(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
27 October 2016 (27.10.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/172115 A1

(51) International Patent Classification:
G01M 3/26 (2006.01) *F16K 11/06* (2006.01)
F16K 11/00 (2006.01) *F16K 11/065* (2006.01)
F16K 11/02 (2006.01) *F16K 11/07* (2006.01)

(21) International Application Number:
PCT/US2016/028301

(22) International Filing Date:
19 April 2016 (19.04.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/149,958 20 April 2015 (20.04.2015) 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, BN, 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, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, 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, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,

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(54) Title: SYSTEM AND METHOD FOR LEAKAGE DETECTION USING A DIRECTIONAL CONTROL VALVE

(57) Abstract: This application describes apparatuses, systems, and methods that combines specific configurations of a pneumatic actuation system together with a pressure measurement device to allow for measurement of pressure inside isolated subsystems within the system to thereby provide detection of leaks within the system, in certain exemplary embodiments, the apparatus comprises a directional control valve that employs at least one port connectivity configuration that creates at least one isolated fluid subsystem within the overall system. When the valve is in this isolated subsystem configuration, a given mass of fluid (i.e., compressed gas) can neither enter nor leave the subsystem. The leak detection method consists of momentarily placing the valve in this isolated subsystem configuration when switching between standard configurations, and measuring pressure with at least one pressure sensor in the isolated fluid subsystem while in this configuration, where loss of pressure in this configuration indicates existence of a leak.

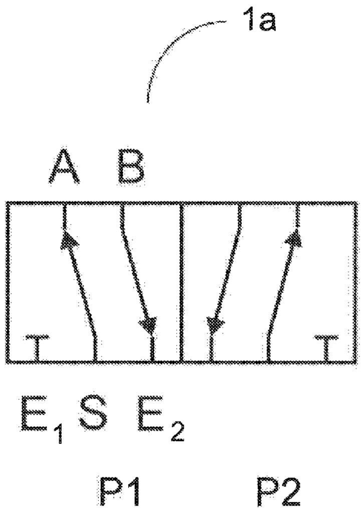

FIGURE 1

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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, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

SYSTEM AND METHOD FOR LEAKAGE DETECTION USING A DIRECTIONAL CONTROL VALVE

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to and the benefit of United States Provisional Patent Application No. 62/149958 that was filed on April 20, 2015, the entirety of which application is hereby incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

SEQUENCE LISTING, TABLE OR COMPUTER PROGRAM ON COMPACT DISC

[0003] Not applicable.

FIELD OF INVENTION

[0004] This invention relates generally to directional control valves and particularly to pneumatic control valves and systems that include leak detection.

BACKGROUND OF THE INVENTION

[0005] Leakage of compressed air in an industrial pneumatic system can be a significant source of energy loss. The compressed air conduits that comprise pneumatic actuation systems in such settings are often complex, tortuous, and comprise a large number of connections between pneumatic components, all of which are potential sites of air leakage. Further, leakage can be difficult to detect in an industrial environment, which is typically noisy, particularly because compressed air is not visible and has no smell. As such, it is desirable to have a system that can identify the presence of compressed air leaks, so that such leaks can be subsequently eliminated. Additionally, because new leaks can appear at any time, it is desirable to have a system that monitors and detects leaks either continuously, or at regular, frequent intervals, without interruption of the normal industrial purpose or functioning of the pneumatic system. Further, it is desirable to do so without additional apparatus that would add to the cost or complexity of a typical pneumatic actuation system.

SUMMARY OF THE INVENTION

[0006] The present invention meets the need in the art and is directed to systems, methods, and an improved valve for detecting leaks in a pneumatic system, particularly a pneumatic system that entails at least a control valve. An exemplary such control valve is a directional control valve that can be used to control the position of a pneumatic actuator. A "standard" two-position directional-control valve is defined for purposes of this application as one that selectively connects a minimum of four fluid ports in at least two port connectivity configurations, and wherein the four fluid ports consist generally of first and second inlet ports and first and second outlet ports. In one common pneumatic system the first and second inlet ports are typically connected respectively to supply pressure and an exhaust pressure, while the first and second outlet ports are typically connected to the first and second ports of one or more two-port pneumatic components, an exemplary example of such component being a double-acting pneumatic actuator. As such, the minimum of four ports associated with a directional control valve are typically supply **S**, exhaust **E**, a first outlet **A**, and a second outlet **B**, respectively.

[0007] The two valve positions and corresponding port connectivity of a standard two-position directional-control valve **1a** are shown schematically in Figure 1. Note that though the typical prior art valve is discussed in terms of four operative ports, in actuality the typical valve comprises at least these four distinct fluid ports. As shown in Figure 1 in certain embodiments, prior art valve **1a** may have two exhaust ports, a first exhaust port $\mathbf{E}_1$ and a second exhaust port $\mathbf{E}_2$, both of which are characterized by the same (typically atmospheric) fluid potential. Thus, in the schematic diagram of Figure 1 one of the exhaust ports $\mathbf{E}_1$, $\mathbf{E}_2$ in the preferred 5-port embodiment valve **1a** is not used in a given valve position. Despite this, the 5-port embodiment valve **1a** is a preferred embodiment because a 5-port configuration is a standard, preferred configuration in the pneumatic industry, and as such, a 5-port embodiment of the valve maintains a standard connectivity with existing pneumatic apparatus (e.g., valve manifolds). As such, illustrations of the valve embodiment and functionality herein are provided in the context of a 5-port embodiment valve. It should be clear to one having ordinary skill in the art that a 4-port embodiment is merely a simplification of the 5-port version, because elimination of the fifth port (which is the second exhaust port) yields a 4-port embodiment of the inventive valve.

[0008] As can further be seen from Figure 1, a standard two-position directional-control valve is typically configured into either a first position **P1** or a second position **P2**. The first valve position **P1** provides a port connectivity configuration in which the first inlet port (or "supply port") provides supply pressure and is connected to the first outlet port, and the second inlet port (or "exhaust port") is connected to the second outlet port. The second valve position **P2** provides a port connectivity configuration in which the supply port is connected to the second outlet port, and the exhaust port is connected to the first outlet port.

[0009] As shown in Figure 2A, a directional-control valve **1b** may also employ a third position, which corresponds to a third port connectivity configuration. This application describes an embodiment method for the detection of leaks in a compressible gas fluid-powered system that employs a directional control valve with a third port connectivity configuration in which the third-position port connectivity creates within the valve and component(s) system at least one isolated fluid subsystem. Two exemplary third-position port connectivity configurations for this purpose are shown in the schematics of Figure 2A and Figure 2B.

[0010] In the configuration shown in Figure 2A, the third (i.e., center) position of valve **1b** provides exclusive fluid connectivity between the first and second outlet ports **A**, **B**, while maintaining the supply and exhaust ports **S**, **E** in fluid isolation. In the case where the first outlet port is connected to a first component chamber (e.g. the chamber on one side of a piston in a double-acting actuator) and the second outlet port is connected to a second component chamber (e.g., the chamber on the other side of the piston in the actuator), the **P3** configuration of port connectivity shown in Figure 2A can be referred to as the "equilibration configuration" of the directional control valve. While in this equilibration configuration, valve **1b** effectively isolates the mass of fluid (i.e., compressed air) within the two chambers of the actuator and the actuator supply lines (feeding the two chambers) from all other compressed air in the pneumatic actuation system, such that fluid mass within the actuator and actuator supply lines can neither flow into nor out of this control volume. The volume of isolated fluid can be considered to be contained within an "isolated fluid subsystem."

[0011] The fluid in the isolated fluid subsystem therefore consists of the volume of compressed air generally confined within the actuator's two chambers, the actuator supply lines, and the flow channels within the directional control valve connecting the two actuator supply lines. Under normal operating conditions, no mass should enter or leave the isolated fluid subsystem while the valve is in the equilibrium configuration (the configuration at which the pressure in the two actuator chambers is moving toward and maintaining equilibrium). This type of system (i.e., a fluid system with constant fluid mass) is generally referred to as a closed thermodynamic system. Because this is a closed thermodynamic system, the mass of the gas (i.e., compressed air) in the closed system can be related algebraically to the pressure of the gas via the constitutive behavior of the gas. The most commonly assumed constitutive behavior is the ideal gas law. Assuming the gas can be described by the ideal gas law, and assuming a constant volume and isothermal behavior (i.e., constant gas temperature), the pressure in the isolated fluid subsystem will be directly proportional to the mass of compressed air in the isolated fluid subsystem. As such, while the valve is maintained in the equilibrium configuration, changes in fluid mass within the isolated fluid subsystem (e.g., due to fluid leakage) can be detected from changes in measured pressure, which is the basis for the embodiment inventions described here.

[0012] In one embodiment, the invention is directed to a method for detecting leaks in a pneumatic system that includes a 3-position directional control valve. The valve comprises a supply port **S**, a first exhaust port **E** or $\mathbf{E}_1$, a first outlet port **A**, and a second outlet port **B**. Per the discussion above, the valve may include a second exhaust port $\mathbf{E}_2$. The valve is fluidly connected to one or more pneumatic components that cumulatively provide for a first component chamber fluidly served by a first component port and a second component chamber fluidly served by a second component port. As noted, a double-acting actuator (a/k/a double-acting cylinder) for example is a single device having a first component chamber fluidly served by a first component port and a second component chamber fluidly served by a second component port. Thus, for sake of simplicity, the invention will be described in the context of a double-acting actuator. This is not intended to be limiting. The first component port and the second component port may be disposed on separate components. In the exemplary, double-acting actuator system, the first actuator port is the first component port fluidly connected to the first valve outlet port and the second actuator port is the second component port fluidly connected to the second valve outlet port.

[0013] The method comprises configuring the valve such that the valve establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and also respective isolation of the first and second valve inlet ports (the supply and exhaust ports), such that the valve creates an isolated fluid subsystem that includes: the first outlet port of the valve, the intra-valve fluid flow path between the first outlet port and the second outlet port, the second outlet port of the valve, the fluid connection between the first outlet port and the first component port, the first component chamber fluidly served by the first component port, the fluid connection between the second outlet port and the second component port and the second component chamber fluidly served by the second component port. In terms of a double-acting actuator, the isolated fluid subsystem would include the actuator; the fluid connection between the first actuator port and the first valve outlet port; the fluid connection between the second actuator port and the second valve outlet port; and the intra-valve fluid flow path between the first and second valve outlet ports. The method further comprises sensing (measuring) the pressure within the isolated fluid subsystem. The sensed pressure can be compared to a value deemed to represent an acceptable system pressure (i.e., a pressure at which no leak exists in the isolated fluid subsystem). The pressure in the isolated system may be sensed over one or more time intervals so as to check whether any rate of pressure drop exceeds any acceptable rate of pressure decay for the system.

[0014] Thus, this application describes a means of detecting leaks in a compressed gas fluid powered system by employing the combination of a directional control valve that utilizes a specific port connectivity configuration to create an isolated fluid subsystem, in combination with a pressure sensor located in the isolated fluid subsystem, to enable detection of leaks within the isolated fluid subsystem. The approach is specifically intended to provide a minimalist, low-cost method for detection of fluid leaks in the isolated fluid subsystem within the valve and actuator.

[0015] Further, because the equilibrium configuration created by the third-position port connectivity shown in Figure 2A creates a single isolated fluid subsystem, a single pressure sensing element, as indicated in Figure 3, can be employed to measure the pressure in this isolated fluid subsystem. In a preferred embodiment, the single pressure sensing element is located within the directional control valve and the measurement of pressure is thus taken there. In a preferred embodiment, a single controller coordinates valve configuration and pressure measurement based upon the processing of sensed pressure, such that the valve configuration and pressure measurement can be appropriately coordinated, as per the leak detection method.

[0016] In another preferred embodiment, the invention is directed to a pneumatic system that comprises a directional control valve fluidly connected to a first component port and a second component port (which again for simplicity of explanation can be described as the first and second ports of a double-acting pneumatic actuator). The directional control valve includes a supply port, a first exhaust port, a first valve outlet port, and a second valve outlet port. The valve may include a second exhaust port. The supply port connects to a fluid supply and the exhaust port connects to exhaust. The double-acting pneumatic actuator includes a first component (actuator) port and a second component (actuator) port. A fluid connection connects the first valve outlet port with the first actuator port and a fluid connection connects the second valve outlet port to the second actuator port. The directional control valve is capable of being configured into a first configuration, a second configuration and a third configuration whereby in the first configuration the valve establishes an exclusive connection of the supply port with the first valve outlet port, and the simultaneous exclusive connection of the exhaust port with the second valve outlet port. In the second configuration the valve establishes the exclusive connection of the supply port with the second valve outlet port, and the simultaneous exclusive connection of the exhaust port with the first valve outlet port. In the third configuration the valve establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and establishes respective isolation of the supply and exhaust ports, such that the valve creates an isolated fluid subsystem that includes: the actuator; the fluid connection between the first actuator port and the first valve outlet port; the fluid connection between the second actuator port and the second valve outlet port; and the intra-valve fluid flow path between the first and second valve outlet ports. The system includes at least one pressure sensor configured to measure pressure within the isolated fluid subsystem established by the third configuration of the valve. In a preferred embodiment system the at least one pressure sensor is a single pressure sensor located within the directional control valve.

[0017] In another preferred embodiment the invention is directed to a directional control valve that comprises a supply port, a first exhaust port, a first outlet port, and a second outlet port. The valve may include a second exhaust port. The directional control valve is capable of being configured into a first configuration, a second configuration and a third configuration whereby in the first configuration the valve establishes an exclusive connection of the supply port with the first valve outlet port, and the simultaneous exclusive connection of the exhaust port with the second valve outlet port. In the second configuration the valve establishes the exclusive connection of the supply port with the second valve outlet port, and the simultaneous exclusive connection of the exhaust port with the first valve outlet port. In the third configuration the valve establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and establishes respective isolation of the supply and exhaust ports. The valve further includes at least one pressure sensor located within the directional control valve, more preferably in the exclusive intra-valve fluid flow path formed by the third configuration.

[0018] As described in more detail hereafter, other embodiments of the invention involve usage of a directional control valve in which the third (i.e., center) position of the valve provides for a configuration in which all ports of the valve are blocked (i.e., isolated). The configuration of this port connectivity is shown in Figure 2B. While in this configuration, the valve effectively creates a separate isolated fluid subsystem at each outlet port. One isolated fluid subsystem includes the first outlet port of the valve, the fluid connection between the first outlet port and the first component port (e.g., a first actuator port) and the first component chamber (e.g., the first chamber of the actuator) fluidly connected to the first component port. The second isolated fluid subsystem includes the second outlet port of the valve, the fluid connection between the second outlet port and the second component port (e.g., a second actuator port) and the second component chamber (e.g., the first chamber of the actuator) fluidly connected to the second component port.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Figure 1 is a schematic diagram of port connectivity for a standard 2-position, 2-way, 5-port valve.

[0020] Figure 2A is a schematic diagram depicting port connectivity for a 5-port valve utilized in the present invention in which configuring the valve in the third position results in an intra-valve fluid flow path between the first and second outlet ports **A**, **B**.

[0021] Figure 2B is a schematic diagram of a valve depicting port connectivity for a 5-port valve utilized in the present invention in which configuring the valve in the third position results in an all-ports blocked status in the valve.

[0022] Figure 3 is a diagrammatic view of the flow-determining cross section of an embodiment of the body and spool configuration for a 3-position, 5-port spool valve utilized in accordance with the present invention. The valve has a sensor located proximate the first outlet port **A** of the valve.

[0023] Figure 4 is a diagrammatic view of the flow-determining cross section of an embodiment of the body and spool configuration for a 3-position, 5-port spool valve utilized in accordance with the present invention. The valve has a sensor located proximate the second outlet port **B** of the valve.

[0024] Figure 5 is a section view of an embodiment valve (a spool valve) of the present invention showing the spool (i.e., a fluid diverter) in the first position **P1**, which provides for port connectivity between supply port S and first outlet port **A**, and between second exhaust port **E2** and second outlet port **B**. First exhaust port **E1** is not used and is fluidly isolated.

[0025] Figure 6 is a section view of an embodiment valve of the present invention showing the spool in the second position **P2**, which provides port connectivity between first exhaust port **E1** and first outlet port **A**, and between supply port **S** and second outlet port **B**, respectively. Second exhaust port **E2** is not used and is fluidly isolated.

[0026] Figure 7 is a section view of an embodiment valve of the present invention showing the spool in the third position **P3**, which is between spool positions **P1** and **P2** and provides port connectivity between first outlet port A and second outlet port **B**, and fluidly isolates supply port S and first and second exhaust ports **E1** and **E2**.

[0027] Figure 8 is a schematic diagram showing an embodiment pneumatic system according to the present invention in the context of a double-acting cylinder. The valve is shown in the first position. Setting of the valve in the first position results in pressurization of the first chamber of the cylinder. This pressurization, in turn, results in extension of the piston rod.

[0028] Figure 9 is a schematic diagram showing the embodiment pneumatic system depicted in Figure 8. The valve is shown in the third position when transitioning from piston rod extension to retraction. This position creates an isolated fluid subsystem comprising the first chamber of the actuator, the second chamber of the actuator, the fluid connections between the actuator and the valve and the intra-valve fluid flow path created between first outlet port **A** and second outlet port **B**.

[0029] Figure 10 is a schematic diagram depicting the embodiment system of Figure 8. The valve is shown in the second position. Setting of the valve in the second position results in the pressurization of the second chamber of the cylinder and effects retraction of the piston rod.

[0030] Figure 11 is a schematic diagram showing the embodiment pneumatic system depicted in Figure 8. The valve is shown in the third position when transitioning from piston rod retraction to extension. This position creates an isolated fluid subsystem comprising the first chamber of the actuator, the second chamber of the actuator, the fluid connections between the actuator and the valve and the intra-valve fluid flow path created between first outlet port **A** and second outlet port **B**.

[0031] Figure 12 is a schematic diagram showing another embodiment pneumatic system according to the present invention in context of a double-acting cylinder. The valve is shown in a third (center) position in which all ports are blocked. Setting of the valve in this position results in two isolated fluid subsystems. The actuator is shown with its rod extended.

[0032] Figure 13 is a schematic diagram showing the system of Figure 12 in which the valve is in a first position, which provides for port connectivity between supply port **S** and first outlet port **A**, and between second exhaust port **E2** and second outlet port **B**. First exhaust port **E1** is not used and is fluidly isolated.

[0033] Figure 14 is a schematic diagram showing the system of Figure 12 in which the valve is in a second position, which provides for port connectivity between supply port **S** and second outlet port **B**, and between second exhaust port **E1** and second outlet port **A**. Second outlet port **E2** is not used and is fluidly isolated.

[0034] Figure 15 is a schematic diagram showing the system of Figure 12 in which the valve is in the third (center) position in which all ports are blocked. The actuator is shown with its rod retracted.

DETAILED DESCRIPTION

[0035] The present invention is directed to a valve, valve system, and method for detecting leaks in a pneumatic system. Diagrams of the flow determining positions of an embodiment valve **100** are depicted in Figures 3 and 4. These figures show a fluid diverter in the form of valve spool **5** and body **6** that provide the three-position port connectivity corresponding to the schematic of Fig. 2A and additionally show two preferred locations for a pressure sensor 7 in valve **100**. When valve spool **5** is configured in the third position **P3**, an intra-valve fluid flow path **4** is established between the outlet ports **A** and **B**, where the intra-valve fluid flow path **4** includes a first intra-valve segment **8** and a second intra-valve segment **9**. When configured in the third position **P3**, compressed gas can flow from outlet port **A**, around the valve spool, through intra-valve segment **8**, around the valve spool, through intra-valve segment **9**, and around the valve spool again to outlet port **B** (or in the opposite direction, depending on the pressure differential). In one variation, pressure sensor 7 measures the pressure in intra-valve segment **8** (Figure 3), while in a second variation, pressure sensor 7 measures the pressure in intra-valve segment **9** (Figure 4). In both variations, pressure sensor 7 measures the pressure in an isolated fluid subsystem comprising the intra-valve fluid flow path **4** between the outlet ports A and **B** when valve **100** is placed in the third position. The two variations, however, measure different pressures when the valve spool is in either the first or second positions, **P1** and **P2**. Specifically, in the variation shown in Figure 3, pressure sensor 7 measures the pressure at port A when valve **100** is configured in the first and second valve positions **P1**, **P2**. In the variation shown in Figure 4, pressure sensor 7 measures the pressure at port **B** when valve **100** is configured in the first and second valve positions **P1**, **P2**.

[0036] A design embodiment of leak-detecting directional control valve **100** is shown in cross section in Figures 5 through 7. Specifically, Figures 5 through 7 depict the three respective spool positions (a/k/a valve positions) corresponding to the design variation depicted schematically in Figure 3. Figure 5 shows spool **5** in the first position **P1** in Figure 3, which provides port connectivity between ports **S** and A, and between ports **E2** and **B**, respectively. Figure 6 shows spool **5** in the second position (**P2** in Figure 3), which provides port connectivity between ports **E1** and A, and between ports **S** and **B**, respectively. Figure 7 shows spool **5** in the third (i.e., equilibration) position (**P3** in Figure 3), which provides exclusive fluid communication between ports A and **B** (via intra-valve flow segments **8** and **9**) and fluid isolation of the **S** and **E** ports. Note that spool position **P3** is physically in between spool positions **P1** and **P2**. Note also that in this embodiment pressure sensor 7 is located within valve **100**, such that it measures the pressure in the isolated fluid subsystem within intra-valve flow path **4** when valve **100** is placed in the third position **P3** (specifically, in the design embodiment as drawn, it measures the pressure in flow path **8** between ports A and **B**). As in the schematic shown in Figure 3, pressure sensor 7 in the design embodiment shown measures the pressure at port A when in either spool position **P1** or **P2**.

[0037] Figures 8 through 11 depict valve **100** as part of a fluid subsystem **50** (of overall fluid system **10**) that includes a double-acting cylinder (actuator) **20**. Actuator **20** includes a first component chamber **24** and a second component chamber **23**. Port **41** fluidly connects chamber **24** to fluid connection **31** leading to first outlet port **A** of valve **100**. Port **42** fluidly connects chamber **23** to fluid connection **32** leading to second outlet port **B** of valve **100**. In depicted embodiment system **10**, the fluid subsystem **50** becomes an isolated fluid subsystem when valve **100** of fluid system **10** is in the third-position **P3** (i.e., the equilibrium configuration). This position **P3** can be utilized to detect potential leakage from isolated fluid subsystem **50** to the environment. Specifically, in circumstances during which the pneumatic actuation system **10** is transitioning between a first actuator position (e.g., position **P1** with rod **21** extended) and a second actuator position (e.g., position **P2** with rod **21** retracted), directional control valve **100** can briefly employ the equilibrium configuration **P3**, which allows compressed air (or similar gas) to flow from the previously pressurized chamber **24** of actuator **20** to the previously depressurized chamber **23** on the other side of piston **22**. Once this mass flow transient has completed, the pressure throughout the entire isolated fluid subsystem **50** should remain essentially constant. If, however, the pressure decays following the initial pressure equilibration, one can infer that the pressure decay indicates a loss of fluid mass (i.e., a leak) from isolated subsystem **50** to the environment. As such, a method can detect leakage from isolated fluid subsystem **50** into the environment by measuring a single pressure within isolated fluid subsystem **50** (most preferably by measuring the pressure inside intra-valve flow path **4** located inside the directional control valve **100**), while valve **100** is in the equilibrium configuration (i.e., the third position **P3**). The method does not substantially interrupt the normal operation of the pneumatic actuator, because the third position in which the leak is detected is employed only briefly between configuring the valve (and actuator) between the first and second valve and actuator positions. As such, a leak can be detected with minimal additional apparatus (i.e., a single pressure sensor embedded in the valve); without substantially altering the normal operation of the pneumatic system; and is easily employed during every cycle in which the actuator is moved between the first and second actuator positions, such that the leak detection occurs repeatedly and frequently.

[0038] The sequence of actions corresponding to a preferred leak detection method is shown in Figures 8 through 11. This sequence of actions can be described as follows. Actuator **20** is initially configured into the first actuator position by configuring valve **100** into the first valve position (also known as first spool position) **P1**. Specifically, configuring valve **100** in the first valve position pressurizes a first side (chamber **24**) of actuator **20** and exhausts a second side (chamber **23**), which configures actuator **20** to a first actuator position with rod **21** extended as depicted in Figure 8. Actuator **20** is configured into a second actuator position with rod **21** retracted as depicted in Figure 11 by configuring valve **100** into the second valve position **P2**. In particular, configuring valve **100** in the second valve position **P2** pressurizes the chamber **23** of actuator **20** and exhausts chamber **24**, which configures actuator **20** into the second actuator position with rod **21** retracted as depicted in Figure 11. Figure 8 shows valve **100** configured in the first position, and actuator **20** correspondingly also configured in the first actuator position (shown in this example as the fully extended position). Note that pressure sensor 7 is depicted in Figure 8 at the first outlet port **A**, although the single pressure sensor 7 could have alternatively been depicted at the second outlet port **B**. As Figures 8 through 11 are schematic depictions of a pneumatic system, the placement of sensor 7 on the line representing the fluid connection **31** between valve **100** and first chamber **24** of actuator **20** is not meant to indicate that sensor 7 is not contained within valve **100**. Although the pressure sensor could be located outside the valve, as noted above, a preferred embodiment of valve **100** includes the sensor 7 within the valve structure **6**, particularly within the intra-valve flow path **4**, or more specifically within intra-valve pathway segments **8** and/or **9** between ports **A** and **B**.

[0039] When switching actuator **20** from the first actuator position to the second actuator position, rather than configuring valve **100** directly into the second valve position, valve **100** is instead configured briefly into the third valve position (i.e., the equilibrium configuration), as shown schematically in Figure 9. When valve **100** is configured into the third valve position, isolated fluid subsystem **50** is created. Isolated fluid subsystem **50** comprises a first component chamber **24**, a second component chamber **23**, fluid connection **31**, fluid connection **32** and intra-valve flow paths **8** and **9**. When valve **100** is configured into the third valve position, isolated fluid subsystem **50** first undergoes a rapid flow transient, in which pressurized gas from the previously pressurized chamber **24** of actuator **20** flows rapidly to the previously depressurized chamber **23** of actuator **20**. During this time, the pressure in isolated fluid subsystem **50** rapidly changes. For the case depicted, because pressure sensor 7 was fully pressurized in Figure 8, the pressure measured by the single pressure sensor 7 will rapidly decay during the initial flow transient, until the pressure in both component chambers **23**, **24** of actuator **20** have equilibrated at some intermediate pressure between the supply pressure and exhaust pressure. Following this rapid equilibration event, the pressure is expected to reach an equilibrium pressure for the remainder of time valve **100** is configured in the **P3** equilibrium configuration. During this equilibrium phase, assuming no mass leaves isolated subsystem **50** (i.e., assuming no leakage), the measured pressure at pressure sensor 7 is expected to remain essentially constant (i.e., the pressure should remain essentially constant in the absence of fluid leaks). If, conversely, fluid mass is leaving fluid subsystem **50** due to leakage, the pressure in isolated fluid subsystem **50** (as measured by pressure sensing element 7) should decay at a rate proportional to the rate of fluid leakage (i.e., proportional to the rate at which mass is leaving the system. As such, pressure measurement during this equilibrium phase can indicate a leak within the isolated fluid subsystem **50** (i.e., a leak within actuator **20**, actuator supply lines **31**, **32**, actuator ports **41**, **42**, outlet ports **A**, **B** of the valve, or intra-valve flow path **4**). The brief nature of the pressure transient during the period of time valve **100** is configured in the third position is sufficiently rapid to allow the system to reach pressure equilibrium such that pressure sensing element 7 can be employed to detect a leak in isolated fluid subsystem **50** during the brief period of time valve **100** is configured in the third position **P3**. This brief period of time that valve **100** is configured in the third position is referred to here as the "dwell period."

[0040] Following the dwell period, valve **100** is configured in the second valve position **P2**, which subsequently configures actuator **20** into the second actuator configuration, as depicted in Figure 10 (which in this example is the fully retracted position). The third-position dwell period, and corresponding leak detection procedure, can again be employed when reconfiguring the system from the second position to the first position, as shown in Figure 11. Note that the leak detection method can either employ a dwell when configuring the valve from the first to the second position (i.e., Figure 9), a dwell when configuring the valve from the second to the first position (i.e., Figure 11), or both. Note also that the method enables leak detection without knowledge of system parameters, such as total volume or supply pressure, and enables leak detection with a single pressure sensor. In a preferred embodiment, pressure sensor 7 is located in the equilibrium flow channel **8**, equilibrium flow channel **9**, or both channels, within directional control valve **100**, as indicated in the two embodiment schematics shown in Figures 3 and 4.

[0041] When in the third position **P3** for the dwell period, the essential procedure for leak detection can proceed as follows. Upon configuring valve **100** into the third position, valve **100** is maintained in the third position for a period of time determined sufficient to allow for the equilibration pressure transient to conclude, plus a period of time determined sufficient to allow sufficient measurement sensitivity for leak detection. In a typical subsystem like that depicted, the equilibration event could reasonably have a duration on the order of 100 ms, but this duration of dwell will depend on various system parameters (e.g. volume of fluid channels within a given system) and can be adjusted accordingly. For purposes of explanation, the dwell period will be assumed as 100ms, but this example is not meant to be limiting. Following the equilibration transient (e.g., after approximately 100 ms), the isolated subsystem will enter a nominal equilibrium state. The pressure can then be measured for a selected period of time (in this example, again, on the order of 100 ms would be reasonable) while the system is in the nominal equilibrium state. Based upon the measured pressure during this equilibrium state period, the average rate of change of pressure in the isolated subsystem can be calculated. If the rate of change of pressure (i.e., the pressure decay rate) exceeds an acceptable threshold, then a leak is indicated. The magnitude of the leak will be related to the magnitude of pressure decay rate.

[0042] In a preferred embodiment, pressure sensor 7 will output an electric signal based upon the fluid pressure impacting sensor 7. Sensor 7 is in electrical communication with a processor (not shown) that processes the output signals into values that can be recorded and compared against values deemed to represent acceptable pressure levels or changes. In a preferred embodiment, the processor is the same one or part of the same controlling unit that controls the valve, such that it has knowledge of both the pressure measurement and valve position. The existence and extent of the leak can be reported by the leak detection system in various ways, including via an indicator light (e.g., on the valve or manifold), or by transmitting data via a wired or wireless connection to a remote data node or terminal. Note that a leakage detection algorithm can be employed to combine leakage detection over multiple actuator switching cycles in order to increase the confidence of leak detection. The system can include a controller (not shown) in communication with the processor and the valve that can control switching of valve positions. In one embodiment, the controller can control valve switching based upon measured pressure or pressure decay.

[0043] Note that this method is enabled by the intermittent existence of the isolated subsystem **50**, which exists only during the period of time in which valve **100** is held in the equilibrium configuration **P3**. In the absence of the equilibrium configuration (and corresponding isolated subsystem **50**), leak detection would become substantially more complex, and would require for example, measurement of mass flow into valve **100**, measurement of mass flow out of valve **100**, and accounting for the compressed air mass within valve **100** (which will generally require several additional components and measurements). Measurement of mass flow is considerably more complex than measurement of pressure. Hence, by creating an isolated subsystem **50**, the present inventive method provides for a more simplified leak detection method.

[0044] In addition to detecting a leak, the pressure measurement using pressure sensor **7** can be used to determine the period of time valve **100** should be held in the equilibration configuration **P3** when switching between the two standard valve configurations **P1** and **P2**. While in the equilibration configuration **P3**, the compressed air will initially flow from the pressurized side to the depressurized side, until the pressure throughout isolated subsystem **50** has equilibrated. In order to maintain a favorable speed of response from the first position of actuator **20** to the second, the time spent in the equilibration configuration beyond equilibration of pressure should be minimized. As such, in one embodiment, pressure can be measured in the equilibration flow channels **8** and/or **9** within valve **100**, and the rate of change in pressure can be used to determine how long valve **100** should spend in the equilibration configuration. For example, in one embodiment, when switching between the first and second positions of actuator **20**, the processor and controller can maintain valve **100**

in the equilibration configuration until the rate of change of pressure in isolated subsystem **50** falls below a predetermined threshold.

[0045] In another embodiment, rather than the single isolated subsystem **50** created by the equilibrium configuration shown in Figure 2A, a directional control valve **1c** with an all-ports-blocked (APB) port connectivity configuration (an APB valve) can be employed. This valve schematic is shown in Figure 2B and the corresponding valve system **10a** is shown in Figures 12 through 15. In the first and second valve positions, the APB valve **100a** provides standard directional-control valve port connectivity, while in the third position, the APB valve **100a** maintains all outlet ports in fluid isolation. Unlike the valve described by Figure 2A and Figures 3 through 7, the physical design of a valve that provides APB port connectivity is known in the existing art. Such valves, however, are not typically employed with pressure sensing to temporarily or intermittently create isolated fluid subsystems that enable the leak detecting method disclosed here. Specifically, as depicted in Figures 13 and 14, when the APB valve **100a** is configured in the first or second valve positions, **P1** or **P2** respectively, the standard port connectivity configures the actuator into the first or second actuator positions, respectively, as depicted in Figures 13 and 14. As shown in Figures 12 and 15, when the APB valve **100a** is configured in the third valve position **P3**, the third-position connectivity configuration will create two isolated subsystems **50a**, **50b**, wherein subsystem **50a** comprises the first chamber **24** of actuator **20** and the associated actuator supply line **31** communicating with first outlet port **A**, and wherein subsystem **50b** comprises the second chamber **23** of actuator **20** and supply line **32** communicating with second outlet port **B**. If in a preferred embodiment each of the respective isolated subsystems **50a** and **50b** include at least one pressure sensor, the third valve position can be employed briefly when configuring the valve (and actuator) between the first and second valve (and actuator) positions to create a pair of temporary isolated fluid subsystems. Like in the valve of Figure 2A, the isolated fluid subsystems **50a** and **50b** enable detection of fluid mass loss via fluid pressure loss (assuming isothermal conditions). Specifically, if valve **100a** is placed in the third position when transitioning between the first and second actuator positions, as shown in Figures 13 and 15, pressure measurement in the respective isolated subsystem **50a** or **50b** that was previously pressurized can be used to detect leakage out of the respective isolated subsystems **50a** or **50b**, in the same manner previously described (e.g., based on pressure decay). Further, pressure measurement in the isolated subsystem previously depressurized can be used to detect leakage across the actuator piston **22** (as opposed to leakage from the isolated subsystem to the environment). When employing this configuration, the presence of a leak can be localized as existing on either the first or second sides of actuator **20** (i.e., the leak can be localized as either being in subsystem **50a** or **50b**). Unlike the valve of Figure 2A, the APB valve **100a** does not entail an equilibration transient in the third position. As such, rather the isolated fluid subsystems **50a** and **50b** exhibit an initial rapid pressure change followed by a nominal equilibrium period, the system behavior in the respective isolated fluid subsystems in the absence of a leak would be an immediate fluid equilibrium. As such, any rate of pressure decay (beyond some predetermined threshold) in a previously pressurized side of the actuator while in the third valve position would indicate a loss of fluid (i.e., would indicate a leak). Further, any rate of pressure increase in a previously depressurized side of the actuator while in the third valve position would indicate a leak across the actuator piston from the pressurized side of the actuator into the depressurized side. As in the previously described method, once the valve **100a** dwells in the third position **P3** for a period of time sufficient to detect such leakage, the valve would then be configured to the respective desired standard first or second position. Although Figures 12-15 illustrate the method on a double-acting cylinder, the method could also be employed using only of the two outlet ports, such as when used with a single-acting cylinder or a single component chamber.

[0046] While exemplary embodiments are described herein, it will be understood that various modifications to the systems, methods and apparatus can be made without departing from the scope of the present invention.

CLAIMS

What is claimed is:

1. A method for detecting leaks in a pneumatic system comprising: a) a directional control valve comprising a supply port, one or more exhaust ports, a first valve outlet port, and a second valve outlet port; b) a first component chamber fluidly connected to a first component port and a second component chamber fluidly connected to a second component port; and c) the first component port being fluidly connected to the first valve outlet port and the second component port being fluidly connected to the second valve outlet port, the method comprising:

A. configuring the valve such that the valve establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and establishes respective isolation of the supply port and the one more exhaust ports and thereby creates an isolated fluid subsystem that includes:

the first component chamber;

the second component chamber;

the fluid connection between the first component port and the first valve outlet port;

the fluid connection between the second component port and the second valve outlet port; and

the intra-valve flow path between the first and second valve outlet ports;

B. sensing the pressure within the isolated fluid system; and

C. comparing the sensed pressure to a value determined to represent an acceptable system pressure for the isolated fluid system.

2. The method of Claim 1, wherein the valve is sequentially configured into the configuration of step A:

a. directly after the valve is placed in a first configuration in which the valve establishes an exclusive fluid connection of the supply port with the first valve outlet port and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the second valve outlet port and directly before the valve is placed in a second configuration in which the valve establishes an exclusive fluid connection of the supply port with the second valve outlet port, and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the first valve outlet port; or

b. directly after the valve is placed in the second configuration and directly before the valve is placed in the first configuration.

3. The method of Claim 2, wherein the sensing of pressure is performed after a period of time that allows for the equilibration of pressures at the first component port and the second component port.

4. The method of Claim 2, wherein the value determined to represent an acceptable system pressure is determined based upon a measurement of pressure in the pneumatic system while the valve is in the first or second configurations.

5. The method of Claim 1 wherein the sensing of pressure is performed by a pressure sensor located in the intra-valve fluid flow path between the first and second valve outlet ports.

6. A method for detecting leaks in a pneumatic system comprising: a) a directional control valve comprising a supply port, one or more exhaust ports, a first valve outlet port, and a second valve outlet port; b) a first component chamber fluidly connected to a first

component port and a second component chamber fluidly connected to a second component port; and c) the first component port being fluidly connected to the first valve outlet port and the second component port being fluidly connected to the second valve outlet port, the method comprising:

A. configuring the valve such that the valve establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and establishes respective isolation of the first and second valve inlet ports and thereby creates an isolated fluid subsystem that includes:

the first component chamber;

the second component chamber;

the fluid connection between the first component port and the first valve outlet port;

the fluid connection between the second component port and the second valve outlet port; and

the intra-valve flow path between the first and second valve outlet ports;

B. sensing the pressure within the isolated fluid subsystem for a plurality of time intervals during the time the valve is in the configuration that creates the isolated fluid subsystem; and

C. comparing the sensed pressures associated with one or more time intervals to determine a rate of pressure change in the isolated fluid subsystem and comparing the determined rate of pressure change to a value representing an acceptable level of pressure decay for the isolated fluid subsystem.

7. The method of Claim 6 wherein the sensing of pressure is performed by a pressure sensor located in the intra-valve fluid flow path between the first and second valve outlet ports.

8. The method of Claim 6, wherein the valve is sequentially configured into the configuration of step A of Claim 6:

a. directly after the valve is placed in a first configuration in which the valve establishes an exclusive fluid connection of the supply port with the first valve outlet port and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the second valve outlet port and directly before the valve is placed in a second configuration in which the valve establishes an exclusive fluid connection of the supply port with the second valve outlet port, and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the first valve outlet port; or

b. directly after the valve is placed in the second configuration and directly before the valve is placed in the first configuration.

9. The method of Claim 6, wherein if the determined rate of pressure change in the isolated fluid subsystem is above a certain value, maintaining the valve in the configuration until the rate of pressure of pressure change in the isolated fluid system falls below a specified value.

10. A method for detecting leaks in a pneumatic system comprising: a) a directional control valve comprising a supply port, one or more exhaust ports, a first valve outlet port, and a second valve outlet port; b) a first component chamber fluidly connected to a first component port and a second component chamber fluidly connected to a second component port; and c) the first component port being fluidly connected to the first valve outlet port and the second component port being fluidly connected to the second valve outlet port, the method comprising:

A. configuring the valve such that the valve establishes the fluid isolation of the supply port, the one or more exhaust ports, the first valve outlet port and the second valve outlet port from each other and thereby creating:

a first isolated fluid subsystem comprising:

the first component chamber and the fluid connection between the first component port and the first valve outlet port; and

a second isolated fluid subsystem comprising:

the second component chamber and the fluid connection between the second component port and the second valve outlet port;

B. sensing the fluid pressure within at least one of the first and second isolated fluid subsystems; and

C. then performing one or more of the following comparisons:

i) if fluid pressure was sensed from the first isolated fluid subsystem, comparing the sensed pressure to a value determined to represent an acceptable system pressure for the first isolated fluid subsystem; or

ii) if fluid pressure was sensed from the second isolated fluid subsystem, comparing the sensed pressure to a value determined to represent an acceptable system pressure for the second isolated fluid subsystem.

11. The method of Claim 10 wherein the sensing of pressure is performed by a pressure sensor located in the directional control valve.

12. The method of Claim 10, wherein the valve is sequentially configured into the configuration of step A of Claim 10:

a. directly after the valve is placed in a first configuration in which the valve establishes an exclusive fluid connection of the supply port with the first valve outlet port and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the second valve outlet port and directly before the valve is placed in a second configuration in which the valve establishes an exclusive fluid connection of the supply port with the second valve outlet port, and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the first valve outlet port; or

b. directly after the valve is placed in the second configuration and directly before the valve is placed in the first configuration.

13. The method of Claim 12 wherein the value determined to represent an acceptable system pressure is determined based upon a measurement of pressure in the pneumatic system while the valve is in the first or second configurations.

14. A method for detecting leaks in a pneumatic system comprising: a) a directional control valve comprising a supply port, one or more exhaust ports, a first valve outlet port, and a second valve outlet port; b) a first component chamber fluidly connected to a first component port and a second component chamber fluidly connected to a second component port; and c) the first component port being fluidly connected to the first valve outlet port and the second component port being fluidly connected to the second valve outlet port, the method comprising:

A. configuring the valve such that the valve establishes the fluid isolation of the supply port, the one or more exhaust ports, the first valve outlet port and the second valve outlet port from each other and thereby creating:

a first isolated fluid subsystem comprising:

the first component chamber and the fluid connection between the first component port and the first valve outlet port; and

a second isolated fluid system comprising:

the second component chamber and the fluid connection between the second component port and the second valve outlet port;

B. sensing the fluid pressure within at least one of the first and second isolated fluid subsystems for a plurality of time intervals during the time the valve is in the configuration that creates the first and second isolated fluid subsystems; and

C. comparing the sensed pressures associated with one or more time intervals to determine a rate of pressure change in the at least one isolated fluid subsystem and comparing the determined rate of pressure change to a value representing an acceptable level of pressure decay for the at least one isolated fluid subsystem.

15. The method of Claim 14 wherein the sensing of pressure is performed by a pressure sensor located in the directional control valve.

16. The method of Claim 14, wherein the valve is sequentially configured into the configuration of step A of Claim 14:

a. directly after the valve is placed in a first configuration in which the valve establishes an exclusive fluid connection of the supply port with the first valve outlet port and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the second valve outlet port and directly before the valve is placed in a second configuration in which the valve establishes an exclusive fluid connection of the supply port with the second valve outlet port, and a simultaneous exclusive fluid connection of one of the one or more exhaust ports with the first valve outlet port; or

b. directly after the valve is placed in the second configuration and directly before the valve is placed in the first configuration.

17. A pneumatic system comprising:

a directional control valve and at least one pneumatic component;

the directional control valve including a supply port, one or more exhaust ports, a first valve outlet port, and a second valve outlet port;

the supply port connecting to a fluid supply and the one or more exhaust ports connecting to exhaust;

the at least one pneumatic component including a first component port in fluid communication with a first component chamber and a second component port in fluid communication with a second component chamber;

a fluid connection connecting the first valve outlet port with the first component port and a fluid connection connecting the second valve outlet port to the second component port, and

the directional control valve capable of being configured into a first configuration, a second configuration and a third configuration whereby:

a. in the first configuration the valve establishes an exclusive fluid connection of the supply port with the first valve outlet port, and the simultaneous exclusive fluid connection of one of the one or more exhaust ports with the second valve outlet port;

b. in the second configuration the valve establishes an exclusive fluid connection of the supply port with the second valve outlet port, and the simultaneous exclusive fluid connection of one of the one or more exhaust ports with the first valve outlet port; and

c. in the third configuration the valve establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and establishes respective isolation of the first valve inlet port and the second valve inlet port, such that the valve creates an isolated fluid subsystem that includes:

the first component chamber;

the second component chamber;

the fluid connection between the first component port and the first valve outlet port;

the fluid connection between the second component port and the second valve outlet port; and

the intra-valve flow path between the first and second valve outlet ports; and

at least one pressure sensor configured to measure pressure within the isolated fluid subsystem established by the third configuration of the valve.

18. The system of Claim 17 wherein the at least one pressure sensor is located within the intra-valve fluid flow path between the first and second valve outlet ports.

19. The system of Claim 17 wherein the at least one pressure sensor outputs a signal that varies based upon the sensed pressure and the system further includes a processor in electrical communication with the sensor and that is configured to process the signal output by the sensor and determine if any leakage exists in the isolated fluid subsystem of the third configuration.

20. The system of Claim 19 further including an indicating device in wired or wireless electrical communication with the processor, the processor being configured to activate the indicating device based upon a determination of leakage by the processor.

21. The system of Claim 19 wherein the at least one pressure sensor is configured to obtain and transmit to the processor a plurality of pressure readings in the isolated fluid system after a time period that allows for the equilibration of pressures at the first component port and the second component port and the pressure sensor, and the processor is configured to process the plurality of pressure readings from the sensor to determine a rate of pressure decay in the isolated fluid system of the third configuration.

22. The valve of Claim 21 further including an indicating device in wired or wireless electrical communication with the processor, the processor being configured to activate the indicating device based upon a sensed rate of pressure decay in the isolated fluid subsystem.

23. The system of Claim 21 wherein the processor is further configured to compare the determined rate of pressure decay against a rate of decay deemed minimally acceptable.

24. The system of Claim 23 wherein the processor is part of or in electrical communication with a controller, the controller being configured to maintain the valve in the third configuration for a predetermined period of time.

25. A pneumatic directional control valve comprising:

a valve body housing a fluid diverter, the valve body comprising a supply port, one or more exhaust ports, a second valve outlet port and second valve inlet port;

the fluid diverter of the pneumatic directional control valve capable of being configured into a first configuration, a second configuration and a third configuration whereby:

a. in the first configuration the fluid diverter establishes an exclusive fluid connection of the supply port with the first valve outlet port and the simultaneous exclusive fluid connection of one of the one or more exhaust ports with the second valve inlet port;

b. in the second configuration the fluid diverter establishes the exclusive fluid connection of the supply port with the second valve outlet port and the simultaneous exclusive fluid connection of one of the one or more exhaust ports with the first valve outlet port; and

c. in the third configuration the fluid diverter establishes an exclusive intra-valve fluid flow path between the first and second valve outlet ports and establishes respective isolation of the supply port and the one or more exhaust ports; and

at least one pressure sensor disposed within the valve body and configured to measure pressure of a fluid within the exclusive intra-valve fluid flow path between the first and second valve outlet ports established by the third valve configuration.

26. The valve of Claim 25 wherein the at least one pressure sensor is located within the intra-valve fluid flow path between the first and second valve outlet ports.

27. The valve of Claim 26 wherein the pressure sensor is configured to output a signal that varies based upon the sensed pressure and the valve further includes a processor in electrical communication with the sensor and that is configured to receive the signal output

by the sensor and process it so as to compare a pressure sensed by the sensor to a pressure value deemed acceptable for the isolated fluid subsystem comprising the intra-valve fluid flow path.

28. The valve of Claim 26 wherein the pressure sensor is configured to output a signal that varies based upon the sensed pressure and the valve further includes a processor in electrical communication with the sensor and that is configured to receive signal outputs by the sensor over time and process the signal outputs so as to compare pressures sensed by the sensor over one or more time intervals to calculate a rate of pressure decay for the isolated fluid subsystem and compare that calculated rate of decay to a rate of decay deemed acceptable for the isolated fluid subsystem.

29. The valve of Claim 27 further including an indicating device in wired or wireless electrical communication with the processor, the processor being configured to activate the indicating device based upon a pressure level sensed by the sensor.

30. The valve of Claim 28 further including an indicating device in wired or wireless electrical communication with the processor, the processor being configured to activate the indicating device based upon a sensed rate of pressure decay in the isolated fluid subsystem.

31. The valve of Claim 25 wherein the position of the fluid diverter when the valve is in the third configuration is in between the position of the fluid diverter when the valve is in the first configuration and the second configuration.

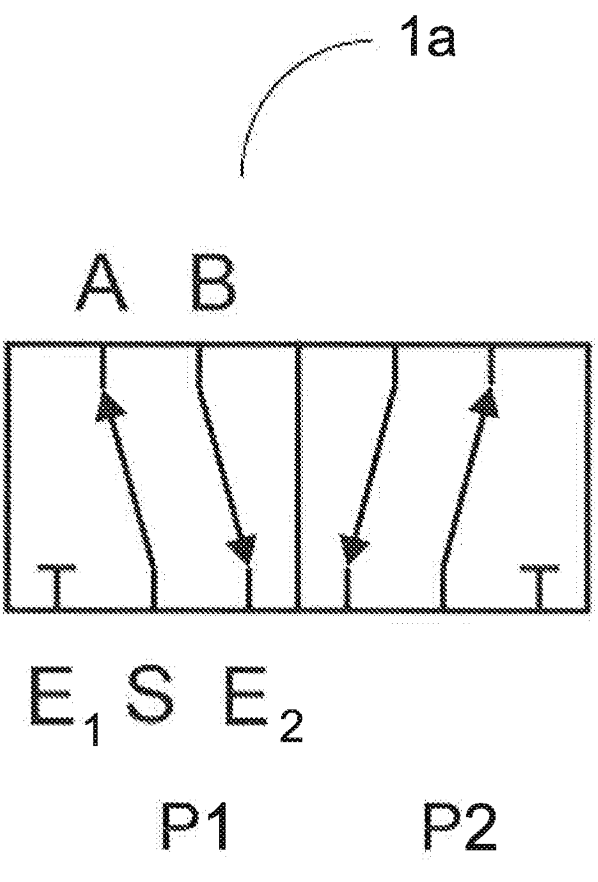

FIGURE 1

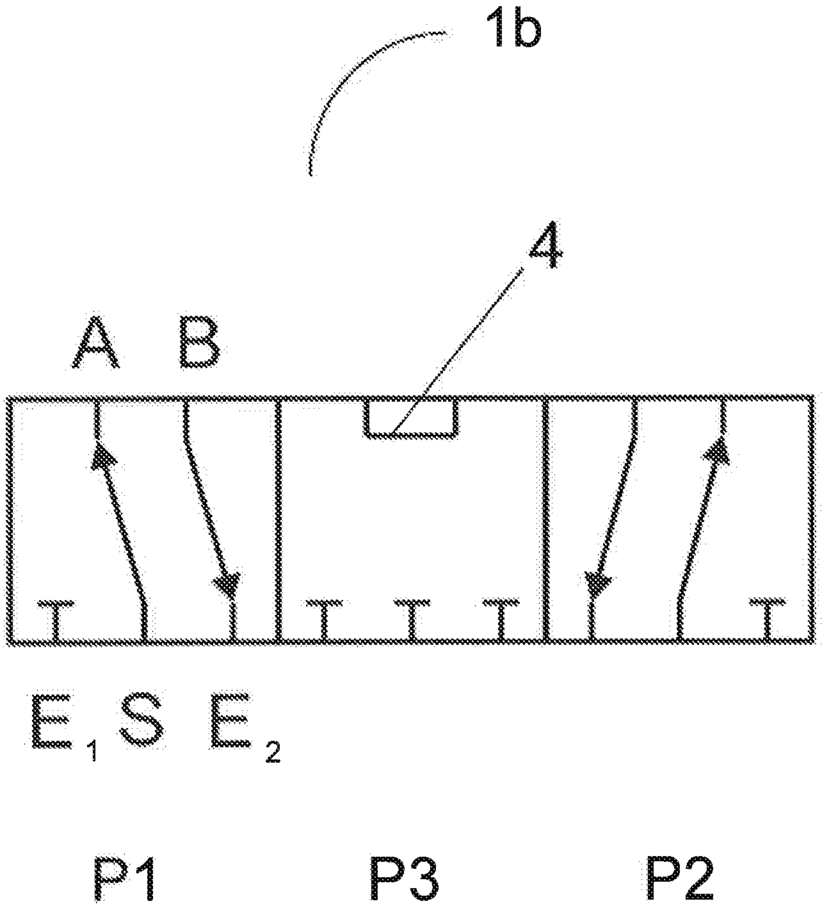

FIGURE 2A

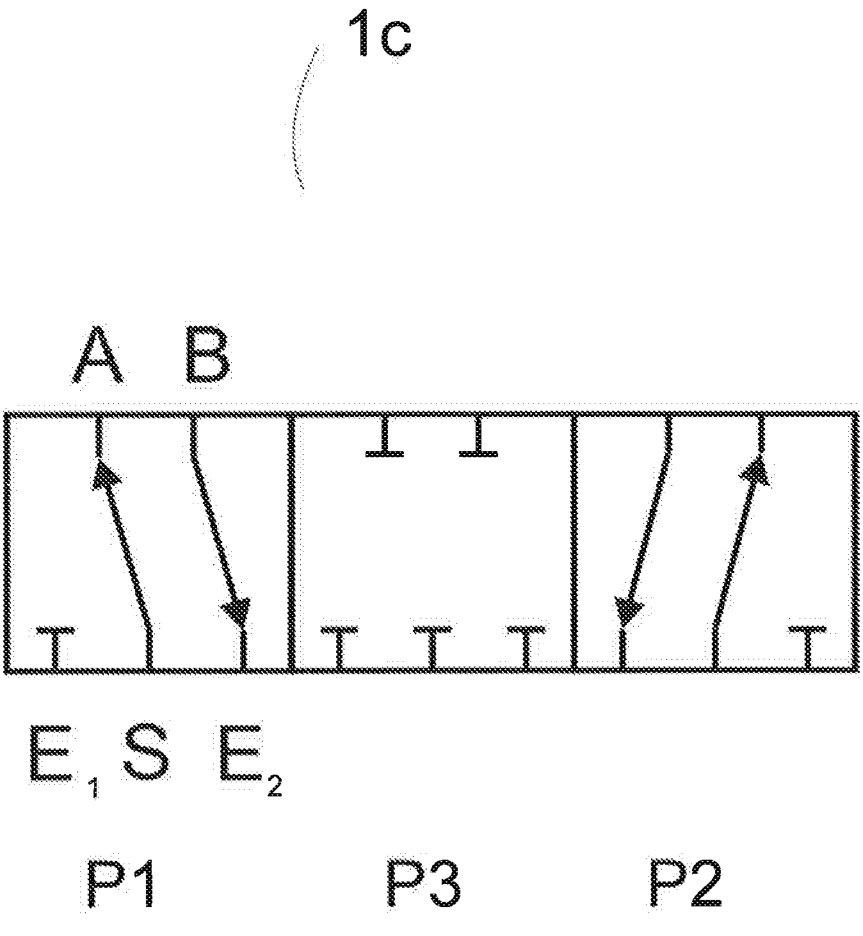

FIGURE 2B
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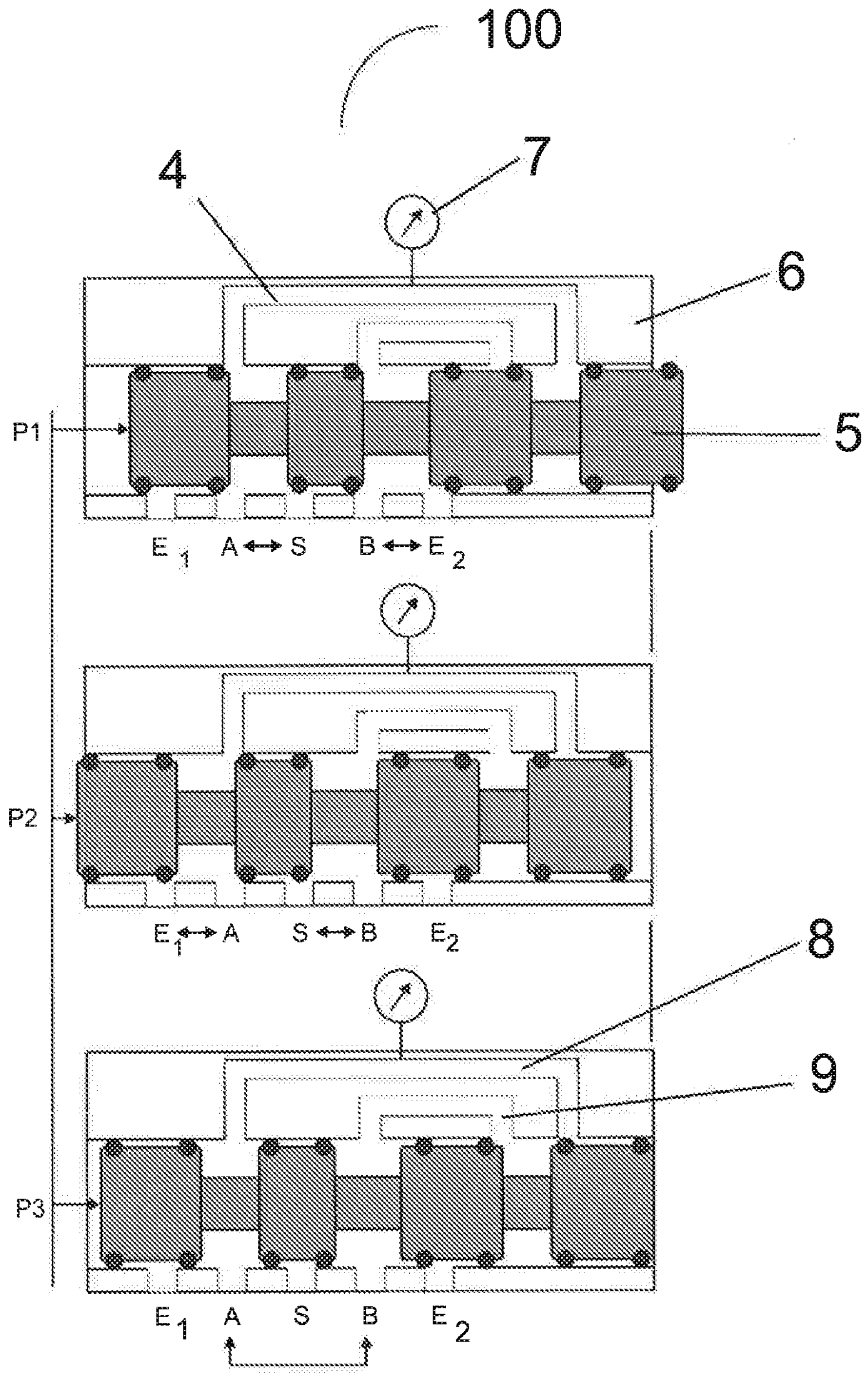


FIGURE 3

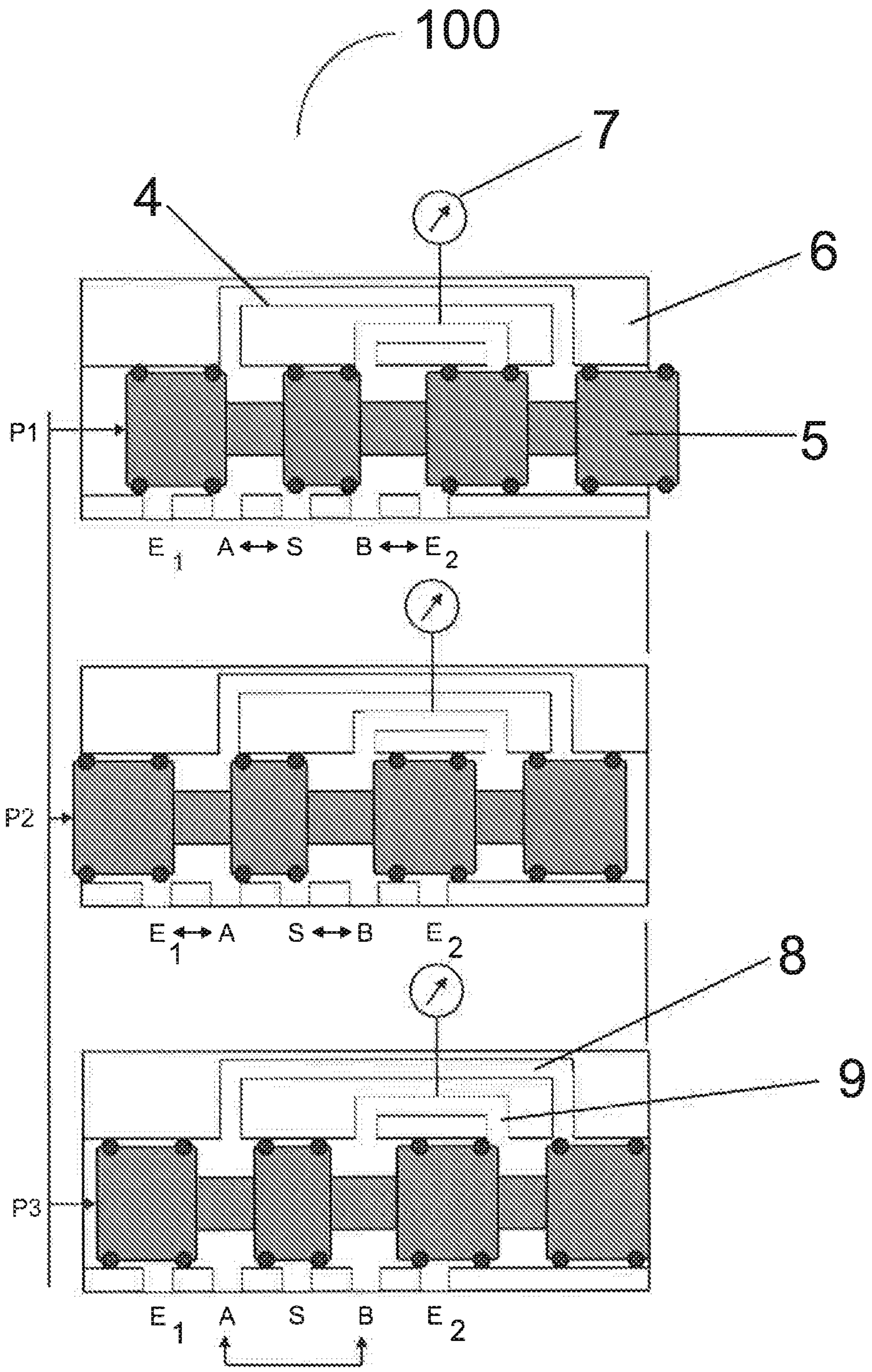
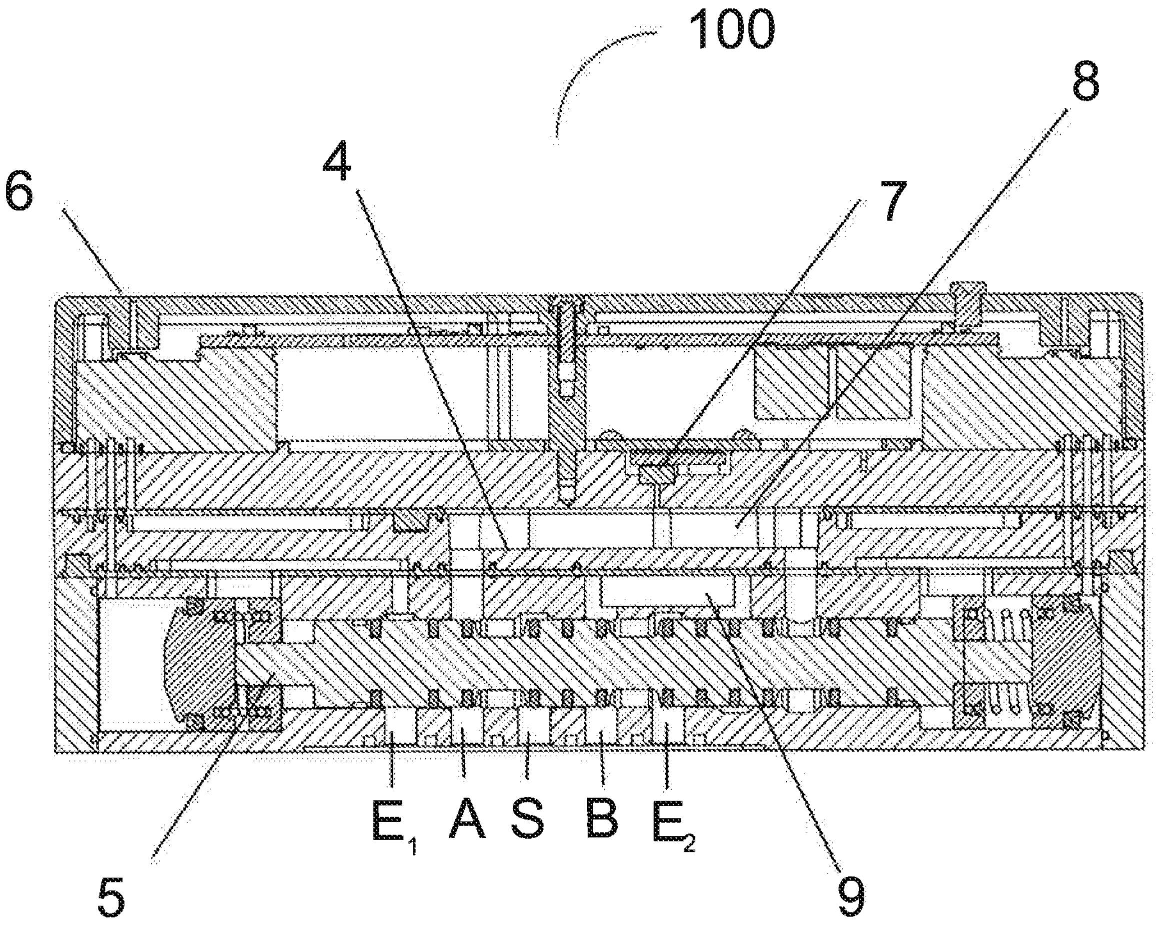


FIGURE 4



P1

FIGURE 5

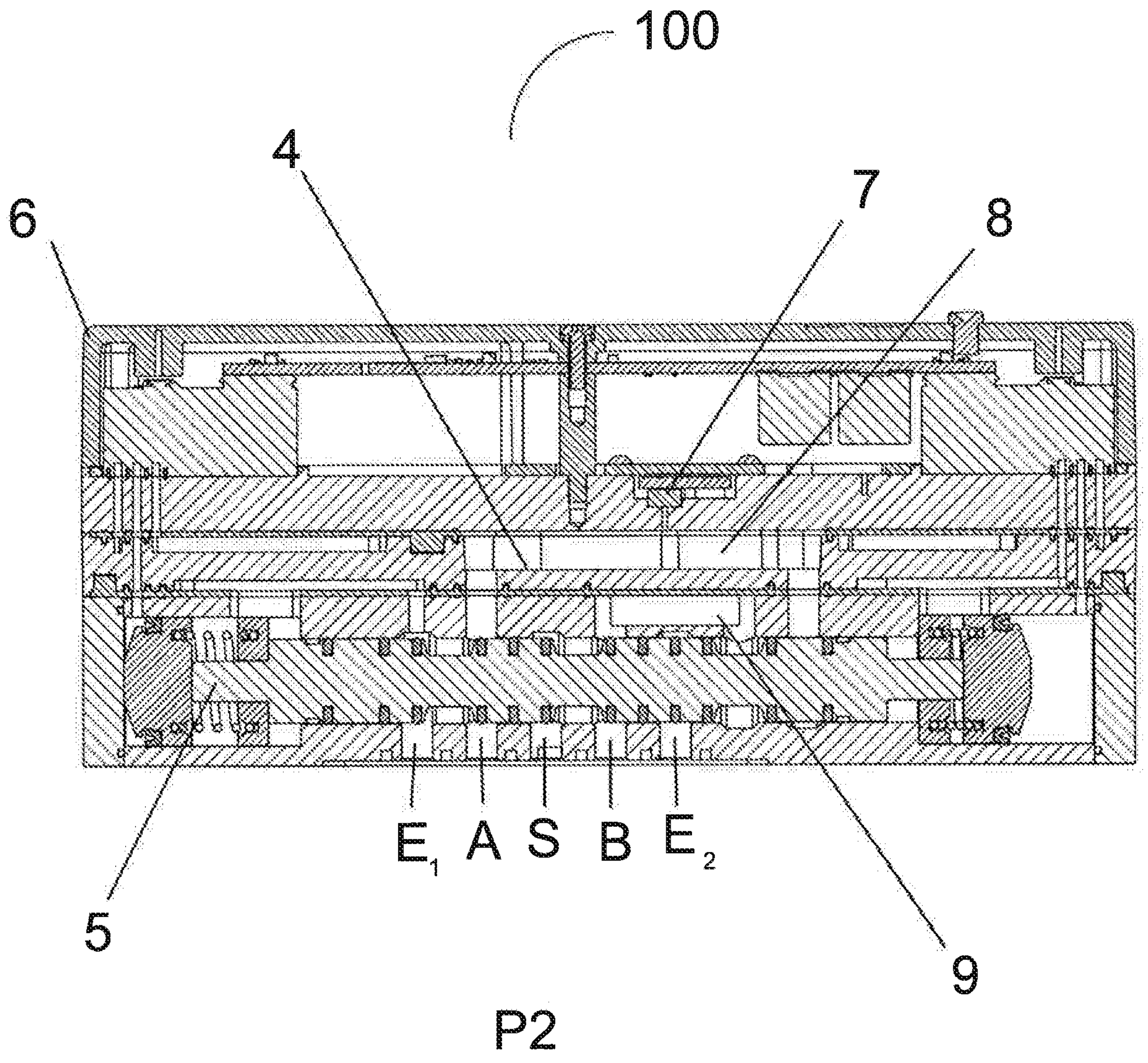


FIGURE 6

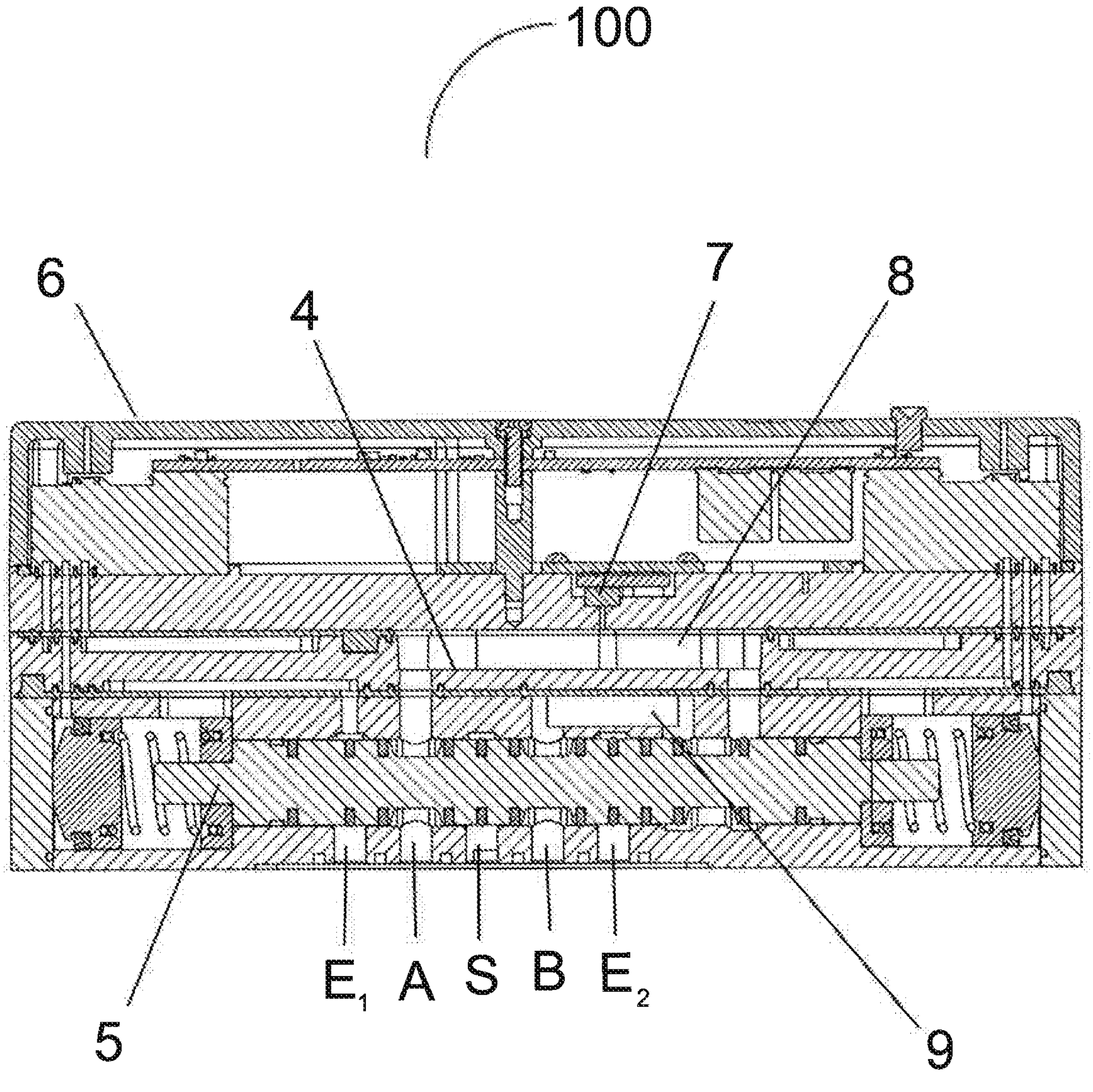


FIGURE 7

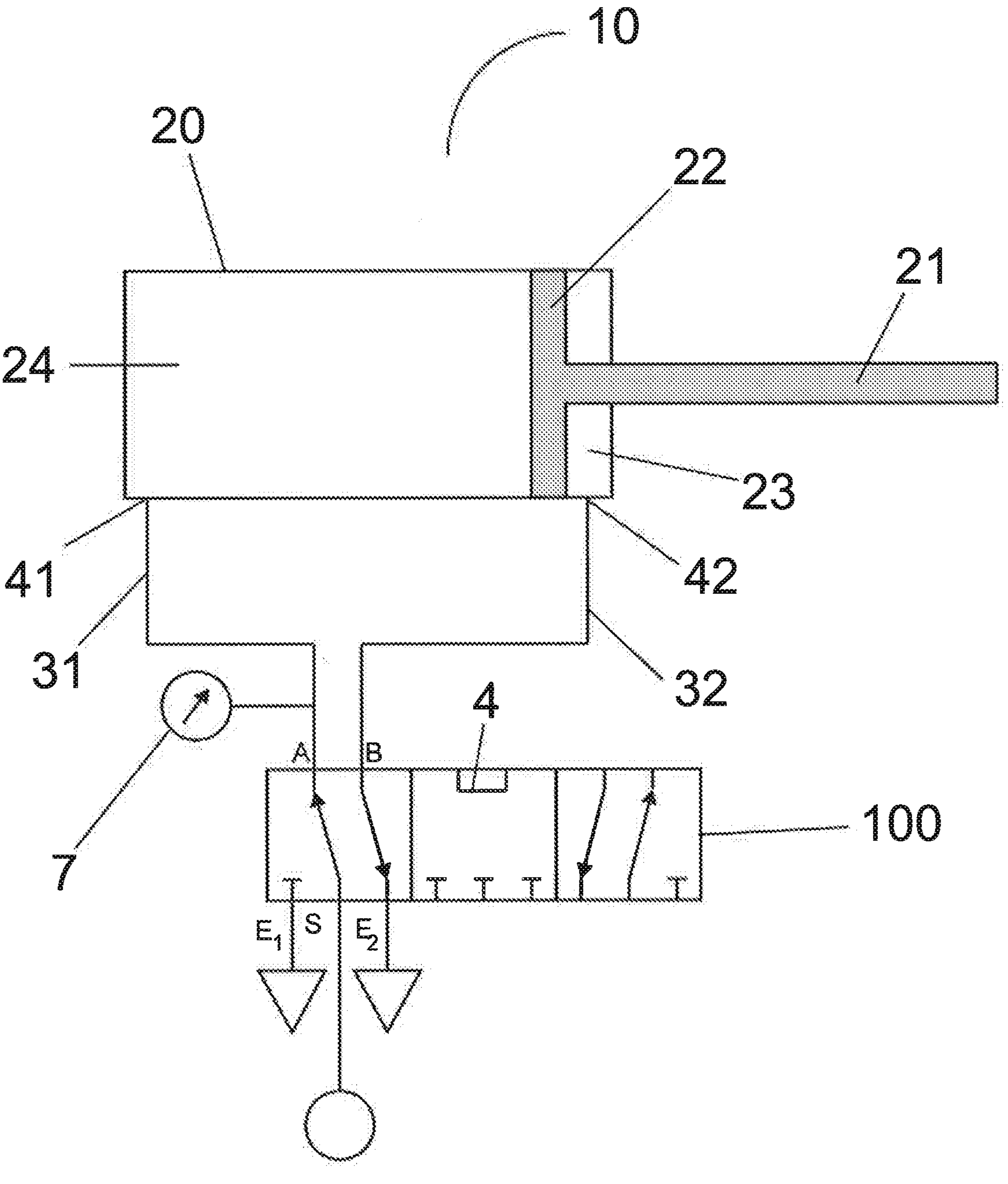


FIGURE 8

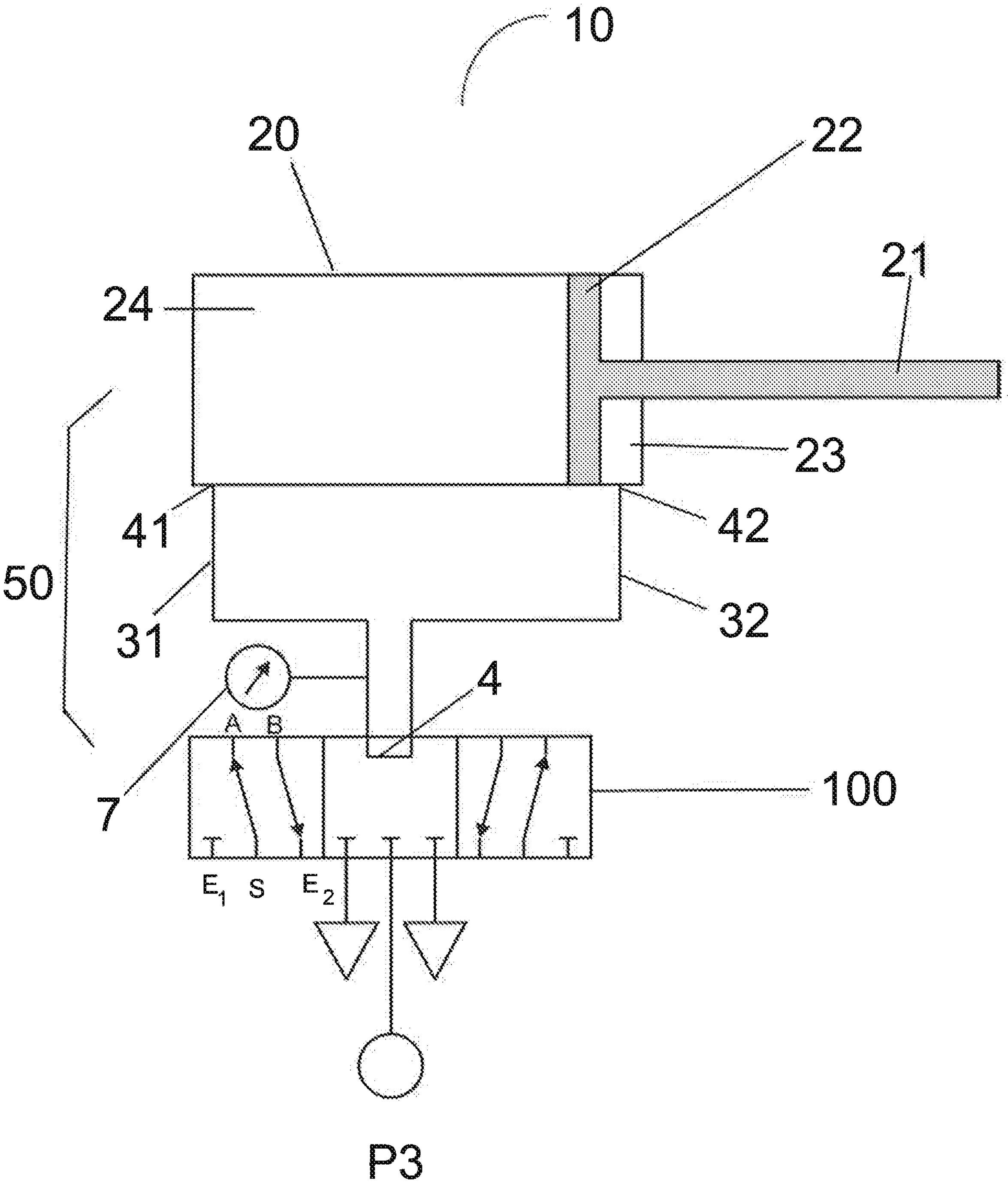


FIGURE 9

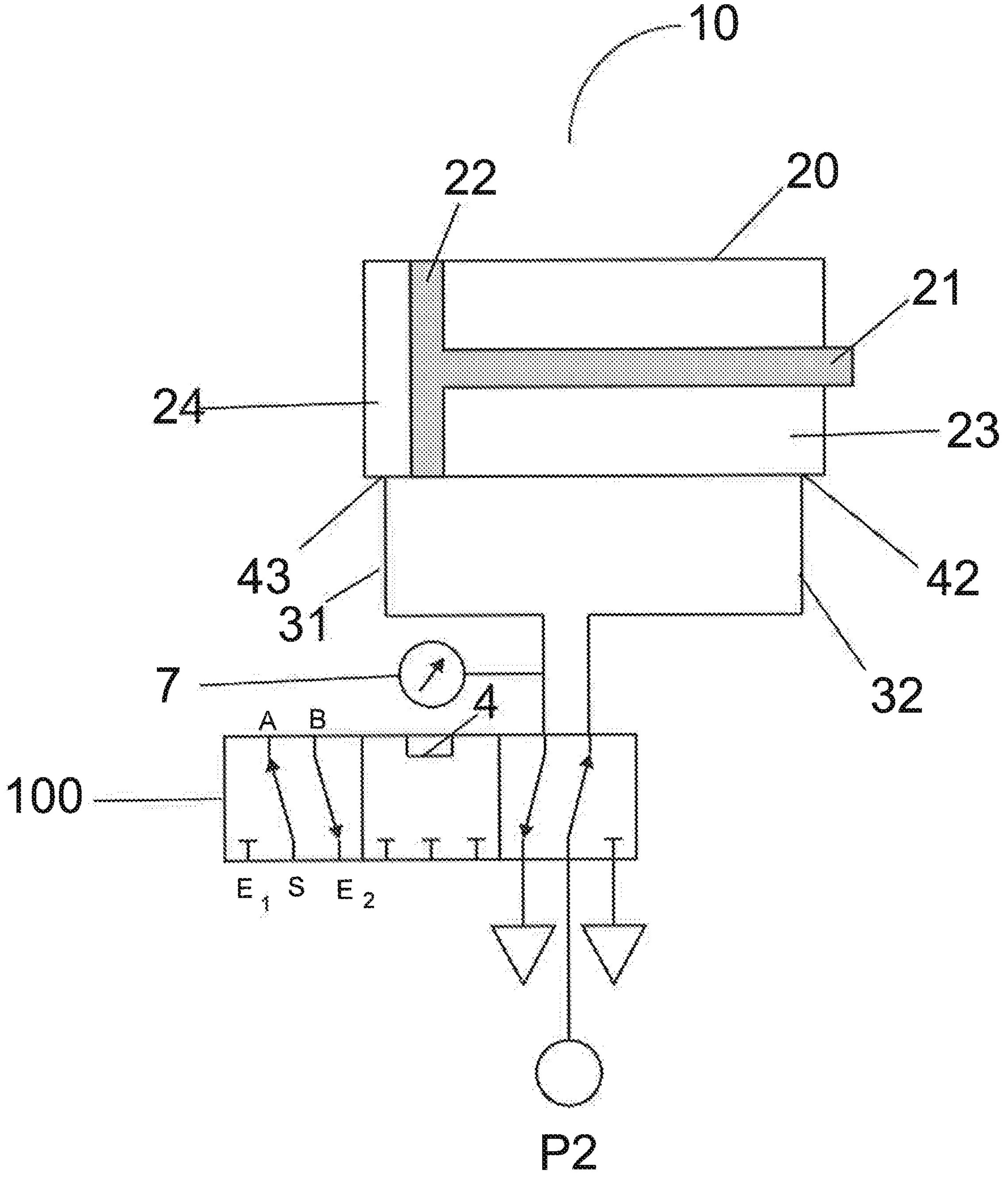


FIGURE 10

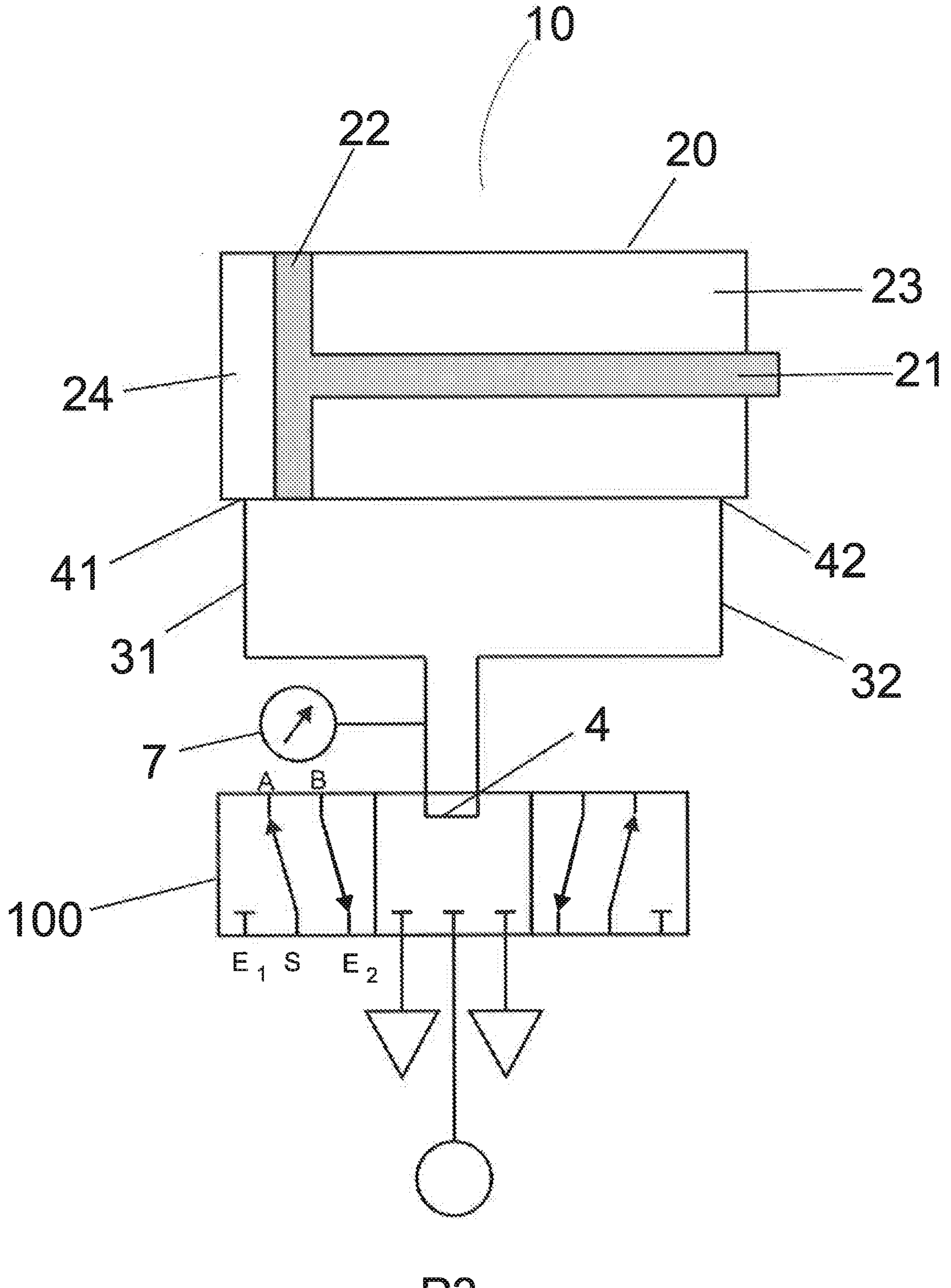


FIGURE 11

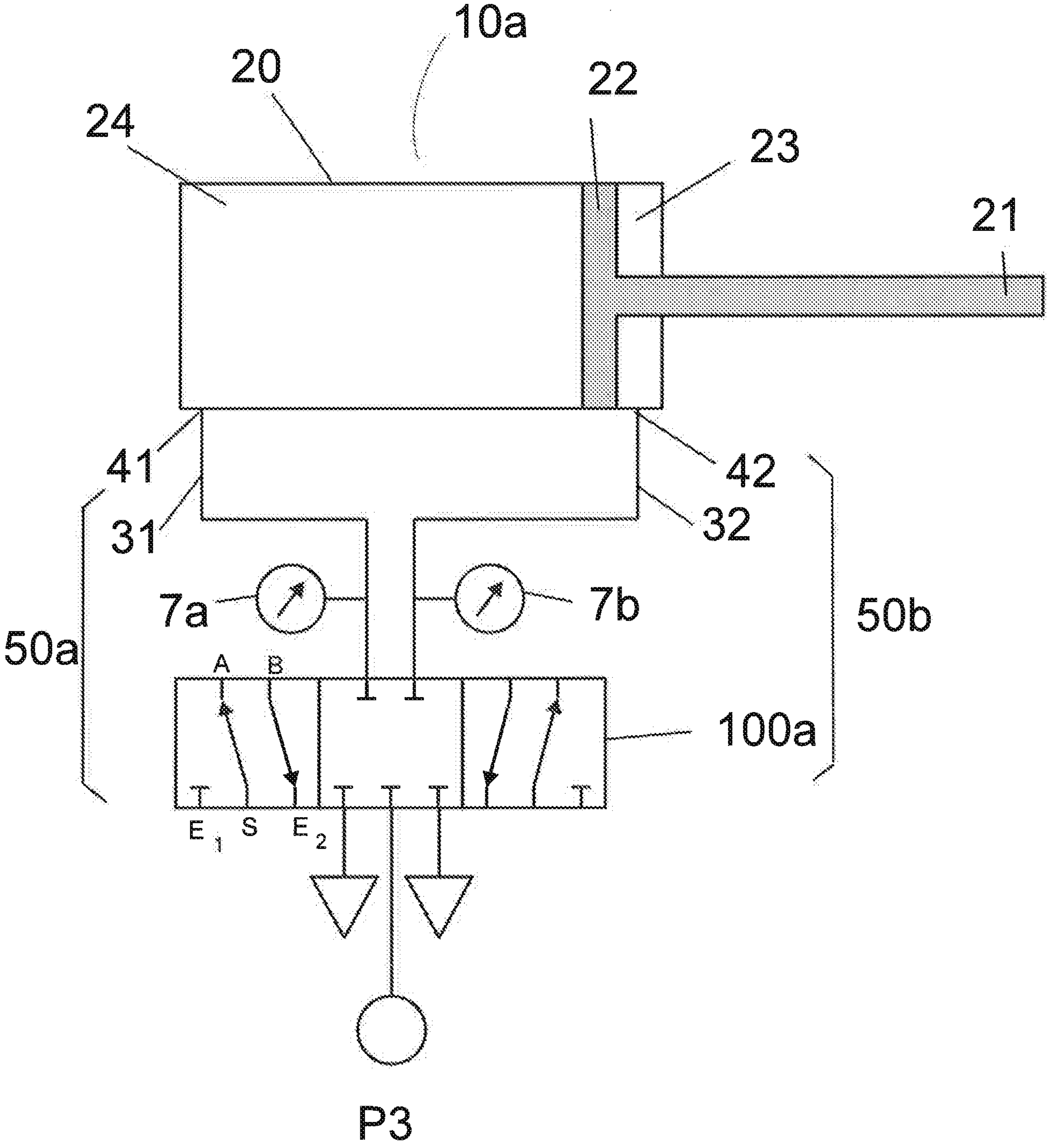


FIGURE 12

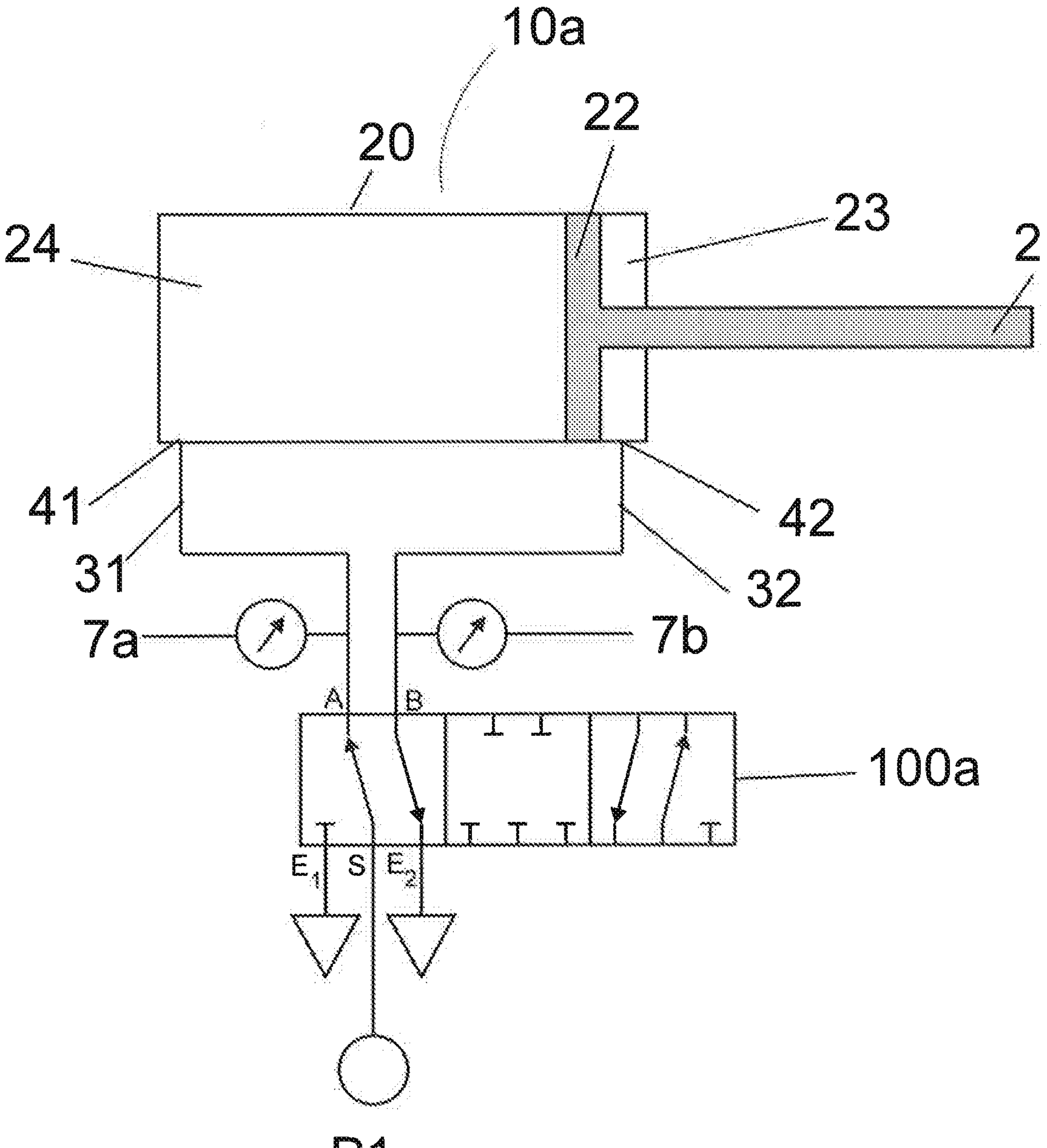


FIGURE 13

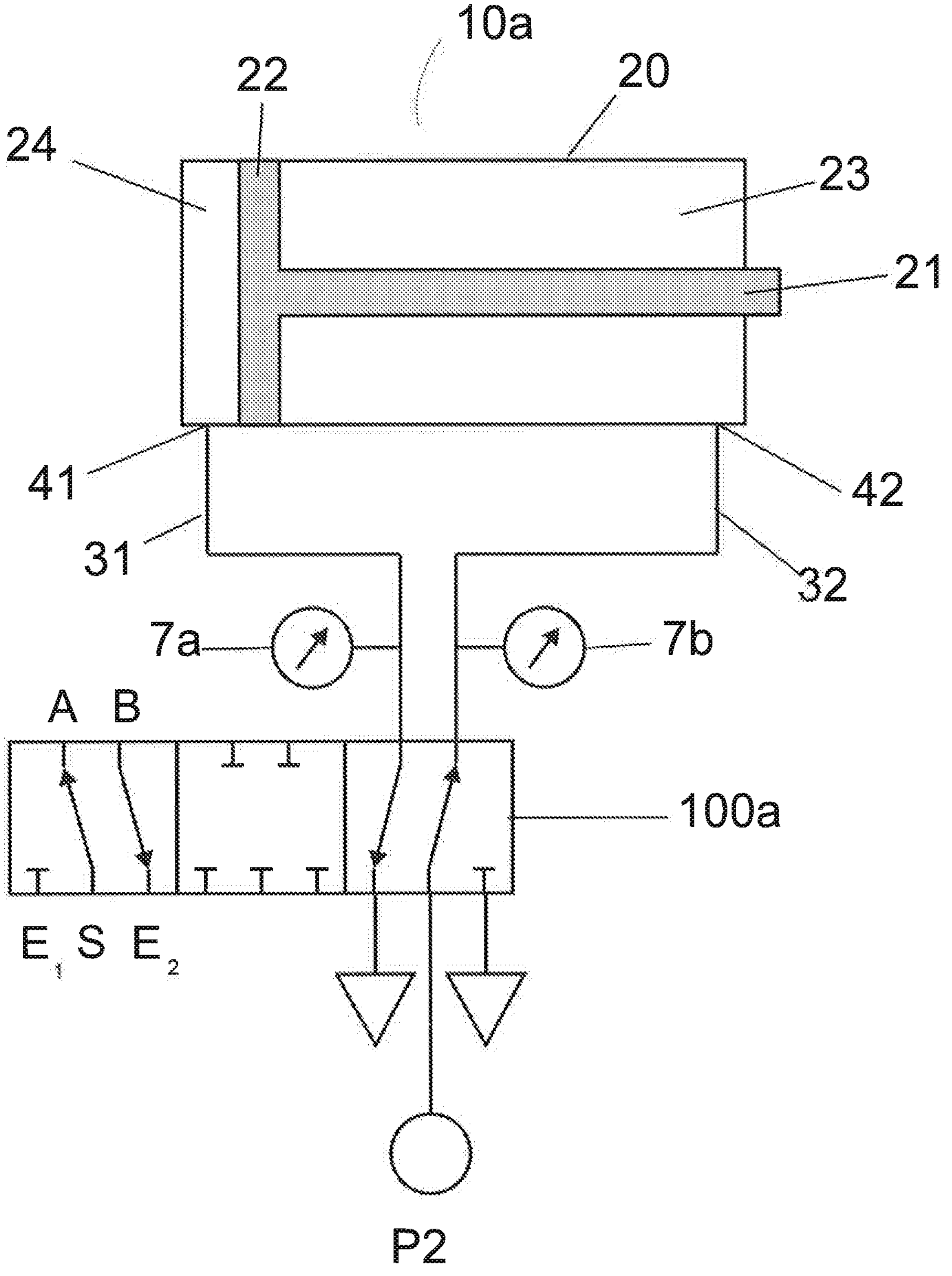


FIGURE 14

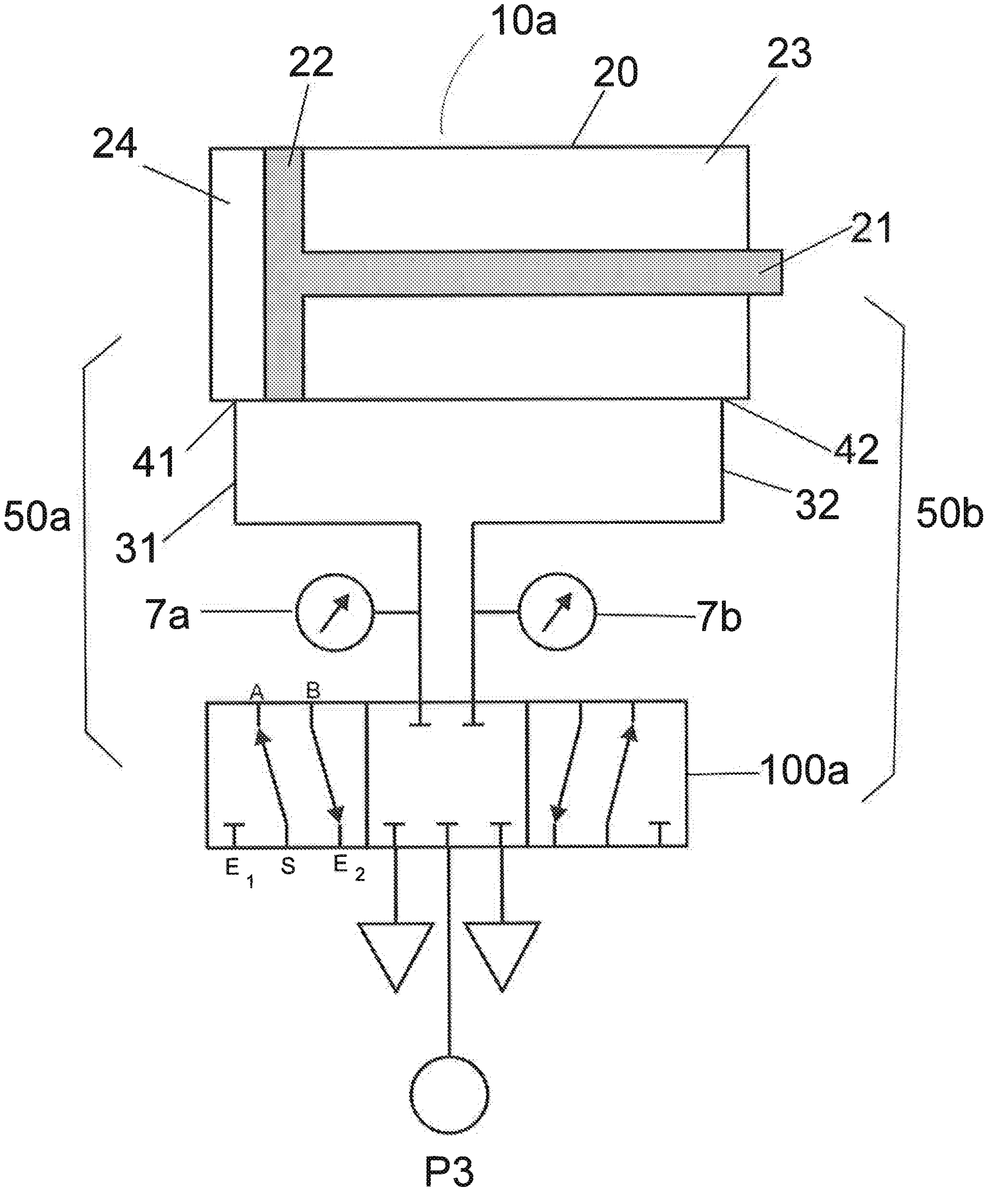


FIGURE 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/028301

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01M 3/26; F16K 11/00; F16K 11/02; F16K 11/06; F16K 11/065; F16K 11/07 (2016.01)
CPC - G01M 3/26; F16K 11/00; F16K 11/02; F16K 11/06; F16K 11/065; F16K 11/07 (2016.05)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - F16K 11/00; F16K 11/02; F16K 11/06; F16K 11/065; F16K 11/07; F16K 11/072; F16K 31/122; G01M 3/00; G01M 3/02 (2016.01)
CPC - F16K 11/00; F16K 11/02; F16K 11/06; F16K 11/065; F16K 11/07; F16K 11/072; F16K 31/122; G01M 3/00; G01M 3/02; G01M 3/26 (2016.05)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 73/37; 137/625; 137/625.17; 137/625.18; 137/625.19; 137/625.25; 251/30.01; 251/30.02
IPC(8) (Cont.) - G01M 3/26 (2016.01) (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Orbit, Google Patents, Google, YouTube
Search terms used: leak, detect, detector, pressure, sense, sensor, indicate, indicator, pneumatic, directional control valve, directional, control valve, valve, port, supply, exhaust, outlet, component, chamber, connected, coupled, intra-valve, flow, path, isolate, exclusive

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/0065355 A1 (BREDAU et al) 13 March 2008 (13.03.2008) entire document	1, 6, 17, 19-25, 31
A	CN 103453176 A (ANHUI WANYI SCIENCE & TECHNOLOGY CO LTD) 18 December 2013 (18.12.2013) see machine translation	1-31
A	CN 201060087 Y (DEERFU (SHANGHAI) ENGINE PROPELLER SYSTEM CO LTD) 14 May 2008 (14.05.2008) see machine translation	1-31
A	CN 201739564 U (ZHEJIANG UNIVERSITY OF TECHNOLOGY) 09 February 2011 (09.02.2011) see machine translation	1-31

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
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"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 16 June 2016	Date of mailing of the international search report 26 JUL 2016
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774