Lecture 34

PREPARATION OF COMPRESSED AIR.

Learning Objectives

Upon completion of this chapter, Student should be able to

- Explain the various stages of air preparation
- Describe the working of various compressors
- List the advantages and disadvantages of various compressors
- Carry out thermodynamic analysis of compressors
- Compare various types of compressors
- List various ways to control compressor
- Understand the selection criteria for compressor
- List various hazardous of compressed air.

1.1 AIR PREPARATION

Pneumatic control systems operate on a supply of compressed air, which must be made available in sufficient quantity and at a pressure to suit the capacity of the system. The operational reliability and service life of a pneumatic system depend to a large extent on the preparation of the compressed air. Impurities in the compressed air such as scale, rust and dust as well as the liquid constituents in the air which deposit as condensate can cause a great deal of damage in pneumatic systems. These contaminants accelerate wear on sliding surfaces and sealing elements, adversely affecting the functioning and service life of pneumatic components. As a result of switching the compressors on and off, pressure fluctuations occur which have an unfavourable effect on the functioning of the system. In order to eliminate these effects, compressed air preparation should be given utmost importance. There are four distinct stages of air preparation they are:

Stage 1 : This consist of air intake system

Stage 2: This stage consist of compressors, with drives controls, inter-cooling, compressor cooling, waste heat recovery and air inlet filtration

Stage 3: This stage includes Conditioning equipment, consisting of air receivers, after coolers, separators, traps (also frequency called drain traps or drains) , filters and air dryers

Stage 4: This stage consist of air distribution subsystems, including main trunk lines, drops to specific usage, valving, additional filters and traps(drains) , air hoses, possible supplement air conditioning equipment, connectors, often pressure regulators and lubricator.

Stage 1 : An Intake filter removes larger particles which can damage the air compressor.

a) Location: The intake for a compressor will located either outdoors or indoors, whichever provides the better air quality. Elevation of the compressor relative to sea level is required to determine the atmospheric pressure and density of intake air. Air quality is judged by its temperature, humidity and cleanliness. We must ensure that air intage is free of moisture or pollution.

b) **Intake Temperature:** The density of air varies inversely with its temperature : an increase in delivery of approximately 1 percent is gained for -20 ℃ reduction of intake temperature.

c) **Intake pipe material**: The inside of intake piping must be smooth and not subject to rusting or oxidation. Rust that flakes off will enter and damage the compressor.. Acceptable intake air piping materials include plastic, cooper, stainless steel, aluminium or galvanized steel. On metallic piping, mechanical couplings will be used. Welded joint must be avoided since weld beads can break free, enter and damage the compressor.

d) **Critical pipe length:** resonance of intake piping will reciprocating air compressor is prevented by avoiding certain pipe lengths. These are called critical pipe lengths, and are a function of the air temperature and the speed of the compressor in revolutions per minute. Critical pipe lengths must be verified with equipment manufacturers.

e) **Intake air filter:** The selection of filter type is based on whether air compressor to be used is lubricated or non lubricated, and on the quality of ambient air.

- Viscous impingement filters have an efficiency of 85 to 90 percent of particle size larger than 10 microns. This type of filter is acceptable for lubricated reciprocating compressor operating under normal conditions
- Oil bath filters have an efficiency of 96 to 98 percent of particle sized larger than 10 microns. This type of filter is more expensive, and for the most part no longer recommended by compressor manufacturers, but may be considered for lubricated reciprocating compressor operating under heavy duty conditions.

- Dry filters have an efficiency of 99 percent of particles larger than 10 microns. Because of their high filtration efficiency, these filters are the best selection for rotary and reciprocating compressors. They must be used for non-lubricated compressors and whenever air must be kept oil free.

- Two stage dry filters , to provide 99 percent efficiency of particles larger than 0.3 micron, will be used for centrifugal units

- With all types of filters, a means of monitoring the air pressure drop through the element must be provided, which indicates element contaminations.

Stage 2: In this stage air is compressed using compressor. This book is not meant to be a comprehensive analysis of all types of air compression system that can be designed. Instead, it will concentrate on those most often found in industry and on thermodynamic analysis in those systems. It will explore positive displacement types in great detail and dynamic compressor in brief.

Stage 3: In this stage outlet temperature at the compressor is reduced, solid contaminants usually large than 100 micron are removed, and air is dried to reduce to its humidity. The units used in the primary stage are after cooler, main line filter and dryer.

Stage 4: In this stage moisture and fine dirt particles are removed. In this stage pressure is regulated to suit individual machine’s requirement and introduces the fine mist of oil to the compressed air to aid lubrication. The units used in secondary air treatment are filter , regulator and lubricator (Called FRL or service units)

Figure 1.1 shows all four stages of air preparation. Figure 1.2 illustrates a typical compressed air system.

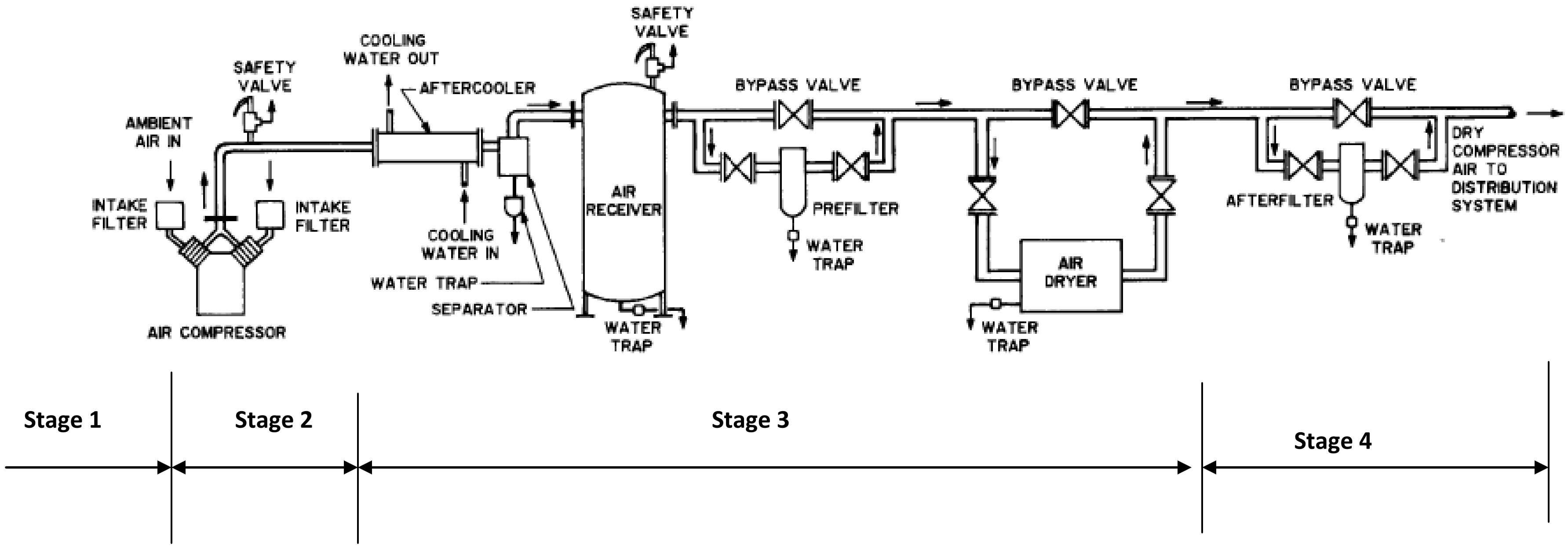

Figure 1.1 Four stages of air preparation

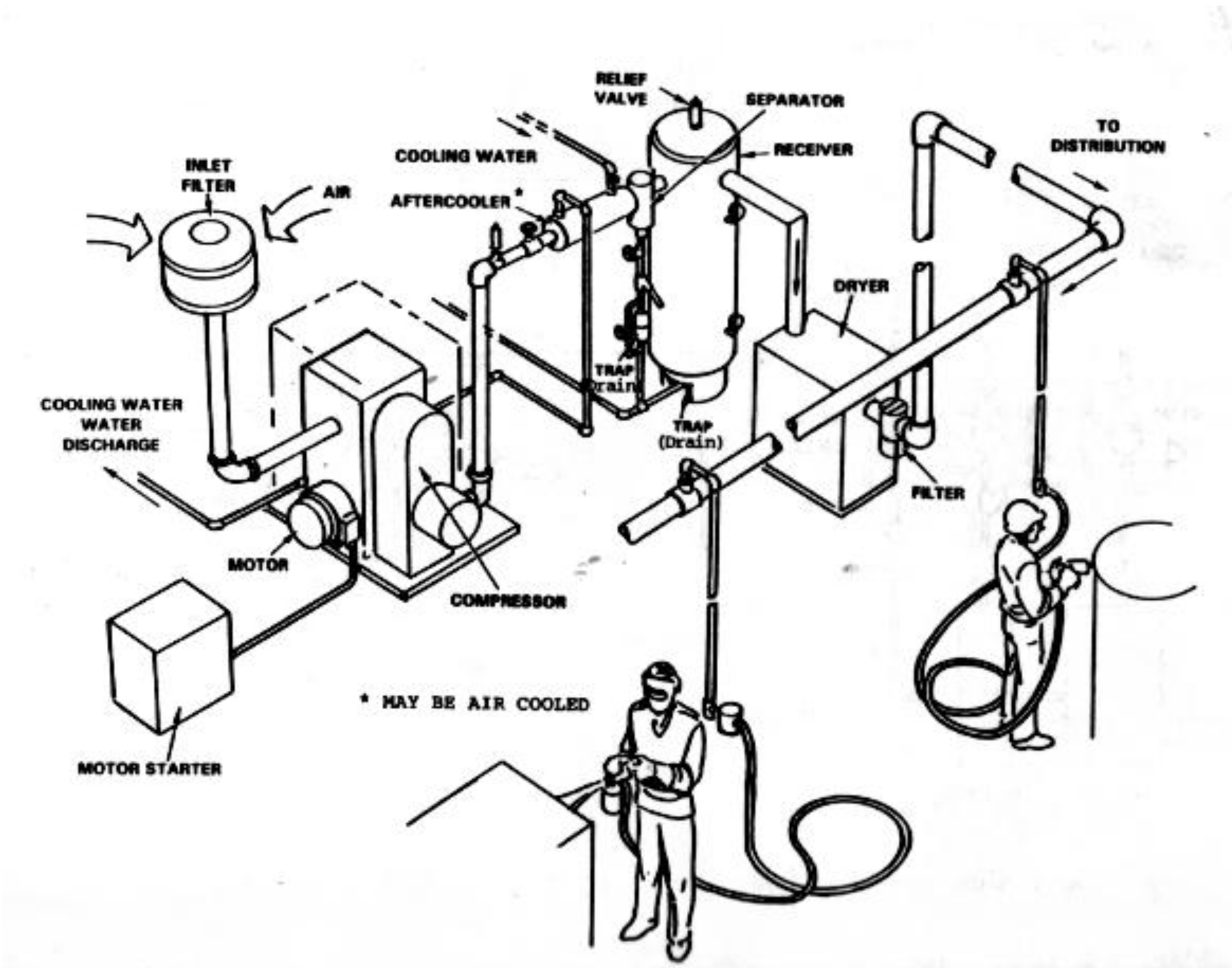

Figure 1.2 An Industrial compressed air system.

1.2 AIR COMPRESSORS: HISTORY AND ITS CLASSIFICATION

The first air compressor were human lungs; by blowing on cinders man started his fires. Then with birth of metallurgy man began to melt metal and high temperatures were needed. A more powerful compressor was required.

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).

The first mechanical compressor, the hand-operated bellows, emerged in 1500 B.C. In the 1850s, while trying to find a replacement for the water wheel at their family’s woollen 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 multistage axial turbine, and a regenerator utilizing exhaust gases to heat the compressor discharge gas.

A Compressor is a machine that compresses the air or another type of gas from a low inlet pressure (usually atmospheric pressure) to a higher desired pressure level. Compressor increases the pressure of the air by reducing its volume. Work required for increasing pressure of air is available from the prime mover driving the compressor. Generally, electric motor, internal combustion engine or steam engine, turbine etc. are used as prime movers. Compressors are similar to fans and blowers but differ in terms of pressure ratios. Fan is said to have pressure ratio up to 1.1 and blowers have pressure ratio between 1.1 to 4 while compressors have pressure ratios more than 4.

Compressors can be classified in the following different ways.

(a) **Based on principle of operation:** Based on the principle of operation compressors can be classified as.

   (i) Positive displacement compressor.

   (ii) Non-positive displacement compressors.

In positive displacement compressors the compression is realized by displacement of solid boundary and preventing fluid by solid boundary from flowing back in the direction of pressure gradient. Due to solid wall displacement these are capable of providing quite large pressure ratios. Positive displacement compressors can be further classified based on the type of mechanism used for compression. These can be

(i) Reciprocating type positive displacement compressors

(ii) Rotary type positive displacement compressors.

Reciprocating compressors generally, employ piston-cylinder arrangement where displacement of piston in cylinder causes rise in pressure. Reciprocating compressors are capable of giving large pressure ratios but the mass handling capacity is limited or small. Reciprocating compressors may also be single acting compressor or double acting compressor. Single acting compressor has one delivery stroke per revolution while in double acting there are two delivery strokes per revolution of crank shaft. Rotary compressors employing positive displacement have a rotary part whose boundary causes positive displacement of fluid and thereby compression. Rotary compressors of this type are available in the names as given below;

(i) Roots blower

(ii) Vane type compressors

Rotary compressors of above type are capable of running at higher speed and can handle large mass flow rate than reciprocating compressors of positive displacement type.

Non-positive displacement compressors also called as steady flow compressors use dynamic action of solid boundary for realizing pressure rise. Here fluid is not contained in definite volume and subsequent volume reduction does not occur as in case of positive displacement compressors. Non-positive displacement compressor may be of ‘axial flow type’ or ‘centrifugal type’ depending upon type of flow in compressor.

(b) **Based on number of stages:** Compressors may also be classified on the basis of number of stages. Generally, the number of stages depends upon the maximum delivery pressure. Compressors can be single stage or multistage. Normally maximum compression ratio of 5 is realized in single stage compressors. For compression ratio more than 5 the multistage compressors are used.

Type values of maximum delivery pressures generally available from different type of compressor are,

(i) Single stage Compressor, for delivery pressure upto 5 bar.

(ii) Two stage Compressor, for delivery pressure between 5 to 35 bar

(iii) Three stage Compressor, for delivery pressure between 35 to 85 bar.

(iv) Four stage compressor, for delivery pressure more than 85 bar

(c) **Based on Capacity of compressors**: Compressors can also be classified depending upon the capacity of Compressor or air delivered per unit time. Typical values of capacity for different compressors are given as;

(i) Low capacity compressors, having air delivery capacity of 0.15 m^3/s or less

(ii) Medium capacity compressors, having air delivery capacity between 0.15 to 5 m^3/s.

(iii) High capacity compressors, having air delivery capacity more than 5 m^3/s

(d) **Based on highest pressure developed:** Depending upon the maximum pressure available from compressor they can be classified as low pressure, medium pressure, high pressure and super high pressure compressors. Typical values of maximum pressure developed for different compressors are as under:

(i) Low pressure compressor, having maximum pressure upto 1 bar

(ii) Medium pressure compressor, having maximum pressure from 1 bar to 8 bar

(iii) High pressure compressor, having maximum pressure from 8 to 10 bar

(iv) Super high pressure compressor, having maximum pressure more than 10 bar.

Detailed classification is given in the Figure 1.3. Air compressors are generally positive displacement units and either of reciprocating piston type or the rotary screw or rotary vane types. These three types are explained in detail.

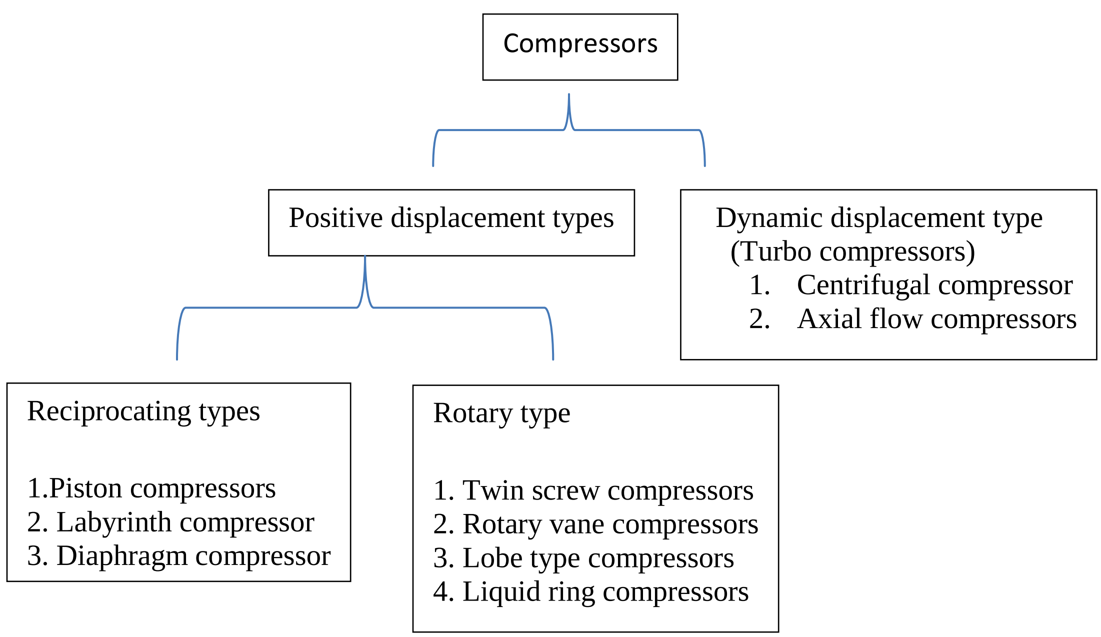

Figure 1.3 Classification of Compressors

Piston type of compressors are used commonly in Industries. Therfore only detailed discussion on piston type of compressor is presented in this chapter.

1.2.1 RECIPROCATING COMPRESSORS

Reciprocating compressors have been the most widely used for industrial plant air systems. The two major types are single acting and double acting, both of which are available as one or two stage compressors. The Single acting cylinder performs compression on one side of the piston during one direction of the power stroke. Two stage compressions reach the final output pressure in two separate compression cycles, or stages, in series.

The double acting compressor is configured to provide a compression stroke as the piston moves in either direction. This is accomplished by mounting a cross head on the crank arm which is then connected to a double acting piston by a piston rod. Distance pieces connect the cylinder to the crankcase. They are sealed to prevent mixing of crank shaft lubricant with the air, but vented so as to prevent pressure built up.

1.2.1.1 PISTON COMPRESSORS

Piston type compressors are the oldest and most commonly used compressor in the pneumatic industry because of its flexibility, high pressure capability, ability to rapidly dissipate heat of compression and oil free. They are built for either stationary or portable services.

A. SINGLE CYLINDER COMPRESSOR

Piston compressors are available as single or double acting, oil lubricated or oil free with different number of cylinders in different configurations. With the exception of really small compressors with vertical cylinders, the V configuration is the most common for small compressors. On double acting, large compressors the L type with vertical low pressure cylinder and horizontal high pressure cylinder, offer immense benefits and is why this the most common design. The construction and working of a piston type reciprocating compressor is very much similar to that of an internal combustion engine**.**

a) Construction: Piston type compressor consists of cylinder, cylinder head, and piston with piston rings, inlet and outlet spring loaded valves, connecting rod, crank crankshaft and bearings.

b) Operation

Compression is accomplished by the reciprocating movement of a piston within a cylinder. This motion alternately fills the cylinder and then compresses the air. A connecting rod transforms the rotary motion of the crankshaft into the reciprocating motion of piston in the cylinder. Depending on the application, the rotating crank (or eccentric) is driven at constant speed by a suitable prime mover (usually electric motor). Schematic diagram of single cylinder compressor is shown in Figure 1.4

Inlet stroke: -suction or inlet stroke begins with piston at top dead centre (a position providing a minimum or clearance volume). During the downward stroke, piston motion reduces the pressure inside the cylinder below the atmospheric pressure. The inlet valve then opens against the pressures of its spring and allows air to flow into the cylinder. The air is drawn into the cylinder until the piston reaches to a maximum volume position (bottom dead centre).The discharge valve remains closed during this stroke

Outlet stroke: During compression stroke piston moves in the opposite direction (Bottom dead centre to top dead centre), decreasing the volume of the air. As the piston starts moving upwards, the inlet valve is closed and pressure starts to increase continuously until the pressure inside the cylinder is above the pressure of the delivery side which is connected to the receiver. Then the outlet valve opens and air is delivered during the remaining upward motion of the piston to the receiver.

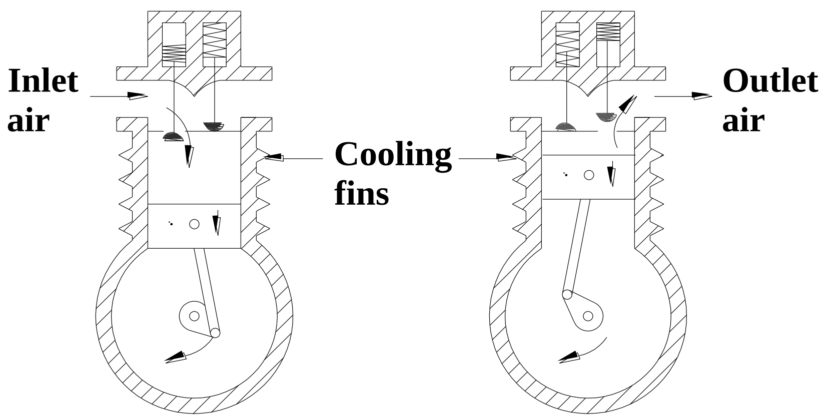

Figure 1.4 Single cylinder compressors

B. ANALYSIS OF SINGLE CYLINDER SINGLE STAGE AIR COMPRESSOR

A typical indicator diagram for reciprocating compressor with three different types of compression is shown in the Figure 1.5. Clearance volume is neglected.

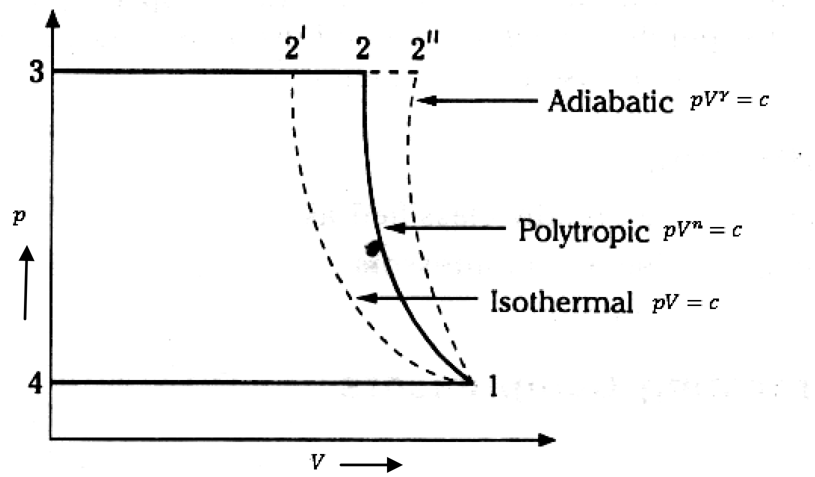

Figure 1.5 Types of compression

Constant pressure line 4-1 represents the suction stroke. The air is then compressed adiabatically (process line 12”,) and is then forced out of the cylinder at constant pressure (process 2”3). Area 12”34 represents the work. If the compression is carried out isothermally, then it follows the curve 12’ which has less slope than both isentropic and polytrophic processes. This work done that is area 12’34 in isothermal process is considerably less than that due to adiabatic compression. Thus compressor will have higher efficiency if compression follows isothermal process. It is not possible in practice as to achieve isothermal process, as the compressor must run very slowly. In practice compressors run at high speeds which results in polytropic process. The cold water spray and multi stage compression are used for approximating to isothermal compression while still running the compressor at high speeds.

C.WORK DONE IN A SINGLE STAGE COMPRESSOR NEGLECTING CLEARANCE.

Figure 1.6 shows the PV diagram of the air in the cylinder of an air compressor. Constant pressure line **ab** represents the suction stroke. The air is then compressed adiabatically (process line **bc**,) and is then forced out of the cylinder at constant pressure (process **cd**). Area abcd represents the work.

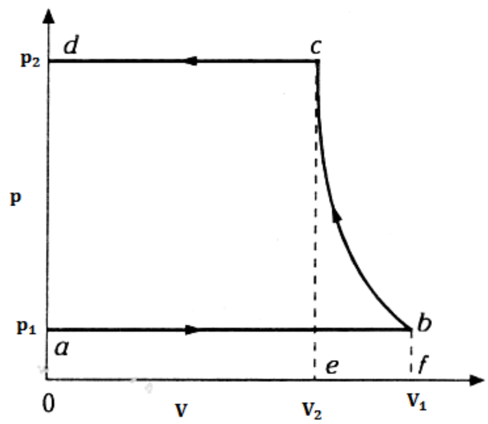

Figure 1.6 PV diagram

There are three types of compression processes possible in compressor they are

Isothermal compression. Compression of air takes place at constant temperature

$$\text{work done during compression} = p_1 V_1 \ln\left(\frac{p_2}{p_1}\right) \text{---------} \ (1.1)$$

Where p_1 = inlet pressure , p_2 = outlet pressure

Adiabatic compression. There is no flow of heat energy into or out of the gas during expansion or compression.

$$\text{work done during compression} = \frac{\gamma}{\gamma-1}(p_2 V_2 - p_1 V_1) \text{-----} \ (1.2)$$

$$workdone\ during\ compression = \frac{\gamma\, p_1 V_1}{\gamma - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

γ *is the ratio of specific heat* $= 1.4$ *for air*

$$c_p = 1.005\frac{kJ}{kg}k, c_v = 0.718\frac{kJ}{kg}k$$

Polytrophic compression This process lies between Isothermal and adiabatic. In pneumatics, most compression/expansions are neither adiabatic (Very fast) nor isothermal (Very slow). It is polytrophic

$$workdone\ during\ compression = \frac{n}{n-1}(p_2 V_2 - p_1 V_1)$$

$$workdone\ during\ compression\ = \frac{n\,p_1V_1}{n-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$n\ is\ the\ polytropic\ = 1.4\ for\ air$

Efficiency of compressor In a reciprocating compressor the work is minimum when compression follows the isothermal process. The ratio of isothermal work done to the actual work done is called isothermal efficiency.

$$\eta_{isothermal} = \frac{Isothermal\ work}{actual\ work}$$

D.**WORK DONE IN A SINGLE STAGE COMPRESSOR CONSIDERING CLEARANCE.**

In practical design of compressors, some clearance is required between the cylinder and piston to prevent hitting of piston to crown of the cylinder. Figure 1.7 shows a PV diagram of single stage compressor with clearance.

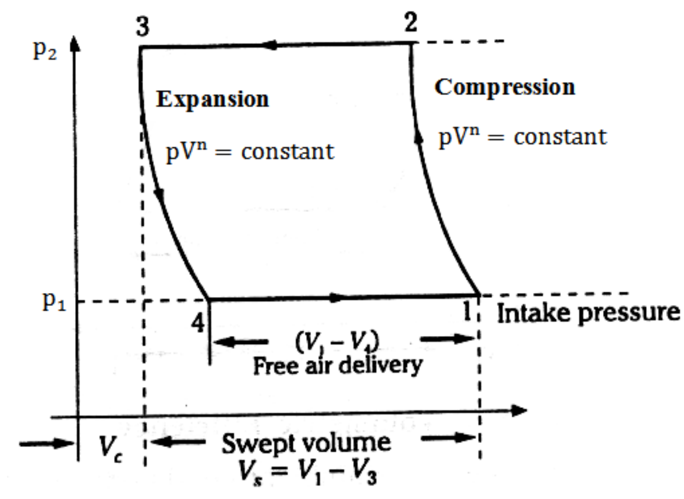

Figure 1.7 PV diagram with clearance

Thus when the compressed air is delivered during the delivery stroke, some amount of air corresponding to clearance volume V_3 at a pressure p_2 will be left over in the cylinder. During the next suction stroke this air expands back to initial pressure p_1 and volume V_4. Thus before the fresh air enters the cylinder some air corresponding to volume V_4 will be already there in the cylinder. This the volume inhaled during the suction stroke will be $V_1 - V_4$ which is less the swept volume V_s

The work done on the air delivered is not affected by the clearance volume as the work required to compress the clearance volume is theoretically regained during its expansion from $V_3\ to\ V_4$. Thus the work done is given by

$$workdone\ during\ compression\ = \frac{n\,p_1(V_1 - V_4)}{n-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

E. **Volumetric efficiency**

Free air delivery It is the amount of atmospheric air that can be sucked by the compressor at suction or inlet condition of compressor at one atmospheric pressure, 20 ℃, 100 percent dry air and compressor motor running at 100 % of the rated value. FAD is an important purchasing parameter and it measures the capacity of a compressor in terms of air flow it can handle. FAD is used to compare different compressors. It is important to note that induced mass per cycle must equal the delivered mass per cycle as per law of conservation of mass, although the induced and delivered volumes will be different.

$$\eta_{volumetric} = \frac{Actual\ volume\ of\ air\ taken\ referred\ to\ free\ air\ conditions}{swept\ volume\ of\ the\ compressor}$$

$$\eta_{volumetric} = \frac{p_1(T_a)}{p_a T_1}\left[1 + \mathrm{k} - \mathrm{k}\left(\frac{p_2}{p_1}\right)^{\frac{1}{\mathrm{n}}}\right]$$

Where $\mathrm{k} = \left(\frac{V_c}{V_s}\right) = \text{clearance ratio}$

Subscript “a” refers to free air or ambient conditions and subscript “1” refer to the condition before compression.

F. Analysis of Air capacity rating of compressors

Air compressors are rated in terms of m^3/min of free air, defined as air at actual atmospheric conditions. Where standard atmospheric condition are 101000 Pa (absolute) and 20 ℃

In Industry we still use British system for air rating of compressors. Air compressors are rated in terms of CFM of free air, defined as air at actual atmospheric conditions. CFM of free air is called SCFM when the compressor inlet air is at standard atmospheric condition of 17.7 (psia) 1 bar and 68F

$Q_1 and\ Q_2 = volume\ flow\ rate\ of\ air\ at\ the\ compress\ inlet\ and\ out\ let\ \ (m^3/min)$
$p_1 and\ p_2 = absoulte\ pressure\ of\ air\ at\ the\ compressor\ inlet\ and\ outlest\ \ (kPa(abs)$
$T_1 and\ T_2 = Absolute\ temperature\ of\ air\ at\ the\ compressor\ \ at\ inlet\ and\ out\ let\ \ (k)$
Using general gas law

$$\mathrm{Q}_1 = \mathrm{Q}_2 \left(\frac{p_2}{p_1}\right)\left(\frac{T_1}{T_2}\right)$$

Example 1.1: A compressor delivers 4 m^3 of the free air per minute at a pressure of 7 bar gauge. Assuming that the compression follows the law $p\,V^{1.3} = Constant$, determine the theoretical work done.

Given data

$n\ is\ the\ polytropic\ = 1.3\ for\ air$

$V_1 = 4\ m^3, p_1 = 1\ bar\ (absolute)$

$p_2 = 7\ bar\ (gauge) = 8\ bar\ (absoulte)$

Solution

$$p_1 V_1^{1.3} = p_2 V_2^{1.3}$$

$$V_2 = V_1 \left(\frac{p_1}{p_2}\right)^{1.3}$$

$$V_2 = 4\left(\frac{1}{8}\right)^{1.3} = 0.807\ m^3/min$$

$$workdone\ during\ compression\ = \frac{n}{n-1}(p_2V_2 - p_1V_1)$$

$$workdone\ during\ compression\ = \frac{1.3}{0.3}(8 \times 0.807 - 1 \times 3) \times 10^5$$

Solving we get Work done = 14.98$\times 10^5$ N.m/minute = 0.2496 $\times 10^5$N.m/s = 0.25$\times 10^5$ Watts =25 kW

Example 1.2: A single stage air compressor running at 80 RPM, compress air from a pressure of 1 bar and temperature of 15 °C to a pressure of 5 bar (see Figure 1.8) The clearance volume is 5 % of swept volume which is 0.42 m^3Assuming that the compression and expansion to follow the law $\mathrm{p\,V}^{1.3} =$ Constant,determine the power required to drive the compressor

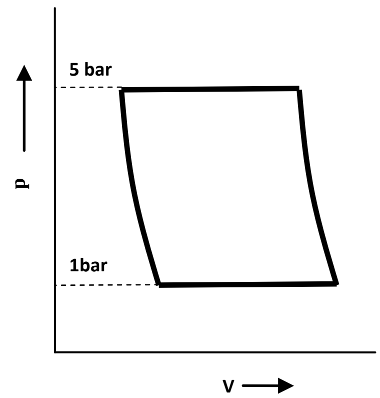

Figure 1.8

Given data

$n\ is\ the\ polytropic\ = 1.3\ for\ air$

$\mathrm{N} = 80\ \mathrm{RPM}\ \ , p_2 = 5 bar\ (absolute)$

$p_1 = 1\ bar\ (absoulte)\ T_1 = 15\ ℃$

Solution

$$\mathrm{k} = \left(\frac{V_c}{V_s}\right) = \frac{5}{100} = 0.05$$

$V_s\ = 0.42\ m^3$

Volumetric efficiency referred to the suction conditions.

$$\eta_{volumetric} = \left[1 + \mathrm{k} - \mathrm{k}\left(\frac{p_2}{p_1}\right)^{\frac{1}{\mathrm{n}}}\right] = \left[1 + 0.05 - 0.05\left(\frac{5}{1}\right)^{\frac{1}{1.4}}\right] = 0.8775$$

$$\eta_{volumetric} = \frac{Actual\ volume\ of\ air\ taken\ referred\ to\ free\ air\ conditions}{swept\ volume\ of\ the\ compressor}$$

$$0.8775 = \frac{V_1}{0.42}$$

$$V_1 = 0.3685\ \mathrm{m}^3/\mathrm{cycle}$$

$$Mass\ of\ air = \frac{p_1 V_1}{RT_1} = \frac{0.3685 \times 1 \times 100}{0.287 \times 288} = 0.445\ kg/cycle$$

$$Mass\ of\ air = \frac{0.445 \times 80}{60} = 0.5933\ kg/sec$$

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{\mathrm{n}-1}{\mathrm{n}}} = 288(5)^{\frac{0.3}{1.3}} = 417.53\ \mathrm{K}$$

$$power\ = \frac{n}{n-1}\mathrm{mR}(T_2 - T_1)$$

$$power\ = \frac{1.3}{1.3-1} \times 0.5933 \times 0.287 \times (417.53 - 288) = 95.5\ \mathrm{kW}$$

C. **MULTI STAGE PISTON COMPRESSOR.**

As per general gas laws, if the pressure increases temperature also increases. For example : if the exit pressure of compressor is 5 bar in a single acting compressor, the compressor air temperature can rise to over 200 ℃ and the motor power needed to drive the compressor rises. Therefore single stage compressors are not used for high pressures. Multistage compressors are used when high pressures are required, because better cooling between stages can effectively increase the efficiency and reduce the input power requirements.

Single stage machines compress the air to pressure of about 6 bars and in exceptional cases to 10 bars, two stage machines normally discharge pressure up to 15 bars. Discharge pressures in the range of 250 bars can be obtained with high pressure reciprocating compressor of three and four stages.

In single stage compressor, entire compression of air takes place in single stroke of the piston. In multi stage compressor, compression takes in stages. For maximum compressor efficiency, it is desirable to cool air after one stage using inter- stage cooler. In two stage compressor, initial compression takes place in the low pressure cylinder. Air from this stage (low pressure cylinder) is passed through the inter cooler to reduce the temperature. Then the cooled air is compressed in the high pressure cylinder.

Working:

Figure 1.11 shows the two stage (inline type) reciprocating air compressor. When the prime mover connected to crank shaft rotates, crank rotates and the piston in the first stage reciprocates. It sucks the air through the suction filter and inlet valve. The air, compressed to a certain degree passes from the left cylinder to right cylinder through the intermediate cooler. The compression ratio in the first stage is determined by the degree of cooling required.

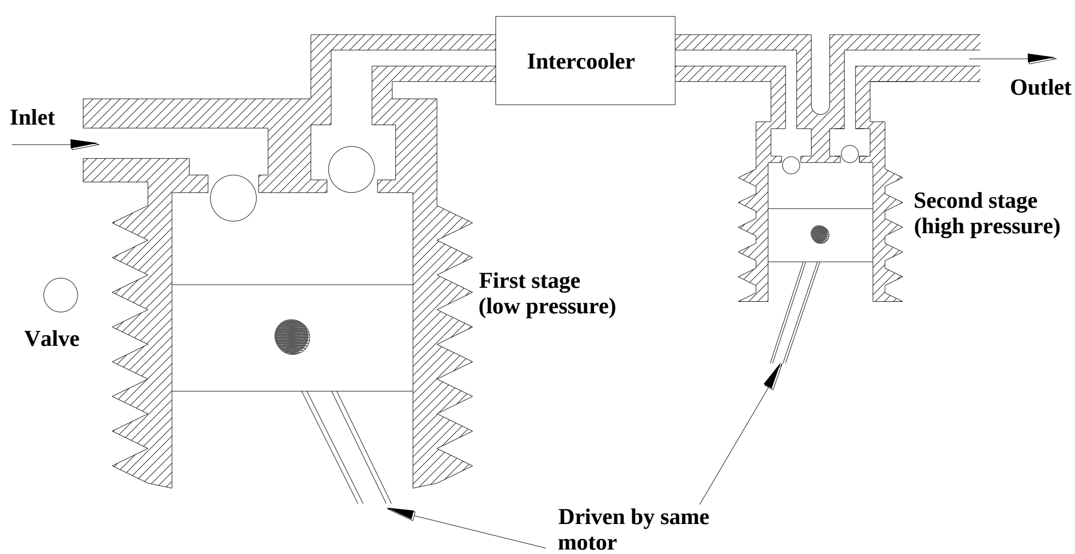

Figure 1.11 Multi stage piston air compressor with intercooler

Figure 1.12 shows various parts of three stage (V type) reciprocating air compressor with receiver (air tank). The pressure switch is connected to the electric motor. When the desired pressure in the air tank is reached it stops the motor and hence the compressor. The safety valve opens when the pressure in air tank exceeds the set safe pressure.

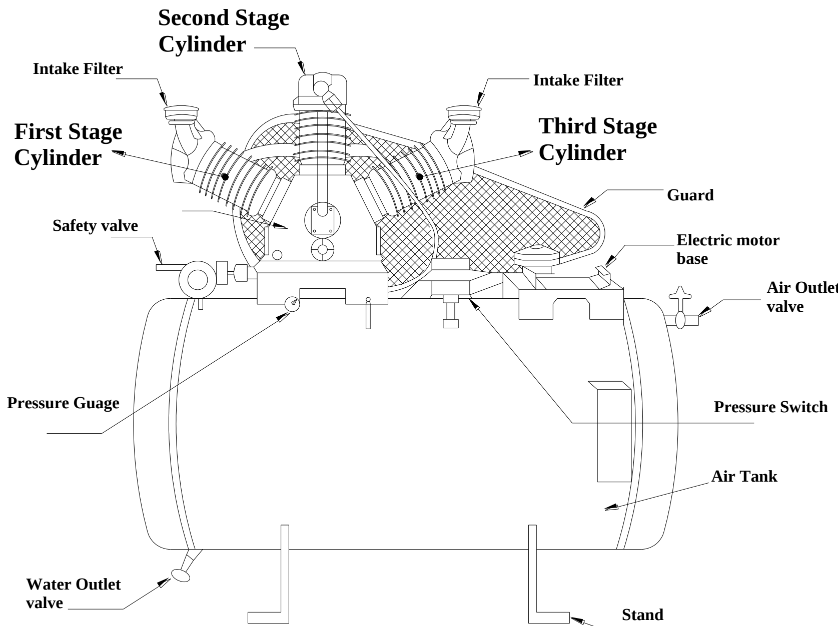

Figure 1.12 Various parts of three stage compressor

The drain valve drains the condensate produced at the condenser and the receiver. Cylinders and intercoolers are either air cooled (with fins) or water cooled (with water jackets in the cylinder). Air cooled compressor are used for low pressure applications and water cooled compressors are used for high pressure applications.

Range: Used of pressures up to 4-30 bar and low delivery volumes (< 10000 m^3/h). For pressures exceeding 30 bar multi stage compressors are required. The multi stage compressors are available with pressure up to 250-350 bar.

Advantages of piston type compressor

1. Piston type compressors are available in wide range of capacity and pressure
2. Very high air pressure (250 bar) and air volume flow rate is possible with multi-staging.

3. Better mechanical balancing is possible by multistage compressor by proper cylinder arrangement.
4. High overall efficiency compared to other compressor

Disadvantages of piston type compressor

1. Reciprocating piston compressors generate inertia forces that shake the machine. Therefore , a rigid frame, fixed to solid foundation is often required
2. Reciprocating piston machines deliver a pulsating flow of air. Properly sized pulsation damping chambers or receiver tanks are required.
3. They are suited for small volumes of air at high pressures.

B. **ANALYSIS OF MULTI SINGLE STAGE AIR COMPRESSOR**

The volumetric efficiency of a reciprocating compressor is a function of a clearance ratio, the pressure ratio and index of expansion. As the pressure ratio is increased, the volumetric efficiency of a compressor having a fixed clearance decreases and finally a stage may be reached when the volumetric efficiency may be zero as see from Figure 1.13

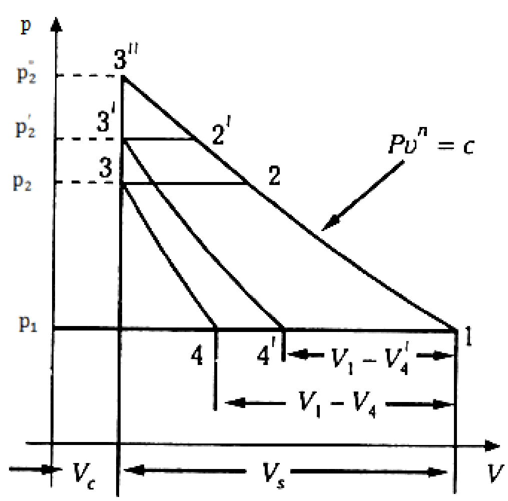

Figure 1.13 Multi stage compressions

It is seen that for a given intake pressure, the volume of air taken into the compressor cylinder decreases with increase in delivery pressure. At some delivery pressure the compression line intersects the line of clearance volume (point 3”) indicating that there is no delivery of air.

At this stage compression and re-expansion of same air takes place over and over again without any delivery of compressed air. As a result it is seen that the maximum pressure ratio attainable with a reciprocating compressor is limited by the clearance volume of the compressor. As clearance volume cannot be reduced beyond a certain limit the only alternative is to resort to multi-staging.

Work done in a two stage air compressor

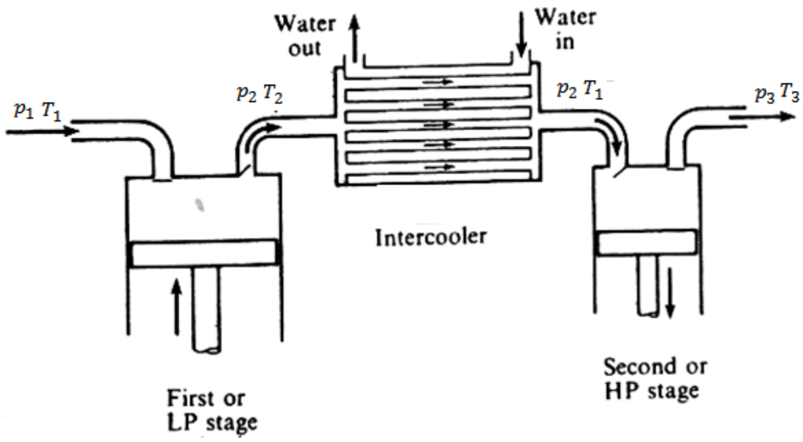

Figure 1.14 Multi stage compressions

Schematic diagram of Two stage air compressor with intercooler is shown in Figure 1.14 The air is first compressed in the LP cylinder to intermediate pressure p2. It is then passed through an intercooler where air is cooled at constant pressure before it is compressed in the HP cylinder. If the air is cooled back to initial temperature, then the inter cooling is said to be perfect.

The PV diagram for two stage compressor is shown in the Figure 1.15

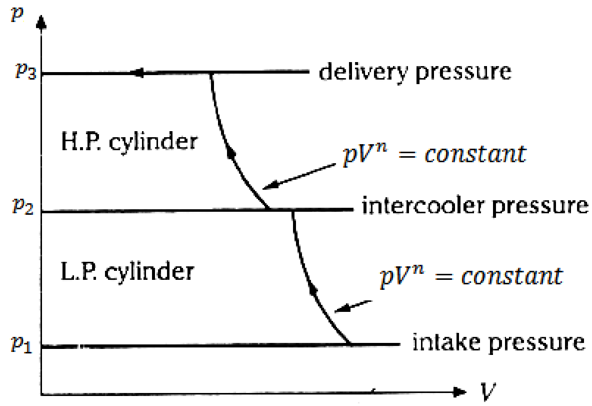

Figure 1.15 PV Diagram for two stage air compressor

Work done per cycle in LP cylinder

$$W_{LP} = \frac{n\, p_1 V_1}{n-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Work done per cycle in HP cylinder

$$W_{HP} = \frac{n\, p_2 V_2}{n-1}\left[\left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 1\right]$$

If the intercooling is perfect then $p_1 V_1 = p_2 V_2$

$$W = \frac{n\, p_1 V_1}{n-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} + \left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 2\right]$$

Condition for minimum power in two stage compressor with perfect intercooling is given by

$$p_2 = \sqrt{p_1 p_3}$$

For a N stage compressor with perfect intercooling , compressing air from p_1 to p_{N+1}

$$W = \frac{Nn\, p_1 V_1}{n-1}\left[\left(\frac{p_{N+1}}{p_1}\right)^{\frac{n-1}{nN}} - 1\right]$$

Example 1.8: A two stage air compressor takes in air at a rate of 0.2 m^3/s Intake pressure is 1 bar and 16℃. Final pressure is 7 bar the intermediate pressure is ideal with perfect intercooling. (See Figure 1.16) The compression takes place according to law $\mathrm{p\,V^{1.25}} = \mathrm{Constant}$. The compressor runs at 600 RPM. Neglecting clearance determine a)The intermediate pressure b) Volume of each cylinder c) cylinder power

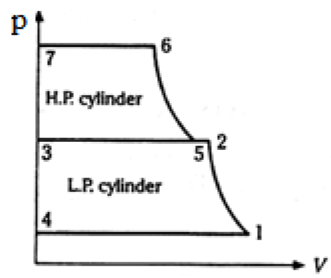

Figure 1.16

Given data

$n\ is\ the\ polytropic\ = 1.25\ for\ air$

$$m = 1\ \frac{kg}{min} = \frac{1}{60} = 0.0166\ kg/sec$$

$$V_1 = 0.2\ \frac{m^3}{sec} \quad T_1 = 16℃$$

$$p_1 = 1\ bar\ , p_3 = 7\ bar$$

Solution

Part a

For perfect intercooling

$$p_2 = \sqrt{\mathrm{p_1 p_3}} = \sqrt{1 \times 7} = 2.645\ \mathrm{bar}$$

Part b

$$V_1 = Volume\ of\ LP\ cylinder = 0.2\ \frac{m^3}{sec} \quad T_1 = 16℃$$

$$V_1 = \frac{0.2}{600/60} \frac{m^3}{cycle} = 0.02 \frac{m^3}{cycle}$$

$$\mathrm{p_1\,V_1}^{1.25} = \mathrm{p_2\,V_2}^{1.25}$$

$$V_2 = V_1 \left(\frac{p_2}{p_1}\right)^{\frac{1}{\mathrm{n}}} = 0.02 \left(\frac{1}{2.645}\right)^{\frac{1}{1.25}}$$

Volume of HP cylinder $= 0.0092 \frac{m^3}{cycle}$

Part c

Minimum power required

$$W = \frac{Nn\,p_1 V_1}{n-1}\left[\left(\frac{p_{\mathrm{N+1}}}{p_1}\right)^{\frac{\mathrm{n-1}}{\mathrm{nN}}} - 1\right]$$

$$W = \frac{2 \times 1.25 \times 100 \times 0.2}{1.25 - 1}\left[\left(\frac{7}{1}\right)^{\frac{1.25-1}{2\times1.25}} - 1\right]$$

$$W = 43\ kW$$

$$W = 42.58\ \mathrm{kW}$$

1.3 **COMPARISON OF DIFFERENT COMPRESSOR**

Flow rate, efficiency and the pressure rise within the compressor are the three most parameters used in defining the performance of a compressor and in its selection. Positive displacement compressors are generally suitable for small flow rates while centrifugal and axial compressors are more commonly applied for medium and large flow applications respectively. The advantages of centrifugal compressors are that they are reliable, compact and robust , have better resistance to foreign object damage and are less affected by performance degradation due to fouling. Positive displacement machines have wider operating domain when compared to other compressor types. Centrifugal compressors are most commonly applied in petrochemical or process industries in the flow rates ranging from 30 m^3/min to 3000 m^3/min. Typical comparison is given in the Table 1.2

Table 1.2 comparison of different compressors

Item	Reciprocating	Rotary vane	Rotary screw	Centrifugal
Efficiency at full load	High	Medium-high	High	High
Efficiency at part load	High due to staging	Poor: below 60% of full load	Poor: below 60% of full load	Poor: below 60% of full load
Efficiency at no load(power as % of full load)	High (10%-25%)	Medium (30%-40%)	High Poor (255-60%)	High-medium (20%-30%)
Noise level	Noisy	Quiet	Quiet it enclosed	Quiet
Size	Large	Compact	Compact	Compact
Oil carry over	Moderate	Low-medium	Low	Low
Vibration	High	Less	Less	Less
Maintenance	Many wearing parts	Few wearing parts	Very few wearing parts	Sensitive to dust in air
Capacity	Low-high	Low-medium	Low-high	Medium-high
Pressure	Medium- very high	Low-medium	Medium-high	Medium-high

1.4 CONTROL OF COMPRESSOR

1.4.1. Compressor drives

Alternating current (AC) electric motor are by far the most common drivers used for industrial plant air compression. Large electric motors are available in two basic types: Induction motor and synchronous motor. Nearly all industrial motors are three phase ac powered. Both the induction and synchronous motors rely upon the production of a revolving magnetic field (RMF) in the field winding.

Induction motors are used in 90 percent of industrial applications and are designed in two types: squirrel cage and wire wound rotor. The primary differences are the starting torque, current and amount of slip. Squirrel cage motors are commonly used.

Normally, gas turbine, diesel or Otto cycle engine power is not economic for stationary, continuous service compressor installation, except in special circumstances.

1.4.2 Control of compressors

There is a growing variety of control systems available for compressed air installations. These most often concern electric driver controls and compressor controls. Compressor controls are described below.

Plant air compressor systems normally are designed to operate at a fixed pressure and to deliver a variable volume. The Compressor is sized to deliver the maximum capacity and a control system is employed to reduce the compressor output to match the system demand.

Compressor may incorporate several different control systems to match the compressor volume and pressure to the demand. All of these controls monitor the system pressure as instantaneous indicator of the status of the match between the compressor output and system demand. Usually the control system will recognize and be designed to deliver air pressures between a design minimum and a design maximum damped system pressure. The damping is required to eliminate the effect of pressure pulses produced by most compressors. Pressure differentials of 0.1 to 0.5 bar between the minimum and maximum are specified in practice, the actual differential being a function of user requirements. This differential is known as the control range.

Energy consumption represents 80 percent of total cost for compressed air. therefore we must choose regulations systems carefully. There are two main groups of such regulation systems

1. **Continuous capacity regulation:** This method involves continuous control of drive motor or valve according to variation in pressure as shown in Figure 1.34. The result is normally a small pressure variations (0.1 to 0.5 bar), depending on the regulation system's amplification and its speed.

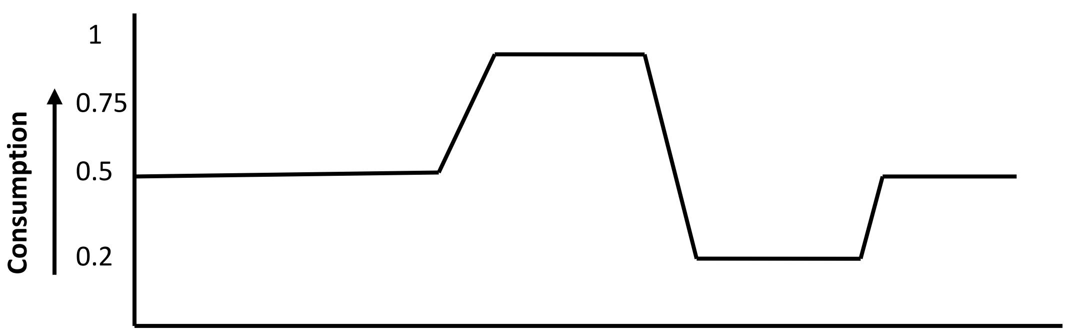

Figure 1.34: Continuous capacity regulation

1. **Load/unload regulation:** This method involves the acceptance of variation in pressure between two values as shown in Figure 1.35. This takes place by completely stopping the flow at the higher pressure (off loading) and resume the flow rate (loading) when the pressure has dropped to the lowest valve. Pressure variation depend on the permitted number of load/unload cycles per time unit, but normally lie within the range of 0.3 to 1 bar.

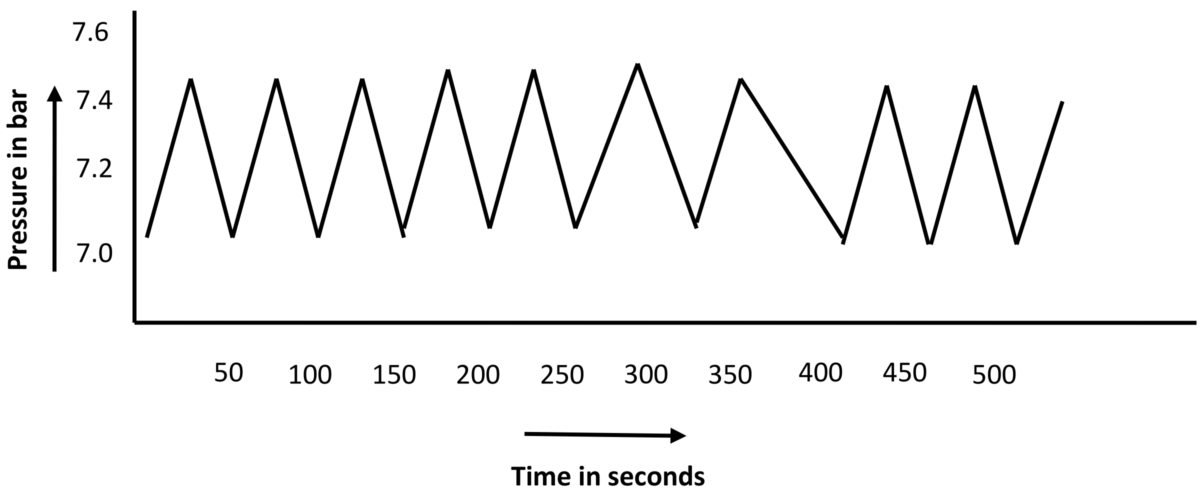

Figure 1.35: Load/unload regulation

1.4.2.1 Regulation principles for displacement compressors

a) Start/Stop and Load/unload controls

The simplest control mechanism turns the compressor on or off in response to system pressure. Schematic diagram of start /stop and unload/load control is shown in Figure 1.36 When the present system high pressure is reached, the compressed is turned off. When the system pressure falls to the preset minimum, the compressor is turned on. Compressors less than 5-10 kW are often controlled by completely stopping the electric motor when the pressure reaches an upper limit valve and restarting it when the pressure passes the lower limit value. The method demands a large system volume or large pressure difference between the start and stop pressure, to minimise the load on the electric motor. This is an effective regulation method under the condition that the number of starts per time unit is kept low.

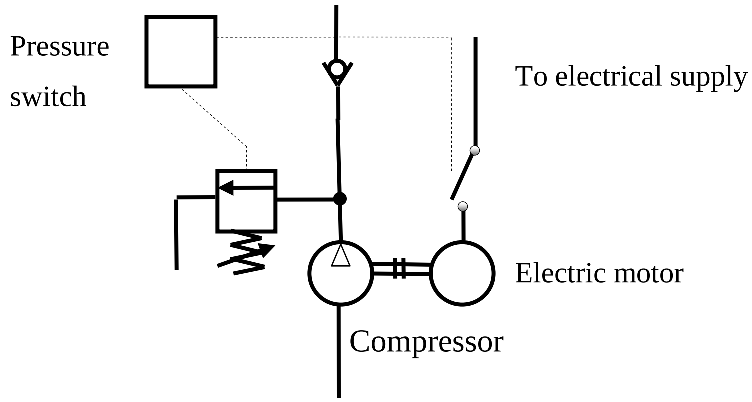

Figure 1.36: Load/unload regulation

b) Pressure Relief valve

The method used Pressure relief valve (PRV). This valve releases excess pressure into the atmosphere when the preset pressure is reached. The preset pressure can be set by adjusting the spring tension of the spring. Now a day, servo valve is used. The pressure can be easily controlled and the valve can also act as off-loading when starting a compressor under pressure. Schematic diagram of control of compressor using PRV is shown in Figure 1.37

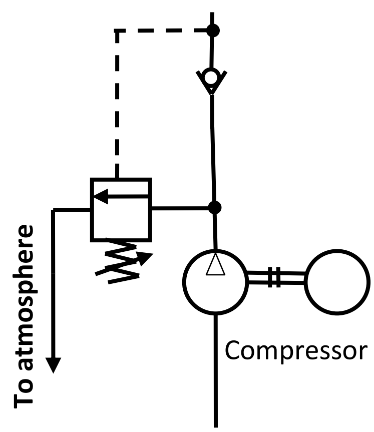

Figure 1.37: Regulation using pressure relief valve

c)**By pass regulation**

In this method, pressure relieved air is cooled and returned to the compressor intake. This method is often used on process compressors where gas is unsuitable or too valuable to release into the atmosphere. Schematic diagram of control of compressor using bypass regulation is shown in Figure 1.38

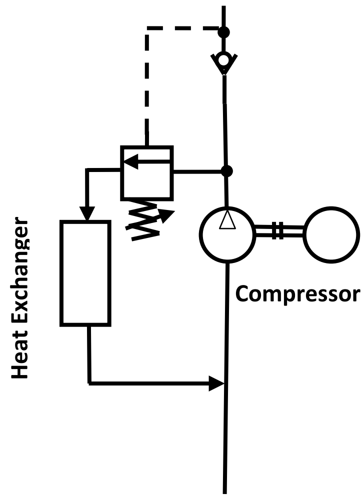

Figure 1.38: Bypass regulation

d) **Throttling the intake**

Throttling is an easy method to reduce the flow. Schematic diagram of control of compressor using throttle intake regulation is shown in Figure 1.39. By increasing the pressure ratio across the compressor, depending on the induced under pressure in the intake, the method is however limited to a small regulation range. Liquid injected compressors, which have a large permitted pressure ratio, can however be regulated down to 10 % of the maximum capacity. This method makes relatively high energy demands, due to the high pressure ratio.

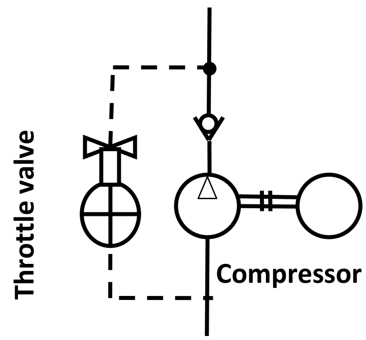

Figure 1.39: Throttle intake control regulation

e) **Pressure relief with throttled intake.**

Schematic diagram of control of compressor using throttle intake and pressure regulation is shown in Figure 1.40.The most common regulation method currently used that unites a maximum regulation range(0-100%) with low energy consumption, only 15-20% of full load power with an off-loaded compressor (zero flow). The intake valve is closed, but with a small opening remaining, at the same time as a blow off valve opens and relieves the outgoing air from the compressor

The compressor element then works with a vacuum in the intake and low counter pressure. It is important that the pressure relief is carried out quickly and that is relieved volume is small to avoid unnecessary losses during the transition from loaded to unloaded. The system demands a system volume (air receiver) , the size of which is determined by the acceptable difference between loading and off loading pressure and by the permitted number of unloading cycles per hour.

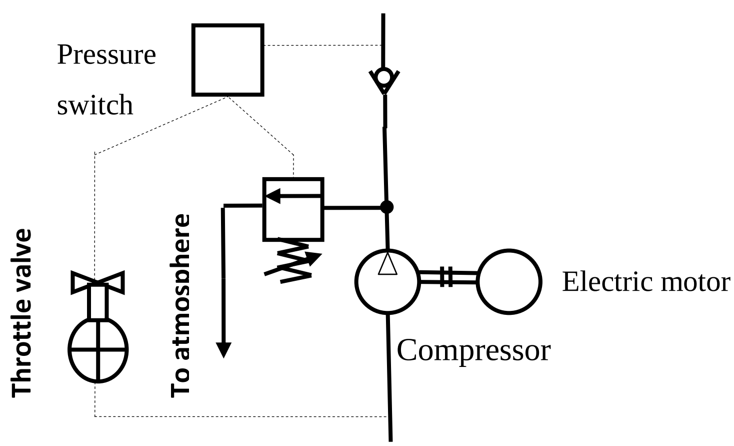

Figure 1.40: Throttle intake and pressure relief control regulation

f) **Speed regulation**

A combustion engine, turbine or frequency controlled electric motor controls the compressor's speed and thereby the flow. It is an efficient method to attain an equal outgoing pressure and low energy consumption.

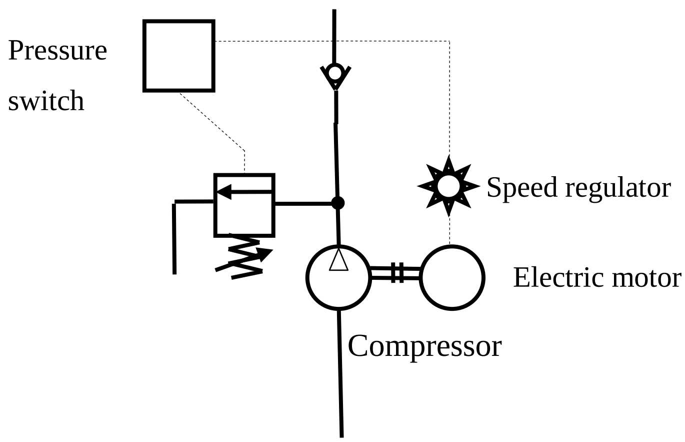

Figure 1.41: Speed regulation

Schematic diagram of speed control of compressor is shown in Figure 1.41.The regulation range varies with the type of compressor, but is greatest for liquid injected compressor. Frequently speed regulations and pressure relief are combined, with or without a throttled intake at low degrees of loading.

g) **Variable discharge port**

The capacity of screw compressors can be regulated by moving the position of the discharge port in the housing, in the screw's lengthways direction, towards the intake. However, the method demands high power consumption with sub-loads and is relative unusual.

g) **Suction valve unloading**

Piston compressors can be effectively relieved by mechanically forcing the intake valves to the open position. Air is then pumped out and in under the position of the piston, with minimal energy losses as result often lower than 10% of the loaded shaft power. On double acting compressors there is generally multi-stage off loading, where one cylinder at a time is balance to better adapt the capacity to demand. An odd method used on process compressor is to allow the valve to be open during a part of the piston stroke and thereby receive a continuous flow control.

Objective Type Questions

1. -----------------types of reciprocating compressors are most commonly used compressors**.**

1. Compare to positive displacement type compressor, dynamic compressor are much -------in size and produce much ----- vibration.

3. If the air compressor has a duty of -------, and the air compressor will be running for 10 minutes, then it should run for a combined maximum of 6 minutes ON and 4 minutes OFF.

4. It is not possible in practice as to achieve isothermal process, as the compressor must run very --------. In practice compressors run at high speeds which results in -------- process

5. In ------------------ control regulation, pressure relieved air is cooled and returned to the compressor intake

6.In a single acting reciprocating compressor, the suction, compression and delivery of air takes place in ___________ of the piston

7. Intercooling in mutli stage compressor is done to -----------the work of compression

8. The ratio of work done per cycle to the stroke volume of the compressor is known as ---------

9. The volume of air delivered by the compressor is called ………………..

10. In a centrifugal compressor, an increase in speed at a given pressure ratio causes increase in flow and --------- in efficiency

11.A large clearance Volume in a reciprocating compressor results in ----------------volume flow rate

12.When the temperature of air leaving the intercooler, in a two stage compression with intercooler, is ___________ the original atmospheric air temperature, then the intercooling is known as perfect or complete intercooling

State True or False

1. A dynamic compressors works with a constant pressure.

2. Positive displacement compressor is selected for larger volume of gas and higher pressure ratios. Dynamic compressor is selected for lower volume of gas fluid and smaller pressure ratios.

3. Compressor will have higher efficiency if compression follows isothermal process.

4. Running on the same operating speed, the two lobes blower can deliver large air flow and volume than conventional three lobes type

5. Continuous capacity regulation is the most common type of control and regulations used in Compressor.

6. The total heat rejected in a reciprocating air compressor is equal to the sum of the heat rejected during polytropic compression per kg of air and heat rejected in the intercooler per kg of air

7. In a four stage compressor, if the pressure at the first and third stage are 1 bar and 16 bar, then the delivery pressure at the fourth stage will be 64 bar

8. The volumetric efficiency for reciprocating air compressors is about 60 to 70 %

9. The minimum work required for a two stage reciprocating air compressor is double the work required for each stage

10. The clearance volume in the compressor is kept minimum because it effects on volumetric efficiency.

11. Work done by a two-stage reciprocating air compressor per cycle is equal to the workdone in LP. cylinder and H.P. cylinder

12. The actual volume of air delivered by a compressor, When reduced to the normal temperature and pressure conditions is called compressor capacity

13.An axial compressor gives optimum performance at high speeds and large volume flows

Review Questions

1. Explain the different stages of preparation of compressed air.

2. Explain the effect of type of compression in reciprocating air compressor

3. Define isothermal efficiency and derive an expression for the same

4 Explain the effect of clearance volume in single cylinder single stage compressor

5. Define volumetric efficiency of an air compressor and derive an expression for the same

6. Explain the effect of increasing delivery pressure on the volume of air delivered

7. Derive an expression for the intermediate pressure which gives minimum power in a two stage compressor with perfect inter cooling

8. What is the advantage of multi stage compressor

9. Differentiate between positive and dynamic displacement compressor

10. Name three types of positive displacement compressor

11. Explain the working principle of screw compressor. What are its advantages and disadvantages?

12. What is a diaphragm compressor? List its types and advantages

13. Explain on/off regulation of compressor with a neat sketch

14. Explain pressure relief and by pass regulation of compressor control with neat sketches.

15. List all factors to be considered in selection of a compressor for a give application.

Answers

Fill in the Blanks

1. Piston
2. smaller/less
3. 60/40
4. Slowly/polytropic
5. Bypass
6. Two strokes
7. minimise
8. Mean effective pressure.
9. Compressor capacity
10. decrease
11. reduced
12. equal to

State True or False

1. True
2. False
3. True
4. False
5. False
6. True
7. True
8. False.
9. True
10. True
11. True
12 False
13. True