Druckluft effizient

Thermodynamics

Compressed air is used in industry as an energy source like electricity from the wall outlet. The effort and expense necessary for producing, treating and distributing the compressed air is frequently overlooked. In order to provide a better understanding, the basic physical correlation are explained here and typical misunderstandings are pointed out.

Composition

Compressed atmospheric air is usually implied by the term 'compressed air'. The major components of unpolluted air are **nitrogen (78 vol-%) and oxygen (21 vol-%)** as well as small amounts of other gases (1 vol-%) (Fig. 1).

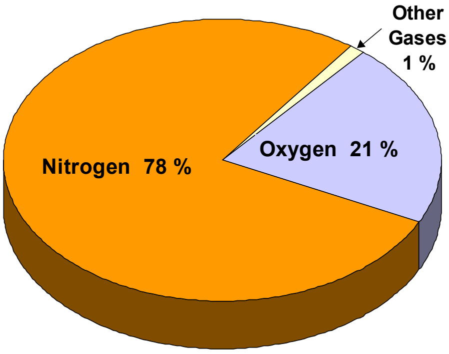

Fig. 1: Composition of dry atmospheric air

Water is also contained in atmospheric air in the form of water vapour, the amount of which varies strongly depending on temperature, volume and geographical conditions. For this reason, the share of water is usually given separately from the other components.

Pressure

This is the main parameter of compressed air which is usually expressed in the units bar or PSI (PSI = pound/(Inch)^2; 1 bar = 10^5 Pa = 10^5 N/m^2 = 14.504 PSI).

Absolute pressure (PSIA) is the pressure measured from a base of absolute zero. It is required for all theoretical observations as well as in vacuum and fan technology.

Gauge pressure (PSIG) is the practical reference value and is determined based on atmospheric pressure. Absolute pressure and gauge pressure are given in the same units. Therefore, when looking at pressure values, care must be taken to determine whether absolute or gauge pressures are involved. In practice, gauge pressures are usually meant since pressure sensors mostly display gauge pressures, i.e. the difference between absolute and atmospheric pressure (see Fig. 2). To avoid confusion, it may be sensible to show the reference in pressure figures using an index.

Compressed Air
Facts

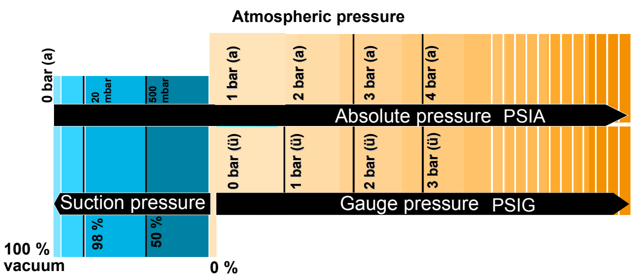

Fig. 2: Gauge, absolute and suction pressure

Water content

The maximum water vapour absorption capacity of air is described by the saturation pressure p_s. How much water can be absorbed is solely a function of the temperature. The absorption capacity increases with increasing temperature (Fig. 3).

If the air is cooled, therefore, there is always the danger that the water vapour contained will be condensed out and that condensate will be formed.

Condensate may also occur if the saturation pressure is exceeded during compression. If humid, atmospheric air is compressed at constant temperature, the partial pressure of the water vapour also increases corresponding to the increase in overall pressure. If the saturation partial pressure at this temperature is exceeded due to compression, condensate is precipitated. Since the air leaves the compressor with a much higher temperature, the condensate is only precipitated if the compressed air is cooled down beneath the pressure dew point. Below this temperature, condensate is precipitated continuously, i. e. in the aftercooler as well. Approx. 60-80 % of the total amount of condensate are formed here. A further intentional separation and drying of the compressed air takes place subsequently in the drier or unintentionally in the pipes.

If air with a relative humidity of 60 % and a temperature of 15 °C is compressed to a pressure of 7 bar and subsequently cooled again down to 25 °C, 30 g of condensate are obtained per cubic metre compressed air.

Further information on this topic can be found in the facts "Treatment".

Power demand for compression

When describing changes in the state of air (compression, expansion, cooling) thermodynamically, air can be regarded as a perfect gas in the temperature and pressure range relevant for compressed air. The perfect gas equation describes the relation between the pressure (p), volume (V) and temperature (T) of a gas.

The following applies:

$$p \cdot V = m \cdot R_i \cdot T$$

or with reference to the amount of substance n

$$p \cdot V = n \cdot R \cdot T$$

with R as the universal gas constant with the value R = 8.3144 J/(mol K). It is then valid that the product from the pressure and volume of the air is proportional to the temperature. The perfect gas equation can be used to describe the changes in state occurring.

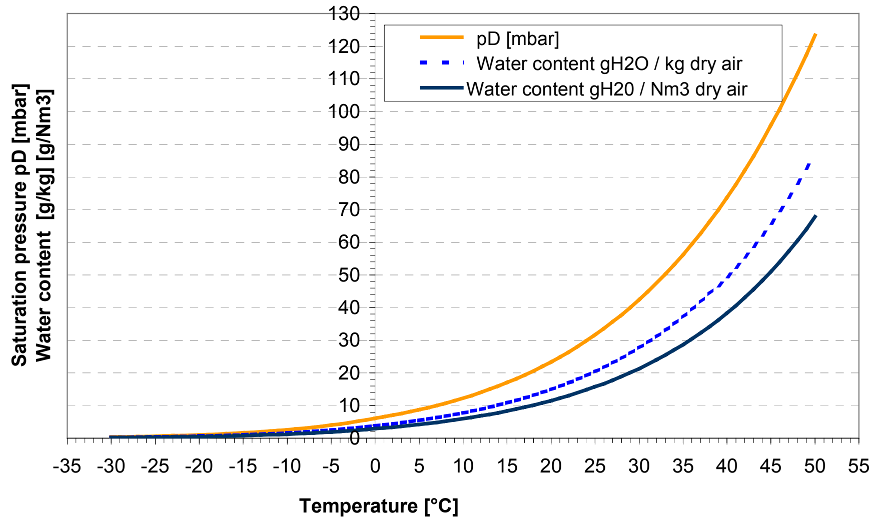

Fig. 3: Saturation pressure and water content of air

The two most important kinds of state changes are the isothermal (pressure change at constant temperature) and the adiabatic (isentropic) (pressure change without heat exchange with the surroundings).

For isothermal changes, the following applies:

$$p_1 V_1 = p_2 V_2$$

with *R* and *T* = const.

The specific work for compression results from the work for changing the volume

$$w_{12} = -\int_1^2 p \cdot d\upsilon = -p_1 \cdot \upsilon_1 \cdot \ln \frac{\upsilon_2}{\upsilon_1}$$

The following applies to **adiabatic** changes:

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

with R = const.

For temperature:

$$\frac{T_1}{T_2} = \left[\frac{\upsilon_2}{\upsilon_1}\right]^{(\kappa-1)} = \left[\frac{p_1}{p_2}\right]^{\frac{\kappa-1}{\kappa}}$$

and for the specific work

$$w_{t,12} = \int_1^2 \upsilon \cdot dp = \int_1^2 c_p \cdot dT = c_p \cdot (T_2 - T_1)$$

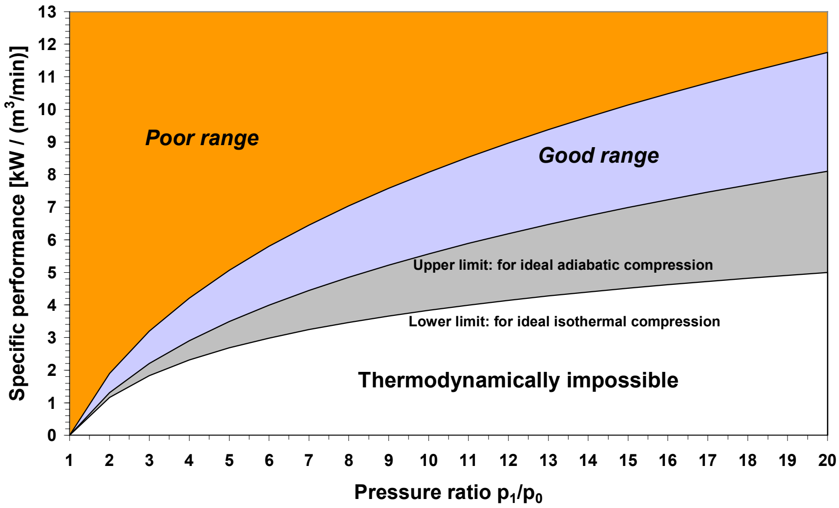

Fig. 4: Specific power demand for compressed air production

For air in the relevant range for compressed air, the adiabatic exponent κ has a value of κ = 1.4 kJ/(kg K).

The theoretical energy demand for compressing air is thus dependent on the compression ratio and the type of change of state. Whereas the isothermal compression results in the lowest specific work, the actual state characteristics during compression (polytropic compression) are closer to reversible adiabatic compression.

These optimimum values are not achievable in practice, since the compression process is afflicted with losses. Good compressed air systems are characterised by specific capacities which are approx. 45 % above the theoretically possible ones of adiabatic compression (Fig. 4). It should be noted that the specific energy required decreases with increasing system size. The specific performance data given incorporate all electrical and mechanical losses during compressed air production. They are not directly comparable with the rated power listed on the nameplate of the drive motor of the compressor. The specific power consumption of a compressed air system should lie within the good range. The lower limit of the good range is described by the adiabatic compression which represents an ideal case and therefore cannot be achieved by real compressors.

Further information on compressed air production can be found in the facts "Production".

Pressure losses

After production and treatment, the compressed air has to be distributed in a network to the user points. As well as the pressure losses occurring during treatment, other losses occur during distribution due to the pipe resistance which represent a loss of energy. The loss due to friction is much greater in turbulent flows than in laminar flows (Fig. 5).

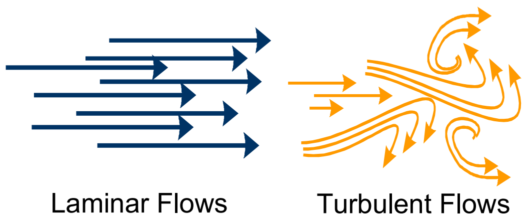

Fig. 5: Laminar and turbulent flows

Whether a laminar flow occurs in a pipe depends mainly on the velocity of flow. The influence of pipe roughness is negligible and can be ignored, more decisive are the changes in pipe diameters at joints. Turbulent flows in the whole of the distribution system are predominant in compressed air systems. The degree of turbulence increases with increasing flow velocity. The greater the velocity of flow, the greater the flow losses.

The flow velocity results from the relation of volume flow and cross-sectional area for incompressible flows.

$$v = \frac{\dot{V}}{A}$$

Pipe diameters which are too small result in high flow rates and high pressure losses in the piping. To restrict these losses, the flow rate in compressed air distribution should be preferably smaller than 6 m/s.

Further information on distribution can be found in Facts "Distribution".

Measuring compressed air

Although compressed air is a high quality and expensive energy source, usually neither the compressed air consumption nor the energy demand for its generation and treatment is recorded. Measuring and recording the consumption is, however, a key element for optimising the costs and energy use in the field of compressed air. Further details can be found in the facts "Measurement technology".

More information can be found in the fact sheets on other topics. These facts aim to supply initial information but cannot replace the problem-specific advice given by specialists.

The campaign "Druckluft effizient" aims to motivate the operators of compressed-air systems to optimise their systems and save substantial costs. It is conducted by the **German Energy Agency** (dena), the **Fraunhofer Institute Systems and Innovation Research** (Fraunhofer ISI; project management), and the **Federation of the Engineering Industries** (VDMA) with support of the Federal Ministry for Economics and Labour (BMWA) and the following industrial enterprises:

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