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## SCOPE

This subsection presents aspects of reciprocating compressors pertaining to compression service design and compressor type selection. Background material is included to acquaint the compression service designer with factors which affect equipment selection and installation design.<sup>(1)</sup>

## REFERENCES

### DESIGN PRACTICES (BESIDES SUBSECTIONS OF SECTION XI)

- Section V      Drums
- Section XV     Safety In Plant Design
- ♦ Section XVIII   Air Pollution Control, Industrial Hygiene and Noise Control

### GLOBAL PRACTICES

- GP 03-03-05      Suction, Discharge, and Interstage Piping for Reciprocating Compressors
- ♦ GP 03-03-06      Closed Cooling Water Systems for Internal Combustion Engines and Reciprocating Compressors
- GP 03-09-01      Winterizing and Protection Against Ambient Temperatures
- ♦ GP 04-06-02      Supporting Structures and Foundations for Heavy Machinery
- GP 10-04-01      Reciprocating Process Compressors
- GP 15-01-02      Instrumentation for Compressors and Drivers

### OTHER REFERENCES

API-618, Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services

## DEFINITIONS

**Clearance Volume** - The volume remaining in the end of a cylinder at the end of the piston stroke. It includes the volume between the face of the piston and cylinder end wall, volume under the valves, etc.

**Volumetric Efficiency** - The ratio of the inlet volume flow rate of a reciprocating compressor stage versus the piston displacement of that stage. Piston displacement is the product of the cylinder swept volume and the compressor speed in revolutions per minute. Swept volume of a cylinder is the product of piston area and stroke for each acting end of the cylinder.

## BACKGROUND

### GENERAL

The reciprocating compressor was the first type of compressor developed for industrial air and gas compression, and it remains the most versatile. It is applied at pressures ranging from deep vacuum to the 20,000 to 65,000 psi (1400-4500 bara) range typical of high pressure polyethylene services. Large numbers are applied in air and natural gas transmission service. In process plants, the most common gas applications are in hydrogen rich low molecular weight streams, fractionator overhead gas, fuel gas, and refrigeration services.

### SERVICEABILITY AND SPARING

See [Design Practice XI Section C](#), **Compression Machinery Serviceability and Sparing**, for reliability factor information and recommended sparing practices.

### OPERATING PRINCIPLES

The reciprocating compressor is a positive displacement type compressor which uses the reciprocating motion of a piston to raise gas pressure by reducing the volume of the gas trapped in a cylinder. The volume reduction causes the pressure to rise until the pressure existing in the discharge system is reached. The piston then displaces the trapped gas through the cylinder discharge valve.

#### Note:

- (1) API compressor data sheets specify pressure in psi, bar, and kPa. In this section, bar is the metric unit used for pressure.

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## VALVES

Valves are provided in the cylinder to admit and discharge gas thus regulating the cycle of operation of the compressor cylinder. They are basically spring loaded check valves. The valves are opened solely by the difference in pressure across the valve; no mechanical device is used. The inlet valve(s) open when the reciprocating motion of the piston results in decreasing the pressure in the cylinder below the inlet system pressure. The discharge valve closes, upon completion of the discharge stroke, when the pressure in the cylinder no longer exceeds discharge system pressure. The best illustration of a compressor valve cycle is obtained by correlating the piston movement to the pressure volume diagram. See [Figure 1](#).

**Valve types** - There are many valve designs available, however, these designs can be classified into a few types, defined by the shape of moving elements and the nature of damping used to control the motion.

- **Rectangular (Strip)** - Typical valve designs that use rectangular elements are feather valves, channel valves and reed valves. These valves are applied to the industrial air machines for the most part.
- **Concentric Ring** - These valves use one or more relatively narrow metallic or nonmetallic rings arranged concentrically about the center line of the valve.
- **Ported Plate** - Similar to the concentric ring valves, except the rings are joined together into a single element. This valve element is probably one of the most commonly used in process reciprocating compressors.
- **Disc (Poppet)** - The design characteristics of poppet valves for gas transmission service are multiple nonmetallic and streamlined sealing elements in single- or double-deck valves. They can be found in applications ranging from a few hundred psi, as in gas transmission compressors, to over 50,000 psi in hyper-compressors.

**Valve Materials** - Valve components are made of various materials depending on the operating pressures and type of gas to be handled.

- **Valve seats and guards** - Materials used include cast iron (most common for low and medium pressures), ductile iron (for medium pressures), cast steel and steel (for high pressures).
- **Sealing elements** - Materials used for sealing elements fall into two classes: high strength steels and plastic composites. The 410 SS is used for most applications of high strength steels but 302 SS, 316 SS, 420 SS, 17-4 PH SS, monel, Inconel or even titanium are used for special applications. The plastic composites include Nylon, PEEK (Polyether-ether-ketone), MT Polymers and MC (a blend of MT material and carbon fibers).
- **Springs** - Springs used on the sealing elements include AISI 410 and 420, 17-4 PH, Inconel, and cadmium-plated chrome-vanadium steels.

## BASIC FRAME AND RUNNING GEAR CONSTRUCTION

The piston is driven by a piston rod connected to a rotating crankshaft. All heavy duty and double acting reciprocating compressors use a slider-crank mechanism to change the rotary motion of the crank shaft to the reciprocating motion of the piston rod. The slider is named the "crosshead." The use of the crosshead provides long life for the piston rings and liners by avoiding the piston rocking forces which are present with "trunk" (no separate crosshead) arrangements such as used in automobile engines. See [Figure 2](#).

The crankcase supporting the crankshaft including the crosshead guide housing(s) is referred to as the compressor "frame." The crankshaft with flywheel and slider-crank assembly is referred to as the compressor "running gear." The piston, piston rod, cylinder, cylinder heads and valves are referred to as the "cylinder assembly."

The running gear uses bearings in four locations as follows:

- Main bearings are used to support the crankshaft.
- Connecting rod bearings are used to allow rotation of the crankshaft relative to the connecting rod.
- The crosshead to connecting rod pinned joint has a bearing surface to allow rocking of the connecting rod with respect to the crosshead.
- Crosshead guide bearings guide the free sliding of the crosshead in the crosshead housing. These bearings are lubricated by circulating oil from the frame lubrication system.

## CYLINDER ASSEMBLY MATERIALS AND ARRANGEMENTS

Cylinders are of cast construction for low pressures and of forged steel construction with drilled ports and passages for high pressures. Cast iron cylinders are used to a maximum allowable working pressure of 1000 psig (70 barg). Cast steel is used to 2500 psig (170 barg); and forged steel to about 7500 psig (520 barg). Special materials are used at higher pressures.

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Cylinders with very low clearance volume are used in high pressure ratio applications to increase cylinder volumetric efficiency. Reduced clearance volume can be achieved by placing valve assemblies in the head of the cylinder. The volumetric efficiency of a cylinder decreases with increasing pressure ratio and increases with decreasing cylinder volume. See [Design Practice XI Section D, Compression Calculations](#), for a discussion of volumetric efficiency.

Pistons are double acting for all but very high pressures. For high pressures single acting cylinders are applied.

Most heavy duty and gas compressors are provided with horizontal cylinders. Most multicylinder compressor models place the horizontal cylinders on opposite sides of the frame to achieve mechanical balance of reciprocating forces. A few models use vertical cylinders. Some commercial air compressors and a few gas compressors use Y and L shaped arrangements for two cylinders.

## WEARING PARTS

The cylinder assembly wear points, experiencing friction forces, are the piston rod packing against the piston rod and the piston rings against the cylinder liner. In lubricated compressors, small quantities of lubricant are injected to significantly reduce friction forces. A forced feed packing and cylinder lubrication system, independent of the frame lubrication system, is used.

Pistons for conventional reciprocating compressors are provided with two or more flexible piston rings that expand in the annulus between the piston outer diameter and the cylinder bore. These prevent leakage from the discharge pressure zone to the inlet pressure zone. This leakage is called slip or blowby. For services where wear rates tend to be high, fixed solid bands of low friction coefficient material (PTFE, babbitt, bronze) are also provided to minimize cylinder liner and piston surface wear. These are called wear bands.

Within the inlet and discharge valves, moving plates impact against seats and stops, and valve plates and springs flex. The compressor valves are the highest maintenance item in a reciprocating compressor and generally limit compressor reliability.

## BASIC DESIGN CONSIDERATIONS

### INLET TEMPERATURE

The lowest inlet temperature for lubricated compressors is -55°F (-48°C). The lube oil must be very carefully selected for sub-zero inlet temperatures. Non-lubricated compressors are required if the inlet temperature is below -55°F (-48°C).

### COMPRESSOR STAGING

The choice of the number of compressor stages is determined by discharge temperature and pressure ratio limitations.

**Allowable Discharge Temperature** - See [Table 1](#). The factors which limit the allowable discharge temperature are as follows:

- In all lubricated compressors, maintenance of adequate viscosity in the lubricant film and prevention of lube oil degradation into coke deposits.
- In air or other oxygen rich services, prevention of ignition of lube oil deposits in the discharge system.
- In low molecular weight gas services, a conservative design value must be used to allow for performance deterioration due to inevitable valve leakage and piston blowby.
- In high pressure polyethylene service, prevention of gas polymerization.
- Prevention of compressor fouling.

The discharge temperature of PTFE trimmed non-lubricated compressors is limited by the PTFE which is exposed to friction and compression generated heat.

For guidance in determining reciprocating compressor discharge temperatures, see [Design Practice XI Section D, Compression Calculations](#). The recommended discharge temperature limits should be observed in determining the number of reciprocating compressor stages used in a given compression service.

**Pressure Ratio** - In general, the pressure ratio for a single stage of compression is limited to 4.5 to 5.0 at low pressures and to 2.0 to 2.5 at inlet pressures above 1000 psig (70 barg).

The pressure ratio is limited by the stress imposed on the piston rod. For a double acting cylinder, the rod stresses in compression and tension can be estimated by determining the net force across the piston due to inlet pressure on one side and discharge pressure on the other, and dividing by the piston rod cross sectional area. For a given piston and rod selection and a given pressure ratio, the force across the piston increases as the inlet pressure rises. This increases rod load so that at high inlet pressures the achievable pressure ratio is less than that at lower inlet pressures. Pressure ratio is also limited by the decrease in volumetric efficiency and increase in discharge temperatures which occur as the pressure ratio increases.

**Sensitivity to Liquids** - Reciprocating compressors are especially sensitive to damage by liquid in the gas stream. In mist form and droplets, liquid tends to remove the lubricant film from the cylinder liner and piston rings and damage to valves.

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The result is a drastic shortening of run time between repairs. A slug of liquid to the compressor inlet is extremely dangerous because of its incompressibility. Many serious explosions and fires have occurred due to cylinder rupture as a result of accumulation of liquid in cylinders.

- ♦ **API-618** requires that a horizontal cylinder arrangement be used when handling saturated gases or gases carrying injected flushing fluids. It is also required that all horizontal cylinders be provided with bottom discharge connections. This is done so that any liquid entering a horizontal cylinder drains through with as little chance for slug accumulation as possible. Exceptions are permitted for air or dry inert gas services with Purchaser approval. See [Design Practice XI Section A, COMPRESSION SERVICE DESIGN PROCEDURES - Fouling Tendency](#), and [Design Practice XI Section O, COMPRESSOR UNIT PIPING AND PROCESS TRAIN EQUIPMENT - Compressor Flushing Systems](#), for discussions of compressor flushing.

Additional requirements to minimize the potential for liquid carryover are the use of compressor inlet and interstage knockout drums (See [Design Practice V - Drums](#)), and heat tracing and insulation of compressor cylinder inlet lines when ambient temperature is below the dew point of the gas at the compressor inlet or when handling hydrocarbon gas components heavier than ethane. See **GP 3-9-1, Winterizing and Protection Against Ambient Temperatures**.

**Sensitivity to Solids** - Inlet filters should be specified as required in services where solids or products of corrosion are present. See [Design Practice XI Section O, COMPRESSOR UNIT PIPING SERVICE DESIGN PROCEDURES - Inlet Filters for Reciprocating Compressors](#).

## CYLINDER COOLING

- ♦ **General - API-618, Reciprocating Compressors For Petroleum, Chemical and Gas Industry Services**, requires that compressor cylinders be cooled. Cylinder cooling jackets are used to avoid thermal distortion due to the heat of compression and packing and piston ring friction and ensure an adequate viscosity of the cylinder lubricant. This greatly extends the life of wearing parts.

**Coolant Systems** - The specific **API-618** requirements for cylinder cooling are as follows:

- Static filled coolant systems (See [Figure 3, Plan A](#)) may be supplied where cylinders will not be required to operate fully unloaded for extended periods of time, the expected maximum discharge temperature is less than 190°F (88°C), and the adiabatic gas temperature rise (difference between inlet temperature and discharge temperature based on isentropic compression) is less than 150°F (83°C).
- ♦ • Thermosyphon coolant systems (See [Figure 3, Plan B](#)) may be supplied where cylinders will not be required to operate fully unloaded for extended periods of time, and either the expected maximum discharge temperature is between 190°F (88°C) and 210°F (99°C), or the adiabatic gas temperature rise is less than 150°F (83°C).
- ♦ • Forced liquid coolant systems (See [Figure 3, Plan C](#)) shall be provided where cylinders will operate fully unloaded for extended periods of time and either (a) the expected maximum discharge temperature is above 210°F (99°C) or (b) the rise in adiabatic gas temperature is 150°F (66°C) or greater.

If valve unloaders are being used as a normal flow control means, the use of a forced liquid coolant system will be required since it can be expected that the compressor will operate for extended periods with the cylinder fully or partially unloaded. Vendors do not recommend the static filled and thermosyphon coolant systems for extended operation at full or partial load using valve unloaders.

- ♦ **Cooling Water Requirements** - The cooling jackets of most reciprocating compressor cylinders are rough surfaced cored passages which are not easily accessed for cleaning. Removal of debris and surface cleaning are much more difficult than with shell and tube exchangers. Repair of corrosion damage to the cooling passages is difficult. Clean water is therefore recommended for cooling. Fresh water from a refinery cooling water system or treated water from a closed cooling water system are satisfactory.

According to API-618 the cooling water inlet temperature should be a minimum of 10°F (6°C) higher than the gas inlet temperature to avoid gas condensation. For all services, cylinder coolant exit temperature should be a maximum of 30°F (17°C) higher than gas inlet temperature to avoid cylinder capacity reduction due to increased inlet gas temperature. When clean fresh water is available, the cooling arrangement of [Figure 3, Plan C](#) can be applied. Some means of heating may be required to achieve the required coolant temperature.

When clean fresh water at the required temperature is not available, the designer should specify that a self contained closed jacket coolant system be furnished. Details of this system are covered by the Global Practices and need not be included in the Design Specification.

**Cooling Water for Engines** - Gas and diesel engines require continuous cooling of the power cylinders with water that will not leave deposits on the cooling jacket high temperature surfaces. For this reason, closed cooling water systems are required for engines per **GP 3-3-6**. There is no need to specify the provision of a closed water coolant system in the compressor Design Specification.

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**Estimating Cooling Duty** - For estimating the cooling water flow to compressor cylinder jackets assume a 15°F (8°C) rise in cooling water temperature through the jackets and a cooling duty of 250 Btu/Bhp-Hr (350 kJ/kW.Hr) based on compressor maximum Bhp (kW) or driver rated power.

## DISTANCE PIECES, PACKING CASES AND PRESSURE PACKING

**General** - The packing case, pressure packing, and the housing which surrounds the piston rod inboard of the cylinder (called the distance piece) perform the functions of minimizing total cylinder gas leakage, preventing gas from reaching the compressor crankcase, and minimizing crankcase lube oil ingress into the gas stream. In most flammable gas services, oil ingress to the gas stream is tolerable but gas leakage past the rod packing could pose an explosion hazard in the compressor crankcase and a fire and pollution hazard in the area of the compressor. In corrosive gas services, pressure packing leakage could contaminate the crank case lubricating oil and corrode critical running gear parts. In non-lubricated compressors, frame lubricating oil which wets the rod can enter the gas stream along the rod surface if preventive measures are not taken.

Cylinder gas leakage is minimized by the use of well designed rod packing and by venting from an annular chamber within the packing case near the case outboard end. The vent handles most of the packing leakage and is piped to a safe and suitable location. The piston rod also passes through a wiper packing at a crosshead end partition wall. The oil wiper packing removes most of the compressor frame lube oil from the rod surface.

**Distance Pieces** - **API-618** requires that the Purchaser of reciprocating compressors specify the type of distance piece required. **Figure 4** illustrates the **API-618** available arrangements. They are as follows:

- **Type A - Figure 4a** - Short single-compartment distance piece used for lubricated service only where oil carryover (at the oil wiper packing and at the gas cylinder pressure packing) is not objectionable. This arrangement should not be used when cylinders are lubricated with synthetic oil. Used only for non-flammable and non-hazardous gases.  
For the Type A distance piece, the distance piece length is less than the piston stroke. Portions of the piston rod alternately travel between the crankcase (crosshead housing) and the gas cylinder pressure packing.
- **Type B - Figure 4b** - Long single-compartment distance piece used for non-lubricated service, or when specified. It is of sufficient length to prevent oil carryover. No part of the piston rod alternately enters the crankcase (crosshead housing) and the gas cylinder pressure packing. The rod is fitted with an oil slinger of spark resistant material and preferably of a split design for easy access to the piston rod packing. Since no part of the rod alternately enters the crosshead housing and pressure packing, the potential for lube oil and gas carryover between cylinder and crankcase is significantly reduced.
- **Type C - Figure 4c** - Long/long two compartment distance piece designed to contain flammable, hazardous, or toxic gases. No part of the piston rod alternately enters the oil wiper packing, intermediate partition packing, and the gas cylinder pressure packing. Segmental packing is provided between the two compartments. Provisions for the lubrication of this segmental packing, if necessary, is provided by the compressor vendor.
- **Type D - Figure 4d** - Long/short two compartment distance piece is designed to contain flammable, hazardous or toxic gases. No part of the piston rod alternately enters the wiper packing and the intermediate seal packing. Segmental packing is provided between the two compartments. Provisions for the lubrication of this segmental packing, if necessary, is provided by the compressor vendor.

It should be noted that in the two compartment distance piece arrangement one of the compartments may be purged with inert gas or evacuated to further control the path of leakage.

**Packing Case Vent and Buffer** - To reduce process gas emissions to a minimum, the gas cylinder pressure packing should include venting and buffer gas cups. See **Figure 4e**. Vented and buffered gas cylinder pressure packing arrangement must be specified. Vented packing without buffer is required as a standard by **API-618** for flammable, hazardous, toxic or wet gas services.

**Distance Piece and Packing Arrangement Recommendations** - Four considerations in the selection of a distance piece and packing arrangement are as follows:

- Avoidance of gas contamination of crankcase oil or vice versa
- Personnel exposure
- Control of fugitive emissions
- Safety

The following recommendations assume that specialists in the areas of industrial hygiene, air quality, and safety will review the service and provide the inputs necessary to determine the adequacy of the proposed arrangements.

- For reasons of standardization and flexibility, the use of **Type A** distance pieces is not recommended.
- The **Type C** distance piece is not normally used on process compressors. It is used only for special services such as oxygen. This distance piece causes the overall length of the gas end assembly to be excessive and increases the