

DIAGNOSTIC DEVICE AND
METHOD FOR PRESSURE REGULATOR

This application is related to co-pending U.S. Patent application entitled "Intellegent Pressure Regulator," Serial No. _____, filed on the same day as this application by the same inventors, the entire specification of which is hereby
5 incorporated by reference.

FIELD OF THE INVENTION

The invention relates to fluid pressure regulators and more particularly, to an improved fluid pressure regulator having intelligent electronics and software to enhance performance.

10 **BACKGROUND OF THE INVENTION**

In general, the four basic elements of a process control loop include a process variable to be controlled, a process sensor or measure of the process variable's condition, a controller, and a control element. The sensor provides an indication of the process variable's condition to the controller, which also contains an indication of the desired
15 process variable condition, or the "set point." The controller compares the process variable's condition to the set point and calculates a corrective signal, which it sends to the control element to exert an influence on the process to bring it to the set point condition. The control element is the last part of the loop, and the most common type of final control element is a valve, though it may also comprise a variable speed drive or a
20 pump, for example.

A pressure regulator is a simple, self-contained control system that combines the process sensor, the controller and the valve into a single unit. Pressure regulators are

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widely used for pressure control in fluid distribution applications and the process industries, for example, to maintain a desired, reduced outlet pressure while providing the required fluid flow to satisfy a variable downstream demand. Pressure regulators fall generally into two main categories: direct-operated regulators and pilot-operated regulators.

A typical prior art direct-operated regulator 11 is illustrated in Figure 1. Typical applications for direct-operated regulators include industrial, commercial, and gas service; instrument air or gas supply; fuel gas to burners; water pressure control; steam service; and tank blanketing. The direct-operated regulator 11 includes a regulator body 12 which has an inlet 13 and an outlet 14. A fluid flow passage area 15 having a restriction area 16 connects the inlet 13 and outlet 14. The restriction area 16 has a throttling element 17, such as a plug, membrane, vane, sleeve or similar restricting device which, when moved, limits the flow of the fluid (gas or liquid). An actuator including a sensing element having two sides responds to variations in the fluid pressure being controlled. Examples of sensing elements include membranes, diaphragms or pistons. The embodiment illustrated in Figure 1 uses a diaphragm 18 for the sensing element. Control pressure is applied to the first side, or control side 19 of the sensing element via a control line or a passage 20 internal to the regulator body 12. If a control line is used for this purpose, it may be integral to the regulator body 12 or located in the adjacent piping. The second side, or reference side 21 of the sensing element is typically referenced to atmosphere. An additional force such as a spring 22 may be applied to the

actuator, which biases the throttling element into a predetermined position representing a set point.

The direct-operated regulator 11 illustrated in Figure 1 is considered a "pressure reducing" regulator because the sensing element (diaphragm 18) is connected by an internal passage 20 to pressure downstream of the regulator (on the fluid outlet-side) 14. An increase in downstream pressure is applied to control side 19 through the internal passage 20, applying pressure to the diaphragm 18, and forcing it up against the force of the spring 22. This, in turn, moves the throttling element up into the flow restriction area 16, reducing the fluid pressure to the regulator outlet 20.

Pressure reducing regulators regulate flow by sensing the pressure downstream of the regulator. A typical application of a pressure reducing regulators is on steam boilers, where pressure reducing regulators provide the initial pressure regulation. If the diaphragm 18 were connected to upstream pressure and the throttling element 17 were moved to the other side of the restrictor 16, the direct-operated regulator 11 would be considered a "back pressure" regulator. Back pressure regulators are applied, for example, in association with compressors to ensure that a vacuum condition does not reach the compressor.

A pilot-operated regulator is similar in construction to a direct-operated regulator. A typical prior art pressure reducing pilot operated regulator 23 is illustrated schematically in Figure 2A, and a prior art back pressure pilot operated regulator is illustrated in Figure 2B. The pilot operated regulator includes all the structural elements of the direct operated regulator with the addition of the pilot 24 (also called a relay,

amplifier, or multiplier). The pilot is an auxiliary device which amplifies the loading pressure on the regulator actuator to regulate pressure. The pilot is similar in construction to a self operated regulator, having essentially the same elements as the self operated regulator.

5 In the pilot operated regulator 23 illustrated in Figure 2A and Figure 2B, inlet pressure is supplied via a pressure tap 27 in the piping upstream of the regulator 23. In the back pressure pilot operated regulator 23 in Figure 2B, the pressure tap 27 further may include a restriction 26 therein. Inlet pressure to the pilot may also be supplied through an integral pressure tap to the regulator body. Outlet pressure is fed back through
10 piping 20 connected downstream of the regulator 23. The downstream pressure is connected to the pilot 24 and the main regulator 10. The pilot 24 amplifies the pressure differential across the main regulator diaphragm 18 in order to control either the upstream (back pressure) or downstream (pressure reducing) fluid pressure.

Pressure regulators have many advantages over other control devices. Regulators
15 are relatively inexpensive. They generally do not require an external power source to perform the pressure control function; rather, regulators use the pressure from the process being controlled for power. Further, the process sensor, controller and control valve are combined into a relatively small, self-contained package. Other advantages include good frequency response, good rangeability, small size, and there is generally little or no stem
20 leakage.

There are also disadvantages associated with known regulators. Significant problems associated with existing pressure regulators include "droop" and "build-up," also referred to as offset or proportional band. Droop is defined as the decrease in

controlled pressure in a pressure reducing regulator and build-up is defined as an increase in controlled pressure for a back pressure regulator that occur when moving from a low load to full load flow condition. They are normally expressed as a percent. Droop and build-up are especially prevalent with direct-operated regulators, but it also exists to a
5 lesser degree with known pilot-operated regulators.

Regulators are often required to go to a no flow condition which is referred to as "lock-up" or "reseat." In a pressure reducing regulator such as the self operated regulator 11 in Figure 1 or the pilot operated regulator 23 in Figure 2A, down stream pressure may reach a point where it is desirable for the regulator 11 to completely stop fluid flow. At
10 this down stream pressure, the control pressure fed back to the diaphragm 18 moves the throttling element 17 completely into the flow restriction area 16, thereby blocking flow. This condition is known as "lock-up." In a back pressure regulator such as the pilot operated regulator 23 shown in Figure 2B, pressure up stream of the regulator may drop to a level where the regulator is required to shut off flow. In this case, the up stream
15 control pressure falls to a level where the load spring and/or the pilot pressure cause the throttling element 17 to move to a position completely blocking fluid flow. Internal parts problems, contamination or binding in the movement of the internal parts can all contribute to a loss of lock-up capability.

Since a regulator is a self-contained control system, existing regulators typically
20 do not contain the capability to communicate with other portions of a process control system. This creates several drawbacks. Since there is not a means to remotely provide a set point or tune a regulator, they generally must be adjusted manually. Adjustments are

made by turning an adjustment knob on the regulator to achieve the desired force on the actuator. This is especially undesirable in remote applications or in processes controlling the pressure of hazardous substances. There are no control room indications of regulator performance, leaving operators to inferentially determine regulator malfunctions through
5 readings of other process indications.

The lack of communications and processing capabilities may also lead to maintainability problems. It is difficult or impossible to closely monitor regulator performance over time, so there is little advance warning of the need to fix or replace a regulator. There is also a lack of advance warnings for impending failure, which is
10 especially troublesome with existing pressure regulators: since they are process powered, they typically do not include a failure mode operation. If the operating diaphragm of a spring-loaded pressure reducing regulator fails, the regulator will open fully. This creates issues if the downstream piping cannot withstand upstream pressure conditions, or if a relief valve that can handle the maximum flow of the regulator is not present. Back-
15 pressure regulators will completely close upon diaphragm failure, creating similar issues for the upstream portion of the process.

It is well known that in many situations to which pressure regulators could be applied, control valves are used instead. The control valve includes a powered actuator which is responsive to externally supplied signals for moving a throttling element to
20 control flow. It has been estimated that properly utilized, regulators could replace control valves in 25% of applications using control valves. The hesitancy to use regulators in place of control valves is due, in large part, to the shortcomings associated with known

pressure regulators. Primary concerns include droop characteristics and the lack of remote operability. Process equipment users, however, are continually looking to be more cost competitive. In addition to seeking improvements in process efficiency and up-time with existing process equipment, process equipment users are seeking lower cost solutions to process control. If the above discussed limitations of regulators were eliminated, they could provide a lower cost option for many control valve applications.

U.S. industries spend approximately \$200 billion each year in maintenance of plant equipment. This results in maintenance costs representing 15-40% of the cost of goods sold per year. Further, one-third of the dollars spent on maintenance is wasted from unnecessary or ineffective maintenance. For example, since known regulators do not have diagnostics or communications capabilities to exchange information with external systems, they are difficult to troubleshoot. Often, in an attempt to correct unidentified process problems, regulators are replaced, only to learn that the regulator was functioning properly. Changing the regulator may require halting the entire process, resulting in significant lost production time. Improving the performance of process instruments such as pressure regulators as well as improving maintainability through processing capabilities and communications will significantly reduce manufacturing costs.

Thus, a need clearly exists for an improved pressure regulator that compensates for droop characteristics and exhibits improved performance. Further, it would be desirable for the improved regulator to include communication and diagnostic capabilities to allow remote operation and the exchange of data to enhance maintainability.

Moreover, these additional features are required concurrently with the need for economical solutions for pressure regulation.

SUMMARY OF THE INVENTION

The present invention addresses the above shortcomings of the prior art by providing an intelligent pressure regulator which enhances regulator performance by including processing and communications capabilities. This is accomplished while
5 maintaining the pressure regulator's existing benefits of simplicity and economy.

In a broad aspect, an exemplary embodiment of the invention provides an intelligent regulator for maintaining a fluid in a process at a predetermined pressure which comprises a fluid inlet, a fluid outlet, a fluid flow passage connecting the inlet and the outlet, and a throttling element moveable within the flow passage for selectively
10 restricting fluid flow through the flow passage. An actuator is coupled to the throttling element for selectively moving the throttling element. The actuator includes a control side and a reference side with a reference load coupled thereto for biasing the throttling element in a predetermined reference position which represents the predetermined pressure. A feedback line applies pressure from the fluid being controlled to the control
15 side to move the actuator against the reference load to move the throttling element within the flow passage to adjust the fluid flow thereby controlling the pressure of the fluid in the process. The invention further includes a pressure sensor which provides a signal indicating the pressure of the fluid being controlled, an adjusting pressure for adjusting the position of the throttling element, and a controller which receives the signal indicating
20 the pressure of the fluid being controlled and applies the adjusting pressure to the actuator in response to the signal. Further embodiments provide capabilities for proportional,

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integral and derivative (PID) control, diagnostics processing, and communications with external devices.

In accordance with another embodiment of the invention, an electronic controller for a pressure regulator that roughly maintains fluid pressure at a predetermined level by using the pressure of the fluid being controlled to position a throttling element to restrict fluid flow through the self operating pressure regulator is presented, which comprises a pressure sensor which provides a signal indicating the pressure of the fluid being controlled, a processor which receives the signal indicating the pressure of the fluid being controlled and outputs a signal representing an adjustment to the throttling element, and an adjusting pressure which is applied to the throttling element in addition to the pressure of the fluid being controlled in response to the signal output by the processor.

In another broad aspect, a method in accordance with the present invention for compensating for droop in a pressure regulator that roughly maintains fluid pressure at a predetermined level by using the pressure of the fluid being controlled to position a throttling element to restrict fluid flow through the self operating pressure regulator is provided. The method comprises the acts of determining the pressure of the fluid being controlled, calculating an error value by comparing the pressure of the fluid being controlled to the predetermined level, converting the error value to an adjusting pressure, and repositioning the throttling element by applying the adjusting pressure in addition to the pressure of the fluid being controlled to the throttling element.



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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram illustrating a typical prior art direct-operated pressure regulator.

Figure 2A is a schematic diagram illustrating a typical prior art pilot-operated pressure reducing regulator.

Figure 2B is a schematic diagram illustrating a typical prior art pilot-operated back pressure regulator.

Figure 3 is a schematic diagram illustrating an exemplary embodiment of a back pressure control intelligent regulator in accordance with the present invention.

Figure 4 is a schematic diagram illustrating an exemplary embodiment of a pressure reducing intelligent regulator in accordance with the present invention.

Figure 5A graphically illustrates the electronic controller's droop compensation function for an embodiment of the invention.

Figure 5B graphically illustrates the electronic controller's build-up compensation function for an embodiment of the invention.

Figure 6 is a block diagram of the intelligent regulator, highlighting the functional areas of the self operating regulator and electronic controller.

Figure 7 schematically illustrates the electronic controller of an embodiment of the invention.

Figure 8A is a regulator offset chart, plotting set point pressure value and control pressure against flow for a pressure reducing regulator.

Figure 8B is a regulator offset chart, plotting set point pressure value and control pressure against flow for a back pressure regulator.

Figure 9A is a regulator inlet sensitivity chart, illustrating control pressure curves for various inlet pressures for a pressure reducing regulator.

5 Figure 9B is a regulator inlet sensitivity chart, illustrating control pressure curves for various inlet pressures for a back pressure regulator.

Figure 10 is a chart illustrating a measure of hysteretic error for a pressure regulator.

Figure 11A is a chart illustrating "lock-up" in a pressure reducing regulator.

10 Figure 11B is a chart illustrating "reseat" in a back pressure regulator.

Figure 12 illustrates a communications link between an intelligent regulator in accordance with the present invention and an external control room using a single twisted pair with Fieldbus.

15 Figure 13 illustrates a communications link between an intelligent regulator in accordance with the present invention and an external control room using a single twisted pair with HART.

Figure 14 illustrates a communication link between an intelligent regulator in accordance with the present invention and an external control room using a four-wire, dual twisted pair arrangement.

20 Figure 15 illustrates a communication link between an intelligent regulator in accordance with the present invention and an external control room using a radio link

Figure 16 illustrates a communication link between an intelligent regulator in accordance with the present invention and an external control room using alternate communications means such as modem or fiber optics.

DETAILED DESCRIPTION OF THE INVENTION

5 Turning to the drawings and, in particular, Figure 3 and Figure 4, two embodiments of an intelligent pressure regulator in accordance with the present invention are illustrated schematically. Each embodiment is referenced generally by the numeral 10 and includes a self operating regulator and an electronic controller (shown surrounded by a broken line in Figure 3 and Figure 4). In general, Figure 3 illustrates an intelligent
10 regulator in accordance with the present invention as used in a back pressure control application, while figure 4 illustrates an intelligent regulator in accordance with the present invention in a pressure reducing application. In Figure 3, fluid flow is from right to left. In Figure 4, fluid flow is from left to right. The specific embodiments illustrated in Figure 3 and Figure 4 include a self operating regulator, but one skilled in the art with
15 the benefit of this disclosure could implement the invention using a pilot operated regulator.

Referring to the figures, the self operating regulator 11 includes a body 12 which comprises a fluid inlet 13, a fluid outlet 14, and a flow passage 15 connecting the inlet 13 and the outlet 14. A flow restriction area 16 is situated within the flow passage 15, and a
20 throttling element 17 functions to restrict fluid flow through the restriction area 16. The throttling element 17 may comprise a plug, membrane, vane, sleeve or other suitable item which when moved within the restriction area 16 throttles the fluid flow. The regulator

10 further includes an actuator including a sensing element, which in the particular embodiments illustrated in Figure 3 and Figure 4 comprises a diaphragm 18 which is coupled to the regulator body 12. The sensing element alternately may be in the form of a membrane or a piston. A sliding stem 29 connects the throttling element 17 to the
5 diaphragm 18. The diaphragm 18 includes a control side 19 to which control pressure 30 is applied. The control pressure 30 is connected to the diaphragm 18 by a control line (not shown) or a passage (not shown) within the valve body 12 or external thereto.

The embodiment of the regulator 10 illustrated in Figure 3 is a back-pressure regulator, since the control pressure 30 is applied to the diaphragm 18 upstream of the
10 regulator 10. A pressure reducing regulator is shown in Figure 4, with the diaphragm 18 connected to control pressure 30 which is downstream of the regulator 10. The diaphragm 18 further includes a reference side 21 opposite the control side 19 which is referenced to atmosphere. In known regulators, the reference side typically includes a spring 22 or another suitable means such as a weight which applies an additional force to
15 the reference side 21. Additionally, a set screw 31 is positioned to set the initial position of the spring 22.

In the back pressure regulator 10 of Figure 3, the process fluid is shown flowing through a pipe 32. The spring 22 is biased such that it tends to keep the throttling element 17 in an essentially closed position. The fluid flows into the inlet 13, through the
20 restriction area 16 and goes out through the outlet 14. Control pressure 30 is connected to the control side 19 of the diaphragm 18 in a manner such that system pressure is applied from an upstream location to the control side 19, forcing the diaphragm 18 to move

against the spring 22, which moves the stem and the throttling element 17 as necessary to vary flow through the restriction area 16, thus regulating fluid pressure.

The pressure reducing regulator 10 of Figure 4 operates in a similar manner to the back pressure regulator discussed in association with Figure 3, except that the control pressure 30 is sensed downstream of the regulator 10 and the throttling element 17 is on the opposite side of the restriction area 16. In the pressure reducing regulator 10, the spring 22 applies force to the reference side 21 of the diaphragm 18 a manner to bias the throttling element 17 in an essentially open position, or out of the flow restriction area 16. Control pressure 30 is applied to the control side 19 of the diaphragm 18 from a downstream location, thus moving the throttling element 17 further into or out of the restriction area 16 to control downstream pressure by regulating flow through the restriction area 16.

With the spring loading system of typical self operating regulators, the controlled pressure tends to decrease as the flow varies from a minimum to maximum rate. This is known as droop in a pressure reducing regulator and build-up in a back pressure regulator (also referred to as proportional band or offset). This invention compensates for droop and build-up and enhances the regulator's accuracy by adding an electronic controller 28, which also receives an indication of the set point and control pressure. The controller compares the set point and control pressure, then applies an adjusting pressure to the reference side of the diaphragm to compensate for the limitations of the regulator's spring mass system.

The droop regulation function of the electronic controller is illustrated graphically in Figure 5A, with control pressure on the y-axis and flow rate on the x-axis. In Figure 5A, the curve labeled "a" illustrates the droop or offset of a typical self operated pressure reducing regulator, wherein the control pressure decreases as the flow rate increases. The curve labeled "b" illustrates the output of the electronic controller to compensate for the droop exhibited in curve a of Figure 5A. Ignoring the effects of friction, these curves essentially mirror each other. Curve "c" illustrates the result of combining curves "a" and "b", which equals the set point.

Similarly, the build-up regulation function is illustrated graphically in Figure 5B. As with Figure 5A, the curve labeled "a" in Figure 5B illustrates the build-up or offset of a back pressure regulator, wherein the control pressure increases as the flow rate increases. The curve labeled "b" illustrates the output of the electronic controller to compensate for the build-up exhibited in curve a of Figure 5B. Ignoring the effects of friction, these curves essentially mirror each other in a manner similar to the droop curves illustrated in Figure 5A. Curve "c" illustrates the result of combining curves "a" and "b", which equals the set point.

Referring back to Figure 3 and Figure 4, the electronic controller 28 includes a pressure to current (P/I) converter 33, a processor which functions as a proportional, integral and derivative (PID) controller 34, and a current to pressure (I/P) converter 35. The PID controller 34 may be embodied in a microprocessor. The electronic controller 28 is powered by an external power source 36, which is shown as a 24 volt power supply in Figure 3 and Figure 4. Power may be provided by a number of suitable power sources including an external power source such as a transformer or loop power from a

distributed control system, a power generator internal to the self operating regulator which uses pressure from the process being controlled for an energy source, solar power or battery power. A pressure 37 supplies the I/P converter 35, which provides pneumatic pressure to the reference side 21 of the diaphragm 18 to provide droop or build-up
5 compensation as necessary depending on flow conditions. An alternative to using a pressure supply 37 to provide pneumatic pressure is driving the actuator with an electric motor, in which case the I/P converter 35 would not be included. Rather, the motor would receive a signal directly from the PID controller 34.

The functional areas of the exemplary embodiment of the intelligent regulator 10
10 are illustrated in Figure 6. The rough set point block 38 represents the desired pressure, or set point, which in an embodiment of the invention is in the form of the regulator load spring exerting a force on the reference side of the diaphragm, shown as summing junction 39. The set point 38 is a "rough" set point, since the pressure regulation performed by the self operating regulator 11 is subject to droop. The rough set point 38
15 is input to the self operating regulator by adjusting a set screw which sets the load of the regulator spring. The force exerted by the regulator load spring against the diaphragm is illustrated as a positive (+) force at the summing junction 39.

The force out of summing junction 39, together with the regulator's spring rate, establishes the position of the regulator's throttling element in the restriction area. A gain
20 factor 40 is applied to the position information to establish the regulator's output flow rate W . The output flow W is compared to the desired, or load flow W_L at a summing junction 41. If the output flow W equals the load flow W_L , the system is in steady state and the control pressure P_c remains constant. If the system is not in steady state, the P_c

fed back to the diaphragm, which is shown as a negative (-) force at summing junction 39 will not balance at summing junction 39. This results in the throttling element moving relative to the restriction area until the output of summing junction 39 is zero. In other words, P_c exerts a force on the diaphragm that opposes the force exerted by the load spring to change the position of the throttling element, which adjusts flow, thus regulating pressure.

To compensate for offset and enhance the self operating regulator performance, an indication of the control pressure is also directed to the electronic controller 28. The P/I converter 33, which may be a pressure transducer that is either integral to the regulator or mounted to the adjacent piping external to the regulator, converts P_c to a signal which may be a 4-20 mA signal as provided by a typical analog pressure transducer. The P_c signal is then applied to the electronic controller's PID controller 34. The P_c is multiplied by the derivative constant 42, then applied to a summing junction 43 along with the P_c signal. The output of summing junction 43 is compared to a fine set point signal 44 from an external source such as a host computer or distributed control system at summing junction 45, which produces an error signal. The error signal is applied to the proportional constant 46 and the integral constant 47, and then applied to a summing junction 48 which produces an output signal. The output signal is input to the I/P converter 35, which provides pneumatic pressure to the diaphragm, shown as a positive (+) force at summing junction 39.

The addition of the above discussed processing capabilities to compensate for droop and enhance control also provides a means for enhancing other performance

aspects of a pressure regulator, including remote operation and communications, improved process operation, diagnostics capabilities, increased maintainability, trending, alarm capabilities, etc. These added enhancements will become more evident as the electronic controller is discussed further.

5 An embodiment of the intelligent regulator 10 is illustrated schematically in Figure 7. The self operating regulator 11 is shown in a schematic view. In addition to the PID controller portion 34 described above, the electronic controller 28 further includes diagnostics 49, sensing 50, communications 51, electronic power 52 and alternate inputs 53 sections. These functional sections of the electronic controller may all
10 be embodied in a microprocessor.

 The sensing section 50 provides the error signals to the PID controller 34 based on the signals indicating inlet pressure P1, downstream pressure P2, and actuator loading pressure PL, which are processed according to PID constants. These signals may be provided by sensors integral to the regulator body or from external sensors. Other
15 process variables are received by the alternate inputs section 53. These inputs may include temperature signals 65 from temperature sensors either integral to the regulator or mounted external to the regulators. Audio or vibration transducers 66, for example, provide inputs that may indicate leakage and/or cavitation or flashing in the flow restriction area. Valve stem travel 67 and actuator travel 68 information is supplied to the
20 alternate inputs section 53 via motion transducers to monitor the condition of these elements. Information such as the inputs described above are examples of process elements that may be supplied to the alternate inputs section 53 of the electronic

controller 28. Other appropriate process data, such as pH or flow, may also be provided via sensors integral to the regulator or external thereto. Any or all of the above sensor signals may be analog signals which are converted to digital values by the electronic controller.

5 Baseline diagnostic data can be used to develop a "signature" for a specific regulator, which may be stored in the controller's memory or in the memory of an external system. Performance information provided to the diagnostics section 49 from the sensing section 50 and the alternate inputs section 53 may then be processed and compared to the baseline data, or signature, and the diagnostics section 49 can provide
10 alarms, actual and predicted failures, and other diagnostic information to the system operator if regulator characteristics and performance deviate from the expected signature performance by more than some predetermined amount. The alarm conditions can be reported spontaneously via unsolicited communications to the host computer from the regulator or via polling from the host computer. Polling may occur at predetermined time
15 intervals. Alternately, an alarm device that provides an audio or visual alarm, for example, may signal deviations from the signature. This information may then be used for maintenance forecasting, system performance improvement, life cycle accumulation, etc. Examples of specific information which may be processed by diagnostics section 49 of an embodiment of the invention are discussed as follows.

20 Offset: As described above, known regulators exhibit offset such as droop or build-up. Figures 8A and 8B show graphs with the set point pressure value and control pressure for a self operated regulator plotted against flow on the x-axis. The set point value is constant over the flow range. Control pressure for a pressure reducing regulator

decreases as the flow rate increases as shown by the curve labeled "Regulator" in Figure 8A, while control pressure for a back pressure regulator increases as the flow rate increases as illustrated in Figure 8B (disregarding droop or build-up compensation by the electronic controller). A pilot operated regulator would exhibit a similar curve, though the offset would be smaller. The distance between the droop curve (Figure 8A) or the build-up curve (Figure 8B) and the set point curve at a given flow rate is the offset for the regulator. Offset can be locally determined via

$$\text{Offset} = \Delta P * K_L$$

where ΔP is the difference between controlled pressure and inlet pressure, and K_L is a local flow coefficient. The processor of the intelligent regulator can monitor offset and compare it against a baseline value. A change in offset may indicate a problem with the load force (spring) of the regulator, for example. The operator can then be notified of this condition.

Inlet pressure sensitivity: Figures 9A and 9B each show three plots of control pressure vs. flow rate at various inlet pressures, labeled a, b, and c. This illustrates a regulator's sensitivity to varying inlet pressures. For a given flow rate, the difference between control pressures for different inlet pressures defines inlet sensitivity. The curves in Figure 9A illustrate inlet sensitivity for a pressure reducing regulator, while Figure 9B illustrates inlet sensitivity curves for a back pressure regulator. As with offset, the inlet sensitivity can be compared to baseline information to provide diagnostic and failure prediction information from the electronic controller to a user.

Hysteresis and Deadband: Hysteresis is defined as the tendency of an instrument to give a different output for a given input, depending on whether the input resulted from an increase or decrease from the previous value. Figure 10 illustrates a measure of hysteretic error which includes hysteresis and deadband. The curve labeled "a" shows control pressure plotted against flow rate for a decreasing flow demand. The curve labeled "b" shows a similar curve for increasing flow demand. In other words, curve "a" plots control pressure for given flow rates when the throttling element is moving in a first direction, and curve "b" plots control pressure for corresponding flow rates when the throttling element is moving in the opposite direction. The difference between the two curves is referred to as "deadband." Monitoring the slope of a hysteresis curve can provide information regarding spring constant, for example. A change in deadband or in the slope of a hysteresis curve may indicate or be used to predict problems with the spring, actuator, throttling element or other component of the regulator.

Lock-up and reseal: Figure 11A and 11B graphically illustrate the lock-up and reseal conditions. In a pressure reducing regulator (Figure 11A), when downstream pressure reaches a predetermined point above the set point value, the control pressure should cause the throttling element to move to a completely closed position, thereby preventing fluid flow. The lock-up point is labeled "a" in Figure 11A. Figure 11B illustrates reseal, which is the back pressure regulator's counterpart to lock-up. The reseal condition occurs when the up stream pressure drops to a level below the set point such that the throttling element moves to a closed position, labeled "b" in Figure 11B. The lock-up/reseal control pressure value and the slope of the segment of the regulator

pressure curve between the setpoint value and the lock-up or reseal point may be determined and stored in intelligent regulator diagnostics section or an external computer. Alternately, a leakage transducer, such as an audio or seismic transducer, may be used to correlate lock-up or reseal condition with known flow conditions. The regulator's lock-up/reseal performance is compared to these baseline values to diagnose regulator operation. Changes in the lock-up/reseal performance may indicate internal parts problems or binding in the movement of the internal parts, for example.

Expected PID control: Overall regulator performance can be achieved by looking at control pressure, offset, flow, and/or hysteretic error and comparing these variables to the performance of the expected PID control. A flow rate may be calculated internal to the electronic controller using parameters of the flow coefficient for the body of the regulator in relationship to the fluid liquid flow, gas flow and steam flow. This internal flow is then compared to actuator travel and a regulator body correction factor to calculate main regulator flow. These calculations may be made in the electronic regulator's processor, or the information may be communicated to a host computer for calculation via the communications section.

Auto tuning: The above factors can also be used for developing P, I and D tuning constants. A step change is input to the set point via the electronic controller, then the output response is measured to perform diagnostics on the system dynamics.

Travel: Actuator travel is an important diagnostic factor. Among other things, actuator travel is used to calculate throttling element loading and position. An example of using travel for diagnostic purposes is to calculate and compare the forces on opposing

sides of the diaphragm. The processor's diagnostic section may calculate the force exerted by the regulator load spring on the reference side of the diaphragm:

$$(T_1 + I_s) * K_1$$

where T_1 = actuator travel, I_s = the initial spring adjustment as set by the set screw, and

5 K_1 = the spring constant. This is compared to the force exerted on the control side of the diaphragm:

$$P_c * A$$

where P_c = control pressure and A = diaphragm area. In a pilot operated regulator, the pilot actuator travel can also be used for diagnostics in a similar manner. Further, in
10 regulators using an electric motor to adjust the throttling element, the motor voltage and current can be viewed with respect to travel for diagnostics purposes. These comparisons, as well as indications of inlet and control pressure, inlet sensitivity, hysteretic error, and flow are used to provide diagnostic information regarding regulator health and performance.

15 Flashing and cavitation: These are phenomena encountered in liquid flow which may introduce noise and vibration to the regulator, possibly limiting the regulator's life. Flashing and cavitation both are related to the formation of vapor bubbles in the fluid. When the fluid flows through the restriction area, velocity increases and pressure decreases, which causes the vapor bubbles to form. Once the fluid flows through the
20 restriction, the fluid flow decelerates and the pressure recovers, causing the vapor bubbles to violently collapse. Either audio or vibration sensors may be used to sense the presence of cavitation or flashing directly by comparing the sensed noise/vibration characteristics

and comparing them to baseline characteristics, or an alternate process variable, ΔP_A can be calculated by

$$\Delta P_A = K_c(P_1 - r_c P_v)$$

where K_c = a cavitation or flashing index, P_1 = inlet pressure, r_c = critical pressure ratio
5 constant and P_v = vapor pressure. This value is compared to the input constants of the fluid stream vapor pressure to indirectly ascertain the presence of flashing or cavitation, and transmit an alarm.

With the novel diagnostics capabilities added to the regulator, on-line diagnostics may now be performed in the various categories described above and in other areas. An
10 electronic "bump" -- a sudden step-change to the set point value -- may be introduced into the system. This causes an upset to the process control loop, which the intelligent regulator will attempt to correct. As the regulator reacts to the electronic bump, the regulator's performance with regards to the various factors described above (and other factors) is measured and compared to the regulator's signature by the electronic
15 controller's diagnostics section. This provides a basis to do on-line diagnostics without significantly upsetting or disturbing the process.

Set point, configuration, diagnostics, and other information from the exemplary intelligent regulator may be exchanged with external systems and devices through various communications means. This provides the capability for remotely controlling the
20 regulator, which is an important feature missing from known mechanical pressure regulators. An operator may send commands to the regulator changing operating parameters and report parameters. Further, diagnostic information may be sent to an

external system for processing, rather than processing this data within the regulator. The communications capabilities of the exemplary intelligent regulator are especially useful in remote and hazardous environments where maintenance and operations are difficult.

A variety of communications media may be used with the intelligent regulator of the present invention, such as a single twisted pair having communications overlaid on power or modulated with power, a single twisted pair for data communications only, radio, modem, fiber optics, coax, and several other communications technologies. The communications capabilities of the exemplary embodiment of the invention also allow exchanging configuration and control information with other process instruments or with an external control system or host computers.

Figure 12 illustrates a two wire communications scheme which could be implemented with an embodiment of the intelligent regulator of the present invention using the digital Fieldbus communications protocol, wherein digital data is combined with power for the intelligent regulator's electronic controller on the single twisted pair. The signal sent from the control room 54 is passed through a low pass filter 55 to separate the system power from the data. The power then may be passed through power conditioning circuits 56 and provided to an intelligent regulator in accordance with the present invention and to other devices. The received Fieldbus signal is passed through high pass filters 57 to separate the communications data from the system power, which is then passed on to the electronic controller's communications section 51. Information transmitted back to the host system is passed through a modulator 58 to combine the data with the system power signal.

Figure 13 illustrates an alternate communication scheme which could be implemented with an embodiment of the invention using the HART protocol, wherein the digital communications data is superimposed on a 4-20 mA analog signal. The signal from the control room 54 is passed through impedance control and filtering circuits 59. The 4-20 mA signal is then conditioned to provide the appropriate power to the intelligent regulator and other devices. The received signal is filtered 57 to remove the communications data from the 4-20 mA HART signal, which is passed on to the electronic controller's communications section 51. Transmit data is passed through a modulator 58 to combine the data with the 4-20 mA signal.

Figure 14 illustrates an example of a communications system using dual twisted pairs. Power is conditioned 56 and provided to the intelligent regulator and other devices on one of the two-wire pairs. Data is passed over the other two-wire pair from the control room 54 through transmit and receive circuits 60 to the electronic controller's communications section. 51

In Figure 15, an example communications arrangement using radio communications is illustrated. A radio signal containing data is sent from the control room to a radio 61 associated with the intelligent regulator. The signal is passed through a power control device 62 (if the regulator's radio is not equipped with data transmit ready control) and appropriate data communications hardware 63, then the information is provided to the regulator's communications section 51. Similarly, Figure 16 shows a configuration for communicating between a control room 54 and an intelligent regulator in accordance with the invention using a modem or fiber optics. Other communications media may also be used with a configuration as illustrated in Figure 16. Data is sent from

the control room 54 to an appropriate transceiver 64, which processes the data and passes it through communications hardware 63 to the communications section 51 of the electronic controller.

The above description of several exemplary embodiments is made by way of
5 example and not for purposes of limitation. Many variations may be made to the
embodiments and methods disclosed herein without departing from the scope and spirit
of the present invention. The present invention is intended to be limited only by the
scope and spirit of the following claims.

WHAT IS CLAIMED IS:

1. A pressure regulator for maintaining a fluid in a process at a predetermined pressure comprising:
 - a body defining a fluid inlet, a fluid outlet, and a fluid flow passage in fluid connection with the inlet and the outlet;
 - a throttling element moveable within the flow passage for selectively restricting fluid flow through the flow passage;
 - an actuator coupled to the throttling element for selectively moving the throttling element, the actuator having a control side and a reference side;
 - a reference load coupled to the reference side of the actuator for biasing the throttling element to a predetermined reference position;
 - a feedback line for applying pressure from the fluid in the process to the control side of the actuator for moving the actuator against the reference load to position the throttling element within the flow passage;
 - a first pressure sensor which provides a signal indicating the pressure of the fluid in the process at a first point in the process; and
 - a controller which receives the signal indicating the pressure of the fluid and outputs an error signal corresponding to the difference between the sensed pressure and a predetermined pressure level, the controller including a digital memory for storing the error signals at different times during the operation of the pressure regulator, and a processor for running a routine that compares the error signals at different times to obtain diagnostic data corresponding to the operation of the pressure regulator.



1 2. The pressure regulator of claim 1 wherein the controller digital memory includes
2 baseline data corresponding to a baseline operating characteristic of the pressure
3 regulator.

1 3. The pressure regulator of claim 2 further comprising an alarm device coupled to
2 the controller, wherein the controller is adapted to compare the diagnostic data and the
3 baseline data and actuate the alarm device whenever the comparison indicates that the
4 diagnostic data has deviated from the baseline data by a predetermined amount.
5

1 4. The pressure regulator of claim 1 further comprising a second pressure sensor for
2 sensing the pressure of the fluid at a second point in the process, wherein the controller is
3 adapted to calculate, at various points in time, regulator offset values that correspond to
4 the difference between the pressure detected by the first sensor and the pressure detected
5 by the second sensor, and wherein the controller is adapted to store digital representations
6 of the calculated regulator offset values in the controller memory.

1 5. The pressure regulator of claim 4 wherein the first pressure sensor is adapted to
2 detect the fluid pressure at the inlet and the second pressure sensor is adapted to detect the
3 fluid pressure at the outlet, and wherein the processor is adapted to run a routine that
4 determines and stores in the controller memory, regulator offset values for a plurality of
5 different inlet pressures.



1 6. The pressure regulator of claim 1 further comprising a sensor for detecting the
2 direction of movement of the throttling element, wherein the processor is adapted to
3 generate diagnostic data concerning the hysteric error of the pressure regulator by: (i)
4 storing in the controller memory a first digital signal reflecting the pressure detected by
5 the first pressure sensor when the throttling element is moving in a first direction; (ii)
6 storing in the controller memory a second digital signal reflecting the pressure detected
7 by the first pressure sensor when the throttling element is moving in a second direction,
8 opposite to the first direction; and (iii) comparing the first and second digital signals to
9 produce a difference signal that is reflective of the hysteretic error of the pressure
10 regulator.

1 7. The pressure regulator of claim 1 wherein the controller memory includes a
2 baseline datum reflective of a predetermined fluid pressure at which the throttling
3 element will move to a completely closed position and wherein the processor is adapted
4 to: (i) store in controller memory a digital signal corresponding to the fluid pressure
5 detected by he first pressure sensor at which the throttling element moves to a completely
6 closed position; and (ii) compare the baseline datum with the digital signal corresponding
7 to the fluid pressure detected by he first pressure sensor at which the throttling element
8 moves to a completely closed position to generate a diagnostic signal corresponding to
9 the difference between the compared signals.

1 8. A device for sensing cavatation and flashing in a pressure regulator that uses the
2 pressure of a fluid in the process to position a throttling element to restrict fluid flow



3 through the pressure regulator, the pressure regulator including an inlet, the device

4 comprising:

5 an inlet pressure sensor;

6 a processor including a memory having a cavitation/flashing index, a critical
7 pressure ratio constant, and input constants of the fluid stream vapor
8 pressure stored therein;

9 the processor including a routine for calculating absolute pressure drop (ΔP_A)
10 according to $\Delta P_A = K_c(P_I - r_c P_v)$ where K_c = the cavitation/flashing index,
11 P_I = sensed inlet pressure, r_c = the critical pressure ratio constant and P_v =
12 vapor pressure; and

13 the processor further including a routine for comparing ΔP_A to the input constants
14 of the fluid stream vapor pressure to detect flashing and cavitation.

1 9. A device for sensing cavitation in a pressure regulator that uses the pressure of a
2 fluid in the process to position a throttling element within a flow passage to restrict fluid
3 flow through the pressure regulator, the device comprising:

4 a sensor adapted to detect at least one physical parameter associated with the
5 pressure regulator and provide electrical signals corresponding to the detected physical
6 parameter, wherein the physical parameter is subject to change upon the onset and
7 presence of cavitation,



8 a memory having a first set of electrical baseline physical parameter signals stored
9 therein, the first set of baseline physical parameter signals corresponding to the physical
10 parameter characteristics associated with at least one stage of flashing; and
11 a processor adapted to receive from the sensor the electrical signals corresponding
12 to the detected physical parameter and to receive from the memory the baseline physical
13 parameter signals and to compare the identified signals and provide an electrical signal
14 reflecting the occurrence of flashing whenever there is an approximate match of the
15 signals.

1 10. The device of claim 9 wherein the sensor is an acoustic sensor coupled to the flow
2 passage for sensing acoustic noise characteristics within the flow passage and wherein the
3 the first set of baseline physical parameter signals correspond to the noise characteristics
4 associated with various stages of flashing.

1 11. The device of claim 9 wherein the sensor is a seismic sensor coupled to the flow
2 passage for sensing vibration characteristics within the flow passage and wherein the first
3 set of baseline physical parameter signals correspond to the vibration characteristics
4 associated with various stages of flashing.

1 12. The device of claim 9 wherein the a memory has a second set of electrical
2 baseline physical parameter signals stored therein, the second set of baseline physical
3 parameter signals corresponding to the physical parameter characteristics associated with
4 at least one stage of cavitation; and wherein the processor is adapted to receive from the
5 sensor the electrical signals corresponding to the detected physical parameter and to



6 receive from the memory the second set of baseline physical parameter signals and to
7 compare the identified signals and provide an electrical signal reflecting the occurrence of
8 cavitation whenever there is an approximate match of the signals.

9 13. A method for performing on-line diagnostics on a pressure regulator which
10 maintains pressure in a process at a set point value by applying the process pressure to an
11 actuator to adjust a fluid flow throttling element, the method comprising the acts of:

12 collecting baseline performance data for the regulator, reflecting the operating
13 characteristics of the pressure regulator under a given set of operating conditions and
14 storing the baseline performance data in a memory device;

15 temporarily introducing a step change to the set point to change the set point to an
16 adjusted set point value;

17 collecting performance data reflecting the operating characteristics of the
18 regulator as it brings the process pressure towards the adjusted set point value.

19 comparing the performance data to the baseline data to obtain diagnostic
20 information concerning the operation of the pressure regulator.

1 14. The method of claim 13 wherein: (i) the act of collecting baseline performance
2 data includes the acts of sensing the pressure of the process and determining a baseline
3 offset value corresponding to the difference between the sensed pressure and a
4 predetermined desired pressure; (ii) the act of collecting performance data includes the
5 acts of sensing the pressure of the process and determining a performance offset value
6 corresponding to the difference between the sensed pressure and the predetermined



7 desired pressure; and (iii) the act of comparing the performance data to the baseline data
8 includes the act of comparing the baseline offset value to the performance offset value.

1 15. The method of claim 13 wherein the act of collecting baseline performance data
2 includes the act of determining the process pressure at which the throttling element
3 moves to a position which completely prevents fluid flow.

1 16. The method of claim 15 wherein the wherein the act of collecting performance
2 data includes the act of determining the process pressure at which the throttling element
3 moves to a position which completely prevents fluid flow.

1 17. The method of claim 13 wherein the actuator includes a reference side and a
2 control side, and wherein the act of collecting baseline performance data and the act of
3 determining performance data each comprise determining a first force exerted on the
4 reference side; determining a second force exerted on the control side; and comparing the
5 first and second forces to identify actuator malfunctions.

1 18. A method for determining the inlet pressure sensitivity of a pressure regulator
2 which maintains pressure in a process at a set point value by applying the process
3 pressure to an actuator to adjust a fluid flow throttling element, the pressure regulator
4 having an inlet, the method comprising the acts of:

5 detecting the pressure at the regulator inlet for a given fluid flow at a first point in
6 time and storing in a digital memory a representation of the given fluid flow and the
7 pressure detected at the first point in time;



8 monitoring the pressure at the regulator inlet over time to identify a second point
9 in time where the pressure at the second point in time is different than the pressure
10 detected at the first point in time;

11 storing in a digital memory a representation of the given fluid flow and the
12 pressure detected at the second point in time;

13 comparing the representation of the given fluid flow and the pressure detected at
14 the first point in time with the representation of the given fluid flow and the pressure
15 detected at the second point in time to provide a difference signal indicative of the inlet
16 pressure sensitivity.

1 19. A method for determining the hysteretic error of a pressure regulator which
2 maintains pressure in a process at a set point value by applying the process pressure to an
3 actuator to adjust a fluid flow throttling element, the pressure regulator having an inlet,
4 the method comprising the acts of:

5 detecting the flow rate of the fluid passing through the regulator;

6 identifying a first point in time where the flow rate through the regulator is a first
7 flow rate;

8 identifying a second point in time following the first point in time, where the flow
9 rate through the regulator is a second flow rate, wherein the second flow rate is less than
10 the first flow rate, and storing in a digital memory a representation of the pressure of the
11 process at the second point in time;

12 identifying a third point in time where the flow rate through the regulator is a third
13 flow rate;



14 identifying a fourth point in time following the third point in time, where the flow
15 rate through the regulator is a third flow rate, wherein the third flow rate is greater than
16 the third flow rate, and storing in a digital memory a representation of the pressure of the
17 process at the fourth point in time; and

18 comparing the representation of the pressure at the second point in time with the
19 representation of the pressure at the fourth point in time to calculate a dead band value for
20 diagnosing the regulator.

1 20. The method of claim 19 wherein the third point in time follows the second point
2 in time.

3

This Sheet Has Been Replaced



THIS SHEET HAS BEEN
REPLACED