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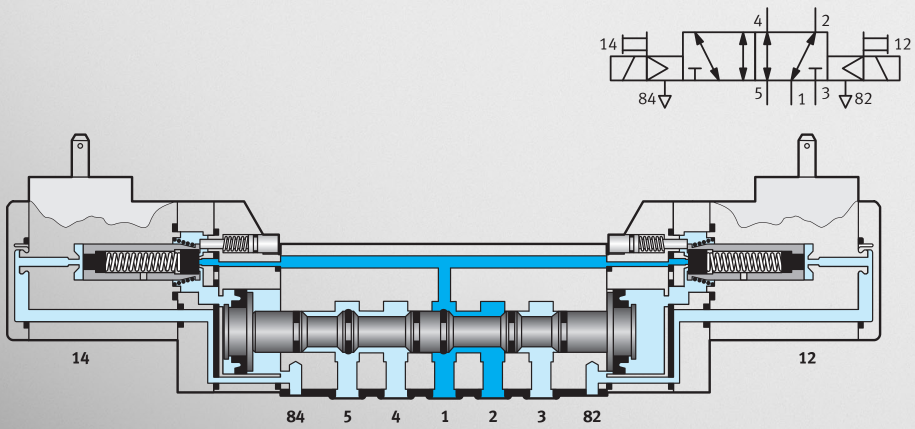
Pneumatics
Electropneumatics

Fundamentals

Textbook



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1 Applications in automation technology

1.1 Overview

Pneumatics play a major role in the automated work environment and are still gaining in importance. Many production processes would be inconceivable without them. Pneumatics are an inherent part of almost every production system in the following industry sectors:

- Automotive industry
- Chemical industry
- Petrochemical industry
- Pharmaceutical industry
- Printing and paper industry
- Machine building
- Food industry
- Drinking water and wastewater technology
- Packaging industry

In these industries, pneumatics are used to perform the following functions:

- Detecting states by means of input elements (sensors)
- Processing information using processing elements (processors)
- Switching operating elements by means of control elements
- Doing work using operating elements (drives)

Controlling machines and systems requires a rather complex logical chain of states and switching conditions to be set up. This is done through the interaction of sensors, processors, control elements and drives in pneumatic or partially pneumatic systems.

The technological advances in materials, design and production methods have helped to improve the quality and variety of pneumatic components, which has contributed to them being used more extensively.

Below are some examples of areas of application for pneumatics:

- Generally in handling technology:
  - Clamping workpieces
  - Moving workpieces
  - Positioning workpieces
  - Orienting workpieces
  - Branching material flows

- General use in various fields
  - Packaging
  - Filling
  - Metering
  - Locking
  - Material transport
  - Turning workpieces
  - Separating workpieces
  - Stacking workpieces
  - Embossing and pressing workpieces

1.2 Characteristics of pneumatics

Parameter	Comment
Quantity	Air is available virtually everywhere in unlimited quantities.
Transport	Air can be very easily transported over long distances in ducts.
Storage ability	Compressed air can be stored in a reservoir and supplied from there. The reservoir (bottle) can also be transported.
Temperature	Compressed air is virtually insensitive to temperature fluctuations. This guarantees reliable operation even under extreme conditions.
Safety	Compressed air does not represent a hazard in terms of fire or explosion.
Cleanliness	Leaks of unlubricated compressed air do not cause environmental pollution.
Design	The operating elements have a simple setup and are therefore inexpensive.
Speed	Compressed air is a fast working medium. It facilitates high piston speeds and fast switching times.
Overload protection	Pneumatic tools and operating elements can be loaded until they give out and are therefore overload-proof.

Table 1.1: Features and advantages of pneumatics

Parameter	Comment
Preparation	Compressed air must be prepared as otherwise there is a risk of increased wear of the pneumatic components by dirt particles and condensed water.
Compression	It is not possible to achieve uniform and constant piston speeds with compressed air.
Force	Compressed air is only economical up to a certain force requirement. With a normal operating pressure of 600 to 700 kPa (6 to 7 bar) and depending on the stroke and speed, this limit is between 40,000 and 50,000 N.
Exhaust air	Escaping air makes a lot of noise. This problem can be solved to a large extent by means of sound-absorbing materials and silencers.

Table 1.2: Disadvantages of pneumatics

The comparison with other forms of energy is an important prerequisite for using pneumatics as a control or working medium. This assessment covers the overall system from the input signals (sensors) and the control section (processor) to the control elements and drives. In addition, the following factors must be considered:

- Preferred control media
- Available equipment
- Available knowledge
- Existing systems

1.2.1 Criteria for working media

Working media are:

- Electric current (electrics)
- Fluids (hydraulics)
- Compressed air (pneumatics)
- Combination of the above media

Selection criteria and system properties that must be taken into consideration for working media:

- Force
- Stroke
- Type of movement
  (linear, swivelling, rotary)
- Speed
- Service life
- Reliability and precision
- Energy costs
- Operability
- Storage ability

1.2.2 Criteria for control media

Control media area:

- Mechanical connections (mechanics)
- Electric current (electrical, electronics)
- Fluids (hydraulics)
- Compressed air (pneumatics, low-pressure pneumatics)

Selection criteria and system properties that must be taken into consideration when using the control media:

- Reliability of the components
- Sensitivity to environmental influences
- Ease of maintenance and repair
- Switching time of the components
- Signal speed
- Space requirement
- Service life
- Alterability of the system
- Training requirements

1.3 Development of pneumatic control systems

The following product groups are available within pneumatics:

- Drives
- Sensors and input devices
- Processors
- Accessories
- Complete control systems

The following considerations must be taken into account when developing pneumatic control systems:

- Reliability
- Ease of maintenance
- Spare part costs
- Assembly and connection
- Maintenance costs
- Interchangeability and versatility
- Compact design
- Economy
- Documentation

2 Basic concepts of pneumatics

2.1 Physical principles

Air is a gaseous mixture with the following composition:

- approx. 78% nitrogen
- approx. 21% oxygen

It also contains traces of carbon dioxide, argon, hydrogen, neon, helium, krypton and xenon.

To help you understand the nature of air, the physical variables that are used in this context are listed below. All specifications are in the "International System of Units", or SI for short.

Variable	Symbol	Unit
Length	l	Metre (m)
Mass	m	Kilogram (kg)
Time	t	Second (s)
Temperature	T	Kelvin (K, 0 °C = 273.15 K)

Table 2.1: Basic units

Variable	Symbol	Unit
Force	F	Newton (N)
Area	A	Square metre (m^2)
Volume	V	Cubic metre (m^3)
Flow rate	q_v	Cubic metre per second (m^3/s)
Pressure	p	Pascal (Pa) 1 Pa = 1 N/m^2 1 bar = 10^5 Pa

Table 2.2: Derived units

2.1.1 Newton's law

Newton's law describes the relationship between force, mass and acceleration:
Force = mass · acceleration

$$F = m \cdot a$$

In the case of free fall, a is replaced by gravitational acceleration $g = 9.81\ m/s^2$.

2.1.2 Pressure

1 Pa corresponds to the pressure exerted by a vertical force of 1 N on an area of 1 m^2.

The pressure against/on the earth's surface is referred to as atmospheric pressure (p_{amb}). This pressure is also called reference pressure. The range above this pressure is called the excess pressure range ($p_e > 0$), while the range below is called the vacuum range ($p_e < 0$). The atmospheric pressure differential p_e is calculated according to the formula:

$$p_e = p_{abs} - p_{amb}$$

This is illustrated in the following diagram:

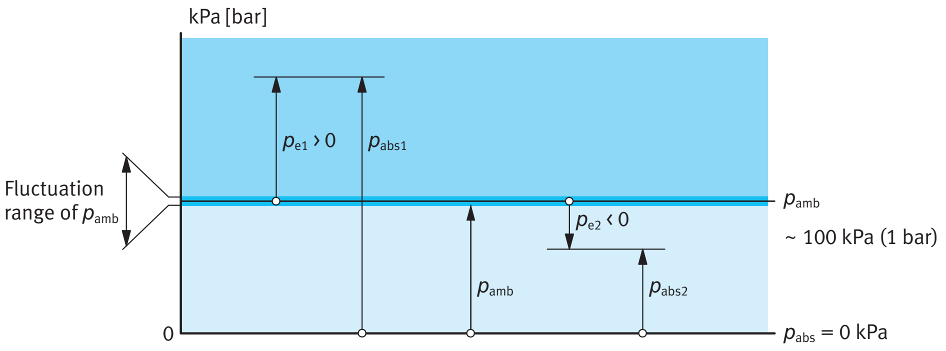


Figure 2.1: Air pressure

Atmospheric pressure is not constant. Its value changes with the geographical position and the weather.

Absolute pressure p_{abs} is the value referred to zero pressure (vacuum). It is equal to the sum of the atmospheric pressure and excess pressure or vacuum. The pressure gauges most often used in practice are those that display only the excess pressure p_e. The absolute pressure value p_{abs} is approximately 100 kPa (1 bar) higher.

In pneumatics, all specifications relating to air quantities are usually referred to as the so-called normal condition. The normal condition according to DIN 1343 is the condition of a solid, liquid or gaseous material defined by means of standard temperature and standard pressure.

- Standard temperature T_n = 273.15 K, t_n = 0 °C
- Standard temperature p_n = 101,325 Pa = 1.01325 bar

2.2 Properties of air

Air is characterised by very low cohesion, i.e. the forces between the air molecules are negligible in the operating conditions usual in pneumatics. Like all gases, air therefore does not have a specific form. It changes its shape with the least application of force and occupies the maximum space available to it.

2.2.1 Boyle's law

Air can be compressed and attempts to expand. Boyle's law describes these properties as follows: the volume of a fixed amount of gas is inversely proportional to the absolute pressure at constant temperature; or, to put it another way, the product of volume and absolute pressure is constant for a fixed amount of gas.

$$p_1 \cdot V_1 = p_2 \cdot V_2 = p_3 \cdot V_3 = \text{constant}$$

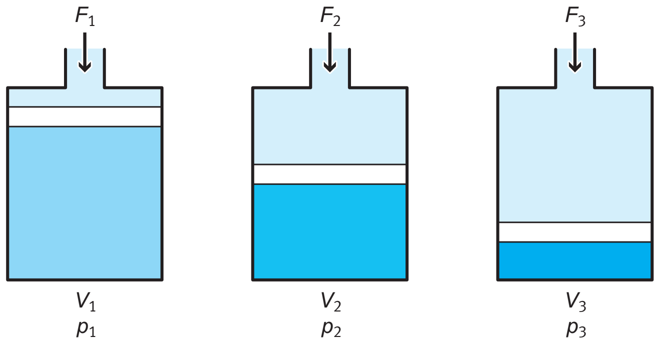


Figure 2.2: Boyle's law

Calculation example

Air is compressed to 1/7 of its volume at atmospheric pressure. What is the pressure if the temperature remains constant?

$$p_1 \cdot V_1 = p_2 \cdot V_2$$

$$p_2 = p_1 \cdot \frac{V_1}{V_2}, \text{ note: } \frac{V_2}{V_1} = \frac{1}{7}$$

$p_1 = p_{amb}$ = 100 kPa = 1 bar
p_2 = 1 · 7 = 700 kPa = 7 bar absolute

This means: $p_e = p_{abs} - p_{amb}$ = (700 – 100) kPa = 600 kPa = 6 bar

A compressor that generates an excess pressure of 600 kPa (6 bar) has a compression ratio of 7:1.

2.2.2 Gay-Lussac's law

Air expands by 1/273 of its volume at constant pressure, a temperature of 273 K and a rise in temperature of 1 K. Gay-Lussac's law states that the volume of a fixed amount of gas is proportional to the absolute temperature as long as the pressure is not changed.

$\frac{V_1}{V_2} = \frac{T_1}{T_2}$, V_1 = volume at T_1, V_2 = volume at T_2

or

$$\frac{V}{T} = constant$$

The change in volume ΔV is: $\Delta V = V_2 - V_1 = V_1 \cdot \frac{T_2 - T_1}{T_1}$

The following holds for V_2: $V_2 = V_1 + \Delta V = V_1 + \frac{V_1}{T_1} \cdot (T_2 - T_1)$

These equations only apply if the temperatures in K are used. The following formula must be used to convert to °C:

$$V_2 = V_1 + \frac{V_1}{273\,°C + T_1} \cdot (T_2 - T_1)$$

Calculation example
0.8 m^3 of air with the temperature T_1 = 293 K (20 °C) is heated to T_2 = 344 K (71 °C). By how much does the air expand?

$$V_2 = 0.8\ \text{m}^3 + \frac{0.8\ \text{m}^3}{293\ \text{K}} \cdot (344\ \text{K} - 293\ \text{K})$$

$$V_2 = 0.8\ \text{m}^3 + 0.14\ \text{m}^3 = 0.94\ \text{m}^3$$

The air expands by 0.14 m^3 to 0.94 m^3.

If the volume is kept constant during the heating process, the increase in pressure can be expressed using the following formula:

$$\frac{p_1}{p_2} = \frac{T_1}{T_2}$$

or

$$\frac{p}{T} = \text{constant}$$

2.2.3 General gas equation

The general gas equation fulfils all the laws:

$$\frac{p_1 \cdot V_1}{T_1} = \frac{p_2 \cdot V_2}{T_2} = \text{constant}$$

With a fixed amount of gas, the product of pressure and volume divided by the absolute temperature is constant.

The above-mentioned laws can be derived from this general gas law, when one of the three factors p, V or T is kept constant.

- Pressure p constant → isobaric change
- Volume V constant → isochoric change
- Temperature T constant → isothermic change

3 Compressed air generation and compressed air supply

3.1 Preparing the compressed air

To be able to guarantee the reliability of a pneumatic control system, compressed air of adequate quality must be supplied. This is determined by the following factors:

- Correct pressure
- Dry air
- Cleaned air

If these requirements are not met, this can result in increased machine downtime coupled with higher operating costs.

Compressed air generation starts with compression. The compressed air flows through a whole series of components before it reaches the consuming device. The compressor type and its location more or less influence the amount of dirt particles, oil and water that get into a pneumatic system. The following components should be used for preparing compressed air:

- Inlet filter
- Compressor
- Air reservoir
- Air dryer
- Compressed air filter with water separator
- Pressure regulator
- Lubricator (if required)
- Drain points for the condensate

3.1.1 Consequences of poorly prepared compressed air

Poorly prepared air increases the number of malfunctions and shortens the service life of pneumatic systems. This is indicated by:

- Increased wear on seals and moving parts in valves and cylinders
- Oil-fouled valves
- Dirty silencers
- Corrosion in pipes, valves, cylinders and other components
- Lubrication of moving components flushed out

If there are leaks, escaping compressed air can impair the materials (e.g. foodstuffs) to be processed.

3.1.2 Pressure level

Pneumatic components are usually designed for a maximum operating pressure ranging between 800 and 1,000 kPa (8 to 10 bar). However, a pressure of 600 kPa (6 bar) is sufficient for economical operation. Due to flow resistances in the individual components (e.g. flow control valves) and in the piping, a pressure loss between 10 and 50 kPa (0.1 and 0.5 bar) is to be expected. The compressor system should therefore supply a pressure of 650 to 700 kPa (6.5 to 7 bar) to ensure the desired operating pressure of 600 kPa (6 bar).

3.2 Compressors

The choice of a compressor depends on the working pressure and the quantity of air required. Compressors are differentiated based on their design.

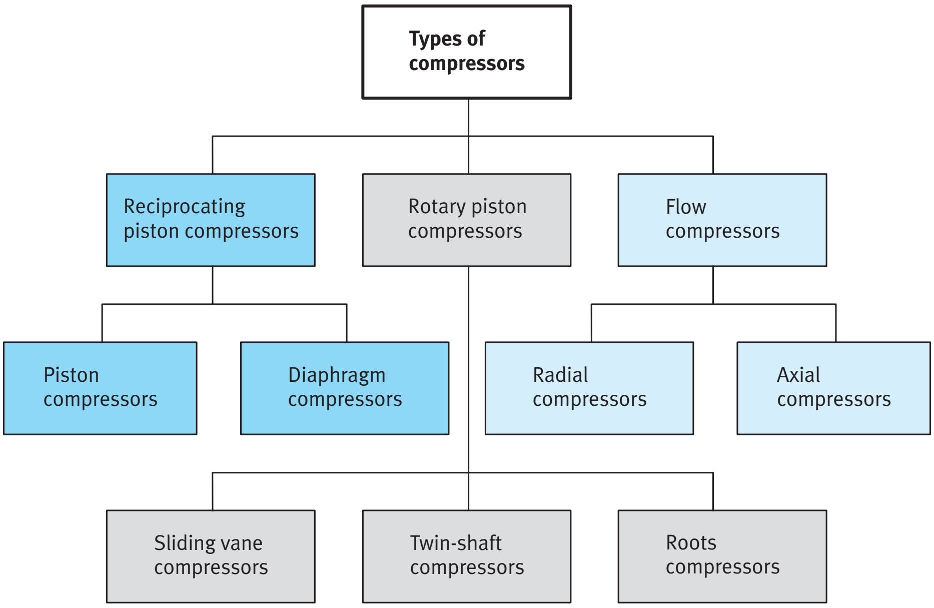


Figure 3.1: Compressor designs

3.2.1 Reciprocating piston compressor

A piston compresses the air taken in via an intake valve. The air is passed on via an exhaust valve.

Reciprocating piston compressors are frequently used as they are available for large pressure ranges. For generating higher pressures, multi-stage compressors are used. With these, the air is cooled between the individual compressor stages.

The optimum pressure ranges for reciprocating piston compressors are:

Up to 400 kPa	(4 bar)	One stage
Up to 1,500 kPa	(15 bar)	Two stages
Above 1,500 kPa	(> 15 bar)	Three or more stages

The following pressure ranges are possible, but not always economical:

Up to 1,200 kPa	(12 bar)	One stage
Up to 3,000 kPa	(30 bar)	Two stages
Above 3,000 kPa	(> 30 bar)	Three or more stages

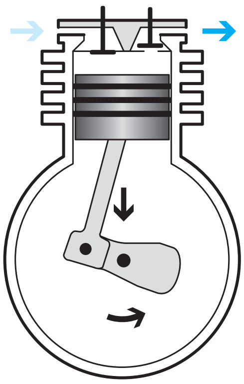


Figure 3.2: Sectional view of a single-stage reciprocating piston compressor

3.2.2 Diaphragm compressor

The diaphragm compressor belongs to the group of reciprocating piston compressors. The compressor chamber is separated from the piston by a diaphragm. This has the advantage that no oil from the compressor can get into the air flow. The diaphragm compressor is therefore frequently used in the food industry and in the pharmaceutical and chemical industry.

3.2.3 Rotary piston compressor

With a rotary piston compressor, the air is compressed using rotary pistons. During the compression process, the compression chamber is continuously constricted.

3.2.4 Screw compressor
Two shafts (slides) with helical profiles turn against each other. The interlocking profile delivers and compresses the air.

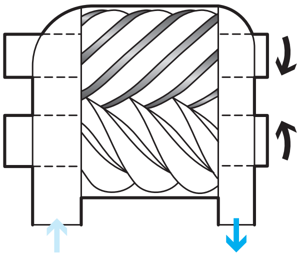


Figure 3.3: Sectional view of a screw compressor

3.2.5 Flow compressor
Flow compressors are especially suitable for high delivery rates. They can have an axial or radial design. Air flow is created using one or more turbine wheels. The kinetic energy is converted into pressure energy. With an axial compressor, the air is accelerated in axial flow direction by the vanes.

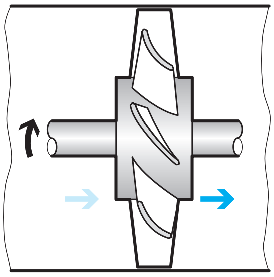


Figure 3.4: Sectional view of an axial compressor

3.2.6 Regulation
The compressor needs to be regulated to adapt the delivery rate of the compressor to fluctuations in demand. The delivery rate is regulated between variable limits for maximum and minimum pressure. There are different types of regulation:

• Idling regulation	Exhaust regulation
	Shut-off regulation
	Gripper regulation
• Partial load regulation	Speed regulation
	Suction throttle regulation
• Intermittent regulation	

Idling regulation
With exhaust regulation, the compressor works against a pressure-relief valve. If the set pressure is reached, the pressure-relief valve opens and the air is exhausted into the open. A non-return valve prevents the reservoir from being emptied. This type of regulation is only used with very small systems.

With exhaust regulation, the suction side is shut off. The compressor cannot take in air. This type of regulation is primarily used with rotary piston compressors.

Gripper regulation is used with larger piston compressors. A gripper keeps the suction valve open; the compressor cannot compress any air.

Partial load regulation
With speed regulation, the speed of the compressor's drive motor is regulated as a function of the achieved pressure.

With suction throttle regulation, regulation takes place by means of a restriction in the compressor's suction nozzle.

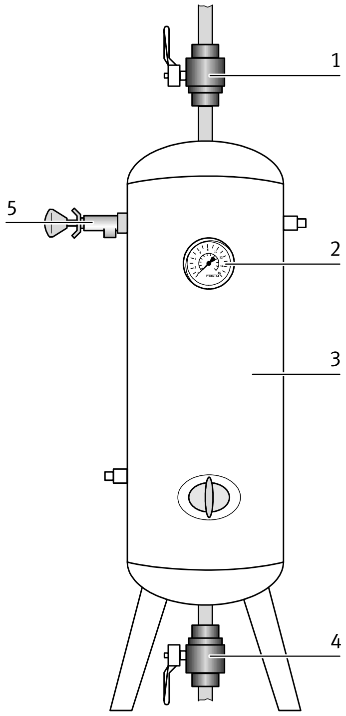
Intermittent regulation
With this type of regulation, the compressor assumes the operating states full load and idle. The compressor's drive motor is turned off when p_{max} is reached and turned on when p_{min} is reached.

3.2.7 Duty cycle
It is recommended to achieve a duty cycle of approx. 75% for a compressor. To do this it is necessary to determine the average and maximum air requirement of a pneumatic system and to tailor the choice of compressor to this. If it is expected that extensions to the system will mean an increase in the air requirement, the compressed air supply unit should be designed bigger since subsequent extension is always associated with high costs.

3.3 Air reservoirs

An air reservoir is placed downstream of the compressor to stabilise the compressed air. The air reservoir compensates pressure fluctuations when compressed air is removed from the system. If the pressure in the air reservoir falls below a certain value, the compressor fills it until the set upper pressure value is reached again. This has the advantage that the compressor does not have to work continuously.

The compressed air in the air reservoir is cooled by the relatively large surface of the reservoir. This produces condensed water, which must be regularly drained via a drain cock.



1: On-off valve; 2: Pressure gauge; 3: Air reservoir; 4: Drain cock; 5: Pressure-relief valve

Figure 3.5: Air reservoir

The size of the air reservoir depends on the following criteria:

- Delivery rate of the compressor
- Air requirement of the system
- Network (in case of additional volume)
- Regulation of the compressor
- Permissible pressure fluctuations in the network