TABLE OF CONTENT

LIST OF TABLE

LIST OF FIGURE

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.

History of Compressors

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.

Transport of Materials

The type of equipment best suited for the pumping of gases in pipelines depends on flow rate, the differential pressure required, and the oeprating pressure. Generally, fans are used where the pressure drop is small (<35 cm H_2O, 0.03 bar), axial flow compressors for high flow rates and moderate differential pressures, centrifugal compressors for high flw rates and by staging, high differential pressures.

Reciprocating compressors can be used over a wide range of pressures and capacities but are normally specified only preference to centrifugal compressors where high pressures are required at relatively low flow rates.

Reciprocating,centrifugal, and axial flow compressors are the principal types used in the chemical process industries, and the range of application of each type is shown in Figure 1., which has been adapted from a similar diagram by Dimophon (1978).

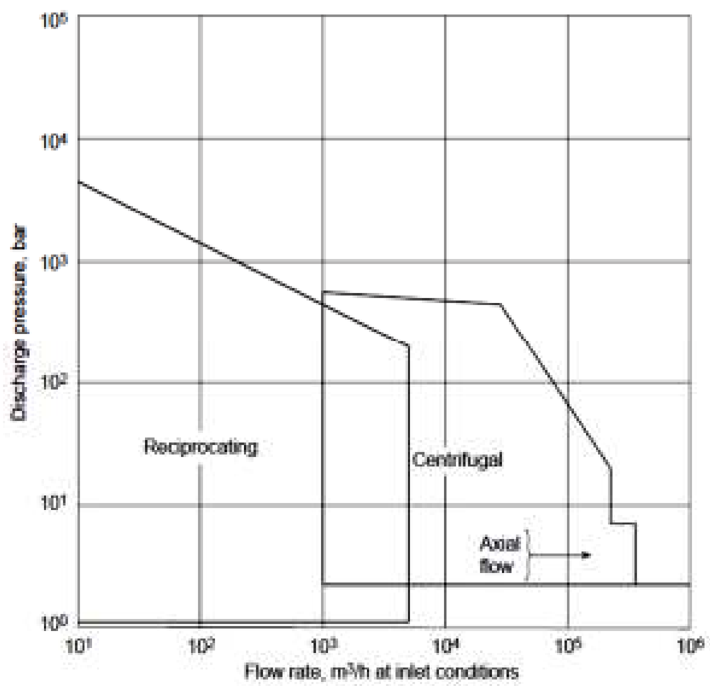

Figure 1. Range of Compressor Application

A comprehensive selection guide for compressor technology is represents in Table 1. Diagrammatic sketches of the compressors listed are given in Figure 2.

Table 1. Operating Range of Compressors (Begg, 1966)

Type of Compressor	*Normal Max. Speed (rpm)*	*Normal Max. Capacity (m^3/h)*	*Normal Max. Differential Pressure (bar)*	
			Single Stage	Multiple Stage
Displacement				
1. Reciprocating.	300	85,000	3.5	5000
2. Sliding Vane.	300	3400	3.5	8
3. Liquid Ring.	200	2550	0.7	1.7
4. Rootes.	250	4250	0.35	1.7
5. Screw.	10,000	12,750	3.5	17
Dynamic				
6. Centrifugal fan.	1000	170,000	0.35	0.2
7. Turbo blower.	3000	8,500	3.5	1.7
8. Turbo compressor.	10,000	136,000	0.35	100
9. Axial flow fan.	1000	170,000	3.5	2.0
10. Axial flow blower.	3000	170,000		10

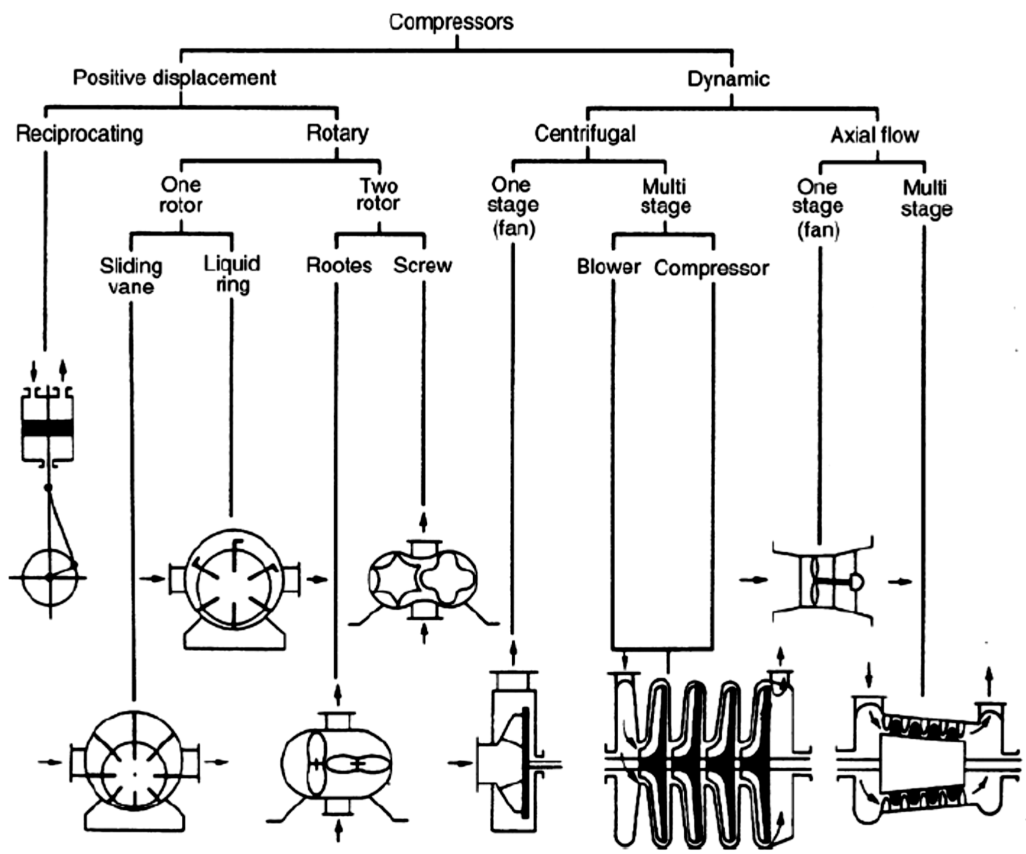

Figure 2. Type of Compressor (Begg, 1966)

Types of Compressors

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

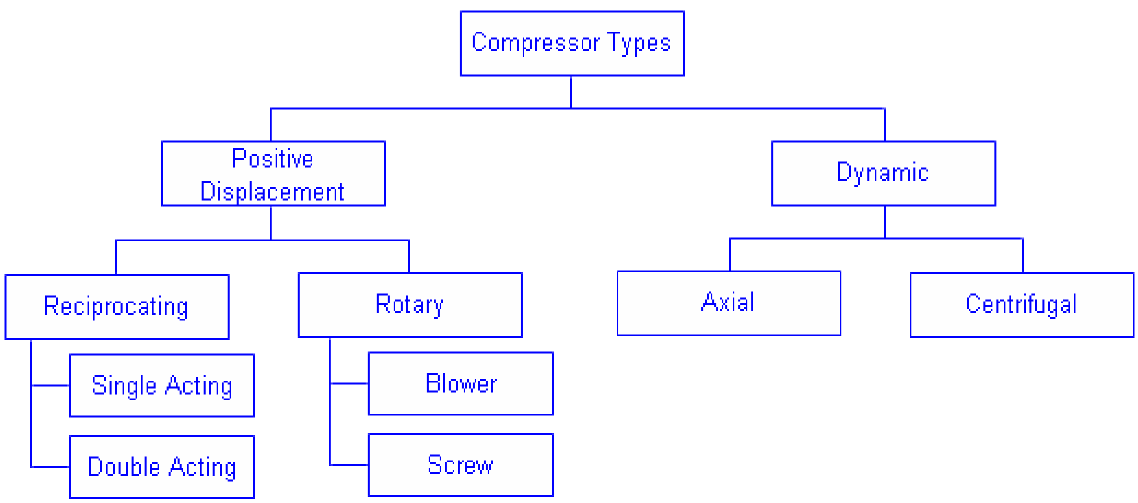

Figure 3. Compressor types based on operating principles

Characteristics of typical Compressor

There are several major characteristic of reciprocating compressor as follows :

- Generally for small to medium flow capacity.
- Discharge temperature limited up to 150°C.
- Suitable for high discharge pressure and high pressure ratio.
- Short life time (for continous operation).
- Flexible in capacity and pressure range.
- Severe limitation of its components.
- Less sensitive for gas composition and density change.

There are several major characteristic of centrifugal compressor following :

- Generally for large flow capacity.
- Limited to 10 stages per one casing (dependable to the size of machine).
- Discharge temperature limited up to 180°C.
- Recommended for continous operation with long life time.
- Have a low initial investment cost (if pressure and volume are favorable).
- Less expensive in maintenance cost.
- Low operating attention needed.

The key point of selecting type of the compressor is compresson ratio and flow capacity. The general schematic of selecting the proper compressor is shown in Figure 4.

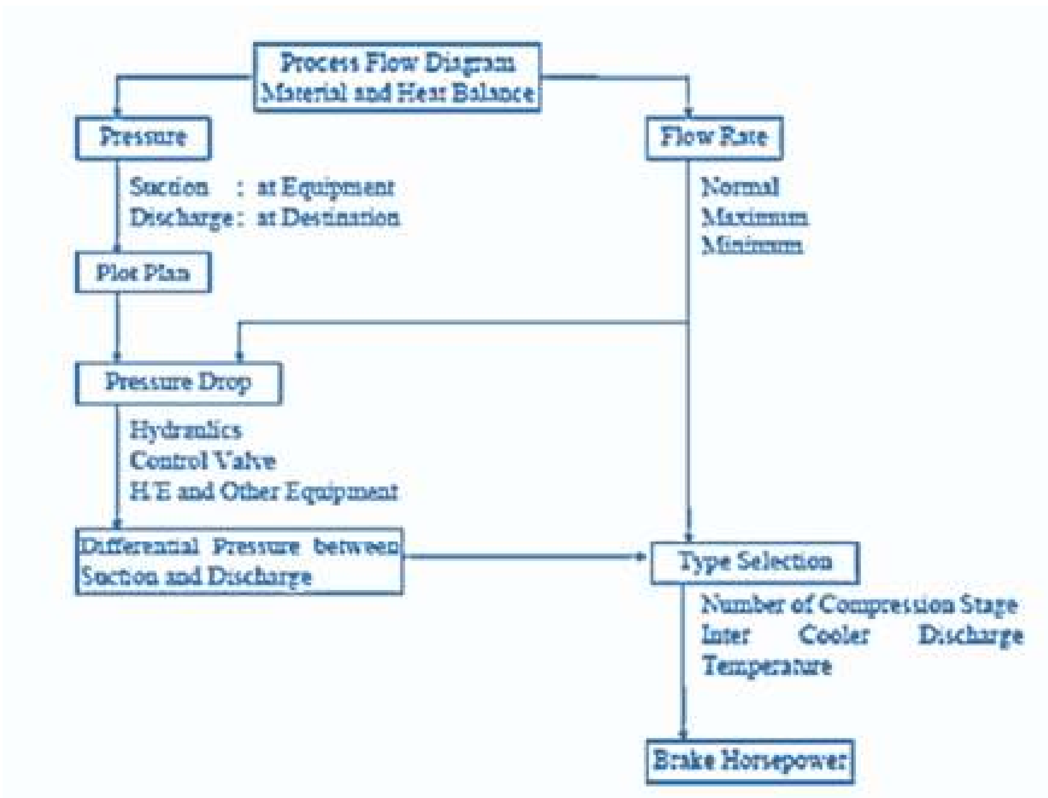

Figure 4. Selecting Compressor

(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 specifies 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 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.

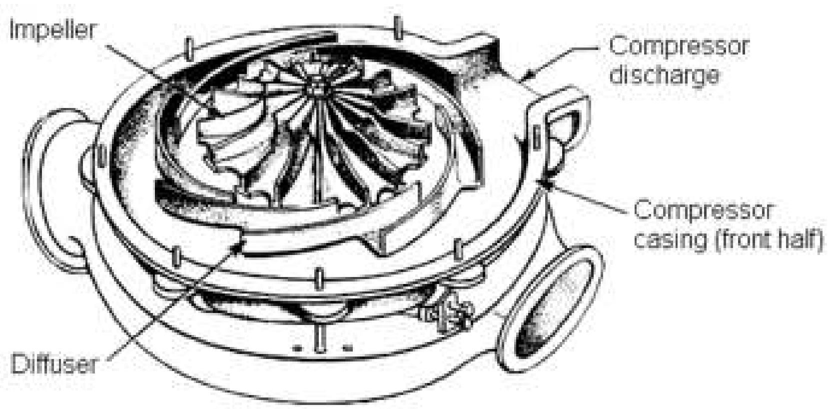

Figure 5. Centrifugal compressor

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.

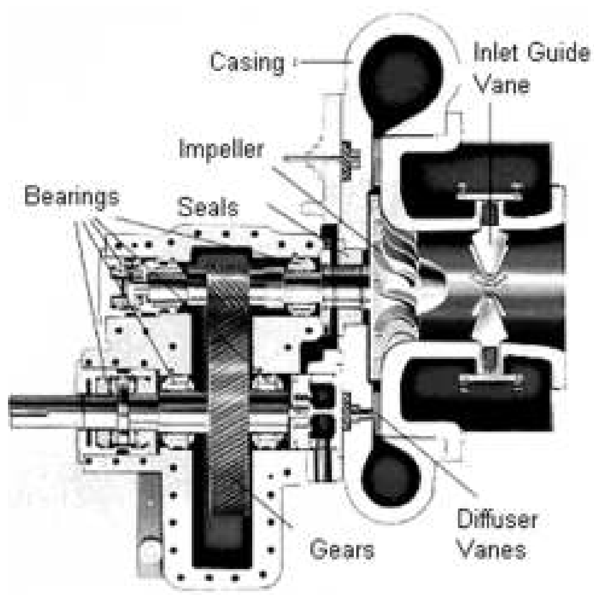

Figure 6. Single stage compressor

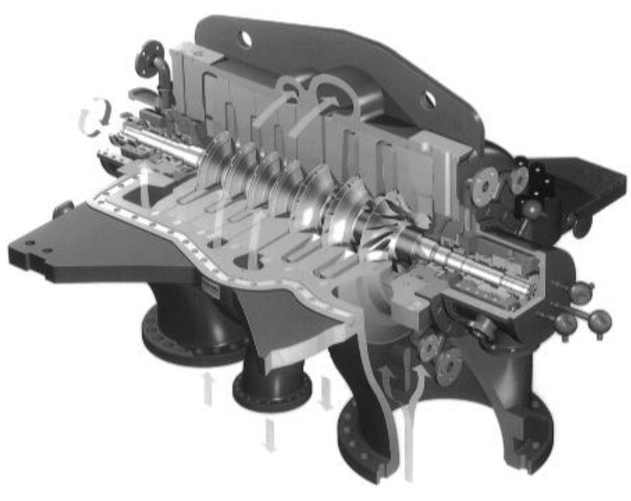

Figure 7. Multi stage compressor

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.

The advantages and disadvantages of centrifugal compressor can be summarized 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	

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.

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. I n 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 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.

Reversible process - The process which can be revered 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.

NOMENCLATURE

p = absolute pressure (lb/ft^2)

v = specific volume (ft^3/lb)

T = absolute temperature (°R)

R $= \frac{\overline{R}}{MW}$ = individual gas constant (ft-lb/lb-°R)

V = volume (ft^3)

n = mole mass (kmol)

$\overline{R}$ = universal gas constant = 1545 (ft-lb/mol-°R)

Q_h = heat into the system (Btu)

$\overline{W}_w$ = 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)

Ps = suction pressure, psia (flange)

Ts = suction temperature, °R

Zstd = compressibility factor at standard conditions

Zs = 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.

rpm = rotative speed

N_t = isentropic temperature exponent defined by real gas properties

Rs = stage pressure ratio

Rt = total ratio

Ns = number of stages

Nc = compression efficiency

Nm = mechanical efficiency

k = polytropic exponent

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

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

L = loss factor, %

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