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Pneumatic Cylinder Exhaust Energy Recovery to Low-Pressure Ring Main

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Abstract

This disclosure describes a system for recovering compressed air from the exhaust port of a pneumatic cylinder and directing it into a low-pressure ring main. The arrangement addresses the significant energy loss inherent in conventional pneumatic systems, where exhaust air is typically vented to atmosphere. It details a recovery circuit that manages pressure levels, mitigating the impact on cylinder return speed, and outlines the conditions under which such a system offers a beneficial energy return. The recovered air can then be used by other low-pressure pneumatic consumers within an industrial facility, thereby reducing overall compressed air generation requirements.

1. Technical Field

[0001] This disclosure pertains to the field of fluid power, specifically relating to pneumatic systems and methods for improving their energy efficiency. More particularly, it describes arrangements for the recovery and reuse of compressed air that has performed work within a pneumatic actuator.

2. Technical Context

[0002] In many industrial applications, pneumatic cylinders are employed for their robustness, speed, and simplicity. However, the operation of these cylinders typically involves a significant energy loss when the compressed air, having extended or retracted the cylinder rod, is vented directly to the atmosphere. This exhaust air often retains considerable pressure, representing a substantial portion of the initial energy input. The direct atmospheric venting of this high-pressure exhaust is the single largest avoidable loss in many compressed air systems. Conventional systems primarily focus on supplying high-pressure air and treating exhaust as a waste product. This disclosure addresses the recovery of this exhaust energy by routing the higher-pressure exhaust air into a lower-pressure pneumatic network, thereby reducing the overall demand on the primary high-pressure compressor system. This approach aims to reduce the net energy consumption associated with pneumatic actuation by utilizing otherwise wasted energy.

3. System Overview

[0003] The described system integrates a recovery circuit into a standard pneumatic cylinder arrangement to capture and reuse exhaust air. A high-pressure supply (10) delivers compressed air, typically at 6 to 8 bar (gauge), to a directional control valve (12). The directional control valve (12) then directs this air to one port of a double-acting pneumatic cylinder (14), while simultaneously allowing air from the opposite port of the cylinder (14) to exit. Instead of venting this exhaust air directly to the atmosphere, it is routed through a dedicated recovery valve block (16).

[0004] The recovery valve block (16) processes the exhaust air, regulating its pressure to a lower, predetermined level, suitable for a low-pressure ring main (18). This low-pressure ring main (18) serves as a network to collect recovered air from multiple sources and distribute it to low-pressure pneumatic consumers, such as blow-off nozzles, air tools requiring lower pressures, or specific process applications. Any residual air that cannot be recovered or that exceeds the capacity of the low-pressure ring main (18) is safely vented to the atmosphere, typically through an exhaust silencer (20) to reduce noise. The primary objective is to maximize the capture of usable energy from the cylinder exhaust, thereby reducing the load on the main compressor and improving the overall energy efficiency of the pneumatic installation. The system is designed to operate without significantly impeding the desired speed or force characteristics of the pneumatic cylinder (14) during its primary work cycle. FIG. 1 provides a high-level block diagram of the overall system.

4. Components

[0005] The core components of the system include:

[0006]

- **High-Pressure Supply (10):** This is the source of compressed air, typically provided by an industrial air compressor and associated air treatment equipment. It delivers air at a standard operating pressure, for example, 6.5 bar.
- **Directional Control Valve (12):** A multi-port, multi-position valve (e.g., a 5/2-way valve) that controls the flow of compressed air to and from the pneumatic cylinder (14) to initiate its extension and retraction movements.
- **Pneumatic Cylinder (14):** A double-acting pneumatic actuator, comprising a cylinder barrel, a piston, and a rod. It performs mechanical work by converting pneumatic pressure into linear force. The cylinder has two ports for pressurization and exhaust.
- **Recovery Valve Block (16):** This critical assembly manages the exhaust air from the pneumatic cylinder (14). It contains several sub-components detailed below.
- **Low-Pressure Ring Main (18):** A network of piping designed to distribute compressed air at a lower pressure, for instance, 1.5 to 2.5 bar, to various consuming devices. This ring main is distinct from the primary high-pressure supply network.
- **Exhaust Silencer (20):** A device connected to the recovery valve block (16) to reduce the noise generated by any air vented directly to the atmosphere.

[0007] Within the **Recovery Valve Block (16)**, as shown in FIG. 2, the following sub-components are integrated:

[0008]

- **Inlet Check Valve (22):** This valve allows air flow from the cylinder exhaust port into the recovery circuit but prevents backflow from the recovery circuit into the cylinder (14). A pair of these, one for each cylinder exhaust port, would be used or a single valve with dual inlets.
- **Pressure Regulator (24):** A pressure reducing valve set to maintain a desired output pressure (e.g., 2 bar) for the air entering the low-pressure ring main (18). This ensures that the low-pressure network is not subjected to the higher cylinder exhaust pressures.

- **Outlet Check Valve (26):** Positioned after the pressure regulator (24), this valve prevents backflow from the low-pressure ring main (18) into the recovery valve block (16) or the cylinder (14), particularly when the cylinder exhaust pressure drops below the ring main pressure.
- **Pressure Sensor (28):** A device for monitoring the pressure within the recovery circuit, typically located between the pressure regulator (24) and the outlet check valve (26). It can provide feedback for system diagnostics or control.
- **Relief Valve (30):** A safety valve set to open and vent air to atmosphere if the pressure within the recovery circuit or the low-pressure ring main (18) exceeds a safe limit, such as 3 bar.
- **Bypass Orifice (32):** An adjustable or fixed restriction that allows a small, controlled amount of cylinder exhaust air to bypass the recovery circuit and vent directly to atmosphere. This component is crucial for tuning cylinder return speed.

5. Operation

[0009] The operation of the compressed air energy recovery system involves distinct phases: cylinder extension, cylinder retraction, and steady-state recovery.

[0010] **Start-up and Cylinder Extension:** Upon system activation, the high-pressure supply (10) delivers air. When the directional control valve (12) is actuated to extend the pneumatic cylinder (14), compressed air flows from the supply (10) through the valve (12) to the cap end port of the cylinder (14). Simultaneously, air in the rod end of the cylinder (14) is pushed out by the advancing piston. This exhaust air enters the recovery valve block (16). The inlet check valve (22) opens, allowing the exhaust air to pass. The pressure regulator (24) then reduces this pressure to the set point of the low-pressure ring main (18), for example, 2 bar. The outlet check valve (26) opens, and the regulated air flows into the low-pressure ring main (18). Any air that exceeds the capacity or pressure set point of the recovery circuit, or which is specifically directed by the bypass orifice (32), exits through the exhaust silencer (20).

[0011] **Cylinder Retraction:** When the directional control valve (12) is actuated to retract the pneumatic cylinder (14), compressed air flows from the supply (10) through the valve (12) to the rod end port of the cylinder (14). Air in the cap end of the cylinder (14) is now the exhaust. This exhaust air follows the same path through the recovery valve block (16) as described for extension, being regulated and directed into the low-pressure ring main (18). The recovery valve block (16) would typically be a dual-input block, or two separate recovery circuits would be used, one for each cylinder port.

[0012] **Steady Running:** During continuous operation, the system cycles through extension and retraction. The recovery valve block (16) continuously captures exhaust air from both ends of the cylinder (14), regulates its pressure, and feeds it into the low-pressure ring main (18). The pressure sensor (28) can monitor the pressure within the recovery circuit. If the pressure in the recovery circuit exceeds a safe limit, the relief valve (30) activates to vent excess pressure to atmosphere, protecting the downstream low-pressure ring main (18) and connected equipment. The bypass orifice (32) plays a critical role in managing cylinder return speed. If the back-pressure created by the recovery circuit significantly impedes the piston's movement, a portion of the exhaust air can be directed through the bypass orifice (32) directly to atmosphere, reducing the back-pressure and allowing the cylinder to move at its desired speed. This orifice can be adjusted to balance recovery efficiency with operational speed requirements.

[0013] **Fault or Interruption:** In the event of a fault, such as a blockage in the low-pressure ring main (18) or a failure of the pressure regulator (24), the relief valve (30) will open to prevent over-pressurization. If the low-pressure ring main (18) becomes fully pressurized to its set point, subsequent exhaust air from the cylinder (14) will either be vented through the relief valve (30) or, if the bypass orifice (32) is present, predominantly through the exhaust silencer (20). The system is designed such that failure of the recovery circuit does not prevent the pneumatic cylinder (14) from operating, although it would revert to a less energy-efficient direct-to-atmosphere exhaust mode.

6. Example Embodiments

[0014] **Embodiment 1** In this configuration, a single double-acting pneumatic cylinder (14) with a bore diameter of 100 mm and a stroke of 500 mm operates at a supply pressure of 7 bar. The recovery valve block (16) is designed to capture exhaust air from both cylinder ports. It incorporates two inlet check valves (22), one for each port, feeding into a common chamber. This chamber is then connected to a single pressure regulator (24) set to 2 bar. Downstream of the regulator (24) is a single outlet check valve (26) and a connection to the low-pressure ring main (18). A fixed bypass orifice (32) with a diameter sized for approximately 10% of the maximum exhaust flow is included to ensure the cylinder's return speed is not unduly restricted, aiming for a cycle time within 10% of the non-recovery system. The relief valve (30) is set to open at 2.5 bar. This embodiment is suitable for applications where the cylinder cycles frequently and consistent return speed is important.

[0015] **Embodiment 2** This embodiment features multiple small-bore pneumatic cylinders (14), for example, six cylinders with 40 mm bore and 150 mm stroke, operating at 6 bar supply pressure. Each cylinder has its own compact recovery valve block (16) integrated directly into its exhaust ports, effectively creating a distributed recovery system. Each compact block contains an inlet check valve (22) and a pressure regulator (24) set to 1.5 bar, with a small outlet check valve (26). These individual regulated outlets then feed into a common low-pressure ring main (18). This arrangement is intended for systems with numerous smaller actuators where a centralized recovery block might be impractical due to piping complexity. The absence of an adjustable bypass orifice (32) in each small unit means that cylinder speed is primarily managed by the setting of the pressure regulator (24) and the inherent flow characteristics of the recovery circuit, allowing for a slight reduction in return speed in favor of higher recovery. A single, larger relief valve (30) is placed on the common low-pressure ring main (18).

[0016] **Embodiment 3** This embodiment is adapted for a large, slow-moving pneumatic cylinder (14), such as one with a 200 mm bore and 1000 mm stroke, operating at 5 bar. The recovery valve block (16) in this case features a proportionally larger pressure regulator (24) and check valves (22, 26) to handle the greater volume of exhaust air. Crucially, it includes an electronically actuated bypass valve in place of a fixed orifice (32). This bypass valve is controlled by a system that monitors the cylinder's position and velocity, allowing for dynamic adjustment of exhaust back-pressure. During the initial phase of cylinder movement, the bypass valve may be opened wider to allow rapid acceleration. As the cylinder approaches its end of stroke, the bypass valve can be partially or fully closed, maximizing air recovery while maintaining the desired deceleration profile. The pressure regulator (24) is set to 2.2 bar, and the recovered air feeds into a high-capacity low-pressure ring main (18). This embodiment is suitable for applications where precise control over cylinder dynamics and maximal energy recovery are both critical.

7. Alternative Configurations

[0017] Several alternative configurations can be considered. Instead of a single recovery valve block (16), individual check valves (22) and pressure regulators (24) could be placed directly at each exhaust port of the directional control valve (12) or cylinder (14), feeding into a common low-pressure manifold that then connects to the low-pressure ring main (18). This distributed approach might simplify piping for some layouts. Another alternative involves a pilot-operated pressure regulator (24) for improved response in high-flow applications. The low-pressure ring main (18) itself could be replaced by a dedicated low-pressure air receiver tank for buffering, which might be beneficial for intermittent high-demand low-pressure applications. Furthermore, the recovery valve block (16) could incorporate a non-return flow sensor to quantify the amount of recovered air, allowing for ongoing assessment of energy savings. For very large cylinders or high-cycle applications, a heat exchanger could be integrated into the recovery path to cool the recovered air before it enters the low-pressure ring main (18), preventing potential temperature increases in the network.

8. Parameter Variations

Parameter	Realistic Range	Effect of Increasing Value	Effect of Decreasing Value
High-Pressure Supply (10)	5 to 10 bar (gauge)	Higher potential energy recovery, increased cylinder force.	Lower potential energy recovery, reduced cylinder force.
Cylinder Bore Diameter (14)	20 to 320 mm	Greater volume of exhaust air, increased recovery potential.	Smaller volume of exhaust air, reduced recovery potential.
Cylinder Stroke (14)	10 to 2000 mm	Greater volume of exhaust air per cycle, increased recovery potential.	Smaller volume of exhaust air per cycle, reduced recovery potential.
Recovery Pressure (Regulator 24)	1 to 3 bar (gauge)	Higher back-pressure on cylinder, increased recovery energy per unit volume.	Lower back-pressure on cylinder, reduced recovery energy per unit volume.
Bypass Orifice Size (32)	0 to 100% of full flow	Faster cylinder return speed, reduced energy recovery.	Slower cylinder return speed, increased energy recovery.
Low-Pressure Ring Main (18) Pressure	1 to 3 bar (gauge)	Higher pressure for low-pressure consumers, potential for reduced recovery flow.	Lower pressure for low-pressure consumers, greater recovery flow.
Cylinder Cycle Rate	1 to 60 cycles/ minute	Increased total volume of recovered air per unit time.	Decreased total volume of recovered air per unit time.

9. Additional Implementations

[0019] The described system's benefit diminishes or ceases to be worthwhile when the energy recovered does not justify the capital cost and complexity of the recovery components or when it significantly impairs the cylinder's primary function. This point is typically reached under several conditions:

[0020] First, for very small pneumatic cylinders (e.g., less than 32 mm bore) or those with very short strokes, the volume of exhaust air is often too small to yield a significant energy return. The energy density of compressed air is relatively low, and the overhead of the recovery components may exceed the value of the recovered air.

[0021] Second, if the pneumatic cylinder (14) operates at a very low cycle rate (e.g., less than one cycle per minute), the total volume of air recovered over time may be insufficient to impact the overall compressor load meaningfully. The system's effectiveness is directly proportional to the frequency and volume of exhaust.

[0022] Third, if the primary high-pressure supply (10) pressure is already low (e.g., below 4 bar), the potential for pressure reduction into a low-pressure ring main (18) of 1 to 2 bar becomes limited. The pressure differential required for efficient recovery and regulation may not be present, or the remaining energy in the exhaust air is too low to be useful.

[0023] Fourth, if the application of the pneumatic cylinder (14) demands extremely fast and precise return speeds, the inherent back-pressure created by the recovery circuit, even with a bypass orifice (32), might be unacceptable. In such cases, the operational constraint on speed may override the energy recovery benefit, leading to a large portion of air being vented to atmosphere through the bypass, diminishing recovery.

[0024] Finally, if there are no suitable low-pressure consumers connected to the low-pressure ring main (18), the recovered air has no immediate application and would eventually be vented, rendering the recovery effort unproductive. The existence of a demand for low-pressure air is a prerequisite for the system's economic viability.

10. Figures

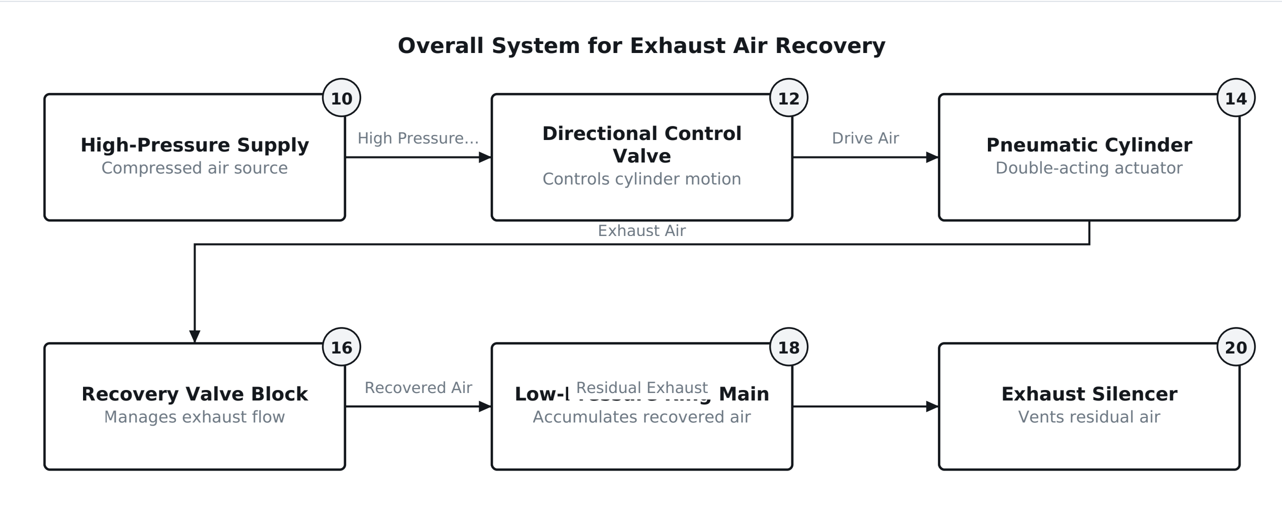

FIG. 1 This diagram illustrates the primary components and flow paths of the compressed air energy recovery system. PNG

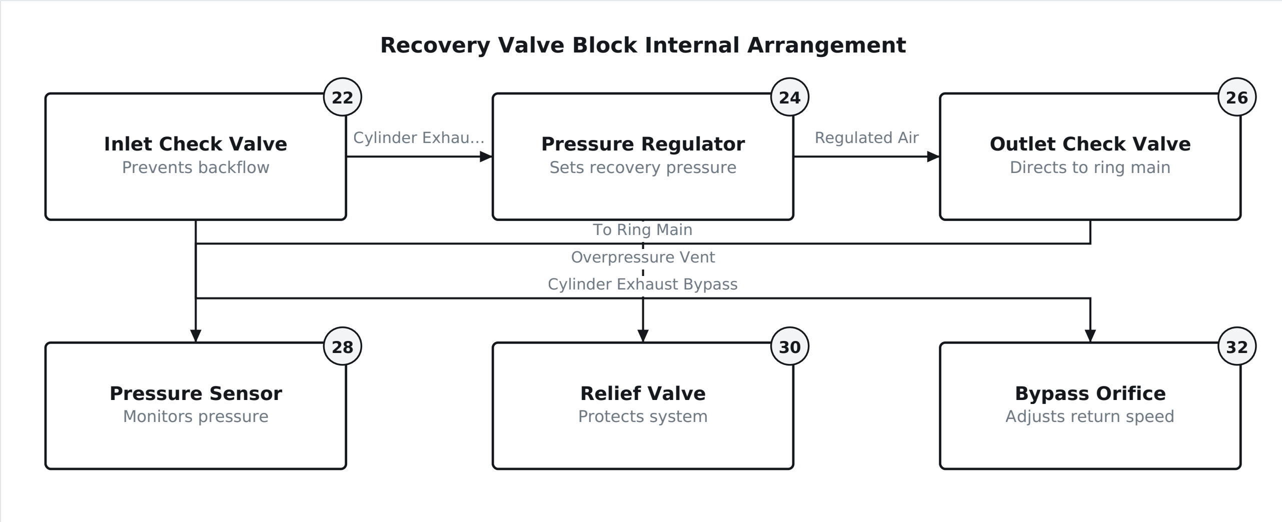

FIG. 2 This diagram shows the internal components and connections within the recovery valve block. PNG

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