Chapter 1 Theory

1.1
Physics General

1.1.1 The structure of matter

Matter primarily consists of protons, neutrons and electrons. There are also a number of other building blocks however these are not stable.

All of these particles are characterised by four properties: their electrical charge, their rest mass, their mechanical momentum and their magnetic momentum. The number of protons in the nucleus is equal to the atom's atomic number.

The total number of protons and the number of neutrons are approximately equal to the atom's total mass.

This information is a part of the data that can be read off from the periodic system. The electron shell contains the same number of electrons as there are protons in the nucleus. This means the atom is electrically neutral.

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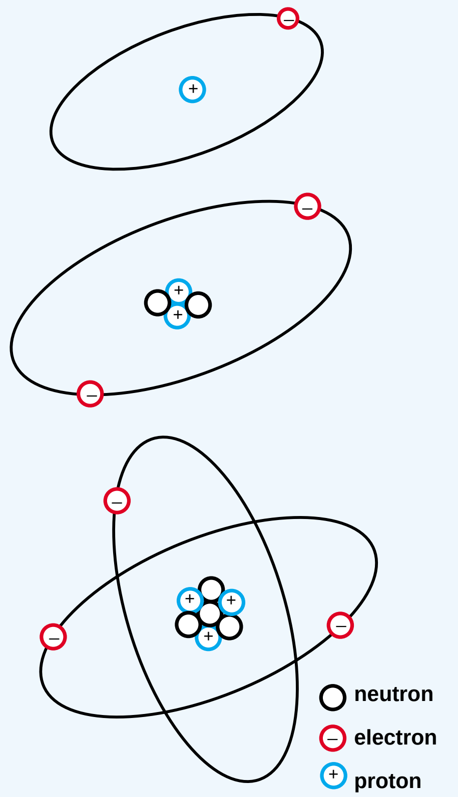


The electron shell gives elements their chemical properties. Here are a few simple examples. Hydrogen (top) has one electron in an electron shell. Helium (middle) has two electrons in an electron shell. Lithium (bottom) has a third electron in a second shell.

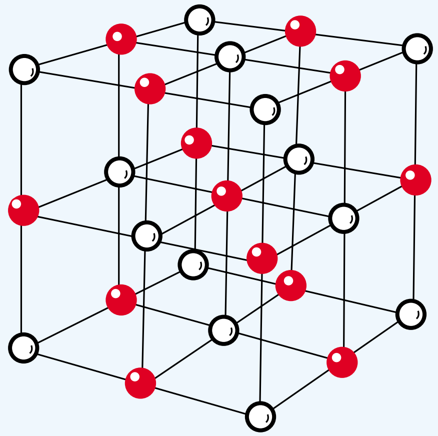
The Danish physicist, Niels Bohr, produced a theory as early as 1913 that proved to correspond with reality where he, among others, demonstrated that atoms can only occur in a so-called, stationary state with a determined energy. If the atom transforms from one energy state to another a radiation quantum is emitted, a photon.

It is these different transitions that makes themselves known in the form of light with different wavelengths. In a spectrograph they appear as lines in the atom's spectrum of lines.

1.1.2 The molecule and the different states of matter

Atoms held together by chemical bonding are called molecules. These are so small that, for example, 1 mm^3 of air at atmospheric pressure contains approx. 2.55 x 10^{16} molecules.

All matter can in principle exist in four different states: solid state, liquid state, gaseous state and plasma state. In the solid state the molecules are tightly packed in a lattice, with strong bonding. At all temperatures above absolute zero a certain degree of molecular movement occurs, in the solid state as a vibration around a balanced position, the faster the greater the temperature becomes. When a substance in



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A salt crystal has a cubic structure. Common table salt (NaCl) is a typical example. The lines show the bonding between the sodium (red) and the chlorine (white).

a solid state is heated so much that the movement of the molecules cannot be prevented by the rigid pattern (lattice), they become loose the substance melts and transforms to a fluid. If the liquid is heated more, the bonding of the molecules is broken, and it transforms into a gaseous state during expansion in all directions and mixes with the other gases in the room. When gas molecules are cooled, they loose speed and bond to each other again, and condensation starts. However, if the gas molecules are heated further, they are broken down into individual particles and form a plasma of electrons and atomic nuclei.

1.2 Physical units

1.2.1 Pressure

The force on a square centimetre area of an air column, which runs from sea level to the edge of the atmosphere, is about 10.13 N. Therefore the absolute atmospheric pressure at sea level is approx. 10.13 x 10^4 N per square metre, which is also called 1 Pa (Pascal), the SI unit for pressure. A basic dimension analysis shows that 1 bar = 1 x 10^5 Pa. The higher above sea level you are the lower the atmospheric pressure and visa versa.

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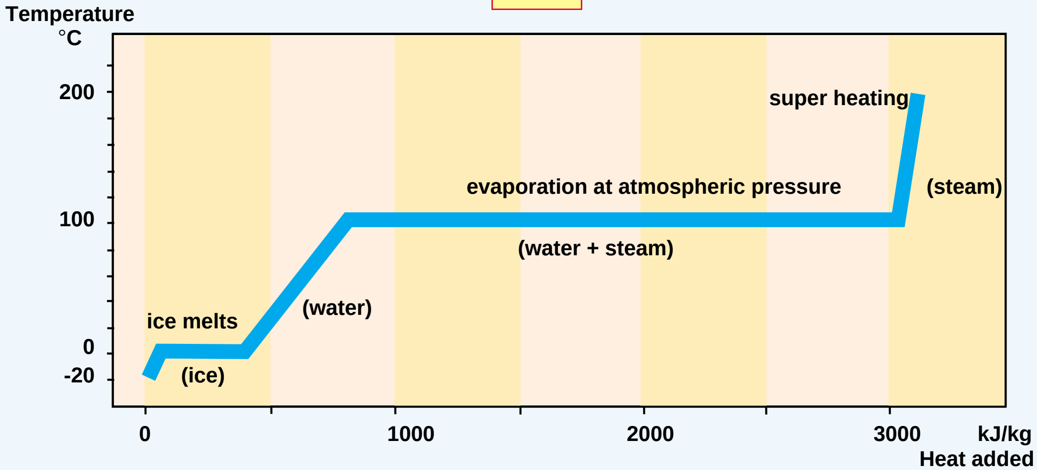

By leading off or applying thermal energy the state of a substance changes. This is how the relation for common water appears.

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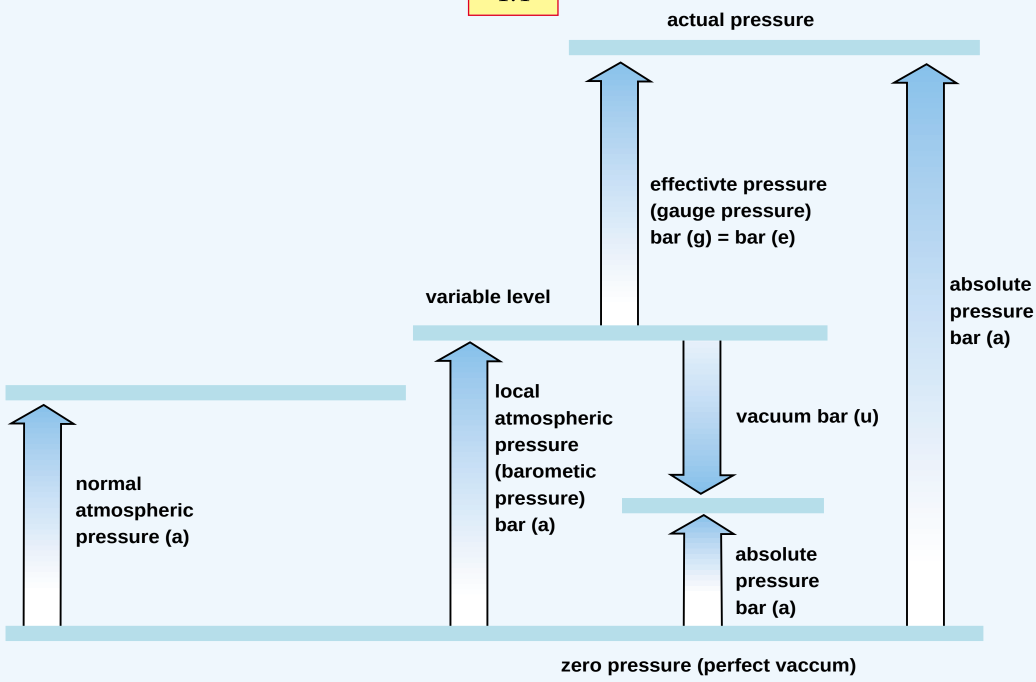

Most pressure gauges register the difference between the pressure in a vessel and the local atmospheric pressure. Therefore to find the absolute pressure the value of the local atmospheric pressure must be added.

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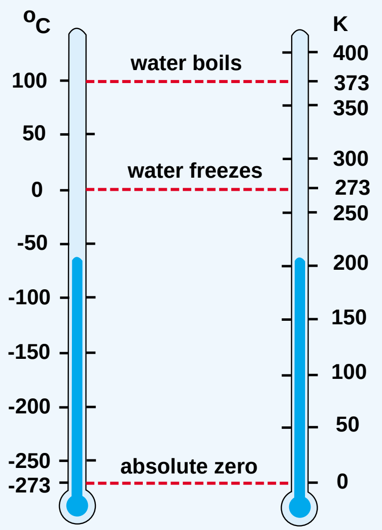

This is how the relation between Celsius and Kelvin scales appear. For Celsius, 0° is set at water's freezing point; for Kelvin, 0° is set at absolute zero.

1.2.2 Temperature

The temperature of a gas is more difficult to clearly define than the pressure. Temperature is an indication of the kinetic energy in the molecules. They move more rapidly the higher the temperature and the movement stops at absolute zero. The Kelvin scale is based on this, but otherwise is graduated the same as the Celsius scale. The relation is:

$T = t + 273.2$
T = absolute temperature (K)
t = temperature (°C)

1.2.3 Thermal capacity

Thermal capacity refers to the quantity of heat required to increase the temperature of 1 kg of a substance by 1 K. Accordingly, the dimension of the thermal capacity will be J/kg x K. Consequently, the molar thermal capacity is dimensioned J/mol x K. The designations commonly used are:

c_p = thermal capacity at a constant pressure
c_v = thermal capacity at a constant volume
C_p = molar thermal capacity at a constant pressure
C_v = molar thermal capacity at a constant volume

The thermal capacity at a constant pressure is always greater than thermal capacity at a constant volume. The thermal capacity for a substance is however not constant, but rises in general with the temperature.

For practical usage a mean value can frequently be used. For liquids and solid substances it is $c_p \approx c_v \approx c$. The power consumed to heat a mass flow from t_1 to t_2 will then be:

$$Q \approx m \times c \times (t_2 - t_1)$$

Q = heat power (W)
m = mass flow (kg/s)
c = specific thermal capacitivity (J/kg x K)
t = temperature (K)

The explanation as to why c_p is greater than c_v is the expansion work that the gas at a constant pressure must perform. The relation between c_p and c_v called kappa κ, is a function of the number of atoms in the molecule.

$$\kappa = \frac{c_p}{c_v} = \frac{C_p}{C_v}$$

1.2.4 Work

Mechanical work can be defined as the product of a force and the distance over which the force affects a body.

Exactly as for heat, work is an energy that is transferred from one body to another. The difference is that it is a question of force instead of temperature.

An example is the compression of a gas in a cylinder by a moving piston. Compression takes place through a force moving the piston. At the same time energy is transferred from the piston to the enclosed gas. This energy transfer is work in a thermodynamic meaning. The sum of the applied and transmitted energy is always constant. Work can give different results, for example, changes to the potential energy, kinetic energy or the thermal energy.

The mechanical work associated with changes in the volume of a gas or gas mixture is one of the most important processes within thermodynamics. The SI unit for work is Joule. 1 J = 1 Nm = 1 Ws.

1.2.5 Power

Power is work per time unit. SI unit for power is Watt. 1 W = 1 J/s.

For example, the power or energy flow to a drive shaft on a compressor is numerically similar with the heat emitted from the system plus the heat applied to the compressed gas.

1.2.6 Volume rate of flow

The SI unit for volume rate of flow is m^3/s. However, the unit litre/second (l/s) is frequently used, when speaking about the volume rate of flow, for example, given by a compressor. This volume rate of flow is called the compressor's capacity and is either stated as normal litre/second (Nl/s) or as free output air rate (l/s). With the unit normal litre/second (Nl/s) the air flow rate is recalculated to “the normal state”, i.e. 1.013 bar and 0°. The unit is primarily used when you wish to specify a mass flow.

With free output air rate the compressor’s output air rate is recalculated to its standard intake condition (intake pressure and intake temperature). Accordingly, you state how many litres of air would fill if it once again were allowed to expand to the ambient condition. The relation between the two volume rates of flow is (note that the formula below does not take the humidity into consideration):

$$Q_i = \frac{Q_n \text{ x } (273 + T_i) \text{ x } 1{,}013}{273 \text{ x } p_i}$$

Q_i = volume rate of flow as free output air flow rate (l/s)
Q_n = volume rate of flow as normal litres / second (Nl/s)
T_i = intake temperature (°C)
p_i = intake pressure (bar)

1.3 Thermodynamics

1.3.1 Main principles

Thermodynamics’ first main principle is a law of nature that can not be proved, but is accepted without reservation. It says that energy can neither be created nor destroyed and from that it follows that the total energy in a closed system is constant. Thermodynamics’ second main principle says that heat can never of “its own effort” be transferred from one source to a hotter source. This means that energy can only be available for work if it can be converted from a higher to a lower temperature level. Therefore in, for example, a heat engine the conversion of a quantity of heat to mechanical work can only take place if a part of this quantity of heat is simultaneously led off without being converted to work.

1.3.2 Gas laws

Boyle’s law says that if the temperature is constant, so the product of pressure and volume are constant. The relation reads:

$$p_1 \text{ x } V_1 = p_2 \text{ x } V_2$$

p = absolute pressure (Pa)
V = volume (m^3)

This means that if the volume is halved during compression, then the pressure is doubled.

Charles’s law says that the volume of a gas changes in direct proportion to the change in temperature. The relation reads:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \Rightarrow \Delta V = \frac{V_1}{T_1} \text{ x } \Delta T$$

V = volume (m_3)
T = absolute temperature (K)
ΔV = volume difference
ΔT = temperature difference

The general law of state for gases is a combination of Boyle’s and Charles’s laws. This states how pressure, volume and temperature affect each other. When one of these variables is changed, this affects at least one of the other two variables. This can be written:

$$\frac{p \text{ x } v}{T} = R = \text{gas constant}$$

p = absolute pressure (Pa)
v = specific volume (m^3/kg)
T = absolute temperature (K)
R = $\bar{R}/M$ = individual gas constant (J/kg x k)

The constant R is called the individual gas constant and only concerns the properties of the gas. If the mass m of the gas takes up the volume V, the relation can be written:

$$p \times V = m \times \bar{R} \times T$$

p = absolute pressure (Pa)
V = volume (m^3)
m = mole mass (kmol)
$\bar{R}$ = universal gas constant
= 8314 (J/kmol x K)
T = absolute temperature (K)

1.3.3 Heat transfer

Each heat difference within a body, or between different bodies, always leads to the transfer of heat, so that a temperature balance is obtained. This heat transfer can take place in three different ways: through conductivity, convection or radiation. In reality heat transfer takes place in parallel, in all three ways.

Conductivity takes place between solid bodies or between thin layers of a liquid or gas. Molecules in movement emit their kinetic energy to the adjacent molecules.

Convection can take place as free convection, with the natural movement that occurs in a medium or as forced convection with movement caused by, for example, a fan or a pump. Forced convection gives significantly more intense heat transfer.

All bodies with a temperature above 0°K emit heat radiation. When heat rays hit a body, some of the energy is absorbed and transforms to heat. Those rays that are not absorbed pass through the body or are reflected. Only an absolute black body can theoretically absorb all radiated energy.

In practice heat transfer is the sum of the heat transfer that takes place through conductivity, convection and radiation.

Generally the relation below applies:

$$q = k \times A \times \Delta T \times t$$

q = the quantity of heat (J)
k = total heat transfer coefficient ($W/m^2 \times K$)
A = area (m^2)
ΔT = temperature difference
t = time (s)

Heat transfer frequently occurs between two bodies, separated by a wall. The total heat transfer coefficient is dependent on the heat transfer coefficient on respective sides of the wall and the coefficient of thermal conductivity for the wall. For such a clean, flat wall the relation below applies:

$$1/k = 1/\alpha_1 + d/\lambda + 1/\alpha_2$$

α = heat transfer coefficient on respective sides of the wall ($W/m^2 \times K$)
d = thickness of the wall (m)
λ = coefficient of thermal conductivity for the wall ($W/m \times K$)
k = total heat transfer coefficient ($W/m^2 \times K$)

The transferred quantity of heat, for example, in a heat exchanger, is at each point a function of the prevailing heat difference and the total heat transfer coefficient. Applicable to the entire heat transfer surface is:

$$Q = k \times A \times \vartheta_m$$

Q = transferred quantity of heat (W)
k = total heat transfer coefficient ($W/m^2 \times K$)
A = heat transferring surface (m^2)
ϑ_m = logarithmic mean temperature difference (K)

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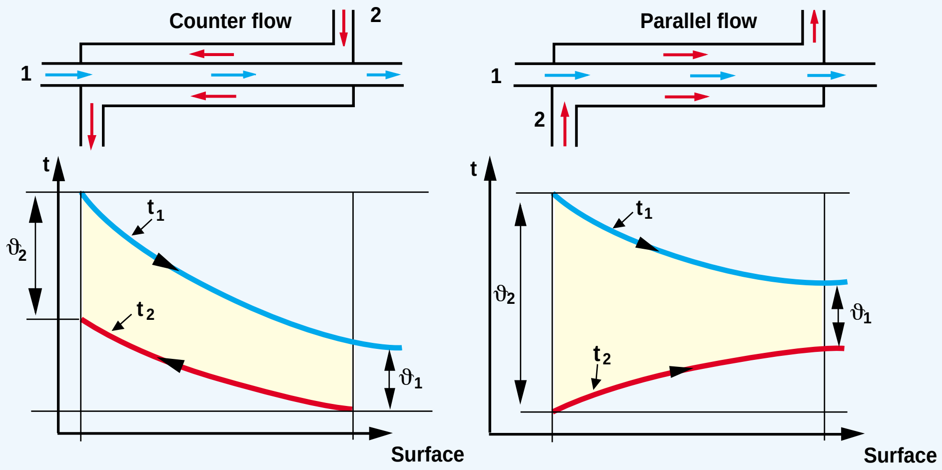

This is how the temperature process appears in counter flow respective parallel flow heat exchangers.

The logarithmic mean temperature difference is defined as the relation between the temperature differences at the heat exchanger's two connection sides according to the expression:

$$\vartheta_m = \frac{\vartheta_1 - \vartheta_2}{\ln \dfrac{\vartheta_1}{\vartheta_2}}$$

ϑ_m = logarithmic mean temperature difference (K)

ϑ = the temperature differences (K) according to figure 1:6.

1.3.4 Changes in state

You can follow the changes in state for a gas from one point to another in a p/V diagram. It should really need three axes for the variables p, V and T. With a change in state you move along a curve on the surface in space that is then formed. However, you usually consider the projection of the curve in one of the three planes, usually the p/V plane. Primarily a distinction is made between five different changes in state:

Isochoric process (constant volume), isobaric process (constant pressure), isothermic process (constant temperature) isentropic process (without heat exchange with the surroundings) and polytropic process (where the heat exchange with the surroundings is stated through a simple mathematical function).

1.3.4.1 Isochoric process

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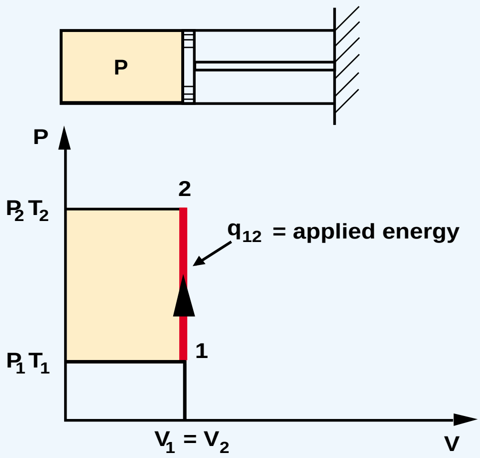

Isochoric change of state means that the pressure increases, while the volume is constant.

Heating a gas in an enclosed container is an example of the isochoric process. The relation for the applied quantity of heat is:

$q = m \times c_v \times (T_2 - T_1)$

q = quantity of heat (J)
m = mass (kg)
c_v = the heat capacity at constany volume (J/kg x K)
T = absolute temperature (K)

1.3.4.2 Isobaric process

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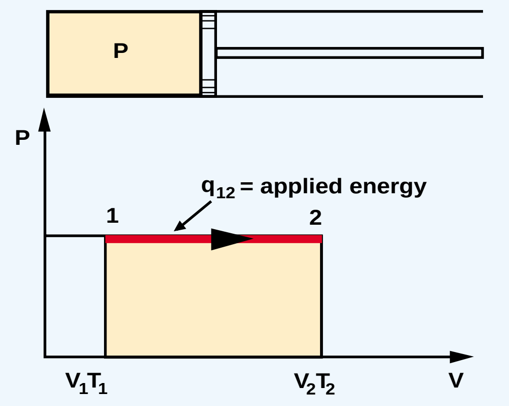

Isobaric change of state means that the volume increases, while the pressure is constant.

Heating of a gas in a cylinder with a constant loaded piston is an example of the isobaric process. The relation for the applied quantity of heat is:

$q = m \times c_p \times (T_2 - T_1)$

q = quantity of heat (J)
m = mass (kg)
c_p = the heat capacity at constant pressure (J/kg x K)
T = absolute temperature (K)

1.3.4.3 Isothermic process

If a gas in a cylinder is compressed isothermally, a quantity of heat that is equal to the applied work must be gradually led off. This is practically impossible, as such a slow process can not be realised.

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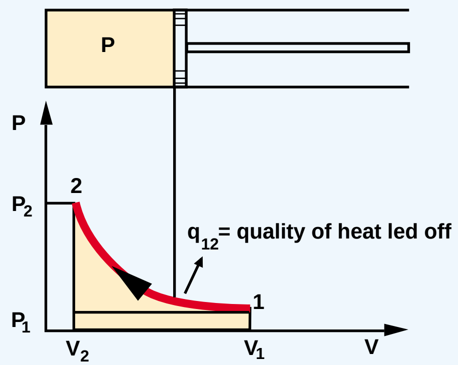

Isothermic change of state means that the temperature of a gas mixture is constant, when the pressure and volume are changed.

The relation for the quantity of heat led off is:

$$q = m \times R \times T \times 1n \left(\frac{p_2}{p_1}\right)$$

$$q = p_1 \times V_1 \times 1n \left(\frac{V_2}{V_1}\right)$$

q = quantity of heat (J)
m = mass (kg)
R = individual gas constant (J/kg x K)
T = absolute temperature (K)
V = volume (m^3)
p = absolute pressure (Pa)

1.3.4.4 Isentropic process

An example of an isentropic process is if a gas is compressed in a fully insulated cylinder without heat exchange with the surroundings. Or if a gas is expanded through a nozzle so quickly that no heat exchange with the surroundings has time to take place. The relation for such a process is:

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\kappa} \Rightarrow \frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\kappa}{\kappa-1}}$$

p = absolute pressure (Pa)
V = volume (m^3)
T = absolute temperature (K)
$\kappa = \frac{c_p}{c_v}$

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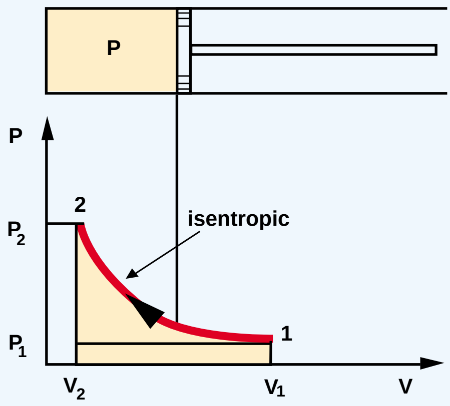

When the entropy in a gas that has been compressed or expanded is constant, no heat exchange with the surroundings takes place. This change in state follows Poisson's law.

1.3.4.5 Polytropic process

The isothermic process involves full heat exchange with the surroundings and the isotropic process involves no heat exchange at all. In reality all processes are something between these extremes and this general process is called polytropic. The relation for such a process is:

$$p \times V^n = \text{konstant}$$

p = absolute pressure (Pa)
V = volume (m^3)
n = 0 means isobaric process
n = 1 means isothermic process
n = κ means isentropic process
n = ∞ means isochoric process

1.3.5 Gas flow through a nozzle

The gas flow through a nozzle depends on the pressure ratio on respective sides of the nozzle. If the pressure after the nozzle is lowered the flow increases, however, only until its pressure before the nozzle is approximately double so high. A further reduction of the pressure after the opening does not bring about an increase in flow.

This is the critical pressure ratio and it is dependent on the gas's isentropic exponent (κ). The critical pressure ratio occurs when the flow velocity is equal to the sonic velocity in the nozzle's narrowest section.

The flow becomes supercritical if the pressure after the nozzle is reduced further, under the critical value. The relation for the flow through the nozzle is:

$$G = \alpha \times \psi \times p_1 \times 10^5 \times A \times \sqrt{\left(\frac{2}{R \times T_1}\right)}$$

G = mass flow (kg/s)
α = nozzle coefficient
ψ = flow coefficient
A = minimum flow area (m^2)
R = individual gas constant (J/kg K)
T_1 = absolute temperature before the nozzle (K)
p_1 = absolute pressure before the nozzle (bar)

1.3.6 Flow through pipes

Reynold's number is a dimensionless ratio between inertia and friction in a flowing medium. It is defined as:

$$Re = D \times w \times \eta / \rho \times = D \times w / v$$

D = a characteristic measurement (for example the pipe diameter) (m)
w = mean flow velocity (m/s)
ρ = the density of the flowing medium (kg/m^3)
η = the flowing medium's dynamic viscosity (Pa x s)
v = η/ρ = the flowing medium's kinematic viscosity (m^2/s).

In principal there are two types of flow in a pipe. With Re<2000 the viscous forces dominate in the media and the flow becomes laminar. This means that different layers of the medium move in relation to each other in good order. The velocity distribution across the laminar layers is usually parabolic shaped. With Re≥4000 the inertia forces dominate the flowing medium and the flow becomes turbulent, with particles that move randomly in the flow's cross section. The velocity distribution across a layer with turbulent flow becomes diffuse.

In the critical area, between Re≤2000 and Re≥4000, the flow conditions are undetermined, either laminar or turbulent or a mixture of the both. The conditions are governed by factors such as the surface smoothness of the pipe or other disturbances.

To start a flow in a pipe requires a specific pressure difference or pressure drop, to overcome the friction in the pipe and couplings. The size of the pressure drop depends on the diameter of the pipe, its length and form as well as the surface smoothness and Reynold's number.

1.3.7 Throttling

When an ideal gas flows through a restrictor, with a constant pressure before and after the restrictor, the temperature remains constant. However, there occurs a pressure drop across the restrictor, through the inner energy transforming into kinematic energy, which is why the temperature falls. However, for real gases this temperature change becomes lasting, even if the gas's energy content is constant. This is called the Joule Thomson effect. The temperature change is equal to the pressure change across the throttling multiplied by the Joule Thomson coefficient.

If the flowing medium has a sufficiently low temperature (≤+329°C for air) a temperature drop occurs across the restrictor, but if the flow medium is hotter, a temperature increase occurs. This condition is used in several technical applications, for example, in refrigeration technology and the separation of gases.

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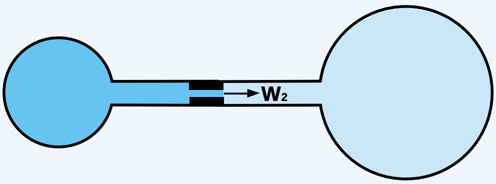

When an ideal gas flows through a small opening between two large containers, the energy becomes constant and no heat exchange takes place. However, a pressure drop occurs with the passage through the restrictor.

1.4 Air

1.4.1 Air in general

Air is a colourless, odourless and tasteless gas mixture. It consists of many gases, but primarily oxygen and nitrogen. Air can be considered a perfect gas mixture in most calculation contexts. The composition is relatively constant, from seal level and up to an altitude of 25 kilometres.

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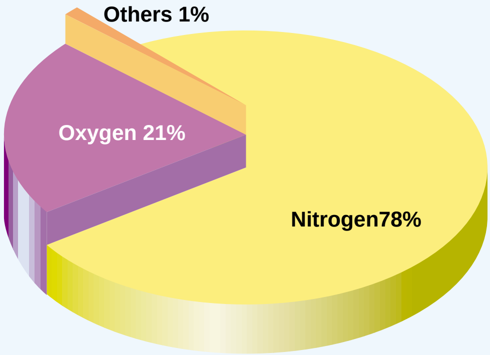

Air is a gas mixture that primarily consists of oxygen and nitrogen. Only approx. 1% is made up of other gases.

Air is always more or less contaminated with solid particles, for example,dust, sand, soot and salt crystals. The degree of contamination is higher in populated areas, less in the countryside and at higher altitudes.

Air is not a chemical substance, but a mechanically mixed substance. This is why it can be separated into its constituent elements, for example, by cooling.

1.4.2 Moist air

Air can be considered as a mixture of dry air and water vapour. Air that contains water vapour is called moist air, but the air's humidity can vary within broad limits. Extremities are completely dry air and air saturated with moisture. The maximum water vapour pressure that air can hold increases with rising temperatures. A maximum water vapour pressure corresponds to each temperature.

Air usually does not contain so much water vapour that maximum pressure is reached. Relative vapour pressure (also known as relative humidity) is a state between the actual partial vapour pressure and the saturated pressure at the same temperature.

The dew point is the temperature when air is saturated with water vapour. Thereafter with a fall in temperature the condensation of water takes place. Atmospheric dew point is the temperature at which water vapour starts to condense at atmospheric pressure. Pressure dew point is the equivalent temperature with increased pressure. The following relation applies:

$$(p - \varphi \times p_s) \times 10^5 \times V = R_a \times m_a \times T$$
$$\varphi \times p_s \times 10^5 \times V = R_v \times m_v \times T$$

p = total absolute pressure (bar)
p_s = saturation pressure at the actual temperature (bar)
φ = relative vapour pressure
V = total volume of the moist air (m^3)
R_a = gas constant for dry air = 287.1 J/Kg x K
R_v = gas constant for water vapour = 461.3 J/Kg x K
m_a = mass of the dry air (kg)
m_v = mass of the water vapour (kg)
T = absolute temperature of the moist air (K)

1.5 Types of compressors

1.5.1 Two basic principles

There are two basic principles for the compression of air (or gas), the displacement principal and dynamic compression. Among displacement compressors are, for example, piston compressors and different types of rotary compressors. They are the most common compressors in most countries.

On a piston compressor for example, the air is drawn into a compression chamber, which is closed from the inlet. Thereafter the volume of the chamber decreases and the air is compressed. When the pressure has reached the same level as the pressure in the outlet manifold, a valve is opened and the air is discharged at a constant pressure, under continued reduction of the compression chamber's volume.

In dynamic compression air is drawn into a rapidly rotating compression impeller and accelerates to a high speed. The gas is then discharged through a diffuser, where the kinetic energy is transformed to static pressure. There are dynamic compressors with axial or radial flow. All are suitable for large volume rates of flow.

1.5.2 Displacement compressors

A bicycle pump is the simplest form of a displacement compressor, where air is drawn into a cylinder and is compressed by a moving piston. The piston compressor has the same operation principle, with a piston whose forward and backward movement is accomplished by a connecting rod and a rotating crankshaft. If only one side of the piston is used for compression this is called single acting. If both the piston's top and undersides are used the compressor is called double acting. The difference between the pressure on the inlet side and the pressure on the outlet side is a measurement of the compressor's work.

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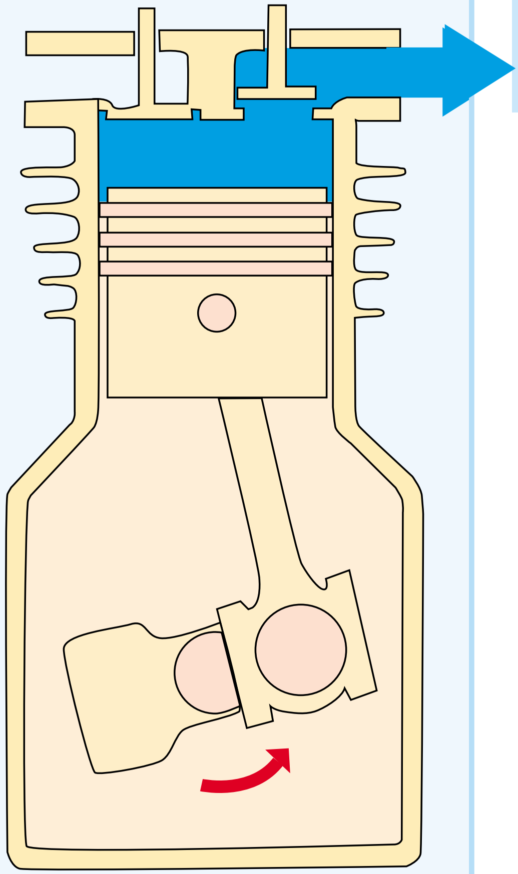
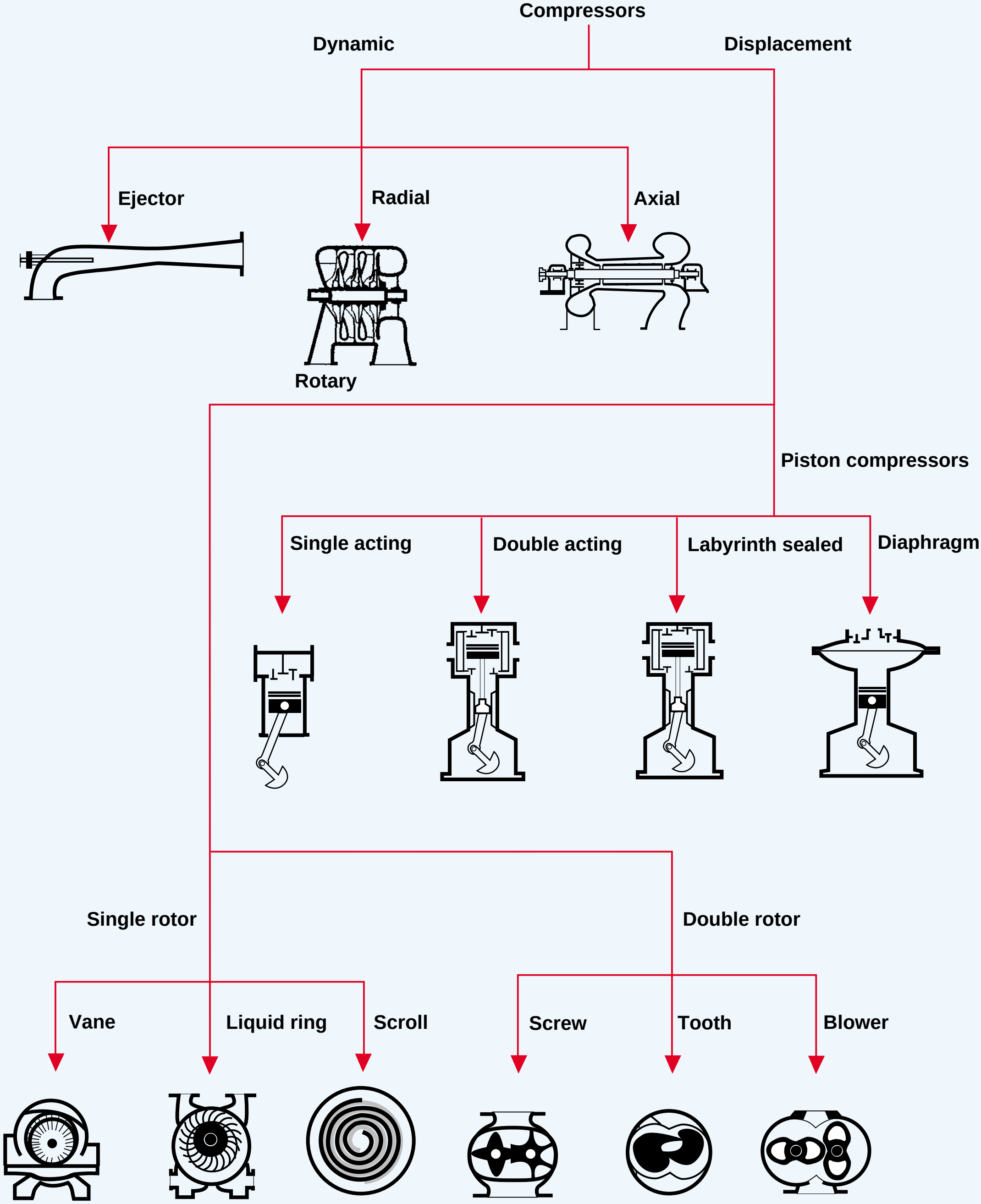


Single stage, single acting piston compressor.

The pressure ratio is the relation between absolute pressure on the inlet and outlet sides. Accordingly, a machine that draws in air at atmospheric pressure and compresses it to 7 bar overpressure works with a pressure ratio of $(7 + 1)/1 = 8$.



The chart shows the most common types of compressor, divided according to their working principles. They can also be divided according to other principles, for example, air or liquid cooled, stationary or portable, etc.

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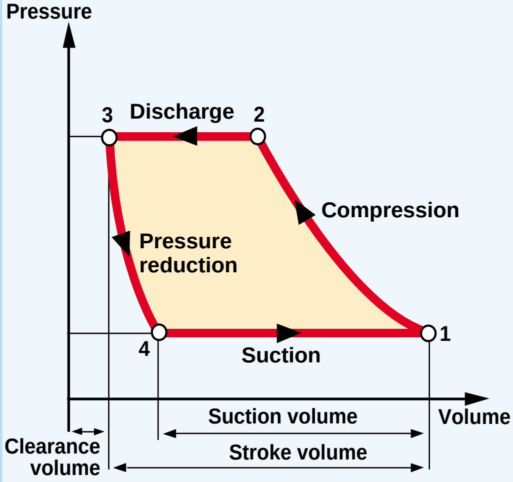

This is how a piston compressor works in theory with self-acting valves. The p/V diagram shows the theoretical process, without losses with complete filling and emptying of the cylinder.

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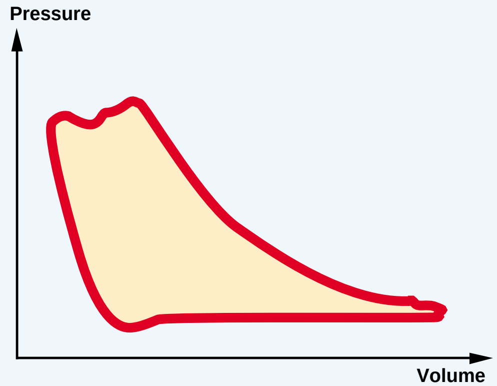


This is how the actual p/V diagram can appear for a piston compressor. The pressure drop on the inlet side and the overpressure on the discharge side are minimised primarily by giving the compressor sufficient valve area.

1.5.3 The compressor diagram for displacement compressors

Figure 1:15 illustrates a theoretical compressor diagram and figure 1:16 illustrates a real compressor diagram for a piston compressor. The stroke volume is the cylinder volume that the piston travels during the suction stage. The clearance volume is the area that must remain at the piston's turning point for mechanical reasons, together with the area required for the valves, etc.

The difference between the stroke volume and the suction volume is due to the expansion of the air remaining in the clearance volume before suction can start. The difference between the theoretical p/V diagram and the real diagram is due to the practical design of a compressor, e.g. a piston compressor. The valves are never fully sealed and there is always a degree of leakage between the piston and the cylinder wall. In addition, the valves can not open and close without a delay, which results in a pressure drop when the gas flows through the channels. Due to reasons of design the gas is also heated when it flows into the cylinder.

Compression work with isothermic compression becomes:

$$W = p_1 \text{ x } V_1 \text{ x } 1n(p_2/p_1)$$

Compression work with isentropic compression becomes:

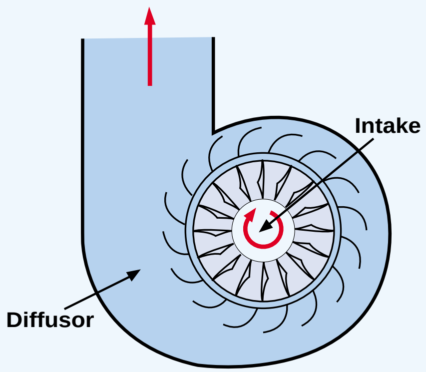
$$W = \frac{\kappa}{\kappa - 1} \text{ x } (p_2V_2 - p_1V_1)$$

W = compression work (J)
p_1 = initial pressure (Pa)
V_1 = initial volume (m^3)
p_2 = final pressure (Pa)
κ = isentropic exponent in most cases x $\kappa \approx 1{,}3 – 1{,}4$ applies.

These relations show that more work is required for isentropic compression than with isothermic compression. In reality the requisite work lies between the limits ($\kappa \approx 1{,}3 – 1{,}4$).

1.5.4 Dynamic compressors

1:17



Radial compressor

A dynamic compressor is a flow machine where the pressure increase takes place at the same time as the gas flows. The flowing gas accelerates to a high velocity by means of the rotating blades, after which the velocity of the gas is transformed to pressure when it is forced to decelerate under expansion. Depending on the main direction of the flow they are called radial or axial compressors.

In comparison with displacement compressors, dynamic compressors have a characteristic where a small change in the working pressure results in a large change in the capacity. See figure 1:19.

Each speed has an upper and lower capacity limit. The upper limit means that the gas's flow velocity reaches sonic velocity. The lower limit means that the counter pressure is greater than the compressor's pressure build-up, which means return flow in the compressor. This in turn results in pulsation, noise and the risk for mechanical damage.

1.5.5 Compression in several stages

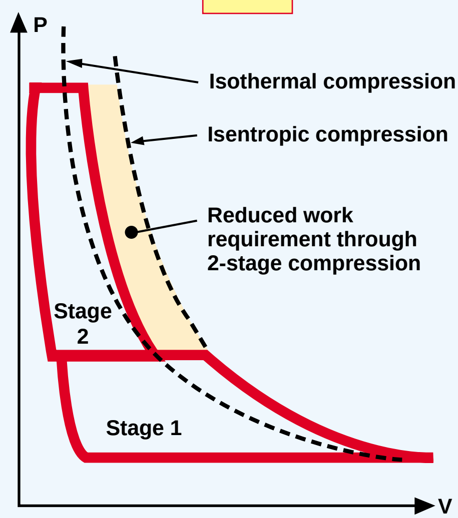
Theoretically a gas can be compressed isentropically or isothermally. This can take place as a part of a reversible process. If the compressed gas could be used immediately, at its final temperature after compression, the isentropic process would have certain advantages. In reality the gas can rarely be used directly without being cooled before use. Therefore the isothermal process is preferred, as this requires less work.

In practice attempts are made to realise this process by cooling the gas during compression. How much you can gain by this is shown, for example, with an effective working pressure of 7 bar that theoretically requires 37% higher output for isentropic compression compared with isothermal compression.

A practical method to reduce the heating of the gas is to divide the compression into several stages. The gas is cooled after each stage, to then be compressed further. This also increases the efficiency, as the pressure ratio in the first stage is reduced. The power requirement is at its lowest if each stage has the same pressure ratio.

The more stages the compression is divided into the closer the entire process

1:18



The shaded area represents the work saved by dividing the compression into two stages.

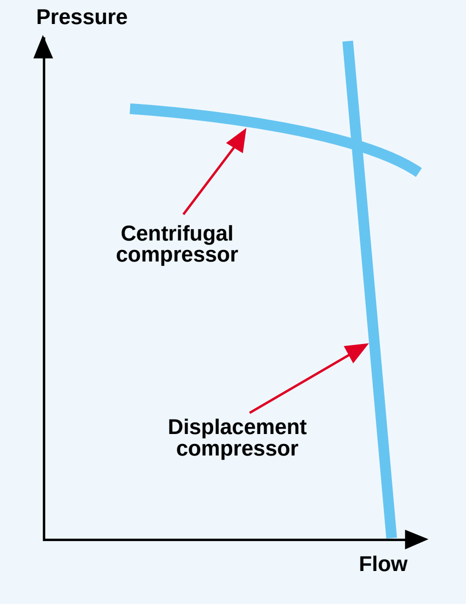
gets to be isothermal compression. However there is an economic limit for how many stages a real installation can be designed with.

1.5.6 Comparison between displacement and centrifugal compressors

The capacity curve for a centrifugal compressor differs significantly from an equivalent curve for a displacement compressor. The centrifugal compressor is a machine with a variable capacity and constant pressure. On the other hand a displacement compressor is a machine with a constant capacity and a variable pressure.

Examples of other differences is that a displacement compressor gives a higher pressure ratio even at a low speed, unlike the more significantly higher speed centrifugal compressors. The centrifugal compressors are well suited to large air flow rates.

1:19



This is how the load curves for centrifugal respective displacement compressors appear when the load is changed at a constant speed.

1.6 Electricity

1.6.1 Basic terminology and definitions

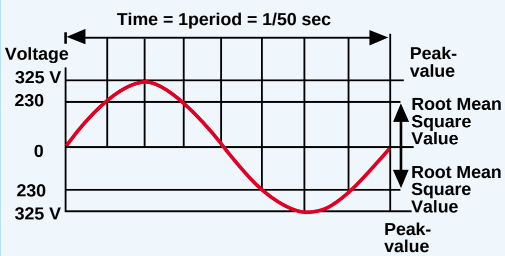
The alternating current used for example to power lighting and motor operations regularly changes strength and direction in a sinusoidal variation. The current strength grows from zero to a maximum value, then falls to zero, changes direction, grows to a maximum value in the opposite direction to then become zero again. The current has then completed a period. The period T is the time in seconds under which the current has gone through all its values. The frequency states the number of complete cycles per second.

$f = 1/T$
f = frequency (Hz)
T = time for a period (s)

When speaking about current or voltage it is usually the root mean square value that is meant. With a sinusoidal current the relation for the current's respective voltage's root mean square value is:

$$\text{root mean square value} = \frac{\text{peak value}}{\sqrt{2}}$$

1:20



This is how a period of a sinusoidal voltage appears (50 Hz).

Voltage under 50V is called extra low voltage. Voltage under 1000V is called low voltage. Voltage over 1000V is called high voltage. Standard voltages at 50 Hz are 230/400V and 400/690V.

1.6.2 Ohm's law for alternating current

An alternating current that passes a coil gives rise to a magnetic flow. This flow changes strength and direction in the same way as the current. When the flow changes an emf (electromotive force) is generated in the coil, according to the laws of induction. This emf is counter directed to the connected pole voltage. The phenomenon is called self-induction.

Self-induction in an alternating current unit partly gives rise to phase displacement between the current and the voltage, and partly to an inductive voltage drop. The unit's resistance to the alternating current becomes apparently greater than that calculated or that measured with direct current.

Phase displacement between the current and voltage is represented by the angle φ. Inductive resistance (reactance) is represented by X. Resistance is represented by R. Apparent resistance in a unit or conductor is represented by Z.

Applicable for impedance is:

$$Z = \sqrt{R^2 + X^2}$$

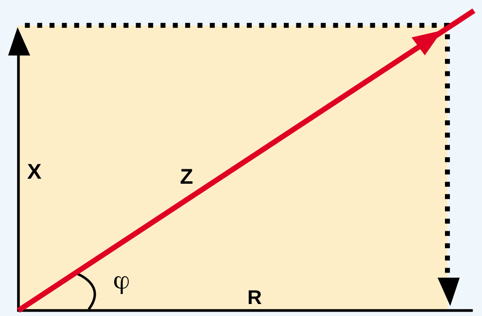
Z = impedance (Ω)
R = resistance (Ω)
X = reactance (Ω)

Ohm's law for alternating current reads:

$$U = I \times Z$$

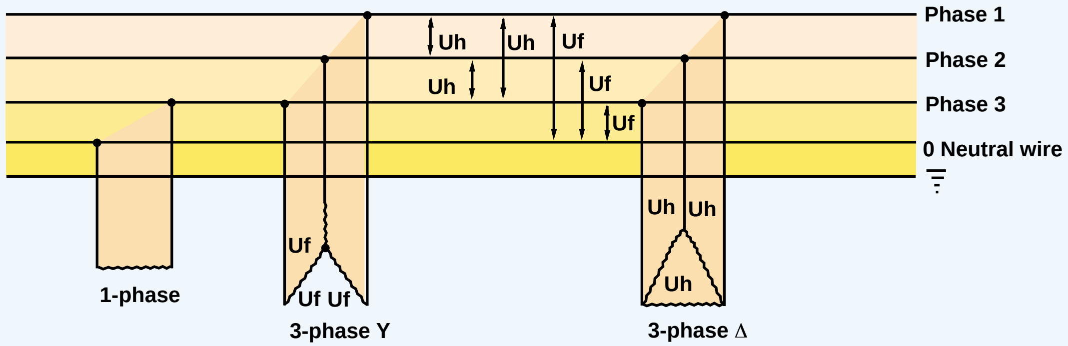
U = voltage (V)
I = current (A)
Z = impedance (Ω)

1:21



Relation between Reactance (X) – Resistance (R) – Impedance (Z) – Phase displacement (φ).

1:22



This is how the different connection options for a three-phase system appears. The voltage between the two phase conductors is called the main voltage (Uh). The voltage between one phase conductor and the neutral wire are called phase voltage (Uf). The phase voltage = Main voltage/$\sqrt{3}$.

1.6.3 Three-phase system

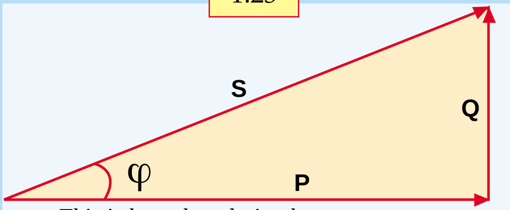
Three-phase alternating current is produced in a generator with three separate windings. All values on the sinusoidal voltage are displaced 120° in relation to each other.

Different units can be connected to a three-phase unit. A single phase unit can be connected between the phase and zero. Three-phase units can be connected in two ways, star (Y) or delta (Δ) connection. With the star connection a phase voltage lies between the outlets. With a delta connection a main voltage lies between the outlets.

1.6.4 Power

Active power, P, is the useful power that can be used for work. Reactive power, Q, is the "useless" power and can not be used for work. Apparent power, S, is the power that must be consumed from the mains supply to gain access to active power. The relation between active, reactive and apparent power is usually illustrated by a power triangle.

1:23



This is how the relation between apparent power (S), reactive power (Q) and active power (P) The angle φ between S and P gives the power factor cosφ.

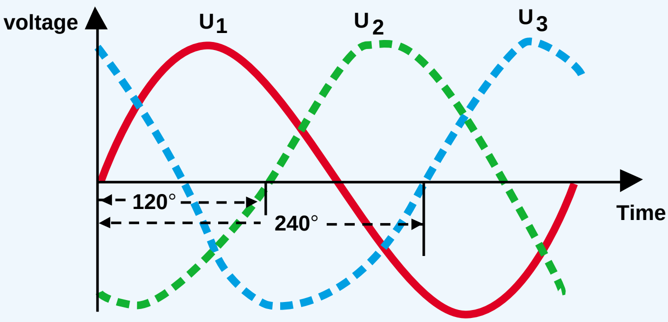
The following relation applies:

Single phase:
$P = U \times I \times \cos\varphi$
$Q = U \times I \times \sin\varphi$
$S = U \times I$
$\cos\varphi = P/S$

Three phase:
$P = \sqrt{3} \times U_h \times I \times \cos\varphi$
$Q = \sqrt{3} \times U_h \times I \times \sin\varphi$
$S = \sqrt{3} \times U_h \times I$
$\cos\varphi = P/S$

U = voltage (V)
U_h = main voltage, (V)
U_f = phase voltage
I = current (A)
I_h = main current (A)
I_f = phase current (A)
P = active power (W)
Q = reactive power (VAr)
S = apparent power (VA)
φ = phase angle
$\cos\varphi$ = power factor

1:24



The displacement between the generator's windings gives a sinusoidal voltage curve on the system. The maximum value is displaced at the same interval as the generator's windings.

1.6.5 The electric motor

The most common electric motor is a three phase, short circuit induction motor. This type of motor can be found within all industries. Silent and reliable, it is a part of most systems, for example, compressors. The electric motor consists of two main parts, the stationary stator and the rotating rotor. The stator produces a rotating magnetic field and the rotor converts this energy to movement, i.e. mechanical energy.

The stator is connected to the mains supply's three phases. The current in the stator windings give rise to a rotating magnetic force field, which induces currents in the rotor and gives rise to a magnetic field there too. The interaction between the stator's and the rotor's magnetic fields creates turning torque, which makes the rotor shaft rotate.

1.6.5.1 Rotation speed

If the motor shaft should rotate at the same speed as the magnetic field, the induced current in the rotor would at the same time be zero. However, due to losses in, for example the bearings, this is impossible and the speed is always approx. 1-5% lower than the magnetic field's synchronous speed (slip). Applicable for this synchronous speed is:

$$n = 2 \times f \times 60 / p$$

n = synchronous speed (r/min)
f = main supply's frequency (Hz)
p = number of poles

1.6.5.2 Efficiency

Energy conversion in a motor does not take place without losses. These are due to, among others, resistive losses, ventilation losses, magnetisation losses and friction losses. Applicable for efficiency is:

$$\eta = \frac{P_2}{P_1}$$

η = efficiency
P_2 = stated power, shaft power (W)
P_1 = applied power (W)

It is always the stated power, P_2, stated on the motor's rating plate.

1.6.5.3 Insulation class

The insulation material in the motor's windings is divided into insulation classes in accordance with IEC 85 (International Electrotechnical Commission). A letter corresponding to the temperature, which is the upper limit for the isolation's calculated application area, designates each class. If the upper limit is exceeded by 10°C the service life of the insulation is shortened by about half.

Insulation class	B=130°C	F=155°C	H=180°C
Ambient temp. °C	40	40	40
Temp. increase °C	80	105	125
Thermal marginal °C	10	10	15
Max. final temp. °C	130	155	180

1.6.5.4 Protection classes

Protection classes state, according to IEC 34-5, how the motor is protected against contact and water. These are stated with the letters IP and two digits. The first states the protection against contact and penetration by a solid object. The other digit states the protection against water. For example IP23 represents: (2) protect against solid objects greater than 12 mm, (3) protect against direct sprays of water up to 60° from the vertical. IP 54: (5) protection against dust, (4) protection against water sprayed from all directions. IP 55: (5) protection against dust, (5) protection against low-pressure jets of water from all directions.

1.6.5.5 Cooling methods

Cooling methods state, according to IEC 34-6, how the motor shall be cooled. This is designated with the letters IC and two digits. For example IC 01 represents: Free circulation, own ventilation and IC 41: Jacket cooling, own ventilation.

1.6.5.6 Installation method

The installation method states, according to IEC 34-7, how the motor should be installed. This is designated by the letters IM and four digits. For example IM 1001 represents: two bearings, shaft with free journalled end, stator body with feet. IM 3001: two bearings, shaft with free journalled end, stator body without feet, large flange with plain securing holes.

1.6.5.7 Star (Y) and delta (Δ) connections

A three-phase electric motor can be connected in two ways, star (Y) or delta (Δ). The winding phases in a three-phase motor are marked U, V and W (U1-U2; V1-V2; W1-W2). With the star (Y) connection the "ends" of motor winding's phases are joined together to form a zero point, which looks like a star (Y).

A phase voltage (phase voltage = main voltage/$\sqrt{3}$; for example 400V = 690/$\sqrt{3}$) will lie across the windings. The current I_h in towards the zero point becomes a phase current and accordingly a phase current will flow $I_f = I_h$ through the windings.

With the delta (Δ) connection you join the beginning and ends between the different phases, which then form a delta (Δ). There will then lie a main voltage across the windings. The current Ih into the motor is the main current and this will be divided between the windings and give a phase current through these, $I_h/\sqrt{3} = I_f$. The same motor can be connected as 690V star connection or 400V delta connection. In both cases the voltage across the windings will be 400V. The current to the motor will be lower with a 690V star connection than with a 400V delta connection. The relation between the current levels is $\sqrt{3}$.

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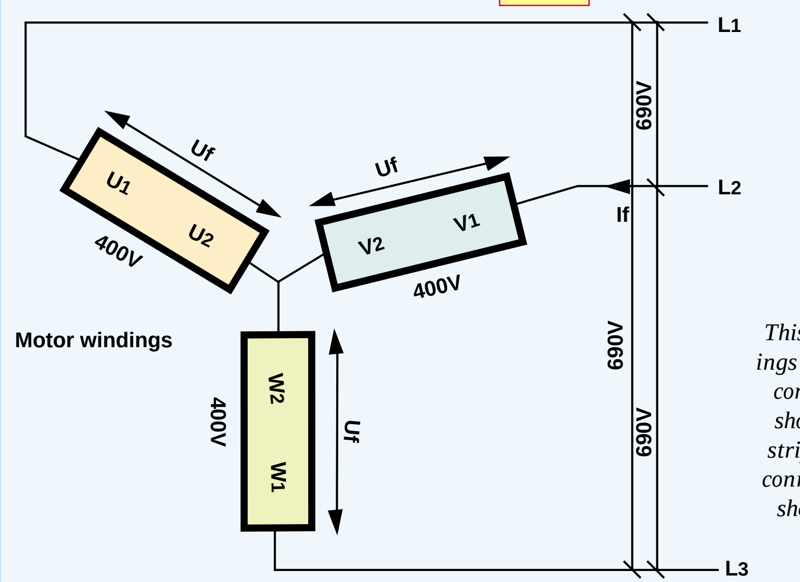
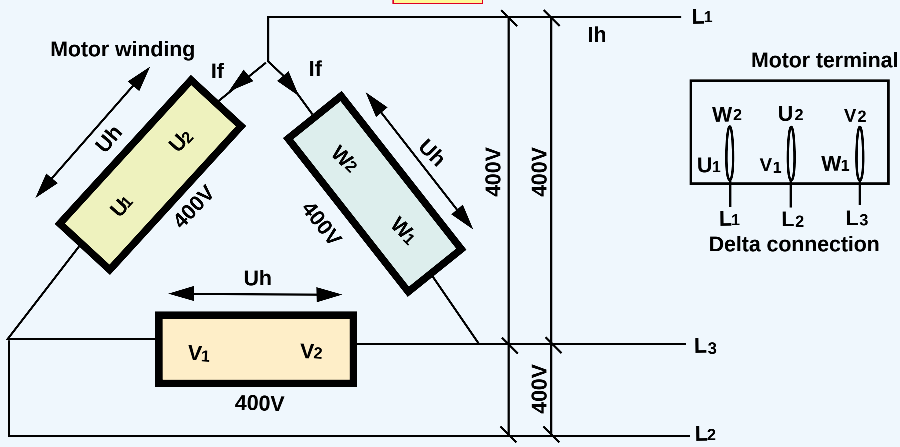


This is how the motor windings are connected with a star connection. The top figure shows how the connection strips are placed on the star connected unit. The example shows the connection to a 690V supply.

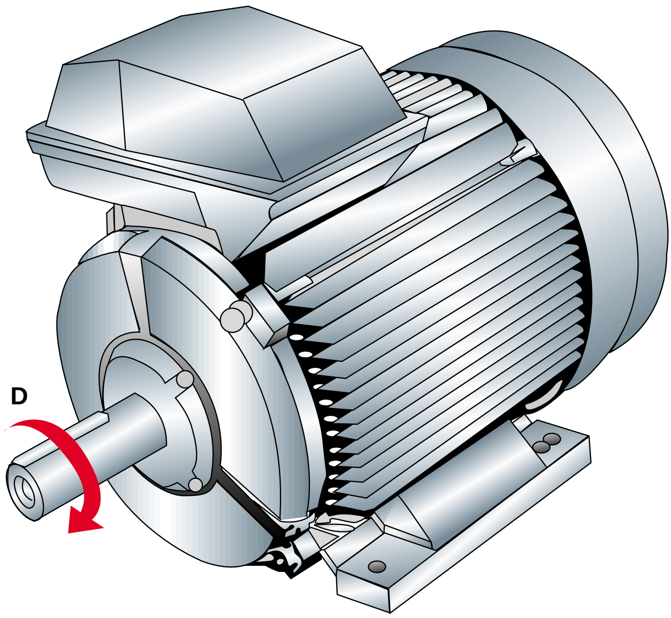
1:26



This is how the motor windings are connected with a delta connection. The top figure shows how the connection strips are placed on the delta connected unit. The example shows the connection to a 400V supply.

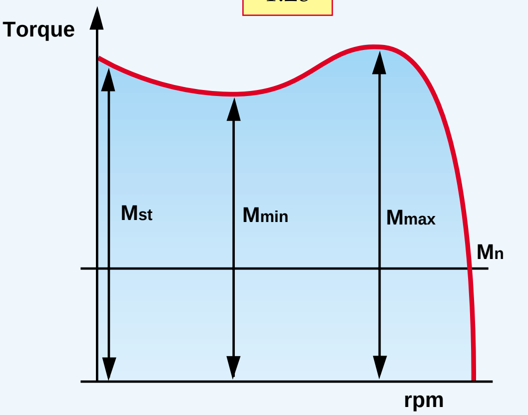
On the motor plate it can, for example, state 690/400 V. This means the star connection is intended for the higher voltage and the delta connection for the lower. The current, which can also be stated on the plate, shows the lower value for the star connected motor and the higher for the delta connected motor.

1:27



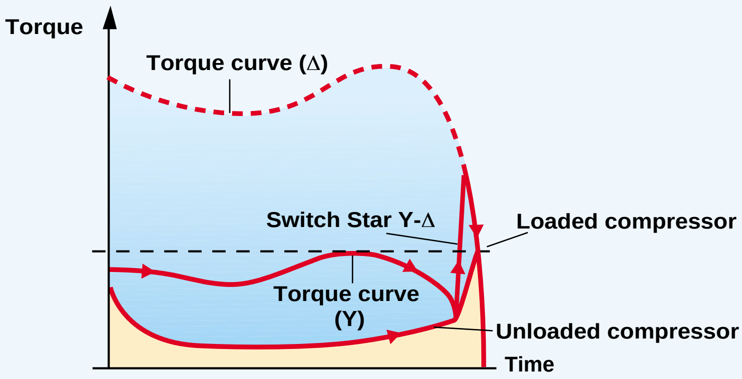
The mains supply is connected to a three-phase motor's terminals marked U, V and W. The phase sequence is L1, L2 and L3. This means the motor will rotate clockwise seen from "D" the drive end. To make the motor rotate anticlockwise two of the three conductors connected to the starter or to the motor are switched. Check the operation of the cooling fan when rotating anticlockwise.

1:28



The torque curve for a short circuited, induction motor. When the motor starts the torque is high, during acceleration the torque first drops a little, to then rise to its max. value before dropping. M = torque, Mst = start torque, Mmax = max torque ("cutting torque"), Mmin = min. torque ("saddle torque"), Mn = rated torque.

1:29



A star/delta started induction motor's torque cure inserted in a torque curve for a screw compressor. The compressor is unloaded (idling) during star operations. When the speed has reached approx. 90-95% of the rated speed the motor is switched to the delta mode, the torque rises, the compressor is loaded and finds its working point.

1.6.5.8 Torque

An electric motor's turning torque is an expression for the rotor's turning capacity. Each motor has a maximum torque. A load above this torque means that the motor does not have the power to rotate. With a normal load the motor works significantly under its maximum torque, however, the start phase involves an extra load. The characteristics of the motor are usually presented in a torque curve.