How to Streamline Air Circuits

Here are some tips for sizing pneumatic systems for performance and efficiency.

Who, What, Where

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Key points
- Calculate flow capacity to prevent oversized valves.
- Using different pressures to extend and retract cylinders saves energy.
- Leaks make even the best designs unattractive performers.

Resources
Festo Corp., festo.com
Monitoring pneumatics, tinyurl.com/5hmcl
Preventing leaks, tinyurl.com/6yy2n1
In today’s manufacturing environments, pneumatics often provides ideal solutions for motion-control applications. Pneumatic systems are well suited for applications involving linear or rotary speeds of 4 m/sec (13 ft/sec) with forces up to 20 kN (4,500 lb). Linear actuators can come in stroke lengths as large as 10 m (33 ft) and, when coupled with a closed-loop system with a servocontroller and proportional valve, they can provide multiple speed, force, and positioning capabilities.

With the advent of fieldbus networking, pneumatic components can be simply attached to a system with less wiring and with the added capability to create centralized or decentralized valve systems.

Given the role pneumatic systems play in many industries, the question then becomes: How can manufacturing companies optimize performance and reduce energy costs associated with compressed air? The following are some important factors to consider.

**Sizing valves**

Sizing an air cylinder for an application is usually a straightforward process. Knowing the force and stroke requirements, and the available air pressure, engineers can readily calculate the minimum piston diameter to get the job done. When sizing a cylinder, a good rule of thumb is to initially make it large enough to provide approximately twice the calculated required force to overcome internal friction, guide friction, and other external forces.

Selecting and sizing pneumatic valves for a circuit is a bit more involved. Initial selection criteria include the type of valve and the operations it must perform; how it’s turned on and off; and whether it’s a stand-alone unit or mounted on a manifold. Beyond these basic criteria, however, flow capacity is arguably one of the most important factors. Oversized valves often lead to bigger-than-necessary connectors, tubing, and actuators, which increase the cost of components as well as the energy costs of electricity and compressed air — while undersized valves hurt system performance.

Flow capacity indicates the amount of resistance a valve presents to a pneumatic circuit, and is typically measured as volume coefficient ($C_v$) or in liters per minute. All devices that conduct air resist flow to some degree, and pressure drop across a device will increase with flow.

In the past, common practice was to match the port size of the valve with the port size of the actuators. Experts no longer recommend this method because today’s valves are smaller yet have greater flow capacity than their counterparts of a few years ago. Smaller valves tend to switch quicker, cost less, and consume less power.

Thus, the first step in selecting a valve means calculating the flow required to move an actuator within an allotted time. The following equation lets you calculate the flow coefficient required for the valve. For U.S. units, flow

$$p_{ti}\,\text{in} \,\text{of} \,\text{flow} \,\text{required} \,\text{for} \,\text{the} \,\text{valve}.$$
Modern pneumatic servodrives offer multiple positioning and other advanced capabilities. This Festo VPWP proportional valve has pressure sensors that report diagnostic data to the controller, letting it monitor the condition of servopneumatic drives.

For this reason, valve ratings alone cannot predict flow rates through a system branch.

Regulating pressure

The pneumatic energy used to perform a task is a function of pressure and volume. In typical pneumatic systems, volume equals cylinder volume plus the volume of the pipe between the valve and cylinder. These volumes are typically pressurized and emptied each time a cylinder extends or retracts. The combined cylinder and pipe volumes should ideally only be charged to the pressure required to successfully stroke the cylinder. Exceeding this pressure wastes energy, and it is easy to both calculate the correct pressure and reduce overpressure.

In many applications there is a significant difference between the cylinder force needed to extend (push a load) versus retract (pull a load). It does not matter which force is larger; the point is, there is usually a big difference between the two. The vast majority of pneumatic controls, however, apply the same pressure for both extend and retract strokes. In addition to wasting energy, charging a cylinder to a higher-than-necessary pressure increases noise.

rate is defined as:
\[ Q = \frac{VC}{(28.8t)} \]
and for SI units,
\[ Q = \frac{VC}{t}. \]

The compression factor \( C_f \) is defined as
\[ C_f = \frac{(P_1 + P_a)}{P_a}. \]

Then determine the required \( C_v \). For U.S. units,
\[ C_v = \frac{Q}{\sqrt{22.48} \Delta P (P_1 + P_a)} \]

For SI units,
\[ C_v = \frac{Q}{\sqrt{114.5} \Delta P (P_1 + P_a)} \]

As an example, consider a double-acting cylinder with a 25-mm bore and 100-mm stroke. Rod diameter is 10 mm, air pressure is 6 bar, and pressure drop across the valve is 0.25 bar. The application requires the cylinder to extend in 0.25 sec and return in 0.2 sec.

The goal is to determine the necessary valve \( C_v \). First calculate areas and volumes on the extend side of the cylinder.
\[ A_e = \pi \left( \frac{d}{2} \right)^2 = 490.87 \text{ mm}^2 \]
\[ V_e = A_e L = 49,087 \text{ mm}^3 = 0.049 \text{ liters} \]

Areas and volumes on the retract side are:
\[ A_r = \pi \left( \left( \frac{d}{2} \right)^2 - \left( \frac{dr}{2} \right)^2 \right) = 412.33 \text{ mm}^2 \]
\[ V_r = A_r L = 41,233 \text{ mm}^3 = 0.041 \text{ liters} \]

Second, calculate the compression factor,
\[ C_f = (6 + 1)/1 = 7. \]

Third, calculate the flow rate required to extend and retract the cylinder.
\[ Q_e = \frac{(VC_f)}{t_e} = 1.372 \text{ liters/sec} \]
\[ Q_r = \frac{(VC_f)}{t_r} = 1.439 \text{ liters/sec} \]

Finally, calculate the \( C_v \) necessary to extend and retract the cylinder.
\[ C_v = \frac{Q}{\sqrt{114.5} \left\{ \frac{(293 \times 1)}{(0.25 \times (5.75 + 1))} \right\} } = 0.158 \]
\[ C_v = \frac{Q}{\sqrt{22.48} \Delta P (P_1 + P_a)} = 0.166 \]

For this example, the valve must have at least a \( C_v = 0.158 \) for the extend stroke and \( C_v = 0.166 \) to retract within the system's time requirements. A valve with the exact specific flows for both extend and retract most likely does not exist, so select a valve with a larger \( C_v \). One with a \( C_v = 0.200 \) should suffice. A slightly larger valve also takes into account restrictions caused by fittings and tubing which can affect reaction time.

Note that any device, fitting, or run of tubing can affect the system flow rate. In time-critical applications, a few extra inches of tubing or the wrong fitting can mean the difference between a circuit that works and one that does not.

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vibration, and leakage and, therefore, lowers mean time between failure (MTBF). Higher pressures also reduce cylinder speed, because the cylinder wastes time charging beyond the level required, and it takes longer to empty the chamber. And overpressurizing magnifies internal and external leaks.

To illustrate the problem, let’s estimate how much energy used to compress air is wasted by pressurizing cylinders beyond the levels necessary to stroke a cylinder. Assume that the cylinder is sized correctly for the push load, but only half the pressure is needed to retract the cylinder. With a 2:1 ratio of loaded versus unloaded cylinder stroke, about 20% of total energy is wasted if the cylinder operates at the same pressure for push/pull loads.

In the cylinder in the above example, reducing pressure on the return stroke from 6 to 3 bar would reduce compressed-air consumption on the return stroke by nearly half. For a setup operating on an 8-hr shift year round, resulting savings could be well over $100/yr for a single cylinder, paying for a regulator in a matter of months.

Many practical, low-cost components can control individual cylinder pressure and help eliminate energy waste. On subbase-mounted valves, for example, sandwich pressure regulators independently control a cylinder’s load and nonload pressure.

Elbow pressure regulators provide another easy and low-cost solution. These compact devices look like elbow flow-control valves, but they control pressure. The regulators have a built-in check valve for reverse flow and a dial to indicate pressure settings.

**Minimizing volume**

The development of decentralized fieldbuses for pneumatic-valve manifolds lets designers reduce the distance between valve and cylinders. This reduces pipe volume. In fact, from an efficiency standpoint, the ideal place to mount a valve is directly on the cylinder and completely eliminate the piping.

Reducing pipe volume between the valve and cylinder saves energy even if pipe volume increases between the compressor and valve manifold. That is because the volume between valve and cylinder pressurizes and empties every cycle, whereas the volume between the compressor and manifold rarely empties.

Some bus protocols, such as AS-Interface, permit a simple, low-cost serial link to a single valve. This lets designers mount valves on the cylinder, considerably reducing air consumption.

**System considerations**

Smaller cylinders and valves require less space, save money, and consume less air. But keep in mind that valves and cylinders are only one part of a complete system — every component that potentially causes a flow restriction or delay must be considered as part of the overall design. Here are some additional factors to consider.

Cylinder and valve ports can restrict airflow due to the fittings’ internal orifices. Flow controls can restrict airflow even in their full-open position. And 90° fittings cause pressure drops and add delays.

Make air lines between the valve and cylinder as straight as possible with minimal bends. And keep in mind air lines have different flow characteristics depending on whether they are rigid pipe or flexible tubing. Each application has an optimum air-line ID. Increasing the air-line diameter increases Cv but also increases the volume that must be filled and emptied each cycle.

For actuators, select cylinder bore sizes to handle the expected load plus a reasonable safety factor. Larger-than-necessary cylinders cost more, waste energy, and add cycle time. Likewise, cylinder stroke should be no more than required. Longer-stroke cylinders are also more expensive, waste energy, and add cycle time.

In general, components with the smallest Cv’s and largest pressure drops limit circuit performance the most. Increase these Cv’s first to have the greatest impact on circuit performance. Similarly, components with the largest Cv’s and smallest pressure drops are possibly oversized. Decreasing these Cv’s could improve circuit performance.

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**Leaks negate good engineering**

It’s critical to keep in mind that all the engineering time and effort involved in refining a pneumatic circuit is a waste if the system is plagued by leaks. For an in-depth look at the effects of leakage on operating costs and performance — and how to pinpoint and fix problems before they get out of hand — see “Monitoring pneumatics makes all the difference,” August 21, 2008, and “Self-monitoring pneumatic systems,” in the April 26, 2007 issues of MACHINE DESIGN. They’re available at machinedesign.com.