EFRC Training Workshop

Design and operation of reciprocating compressors

Compressor Design and Construction

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Types of Compressors

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Aircooled
Watercooled
Lubricated
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Roots
Liquid Ring</td><td>Single Stage
Multi Stage
Integral Gear</td><td>Multi Stage</td></tr>
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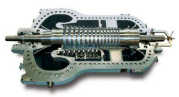


Positive Displacement vs. Dynamic type

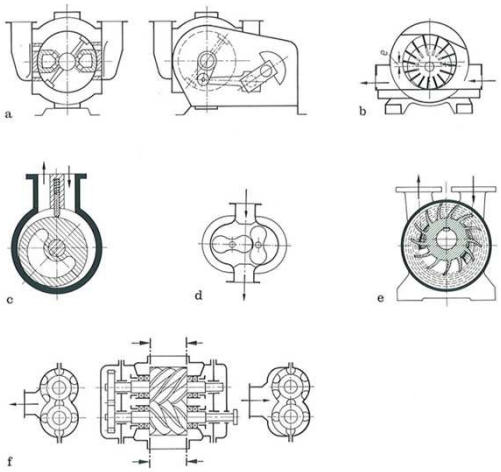
Positive displacement compressors work by filling a gas chamber and increase the pressure by reducing the chamber's volume.

Dynamic type compressors use very high speed spinning impellers (up to 60,000 rpm) to accelerate the gas and then diffusers to decelerate the gas. This process uses velocity to cause an increase in pressure.

Positive Displacement Compressors - Rotary

Different types of rotary positive displacement type compressors:

a - Wing-type
b - Sliding vane type
c - Rotating piston
d - Roots
e - Liquid-ring,
f - Screw-compressor (lubricated or non lube)



Reciprocating Compressors

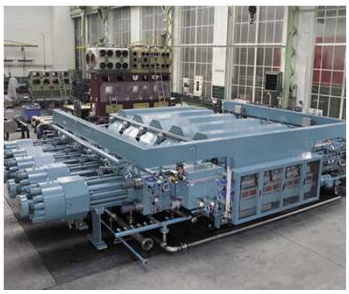
vertical

horizontal – balanced opposed

L – type

V – type

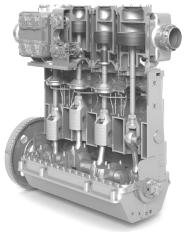
Reciprocating Compressors



Hyper - compressor

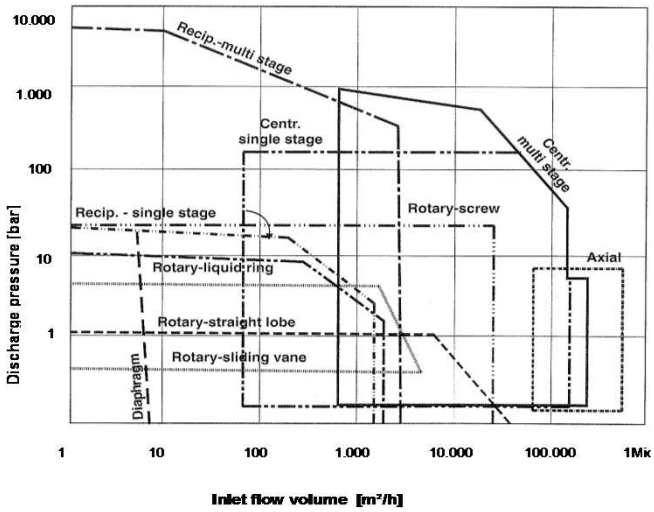
Diaphragm compressor

Labyrinth compressor



Aircooled W -compressor

Compressor Applications



Compression Principle and Gas Laws

Based on the laws of Gay-Lussac and Boyle-Mariotte, the thermo-dynamic parameters for ideal gases are linked by the equation:

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

p	pressure absolute [Pa]
V	volume [m³]
m	mass [kg]
v	spec. volume [m³/kg] (v=1/ρ ... density)
R	spec. gas constant [kJ/kgK]
T	temperature absolute [K]

For any isentropic or adiabatic (no heat transfer in the process) change of conditions the relation of pressure and volume is following the equation:

$$p \cdot v^{\kappa} = const$$

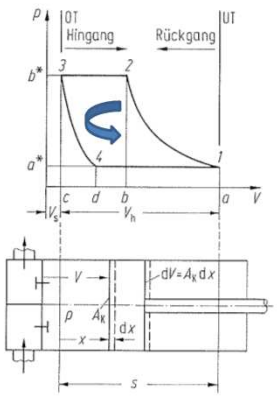
κ	isentropic exponent[1]
C_p	spec. heat at const. pressure [kJ/kgK]
C_v	spec. heat at const. volume [kJ/kgK]
$\kappa = C_p/C_v$	
1,2	index for thermodynamic conditions at point 1 (inlet) or point2 (outlet)

Transformed to calculate the discharge temperature:

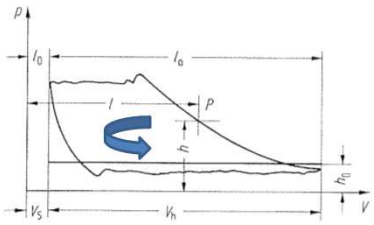
$$T_2 = T_1 \cdot \left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}}$$

Ideal and Real Compression

Ideal compression process



Real compression process



s	stroke [m]
V_h	cylinder volume [m³]
V_s	dead space (volume) [m³]
OT	top dead center TDC
UT	bottom dead center BDC

A detailed explanation will follow in lecture 3

Single versus Multistage Compression, necessary Compression Power

The equation $T_2 = T_1 \cdot \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}$ limits the pressure ratio in one stage as neither material nor gas may stand such a high discharge temperature value.

Practice shows, that reasonable maximal pressure ratios per stage are:

p_2/p_1 = **5** for polyatomic gases with κ = 1,3 (natural gas, CO_2 etc. …..)
p_2/p_1 = **4** for diatomic gases with κ = 1,4 (air, N_2, H_2, CO etc. …..)
p_2/p_1 = **3** for monoatomic gases κ = 1,67 (He, Ne, Xe, Ar etc. …..)

Another reason for using multistage compression is the consumption of power for driving the compressor. The isotherm compression process needs the lowest required power for the drive. For saving the energy consumption of the compressor drive the outlet temperature has to be on a low base.

Isotherm and Adiabatic compression

An **isotherm power** is based on the theory that the process of compression is done with an optimized cooling system, that means that the temperature rise during the compression is zero.

$$P_{eff} = \frac{P_{isotherm}}{\eta_{isotherm} \cdot \eta_{mech}} \qquad \eta_{isotherm} \cdot \eta_{mech} \approx 0{,}55$$

The **adiabatic power** is based on the theory that the process of compression is done without any change of thermal energy during the process. In reality, the practical process is very close to the adiabatic.

$$P_{eff} = \frac{P_{adiabat}}{\eta_{adiabat} \cdot \eta_{mech}} \qquad \eta_{adiabatic} \cdot \eta_{mech} \approx 0{,}65 \text{ for all gases}$$

Efficiency and Power

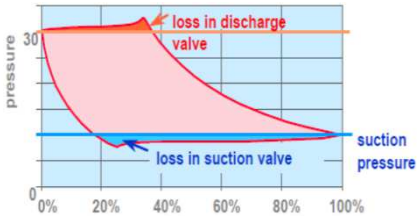
Each technical and particular each thermodynamic process has losses of energy. The measurement of the power on a 6-stage compressor shows what happens with the power which is fed in the main drive. The following compressor part descriptions will include indications of power losses.

isotherm compression power	55	%	← power input
loss for adiabatic compression	10	%	
flow loss in compressor valves	5	%	
flow loss in cylinders	5	%	
flow loss in pipes and apparatus	10	%	
loss because of leakages	1	%	
loss because of temperature rise	7	%	
friction in bearings, cylinders etc.	7	%	
∑ input shaft power	**100**	**%**	
loss of radiant heat + oil cooler	10	%	power output →
in compressed gas contained energy	3	%	
heatdissipation by cylinder cooling	7	%	
heatdissipation 1-stage cooler	19	%	
heatdissipation 2-stage cooler	17	%	
heatdissipation 3-stage cooler	14	%	
heatdissipation 4-stage cooler	12	%	
heatdissipation 5-stage cooler	10	%	
heatdissipation 6-stage cooler	8	%	
∑ dissipation of power	**100**	**%**	

Losses in Compression

Efficiency and necessary power for compression is a very critical matter and very often depending on details in cylinder design.

Following losses have to be evaluated:



- flow loss in compressor valves – size, Cv, flow restrictions, etc.
- flow loss in cylinders – clearance volume areas (volume of compressed gas at discharge pressure that remains in the cylinder - deadspace), flow losses in valves channels, pockets in cylinder design as additional clearance volume, etc.
- flow loss in pipes and apparatus – mainly gas pipe interface points on the cylinder
- loss because of leakages – critical in hydrogen rich services or helium
- loss because of temperature rise – in the nature of the compression
- friction in bearings, cylinders etc. – rider rings, piston rings, packing rings

Speed, Stroke, average Piston Speed

The average piston speed is defined as:

$$c_m = \frac{s \cdot n}{30} \qquad (16)$$

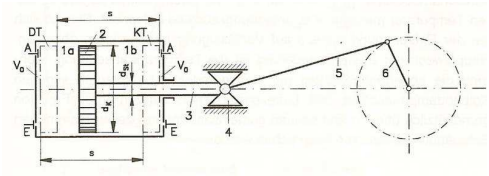
c_m ..... *average piston speed [m/sec]*

s ..... *stroke [m]*

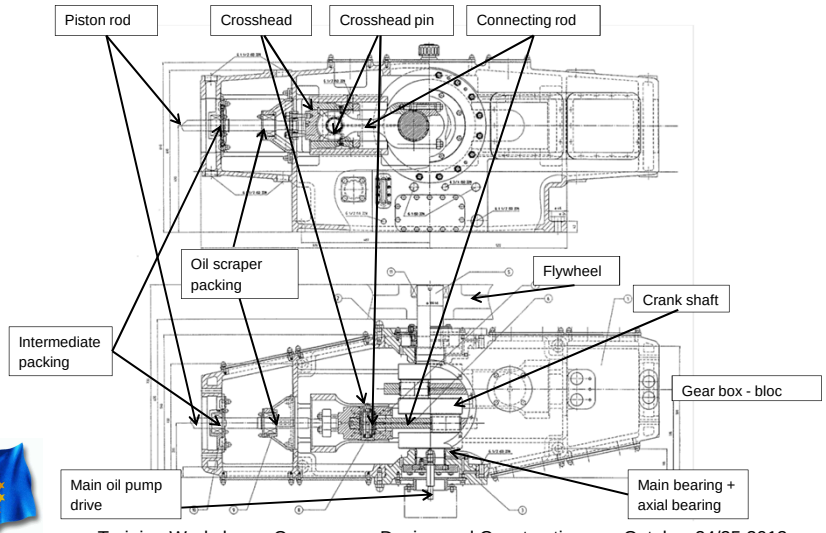
n ..... *compressor speed [rpm]*

Typically values for different compressors are:

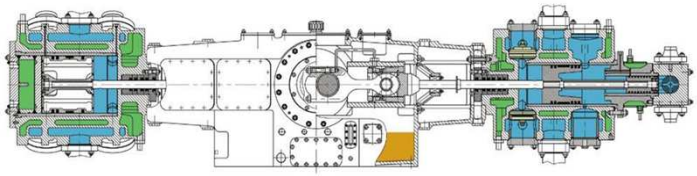
- **6 m/s for high speed compressors for all services**
- **4 m/s for API compressors lubricated for refineries & chemical plants**
- **3,4 m/s for API compressors non lube for refineries & chemical plants**



Parts of a balanced opposed Reciprocated Compressor



Balanced opposed reciprocating compressor according API618

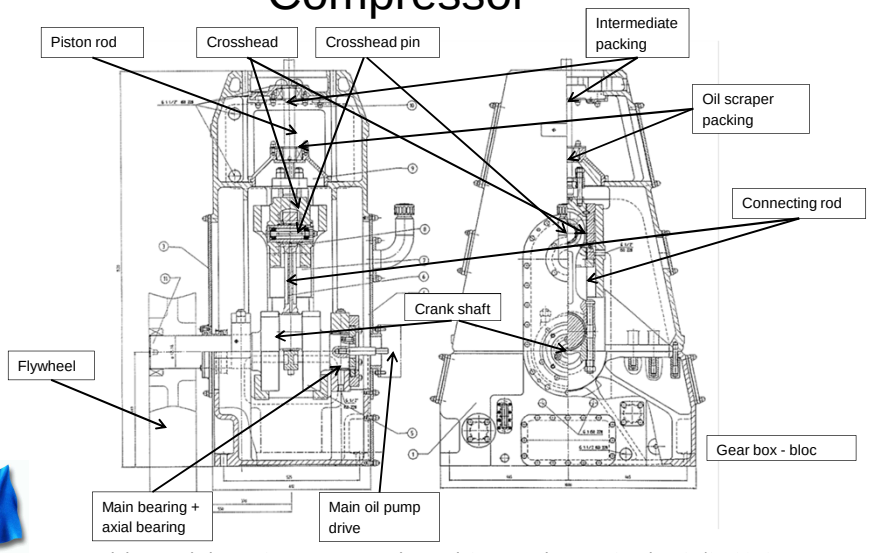


3-stage high pressure compressor with horizontal cylinder arrangement (balanced opposed), heavy duty design accordance to API 618 standard.

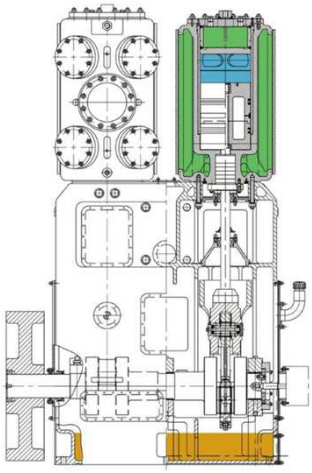
Lubricated 1.200 rpm for the smallest (100 kW) down to 250 rpm for the biggest (10 MW) sizes – with average piston speed $\mathbf{c_m}$ max. **4,0 m/s.** The advantage of lubricated cylinders is less wear in the piston- and rider-rings and in the cylinder packings.

Non lubricated operations are 1.000 rpm for small size down to 200 rpm for the biggest sizes with average piston speed $\mathbf{c_m}$ max. **3,5 m/s**. In the chemical and petrochemical industries, where the existence of a little content of oil is a problem for the chemical process, non lubricated cylinders are standard.

Parts of a vertical Reciprocated Compressor

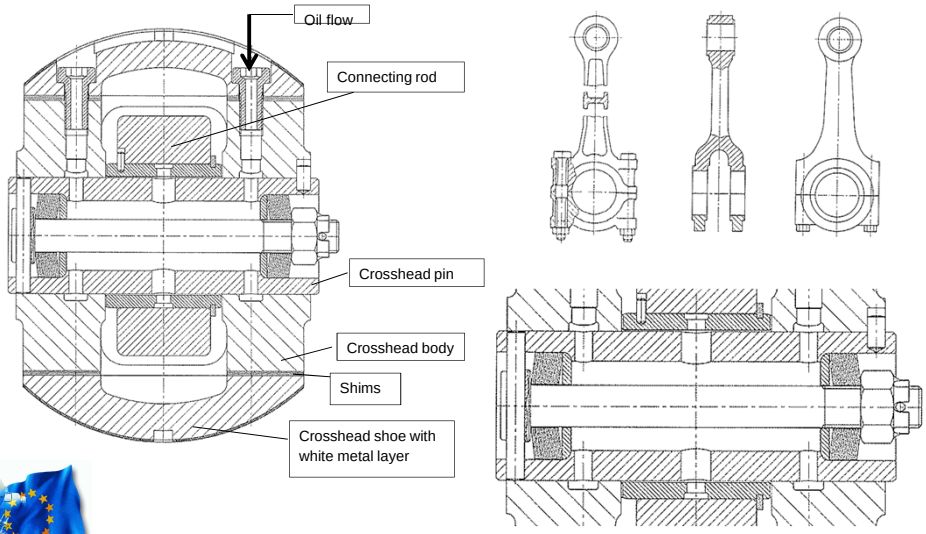


Vertical reciprocating compressor according API618



- Different mechanical design
- Basically the same parts and functions per rod compared to balanced opposed compressors
- Higher vibration levels (1 or 2 cylinders)
- Better compensation is necessary
- Less mechanical wear
- Especially for non lubricated operations and dry process gases vertical arranged compressors are common.
- Number of cylinders 1 to 4 and shaft power up to 1.000 kW.

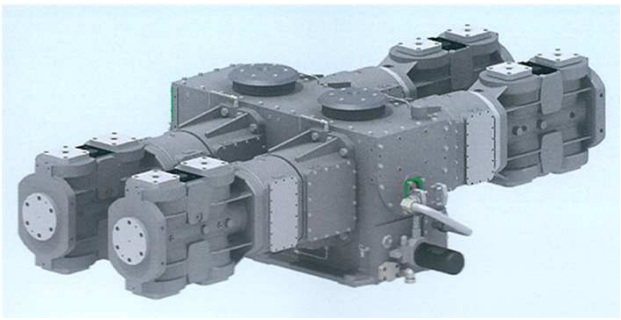
Crosshead and Connecting Rod



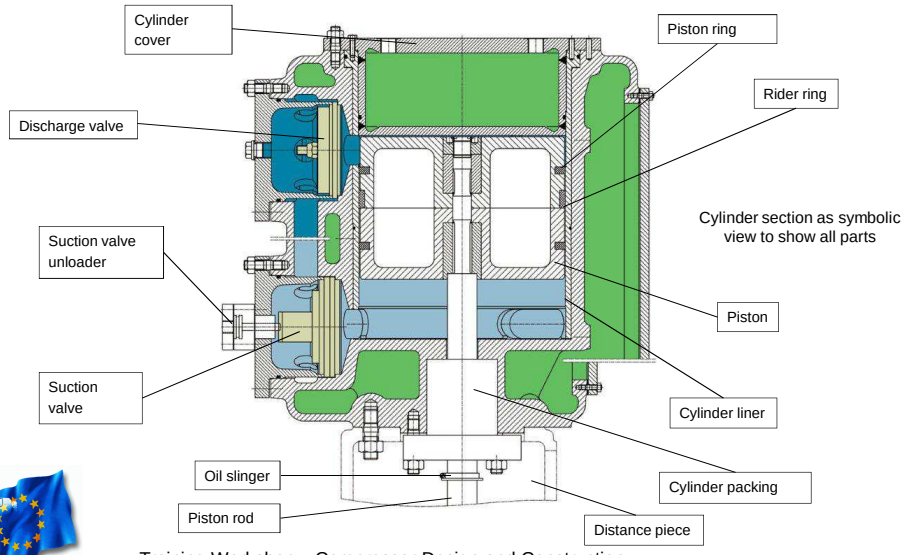
High speed balanced opposed reciprocating compressor

Most common solution for oil- and gas field services. High speed compressors are running with speeds up to 1.800 rpm or more, the average piston speed is up to 6,0 m/s - 50 % more compared with API 618 compressors. Consequently, the specific power of a high speed compressor is higher related to the cylinder volume and compressor weight. Normally air cooled cylinders are used.

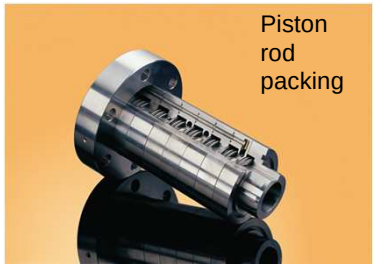
The number of cranks is varying between 1 and 6. Because of the shaking forces, coming from the mass forces, only horizontal or balanced opposed compressors are available.



Watercooled cylinder according API618



Wear parts in Cylinder and Distance Pieces


Piston rod packing

Piston and rider rings

Intermediate packing

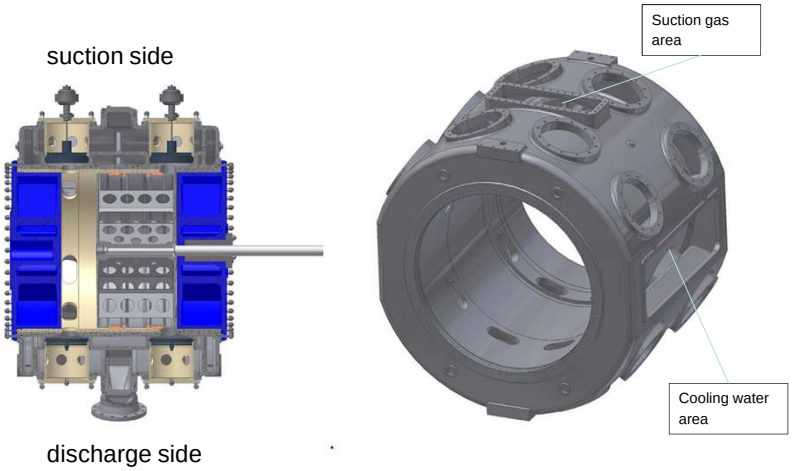
Oil scraper

A detailed explanation will follow in lecture 4

Plate valves

Ring valves

Cylinder and Piston design

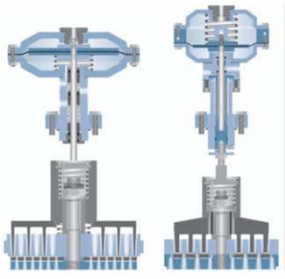


Compressor Capacity Control

Only conventional and simple control possibilities are shown.

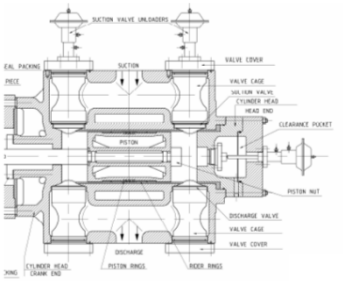
If a compressor has double acting cylinders valve **unloaders** are the most popular control method. The suction valve is forced to stay open during compression (actuators are driven by pneumatic, hydraulic, rotating, spring force) and therefore the volume inside the cylinder chamber is not compressed. If these unloaders are switched by the control sequence a flow of 50% may be performed. If two cylinders work in the same stage steps of 0 / 25 / 50 / 75 / 100% may be switched, if the gas and mass forces are calculated not to exceed the piston rod load.

For any intermediate flow an additional bypass control may be necessary.



Compressor Capacity Control

Clearance pockets are the second conventional method to influence the flow rate of a compressor cylinder. It can be used to reduce the capacity of one cylinder side. The clearance pocket is an extra volume normally located on top of the head-end cover and changes the volumetric efficiency of the compression.



The capacity may be reduced by 25% of the full flow. Clearance pockets may be switched manually, pneumatically or hydraulically. An increased discharge temperature may become a limiting factor.

More sophisticated control methods (valve control) are presented in lecture 4

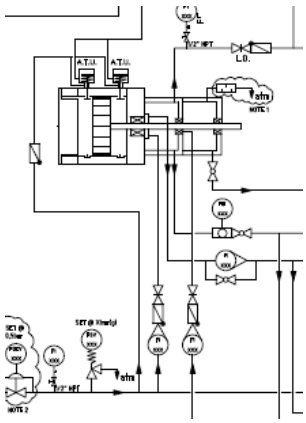
Distance pieces

The distance piece is mounted between the crank gear and the cylinder.
Four different versions of distance pieces are defined in API 618:

Type A short single compartment distance piece
Type B long single compartment distance piece (=necessary for non lube service)
Type C long two compartment distance piece (=common for process gases)
Type D short two compartment distance piece

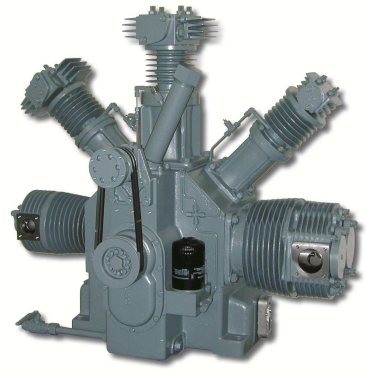
Distance pieces are made from grey cast iron, nodular graphite cast iron or for some applications as welded design from steel plates

Purge, Vent, Drain



Distance pieces have to be vented drained, purged etc. – all according the risk potential of the compressed gases. Piston rod packings may be lubricated, water cooled or equipped with a seal gas connection. Normally nitrogen is used as vent and/or seal gas and the outbound distance piece is permanently vented. Drain connections are necessary for lubricated services.

Aircooled Cylinder design



Only API618 requests a watercooled cylinder design. Gas compressors may be calculated with an aircooled cylinder design, as due to the smaller molecular weight a higher pressure ratio is possible and no additional cylinder cooling is necessary

Different air cooled cylinder designs

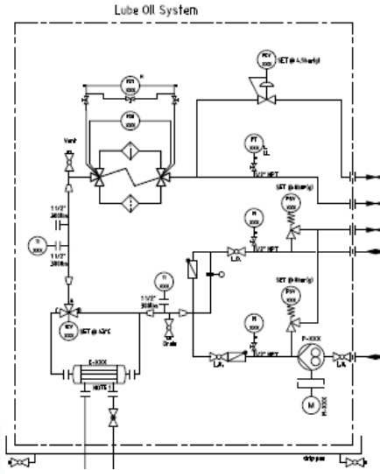
Auxiliary Systems

- Cylinder lubrication
- Frame lubrication system
- Cooling water system – pressurized or atmospheric

Cylinder lubricator box and pump system

Cooling water system on compressor frame

Auxiliary Systems



Frame lube oil system with one mechanically driven main oil pump (normally driven from the crankshaft) and one auxiliary electrically driven oil pump.

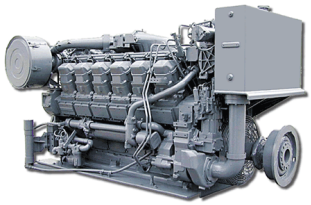
Design according API 614

Compressor Main Drives

Several usual possibilities to drive a reciprocating compressor:

- Electrical drive – low/high voltage
- Diesel engine
- Gas engine
- Gas turbine – more common for axial turbo compressors
- Steam turbine – in redundant refinery services

Very different torque characteristics !



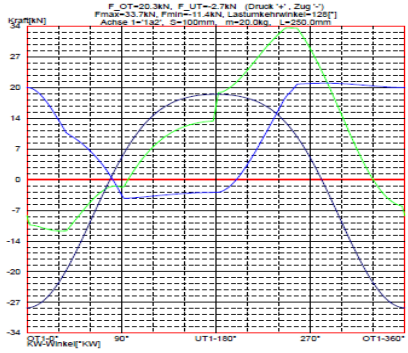
Rod Load and Rod Reversal

All different forces and resulting loads in the driving elements of a compressor are based on:

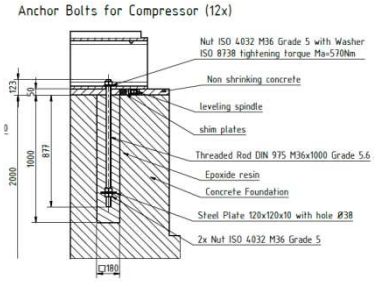
- **gas forces** resulting from the compression job and
- **mass forces** (inertia) resulting from the moving masses of the compressor elements itself.

According API618:

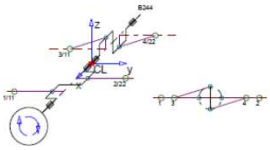
- The combined load shall not exceed the manufactures maximal allowable continuous rod load
- For each revolution the load shall fully reverse between the crosshead pin and the bushing
- The area of the reversal may be depending on the bushing and has to be checked by the manufacturer to maintain proper lubrication

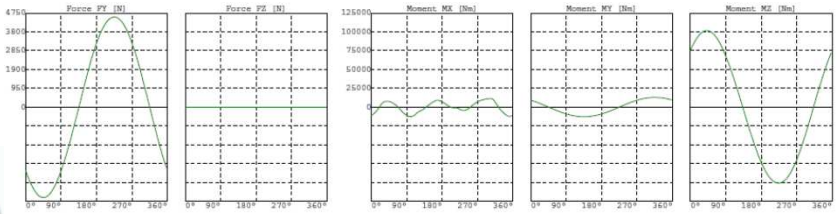


Forces, Torque and Foundation



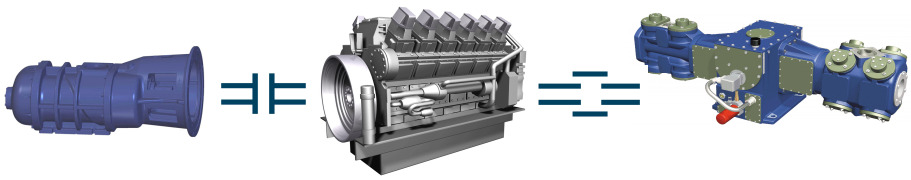
Calculation example for **unbalanced mass** forces and couples of a 4 cylinder, balanced opposed compressor





Torsional Analyses

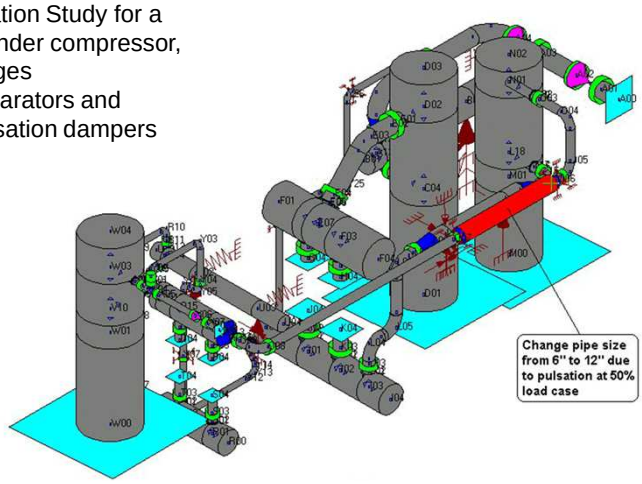
All driving elements and all users on the same mechanical shaft are simulated by masses / inertia and spring elements to detect torsional resonance frequencies of the system.
The example shows a screw compressor – coupling – diesel engine – coupling – piston compressor system on one shaft. The gas flow of this unit is controlled by the rotational speed and is very critical not to reach a mechanical shaft resonance.



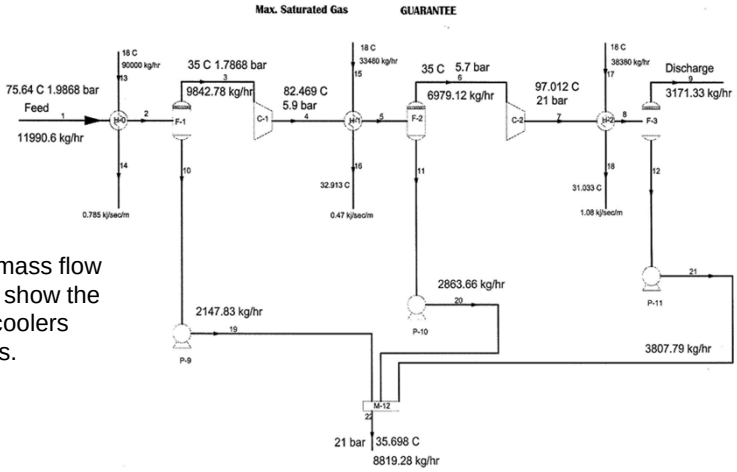
First experiences showed early damage in flexible couplings due to torsional resonances. In electrical drive systems with speed control critical frequencies may be faded out in software.

Pulsation Suppression and Analyses

Pulsation Study for a
4 cylinder compressor,
2 stages
3 separators and
4 pulsation dampers

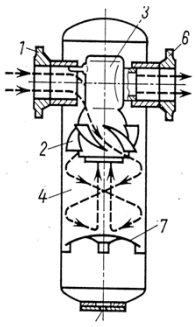


Compressor Package Design

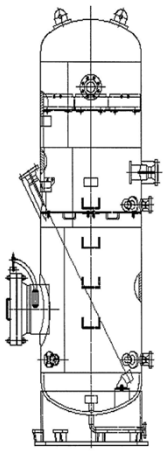


Compressor mass flow calculation to show the necessity of coolers and scrubbers.

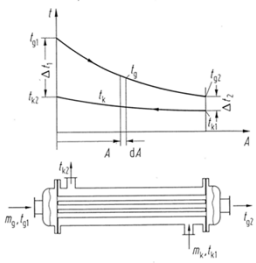
Coolers, scrubbers



Cyclon scrubber



API separator
with mesh



Shell and tube cooler

Scrubbers and Pulsation Suppression

Separator with 2oo3
level measurement

Pulsation dampers on
each cylinder, independent
scrubbers

Material of Compressor Parts

- **Compressor block/gear box** – grey cast iron or nodular graphite cast iron for special purpose (low temperature), sometime welded construction.
- **Crankshafts** are normally made from tempered steel, the area of the bearings can be hardened, sometimes it is normalized. API 618 don't allow a multi-part design
- **Connecting rods** - forged design made from tempered steel – this is common for API 618 compressors. Sometimes also from steel cast in forged design or made from a steel sheet. For non high load compressors, nodular graphite cast iron may used.
- **Crossheads** are made of forged steel, steel castings and nodular graphite cast iron. **Crosshead shoes** are made from nodular graphite cast iron or aluminum. **Crosshead pins** are made of tempered high strength steel and the surface is hardened.
- **Cylinders** – nodular graphite cast iron or forged blocks for high pressure
  - Specific materials for **cylinder and liner** for NACE applications (sour and corrosive gases) – less hardness

Materials for Compressor Parts

MECHANICAL SPECIFICATION SHEET
API 618 RECIPROCATING COMPRESSOR

Document No.	B362-300hub-370rpm.REC / LMF V545/NDII_V1103moser/mf52180	Sheet 7 of 8

1		[ ] CONSTRUCTION FEATURES					
2	STAGE / PROCESS	1 / 1					
3	CYLINDER SIZE (BORE DIA), mm	500					
4	ROD RUN-OUT: NORMAL COLD VERTICAL, mm						
5	CYLINDER(S)	GGG40.3					
6	CYLINDER LINER(S)	GG2-25					
7	PISTON(S)	CS					
8	PISTON RINGS	PTFE					
9	PISTON WEAR BANDS	PTFE					
10	PISTON ROD(S): MATL./YIELD, N/mm²	X20Cr13/ÜS50					
11	THREAD ROOT STRESS @ MACRL * @X-HD END	--					
12	PISTON ROD HARDNESS, BASE MATERIAL, Rc	22					
13	PISTON ROD COATING	Flame Hardening					
14	PISTON ROD COATING, HARDNESS, Rc	52					
15	VALVE SEATS / MIN HARDNESS, Rc	X20Cr13/22					
16	VALVE GUARDS (STOPS)	X12CrS13					
17	VALVE DISCS	PEEK					
18	VALVE SPRINGS	X7CrNiAl177					
19	PISTON ROD PACKING HOUSING RINGS	X20Cr13					
20	PISTON ROD PACKING CASE	CS					
21	PISTON ROD PACKING SPRINGS	X12CrNi177					
22	PISTON ROD PACKING SEAL ELEMENTS	PTFE					
23	DISTANCE PIECE PACKING HOUSING	X20Cr13					
24	DISTANCE PIECE PACKING SEAL ELEMENTS	PTFE					
25	INTERMEDIATE SEAL/BUFFER PACKING	PTFE					
26	WIPER PACKING RINGS	PTFE					
27	MAIN JOURNAL BEARINGS, CRANKSHAFT	C10/WM					
28	CONNECTING ROD BEARING, CRANKPIN	C10/WM					
29	CONNECTING ROD BUSHING, X-HD END	C10/PbBz					
30	CROSSHEAD (X-HD) PIN BUSHING	NA					
31	CROSSHEAD PIN	C15					
32	CROSSHEAD	GS-45N					
33	CROSSHEAD SHOES	GGG40/WM					
34	( ) CYLINDER INDICATOR VALVES ( )						
35	( ) FLUOROCARBON SPRAYED CYLINDER						
36							
37							
38	* MAXIMUM ALLOWABLE CONTINUOUS ROD LOAD						
39							

Example of an API618 datasheet for compressor part material nomination (out of an API618 quotation)

Compressor Design Codes

- **EN 1012-1:2010** Compressors and Vacuum pump – safety precautions part 1 – compressors – air, nitrogen and inert gases
- **EN 1012-3:2010** Compressors and Vacuum pump – safety precautions part 1 – process gas compressors – all other than EN 2012-1
- **EN 12583:2000 / DVGW G 497:2008** gas compressor stations above 1MW, for natural gas compressors above 16 bars and 1 MW
- **EN ISO 13631:2002** based on API11P:1989 – oil and gas industries – gas compressor stations – mainly for lubricated cylinders and hydrocarbons
- **ISO 13707:2000** – oil and gas industries – gas compressor stations – for lubricated and oil free cylinders and hydrocarbons
- **API 618:2007 5.Edition** Reciprocating compressors for Petroleum, Chemical and Gas - Industry Services - for lubricated and oil free cylinders for process gases
- **API Spec 11P:1989 2.Edition** Specification for Packaged Reciprocating compressors for Petroleum and Gas Production Service (will be replaced by ISO 13631)

Conclusion and Summary

- In history at the beginning of compressing gases only reciprocating piston compressor where on the market – soon replaced at the low end pressure side by screws and other rotary machines and at the high end by radial or axial turbo machines.
- But reciprocating piston compressors have their firm position on the market also nowadays.
- Advantages are higher efficiency and lower specific power consumption, the capability in the handling higher pressures and handling smaller volumes.
- They have more flexibility when pressure and/or capacity are changed and no big sensitivity in changes gas density or composition
- Generally reciprocating piston compressors are flexible and reliable machines for a variety of different uses.

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Thank you for your attention !