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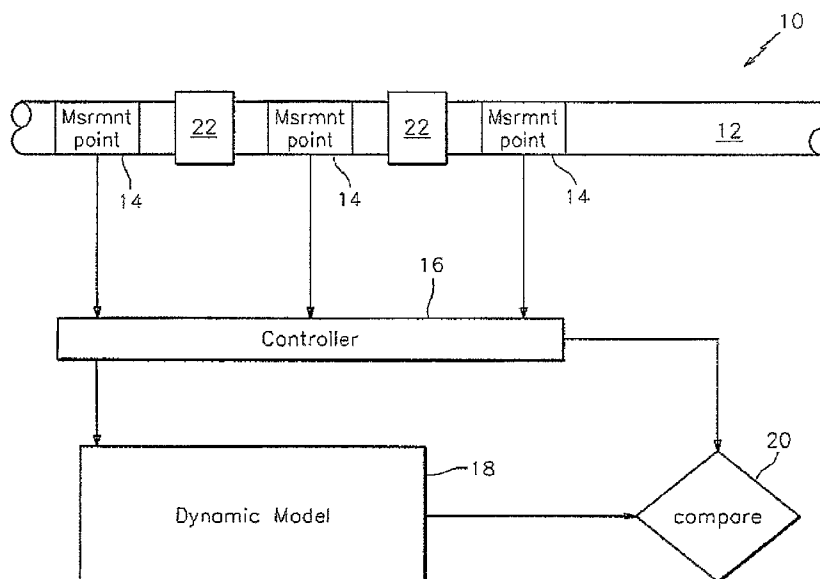
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(57) Abstract: In a method for monitoring a fluid flowing in a pipeline, a dynamic model of the flowing fluid is provided. At least one operational parameter forming part of the dynamic model is provided for measurement. At least one sonar-based sensor is coupled to the pipeline and is operable to measure the operational parameter. This sensor is also operable to generate signals indicative of the operational parameter. A controller is in communication with the sensor and is associated with the dynamic model. The controller receives the signals generated by the sensor, interprets and compares these signals to the dynamic model, and determines when the operational parameter has deviated from values corresponding to the operational parameter forming part of the dynamic model. The operational parameter can be a speed of sound of the fluid flowing in the pipeline, pressure, temperature, pump speed, flow rate, or the like.

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*Attorney Docket No. CC-0932PCT**Express Mail No. EV677164381US***Method for Monitoring a Flowing Fluid****Cross Reference to Related Applications**

[0001] This application is entitled to the benefit of and incorporates by reference the disclosure of U.S. Patent Application 60/835,019 filed on August 1, 2006 and entitled "SONAR Based Flow and/or SOS Augmented Pipeline Leak Detection Systems."

Field of the Invention

[0002] The present invention generally relates to monitoring fluid flowing in a pipe and is more specifically directed to a method using sonar-based sensors to aid in the detection of anomalies such as leaks in the pipe.

Background of the Invention

[0003] Detecting and locating leaks or other detrimental anomalies in a pipe or pipeline can prove daunting. Pipelines are often hundreds to thousands of miles long and run through remote areas, underground, and underwater. The pipeline is often exposed to harsh environmental conditions in areas not readily accessible for visual monitoring.

Accordingly, if a problem such as a leak occurs, it can potentially go undetected for extended periods of time. This can have a significant, harmful impact on the environment, and can result in substantial losses of whatever is being transported through the pipeline.

[0004] In an effort to detect anomalies such as, for example, leaks in the pipeline, resort has been had to monitoring parameters of the flowing fluid looking for changes in these parameters that would indicate a problem. To date, systems and approaches for detecting leaks in a pipeline are governed by the operational parameters of the pipeline such as flow rate, length of the pipeline, and the probability of a leak occurring. This probability usually increases, for example, when corrosive or erosive materials flow through the pipeline.

[0005] Typically instrumentation is used to monitor flow and pipeline conditions. Certain flow parameters are measured and then these measured parameters are compared to a mathematical model that simulates an idealized flow of the fluid through the pipeline. Under normal operating conditions, the simulated and measured parameters agree to within

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a certain degree. If a leak develops, the difference between the simulated and measured parameters increases. The effectiveness of these systems is directly related to the fidelity of the simulation and the quality and quantity of the sensed data used in the comparison between the simulation and reality. The better the model represents reality, the more effective the leak detection system will be in quickly detecting and locating small leaks.

Summary of the Invention

[0006] The present invention is directed in one aspect to a method for monitoring a flowing fluid in a pipeline wherein a dynamic model of the fluid flowing in the pipeline is provided with a parameter forming part of the dynamic model being a speed of sound of the fluid. At least one sonar-based sensor is coupled to the pipeline and is operable to measure the speed of sound of the fluid flowing through the pipeline and to generate signals indicative thereof. A controller is provided and is in communication with the sonar-based sensor and associated with the dynamic model. In the preferred embodiment of the present invention, the controller receives the signals generated by the sonar-based sensor and then interprets and compares these signals to the dynamic model. The controller, based on the comparison, then determines when the simulated state of the fluid is sufficiently different from the measured state to indicate an anomaly.

[0007] Preferably, the method of the present invention also includes the measurement of one or more operational parameters, in addition to the speed of sound, relevant to the fluid flowing in the pipe. These operational parameters can include such things as, but are not limited to, pressure, temperature, pump speed and volumetric flow rate. Each of these operational parameters also form part of the above-described dynamic model.

[0008] During operation, the controller interprets and compares the measured operational parameters to the dynamic model to determine if the measured operational parameters deviate from values corresponding to the operational parameters forming part of the dynamic model. Once the comparison is conducted, the controller can perform further analysis, particularly if a deviation between the dynamic model and the measured parameters is detected. This further analysis can take the form of determining where in the pipeline the anomalous behavior originated. The larger the amount of measured data, and thereby the greater the amount of sonar-based or other sensors, the more accurate the determination of the location of any anomalous behavior will be.

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[0009] Preferably, the sonar-based sensors are non-invasive and can be removably clamped onto the pipeline at virtually any desired location. It is also preferable that the at least one sonar-based sensor includes a plurality of sonar-based sensors positioned along the pipeline, each generating signals receivable by the controller indicative of the speed of sound of the fluid flowing through the pipeline adjacent to the particular sonar-based sensor.

[0010] In an embodiment of the present invention, stratification within the pipeline is measured and monitored by providing at least one first sensor having a first spatial array of at least two sensors disposed at different axial locations spaced along the pipeline. Each of the sensors in the first spatial array generates a first signal indicative of pressure convecting with a portion of the flow passing through an upper portion of the pipeline. At least one second sensor having a second spatial array of at least two sensors disposed at different axial locations is provided and is spaced along the pipeline. Each of the sensors in the second spatial array generates a second signal indicative of pressure convecting with a portion of the flow passing through a lower portion of the pipeline. The controller uses the first signals to determine a first velocity of the flow passing through the upper portion of the pipeline, and the second signals to determine a second velocity of the flow passing through the lower portion of the pipeline. Using the first and second velocities, a level of stratification in the flow is determined.

[0011] Preferably, the first spatial array is aligned axially along a top portion of the pipeline, and the second spatial array is aligned axially along a bottom portion of the pipeline. In addition, the at least one first and second sensors described above can include a plurality of first and second sensors with the controller comparing the level of stratification for each of the first and second sensors to the dynamic model. The first and second sensors can be used along with the sonar based sensors described above, as well as other sensors and instrumentation to monitor other flow parameters, all of which can be compared by the controller with the dynamic model to determine if any unacceptable deviations from the dynamic model are present in the pipeline. This information can also be used to ascertain the location of anomalies that are causing the deviant behavior in the flowing fluid.

Brief Description of the Drawings

[0012] FIG. 1 is a schematic illustration showing sonar-based sensors coupled to a pipeline and used to monitor fluid flow conditions in the pipeline.

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[0013] FIG. 2 is a schematic diagram of an apparatus for determining at least one parameter associated with a stratified fluid flowing in a pipe.

[0014] FIG. 3 is a cross-sectional schematic view of non-stratified, turbulent, Newtonian flow through a pipe.

Detailed Description of Preferred Embodiments of the Present Invention

[0015] As shown schematically in FIG. 1, a pipeline monitoring system generally designated by the reference number 10 includes a pipeline 12 having three sonar-based sensors 14 coupled thereto and spaced axially apart from one another along the pipeline. Sonar-based sensors 14 of the type described herein are offered by Cidra Corporation of Wallingford, Connecticut under the trademark SONARtrac. The sonar-based sensors 14 are configured to measure the speed of sound of fluid flowing in the pipeline 12 and to generate signals indicative thereof, the signals being receivable by a controller 16. In addition to the speed of sound, other operational parameters such as pump speed, fluid pressure, flow rate, flow temperature, and the like can also be monitored with signals indicative of these measured parameters being sent to and received by the controller 16. While three sonar-based sensors 14 have been shown and described, the present invention is not limited in this regard as less than, or more than, three sonar-based sensors can be positioned along the pipeline 12 without departing from the broader aspects of the present invention.

[0016] Still referring to FIG. 1, a dynamic model 18 of the fluid flowing in the pipeline 12 is associated with the controller 16. The dynamic model 18 is a mathematical representation of the fluid flowing in the pipeline 12 and has stored therein values corresponding to operational parameters, as well as the speed of sound of the fluid flowing in the pipeline. Historically, speed of sound was considered to be constant in a fluid flowing in a pipeline. However, this is not the case as the speed of sound can vary in the pipeline. Accordingly, the sonar-based sensors 14 can, during normal operating conditions, be employed to provide data indicative of the speed of sound of the flowing fluid in the pipeline, the data being used in the dynamic model to optimize the model. In addition, the greater the number of parameters used in forming the dynamic model 18, the more accurate the dynamic model will be in approximating real-world conditions.

[0017] Once the signals indicative of the above-described operational parameters and the speed of sound are received by the controller 16, the values corresponding thereto are compared in a comparing step 20, to corresponding values in the dynamic model 18. The comparison 20 will provide for a determination of when one or more of the operational

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parameters and/or the speed of sound have deviated from the dynamic model, thereby indicating a potentially detrimental condition within the flow and or the pipe comprising the pipeline 12. Anomalous behavior can be monitored in this manner. In addition, the comparison can be employed to aid in the determination of the locations of leaks within the pipeline by analyzing which sensors transmitted the deviant data.

[0018] As shown in FIGS. 1-3, in addition to the sonar-based sensors 14, stratification sensors 20 can also be coupled to the pipeline 12. As described in commonly-owned U.S. Patent No. 6,609,069 to Gysling, entitled "Method and Apparatus for Determining the Flow Velocity within a Pipe", and U.S. Patent Application, Serial No. 10/007,736, filed on November 11, 2001, which are incorporated herein by reference in their entirety, unsteady pressures along a pipe caused by coherent structures (e.g., turbulent eddies and vortical disturbances) that convect with a fluid flowing in the pipe, contain useful information regarding parameters of the fluid. The present invention provides various means for using this information to measure parameters of a stratified flow, such as, for example, velocity, level/degree of stratification, and volumetric flow rate.

[0019] Referring to Fig. 2, an apparatus 30 for measuring at least one parameter associated with a flow 32 flowing within a duct, conduit or other form of pipeline 12, is shown. The parameter of the flow 32 may include, for example, at least one of: velocity of the flow, volumetric flow rate, and level of stratification. In Fig. 2, the flow 32 is depicted as being stratified, where a velocity profile 34 of the flow 32 is skewed from the top of the pipe 12 to the bottom of the pipe, as may be found in industrial fluid flow processes involving the transportation of a high mass fraction of high density, solid materials through a pipe where the larger particles travel more slowly at the bottom of the pipe. For example, the flow 32 may be part of a hydrotransport process.

[0020] Referring to Fig. 3, the flow 32 is again shown passing through the pipe 12. However, in Fig. 3, the flow 32 is depicted as a non-stratified, Newtonian flow operating in the turbulent regime at Reynolds numbers above about 100,000. The flow 32 of Fig. 3 has a velocity profile 34 that is uniformly developed from the top of the pipe 12 to the bottom of the pipe. Furthermore, the coherent structures 36 in the non-stratified, turbulent, Newtonian flow 32 of Fig. 3 exhibit very little dispersion. In other words, the speed of convection of the coherent structures 36 is not strongly dependent on the physical size of the structures. As used herein, dispersion describes the dependence of convection velocity with wavelength, or equivalently with temporal frequency. Flows for which all wavelengths

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convect at a constant velocity are termed “non-dispersive”. For turbulent, Newtonian flow, there is typically not a significant amount of dispersion over a wide range of wavelength to diameter ratios.

[0021] Sonar-based flow measurement devices, such as, for example, the device described in aforementioned U.S. Patent No. 6,609,069 to Gysling, have advantageously applied the non-dispersive characteristic of turbulent, Newtonian flow in accurately determining flow rates. For stratified flows such as those depicted in Fig. 2, however, some degree of dispersion is exhibited. In other words, the coherent structures 36 convect at velocities that depend on their size, with larger length scale coherent structures tending to travel slower than smaller length scale structures. As a result, some of the underlying assumptions associated with prior sonar-based flow measurement devices, namely that the speed of convection of the coherent structures 36 is not strongly dependent on the physical size of the structures, are affected by the presence of stratification.

[0022] The apparatus 30 of Fig. 2 accurately measures parameters such as velocity, level of stratification, and volumetric flow rate of a stratified flow 32. The apparatus 30 includes a spatial array 38 of at least two sensors 40 disposed at different axial locations $x_1 \dots x_N$ along the pipe 14. Each of the sensors 40 provides a pressure signal $P(t)$ indicative of unsteady pressure created by coherent structures convecting with the flow 32 within the pipeline 12 at a corresponding axial location $x_1 \dots x_N$ of the pipeline. The pressure generated by the convective pressure disturbances (e.g., eddies 36) may be measured through strained-based sensors 40 and/or pressure sensors. The sensors 40 provide analog pressure time-varying signals $P_1(t), P_2(t), P_3(t) \dots P_N(t)$ to a signal processor 42, which determines the parameter of the flow 32 using pressure signals from the sensors 40, and outputs the parameter as a signal 44.

[0023] While the apparatus 30 is shown as including four sensors 40, it is contemplated that the array 38 of sensors 40 includes two or more sensors 40, each providing a pressure signal $P(t)$ indicative of unsteady pressure within the pipeline 12 at a corresponding axial location X of the pipeline. For example, the apparatus may include two to twenty four sensors 40. Generally, the accuracy of the measurement improves as the number of sensors 40 in the array 38 increases. The degree of accuracy provided by the greater number of sensors 40 is offset by the increase in complexity and time for computing the desired output parameter of the flow. Therefore, the number of sensors 40 used is dependent at least on the

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degree of accuracy desired and the desired update rate of the output parameter provided by the apparatus 30.

[0024] The outputs 44 of the apparatus 30 can be received by the controller 16 for comparison to the dynamic model 18. Alternately, the signal processor 42 can form part of the above-described controller 16. Where stratification levels form part of the dynamic model and during normal operating conditions, the stratification sensors 40 can be employed to generate signals indicative of normal stratification levels that can be used to optimize the dynamic model 18.

[0025] Although this invention has been shown and described with respect to the detailed embodiments thereof, it will be understood by those of skill in the art that various changes may be made and equivalents may be substituted for elements and steps thereof without departing from the scope of the invention. In addition, modifications may be made to adapt a particular situation to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiments disclosed in the above detailed description, but that the invention will include all embodiments falling within the scope of the above description.

What is claimed is:

1. A method for monitoring a flowing fluid, said method comprising the steps of:

providing a dynamic model of a fluid flowing in a pipe, a parameter forming part of said dynamic model being a speed of sound of said fluid;

coupling at least one sonar-based sensor onto said pipeline, said sonar-based sensor being operable to measure a speed of sound of said fluid flowing through said pipeline and to generate signals indicative thereof;

providing a controller in communication with said sonar-based sensor and associated with said dynamic model, said controller receiving said signals generated by said sonar-based sensor; and

operating said controller to interpret and compare said signals generated by said sonar-based sensor to said dynamic model and determining when said speed of sound of said fluid has deviated from values corresponding to said speed of sound forming part of said dynamic model.

2. A method as defined by claim 1, comprising the further steps of:

measuring one or more operational parameters, in addition to said speed of sound, relevant to said fluid flowing in said pipe;

each of said one or more operational parameters forming part of said dynamic model; and wherein

said step of operating said controller includes operating said controller to interpret and compare said measured operational parameters to said dynamic model to determine if said measured operational parameters deviate from values corresponding to said operational parameters forming part of said dynamic model.

3. A method as defined by claim 2 wherein said one or more operational parameters include one or more of pressure, temperature, pump speed and volumetric flow rate.

4. A method as defined by claim 2 wherein said controller generates an output indicative of said comparison of said speed of sound and said operational parameters.

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5. A method as defined by claim 1 wherein:

said at least one sonar-based sensor includes a plurality of sonar-based sensors spaced axially from one another with each sonar-based sensor being coupled to the pipeline at a particular position and operable to measure a speed of sound of said fluid flowing through said pipeline at said particular position and to generate signals indicative thereof;

said step of said controller receiving said signals generated by said sonar-based sensor includes said controller receiving said signals from each of said sonar-based sensors;

said step of operating said controller includes said controller comparing said signals generated by each of said plurality of sonar-based sensors to said dynamic model to determine if said speed of sound of said fluid has deviated from values corresponding to said speed of sound forming part of said dynamic model; and wherein said method includes the further step of

said controller generating an output indicative of said comparison of said speed of sound for each of said plurality of sonar-based sensors to said dynamic model.

6. A method as defined by claim 1 wherein said at least one sonar-based sensor is removably clampable to said pipeline and said step of coupling said at least one sonar based sensor to a pipeline includes clamping said removably clampable sonar-based sensor to said pipeline.

7. A method as defined by claim 2 wherein said step of operating said controller includes determining where in said pipeline a leak is occurring.

8. A method as defined by claim 4 comprising the further steps of:

determining a location of an anomaly in said pipeline that causes said deviation of said measured speed of sound and said operational parameters from said speed of sound and said operational parameters forming part of said dynamic model.

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9. A method as defined by claim 1 comprising the further steps of:

providing at least one first sensor having a first spatial array of at least two sensors disposed at different axial locations spaced along said pipeline, each of said sensors in said first spatial array generating a first signal indicative of pressure convecting with a portion of the flow passing through an upper portion of said pipeline;

providing at least one second sensor having a second spatial array of at least two sensors disposed at different axial locations spaced along said pipeline, each of said sensors in said second spatial array generating a second signal indicative of pressure convecting with a portion of the flow passing through a lower portion of said pipeline;

said controller using said first signals to determine a first velocity of said flow passing through said upper portion of said pipeline;

said controller using said second signals to determine a second velocity of said flow passing through said lower portion of said pipeline; and

determining, based on said first velocity and said second velocity, a level of stratification in said flow.

10. A method as defined by claim 9 wherein said first spatial array is aligned axially along a top portion of said pipeline, and said second spatial array is aligned axially along a bottom portion of said pipeline.

11. A method as defined by claim 9 wherein said at least one first sensor includes a plurality of first sensors, and said at least one second sensor includes a plurality of second sensors; said method comprising the further steps of:

said controller comparing said determined level of stratification for each of first and second sensors.

12. A method as defined by claim 9 wherein each of said at least one first sensor and said at least one second sensor is formed from a piezoelectric film material.

13. A method as defined by claim 12 wherein said at least one first sensor and said at least one second sensor are removably clampable onto said pipeline and said method includes the further step of removably clamping said at least one first sensor and said at least one second sensor onto said pipeline.

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14. A method as defined by claim 11 wherein said comparing step further includes comparing said level of stratification for said first and second sensors to said dynamic model, said dynamic model having parameters indicative of acceptable levels of stratification forming part thereof.

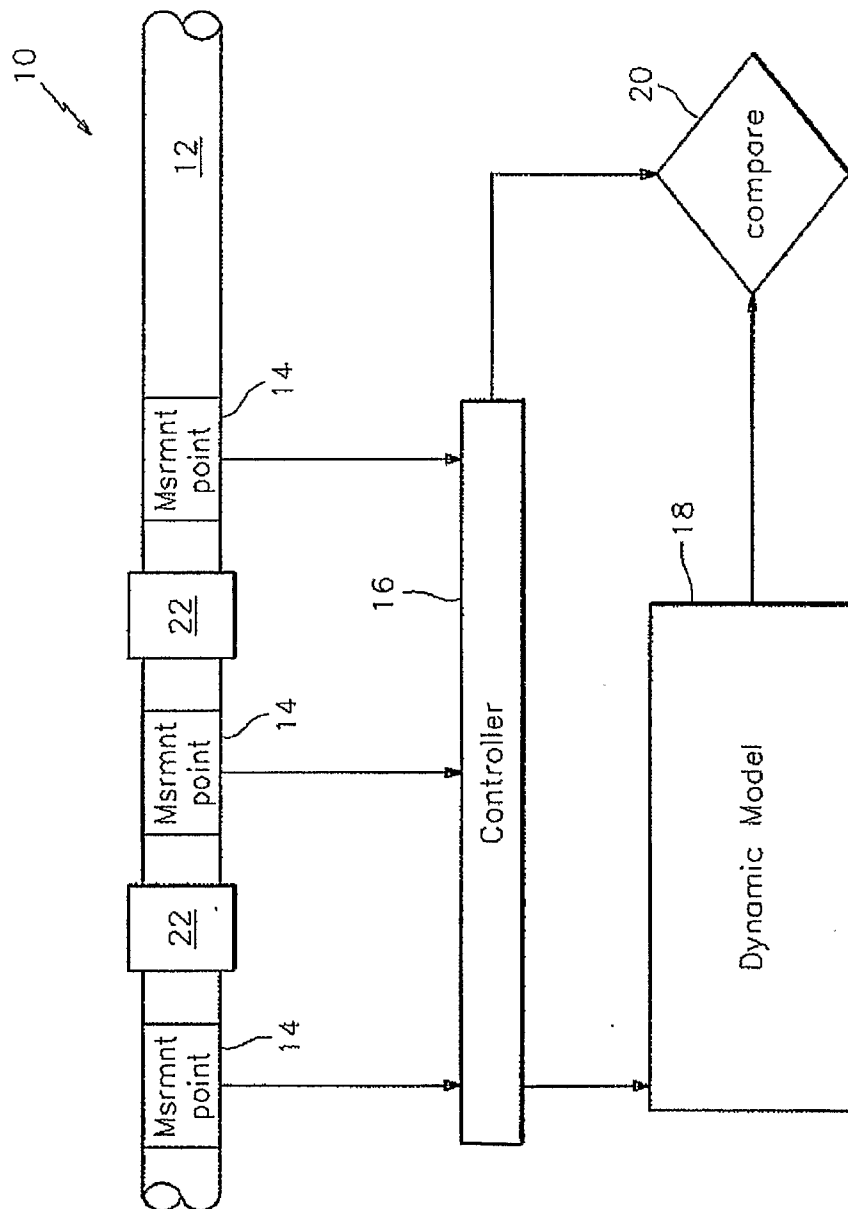
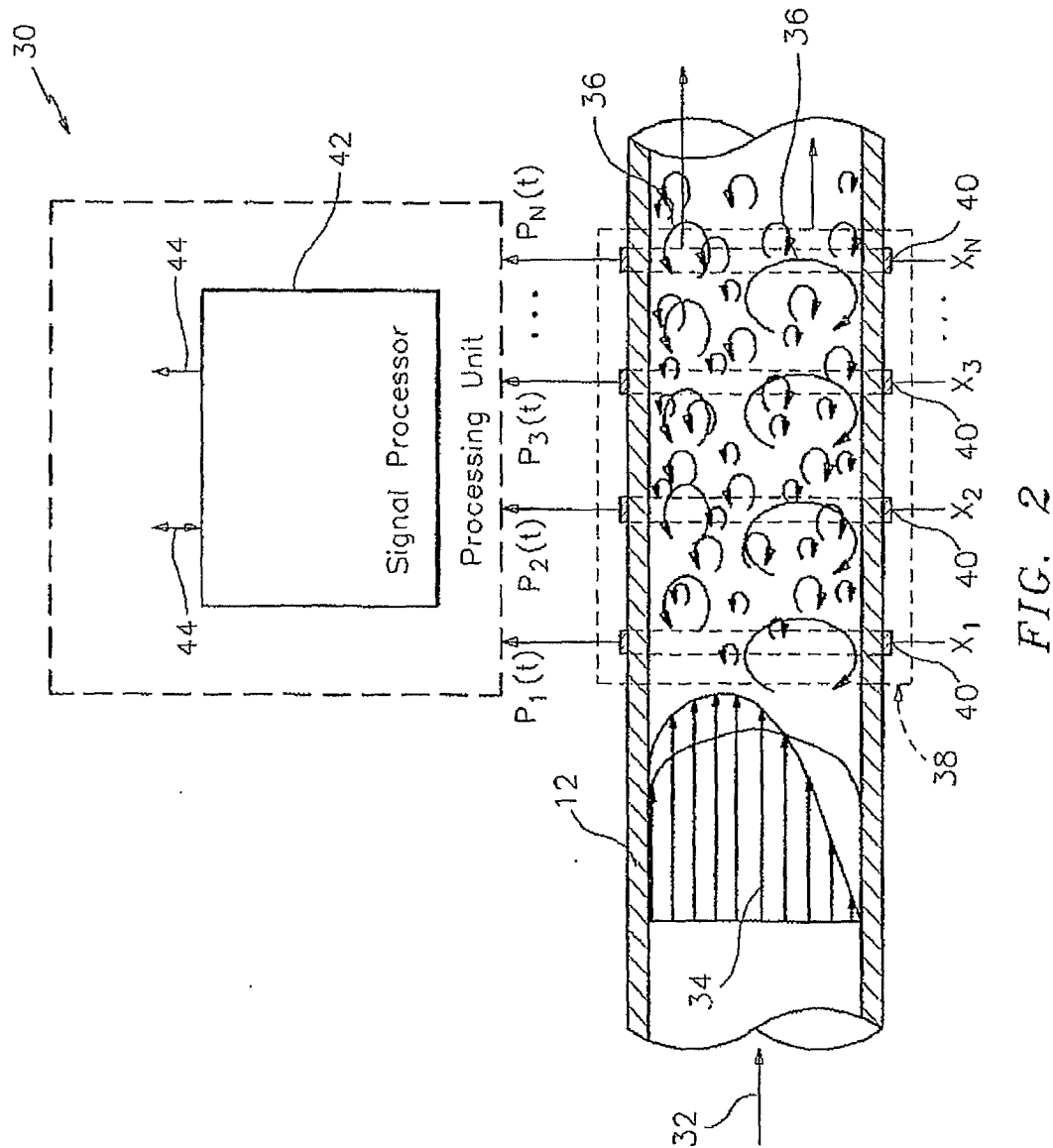
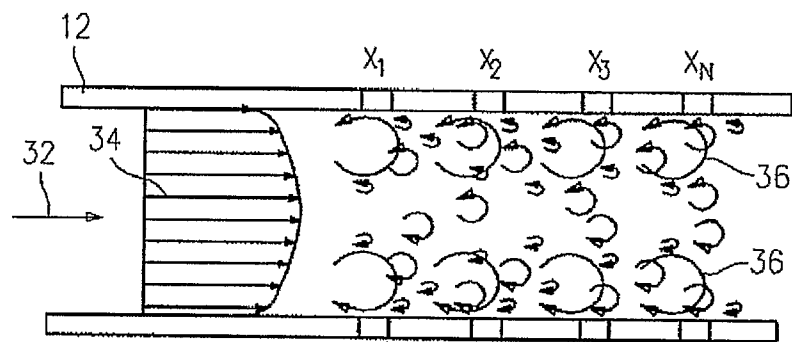


FIG. 1



*FIG. 3*