

<p><b>KLM Technology Group</b></p> <p>Practical Engineering Guidelines for Processing Plant Solutions</p>	 <p><b>Engineering Solutions</b></p> <p><a href="http://www.klmtechgroup.com">www.klmtechgroup.com</a></p>	<p>Page : 1 of 64</p>
		<p>Rev: 01</p> <p>Rev 01 Sept 2013</p>
<p>KLM Technology Group P. O. Box 281 Bandar Johor Bahru, 80000 Johor Bahru, Johor, West Malaysia</p>	<p><b>Kolmetz Handbook Of Process Equipment Design</b></p> <p><b>ETHYLENE / OLEFIN COMPRESSOR SELECTION, SIZING AND TROUBLESHOOTING</b></p> <p><b>(ENGINEERING DESIGN GUIDELINES)</b></p>	<p>Co Author Rev 01 Aprilia Jaya</p>
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## INTRODUCTION

### Scope

This design guideline covers the basic elements in the field of olefin compressors in sufficient detail to allow an engineer to design an olefin compressor. An Olefin compressor is one of the most critical pieces of equipment in an ethylene plant.

Compressor operation must be fine-tuned to maximize performance and reduce spurious trips that result in downtime and unnecessary maintenance. The best way to monitor compressor performance is to calculate the polytropic efficiency of each stage and to compare this to the stage design efficiency based on volumetric flow and rotor speed.

The design of olefin compressor may be influenced by factors, including process requirements, economics and safety. In this guideline there are figures that assist in making these factored calculations from the vary reference sources and there is a calculation spreadsheet for the engineering design. All the important parameters use in the guideline are explained in the definition section.

In the application section of this guideline, two case studies are shown and discussed in detail, highlighting the way to apply the theory for the calculation. The theory section explained about thermodynamic and properties which are used in calculations, power required, olefin compressor sizing and multistage compressor, and compression revamp guidelines.

Example Calculation Spreadsheets are part of this guideline. This Example Calculation Spreadsheets are based on case studies in the application section to make them easier to understand.

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## General Design Consideration

The 3<sup>rd</sup> largest volume of petrochemicals produced on an annual global production is ethylene with about 120 million tons with a continuous annual increase of some 4 - 5 %. Ethylene and propylene are building blocks for a large variety of chemicals and petrochemical products. Polymers are the dominating end-users.

The cracked-gas compressor (CGC) is one of the most critical pieces of equipment in an ethylene plant. Compressor operation must be fine-tuned to maximize performance and reduce spurious trips that result in downtime and unnecessary maintenance. By increasing operating efficiency, boosting unit availability and production, and reducing maintenance costs, producers can increase their ethylene plant's throughput to meet market demands. Cracked gas compression is used to compress the cracked gas in order to separate methane from ethylene, and ethylene from heavier hydrocarbons in the recovery sections of the plant.

A cracked gas compressor (CGC), which is a 4 – 6 step centrifugal compressor, is used to increase the cracked gas low pressure (0.3 – 0.9 barg) to the desired level. A steam turbine is usually used for driving the CGC for economic reasons and for effective speed control. The compressor's suction pressure can be controlled by altering the speed of the compressor. The cracked gas is cooled between each stage of the compressor usually by cooling water, and the condensed liquids are separated from the gas in interstage drums.

The temperatures of the maximum discharge from each of the stages in the compressor are set according to specification for ensuring that the machine does not foul and this can determine the number of CGC steps. Usually, each step in the CGC is followed by an intercooler and a subsequent knockout drum for cooling the discharge after each step and for separating the condensed heavy hydrocarbons and water, in that order, as shown in figure 1. Process water and gasoline are condensed in the interstage coolers and knocked out in the interstage separators. Gasoline is directed to hydrogenation and separation.

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The knockout drums are generally set with high efficiency mist eliminators to minimize the carryover of liquid to the following compressor stage. The condensed hydrocarbon components and water are then recycled and flashed from high pressure suction (or knockout) drums to the ones at lower pressure to recover the lighter hydrocarbon components. Then, the condensed steam is routed to the quench water tower.

Conditions are usually preset for the boiler feed water in each of the CGC stage suction line in order to keep the discharge temperature commonly below 100°C and to check fouling due to polymerization. If required, a provision can also be made to inject wash oil in the suction lines or in each of the impellers to clean off the internals, eliminate deposits causing fouling, maintain efficiency, and to extend on-stream time for the compressor. Caustic scrubbing use to removal of the acid components CO<sub>2</sub> and H<sub>2</sub>S in a 3-stage caustic scrubber

Cracked gas compressor challenges;

1. Poor turbine set points control causes output losses, leading to thermal stress and premature wear
2. Fouling of blades and related washing reduces throughput
3. Trips causes flaring and product loss
4. Spurious trips compromise compressor availability
5. Difficult to control steam during start-up
6. Poor anti-surge control valve performance can cause trips
7. Risk of surge from reducing suction pressure below point needed to maintain flow
8. Additional energy costs from not operating close to surge line
9. Excess vibration that can shut down/trip the compressor
10. Instrument drift creates potential for surge or wasted energy from recycling too much gas

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There are two basic cracked gas compression configurations.

### 1. Conventional plant

In a conventional scheme, the cracked gas is compressed in the first stages with the acid gas removed before the final stage of compression. The hydrocarbon condensate from the first drums is sent to the distillate stripper with the tower overheads to the quench water tower and the tower bottoms typically to the debutanizer. The hydrocarbon condensate from the last drums is sent to the condensate stripper with the tower overheads to the cracked gas compressor and the tower bottoms typically to the depropanizer. After the final stage of compression, the cracked gas is dried.

### 2. DePropanizer System

The second configuration is the DePropanizer System. This scheme also uses a distillate stripper along with front-end depropanizers and front-end acetylene hydrogenation. The front-end high pressure depropanizer removes diolefins and heavier components from the cracked gas prior to the C<sub>2</sub> hydrogenation and limits the amount of C<sub>2</sub>s to the propylene splitter via the LP depropanizer. The overhead of the tower is sent to the last stage of the cracked gas compressor and the bottoms stream is sent to the LP depropanizer. If acetylene extraction is required instead of C<sub>2</sub> hydrogenation when designing the scheme, a condensate stripper is used instead of a HP depropanizer.

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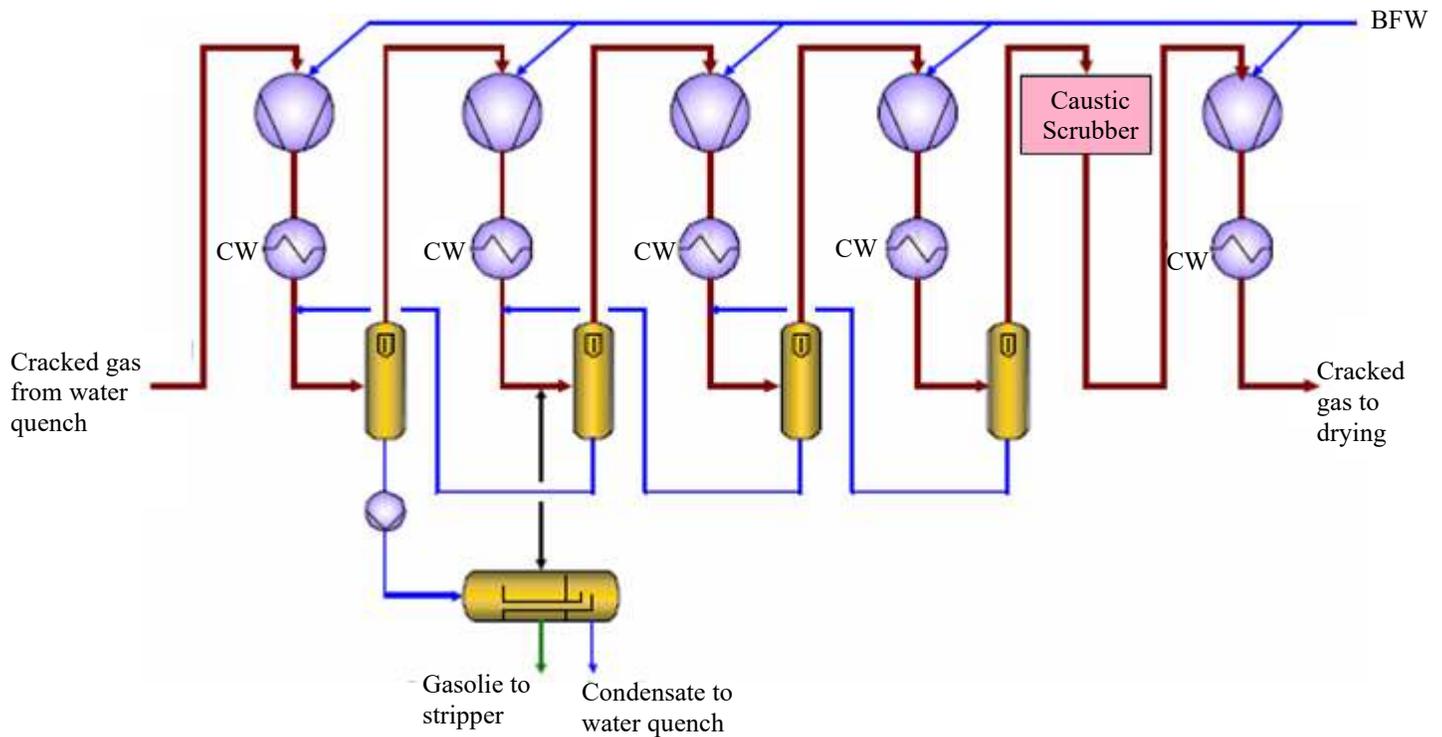


Figure 1: Conventional plant cracked gas compressor

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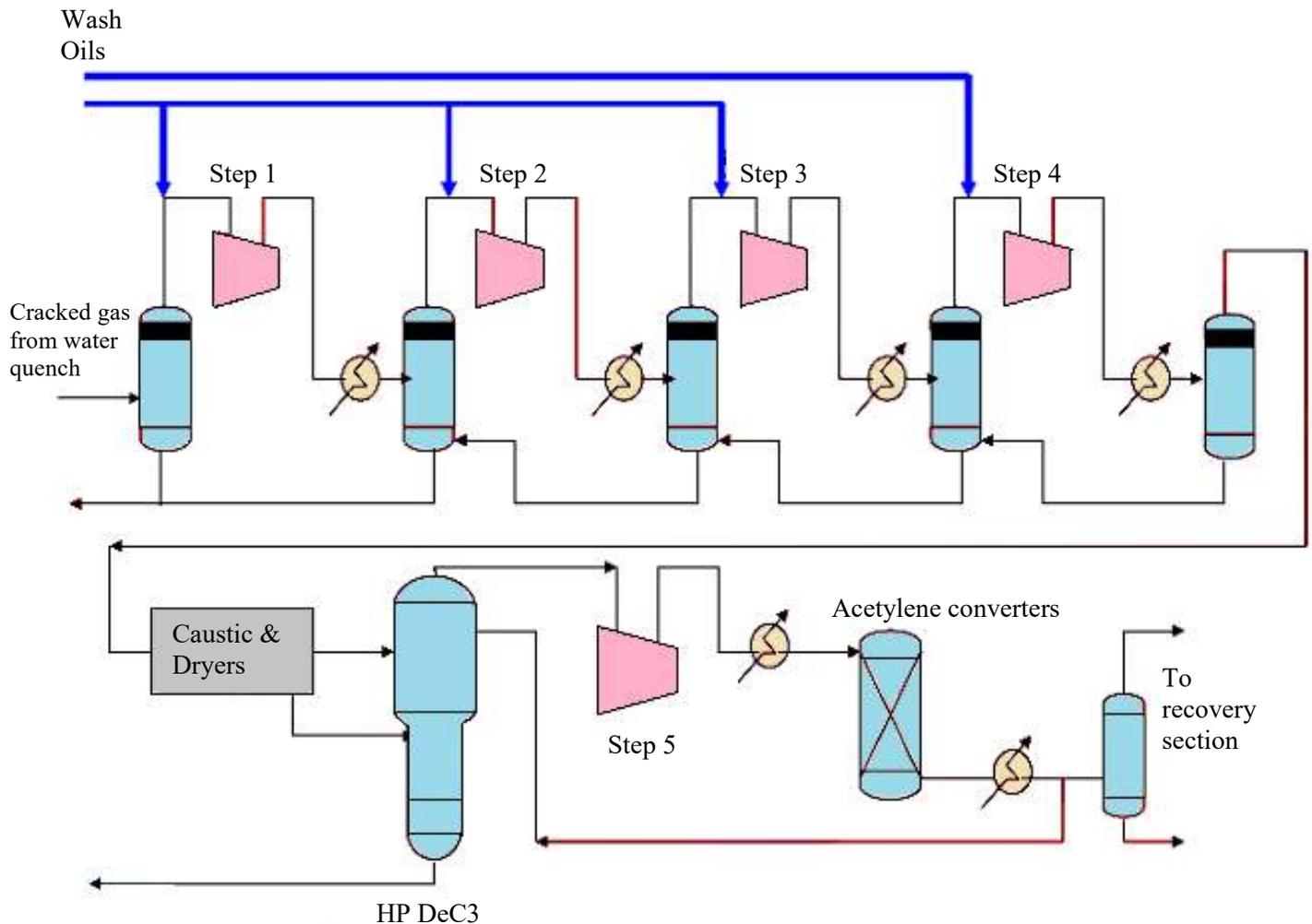


Figure 2: DePropanizer compressor flow diagram

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## Centrifugal Compressor

A centrifugal compressor is a “dynamic” machine. It has a continuous flow of fluid which receives energy from integral shaft impellers. This energy is transformed into pressure partly across the impellers and partly in the stator section, i.e., in the diffusers

Gas is drawn into the compressor through a suction nozzle and enters an annular chamber (inlet volute), flowing from it towards the center from all directions in a uniform radial pattern. At the opposite side of the chamber from the suction nozzle is a fin to prevent gas vortices. The gas flows into the suction diaphragm and is then picked up by the first Impeller. The gas next flows through a circular chamber (diffuser), following a spiral path where it loses velocity and increases pressure (similar to fluid flow through conduits).

The gas then flows along the return channel; this is a circular chamber bounded by two rings that form the intermediate diaphragm, which is fitted with blades to direct the gas toward the inlet of the next impeller. The blades are arranged to straighten the spiral gas flow in order to obtain a radial outlet and axial inlet to the following impeller

Labyrinth seals are installed on the diaphragms to minimize internal gas leaks. These seals are formed by rings made in two or more parts. The last impeller of a stage (the term stage refers to the area of compression between two consecutive nozzles) sends the gas into a diffuser which leads to an annular chamber called a discharge volute. The discharge volute is a circular chamber which collects the gas from the external boundary of the diffuser and conveys it to the discharge nozzle. Near the discharge nozzle there is another fin which prevents the gas from continuing to flow around the volute and directs it to the discharge nozzle

The balance drum (balance piston) is mounted on the shaft after the end impeller. It serves to balance the total thrust produced by the impellers. Having end impeller delivery pressure on one side of the drum, compressor inlet pressure is applied to the other by an external connection. In this way, gas pressures at both ends of the rotor are roughly balanced. To get even closer pressure levels and, therefore, the same operating conditions for the shaft end oil seals, another external connection is made between the balancing chambers. The gas chambers are positioned outside the shaft-

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end labyrinths. They are connected to achieve the same pressure as that used as reference for the oil seal system

The centrifugal compressor is characterized by the radial discharge flow. Air is drawn into the centre of a rotating impeller with radial blades and is thrown out towards the periphery of the impeller by centrifugal forces. Before the air is led to the centre of the next impeller, it passes a diffuser and a volute where the kinetic energy is converted to pressure.

The pressure ratio across each stage is determined by the compressor's final pressure. This also gives a suitable velocity increase for the air after each impeller. The air temperature at the inlet of each stage has a decisive significance for the compressor's power requirement, which is why cooling between stages is needed.

1. Centrifugal compressors with up to six stages and pressure up to 25 bar are not uncommon.
2. The impeller can have either an open or closed design. Open is the most common with air applications. The impeller is normally made of special stainless steel alloy or aluminium.
3. The speed is very high compared with other types of compressor, 15,000-100,000 r/min are common.
4. Journalling on the compressor shaft takes place using plain bearings instead of rolling bearings.
5. Often multi-stage compressors have two impellers mounted on each end of the same shaft to counteract the axial loads caused by the pressure differences.
6. The lowest volume flow rate through a centrifugal compressor is primarily determined by the flow through the last stage. A practical limit value of 160 l/s in the outlet from a horizontal split machine is often a rule-of-thumb.
7. Each centrifugal compressor must be sealed in a suitable manner to reduce leakage along the shaft where it passes through the compressor housing. Many types of seal are used and the most advanced can be found on compressors with a high speed intended for high pressures.

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8. The four most common types are labyrinth seals, ring seals, (usually graphic seals that work dry, but even sealing liquids are used), mechanical seals and hydrostatic seals.

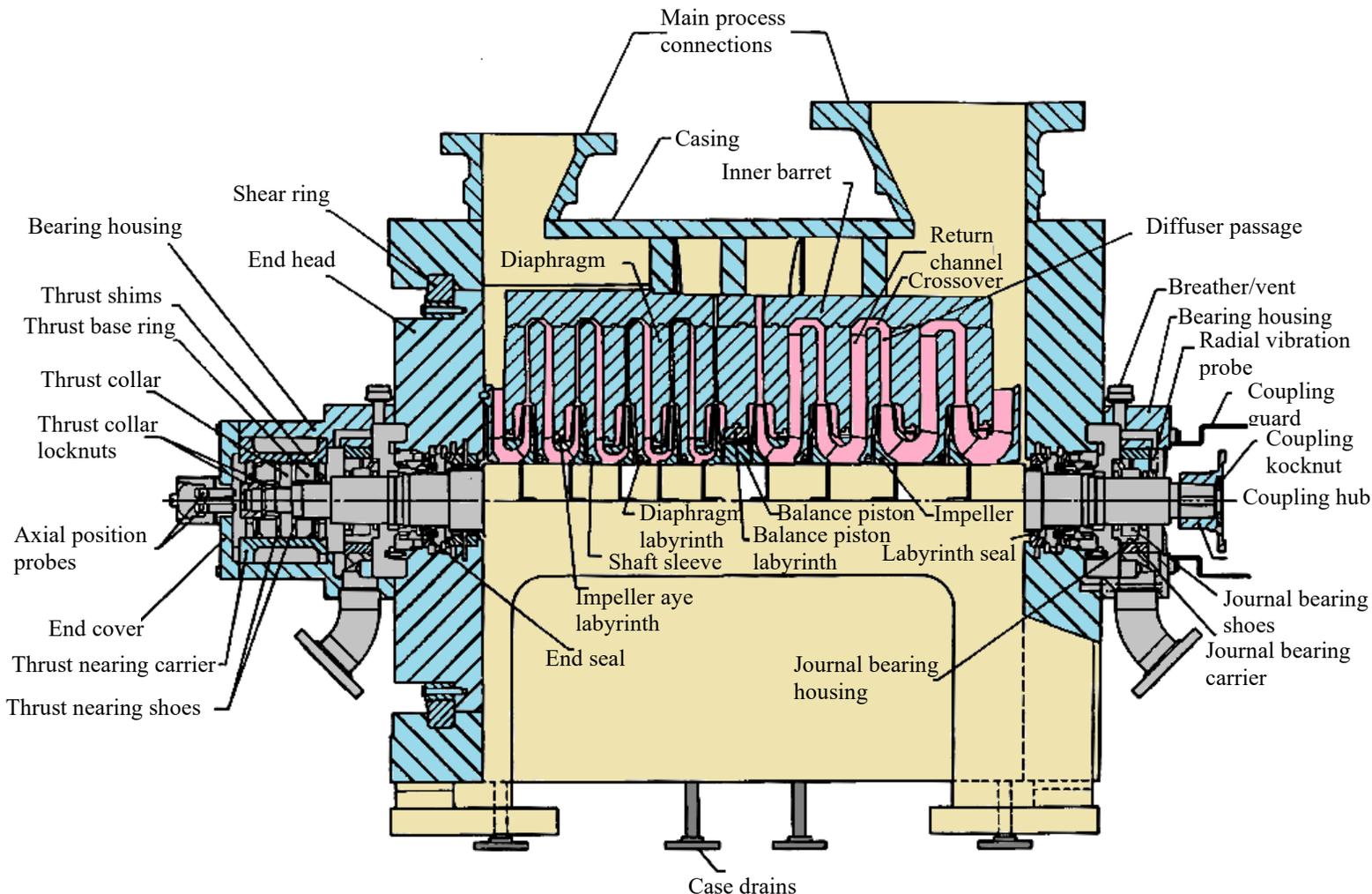


Figure 3: Centrifugal compressor nomenclature. Note: Some compressors may use bolted-head construction.

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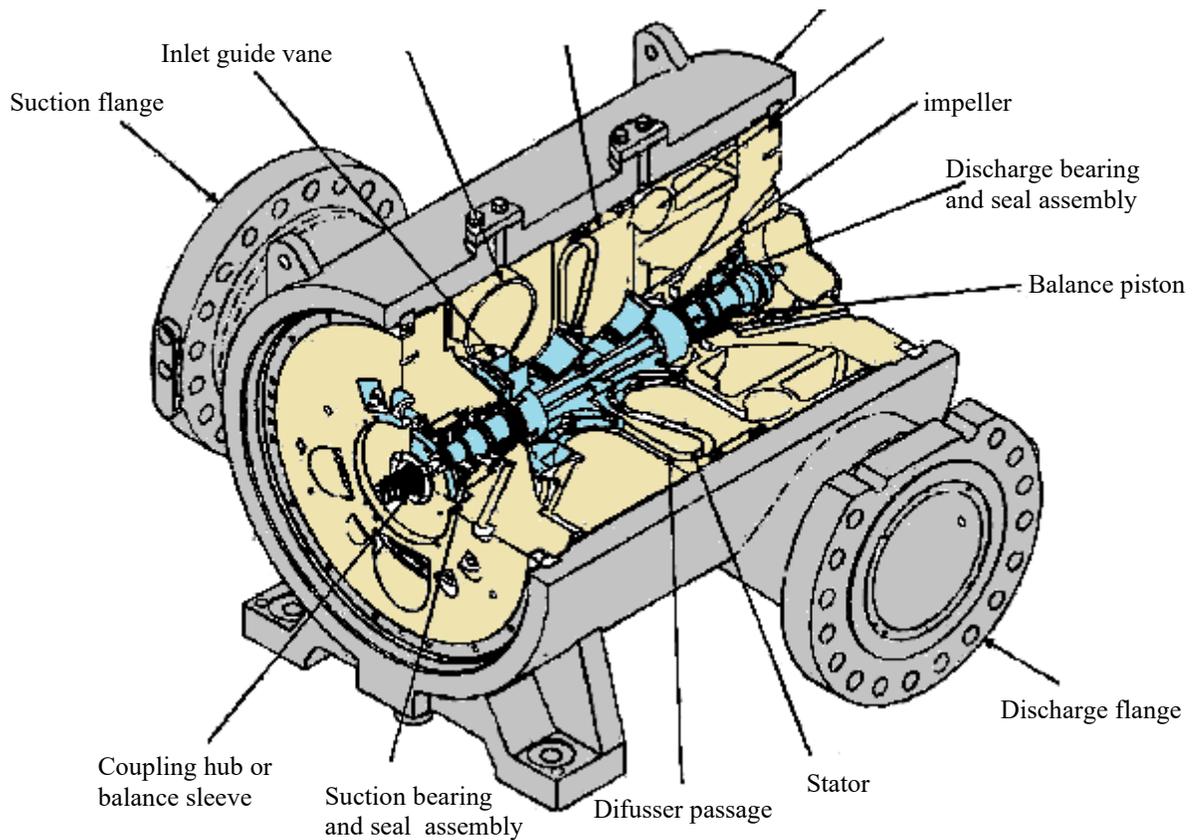


Figure 4: centrifugal compressor cut away

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i. Compressor impellers

The impellers consist of two discs, referred to as the disc and shroud, connected by blades which are shrunk onto the shaft and held by either one or two keys. The impeller pushes the gas outwards raising its velocity and pressure; the outlet velocity will have a radial and a tangential component. On the disc side, the impeller is exposed to discharge pressure and on the other side partly to the same pressure and partly to suction pressure. Thus a thrust force is created towards suction.

Two of the many types of compressor impellers are Open, semiopen, and closed types are found in industry (Semiopen and closed are the most prevalent used). Impellers should be chosen based almost entirely on performance. their respective head and flow parameters ("coefficients") are selected for optimum efficiency over the desired flow range. Fully open impellers, as the name suggests, do not have shrouds and back plates. Usually, the profile of an open impeller is radial and its stability range is limited. Since both of its sides are open due to the absence of the shroud and back plate, an open impeller generates very little axial thrust.

Closed-impeller construction with backward-leaning vanes offers a wide operating range which have two versions: a two-dimensional ("2 D") and a three-dimensional ("3 D").

The backward lean in a 2 D version has the same curvature throughout the blade width. In the case of a singleshaft compressor with multiple stages, the volume at the inlet to the next stage is being reduced and this lowers the stage efficiency. 2 D impellers have optimum performance up to flow coefficients of about 0.06.

Three-dimensional (3 D) impellers with contoured ("twisted") blades seem to be better adapted to varying flow conditions. Decreasing the diameter will increase the flow coefficient and a given flow rate that demands more width. This means that the axial width of a 3 D stage exceeds that of the equivalent 2 D impeller. Since the axial dimension is wider compared to the 2 D version, the number of wheels that can be installed is restricted due to stability considerations. At optimum performance, the flow coefficient of a 3D impeller is in the range of 0.09. As will be seen later, efficiency drops markedly as a flow coefficient of 0.15 is approached.

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ii. Diffusers

Diffusers are the stationary passages in the compressor whose primary function is to “diffuse” or slow down the gas velocity. As the impeller discharges flow into the diffuser passage (Fig. 3-5), the diffusion process converts velocity energy into pressure energy. There are two types of parallel diffusers: “vaneless” and “vaned.” In a vaneless diffuser, the gas travels at the same angle as it leaves the impeller. In vaned diffusers, vanes provided in the diffuser contribute to achieving a particular performance. Within a certain flow range, the performance of the vaned diffuser is excellent; outside this range the gas flow approaches at less than optimum angles, which reduces operating efficiency.

Vaneless diffusers may be the best choice if anticipated operating conditions include prolonged and wide swings in gas flow rate. In multistage machines, variable guide vanes may cover only the first two or three stages. Inlet guide vanes alter gas velocity and direction without incurring the more pronounced pressure drops caused by suction throttling.

iii. Internal Labyrinths

Internal labyrinths are used along the gas path to minimize leakage between stages, along the balance piston, and ahead of the seals separating compressor internals from compressor bearings. Since the gas volume at the last stage of compression is substantially reduced and an elevated pressure gradient exists at the discharge end, balance piston leakage will greatly influence overall compressor performance. separating labyrinths are provided in the sealing areas to avoid mixing of sealing and lubricating oil streams found in certain sealing systems. Some separating seals are configured with a “wind-back feature” that attempts to curtail gas leakage flow by producing counterrotation of the gas attempting to escape.

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#### iv. Bearings

Centrifugal compressors are generally designed to operate above their first critical speeds. Bearing can affect the “critical speed” of compressors.

Regardless of overall geometry, most hydrodynamic bearings with steel backing have a Babbitt lining of about 0.8 mm (0.032 inch) thickness, and clearances of 0.0015–0.002 inch per inch (mm per mm) of journal diameter. They utilize oil supply pressures in the relatively low range of 1 to 2 bar (15–30 psi). Shaft rotation and bearing geometry cause higher pressures to be self-generated within the bearing. An oil film varying in thickness from 0.0001 to 0.001 inches prevents metal-to-metal contact. Since shear action on the oil produces heat, the lubricant must be cooled.

Thrust bearings are used to locate the rotor axially and at the same time absorb any axial rotor thrust. Thrust bearing configurations include flat land, tapered land, and tilting-pad models. Their respective load-carrying capacities range from 50 psi to 250 psi. Bearing material options include tin/lead-base Babbitt and various copper-bearing alloys (bronzes) to suit specific applications. Thrust bearings must have the correct axial clearance, typically 0.008 to 0.010 inches (0.2–0.25 mm), to perform properly.

#### v. Shaft Seals

The primary purpose of compressor shaft seals is to avoid gas leakage into the atmosphere. Labyrinth seals are generally used in sealing duties associated with balance pistons (sometimes called balance drums) and seal gas equalizing region). Gas leaking past the last compressor stage enters a space that is pressure balanced or “equalized” back to compressor suction via balance-line piping. The gas so returned will be at substantially higher temperature and slightly higher pressure than the gas entering at the compressor suction nozzle at normal inlet conditions.

Restrictive carbon ring seals have virtually zero shaft clearance and present a more difficult escape path for the process gas. The rings are segmented and are available in a number of configurations. They are usually surrounded by a garter spring that keeps the individual segments assembled and also serves to apply the desired contact pressure against the shaft surface.

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Liquid film and contact types of compressor seals have been widely accepted in all kinds of hydrocarbon services at high and low pressures, but are specifically excluded from such nonhydrocarbon services as high-pressure air and oxygen compression. Compressors handling charge gas, process refrigerants such as ammonia/propane, hydrogen- rich gases, and fertilizers have generally used liquid film or contact seals.

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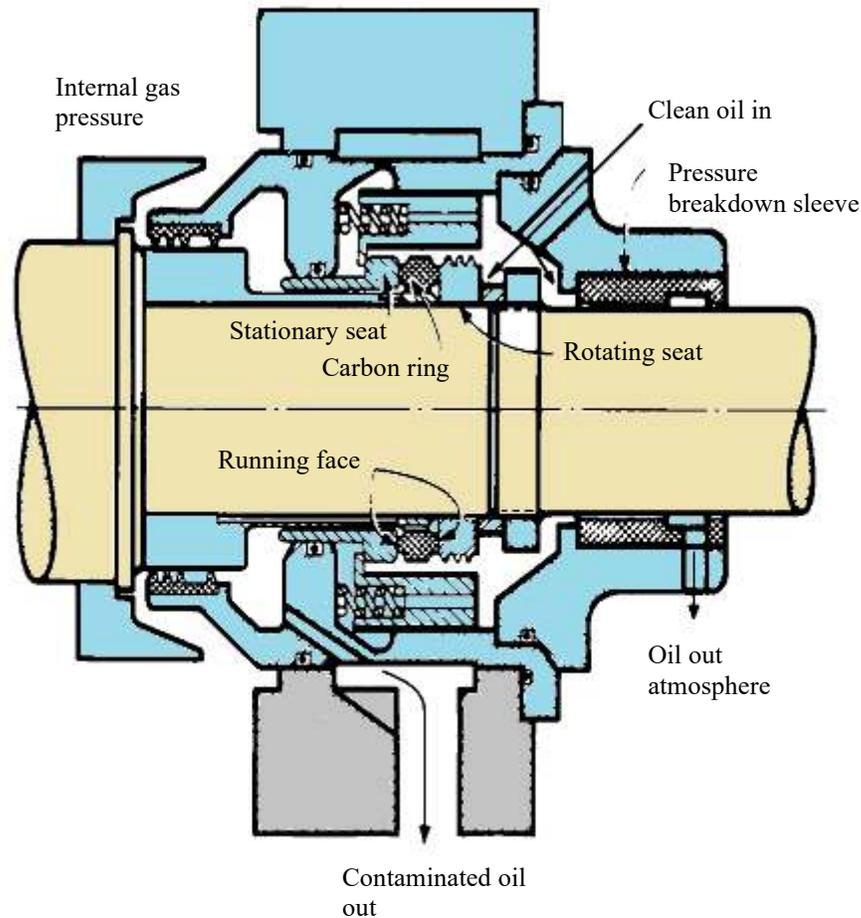


Figure 5: Mechanical (Contact) Shaft Seal

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## DEFINITIONS

**Adiabatic / Isentropic** – This model assumes that no energy (heat) is transferred to or from the gas during the compression, and all supplied work is added to the internal energy of the gas, resulting in increases of temperature and pressure.

**Antisurge**—automatic control instrumentation designed to prevent compressors from operating at or near pressure and flow conditions that result in surge. Antisurge protection—protection that prevents damage to the compressor.

**Bearing** – Is a device to permit constrained relative motion between two parts, typically rotation or linear movement. Compressors employ at least half a dozen types of journal bearings. Essentially all of these designs consist of partial arc pads having a circular geometry.

**Blades**- Rotating airfoils for both compressors and turbines unless modified by an adjective.

**Centrifugal compressor**—a dynamic compressor in which the gas flows from the inlet located near the suction eye to the outer tip of the impeller blade.

**Critical speed** - somewhat analogous to the resonant frequency at which a rotor assembly would vibrate if struck by a hammer.

**Compressor Efficiency** - This is the ratio of theoretical horse power to the brake horse power.

**Cylinder**—a cylindrical chamber in a positive displacement compressor in which a piston compresses gas and then expels the gas.

**Demister**—a device that promotes separation of liquids from gases.

**Diaphragm compressor**—Is a positive displacement reciprocating compressor using a flexible membrane or diaphragm in place of a piston.

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**Discharge Pressure** - Air pressure produced at a particular point in the system under specific conditions measured in psi (pounds per square inch).

**Head polytropic**—The force (or pressure) that a polytropic (heat transfer to/from the fluid can exist and the fluid may not behave as an ideal gas) compression process raises the gas from suction level to discharge level measured in inches or feet of water column

**Impeller** -Is a rotor inside a shaped housing forced the gas to rim of the impeller to increase velocity of a gas and the pressure in compressor.

**Isentropic process** - An adiabatic process that is reversible. This isentropic process occurs at constant entropy. Entropy is related to the disorder in the system; it is a measure of the energy not available for work in a thermodynamic process

**Intercooler** - After compression, gas temperature will rise up but it is limited before entering to the next compression. Temperature limitation is depending to what sealing material to be used and gas properties. Intercooler is needed to decrease temperature before entering to the next compression.

**Labyrinth seal**—a shaft seal designed to restrict flow by requiring the fluid to pass through a series of ridges and intricate paths.

**Liquid ring compressor**—a rotary compressor that uses an impeller with vanes to transmit centrifugal force into a sealing fluid, such as water, driving it against the wall of a cylindrical casing.

**Lubrication system**—a system that circulates and cools sealing and lubricating oils.

**Multistage centrifugal compressor**—A machine having two or more impellers operating in series on a single shaft and in a single casing.

**Polytropic** - This model takes into account both a rise in temperature in the gas as well as some loss of energy (heat) to the compressor's components. This assumes that heat may enter or leave the system, and that input shaft work can appear as both increased

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pressure (usually useful work) and increased temperature above adiabatic (usually losses due to cycle efficiency). Compression efficiency is then the ratio of temperature rise at theoretical 100 percent (adiabatic) vs. actual (polytropic).

**Pressure discharge**—The total gas pressure (static plus velocity) at the discharge port of the compressor.

**Process compression stage** - Is defined as the compression step between two adjacent pressure levels in a process system. It may consist of one or more compressor stages.

**Reduced pressure**—The ratio of the absolute pressure of a gas to its critical pressure.

**Reduced temperature**—The ratio of the absolute temperature of a gas to its critical temperature.

**Rotor**—The rotating element of a compressor composed of the impeller(s), shaft, seals and may include shaft sleeves and a thrust balance piston.

**Seal system**—devices designed to prevent the process gas from leaking from the compressor shaft.

**Separator**—a device used to physically separate two or more components from a mixture.

**Surging**—the intermittent flow of pressure through a compressor that occurs when the discharge pressure is too high, resulting in flow reversal within a compressor.

**Temperature absolute**—The temperature of a body relative to the absolute zero temperature, at which point the volume of an ideal gas theoretically becomes zero. (Fahrenheit scale is minus 459.67°F/Celsius scale is minus 273.15°C).

**Temperature discharge**—The temperature of the medium at the discharge flange of the compressor.

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## NOMENCLATURE

d <sub>2</sub>	impeller diameter, in
H <sub>p</sub>	total required polytropic head, ft lb/lb
H <sub>stg</sub>	head per stage, ft lb/lb
H <sub>stgallow</sub>	allowable Head per stage, ft lb/lb
k	Isentropic exponent
M <sub>w</sub>	Molecular weight
N	compressor shaft speed, rpm
n	polytropic exponent
P <sub>1</sub>	inlet pressure, psia
P <sub>2</sub>	discharge pressure, psia
P <sub>r</sub>	Reduced Pressure, psia
P <sub>c</sub>	Critical Pressure, psia
P	Absolute Pressure, psia
Q <sub>l</sub>	inlet volume flow, ft <sup>3</sup> /min
Q <sub>ls</sub>	volume into last impeller, ft <sup>3</sup> /min
R	Specific gas constant
r <sub>p</sub>	pressure ratio
T	Absolute Temperature, R
T <sub>1</sub>	Absolut inlet temperature, R
T <sub>2</sub>	discharge temperature, R
T <sub>i</sub>	Inlet temperature, F
T <sub>r</sub>	Reduced Temperature,
T <sub>c</sub>	Critical Temperature
u <sub>2</sub>	impeller tip speed, ft/s
w	Mass flow, lb/min
W <sub>p</sub>	power required, hp
Z	Compresibility
z	number of stages

## Greek letters

δ	last stage flow coefficient
η <sub>p</sub>	polytropic efficiency

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