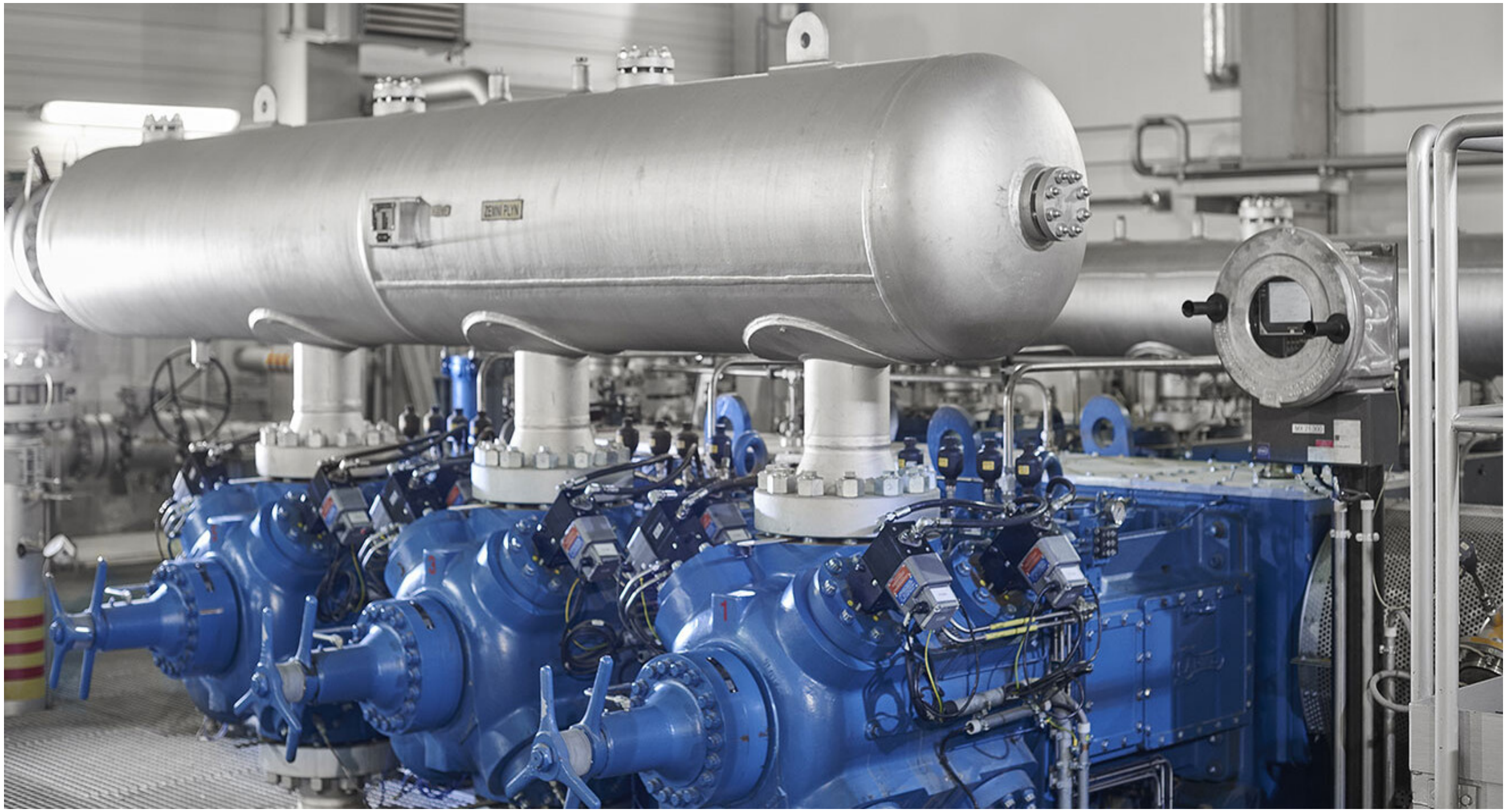
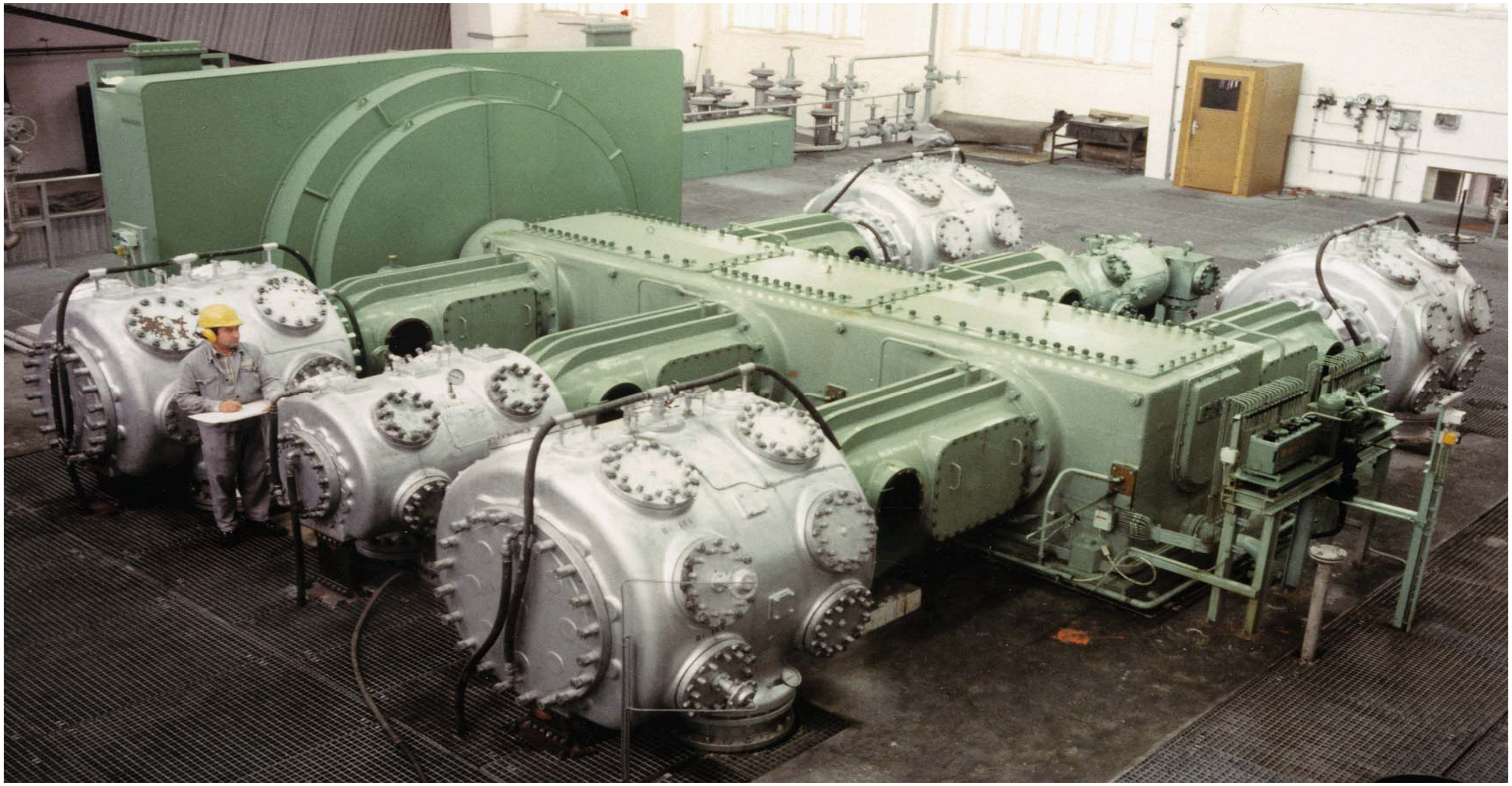


Reciprocating Compressors

HOERBIGER

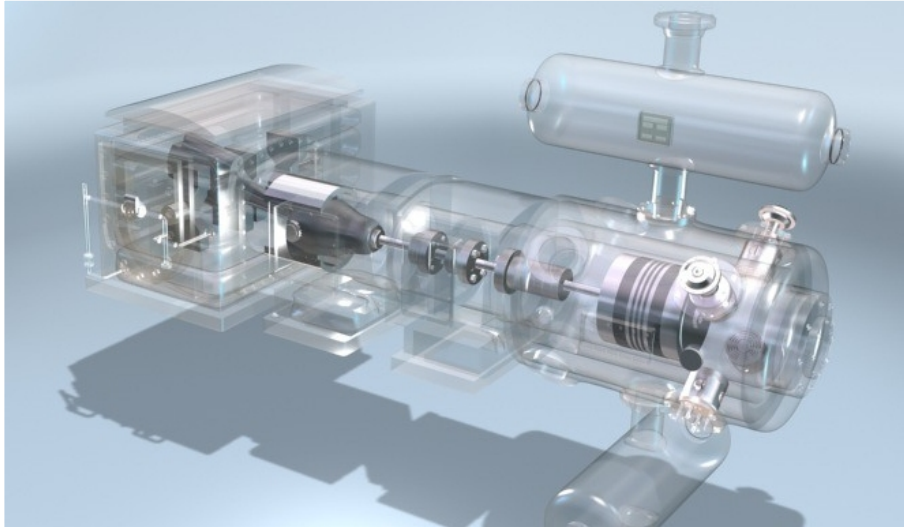
Objective of the Training

- **Acquisition of basic knowledge of reciprocating piston compressors, as far as required for understanding valve-, control systems-, piston ring- and pressure packing performance.**



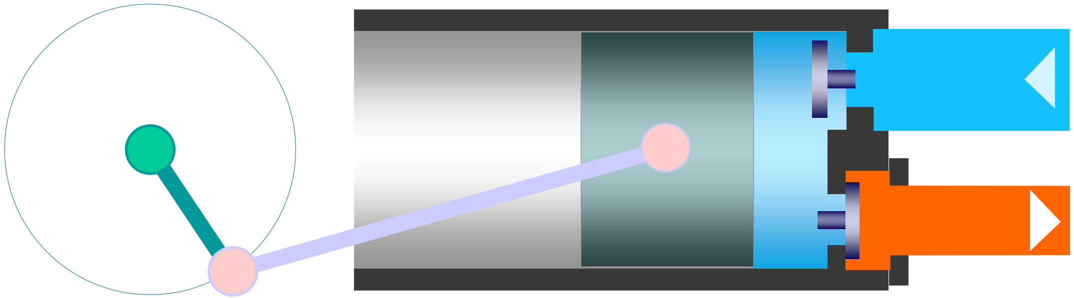
Contents

- Single-Acting Reciprocating Compressor
  Principle, compressor cycle, pV -diagram (indicator diagram)
- Double-Acting Reciprocating Compressor
  compressor cycle, opening and closing of the compressor valves
- Multistage Reciprocating Compressor
- Crank Mechanism
  Components, kinematics, masses, rod forces



Basic principles - working principle

- **Gas is compressed in a reciprocating cycle**



Animation

quick ***slow***

- Basic Principles
- Double Acting Piston Compressor
- Multistage Compressor

Basic principles - indicator diagram

HOERBIGER

Pressure - time diagram

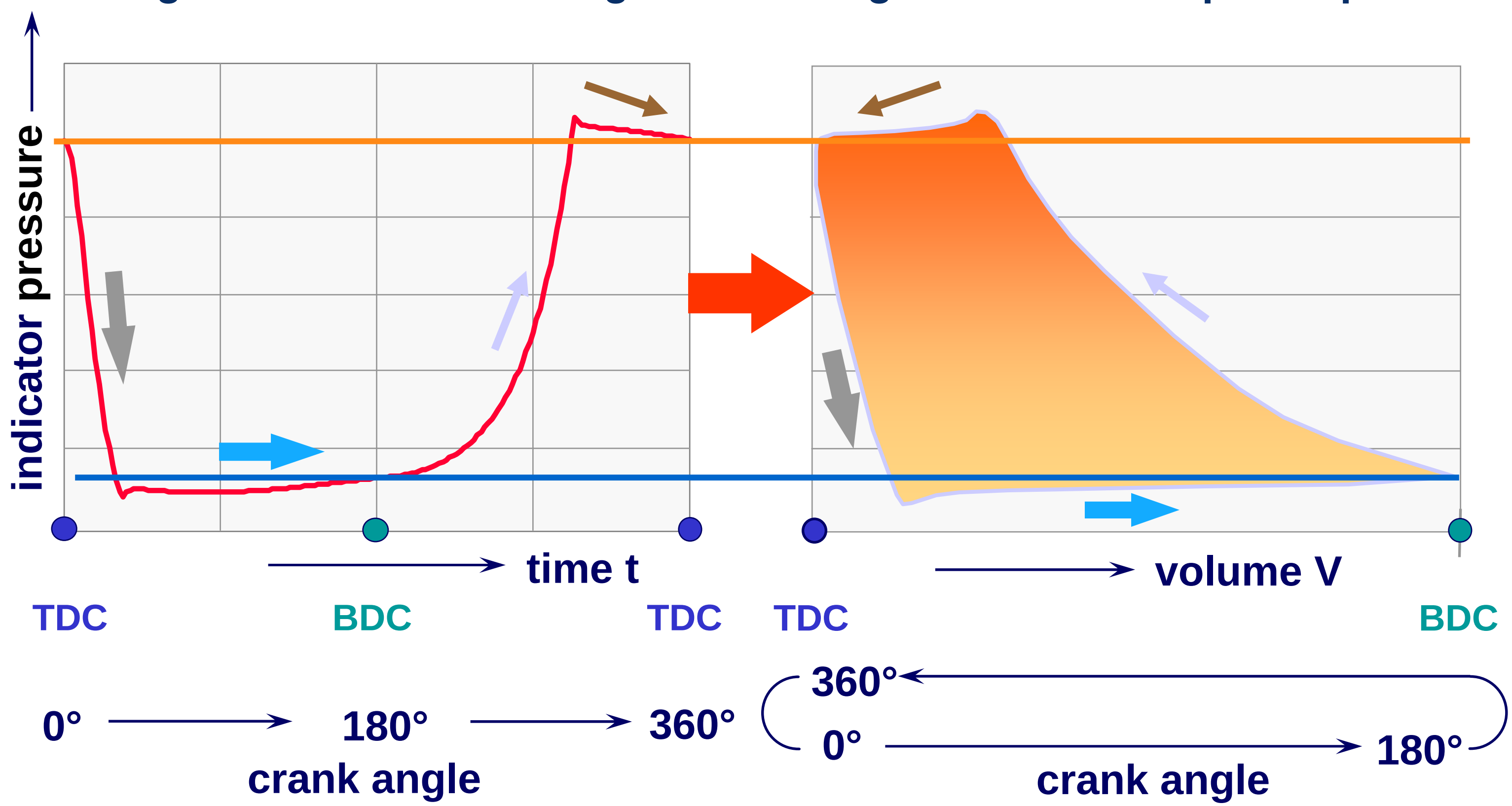
p,t

shows the pressure in the cylinder
at a given time or crank angle

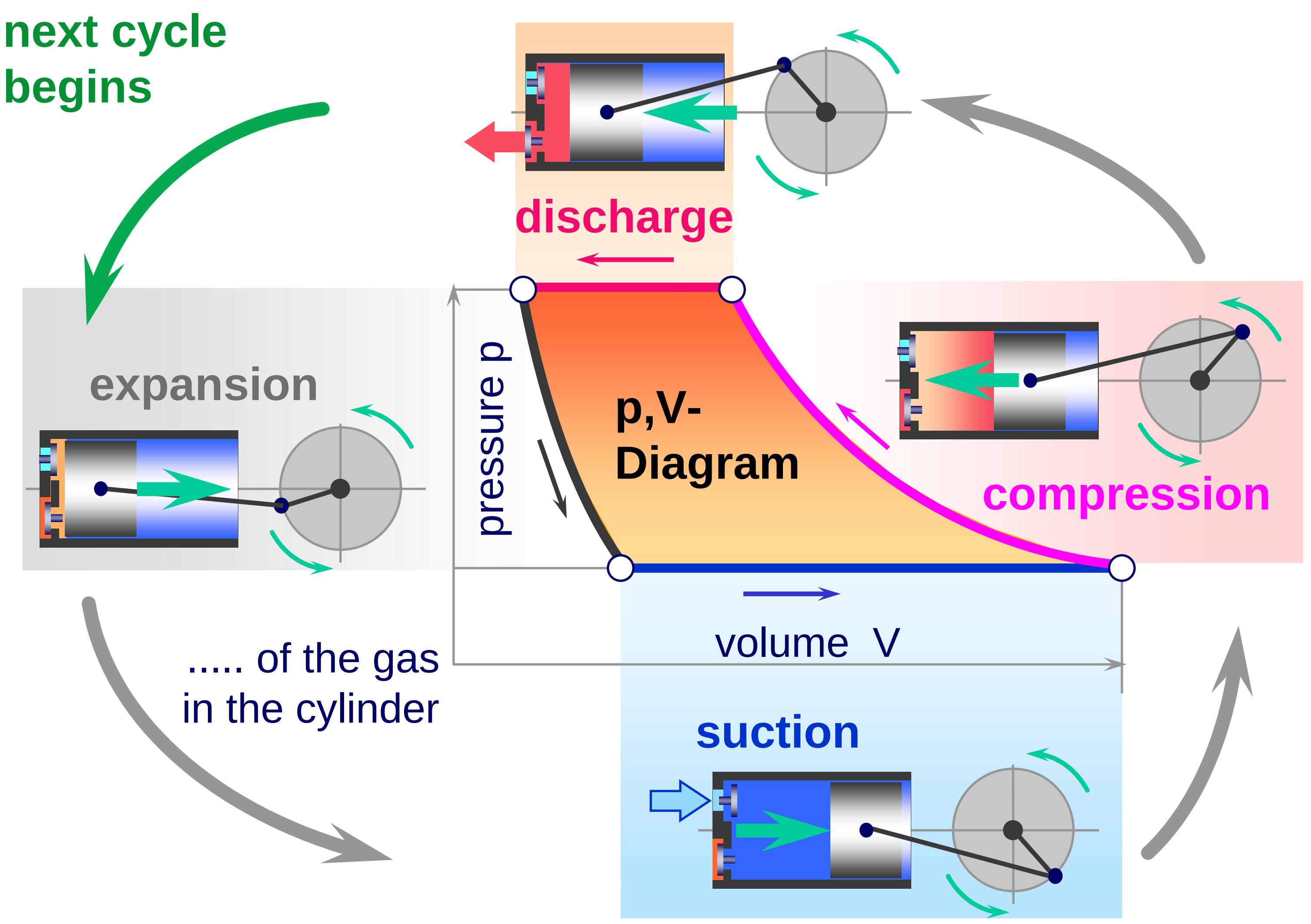
Pressure - volume diagram

p,V

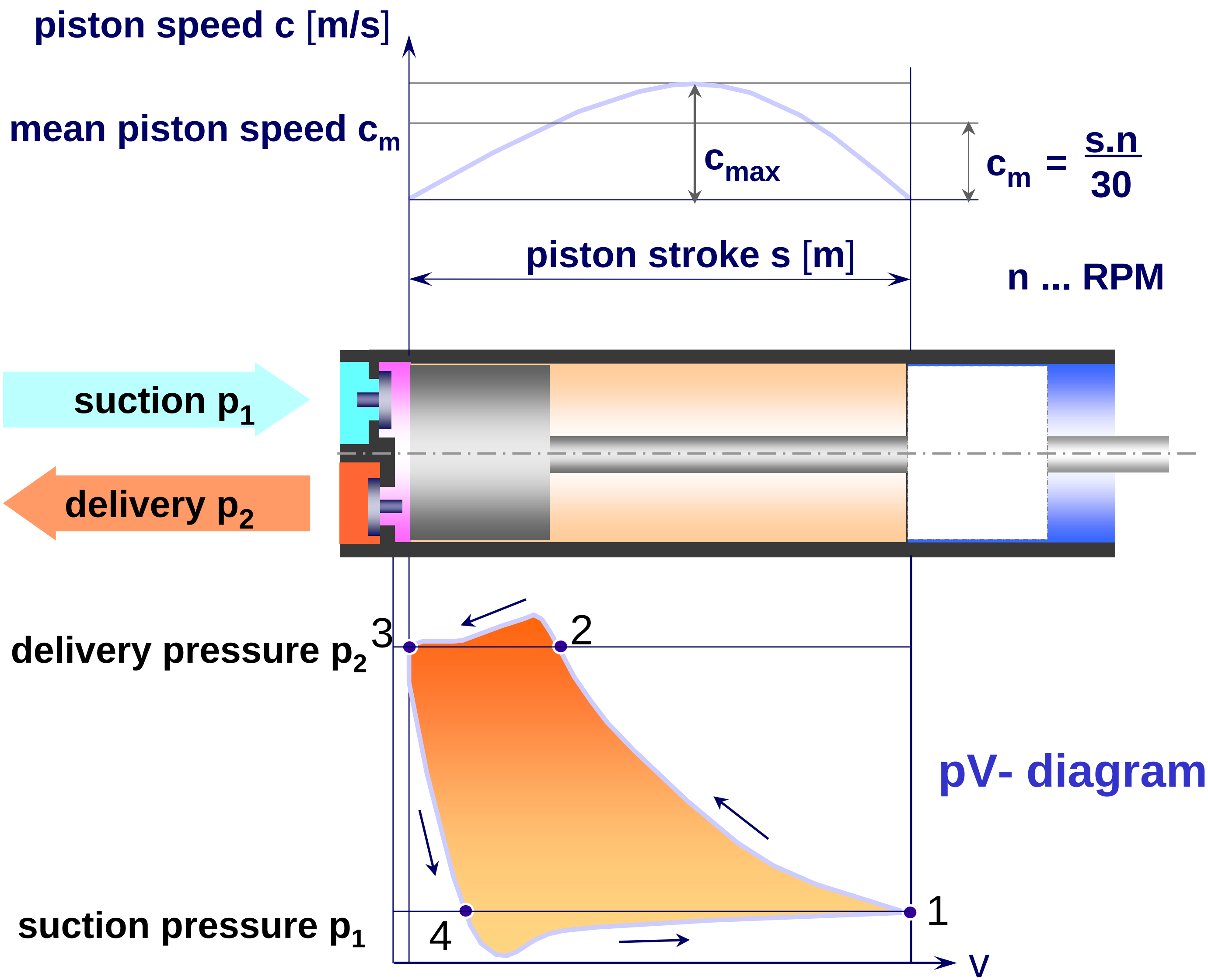
shows the pressure in the cylinder
at a given volume or piston position



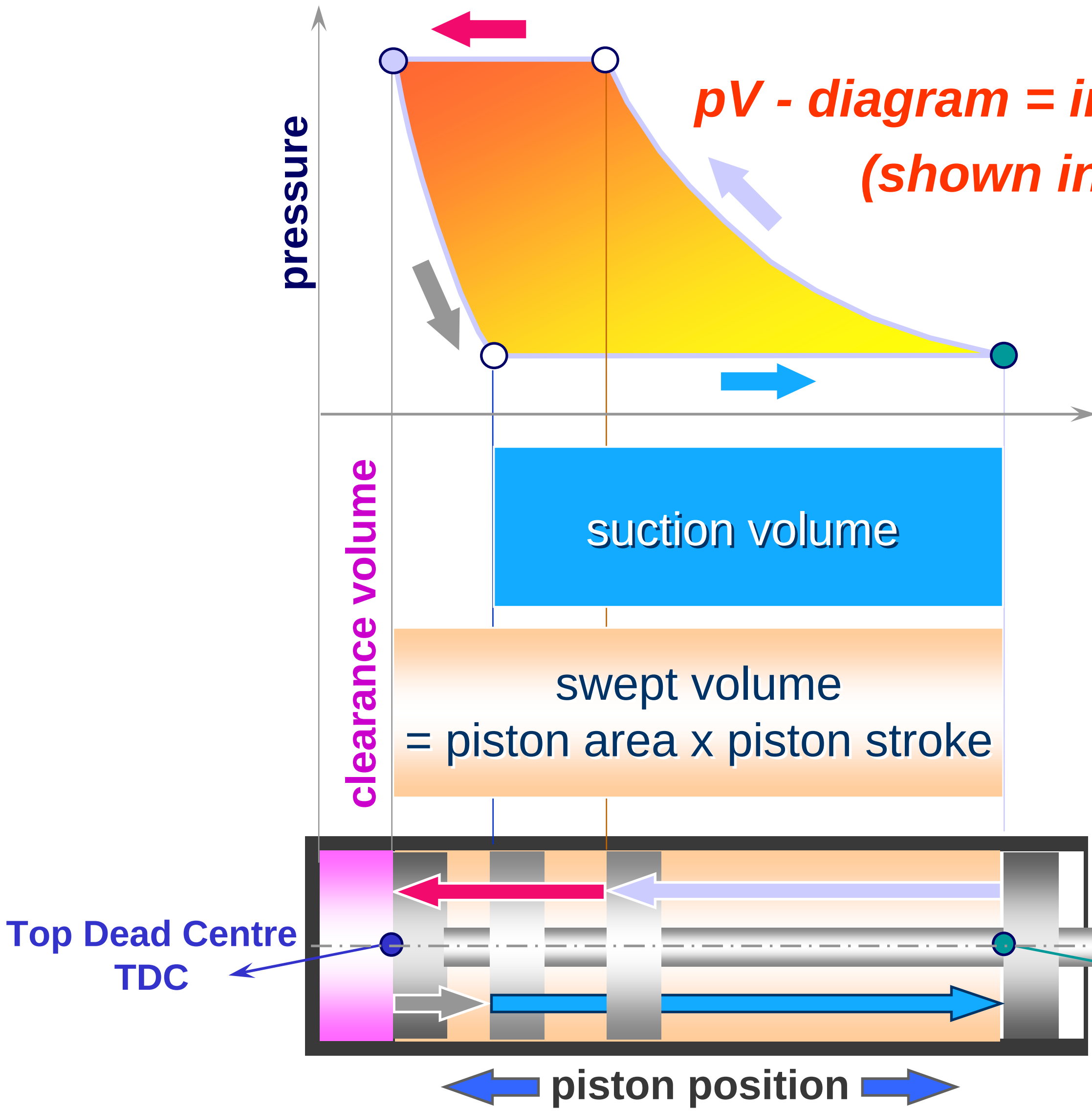
Basic principles - compression cycle



Basic principles - piston speed



Basic principles - efficiency



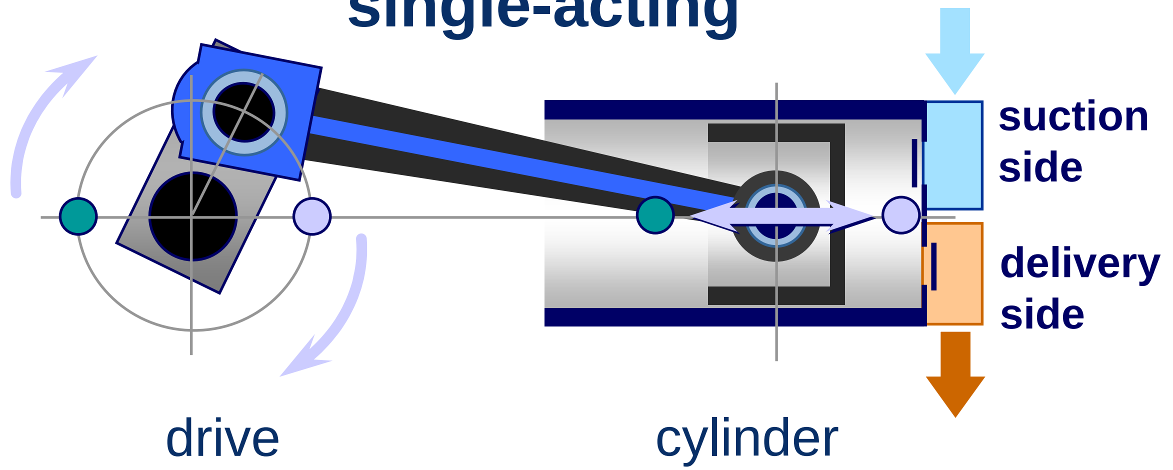
pV - diagram = indicator diagram
(shown in ideal form)

Volumetric efficiency:

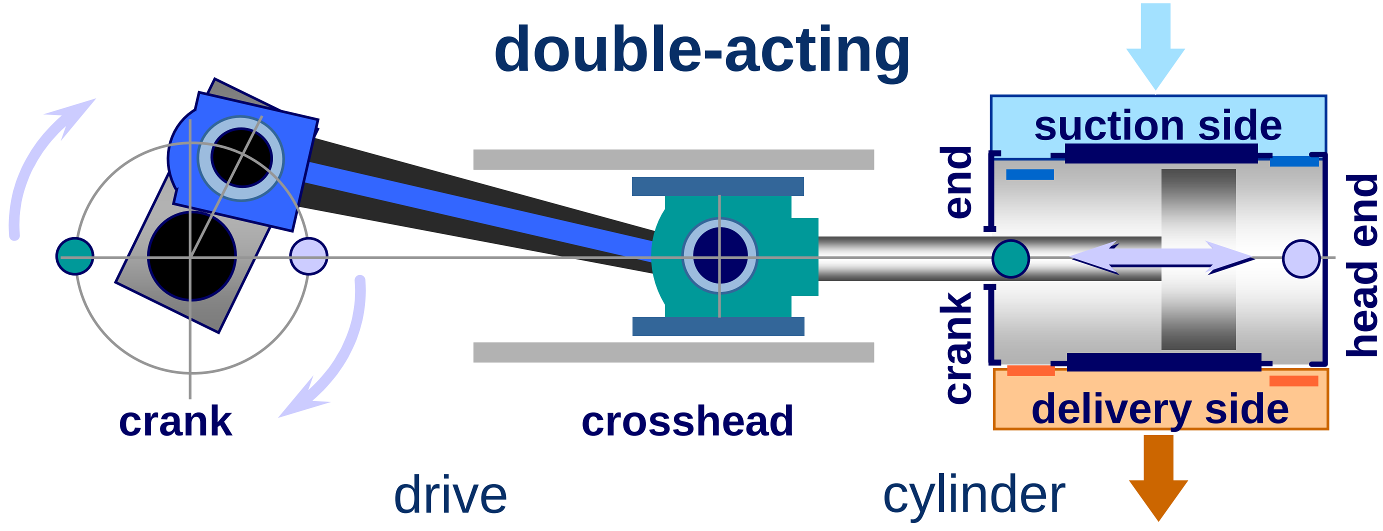
$$\eta_v = \frac{\textbf{suction volume}}{\textbf{swept volume}}$$

Basic principles - single & double acting

single-acting

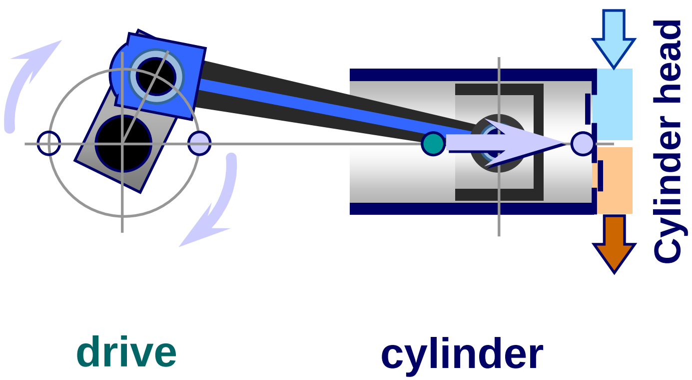


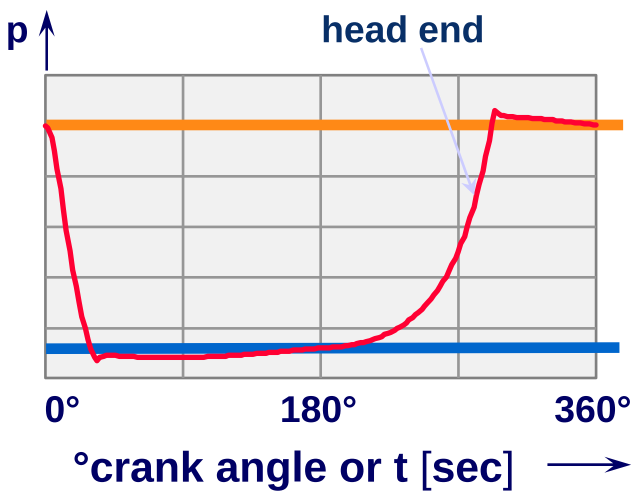
double-acting



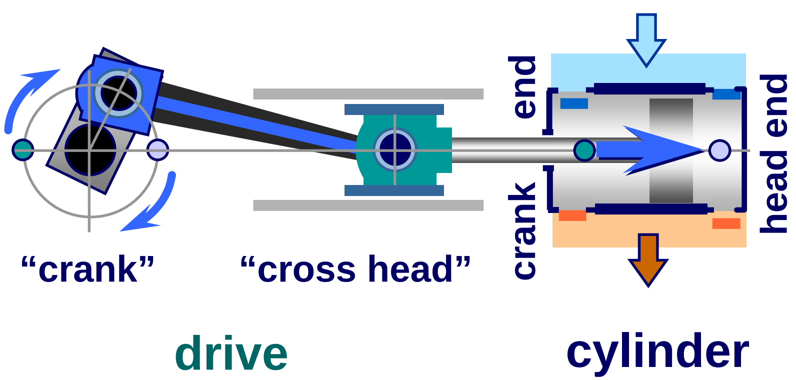
Basic principles - single & double acting

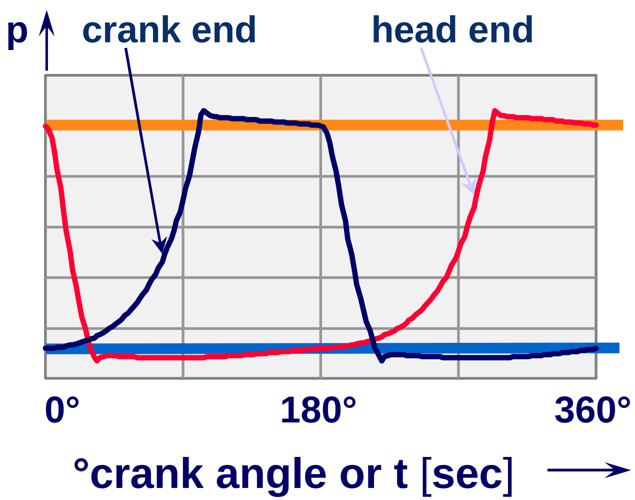
Single-acting compressor



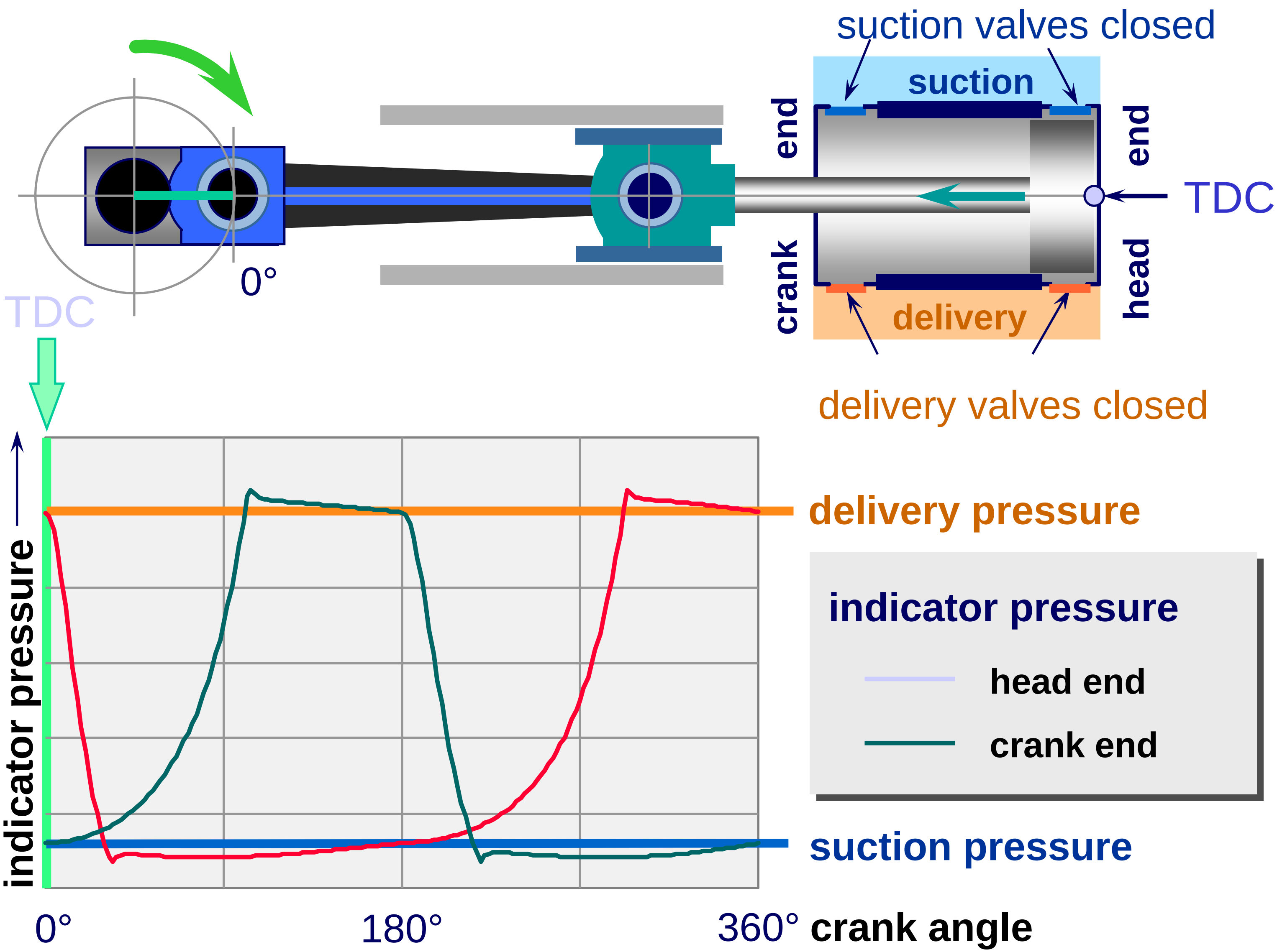


Double-acting compressor

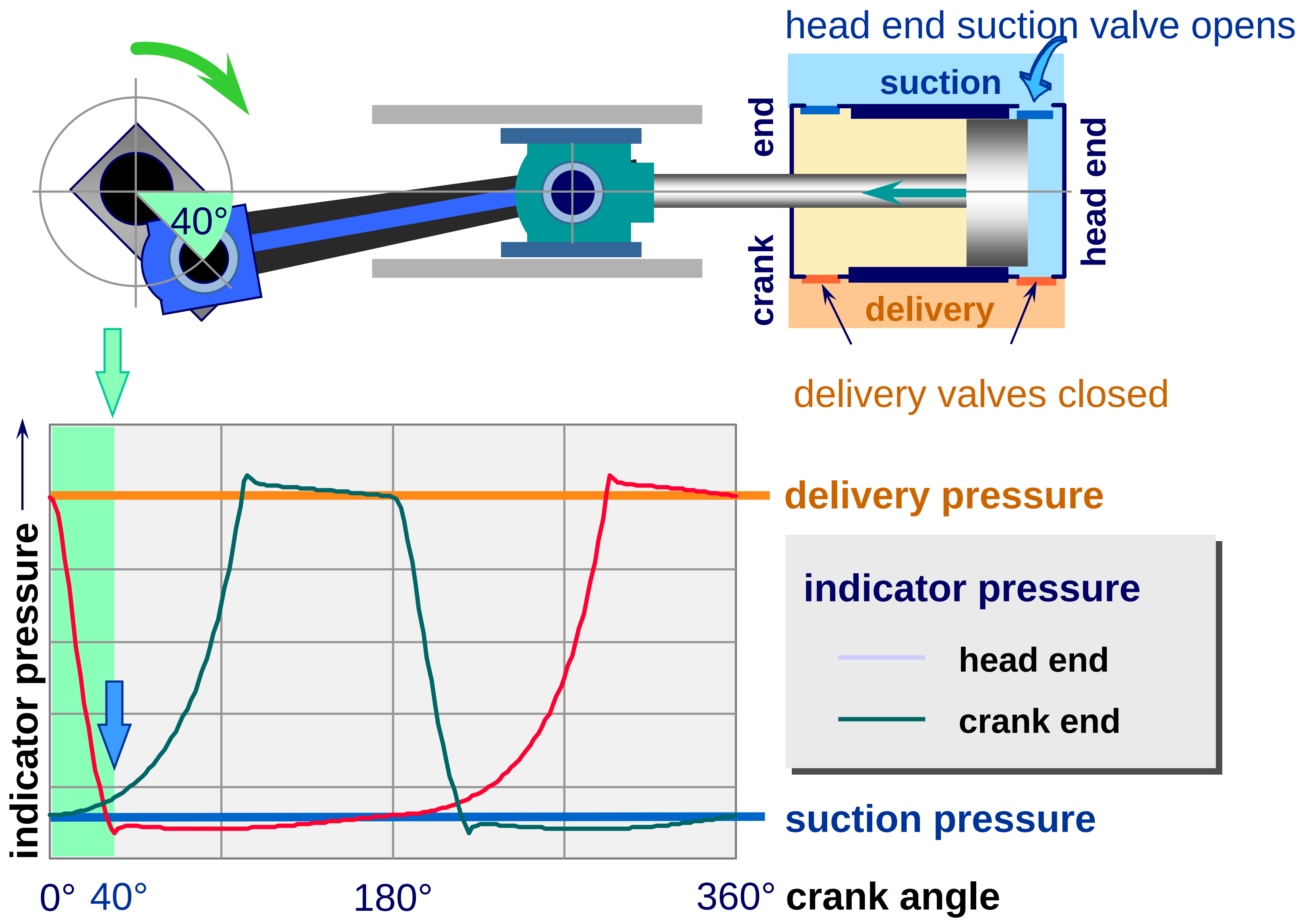




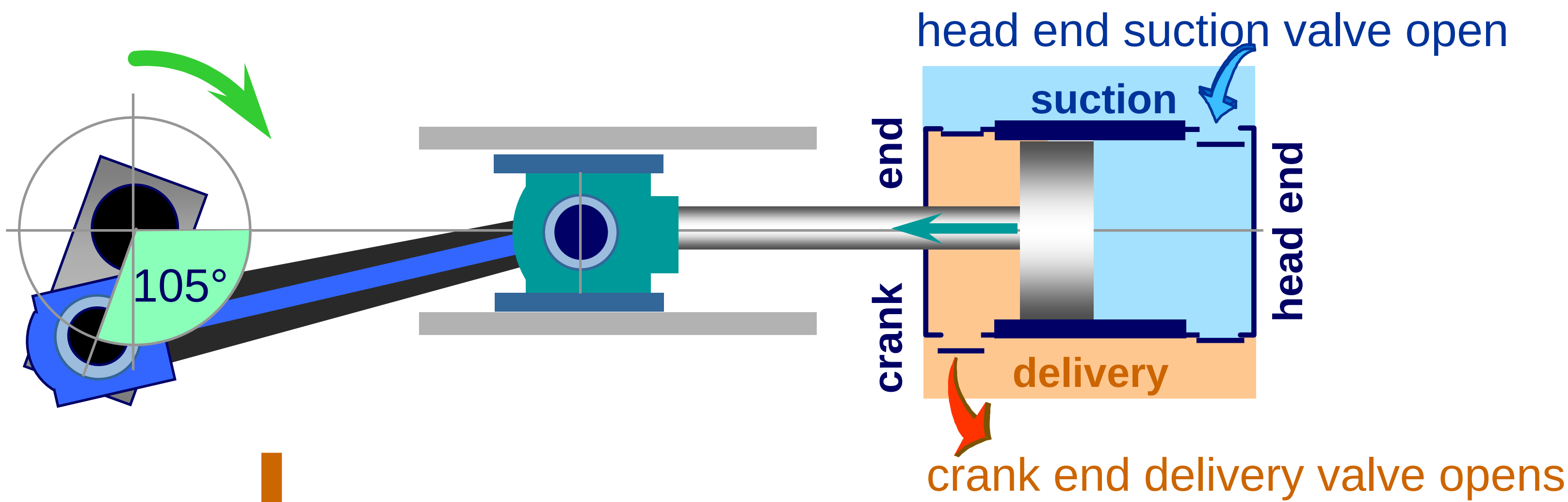
Start of cycle

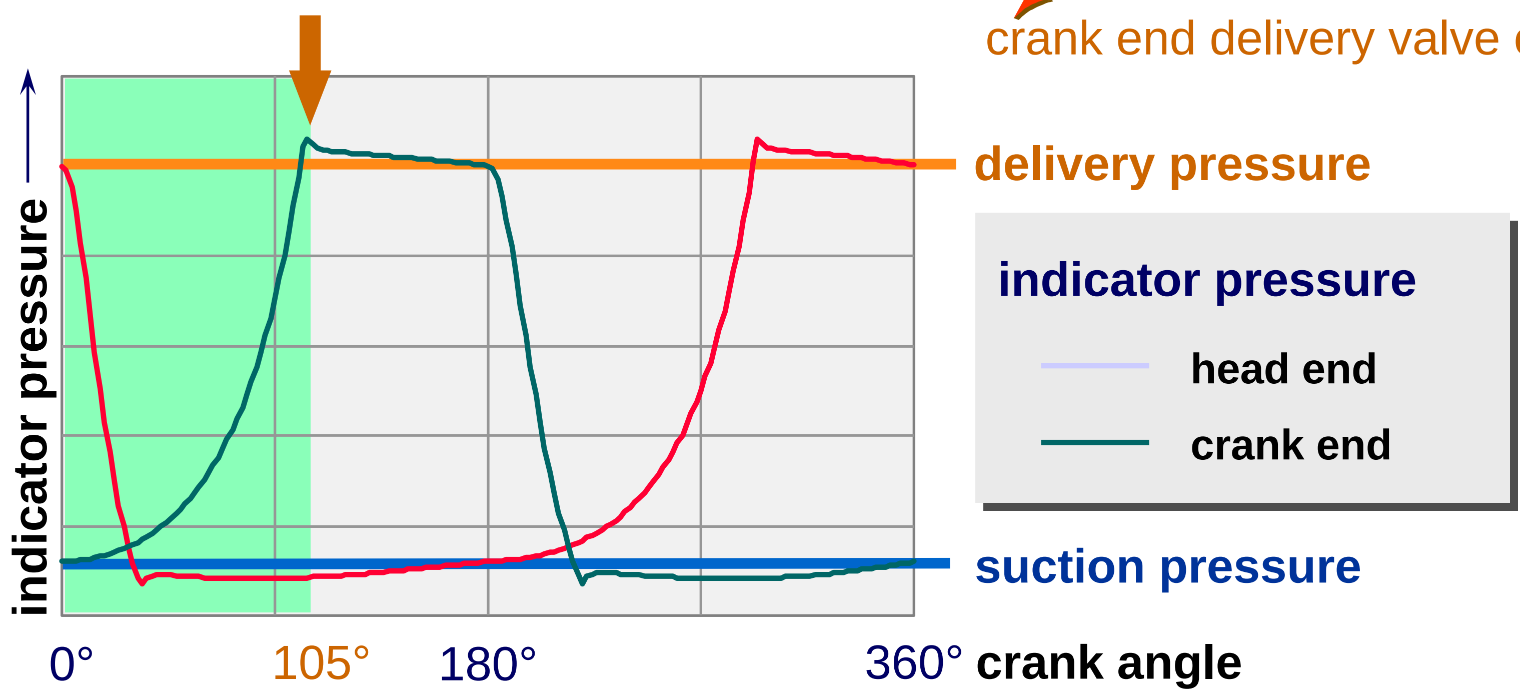


HE suction valve opens

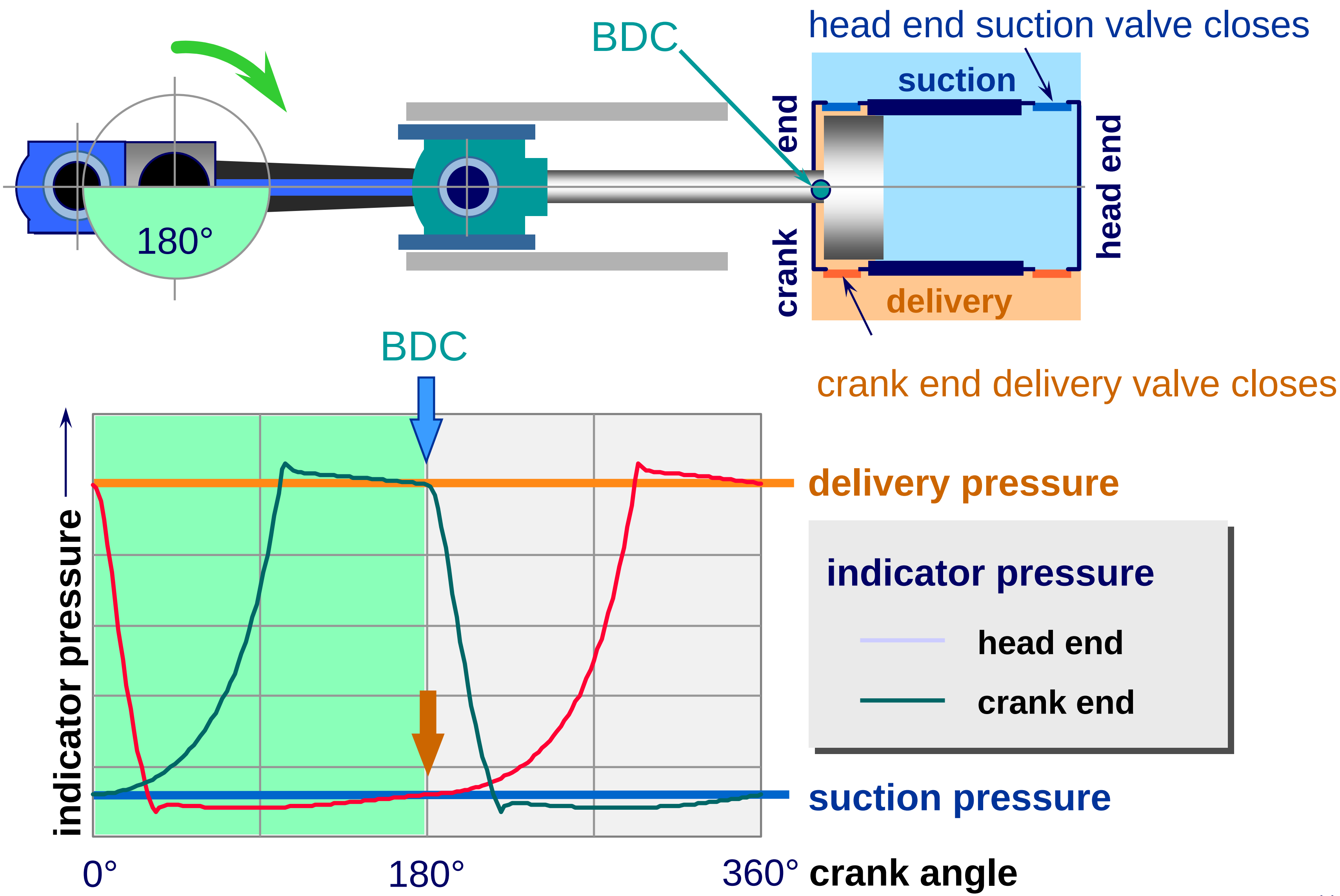


CE delivery valve opens

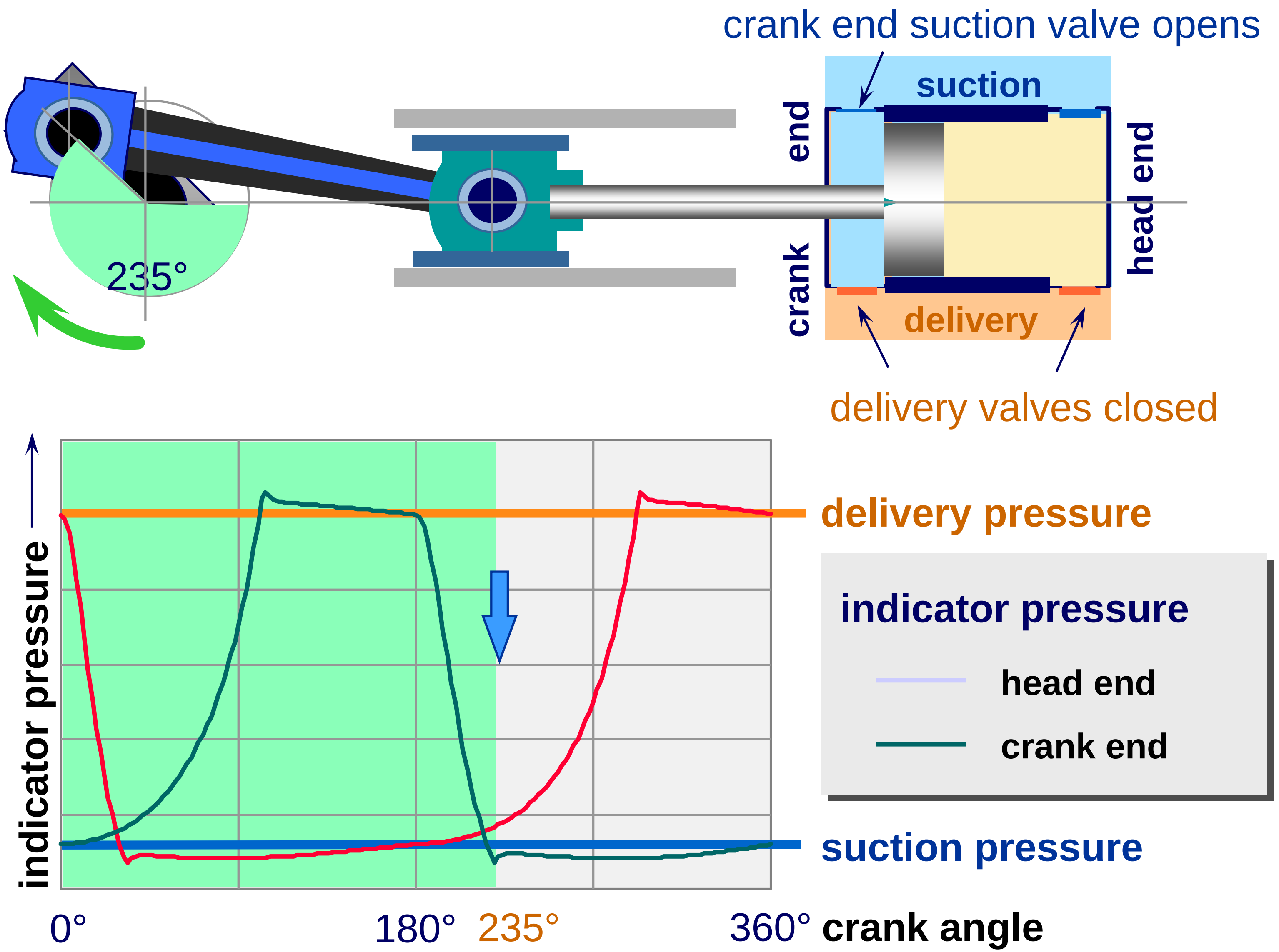




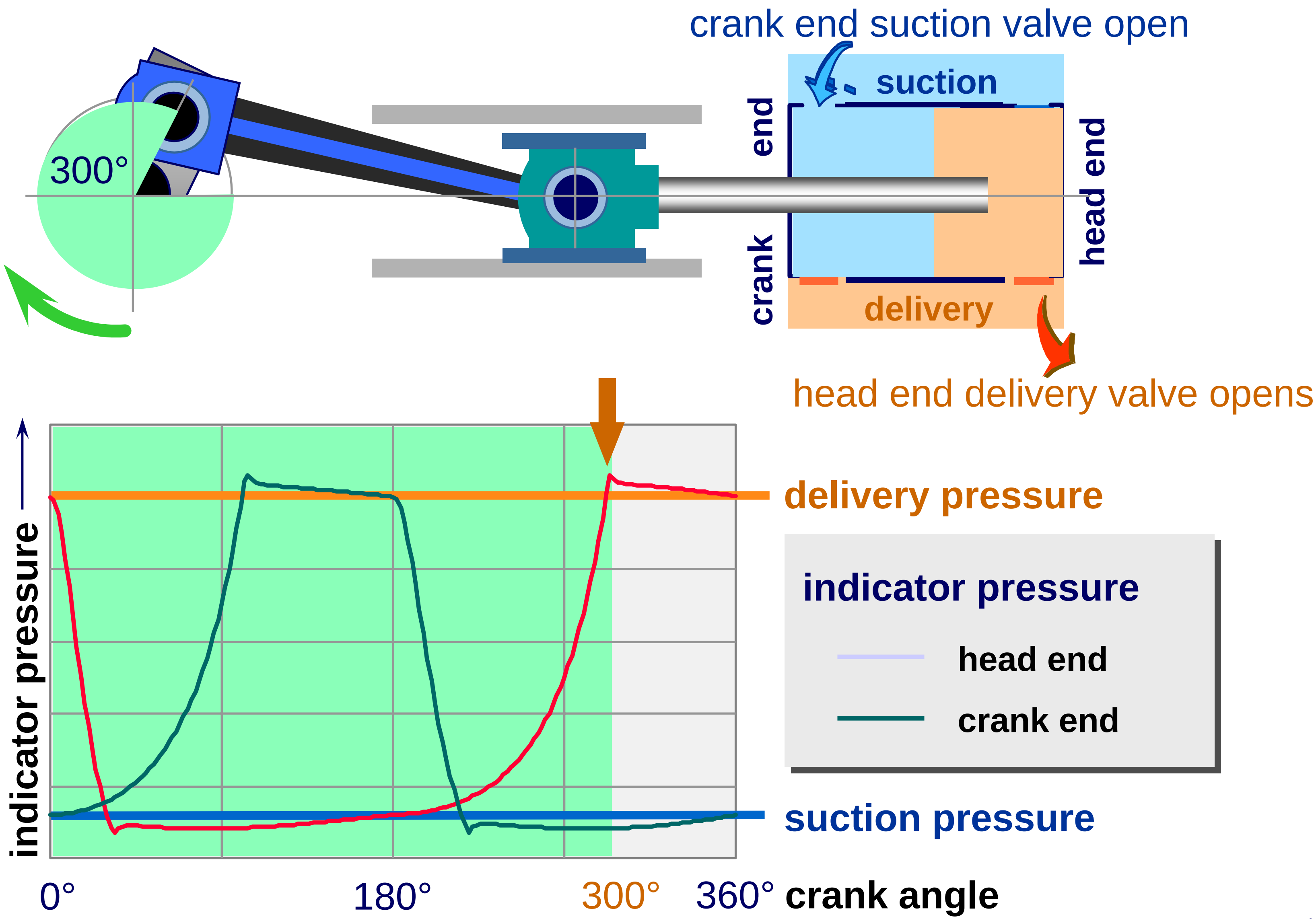
HE suction & CE delivery valve closed



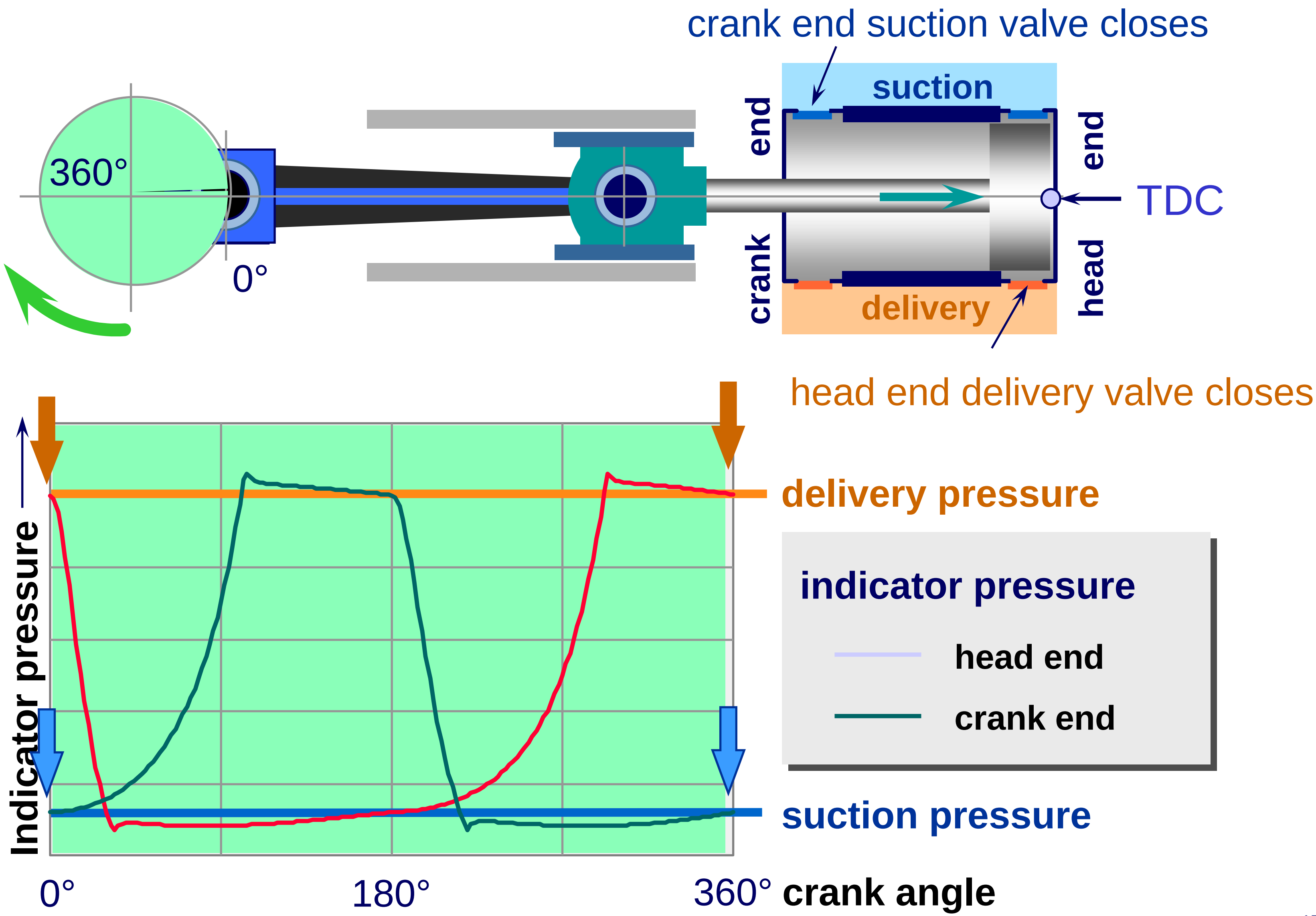
CE suction valve opens



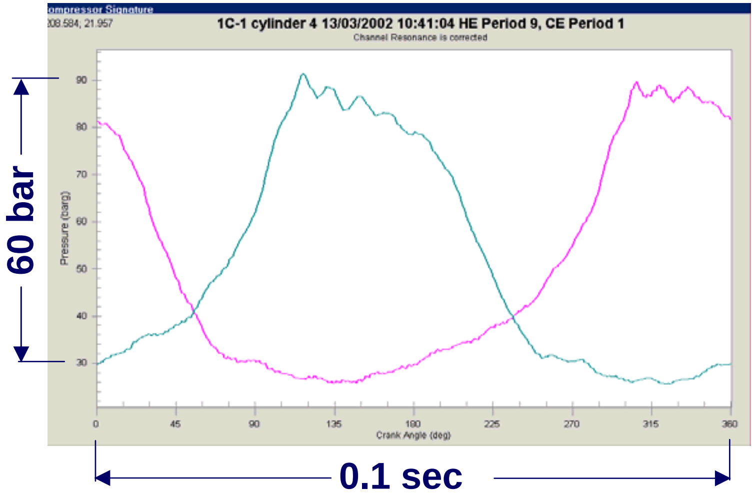
HE delivery valve opens

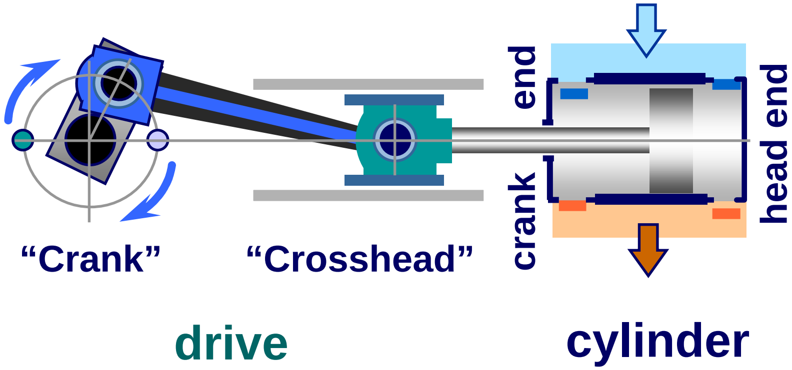


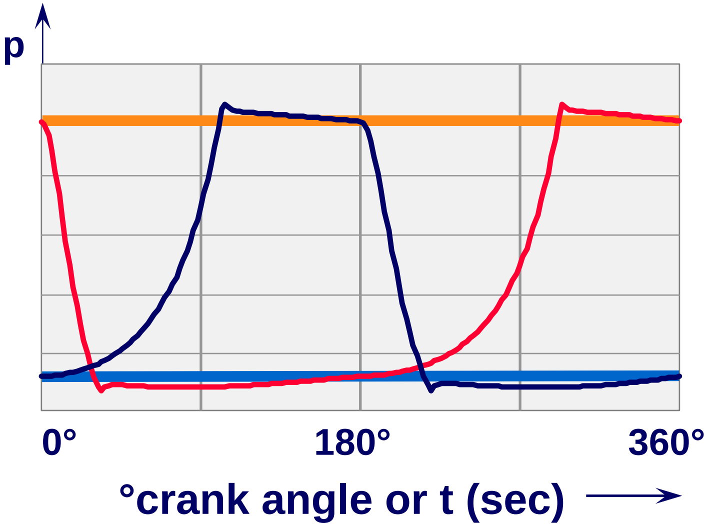
CE suction & HE delivery valve close



Basic principles - real versus ideal pt-diagram

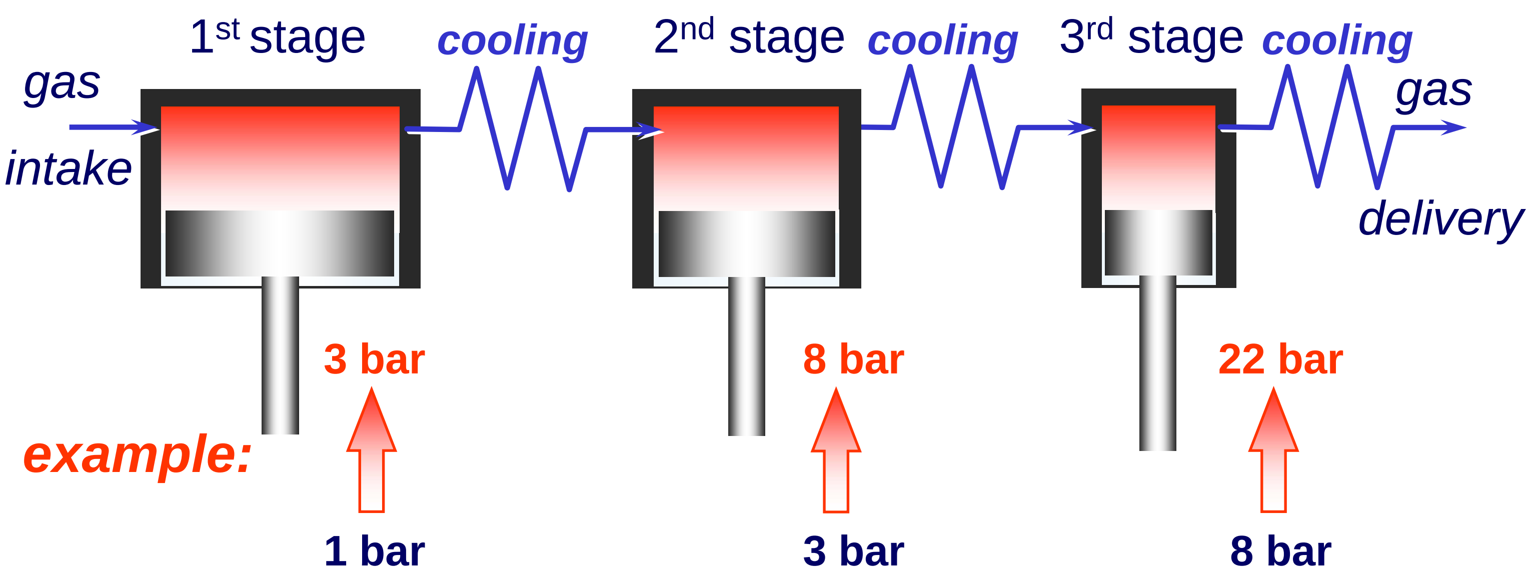






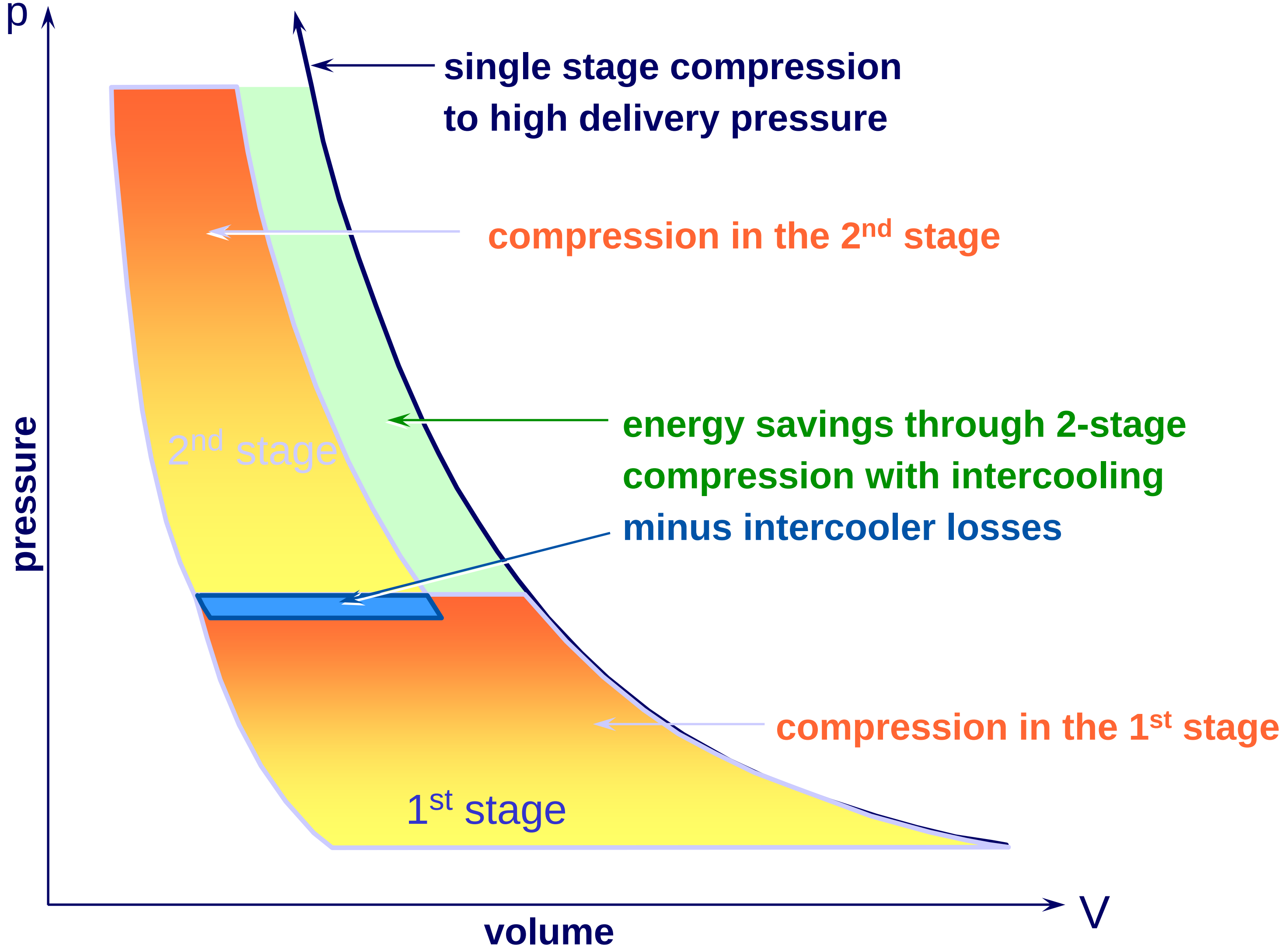
Multistage compressor

- **Compression in 2 - 8 stages**
  - to achieve higher pressures - up to several hundred bars in high pressure and ultra-high pressure compressors
- **Cooling between the compression stages:**
  - to avoid exceeding the permissible temperature for compressor materials and lubricating oil
  - to save energy costs

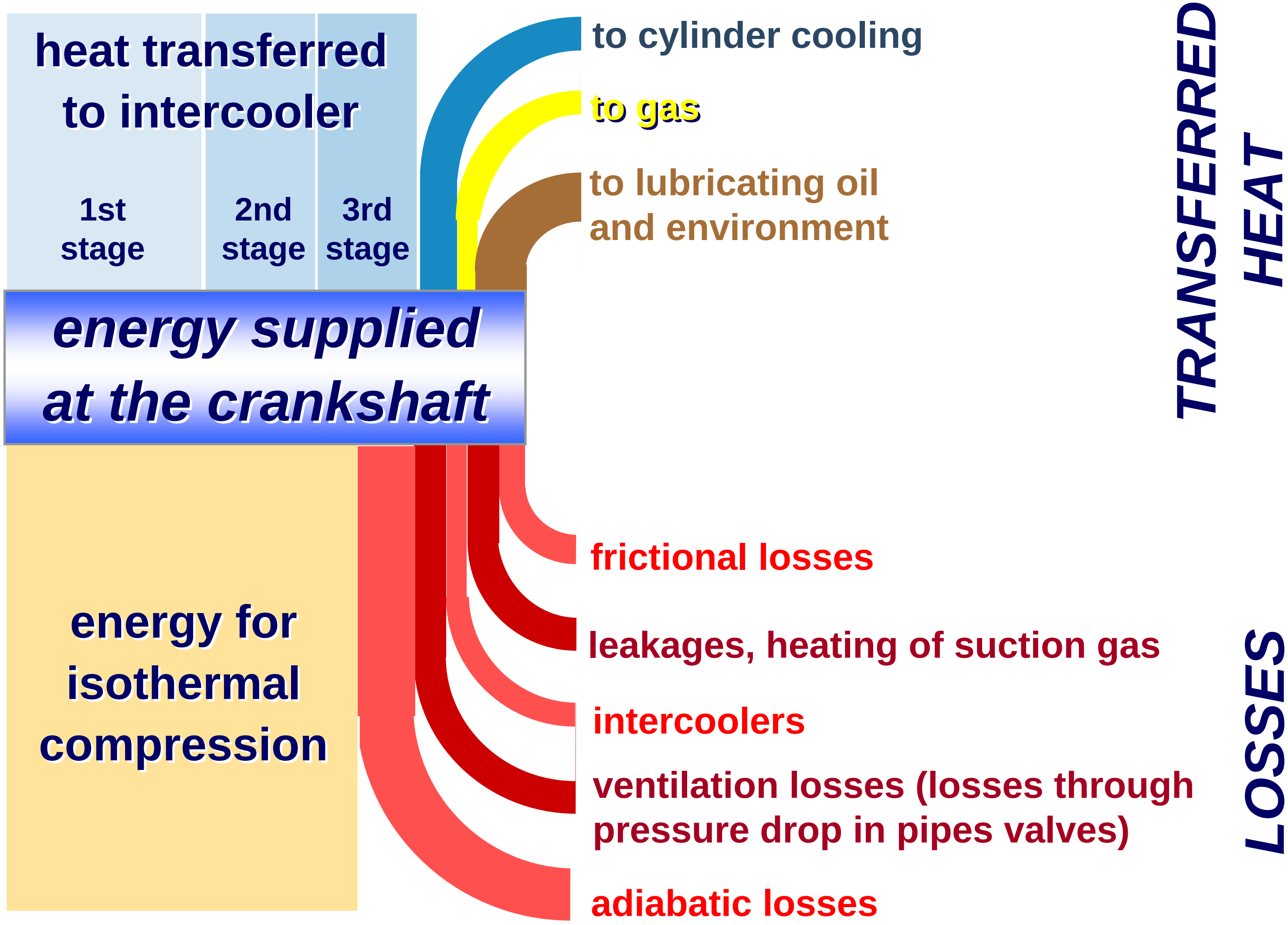


Multistage compressor

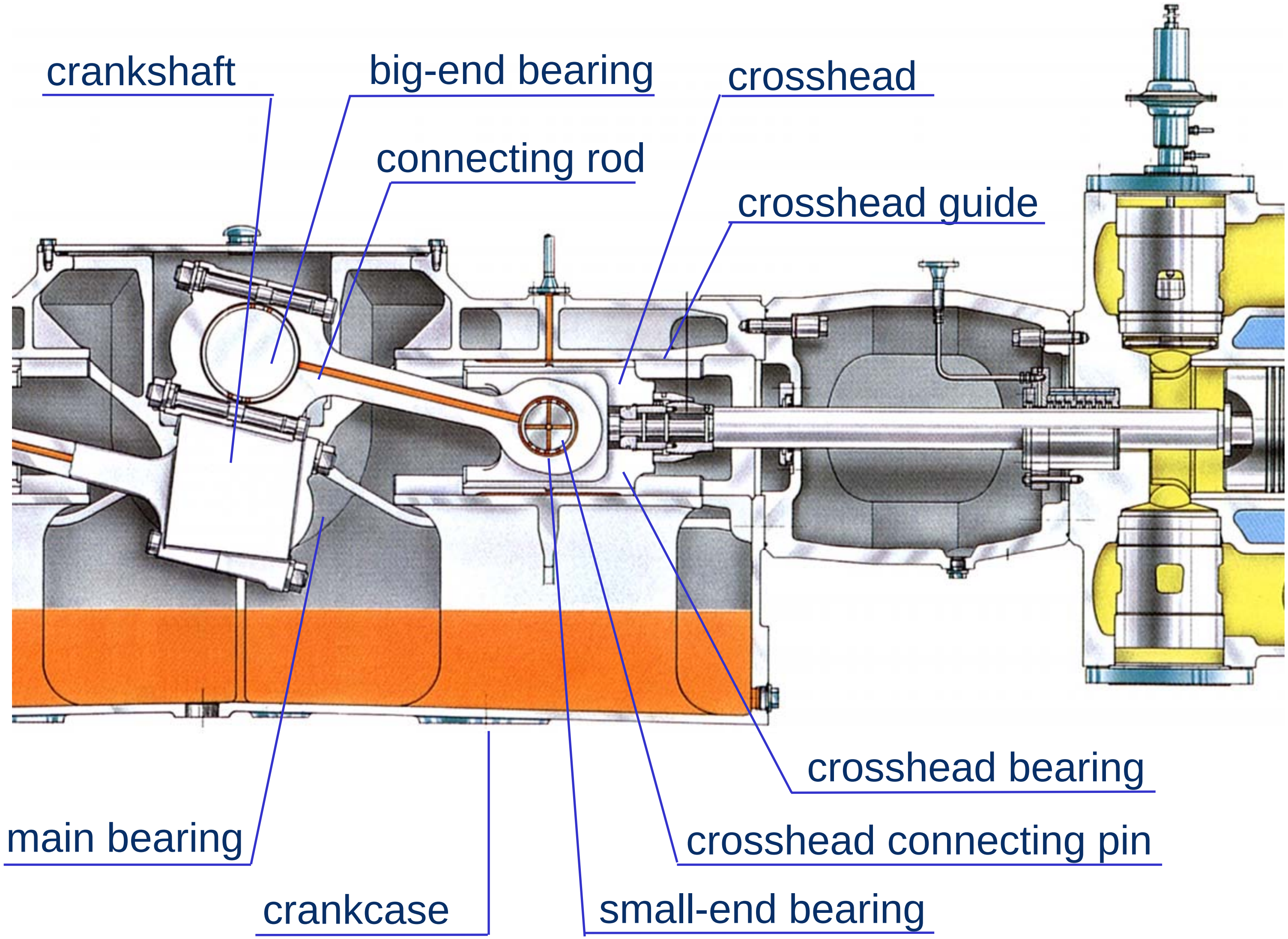
- **Energy saving: Multistage compression with inter-cooling**



Energy balance

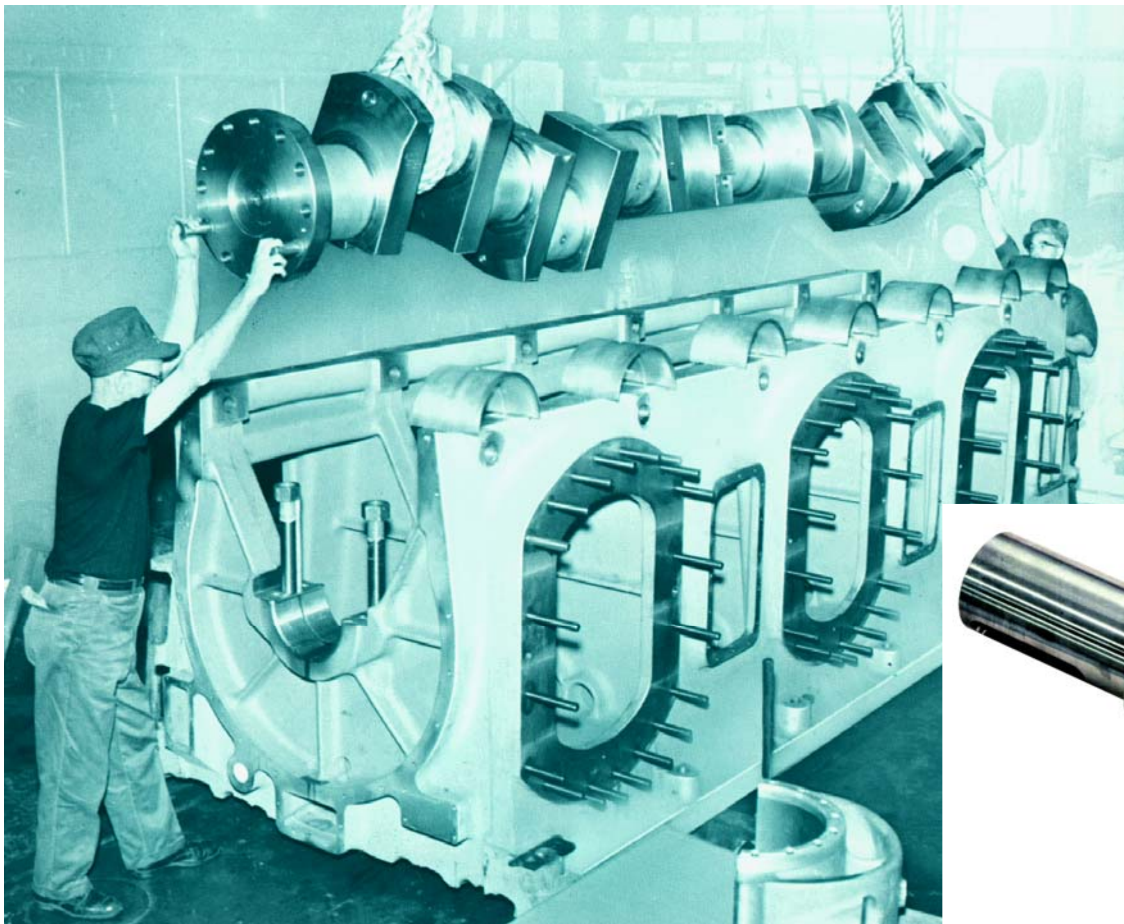


Crank mechanism - components



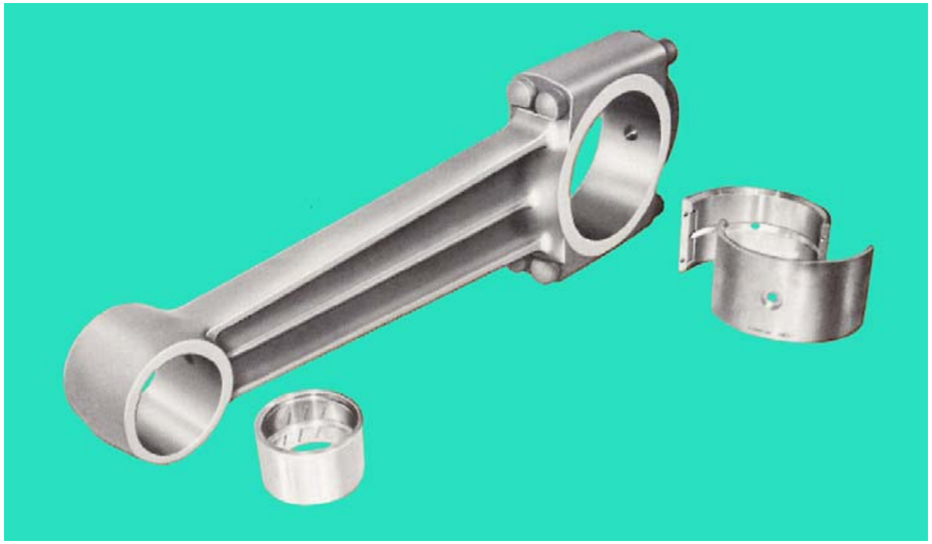
Crank mechanism – crankshaft, crankcase

- **The crankcase houses the crankshaft and forms the bearing structure to the base frame or foundation.**



Crank mechanism - connecting rod

- **Connecting rods convert the rotary motion of the crankshaft into the reciprocating motion of the piston**
  - the “upper” (piston end) connecting rod eyes are usually closed, the “lower” ones usually split (except on overhung cranks or assembled shafts)
- **Materials:**
  - forged steel, nodular graphite cast iron, cast steel. In special designs may be fabricated from sheet steel or aluminium.

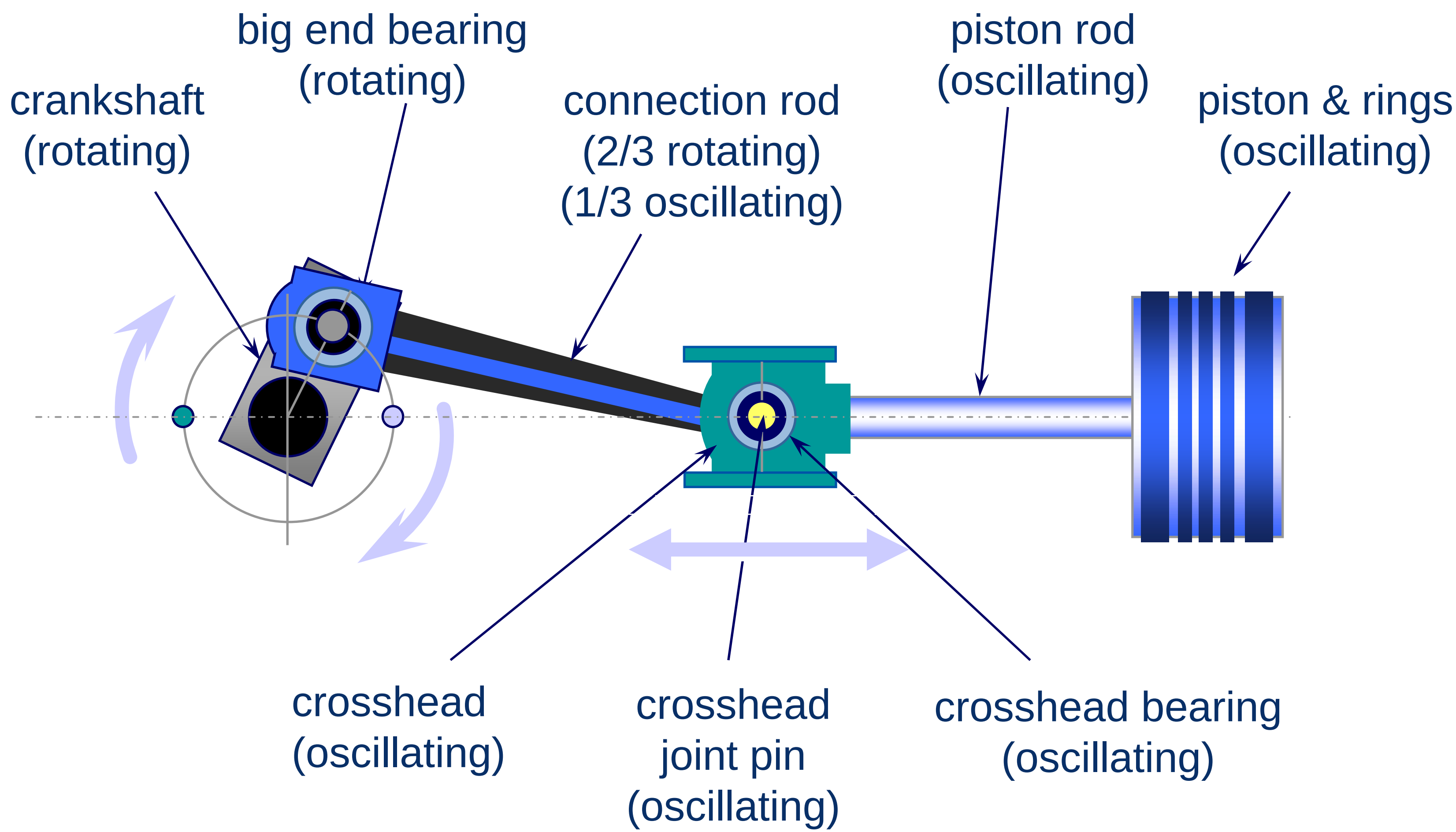


Crank mechanism – crosshead, crosshead pin

- **Crossheads accommodate the piston rod and form an articulated joint with the connecting rod by means of the crosshead joint pin.**
  - the crosshead runs in the slide ways of the crankcase or in its own crosshead slide ways
  - the running surfaces are usually cast iron shells babbitted with white metal, screwed on to the crosshead
- **Materials:**
  - crosshead housing made of cast iron,
  - crosshead joint pin made of hardened steel.

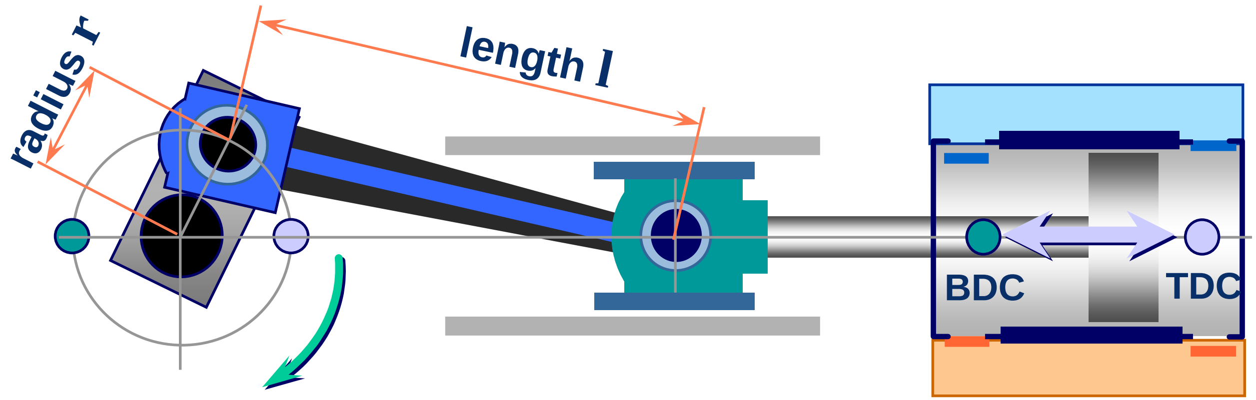
crosshead joint pin

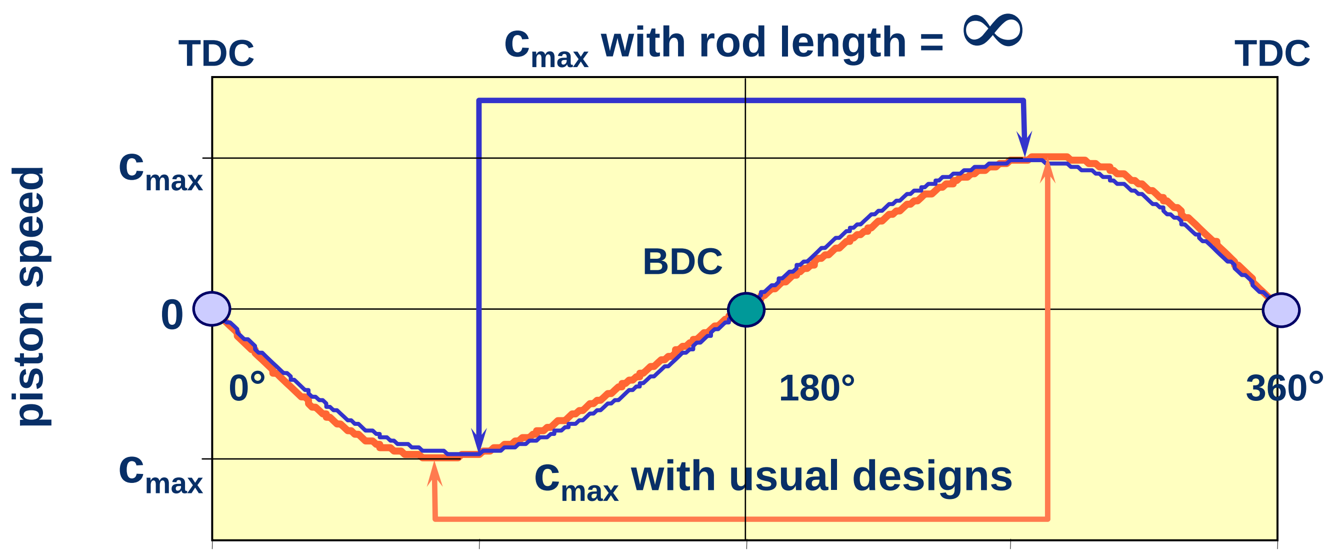
Rotating and oscillating components



Crank mechanism - kinematics: rod ratio λ

$$\lambda = \frac{r}{l}$$

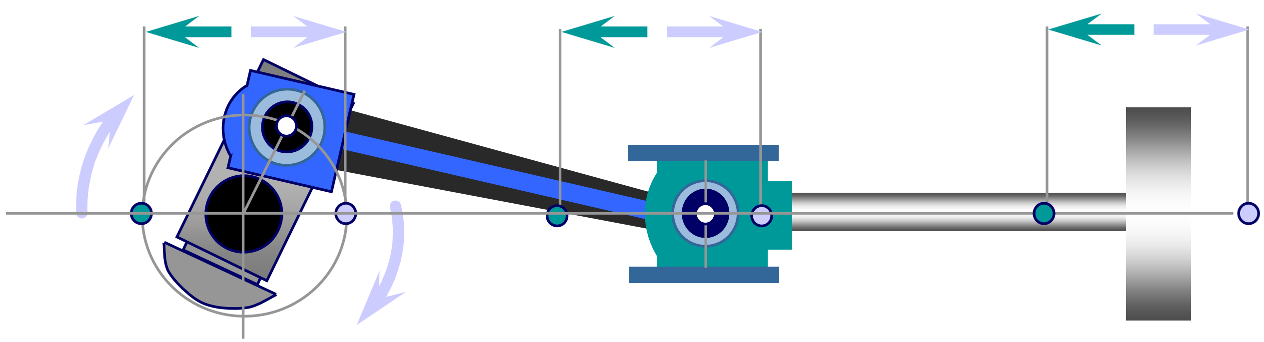




The rod ratio (usually 0,2...0,25) must be taken into account in the design of valves and capacity control systems

Crank mechanism - components, masses, forces

- **Oscillating mass forces and mass moments of inertia**
  - are generated by the acceleration and de-acceleration of the reciprocating masses of the crank mechanism
  - they generate inertia forces in the stroke direction and forces of inertia around the drive's centre of gravity
  - partly avoided by suitable cylinder arrangements or compensated by balancing shafts
- **Rotating masses**
  - centrifugal forces of the rotating parts are balanced by counter weights applied on the cheeks of the crank shaft

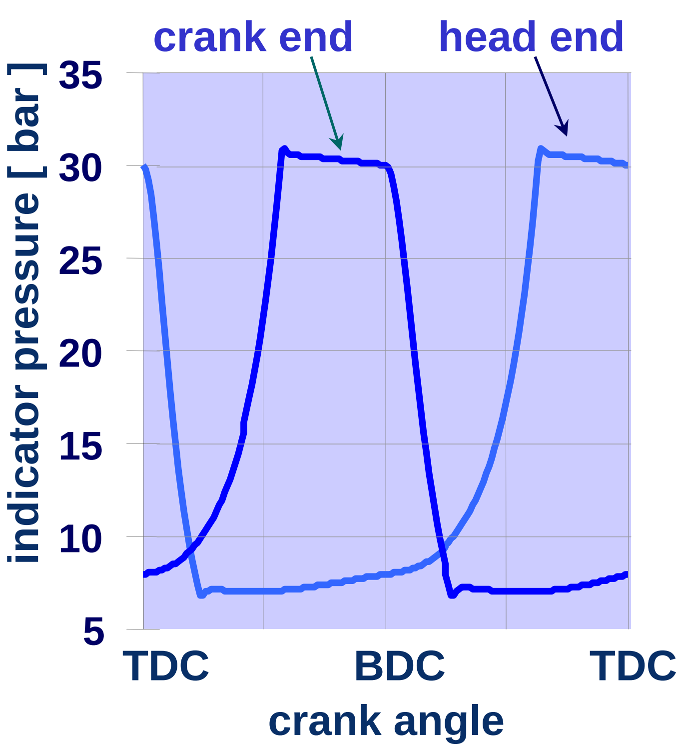


Crank mechanism - rod forces

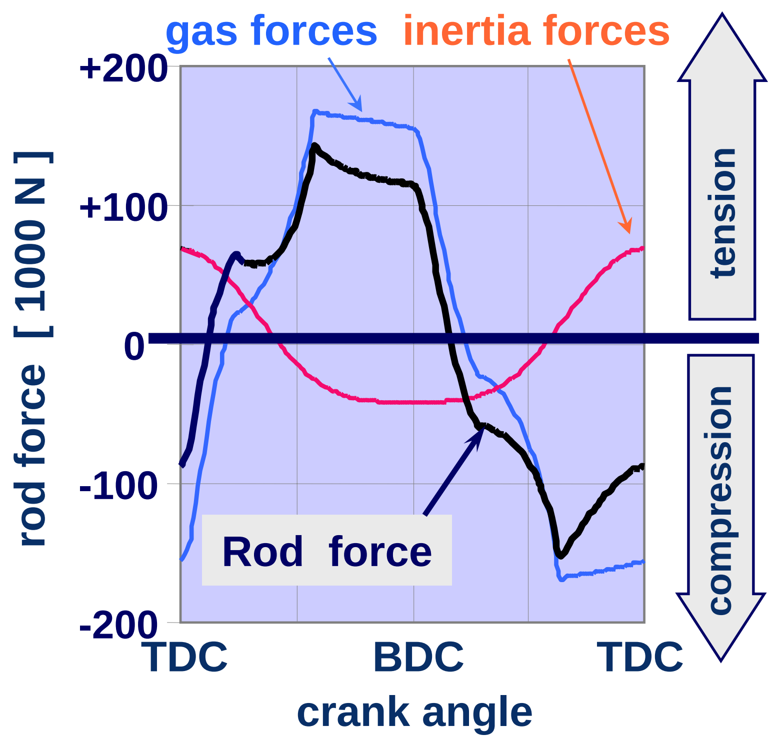
- **The gas acting on the piston and the moment of inertia generate forces which are transferred to the connecting rod via the crosshead and the joint pin**

⇨ **Rod force = gas force + inertia forces**

indicator diagram



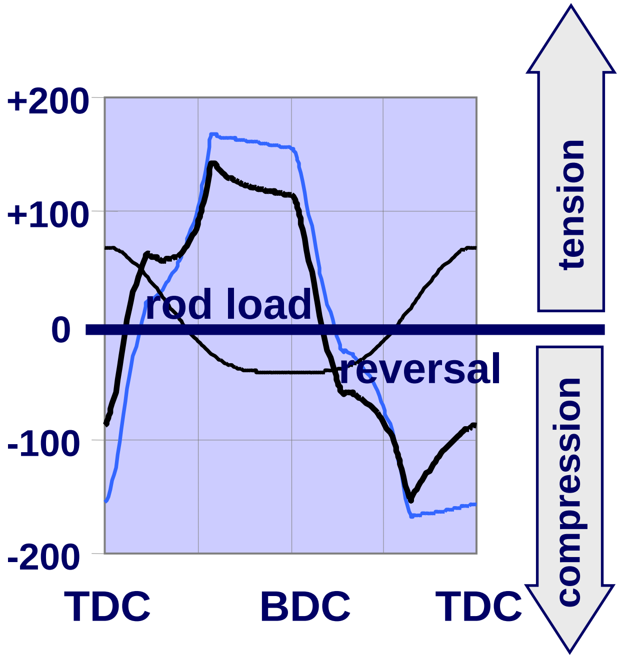
force diagram



Crank mechanism – 'rod load reversal'

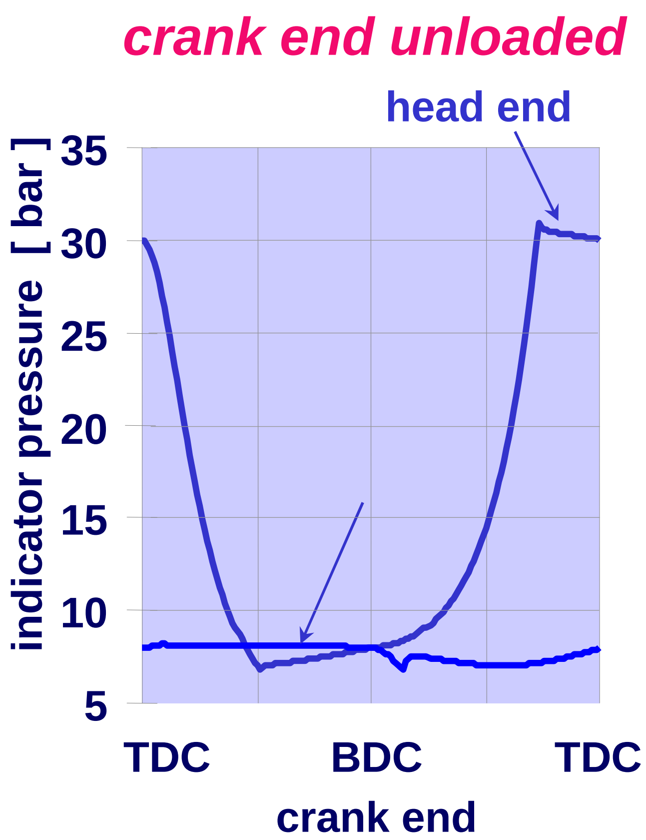
- **When designing the cylinder units the compressor manufacturer makes sure that load reversals take place.**
- **This load reversals ensure that the lubricating film at the crosshead joint pin is maintained. Loss of load reversals can cause damage to pin and bearing as well as further consequential damage.**

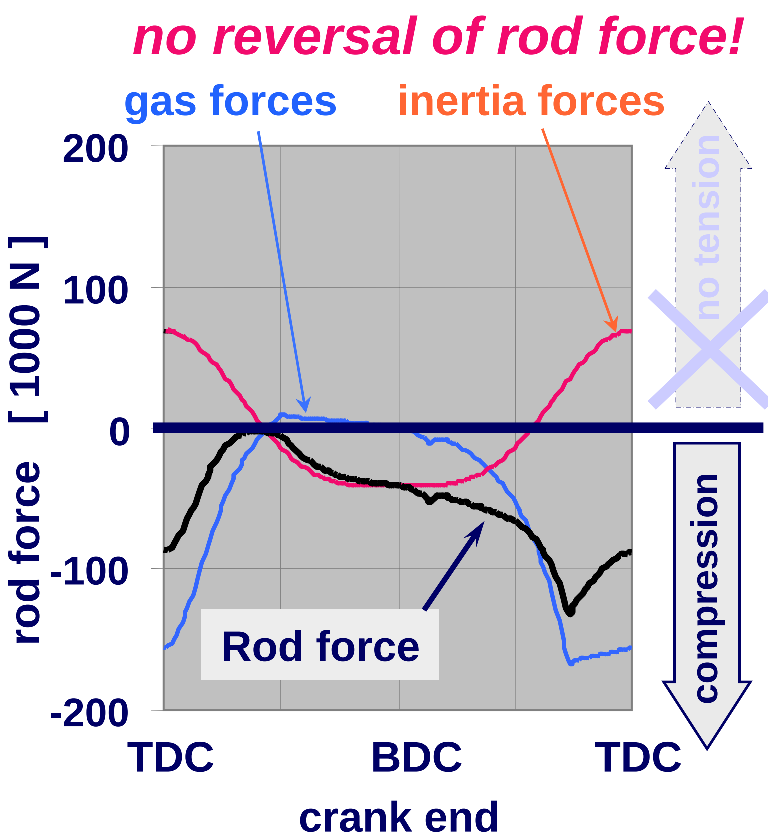
- **As a valve supplier we must take this into account:**
  - Changes in load conditions due to retrofitting of capacity control systems or high valve leakage can lead to loss of rod load reversals.



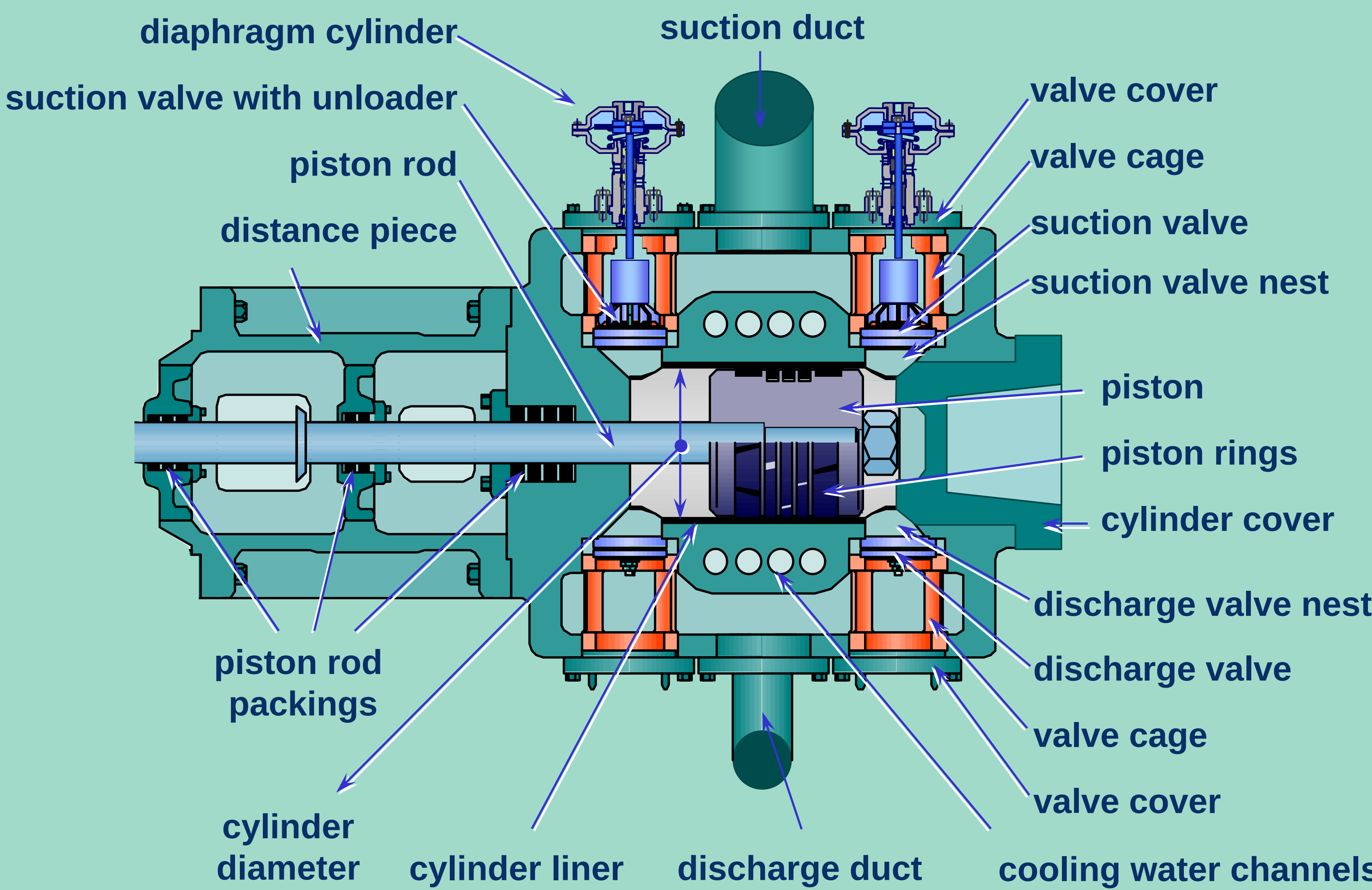
Crank mechanism – 'rod load reversal'

- The rod is only under compression load, when one cylinder is unloaded. There is no tension load and thus no rod load reversal.
  - Lubrication of the connecting pin is not guaranteed !





Cylinder - assembly



Valve types for Recips

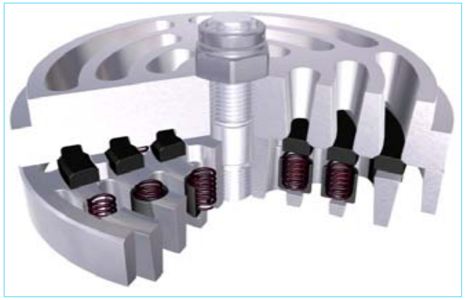
- **Closing Elements**

  Plates - rings - stripes - reeds - poppets - cones - balls ....

  traditionally made of steel, today increasingly of fibre-reinforced plastics.

Closing elements of HOERBIGER Valves are:

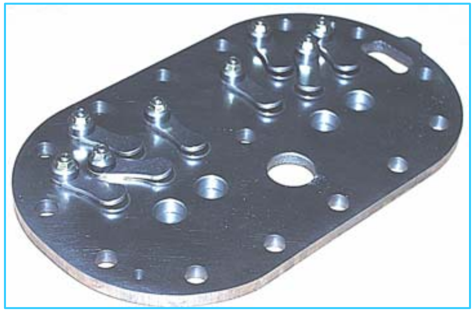
steel plates



profiled plastic rings

plastic plates

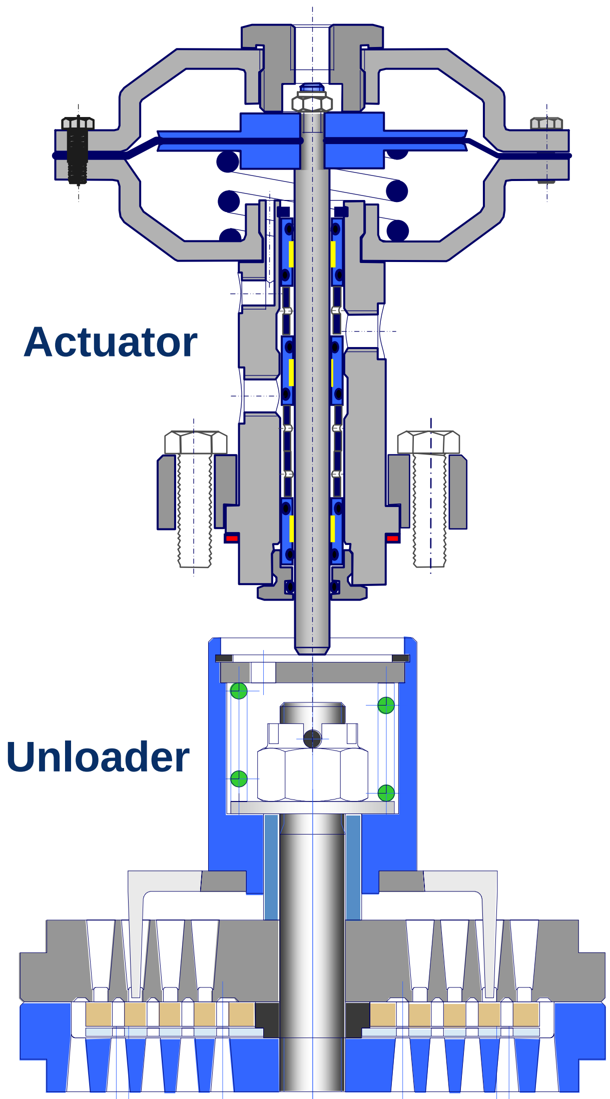
poppets



reeds

flapper plates

Suction valve and discharge valve

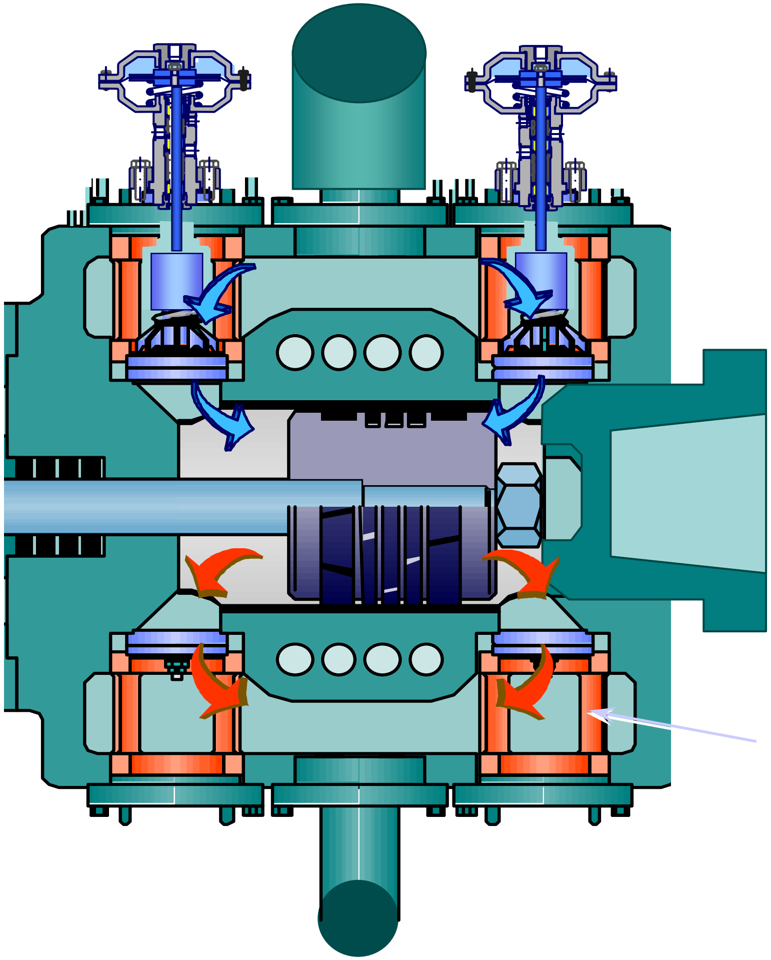


suction Valve

discharge Valve
exploded view

Installation in the valve nest

- **Requirements in Cylinder Design:**

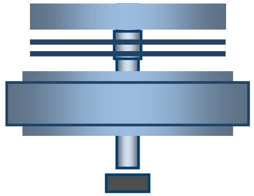


- **easy valve installation and removal**
- **low pressure losses in valves and valve pockets**
- **small clearance volumes**

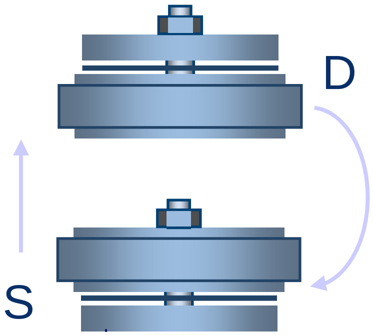
- **the valve cage or the jack bolt arrangement must have adequately sized openings for the gas flow.**

Correct installation in valve nests

1. **Correct valve assembly**

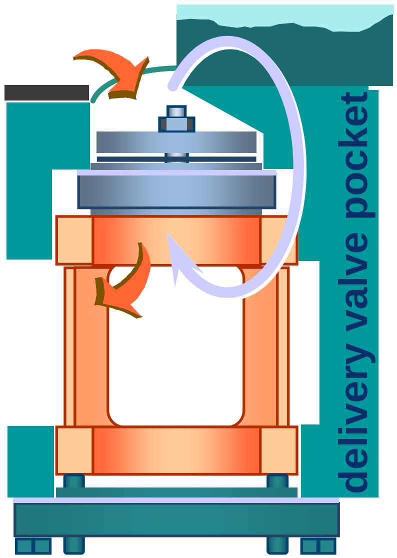


2. **Don't mix up suction valves with delivery valves.**

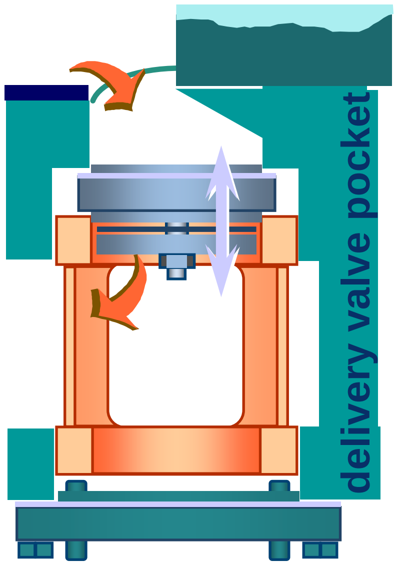


(API 618 describes valve designs which are impossible to mix up).

3. **Correct positioning of valve in valve nest**

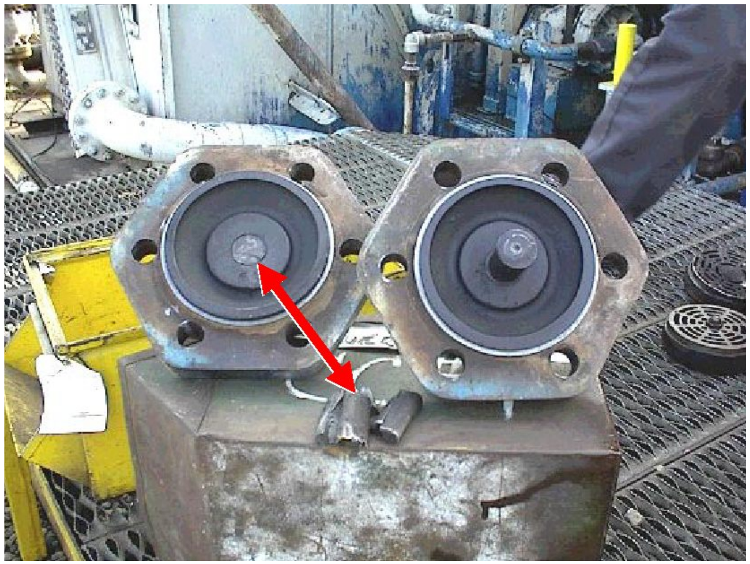


4. **Valve firmly seated in valve nest: Danger of breaking valve seat if valve can move about.**



Incorrect installation

- **Jackbolt failure and consequential damage**



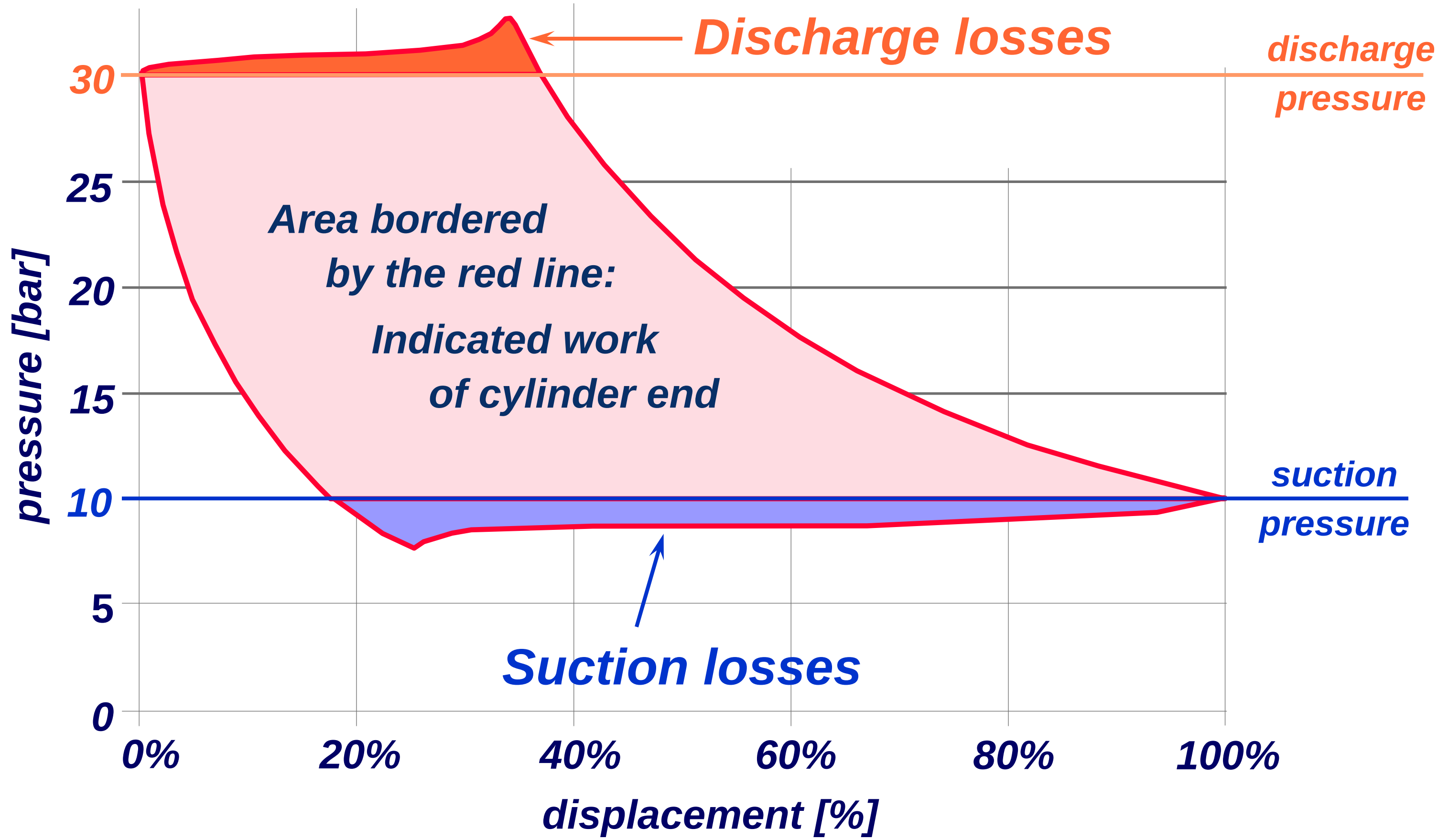
Incorrect installation in the valve nest

- **Valve Installation - Causes of LOOSE VALVES**
  - Wrong assembly sequence of valve cage, cage clamping bolts (jacking bolts) and valve cover bolts
  - Correct sequence:
    1. tighten the valve cover bolts to the specified torque, with valve cage clamping bolts (jacking bolts) withdrawn
    2. tighten the valve cage clamping bolts to the specified torque
  - Missing or defective gaskets
  - Height of valves or valve cages too low after overhaul
- **Gas tightness in valve nest, if valves are installed without gaskets**
  - Adequate quality of sealing surfaces of valve and valve nest, grinding-in may be required
  - For this reason the contact surface of HOERBIGER valves are finished to N5 or N6 quality (HN150).

'Valve losses'

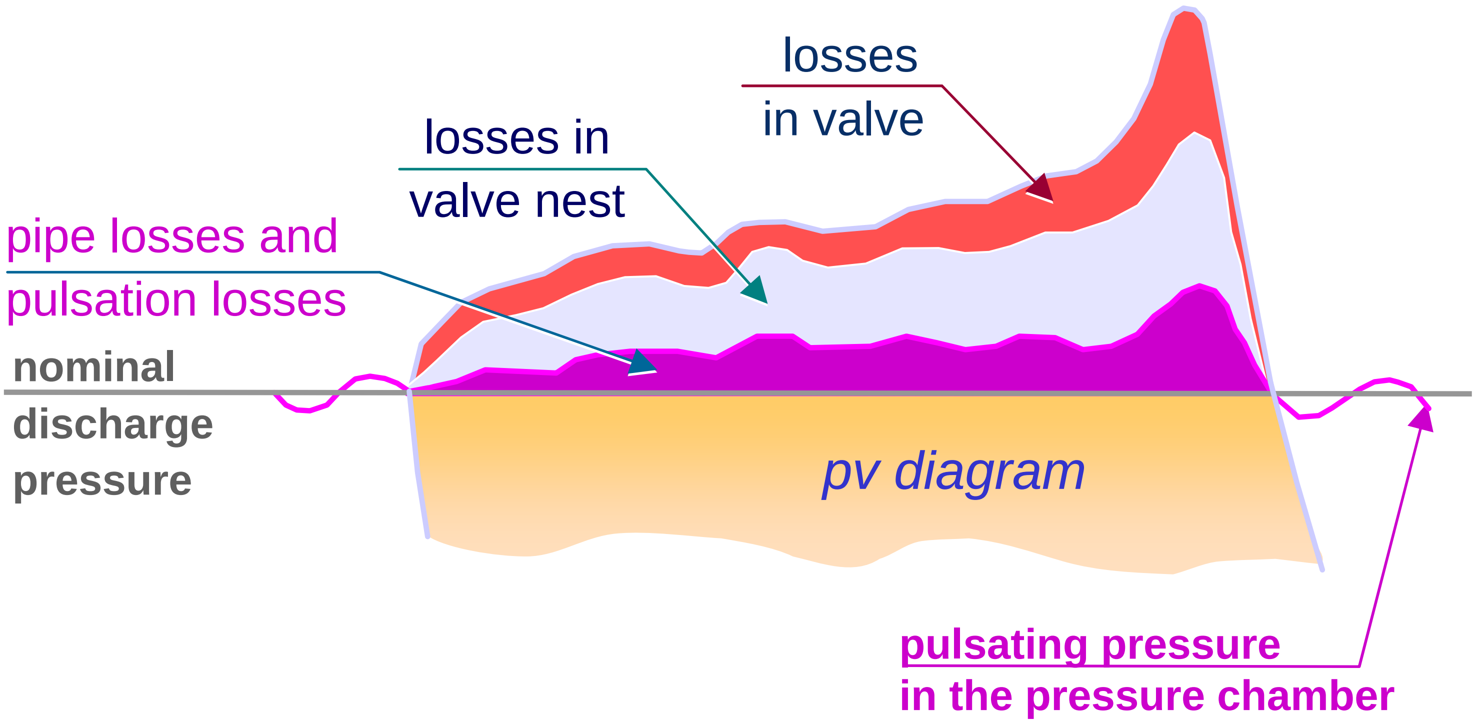
- **Total Gas Flow Losses in Indicator Diagram**

A certain percentage of the indicated power is lost due to:



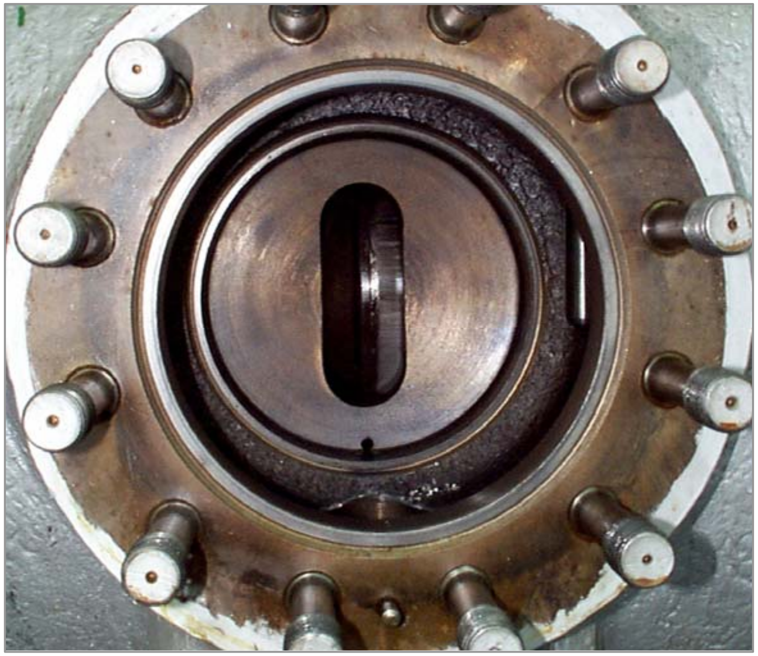
'Valve losses'

- **The areas exceeding nominal delivery pressure show the different losses at the delivery side.**



Shape of valve nest and 'valve losses'

- **The shape of the valve nest in the cylinder has a considerable influence on total gas flow losses. In the calculation of total flow losses with the help of the TKK, the valve nest shape can be taken into account with Pocket Factors.**

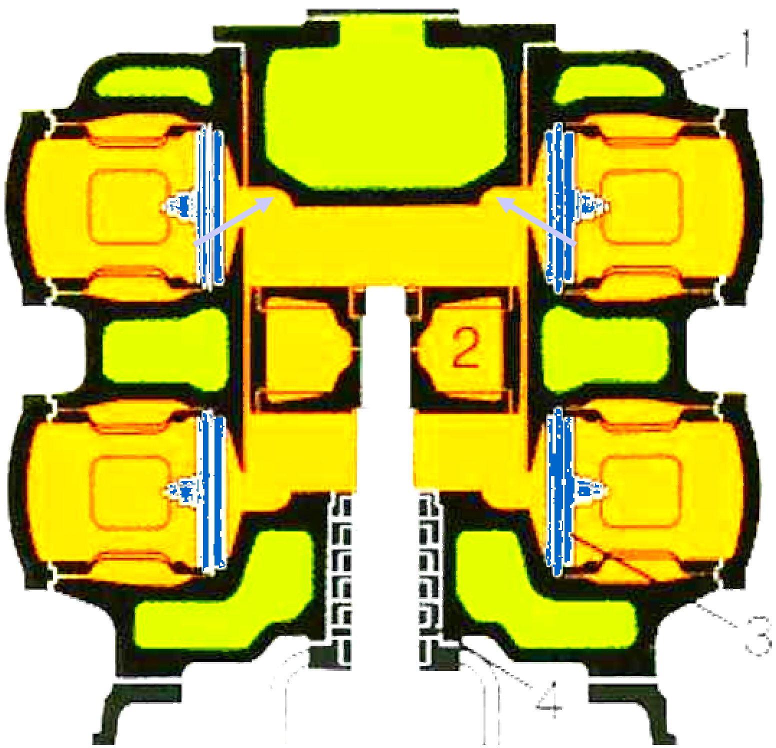


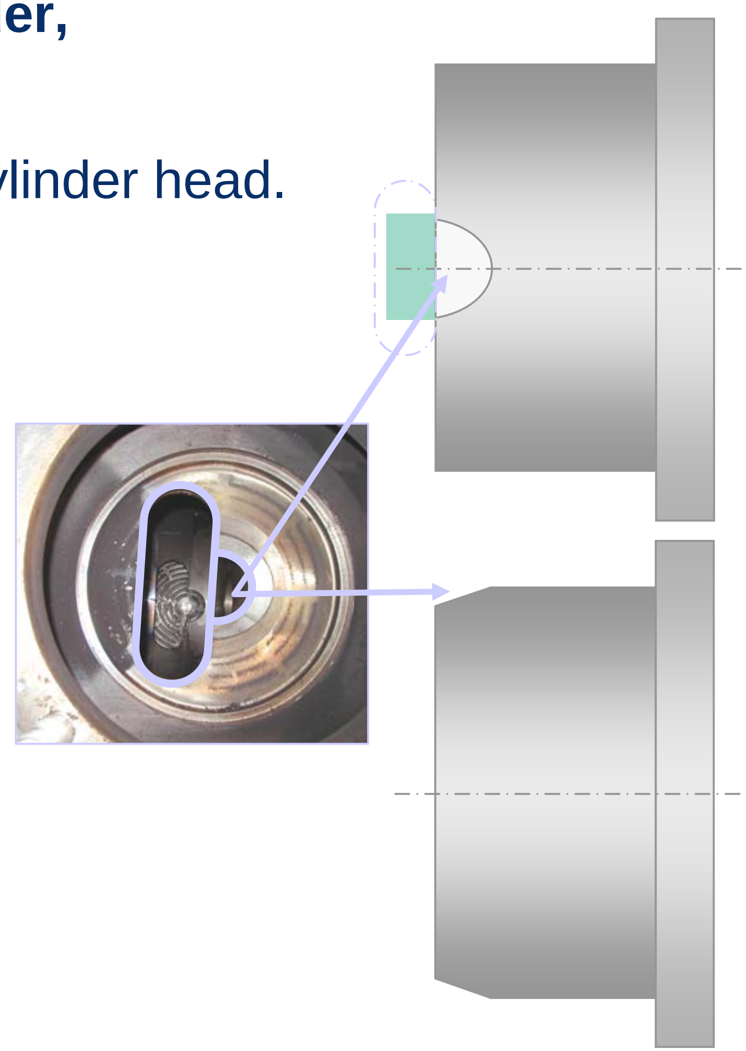
- **Two examples for considerable flow losses → high pocket factors.**

Common pocket shape and 'valve losses'

HOERBIGER

- **Low losses in the cylinder nests can be achieved by minimal restriction of gas flow into cylinder,**
  - by wide passage areas
  - by pockets or recesses in the cylinder head.





Shading of valve nest by cylinder head

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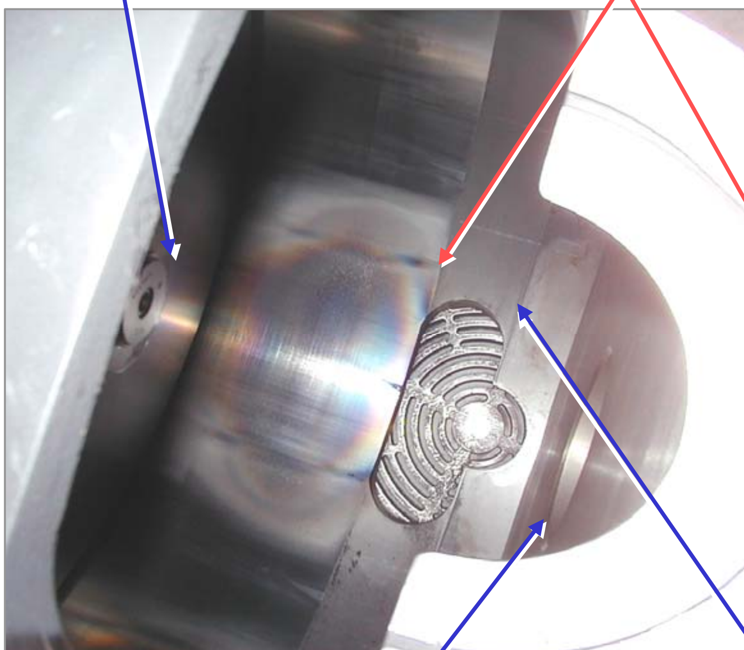
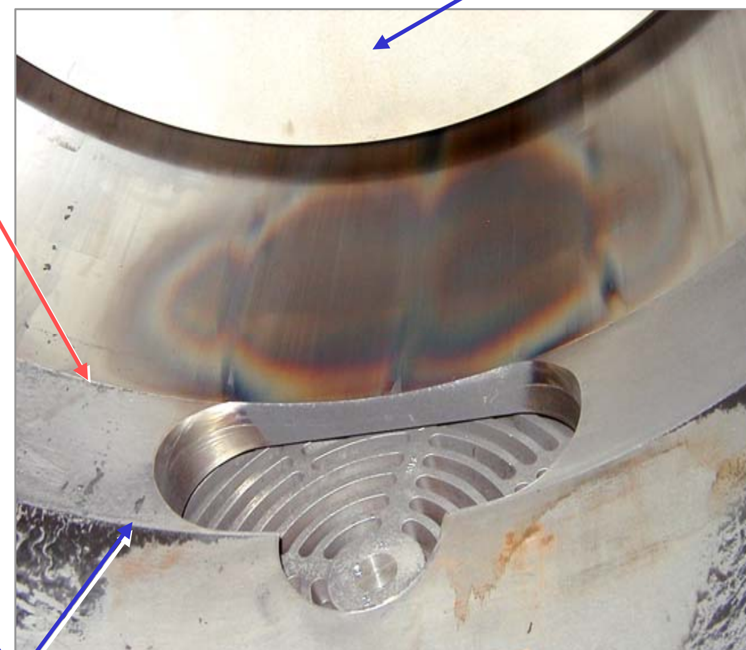
- **Narrow ports and gaps are restricting the gas flow too much.**

retracted piston

end of contact area
of piston rings

retracted piston

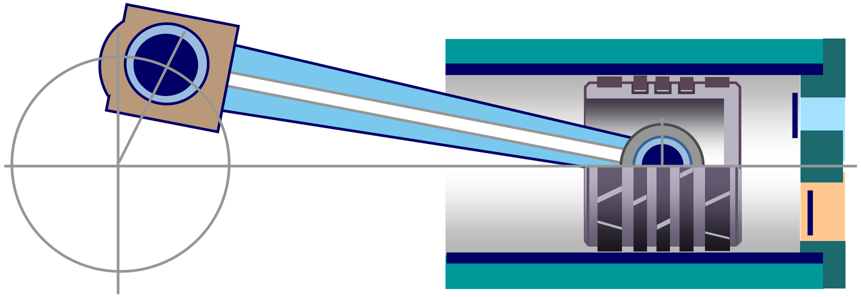


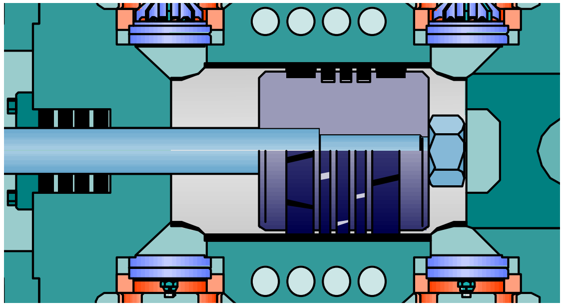


Cylinder head,
retracted

Cylinder head protrudes
until here into cylinder

Piston - types

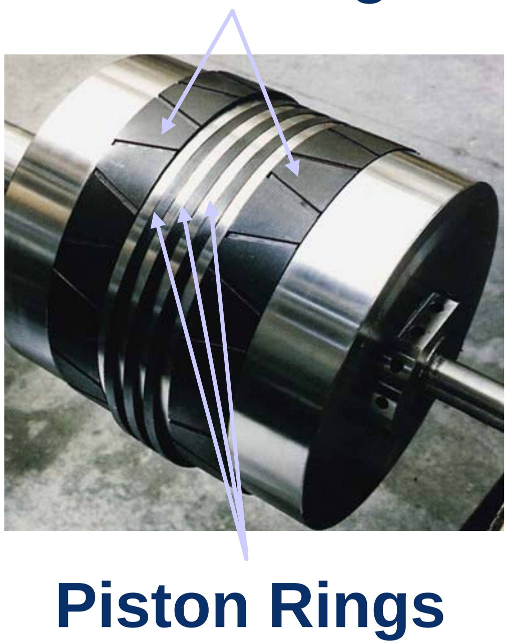


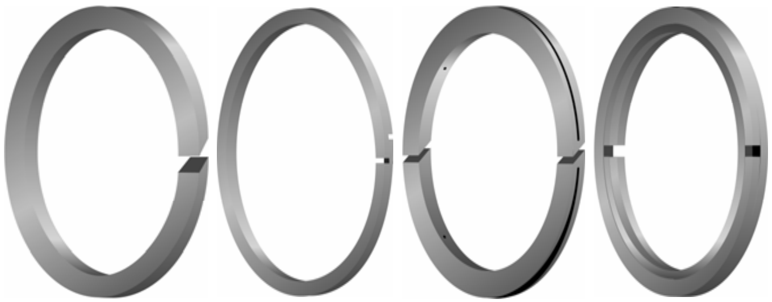


- **Types**
  - Plunger piston (single-acting)
  - Disk piston (double-acting)
  - Differential piston
  - Step piston
  - Tandem piston
- **Materials**
  - Cast iron, steel, and aluminium

Cylinder rings - types

Support the weight of the piston and half of the rod weight, but should not seal gas pressure.

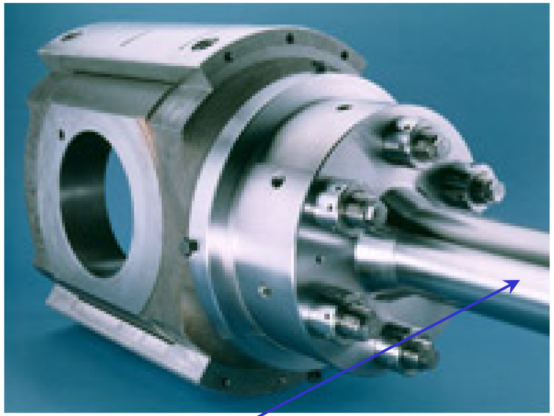




Seal the compression chamber between the piston and the liner.

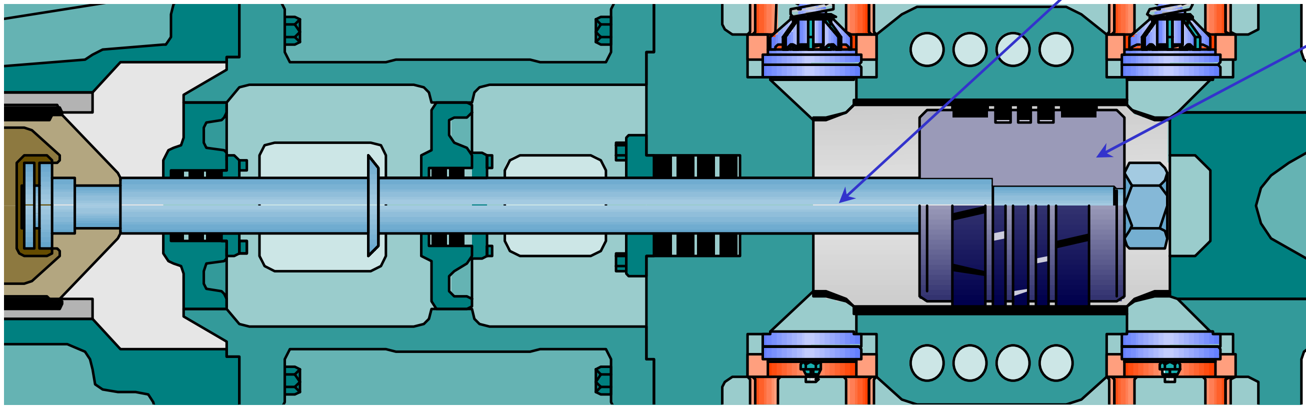
Piston rod - design

- **Double-Acting Compressor:**
  - The piston rod connects the piston to the crosshead and transmits the piston force. The packings and oil wipers slide on the hardened rod surfaces (e.g. tungsten carbide coating).
- **Materials:**
  - Case hardening and tempering steels.



piston rod

piston



'Tailrod' (not shown): If the piston rod extends through the cylinder head for additional guidance

Packings - types

Pressure Packing

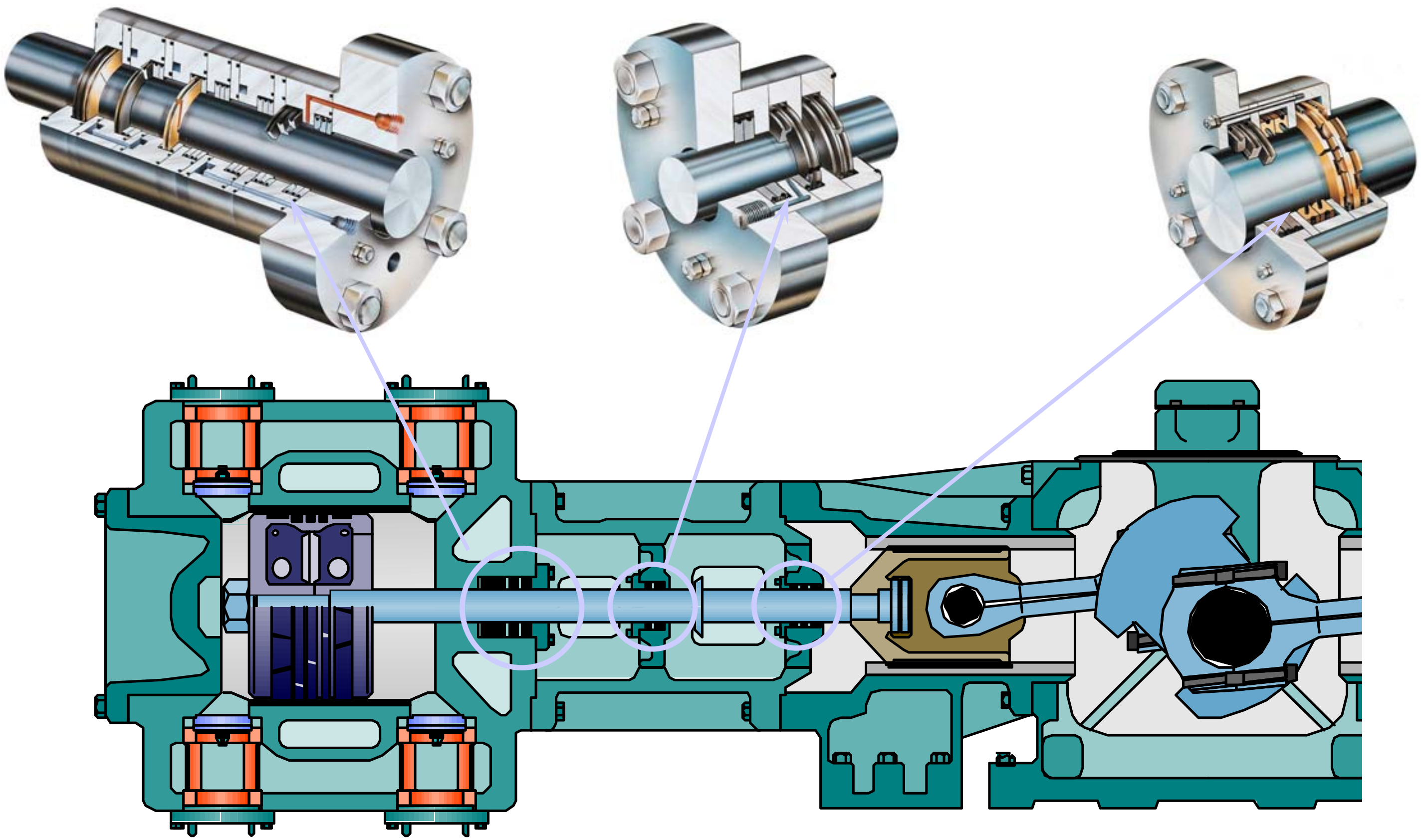
Seals the inboard compression chamber against the distance piece

Intermediate Packing

Seals the first distance piece against the second distance piece

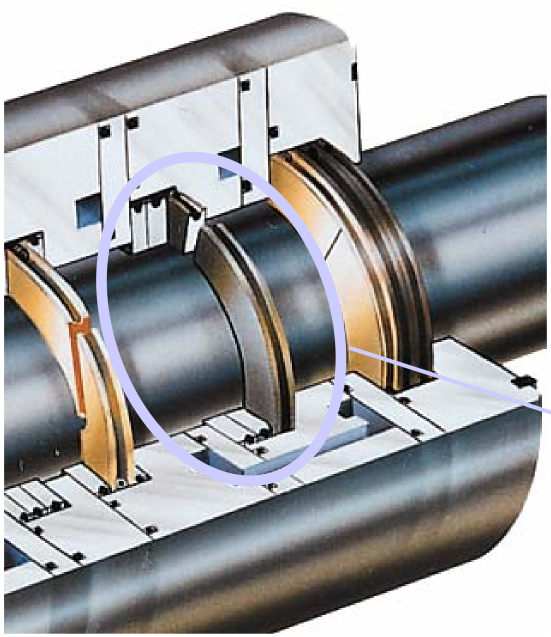
Oil Wiper Packing

Keeps off crank case oil from the distance piece

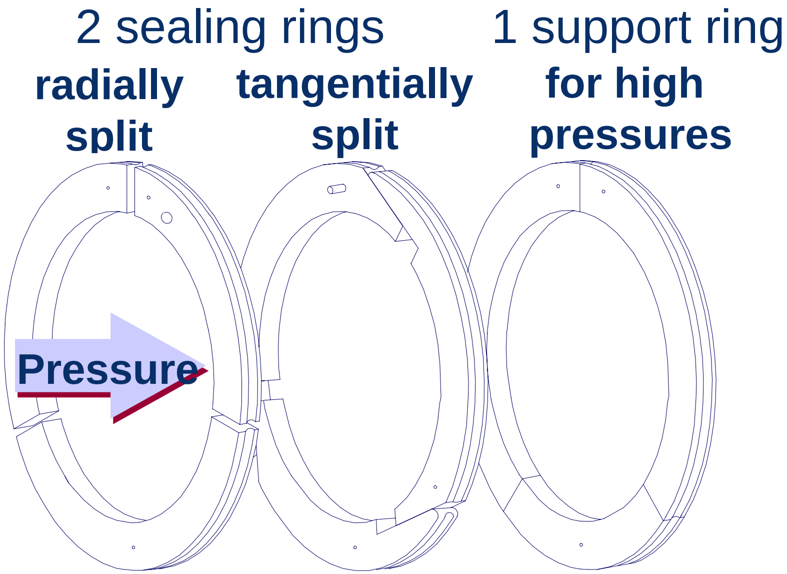


Packings - Pressure Packings Ring Sets

- **Pressure reduction is carried out in steps by a certain number of ring sets which depends on the height of the pressure difference. A gas tight packing system is created by combining various ring types.**
- **For ease of installation and to maintain sealing after wear (self-adjusting action) the rings are split. To seal the cuttings, at least two rings per set are used and positioned offset from each other, e.g.:**



Single-acting ring set

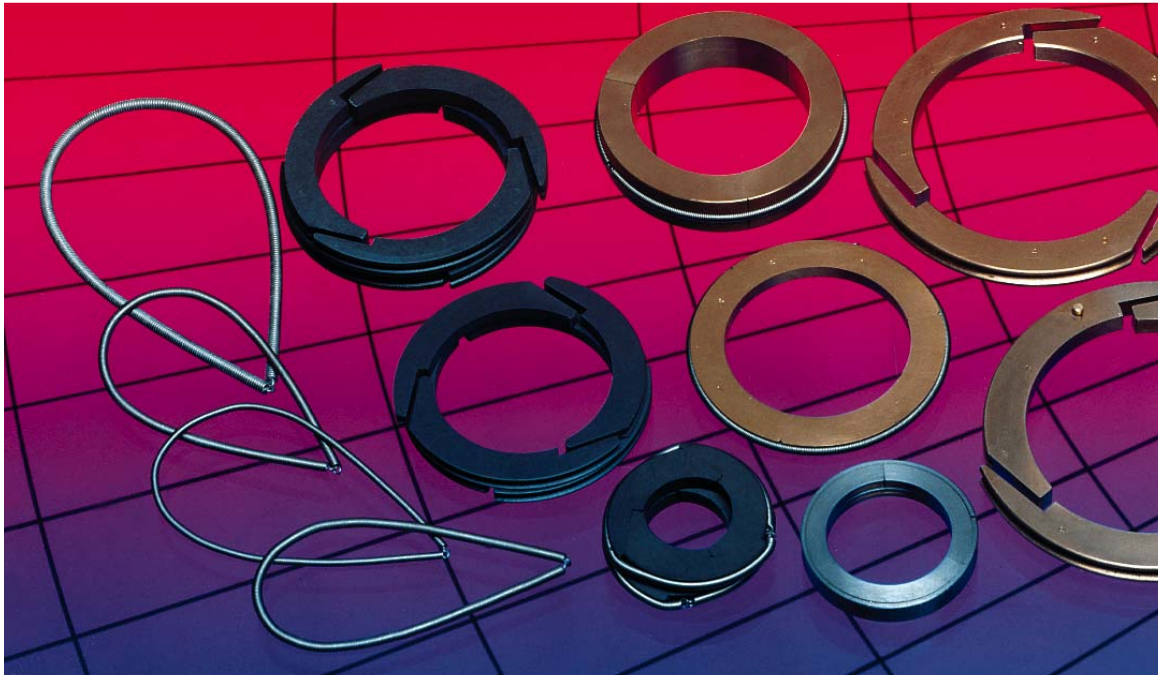


Packings - Components of Ring Sets

Annular springs
(assist assembly)

PTFE rings
with additives

Bronze-rings



Depending on the gas type and operating conditions, lubricated packings with metallic or PTFE rings as well as oil-free packings with PTFE rings are used. For higher compression pressures, oil-free packings must be cooled to extract friction heat.

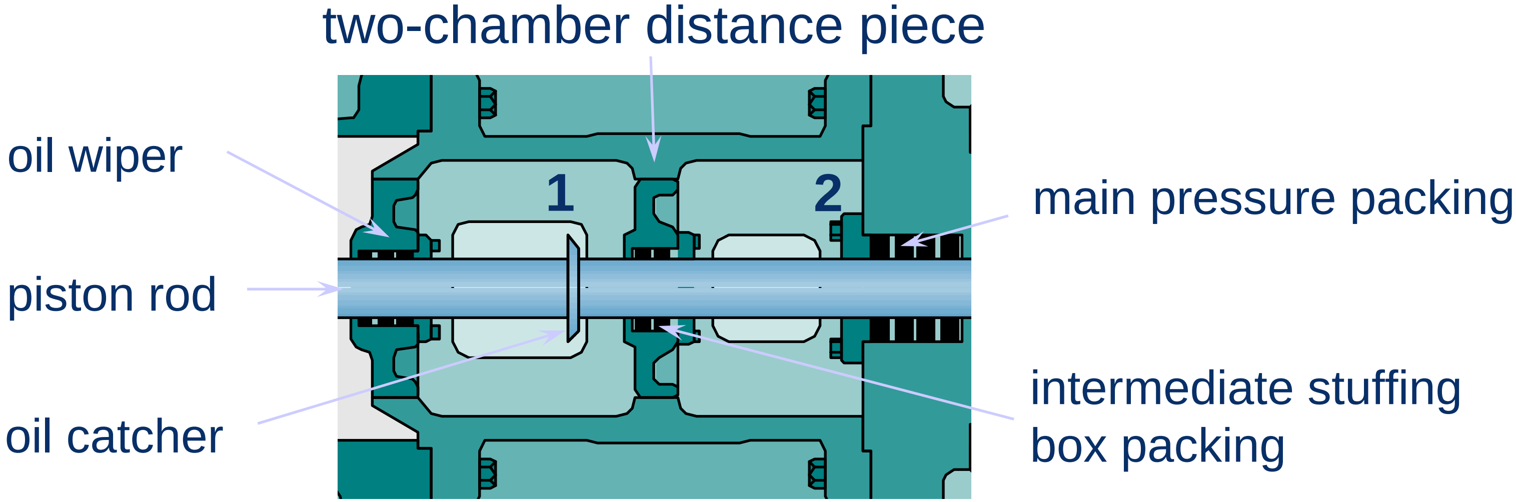
Liner - Designs

- **Cylinder liners are usually made of cast iron, to allow the piston rings to slide smoothly.**
- **Some liners however are made of steel or Ni-resist. The disadvantages of rather poor sliding characteristics and reduced heat dissipation have to be accepted.**

  - Dry liners are in direct contact with the cylinder wall
    - Problem: They tend to hinder cooling.
  - Wet liners have coolant circulating between liner and cylinder wall. These are used for smaller cylinder diameters
    - Problem: keeping the coolant out of the compression chamber.

Distance Piece - Function

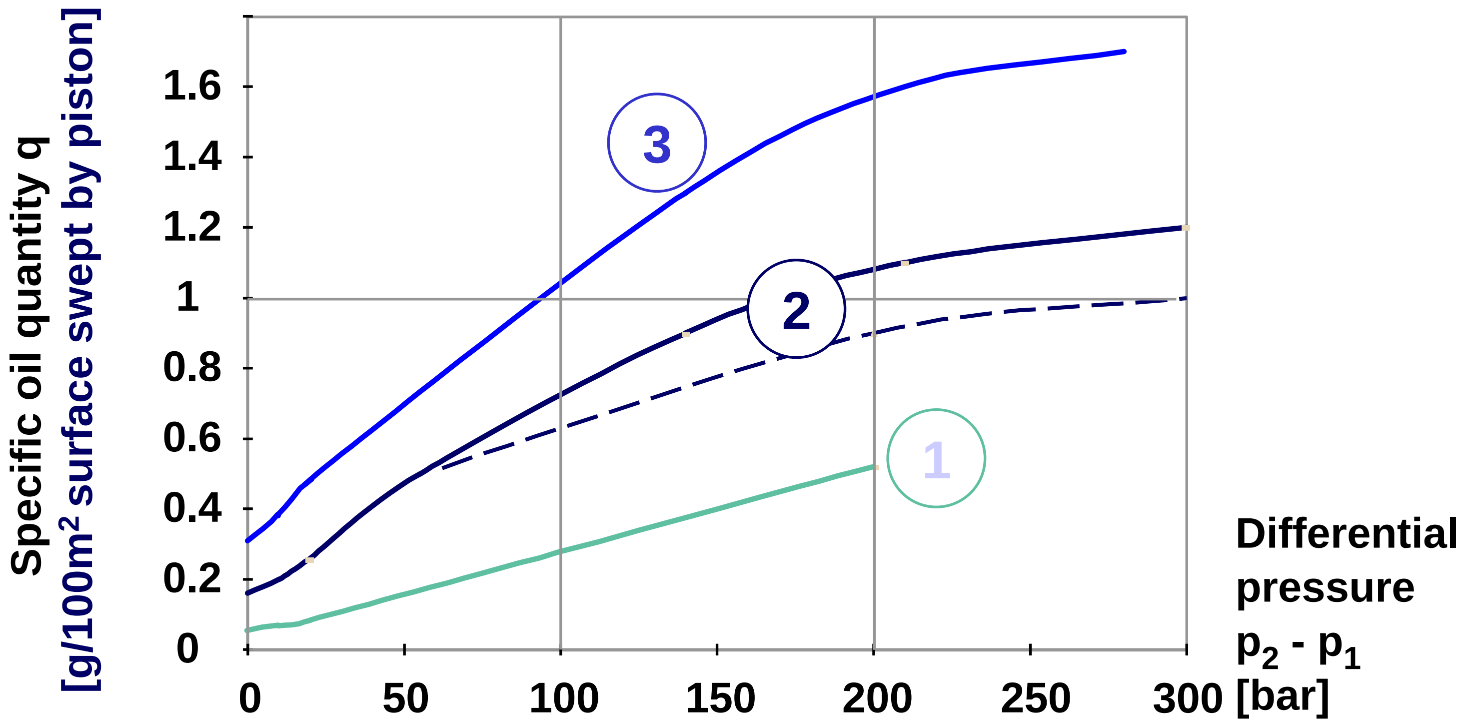
- **In oil-free compressors, the parts of the piston rod which are in contact with the medium must not come into contact with the lubricant of the crank mechanism**
- **A distance piece with two chambers and an intermediate packing between them is used achieve 100% separation**
  - In chamber 1, the piston rod bears an oil catcher.
  - In chamber 2, an inert gas buffer may be maintained to avoid any leakage of (poisonous) gas to the environment.



Lubrication - Cylinder Lubrication

- **It is important to have a sparing, metered oil supply!**
- **With excessive lubrication, the valves and pistons build up oil deposits, oil coke is formed with gases containing oxygen:**
  - The delivery valves clog up and wear.
  - The suction valve plates stick to the valve seats and guards. As a consequence they open and close too late and suffer from heavier impacts. The plates and springs break more often.

Cylinder Lubrication, Oil Quantity Estimation

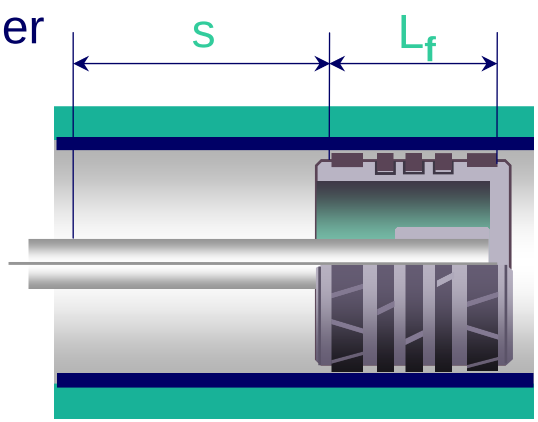


1. Mini lubrication for all gases: PTFE rings and stuffing boxes
2. Full lubrication for air, CO_2, H_2, CH_4, He, Ar, N_2, CO, pure gases: metallic rings, PTFE stuffing boxes.
3. Running-in for all gases, full lubrication for NH_3, C_2, H_4, H_6, C_3, C_4, C_5, C_6 parts, impure gases: metallic sealing elements

Oil Consumption in Cylinder Lubrication

Calculation of oil consumption per cylinder:

$$Q = q \cdot D \cdot (s + L_f) \cdot n \cdot \frac{2\pi}{100} \cdot 60 \cdot 24$$



Q ... Oil quantity in g per 24 hours per cylinder

q ... Specific oil quantity from diagram [g/100m² surface swept by piston]

D ... cylinder diameter [m]

s ... stroke [m]

n ... rpm

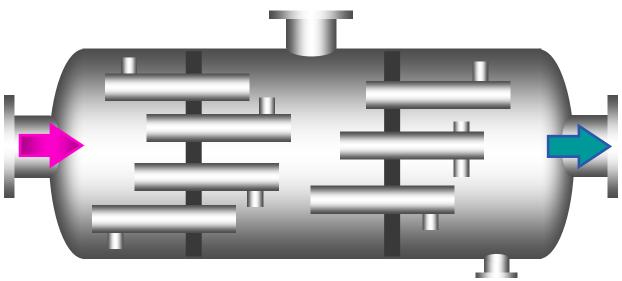
L_f ... length of piston [m] which is equipped with piston and rider rings (approx. 0.8 x s)

Please note:

- Calculation methods of compressor manufacturers differ
- The cylinder lubrication is often measured in droplets per minute (8000 droplets ~ 0.5 litre ~ 0.4 kg)

Peripheral Equipment - Pulsation Dampers

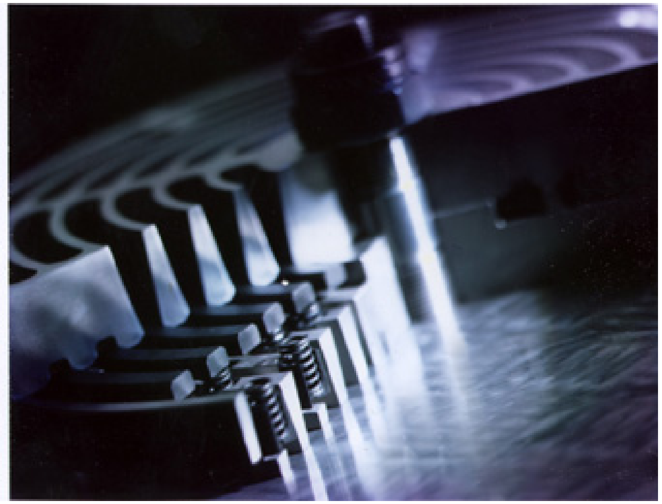
- Pulsation dampers ("buffers") are part of the gas lines. Mostly they are cylindrical pressure vessels, sometimes with internals. They are usually installed immediately before and after the cylinders to reduce gas pulsations in the lines.
- The amplitudes of gas pulsations are limited by various regulations (e.g. API 618). Pressure fluctuations can be calculated by means of computer simulation and design measures can be taken to dampen them.



Low pressure "buffer"
with internals
to dampen strong
pressure pulsations

Gas compressors - process gas compressor

Combined gas engine / compressor
with manual clearance pocket capacity control (USA)



Reciprocating Compressors

End of the Training File

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