum rotational speed, the pump motor speed setpoint **109** can be upwardly (or to a limited degree downwardly) adjusted so that the rate of the passage of the regenerative turbine pump **60** impeller's buckets (**FIG. 2A, 64**) matches the generated bubble production rate. In this way the bubbles flow singularly into the regenerative turbine pump's **60** impeller buckets.

To accomplish this, the controller **100** permits direct interaction between discharge pressure control PLC **102** and pump motor speed control PLC **104** and relays inlet bubble detection apparatus **40** interpolated data that provides the number of bubbles generated per minute (or other time interval) from inlet pressure control PLC **130**, via the controller logic PLC **140**, to pump motor speed control PLC **104**.

Controller logic PLC **140**, in addition to and in support of controller logic **101**, also stores and distributes to the controller's subsystems PLC **130, 102, 104** upon request parametric data describing the operational performance characteristics and limits of the current configurations of the apparatus subsystems, including information about the installed regenerative turbine pump **60**. This pump configuration information can include performance curve data based on the regenerative turbine pump's **60** rotational speed, providing specifications such as maximum discharge pressure, maximum rotational speed, or flow rate, horsepower requirement or NPSHr as a function of the rotational speed. This configuration data is used by the apparatus subsystems' control PLC **130, 102, 104** to verify setpoint data ranges and identify out of limit operational conditions and for operational error control. In addition to this standard pump performance curve information, data regarding the regenerative turbine pump **60** impeller's (**FIG. 2A, 63**) design is stored accessible to the controller logic PLC **140** and reported to pump motor speed control PLC **104**, including the number of impeller buckets (**FIG. 2A, 64**) along the circumference of the pump's impeller.

Controller logic PLC **140**, using the stored subsystem configuration data, controller logic **101**, application logic **106**, and setpoint data **107, 108, 109**, retrieves or calculates and then transmits at operation startup an initial discharge

pressure setpoint **108** to the discharge pressure control PLC **102** and an initial pump motor speed setpoint **109** to the pump motor speed control PLC **104**. The discharge pressure control PLC **102** then recalculates the discharge pressure setpoint **108** and transmits it, along with the process variable, either the pump discharge pipe **75** pressure sensor **113** signal or the discharge bubble detection apparatus **70** signal, to the discharge pressure control PID **103** so it can position the motorized discharge valve pilot regulator **82**. If the bubble collapse rate is insufficient, or the final bubble size is greater than the application specification, or bubbles are to be totally collapsed and yet are still seen by the discharge bubble detection apparatus **70**, then the discharge pressure setpoint **108** is increased. The newly calculated higher discharge pressure setpoint **108** is transmitted directly from discharge pressure control PLC **102** to pump motor speed control PLC **104**. PLC **104** evaluates the current discharge pressure setpoint **108**, and using the stored regenerative turbine pump performance data, in conjunction with the current pump motor speed setpoint **109**, determines whether the maximum pressure at the current pump motor speed setpoint **109** is greater than the transmitted newly calculated higher discharge pressure setpoint **108**. If the current pump motor speed setpoint **109** is too low, pump motor speed control PLC **104** calculates a new pump motor speed setpoint **109** to cause the regenerative turbine pump **60** to output at least the new discharge pressure setpoint **108** requested by the discharge pressure control PLC **102**. Conversely, where the collapsed bubbles are too small or the calculated collapse rate is too great, the discharge pressure setpoint **108**, and possibly the pump motor speed setpoint **109** can be lowered. Both of these processes can be implemented using a ranged analog or digital signal representing the speed setpoint, calculated by pump motor speed control PID **105** and transmitted to the variable frequency drive **126**, which in turn varies the power frequency supplied to the pump's motor so that it rotates at the pump motor speed setpoint **109**. The variable frequency drive **126** continuously returns operational status data, including current actual pump motor rotational speed, to the pump motor speed control PLC **104**, which in turn relays this actual pump motor rotational speed data to the pump motor speed control PID **105** as the process variable. Once the final adjustment of the pump motor speed setpoint **109** is complete and bubble collapse occurs as desired, pump motor

speed control PLC **104** can switch the process variable used by the pump motor speed control PID **105** from the actual rotational speed signal relayed from the variable frequency drive **126** to the bubble properties signal transmitted from the discharge bubble detection apparatus **70**. As with inlet pressure control, the discharge pressure control PID **103** and the pump motor speed control PID **105** process variables can be switched as required between the actual discharge pipe pressure as detected by the discharge pressure sensor **113** or the discharge bubble detection apparatus **70** signal.

Once the minimum discharge pressure setpoint **108** for a bubble collapse rate and final bubble size for a particular application is achieved, fine pump motor speed setpoint **109** adjustment can commence. To accomplish this, pump motor speed control PLC **104** requests the current bubble generation rate from PLC **140**, which in turn retrieves the current inlet bubble detection apparatus **40** bubble property values from inlet pressure control PLC **130**. Once the current bubble production rate is retrieved, pump motor speed control PLC **104** then calculates the current impeller bucket (**FIG. 2A, 64**) passage rate as impeller (**FIG. 2A, 63**) revolutions per minute (or other time interval) multiplied by the total number of impeller buckets on the impeller's circumference, yielding the total number of impeller buckets passing by the pump inlet **61** per minute or other time interval. With this bubble generation rate data and impeller bucket passage rate data, pump motor speed control PLC **104** continuously recalculates a new pump motor speed setpoint **109** that synchronizes the impeller bucket passage rate to the bubble generation rate so that the bubbles are collapsed singly in the impeller buckets **64**.

It should be understood that to accomplish the timing between generated bubble and impeller bucket **64**, and as a pre-requisite step of application design, the number of bubbles generated and number of impeller buckets should be coordinated so that the impeller can be rotated at the minimum speed to collapse the bubbles as required by an application using a particular impeller design and bubble generation apparatus **30** configuration.

The apparatus can be operated in one of at least three separate purpose modes: as directed by an external device or computer, or as directed by algorithms executed by controller logic PLC **140** using controller **100** and residing

controller logic **101**, reduction logic **106** and setpoint data **107, 108, 109**, or manually using panel mounted controls and indicators. In each of these three modes, the operational parameter values and setpoints, or the algorithms used to calculate them, as well as the useful subsystem process variable identities, are known and are input as controller application logic **106** and setpoint data **107, 108, 109** intended and expected to achieve a particular operational result.

In another mode, where the controller **100** is used as a tool to determine the optimal operational parameter values and the identities of those process variables required to produce a particular functional result. In this experimental or application development operational mode, the setpoint data **107, 108, 109** submitted represent test value ranges, or are algorithms used to calculate test value ranges, and include target performance specifications for bubble production and collapse. In this mode, the application logic **106** can provide both an operational test sequence algorithm that controls how each setpoint should be varied across the submitted setpoint data **107, 108, 109** range, as well as an algorithm and criteria to evaluate each set of operational parameter values against the target application performance specifications. During test execution, application logic **106** stores those operational setpoints that provide useful results, either a good fit or a poor match to the target performance.

The controller allows automatic sequential execution of operational trials using electronically stored inlet and discharge pressure setpoint values or value ranges and pump speed setpoint values or value ranges that may produce desirable performance characteristics, as required by a particular application. The controller **100** automatically recalculates and varies the operational setpoints using the originally input setpoint values or value ranges and value modification algorithms residing in the controller. Alternately, the operational trials could be directed using an external computer, PLC or other functionally equivalent device to submit test setpoint data **107, 108, 109** and test application logic to controller PLC **140**, through external interface PLC **118**. Once testing is complete, result data can be read by or uploaded to an external computer or device for storage or further analysis. Rather than storing only criteria matching operational test data, all result data could be stored, locally in the controller **100** or on a remote computer or storage device for further analysis. In this way, an application

protocol describing the operational conditions and process variable selections most likely to produce a desired result with the apparatus can be developed using the apparatus and controller **100** as reporting those setpoint combinations yielding desirable or best fit operational characteristics using controller residing result evaluation algorithms.

The controller can be used as an analytical tool to determine the optimal operational parameter values required for producing bubbles of a certain size and collapsing them at a specific rate to plasma hot spots or as required by a particular application. The controller allows automatic sequential execution of operational trials using electronically stored inlet and discharge pressure setpoint values or value ranges and pump speed setpoint values or value ranges that may produce desirable performance characteristics, as required by a particular application. The controller automatically recalculates and varies the operational setpoints using the originally input setpoint values or value ranges and value modification algorithms residing in the controller. The controller concurrently records and subsequently analyses the trial operational results. In this way, an application protocol describing the operational conditions and process variable selections most likely to produce a desired result with the apparatus can be developed using the apparatus and controller as reporting those setpoint combinations yielding desirable or best fit operational characteristics using controller residing result evaluation algorithms.

Copending U.S. Patent Application Serial No. _____, titled "Chemical Reactor System and Method using Regenerative Turbine Pump to Produce Fuel Gas," discloses a particular application and is filed contemporaneously herewith. The disclosure of this application is expressly incorporated herein by reference.

FIG. 6 is a flowchart showing processing steps that are carried out by the controller logic **101** of the present invention. Beginning in step **1010**, the controller logic **101** inventories subsystems and obtains the status of the subsystems. A determination is made in step **1020** as to whether any errors are present. If errors are present, in step **1030** the errors are displayed and the status of the errors is transmitted for review, and then the system is halted in step **1040**. Otherwise, if there are no errors in step **1020**, a determination is made as whether to initiate automatic control mode in step **1050**. If a negative determination is made, in step

1060 another determination is made as to whether to initiate manual control mode. If a negative determination is made, yet another determination is made as to whether to initiate external control mode in step **1070**. If external control mode is not executed, a control mode error is transmitted ("thrown") in step **1080** and the processing reverts to step **1030** in which error stats are displayed and the status is transmitted.

If automatic control mode is initiated in step **1050**, the setpoint data **107**, **108**, **109** is obtained from controller in step **1090**, and step **1120** occurs. If manual control mode is initiated in step **1060**, the setpoint data **107**, **108**, **109** are obtained from an operator panel in step **1100**, and step **1120** occurs. If external control mode is initiated in step **1070**, the setpoint data **107**, **108**, **109** are obtained from an external device in step **1110**, and step **1120** occurs. In step **1120**, the setpoint data is transmitted, the pump **60** and subsystems are started and the status is obtained. Thereafter, in step **1130** a determination is made as to whether the setpoint range is acceptable. If a negative determination is made, an input setpoint range error is thrown in step **1140**, and the processing reverts to step **1030**. If the setpoint range is acceptable, reduction logic **106** is performed in step **1150**.

Next, in step **1160**, a determination is made as to whether a subsystem error exists. If a positive determination is made, the processing reverts to step **1030**. If no errors exist, a determination is made as to whether to initiate operational command in step **1170**. If a positive determination is made, external or manual control mode operation command is processed in step **1180**, and then, in step **1190**, a determination is made as to whether to initiate new setpoint data. If a positive determination is made, the processing reverts to step **1050**. If not, the processing reverts to step **1150**.

If operational command is not initiated in step **1170**, a determination is made as to whether there is a change in operational mode in step **1200**. If a positive determination is made in step **1200**, a determination is then made as to whether to halt the request in step **1210**. If a positive determination is made, the processing reverts to step **1030**. Otherwise, the processing reverts to step **1050**. If operational mode change is not performed in step **1200**, a determination is made

as to whether to request subsystem data in step **1220**. If a positive determination is made, the subsystem data request is processed in step **1230**, and the operation of the system continues in step **1240**, and the processing reverts to step **1150**. Otherwise, the operation of the system continues in step **1240**, and the processing reverts to step **1150**.

FIG. 7 is a flowchart showing processing steps of the reduction logic **106**. Beginning in step **1300**, bubble generation logic is performed. In step **1310**, a determination is made as to whether any error states or events are present. If any error states or events are present, the processing reverts to step **1150**. Otherwise, bubble collapse logic is performed in step **1320**. In step **1330**, a determination is made as to whether any error states or events are present. If any error states or events are present, the processing reverts to step **1150**. If step **1330** determines that there are no error states or events, control returns to step **1300**.

FIG. 8 is a flowchart showing processing steps of the bubble generation logic. Beginning in step **1400**, a determination is made as to whether any setpoints are out of range. If a positive determination is made, a bubble generation setpoint error is thrown in step **1410** and the processing reverts to step **1300**. Otherwise, a determination is made as to whether the bubble generation is acceptable in step **1420**. If a positive determination is made, the processing reverts to step **1300**. If the bubble generation is not acceptable, the inlet pressure setpoint is adjusted to correct bubble generation in step **1430**, and the process reverts to step **1400**.

FIG. 9 is a flowchart showing processing steps of the bubble collapse logic. Beginning in step **1500**, a determination is made as to whether any setpoints are out of range. If a positive determination is made, a bubble collapse setpoint error is thrown in step **1510** and the processing reverts to step **1320**. Otherwise, a determination is made as to whether the bubble collapse is acceptable in step **1520**. If a positive determination is made, the processing reverts to step **1320**. If the bubble collapse is not acceptable, the discharge pressure setpoint is adjusted to correct bubble collapse in step **1530**. Next, in step **1540**, a determination is made as to whether the available pressure is too low. If a negative determination,

the process reverts to step **1500**. Otherwise, the pump speed setpoint is increased in step **1550**, and the process reverts to step **1500**.

It will be understood that the embodiments described herein are merely exemplary and that a person skilled in the art may make many variations and modifications without departing from the spirit and scope of the invention. All such variations and modifications are intended to be included within the scope of the invention as defined by the appended claims.

CLAIMS**What is claimed is:**

1. A system for the formation and collapse of bubbles, the system comprising:
a bubble generator for generating bubbles in a fluid;
a regenerative turbine pump for receiving the fluid and the bubbles;
at least one sensor sensing at least one process parameter associated with operation of the regenerative turbine pump; and
a controller in communication with the at least one sensor, the controller receiving the at least one process parameter, processing the at least one process parameter, and adjusting operation of the regenerative turbine pump based upon processing of the at least one process parameter.
2. The system of Claim 1, wherein the regenerative turbine pump includes an impeller blade defining a plurality of buckets.
3. The system of Claim 2, wherein the buckets are sized to receive and move a singular bubble.
4. The system of Claim 3, wherein the process parameter comprises at least one of the rotational speed of the buckets, discharge pressure, and temperature.
5. The system of Claim 4, further comprising a bubble detection apparatus attached to the pump, the bubble detection apparatus sized to detect the number and size of the bubbles.
6. The system of Claim 5, wherein the bubble generator comprises a venturi.
7. The system of Claim 5, wherein the bubble generator comprises an eductor.
8. The system of Claim 5, wherein the bubble generator comprises an injector for injecting the bubbles into the fluid.
9. The system of Claim 4, wherein the controller transmits a speed setpoint signal to the pump and the controller calculates the speed, pressure, or flow rate of the pump.
10. The system of Claim 9, wherein the system operates in a closed loop configuration.
11. The system of Claim 10, wherein the at least one sensor senses at least one process parameter associated with operation of the bubble generator.

12. The system of Claim 11, wherein the controller is in communication with the at least one sensor, the controller receiving the at least one process parameter, processing the at least one process parameter, and adjusting operation of the bubble generator based upon processing of the at least one process parameter.

13. A method for the formation and collapse of bubbles, the method comprising the steps of:

- producing a stream of bubbles from a liquid;

- delivering the stream of bubbles to a regenerative turbine pump having an impeller defining a plurality of buckets;

- collapsing the bubbles; and

- monitoring a process parameter associated with the bubbles using a controller and at least one sensor; and

- adjusting operation of the regenerative turbine pump based upon monitoring of the parameter.

14. The method of Claim 13, wherein the bubbles are collapsed in individual bucket chambers of the regenerative turbine pump.

15. The method of Claim 14, wherein the bubbles are entrained in a helical flow in the chambers of the pump.

16. The method of Claim 15, further comprising the step of monitoring pressure or flow rate of the stream of bubbles using at least one sensor and the controller in communication with the at least one sensor.

17. The method of Claim 16, further comprising the step of determining whether the pressure or the flow rate is within an acceptable range using the controller.

18. The method of Claim 17, further comprising the step of adjusting operation of the regenerative turbine pump in response to monitoring of the pressure or the flow rate.

19. A system for the formation and collapse of bubbles, the system comprising:

- a bubble generator for generating bubbles in a fluid;
- a regenerative turbine pump for receiving the fluid and the bubbles;
- at least one sensor sensing at least one process parameter associated with operation of the bubble generator; and

a controller in communication with the at least one sensor, the controller receiving the at least one process parameter, processing the at least one process parameter, and adjusting operation of the bubble generator based upon processing of the at least one process parameter.

20. The system of Claim 19, wherein the regenerative turbine pump includes an impeller blade defining a plurality of buckets.

21. The system of Claim 20, wherein the buckets are sized to receive and move a singular bubble.

22. The system of Claim 21, wherein the bubble generator comprises a venturi.

23. The system of Claim 21, wherein the bubble generator comprises an eductor.

24. The system of Claim 21, wherein the bubble generator comprises an injector for injecting the bubbles into the fluid.

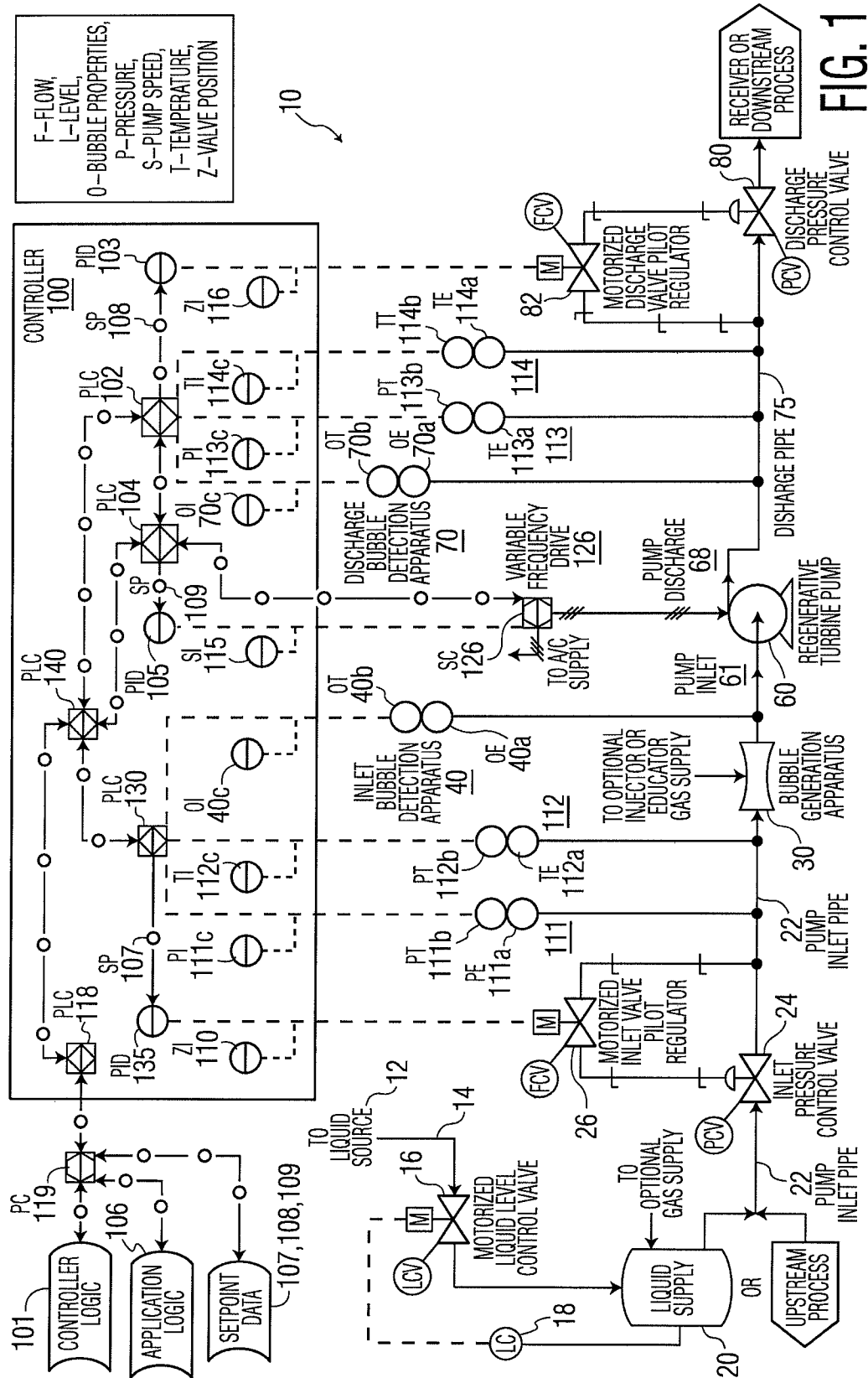


FIG. 1

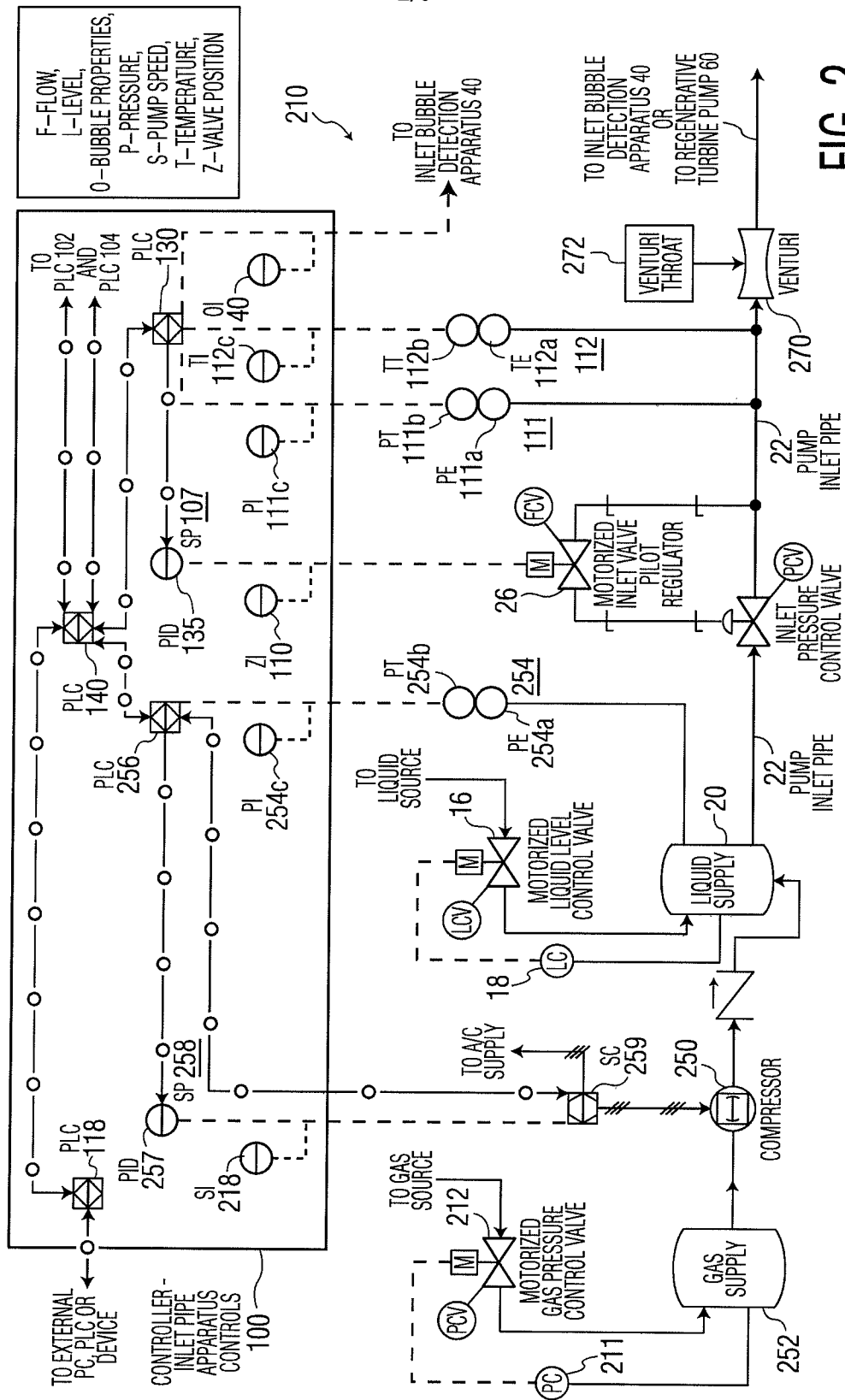


FIG. 2

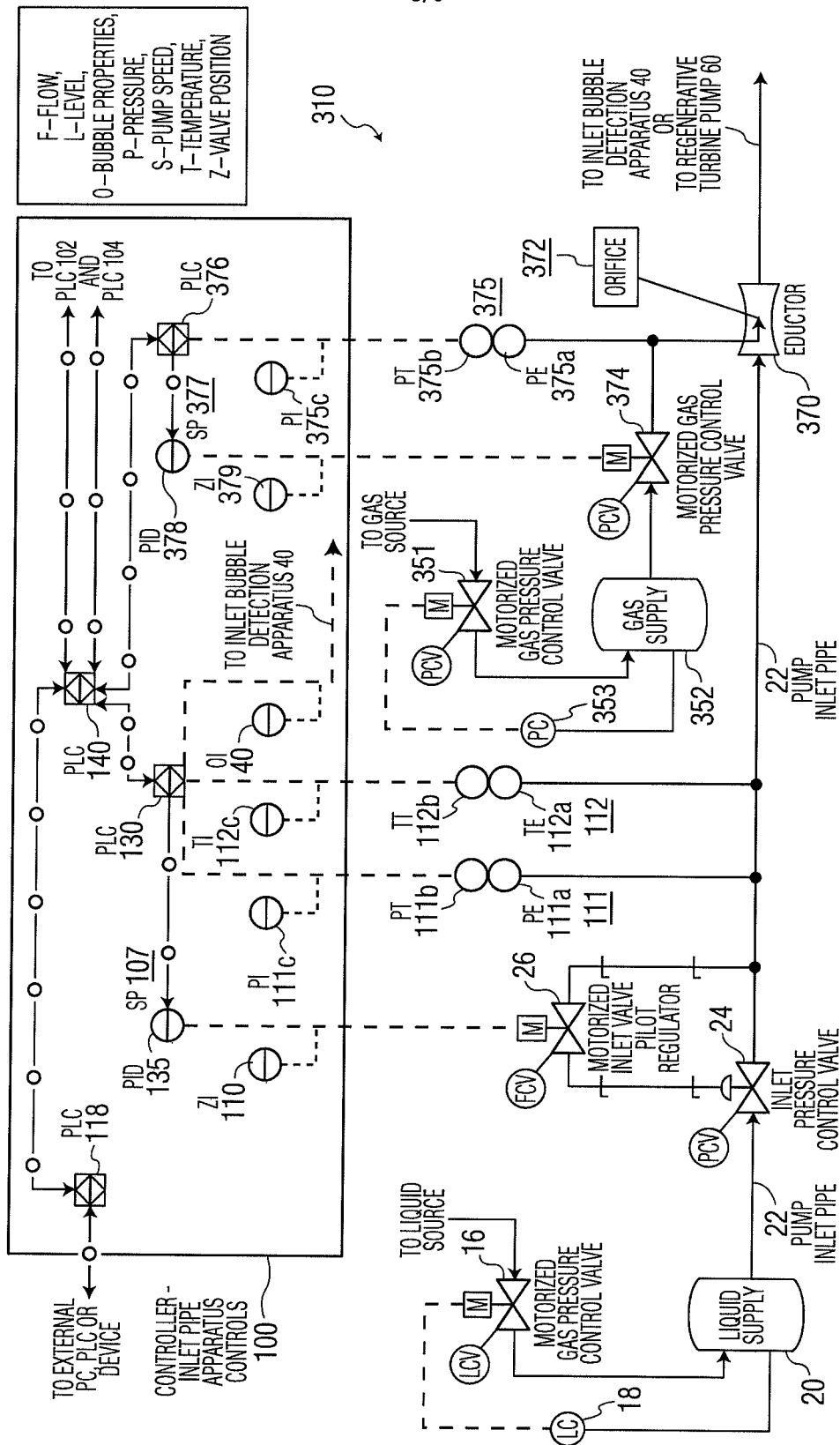


FIG. 3

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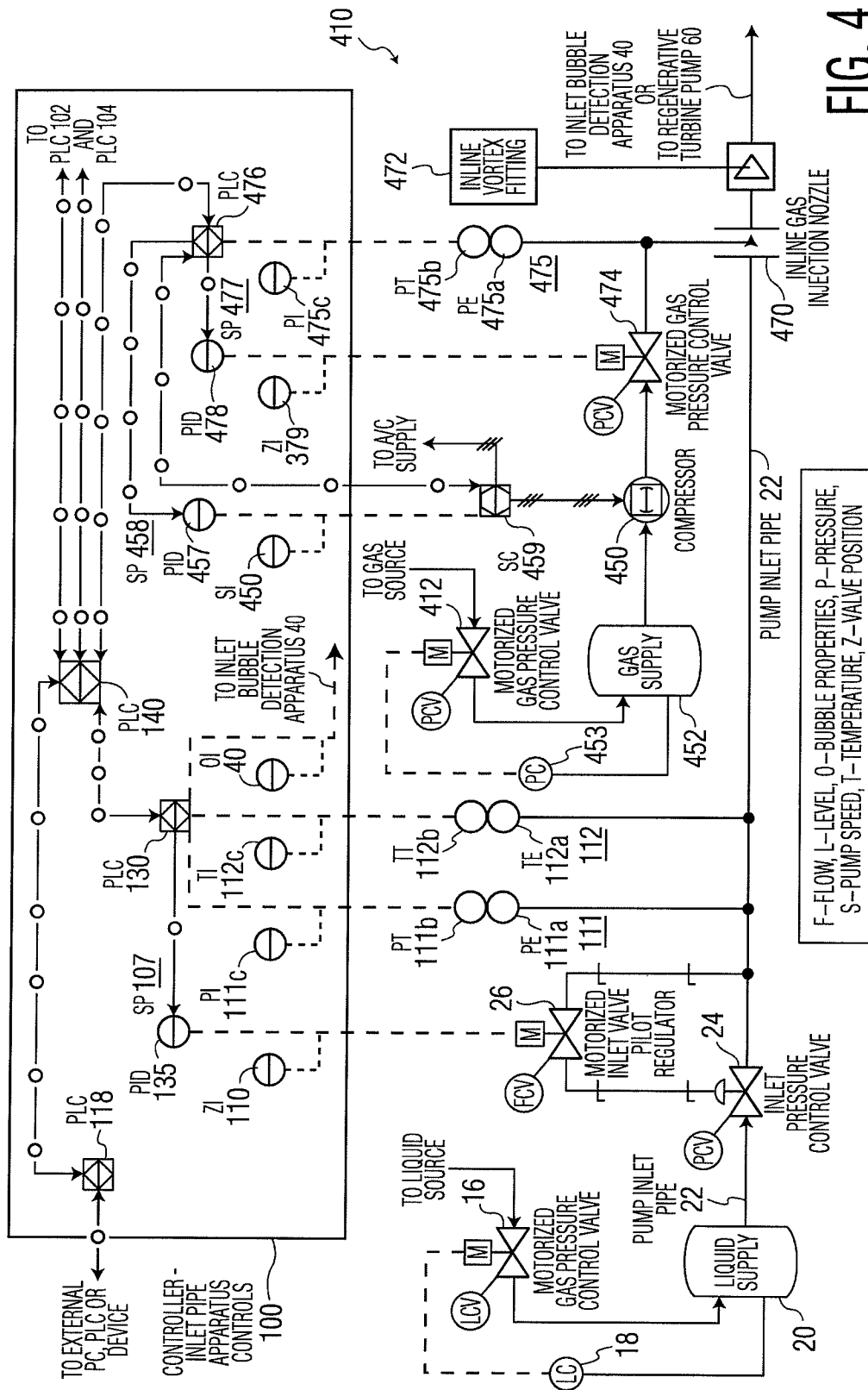


FIG. 4

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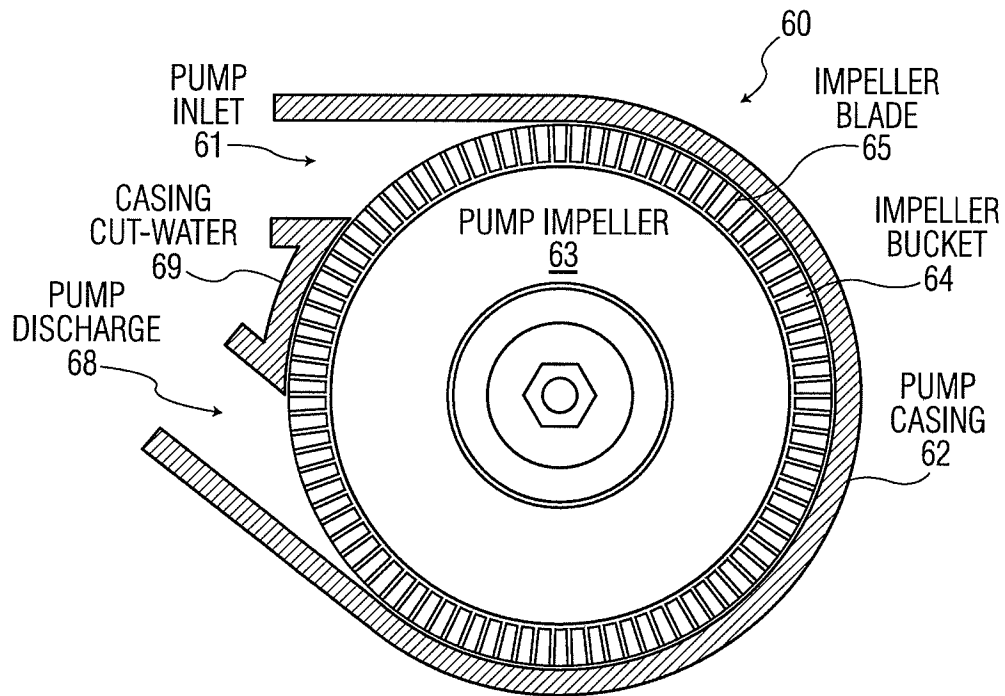


FIG. 5A

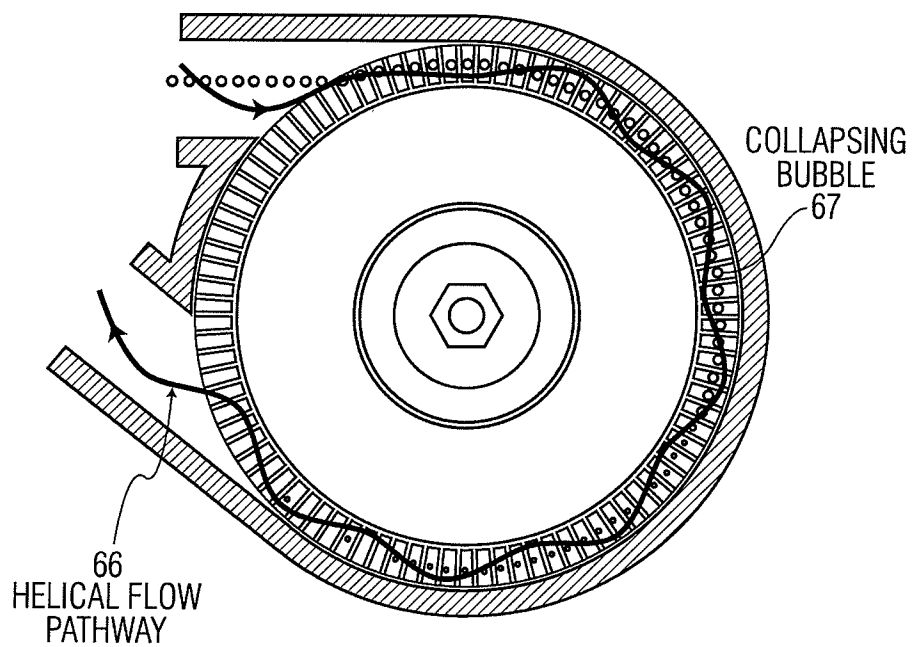


FIG. 5B

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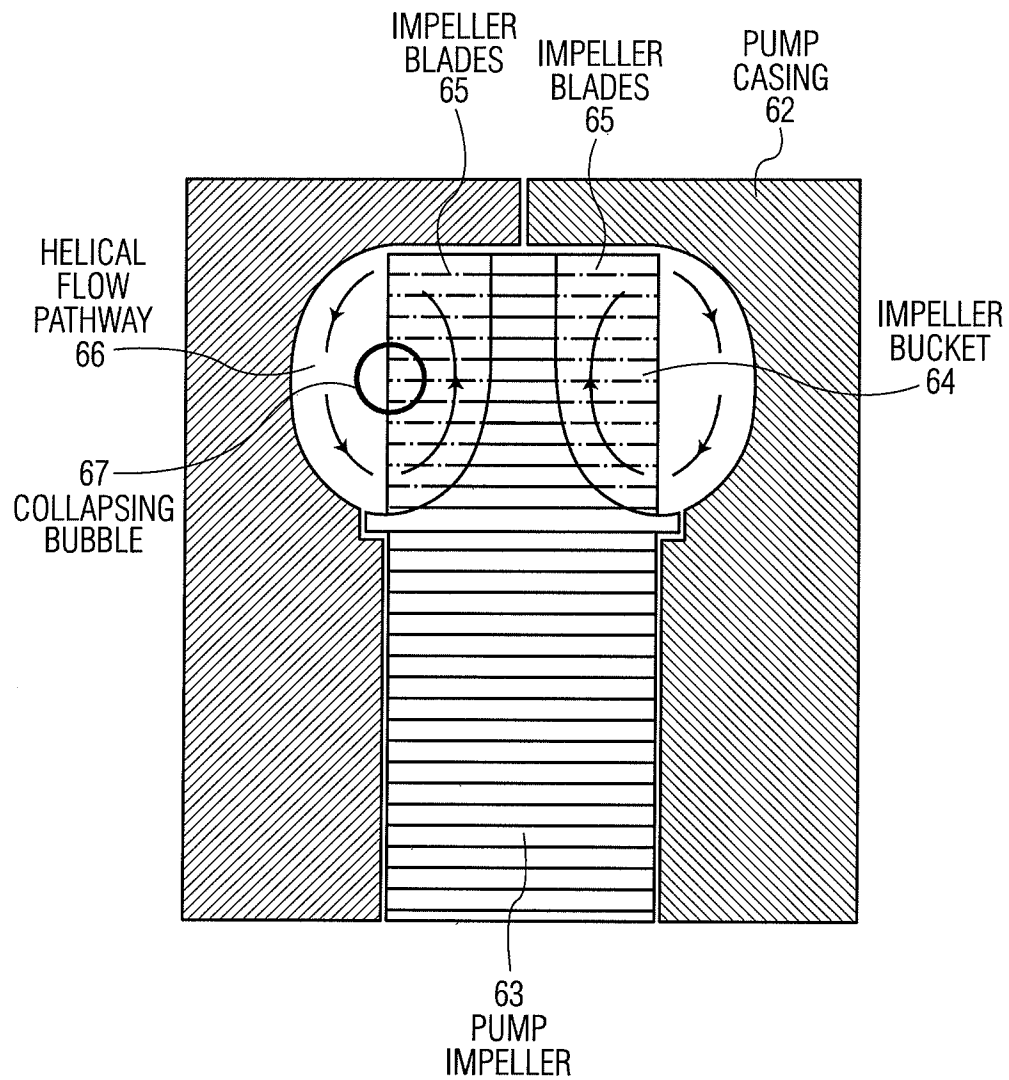


FIG. 5C

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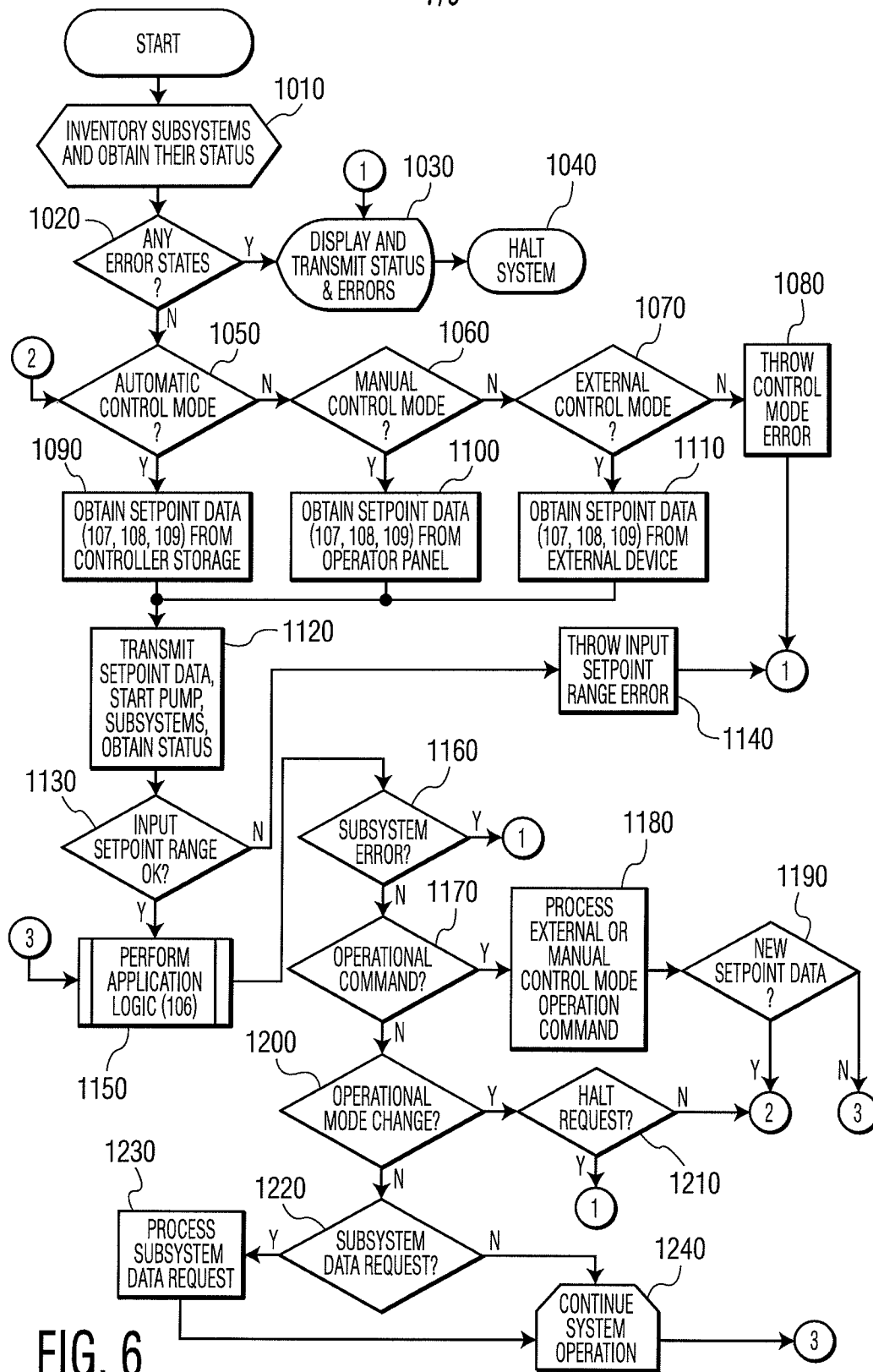


FIG. 6

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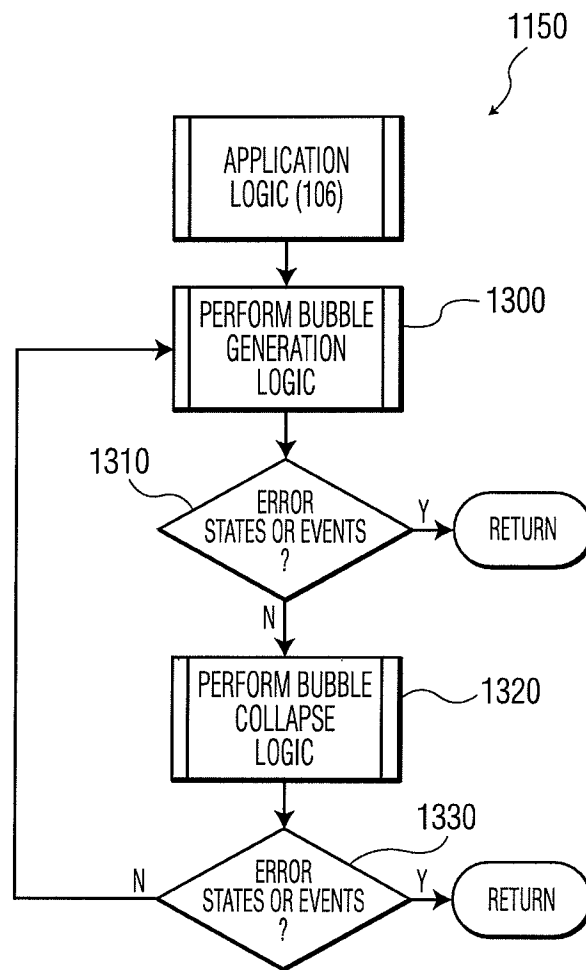


FIG. 7

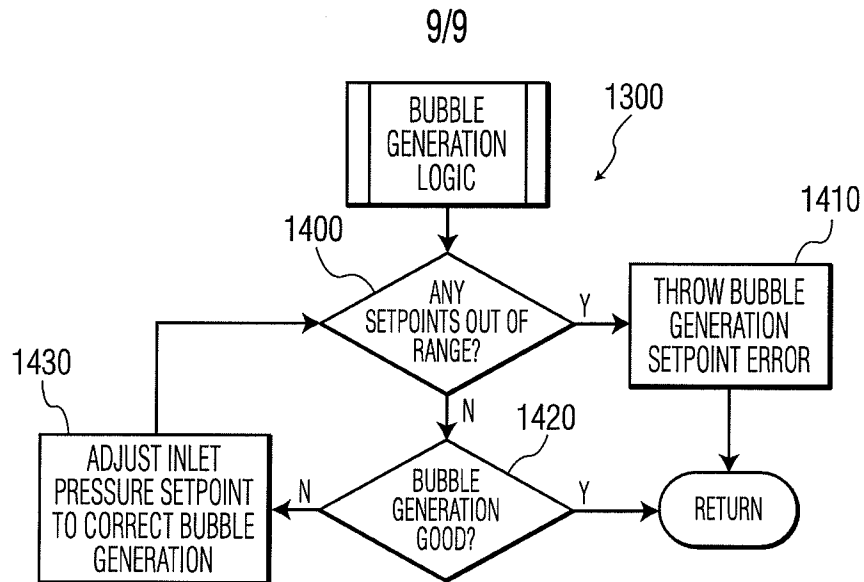


FIG. 8

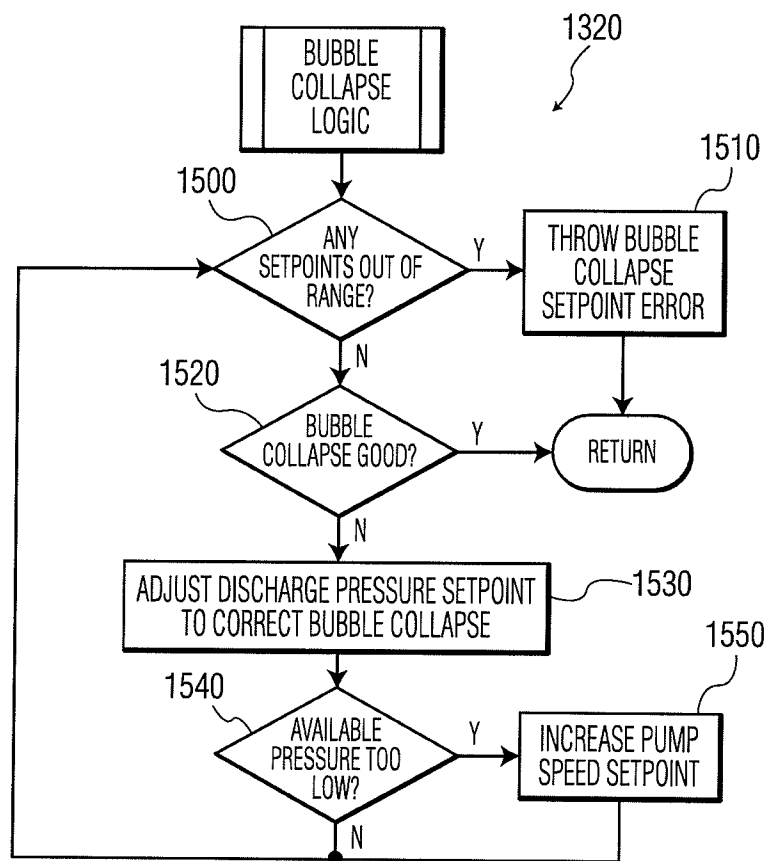


FIG. 9