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		Rev: 02
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KLM Technology Group Unit 23-04 Menara Landmark 12 Jalan Ngee Heng 80000 Johor Bahru, Malaysia	<p style="text-align: center;">COMPRESSOR SELECTION AND SIZING (ENGINEERING DESIGN GUIDELINE)</p>	Author: Rev 01- A L Ling Rev 02- Viska Mulyandasari
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INTRODUCTION

Scope

This design guideline covered the selection and sizing method of compressor used in the typical processing industries. The guideline helps engineers to understand basic design of the difference types of compressor, and gain knowledge in selection and sizing.

Compressors are widely used in industries to transport fluids. It is a mechanical device that compresses a gas. There are many types of compressors, thus a proper selection is needed to fulfil the typical necessity of each industry. Generally, the compression of gases may be accomplished in device with rotating blades or in cylinders with reciprocating pistons. Rotary equipment is used for high volume flow where the discharge pressure is not too high, while the reciprocating compressors are required for high pressures. Besides volumetric flow rate, there are also many parameters to be considered, includes the valid standards to be used.

Compressor selection is important; hence the theory for each type of compressor is included in this guideline as additional information. All the important parameters used in the guideline are well explained in the definition section, which helps the reader to understand the meaning of the parameters or the term used.

The theory section includes thermodynamics as a basic theory of gas compression, comparison of several types of compressor, sizing theory, and formulations for the compressor design. There are many equations found to sizing the compressor, hence the practical (based on ideal condition) and generally used equations are added in this design guideline. In the application section, five cases examples are included to guide the reader o do the compressor sizing.

In the end of this guideline, example specification data sheet is included which is created base on industrial example. Calculation spreadsheet is included as well and to aid user more understand to apply the theory for calculations.

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History of Compressor

One of the earliest recorded uses of compressed gas (air) dates back to 3rd century B.C. This early use of compressed air was the “water organ.” The invention of the “water organ” is commonly credited to Ctesibius of Alexandria. Ctesibius also developed the positive displacement cylinder and piston to move water.

The water organ consisted of a water pump, a chamber partly filled with air and water, a row of pipes on top (organ pipes) of various diameters and lengths plus connecting tubing and valves. By pumping water into the water/air chamber the air becomes compressed. This concept was further improved by Hero of Alexandria (also noted for describing the principles of expanding steam to convert steam power to shaft power).

In the 1850s, while trying to find a replacement for the water wheel at their family’s woolen mill, Philander and Francis Roots devised what has come to be known as the Roots blower. Their design consisted of a pair of figure-eight impellers rotating in opposite directions. While some Europeans were simultaneously experimenting with this design, the Roots brothers perfected the design and put it into large-scale production.

In 1808 John Dumball envisioned a multi-stage axial compressor. Unfortunately his idea consisted only of moving blades without stationary airfoils to turn the flow into each succeeding stage. Not until 1872 did Dr. Franz Stolze combine the ideas of John Barber and John Dumball to develop the first axial compressor driven by an axial turbine.

Due to a lack of funds, he did not build his machine until 1900. Dr. Stolze’s design consisted of a multi-stage axial flow compressor, a single combustion chamber, a multi-stage axial turbine, and a regenerator utilizing exhaust gases to heat the compressor discharge gas.

Type of Compressor

Compressor is a device used to increase the pressure of compressible fluid, either gas or vapour, by reducing the fluid specific volume during passage of the fluid through compressor. One of basic aim of compressor usage is to compress the fluid, then deliver it to a higher pressure than its original pressure.

The inlet and outlet pressure level is varying, from a deep vacuum to a high positive pressure, depends on process’ necessity. This inlet and outlet pressure is related, corresponding with the type of compressor and its configuration. As shown in Figure 1,

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compressors are generally classified into two separate and distinct categories: dynamic and positive displacement.

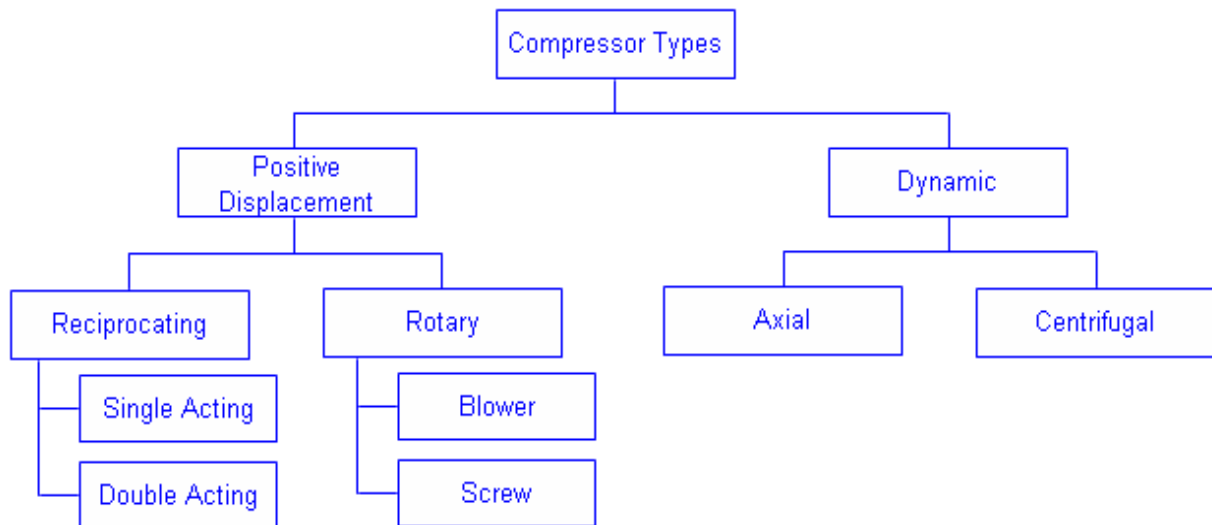


Figure 1 Compressor types based on operating principles

(A) Dynamic Compressor

Dynamic compressor is a continuous-flow compressor which includes centrifugal compressor and axial flow compressor. It is widely used in chemical and petroleum refinery industry for specific services. They are also used in other industries such as the iron and steel industry, pipeline booster, and on offshore platforms for reinjection compressors.

The dynamic compressor is characterized by rotating impeller to add velocity and pressure to fluid. Compare to positive displacement type compressor, dynamic compressor are much smaller in size and produce much less vibration.

(I) Centrifugal Compressor

The centrifugal compressor is a dynamic machine that achieves compression by applying inertial forces to the gas (acceleration, deceleration, and turning) by means of rotating impellers. It is made up of one or more stages; each stage consists of an impeller as the

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rotating element and the stationary element, i.e. diffuser. There are two types of diffuser: vaneless diffusers and vaned diffusers.

Vaneless diffuser is widely used in wide operating range applications, while the vaneless diffuser is used in applications where a high pressure ratio or high efficiency is required. Those parts of centrifugal compressor are simply pictured below.

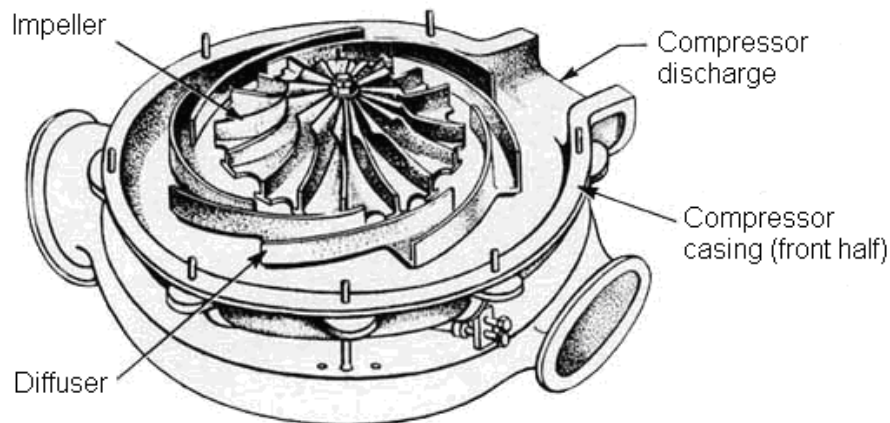


Figure 2 Centrifugal compressor

In centrifugal compressor, the fluid flow enters the impeller in an axial direction and discharged from an impeller radially at a right angle to the axis of rotation. The gas fluid is forced through the impeller by rapidly rotating impeller blades. The gas next flows through a circular chamber (diffuser), following a spiral path where it loses velocity and increases pressure.

The deceleration of flow or “diffuser action” causes pressure build-up in the centrifugal compressor. Briefly, the impeller adds energy to the gas fluid, and then the diffuser converts it into pressure energy.

The maximum pressure rise for centrifugal compressor mostly depends on the rotational speed (RPM) of the impeller and the impeller diameter. But the maximum permissible speed is limited by the strength of the structural materials of the blade and the sonic velocity of fluid; furthermore, it leads into limitation for the maximum achievable pressure rise.

Hence, multistage centrifugal compressors are used for higher pressure lift applications. A multistage centrifugal compressor compresses air to the required pressure in multiple stages.

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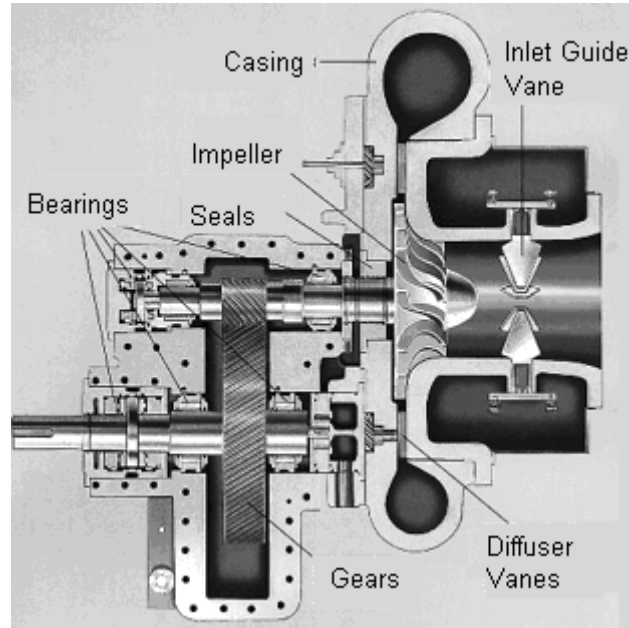


Figure 3 Single stage compressor

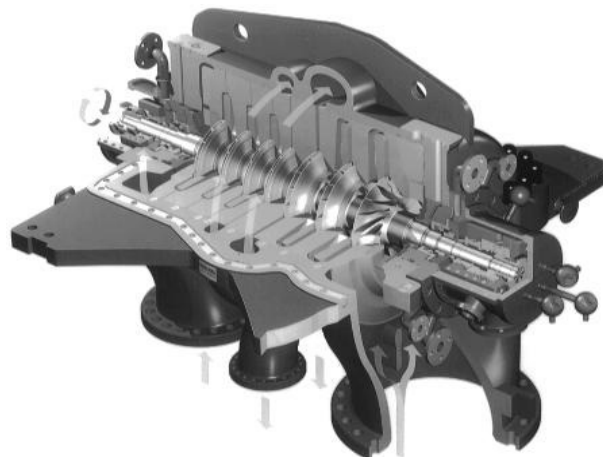


Figure 4 Multi stage compressor

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Typical centrifugal for the single-stage design can intake gas volumes between 100 to 150,000 inlet acfm. A multi-stage centrifugal compressor is normal considered for inlet volume between 500 to 200,000 inlet acfm.

It designs to discharge pressures up to 2352 psi, which the operation speeds of impeller from 3,000 rpm to higher. There is limitation for velocity of impeller due to impeller stress considerations; it is ranged from 0.8 to 0.85 Mach number at the impeller tip and eye. Centrifugal compressors can be driven by electrical motor, steam turbine, or gas turbines.

Based on application requirement, centrifugal compressors may have different configurations. They may be classified as follows:

i. Compressors with Horizontally-split Casings

Horizontally-split casings consisting of half casings joined along the horizontal center-line are employed for operating pressures below 60 bars

ii. Compressors with Vertically-split Casings

Vertically-split casings are formed by a cylinder closed by two end covers. It is generally multistage, and used for high pressure services (up to 700 kg/cm²).

iii. Compressors with Bell Casings

Barrel compressors for high pressures have bell-shaped casings and are closed with shear rings instead of bolts.

iv. Pipeline Compressors

They have bell-shaped casings with a single vertical end cover and are generally used for natural gas transportation.

v. SR Compressors

These compressors are suitable for relatively low pressure services. They have the feature of having several shafts with overhung impellers.

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The advantages and disadvantages of centrifugal compressor can be summarised into this table below.

Advantages	Disadvantages
High efficiency approaching two stages reciprocating compressor	High initial cost
Can reach pressure up to 1200 psi	Complicated monitoring and control systems
Completely package for plant or instrument air up through 500 hp	Limited capacity control modulation, requiring unloading for reduced capacities
Relatives first cost improves as size increase	High rotational speed require special bearings and sophisticated vibration and clearance monitoring
Designed to give lubricant free air	Specialized maintenance considerations
Does not require special foundations	

(II) Axial Flow Compressor

Axial flow compressors are used mainly as compressors for gas turbines. They are used in the steel industry as blast furnace blowers and in the chemical industry for large nitric acid plants.

Compare to other type of compressor, axial flow compressors are mainly used for applications where the head required is low and with the high intake volume of flow. The efficiency in an axial flow compressor is higher than the centrifugal compressor. They are available in sizes producing pressures in excess of 100 psi at intake volumes between 23,500 to 588,500 acfm.

The component of axial flow compressor consist of the rotating element that construct from a single drum to which are attached several rows of decreasing-height blades having airfoil cross sections. Between each rotating blade row is a stationary blade row. All blade angles and areas are designed precisely for a given performance and high efficiency.

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One additional row of fixed blades (inlet guide vanes) is frequently used at the compressor inlet to ensure that air enters the first stage rotors at the desired angle. Also, another diffuser at the exit of the compressor might be added, known as exit guide vanes, to further diffuse the fluid and control its velocity.

Axial flow compressors do not significantly change the direction of the flow stream; the fluid flow enters the compressor and exits from the gas turbine in an axial direction (parallel with the axis of rotation). It compresses the gas fluid by first accelerating the fluid and then diffusing it to increase its pressure.

The fluid flow is accelerated by a row of rotating airfoils (blades) called the rotor, and then diffused in a row of stationary blades (the stator). Similar to the centrifugal compressor, the stator then converts the velocity energy gained in the rotor to pressure energy. One rotor and one stator make up a stage in a compressor. The axial flow compressor produces low pressure increase, thus the multiple stages are generally use to permit overall pressure increase up to 30:1 for some industrial applications.

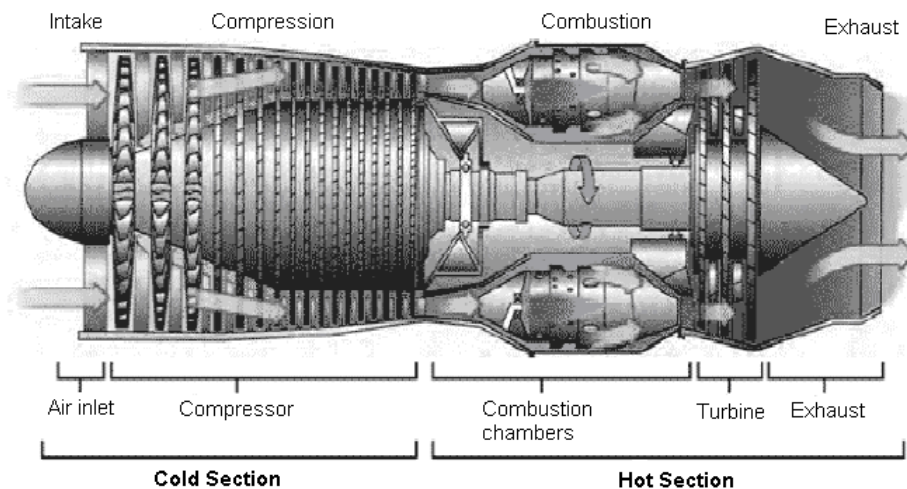


Figure 5 Axial flow compressor

Driver of axial flow compressor can be steam turbines or electric motors. In the case of direct electric motor drive, low speeds are unavoidable unless sophisticated variable-frequency motors are employed. Here are the advantages and disadvantages of axial flow compressor.

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Advantages

High peak efficiency

Small frontal area for given airflow

Straight-through flow, allowing high ram efficiency

Increased pressure rise due to increased number of stages with negligible losses

Disadvantages

Good efficiency over narrow rotational speed range

Difficulty of manufacture and high cost.

Relatively high weight

High starting power requirements

(B) Positive-Displacement Compressor

Positive displacement compressors deliver a fixed volume of air at high pressures; it commonly can be divided into two types: rotary compressors and reciprocating compressors. In all positive displacement machines, a certain inlet volume of gas is confined in a given space and subsequently compressed by reducing this confined space or volume. At this elevated pressure, the gas is next expelled into the discharge piping or vessel system.

(I) Rotary Compressors

Rotary compressor is a group of positive displacement machines that has a central, spinning rotor and a number of vanes. This device derives its pressurizing ability from a spinning component. The units are compact, relatively inexpensive, and require a minimum of operating attention and maintenance. In a rotary compressor, the pressure of a gas is increased by trapping it between vanes which reduce it in volume as the impeller rotates around an axis eccentric to the casing. It is pictured below:

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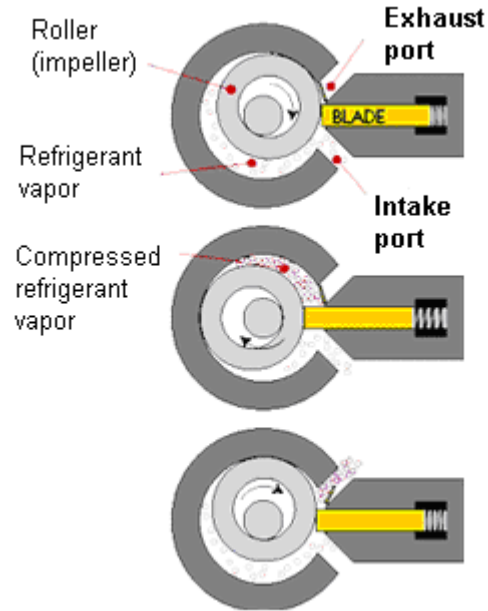


Figure 6 Rotary compressor

The volume can be varied only by changing the speed or by bypassing or wasting some of the capacity of the machine. The discharge pressure will vary with the resistance on the discharge side of the system. Rotary compressors are generally classified as screw compressor, vane type compressor, lobe and scroll compressor. The main difference between each type is their rotating device. The advantages and disadvantages of rotary compressor are shown in a table below.

Advantages	Disadvantages
Simple design	High rotational speed
Low to medium initial and maintenance cost	Shorter life expectancy than any other designs
Two-stages design provide good efficiencies	Single-stage designs have lower efficiency
Easy to install	Difficulty with dirty environment
Few moving parts	

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(II) Reciprocating Compressors

The reciprocating, or piston compressor, is a positive displacement compressor that uses the movement of a piston within a cylinder to move gas from one pressure level to another higher pressure level. Reciprocating compressors might be considered as single acting, when the compressing is accomplished using only one side of the piston, or double acting when it is using both sides of the piston.

They are used mainly when high-pressure head is required at a low flow. Generally, the maximum allowable discharge-gas temperature determines the maximum compression ratio. Reciprocating compressors are furnished in either single-stage or multistage types. For single stage design, the entire compression is accomplished with a single cylinder or a group of cylinders in parallel.

Intercoolers are provided between stages on multistage machines. These heat exchangers remove the heat of compression from the gas and reduce its temperature to approximately the temperature existing at the compressor intake. Such cooling reduces the volume of gas going to the high-pressure cylinders, reduces the power required for compression, and keeps the temperature within safe operating limits.

Typical compression ratios are about 3 per stage to limit discharge temperatures to perhaps 300°F to 350°F. Some reciprocating compressors have as many as six stages, to provide a total compression ratio over 300.

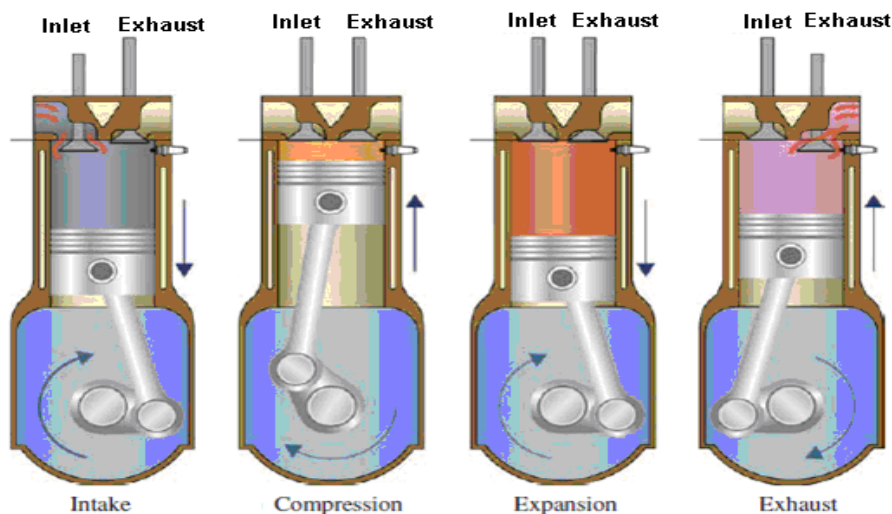


Figure 7 Reciprocating compressor

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The intake gas enters the suction manifold into the cylinder because the vacuum condition is created inside the cylinder as the piston moves downward. After the piston reaches its bottom position it begins to move upward. The intake valve closes, trapping the gas fluid inside the cylinder. As the piston continues to move upward it compresses the gas fluid, increasing its pressure. The high pressure in the cylinder pushes the piston downward. When the piston is near the bottom of its travel, the exhaust valve opens and releases high pressure gas fluid.

Here are some advantages and disadvantages of reciprocating compressor.

Advantages	Disadvantages
Simple design, easy to install	Higher maintenance cost
Lower initial cost	Many moving parts
Large range of horsepower	Potential for vibration problems
Special machines can reach extremely high pressure	Foundation may be required depending on size
Two stages models offer the highest efficiency	Many are not designed to run at full capacity

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Major Components of Compressor

Centrifugal Compressor

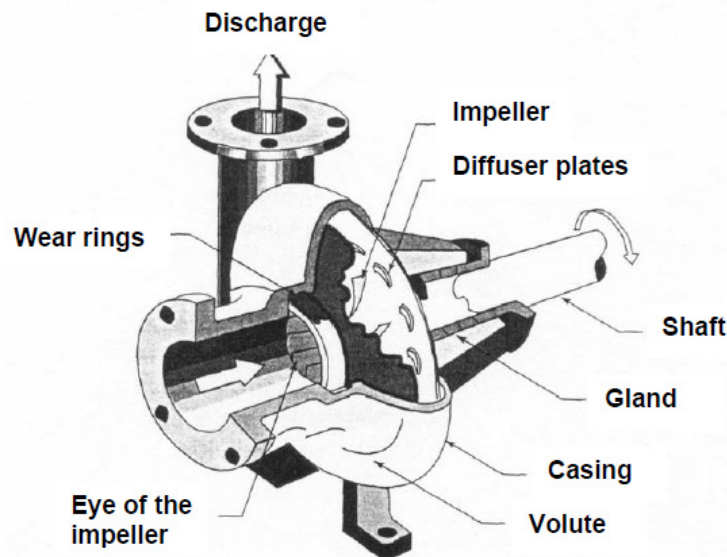


Figure 8 Components of centrifugal compressor

Centrifugal compressor consists of several components, they are:

- i. **Casing**
A typical high pressure compressor consists of inner and outer casing. Commonly, the nozzles are at the outer casing while the inner parts, such as diaphragms, impeller, and shaft are at inner casing.
- ii. **Diaphragm**
The diaphragm might be made of cast steel, alloyed cast iron, forged steel, or stainless steel material. It has several functions in centrifugal compressor: to perform the dynamic flow path of the gas fluid inside the compressor, to form the separation wall between one compressor stage and the subsequent one, and to convert the kinetic energy of the gas leaving the impeller into pressure energy.
- iii. **Rotor assembly**
Rotor in centrifugal compressor has the basic function to impart the required compression energy to gas fluid. The rotor assembles with some equipments and parts, they are:

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- **Impeller**
It has a function to impart the energy to gas fluid and consist of two basic components: an inducer and blades. There are three types of impeller, as shown in table below.

Type of Impeller	Advantages	Disadvantages
Radial blades	<ol style="list-style-type: none"> 1. Reasonable compromise between low energy transfer and high absolute outlet velocity 2. No complex bending stress 3. Ease in manufacturing 	Surge margin is narrow
Backward curved blades	<ol style="list-style-type: none"> 1. Low outlet kinetic energy 2. Low diffuser inlet Mach number 3. Surge margin is widest of three 	<ol style="list-style-type: none"> 1. Low energy transfer 2. Complex bending stress 3. Difficulty in manufacturing
Forward curved blades	High energy transfer	<ol style="list-style-type: none"> 1. High outlet kinetic energy 2. High diffuser inlet Mach number 3. Complex bending stress 4. Difficulty in manufacturing

- **Shaft**
Shaft is commonly made of forged alloy with the impellers, spacers, and the balancing drums are shrunk fitted on it.
- **Bearings**
The bearings provide support and positioning for the rotating components. Radial support is generally provided by journal or roller bearings, while an axial positioning is provided by thrust bearings.

iv. **Seals**

Seals are very important to prevent frictions and wears in centrifugal compressor since it spins at very high speed.

- **Labyrinth seals**
It is the simplest sealing device which has major advantages, such as: their simplicity, reliability, tolerance to dirt, system adaptability, very low shaft power consumption, material selection flexibility, minimal effect on rotor

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dynamic, back diffusion reduction, integration of pressure, lack of pressure limitations, simple to manufacture and tolerance to gross thermal variations.

- Mechanical seals
This device has two major elements: the oil-pressure-gas seal and breakdown bushing. It also has a positive shutdown device which will attempt to maintain gas pressure in the casting when the compressor pressure is at rest and the seal oil is not being applied.
- Dry gas seals
Dry gas seals are basically mechanical seals consisting of a mating ring, which rotates, and a primary ring, which is stationary.

Reciprocating Compressor

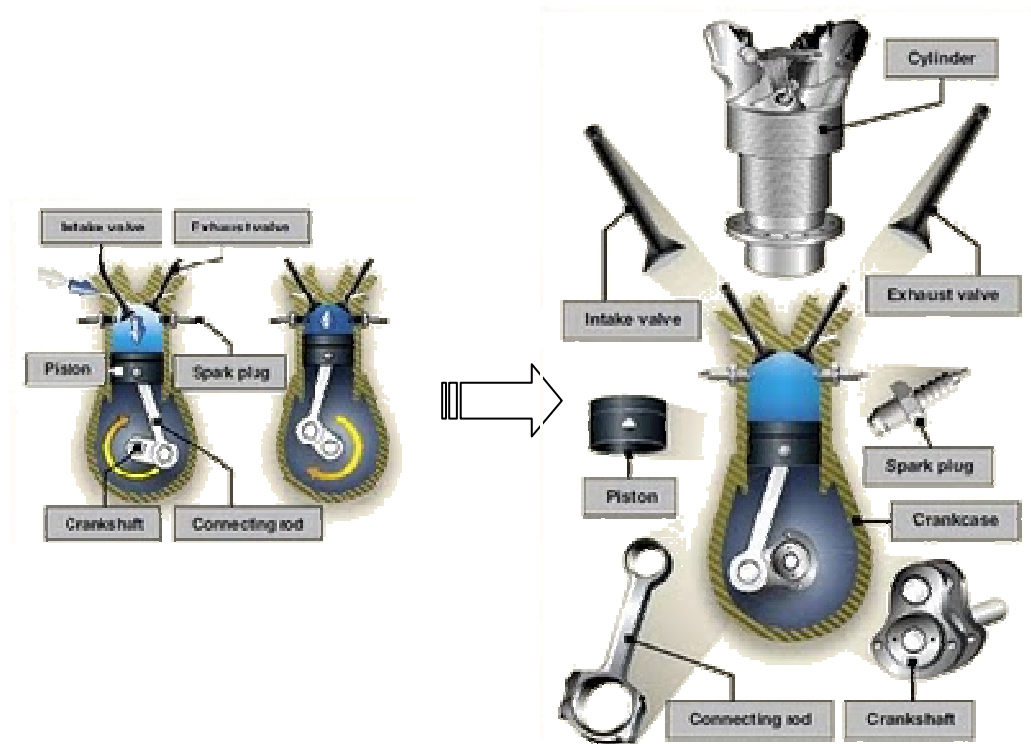


Figure 9 Components of reciprocating compressor

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Major components of reciprocating compressor are:

- i. **Crankcase**
The crankcase or frame of reciprocating compressor is generally made from cast iron or steel plate. Crankcase is the housing of crankshaft and also serves as the oil reservoir.
- ii. **Piston**
Piston is a commonly component of reciprocating devices. It is the moving component that is contained by a cylinder which purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod or connecting rod.
- iii. **Cylinder**
A compressor cylinder is the housing of piston, suction and discharge valves, cooling water passages (or cooling fins), lubricating oil supply fittings and various unloading devices.

There are two types of compressor cylinder designs: valves in bore and valves out of bore. The valves in bore design has the compressor valves located radially around the cylinder bore within the length of the cylinder bore.

These cylinders have the highest percentage of clearance due to the need for scallop cuts at the head-end and crank end of the cylinder bore to allow entry and discharge for the process gas.

The valves out of bore design consists of compressor valves at each end of the cylinder. While this design provides a lower percent clearance it is more maintenance intense.

- iv. **Crankshaft**
The crankshaft is the part of a reciprocating compressor which translates reciprocating linear piston motion into rotation. It is typically made of forged steel, consists of crankpins and bearing journals.
- v. **Connecting rod**
In a reciprocating compressor, the connecting rod or conrod connects the piston to the crankshaft; thus form a simple mechanism that converts linear motion into rotating motion.

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- vi. Crosshead
The crosshead rides in the crosshead guide moving linearly in alternate directions with each rotation of the crankshaft. The piston rod connects the crosshead to the piston. Therefore, with each rotation of the crankshaft the piston moves linearly in alternating directions.
- vii. Piston rod
A piston rod joins a piston to a connecting rod. It may have a collar on the end that connects to the piston.

Design Consideration

Operating Condition

- (I) Fluid properties:
 - a. Gas Composition- In design of compressor, full gas compositions data are very important. It should be analysis and listed in compressor specification sheet with each component name, molecular weight, boiling point. This data are important determined the volume flow rate of the compressed gas, average molecular weight, compressible factor, and specific heat ratio.
 - b. Corrosiveness-Corrosive gas stream constituents must be identified for all operating conditions including transients. This important because corrosion gas as wet H₂S in compression service can cause stress corrosion cracking of high strength materials.
 - c. Fouling tendency- The compressor design specification sheet should include the fouling tendency of the gas and specify compressor flushing facilities if required. This is a important parameter for the selection of the type of compressor design. Axial and high speed, single stage centrifugal is not suitable for fouling service. Flushing allows helical screw and conventional centrifugal compressors to be used in a fouling service.
 - d. Liquid in gas stream-Liquid in the gas stream should be avoided because is harmful to compressors. For feed stream into compressor that content liquid in gas stream, liquid separators and heat tracing and insulation of compressor inlet lines should be provided when ambient temperature is below the dew point of the

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gas at the compressor inlet or when handling hydrocarbon gas components heavier than ethane.

- e. Inlet pressure –Gas stream inlet pressure should be specified in compressor specification sheet for the lowest value; this is to meet the guarantee performance of compressor. The allowance pressure drop of 0.3 psi in through compressor inlet hood, screen, filter and piping should be expected.
- f. Discharge pressure - Centrifugal and axial compressors, the discharge pressure specified is at the discharge flange. Meanwhile reciprocating and rotary compressors, the specification should note that the discharge pressure specified is downstream of the pulsation suppression device for reciprocating compressors and downstream of the discharge silencing device on rotary compressors.
- g. Inlet temperature- For gas stream temperature is affects the volume flow rate, compression service head requirements, and required power. Because of this inlet temperatures for compression process should be specified full range.
- h. Discharge temperature- Discharge temperature of Compressor is affected by inlet temperature, pressure ratio, gas specific heat values, and the efficiency of compression. This temperature is important in determining compressor mechanical design, gas fouling tendency, process compression stage selection, and cooler and piping design.

(II) Mechanical design of compressor:

- a. Casing & cylinder- Maximum allowable working pressure is much parameter listed in compressor specification sheet. This data together with maximum allowable temperature are use for compressor manufacturer to fabricate the casing & cylinder that can withstand for MAWP & maximum allowance temperature or higher. For centrifugal and axial compressors, the casing MAWP is computed by adding the maximum inlet pressure to the maximum differential pressure that the compressor can develop at the most severe combination of conditions. Meanwhile for reciprocating compressor cylinders and screw compressor casings, the MAWP should exceed the rated discharge pressure by 10 percent or 25 psi, whichever is greater.
- b. Casing & cylinder- Maximum allowable temperature for the centrifugal or axial compressor should be the maximum discharge temperature anticipated over the compressor speed and capacity range and include a margin of approximately 50°F. For reciprocating compressor cylinders and screw compressor casings, the

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specified maximum allowable temperature should exceed the rated discharge temperature by 50°F.

- c. Piping flanges and rating – Connection of piping line sizes, flange rating and facing for all compressor inlet and outlet should be indicated in design specification sheet.
- d. Shaft and piston rod sealing – The type of shaft or piston rod seal and supporting auxiliary should be specified
- e. Lube oil and seal oil system -The function of these systems is primarily to provide an uninterrupted supply of clean and cooled fluid to the bearings and seals of the compressor, gear and driver. These are important systems for compressors, thus system design of these systems should be clearly stated in design specification sheet.

(III) Process compression stages

Compression ratio is the relation of discharge pressure (P2) over the suction pressure (P1) for a compressor, $P2/P1$. For the high-pressure compression services the compressor is design for multiple process compression stages and sometime the coolers are include between the stages to remove the heat of compression. Reasons for providing process compression staging are:

- a. To limit the discharge temperature of each stage to acceptable levels from the standpoints of both compressor design restraints and the fouling tendency of the compressed gas.
- b. To make side streams available in the compression sequence at intermediate pressure levels such as in process refrigeration systems.
- c. To reduce “compressor stage” inlet temperatures thereby reducing the amount of work (head) required to achieve a given pressure ratio.
- d. To satisfy differential pressure and pressure ratio limits of various compressor types, e.g., axial thrust load limitations for centrifugals and axial, piston rod stress limits in reciprocating compressors, and rotor lateral deflection and axial thrust in screw compressors.

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- e. Provide the condition for include intercooler between stages, that will help reduce horsepower require for compression, and keeps the temperature within safe operating limits.

DEFINITION

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.

Aftercooler - Aftercooler is a heat exchanger which is used when discharge gas temperature leaving compressor shall be decreased before entering to other equipment or system.

Axially split- A joint that is parallel to the shaft centreline.

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.

Capacity - The amount of air flow delivered under specific conditions, usually expressed in cubic feet per minute (CFM).

Clearance - Some volume which is remains vacant between the top position of the piston and the cylinder

Compression Ratio - The ratio of the discharge pressure to the inlet pressure.

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

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

Discharge Temperature - The temperature at the discharge flange of the compressor.

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Gauge Pressure - The pressure determined by most instruments and gauges, usually expressed in psig. Barometric pressure must be considered to obtain true or absolute pressure (psig).

Horsepower, Brake - Horsepower delivered to the output shaft of a motor or engine, or the horsepower required at the compressor shaft to perform work.

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.

Inlet Pressure - The actual pressure at the inlet flange of the compressor typically measure in psig.

Inlet volume flow: The flow rate expressed in volume flow units at the conditions of pressure, temperature, compressibility, and gas composition, including moisture content at the compressor inlet flange.

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.

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.

Isobaric process – Means that the volume increases, while the pressure is constant.

Isochoric process - Is a constant-volume process, meaning that the work done by the system will be zero. In an isochoric process, all the energy added as heat remains in the system as an increase in internal energy.

Isothermal- This model assumes that the compressed gas remains at a constant temperature throughout the compression or expansion process. In this cycle, internal energy is removed from the system as heat at the same rate that it is added by the mechanical work of compression. Isothermal compression or expansion more closely models real life when the compressor has a large heat exchanging surface, a small gas volume, or a long time scale (i.e., a small power level). Compressors that utilize inter-stage cooling between compression stages come closest to achieving perfect isothermal compression. However, with practical devices perfect isothermal compression is not

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attainable. For example, unless you have an infinite number of compression stages with corresponding intercoolers, you will never achieve perfect isothermal compression.

Maximum allowable temperature – The maximum continuous temperature for the manufacturer has designed the equipment.

Maximum allowable working pressure (MAWP) - This is the maximum continuous pressure for which the manufacturer has designed the compressor when it is operating at its maximum allowable temperature.

Maximum inlet suction pressure – The highest inlet pressure the equipment will be subject to in service.

Multi-Stage Compressors - Compressors having two or more stages operating in series.

Normal operating condition – The condition at which usual operation is expected and optimum efficiency is desired. This condition is usually the point at which the vendor certifies that performance is within the tolerances stated in this standard.

Piston Displacement - The volume swept by the piston; for multistage compressors, the piston displacement of the first stage is the overall piston displacement of the entire unit.

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 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).

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.

Radially split - A joint which is perpendicular to the shaft centerline.

Rated discharge pressure - Is the highest pressure required to meet the conditions specified by the purchaser for the intended service.

Rated discharge temperature - Is the highest predicted operating temperature resulting from any specified operating condition.

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Reversible process - The process which can be reversed back completely. The process can be perfectly reversible only if the changes in the process are infinitesimally small. The changes which occur during reversible process are in equilibrium with each other. Inversely, a process that is not reversible is said to be irreversible.

Rod reversal - Is a change in direction of force in the piston-rod loading (from tension to compression or vice versa) that results in a load reversal at the crosshead pin during each revolution.

Rotor - The rotors are usually of forged solid design. Welded hollow rotors may be applied to limit the moment of inertia in larger capacity compressors. Balancing pistons to achieve equalization of rotor axial thrust loads are generally integral with the rotor. Rotating blades are located in peripheral grooves in the rotor.

Surge - The volume flow capacity below which a centrifugal compressor becomes aerodynamically unstable.

Theoretical Horse Power - This is the horse power required to compress adiabatically the air delivered by a compressor through specified pressure range, without any provision for lost energy.

Volumetric Efficiency - This is the ratio of the capacity of a compressor to the piston displacement of compressor.

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NOMENCLATURE

p	= absolute pressure (lb/ft ²)
v	= specific volume (ft ³ /lb)
T	= absolute temperature (°R)
R	= $\frac{\bar{R}}{MW}$ = individual gas constant (ft-lb/lb-°R)
V	= volume (ft ³)
n	= mole mass (kmol)
\bar{R}	= universal gas constant = 1545 (ft-lb/mol-°R)
Q_h	= heat into the system (Btu)
\bar{W}_w	= work by the system (Btu)
ΔE	= change in system energy (Btu)
Q	= capacity, million standard ft ³ /day
Q_{std}	= capacity, million standard ft ³ /day (ref 14.7 psia, 520°R)
P_s	= suction pressure, psia (flange)
T_s	= suction temperature, °R
Z_{std}	= compressibility factor at standard conditions
Z_s	= compressibility factor at suction conditions
$DISP$	= cylinder displacement, ft ³ /min
CL	= cylinder clearance volume as decimal fraction of displaced volume
R_p	= pressure ratio across cylinder (flange to flange)
N	= isentropic volume exponent at operating conditions (specific heat ratio for ideal gas)
A_p	= piston area, in ²
A_r	= piston rod area, in ²
S	= stroke, in.

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rpm = rotative speed

N_t = isentropic temperature exponent defined by real gas properties

R_s = stage pressure ratio

R_t = total ratio

N_s = number of stages

N_c = compression efficiency

N_m = mechanical efficiency

k = polytropic exponent

\dot{m} = mass flow rate, lbm/min

C = cylinder clearance, % $\left(\frac{\text{cylinder clearance volume}}{\text{displaced volume}} \times 100 \right)$

L = loss factor, %

$P_{s(atm)}$ = suction pressure in atm

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THEORY

Thermodynamic

Thermodynamic is a branch of science which deals with energy. It is core to engineering and allows understanding of the mechanism of energy conversion. Compression theory is primarily defined by the Gas Laws and the First and Second Laws of Thermodynamics.

(I) Gas Laws

The general law of state for gases is based on the laws of Charles, Boyle, Gay-Lussac and Avogadro. This states how pressure, volume, and temperature affect each other. It can be written:

$$\frac{p \times v}{T} = R = \text{gas constant} \quad \text{Eq (1a)}$$

The constant R only concerns the properties of the gas. If the mass m of the gas takes up the volume V, the relation can be written:

$$p \times V = n \times \bar{R} \times T \quad \text{Eq (1b)}$$

An additional term may be considered at this time to correct for deviations from the ideal gas laws. This term is the compressibility factor "Z." Therefore, the ideal gas equation becomes:

$$p \times v = Z \times R \times T \quad \text{Eq (1c)}$$

(II) First Law of Thermodynamics

Thermodynamics' first main principle says that energy can neither be created nor destroyed, but it can be changed from one form to another.

$$Q_h = \bar{W}_w \times \Delta E \quad \text{Eq (2a)}$$

In thermodynamic, system might be classified as isolated, closed, or open based on the possible transfer of mass and energy across the system boundaries. The system in which neither the transfer of mass nor that of energy takes place across its boundary with the surroundings is called as isolated system. A closed system has no transfer of mass with its surroundings, but may have a transfer of energy (either heat or work) with its surroundings.

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And an open system is the system in which the transfer of mass as well as energy can take place across its boundary.

When the variables of the system, such as temperature, pressure, or volume change, the system is said to have undergone thermodynamic process. There are various types of thermodynamic process:

1. Isobaric process
2. Isochoric process
3. Isothermal process
4. Adiabatic process

The heat flow can be prevented either by surrounding the system with thermally insulating material or by carrying out the process so quickly that there is not enough time for appreciable heat flow.

Here is a graphic for various types of thermodynamic process above:

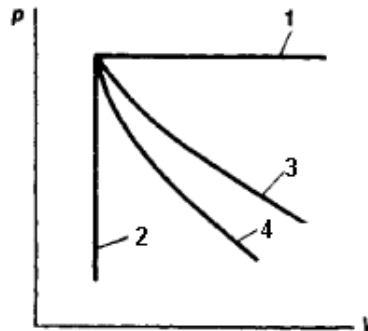


Figure 10. Thermodynamic processes on a pressure-volume diagram

5. Isentropic process
6. Reversible and irreversible process

Compression Process

Compressor is a work absorbing device used for increasing the pressure of a fluid. When gas is compressed, its molecules are made to come closer, by which they occupy less space. As the number of molecules of gas increases in a given volume, its mass and density also increases. Increasing in density would affect to pressure increment.

Pressure of a fluid is increased by doing work upon it, which is accompanied by increase in temperature depending on the gas properties. Figure 11 below presents a compression schematic layout.

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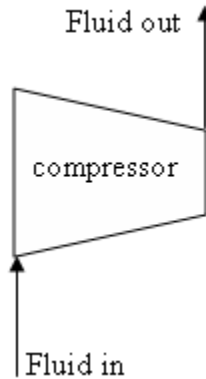


Figure 11. Compression schematic layout

On Figure 12 below, the vertical line from point 1 to point 2' represents the isentropic compression process requiring minimum work of compression from P1 to P2. The actual compression process follows a path from point 1 upward and to the right in the direction of increasing entropy, terminating at point 2 on the isobar for P2 [3].

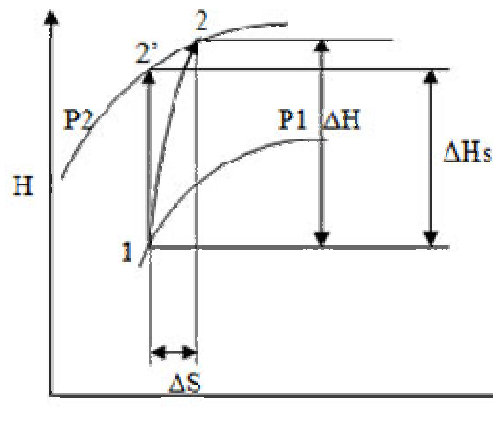


Figure 12. Adiabatic compression process

It is mentioned before that there are two types of compressor: positive displacement and dynamic. They compress the gas fluid in different principle of operation. Positive displacement compressor compresses the fluid by trapping successive volumes of fluid into a closed space then decreasing its volume. Compression occurs as the machine encloses a finite volume of gas and reduces the internal volume of compression chamber.

These design guideline are believed to be as accurate as possible, but are very general and not for specific design cases. They were designed for engineers to do preliminary designs and process specification sheets. The final design must always be guaranteed for the service selected by the manufacturing vendor, but these guidelines will greatly reduce the amount of up front engineering hours that are required to develop the final design. The guidelines are a training tool for young engineers or a resource for engineers with experience.

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The other type of compressor, dynamic compressor, compresses the fluid by the mechanical action of rotating vanes or impeller imparting velocity and pressure to the fluid. The larger the diameter of impeller, the heavier the molecular weight of gas fluid, or the greater the speed rotation would produce greater pressure. Generally, positive displacement compressor is selected for smaller volume of gas and higher pressure ratios. Dynamic compressor is selected for higher volume of gas fluid and smaller pressure ratios.

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