## Basic knowledge

# Cyclic processes

Technology uses **cyclic thermodynamic processes** to describe the conversion of thermal energy to mechanical energy and vice versa.

During this process a medium undergoes periodically different **changes of state**, such as compression and expansion, evaporation and condensation, or heating and cooling over a period of time. In a cyclic process, the medium, after having undergone the different changes of state, goes back to its original state and can thus be reused repeatedly.

Suitable media are substances that remain in a permanent gaseous state during the cyclic process, such as air or helium, or substances that change their aggregate state during the process (phase change), like water, ammonia, fluorocarbons, or $CO_2$.

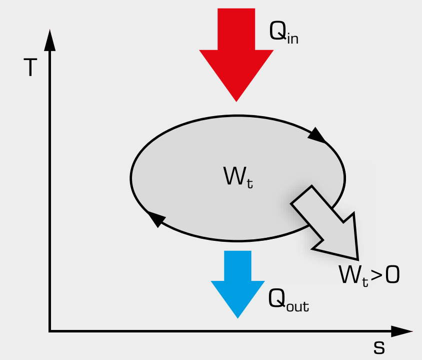
When a **phase change** occurs, more energy is converted than during simple heating or cooling. This means that phase change processes involve a higher energy density and require lower differences in temperature.

Cyclic processes can be used in driving or driven machines. Driving machines convert thermal energy to mechanical energy, such as in steam power plants. Driven machines convert the supplied mechanical energy into thermal energy, like in a compression refrigeration system.

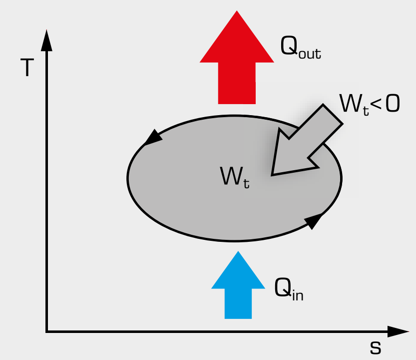
## Representation of cyclic processes in state diagrams

A cyclic thermodynamic process can be illustrated clearly by what are known as state diagrams. The most commonly used state diagrams are:

- **p-v diagram:** pressure **p** against specific volume **v**, suitable for representing mechanical power. It is often used for reciprocating compressors and internal combustion engines with a purely gaseous working medium. Here, cyclic processes can be observed quite well because there is a fixed relationship between volume change and time. The enclosed area is a measure for the mechanical work performed, also known as useful work.
- **h-s diagram:** enthalpy **h** against entropy **s**, for representation of steam turbine processes. It is used for water steam and is well suited as a tool for designing steam turbines.
- **log p-h diagram:** logarithmic representation of the pressure **p** against the specific enthalpy **h**, particularly well suited for cooling processes in refrigeration engineering, as heat fluxes can be read from the diagram directly as horizontal lines. For the vertical pressure scale, a logarithmic division is used, as this is a good way to represent phase limit curves.
- **T-s diagram:** a plot of temperature **T** against entropy **s**, used for the representation of the thermodynamic conditions. The direction of the cyclic process indicates the type of system, driving or driven machine. If the cycle goes **clockwise**, the system is a driving machine, and if it goes **counter-clockwise**, it is a driven machine. In the clockwise direction, heat is absorbed at a high temperature and released at a low temperature. In the counter-clockwise direction, heat is absorbed at a low temperature and released at a high temperature. If the system is operated in the counter-clockwise direction, it is thus suitable as a heat pump or refrigeration machine. As in the p-v diagram, the enclosed area is a measure of the useful work performed.



Clockwise direction: driving machine



Counter-clockwise direction: driven machine

**$W_t$** useful work, **Q** thermal energy, **T** temperature, **s** entropy

## Examples of cyclic thermodynamic processes

| Type | Driving or driven machine | Working medium | Aggregate state |
|---|---|---|---|
| Steam power plant | driving | water | liquid/gaseous |
| Internal combustion engine | driving | air/combustion gas | gaseous |
| Gas turbine | driving | air/combustion gas | gaseous |
| Stirling engine | driving | air, helium | gaseous |
| ORC power plant<br>(Organic Rankine Cycle) | driving | fluorocarbons,<br>hydrocarbons | liquid/gaseous |
| Refrigeration machine | driven | fluorocarbons,<br>hydrocarbons,<br>ammonia, etc. | liquid/gaseous |
| Stirling refrigeration system | driven | air, helium | gaseous |

The following section presents some technically relevant cyclic processes with their diagrams.

## The Carnot process

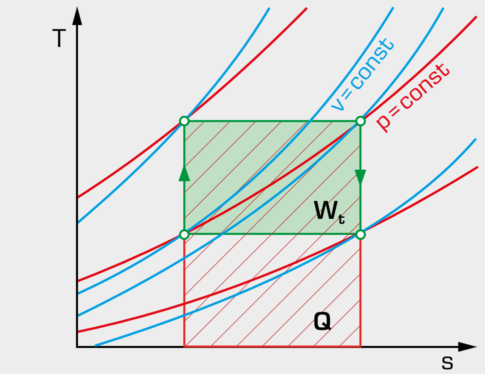
In the T-s diagram, the Carnot process forms a rectangle. The area of the rectangle is a measure of the useful work $W_t$. The area between the temperature zero and the maximum process temperature is a measure of the required thermal energy **Q**. This means that the following efficiency **η** results are derived for the Carnot process:

$$\boxed{\eta = \frac{W_t}{Q} = \frac{T_{max} - T_{min}}{T_{max}}}$$

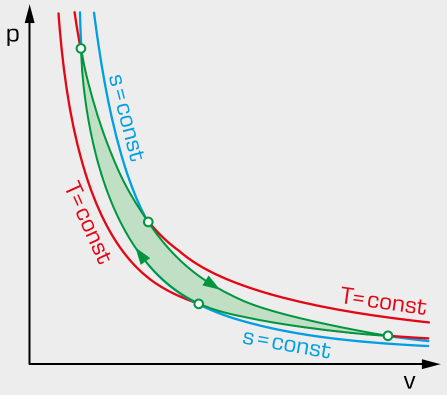
The maximum efficiency of a cyclic thermodynamic process thus only depends on the absolute maximum and minimum temperatures, $T_{max}$ and $T_{min}$. This means that the Carnot process allows statements regarding the quality of any technical cyclic process. Furthermore, it is clear that every thermodynamic process requires a difference in temperatures to perform work. The efficiency of the Carnot process is the highest theoretically possible efficiency of a cyclic process.

The changes of state that are necessary for the Carnot process, like isothermal and isentropic compression and/or expansion, are difficult to realise technically. Despite its high efficiency, this process is therefore of theoretical interest only.

The p-v diagram on the right shows another crucial disadvantage of the Carnot process. Despite large differences in pressure and volume, the surface area of the diagram, and thus the mechanical work performed, is very small. When the Carnot process is applied, this translates to a large and heavy machine with a small output.

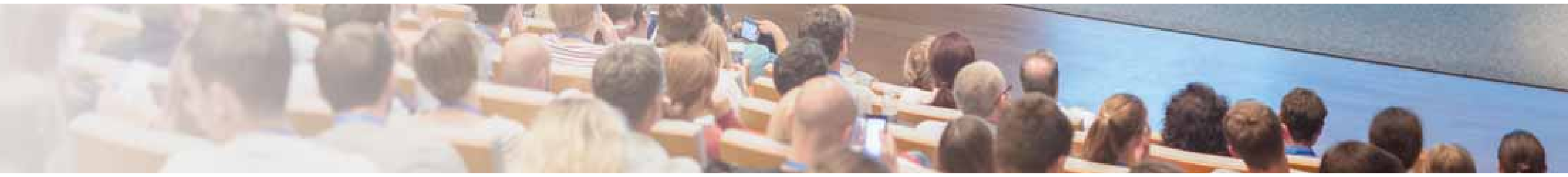


Carnot process in T-s diagram



Carnot process in p-v diagram

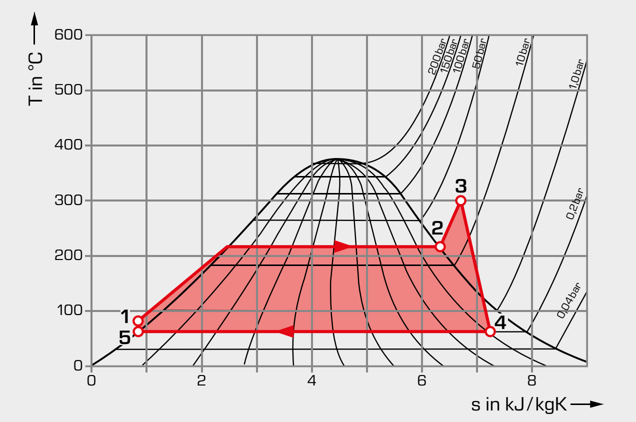
**$W_t$** useful work, **Q** thermal energy, **T** temperature, **p** pressure, **v** specific volume, **s** entropy



## Basic knowledge

# Cyclic processes

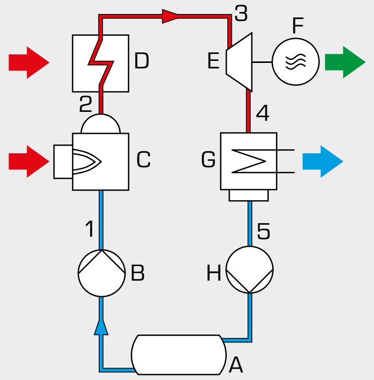
### Steam power plant



T-s diagram of a steam power plant

The above T-s diagram represents the Rankine cycle of a steam power plant. The working medium is water or water steam.

**1 – 2** the water is **isobarically** heated and evaporated in a steam boiler at a pressure of 22 bar
**2 – 3** **isobaric** superheating of the steam to 300°C
**3 – 4** **polytropic** expansion of the steam in the steam turbine to a pressure of 0,2 bar; mechanical energy is released in the process
**Point 4** wet steam area: the wet steam content is now only 90 %
**4 – 5** condensation of the steam
**5 – 1** increase of the pressure to boiler pressure via the condensate and feed water pump, the cyclic process is complete

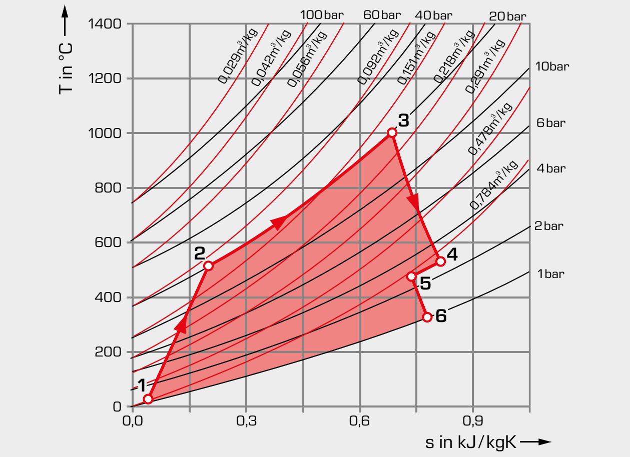


Process schematic for a steam power plant

**A** feed water tank, **B** feed water pump, **C** steam boiler, **D** superheater, **E** steam turbine, **F** generator, **G** condenser, **H** condensate pump;

🟦 thermal energy, low temperature,
🟥 thermal energy, high temperature,
🟩 mechanical/electrical energy

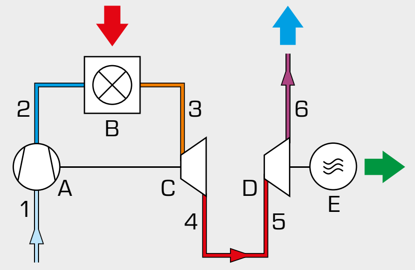
### Gas turbine power plant



T-s diagram of a gas turbine power plant

The T-s diagram represents a gas turbine process with two-stage expansion in a double shaft system.

**1 – 2** **polytropic** compression of air to a pressure of 20 bar; the air has a temperature of 500°C at the outlet of the compressor
**2 – 3** **isobaric** heating of air to the inlet temperature of 1000°C of the high-pressure turbine via injection and combustion of fuel
**3 – 4** **polytropic** expansion in the high-pressure turbine that drives the compressor
**Point 5** in the transition to the power turbine the gas **isobarically** cools down slightly
**5 – 6** second expansion in the power turbine: the exhaust gas exhausts and is not returned to the process again, which is why the process is known as an open gas turbine process; the process heat is released into the surroundings

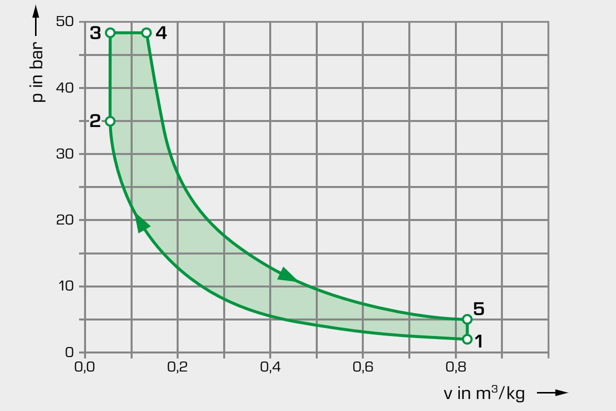


Process schematic for a gas turbine power plant

**A** compressor, **B** combustion chamber, **C** high-pressure turbine, **D** power turbine, **E** generator;

🟦🟦 thermal energy, low temperature,
🟧🟥 thermal energy, high temperature,
🟪 exhaust gas, 🟩 mechanical / electrical energy

### Internal combustion engine



p-v diagram of an internal combustion engine

The p-v diagram shows the Seiliger process of an internal combustion engine. In the case of the internal combustion engine, all changes of state take place in the same space: the cylinder. The changes of state occur one after the other.

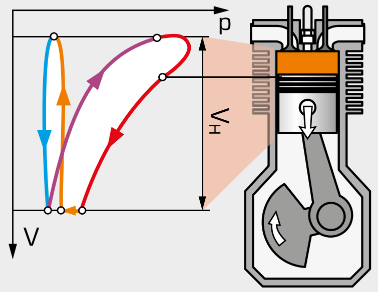
**1 – 2** **polytropic** gas compression
**Point 2** ignition with subsequent fuel combustion

idealised division of the combustion process into:
**2 – 3** **isochoric** proportion of the combustion process
**3 – 4** **isobaric** proportion of the combustion process

**4 – 5** polytropic **(isentropic)** expansion, in this phase the usefull work results
**5 – 1** **isochoric** decompression and exchange of working medium

In the case of a 2-stroke engine this takes place without an additional stroke, in a 4-stroke engine the exhaust and intake stroke follows. The Seiliger process, similar to the gas turbine process, is an open cyclic process.

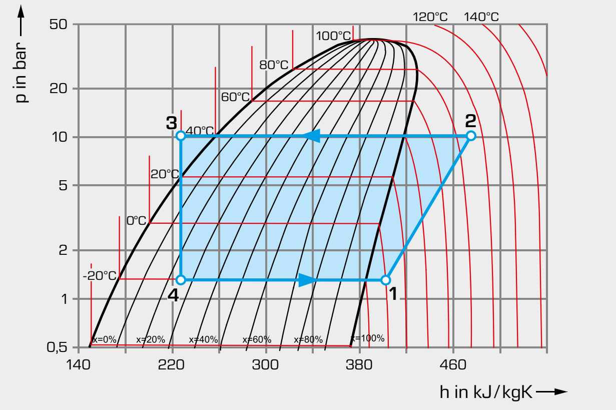
The Seiliger process is a comparative or ideal process that is based on the assumption of a perfect engine. The indicator diagram represents the actual work process.



Indicator diagram of a 4-stroke engine

**p** pressure, **V** volume, **$V_H$** displaced volume;
🟦 intake, 🟪 compression, 🟥 power, 🟧 exhaust

### Refrigeration plant

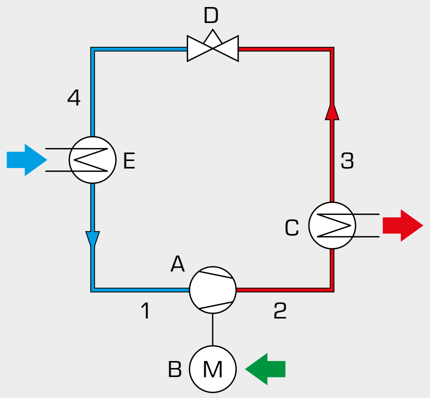


log p-h diagram of a refrigeration plant

This log p-h diagram displays a refrigeration cycle. Working medium is the fluorohydrocarbon refrigerant R134a.

**1 – 2** **polytropic** compression
**2 – 3** **isobaric** cooling and condensation with heat dissipation
**3 – 4** **isenthalpic** expansion to evaporation pressure
**4 – 1** **isobaric** evaporation with heat absorption

After being superheated to a certain degree the refrigerant vapour is once again sucked in and compressed by the compressor at point 1. The cyclic process ends.



Process schematic of a refrigeration plant

**A** compressor, **B** drive motor, **C** condenser, **D** expansion valve, **E** evaporator;
🟦 thermal energy, low temperature,
🟥 thermal energy, high temperature,
🟩 mechanical / electrical energy