3. COMPRESSED AIR SYSTEM

Syllabus
Compressed air system: Types of air compressors, Compressor efficiency, Efficient compressor operation, Compressed air system components, Capacity assessment, Leakage test, Factors affecting the performance and efficiency

3.1 Introduction

Air compressors account for significant amount of electricity used in Indian industries. Air compressors are used in a variety of industries to supply process requirements, to operate pneumatic tools and equipment, and to meet instrumentation needs. Only 10-30% of energy reaches the point of end-use, and balance 70-90% of energy of the power of the prime mover being converted to unusable heat energy and to a lesser extent lost in form of friction, misuse and noise.
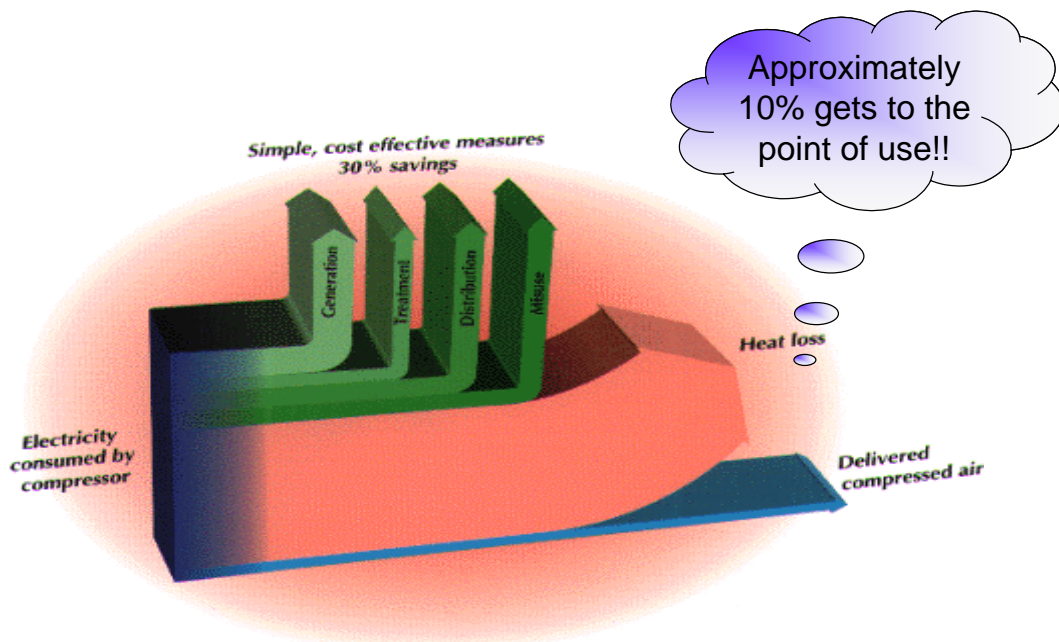

Figure 3.1 Sankey Diagram for Compressed Air System

3.2 Compressor Types

Compressors are broadly classified as: Positive displacement compressor and Dynamic compressor.

Positive displacement compressors increase the pressure of the gas by reducing the volume. Positive displacement compressors are further classified as reciprocating and rotary compressors.

Dynamic compressors increase the air velocity, which is then converted to increased pressure at the outlet. Dynamic compressors are basically centrifugal compressors and are further classified as radial and axial flow types.

The flow and pressure requirements of a given application determine the suitability of a particulars type of compressor.
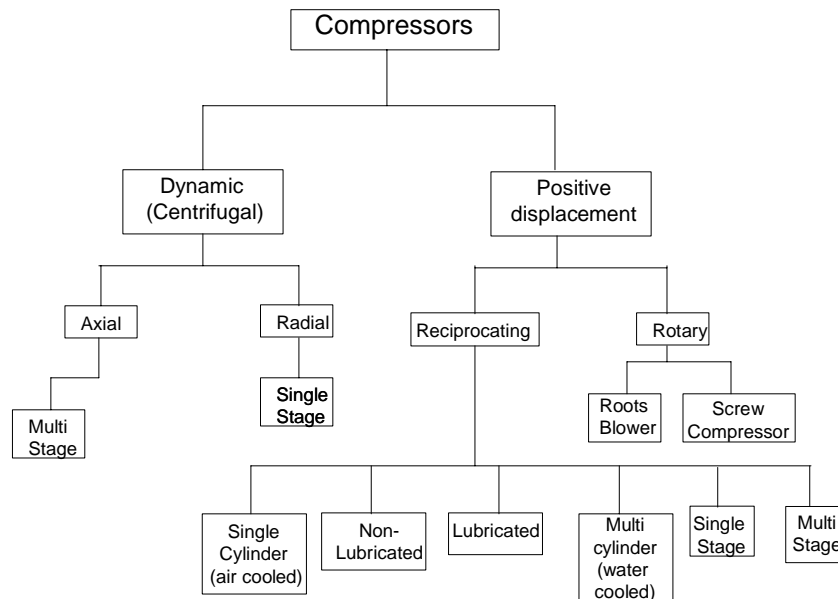

Figure 3.2 Compressor Chart

Positive Displacement Compressors

Reciprocating Compressors

Reciprocating compressors are the most widely used type for air compression. They are characterized by a flow output that remains nearly constant over a range of discharge pressures. Also, the compressor capacity is directly proportional to the speed. The output, however, is a pulsating one.

Reciprocating compressors are available in many configurations, the four most widely used of which are horizontal, vertical, horizontal

Figure 3.3 Reciprocating Compressor

balance-opposed and tandem. Vertical type reciprocating compressors are used in the capacity range of 50 – 150 cfm. Horizontal balance opposed compressors are used in the capacity range of 200 – 5000 cfm in multi-stage design and up to 10,000 cfm in single stage designs.
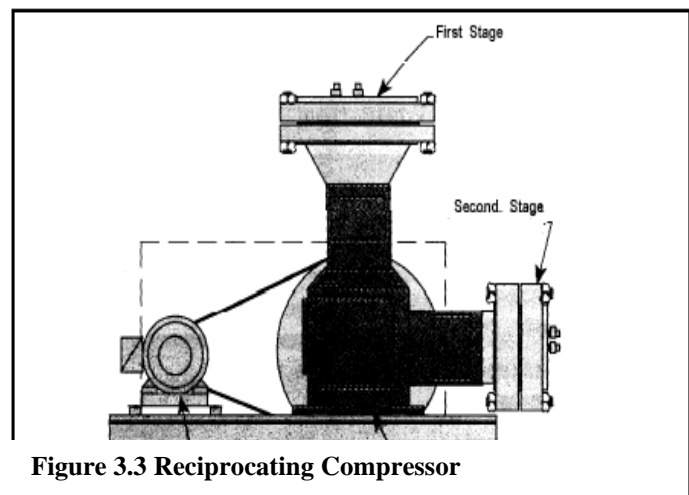
Reciprocating compressors are also available in variety of types:

- Lubricated and non-lubricated

- Single or multiple cylinder

- Water or air-cooled.

- Single or multi stage

In the case of lubricated machines, oil has to be separated from the discharge air. Non-lubricated compressors are especially useful for providing air for instrumentation and for processes which require oil free discharge. However non-lubricated machines have higher specific power consumption (kW/cfm) as compared to lubricated types.

Single cylinder machines are generally air-cooled, while multi-cylinder machines are generally water cooled, although multi-stage air-cooled types are available for machines up to 100 kW. Water-cooled systems are more energy efficient than air-cooled systems.

Two stage machines are used for high pressures and are characterized by lower discharge temperature (140 to 160^{0}C) compared to single-stage machines (205 to 240^{0}C). In some cases, multi-stage machines may have a lower specific power consumption compared to single stage machines operating over the same total pressure differential. Multi-stage machines generally have higher investment costs, particularly for applications with high discharge pressure (above 7 bar) and low capacities (less than 25 cfm). Multi staging has other benefits, such as reduced pressure differential across cylinders, which reduces the load and stress on compressor components such as valves and piston rings.
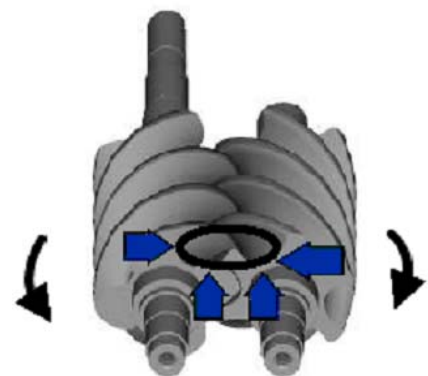
Rotary Compressors

Rotary compressors have rotors in place of pistons and give a continuous, pulsation free discharge air. They are directly coupled to the prime mover and require lower starting torque as compared to reciprocating machine. They operate at high speed and generally provide higher throughput than reciprocating compressors. Also they require smaller foundations, vibrate less, and have a lower number of parts - which means less failure rate.

Among rotary compressor, the Roots blower (also called as lobe compressor) and screw compressors are among the most widely used. The roots blower is essentially a low-pressure blower and is limited to a discharge pressure of 1 bar in single-stage design and up to 2.2 bar in two stage design.

Figure 3.4 Screw Compressors

The most common rotary air compressor is the single stage helical or spiral lobe oil flooded screw air compressor. These compressors consist of two rotors, within a casing where the rotors compress the air internally. There are no valves. These units are basically oil cooled (with air cooled or water cooled oil coolers) where the oil seals the internal clearances. Since the cooling takes place right inside the compressor, the working parts never experience extreme operating temperatures. The oil has to be separated from discharge air. Because of the simple design and few wearing parts, rotary screw air compressors are easy to maintain, to operate and install.

The oil free rotary screw air compressor uses specially designed air ends to compress air without oil in the compression chamber producing true oil free air. These compressors are

available as air-cooled or water cooled types and provide the same flexibility as oil flooded rotary compressors.

There is a wide range of availability in configuration and in pressure and capacity. Dry types deliver oil-free air and are available in sizes up to 20,000 cfm and pressure upto 15 bar. Lubricated types are available in sizes ranging from 100 to 1000 cfm, with discharge pressure up to 10 bar.

Dynamic Compressors

Dynamic compressors are mainly centrifugal compressors and operate on similar principles to centrifugal pump. These compressors have appreciably different characteristics as compared to reciprocating machines. A small change in compression ratio produces a marked change in compressor output and efficiency. Centrifugal machines are better suited for applications requiring very high capacities, typically above 12,000 cfm.

The centrifugal air compressor depends on transfer of energy from a rotating impeller to the air. The rotor accomplishes this by changing the momentum and pressure of the air. This momentum is converted to useful pressure by slowing the air down in a stationary diffuser.

The centrifugal air compressor is an oil free compressor by design. The oil-lubricated running gear is separated from the air by shaft seals and atmospheric vents. The centrifugal is a continuous duty compressor, with few moving parts, and is particularly suited to high volume applications, especially where oil free air is required.

A single-stage centrifugal machine can provide the same capacity as a multi-stage reciprocating compressor. Machines with either axial or radial flow impellers are available.

Axial flow compressors are suitable for higher compression ratios and are generally more efficient than radial compressors. Axial compressors typically are multi-stage machines, while radial machines are usually single-stage designs.

Figure 3.5 Centrifugal Compressor

The general selection criteria for compressor is given in the Table 3.1

Table 3.1 General Selection Criteria for Compressors				
Type of Compressor	**Capacity (m³/h)**		**Pressure (bar)**	
	From	**To**	**From**	**To**
Roots blower compressor single stage	100	30000	0.1	1
Reciprocating				
- Single / Two stage	100	12000	0.8	12
- Multi stage	100	12000	12.0	700
Screw				
- Single stage	100	2400	0.8	13
- Two stage	100	2200	0.8	24
Centrifugal	600	300000	0.1	450

3.3 Compressor Performance

Capacity of a Compressor

Capacity of a compressor is the full rated volume of flow of gas compressed and delivered at conditions of total temperature, total pressure, and composition prevailing at the **compressor inlet**. It sometimes means actual flow rate, rather than rated volume of flow. This also termed as **Free Air Delivery (FAD)** i.e. air at atmospheric conditions at any specific location. Because the altitude, barometer, and temperature may vary at different localities and at different times, it follows that this term does not mean air under identical or standard conditions.

Compressor Efficiency Definitions

Several different measures of compressor efficiency are commonly used: *volumetric efficiency*, *adiabatic efficiency, isothermal efficiency and mechanical* efficiency.

Adiabatic and isothermal efficiencies are computed as the isothermal or adiabatic power divided by the actual power consumption. The figure obtained indicates the overall efficiency of compressor and drive motor.

<u>Isothermal Efficiency</u>

$$\text{Isothermal Efficiency} = \frac{Isothermal Power}{\text{Actual measured input power}}$$

Isothermal power(kW) = P_1 x Q_1 x $\log_e r/36.7$

P_1 = Absolute intake pressure kg/ cm^2
Q_1 = Free air delivered m^3/hr.
r = Pressure ratio P_2/P_1

The calculation of isothermal power does not include power needed to overcome friction and generally gives an efficiency that is lower than adiabatic efficiency. The reported value of efficiency is normally the isothermal efficiency. This is an important consideration when selecting compressors based on reported values of efficiency.

Volumetric Efficiency

$$\text{Volumetric efficiency} = \frac{\text{Free air delivered m}^3\text{/min}}{\text{Compressor displacement}}$$

$$\text{Compressor Displacement} = \frac{\Pi \times D^2 \times L \times S \times \chi \times n}{4}$$

D	=	Cylinder bore, metre
L	=	Cylinder stroke, metre
S	=	Compressor speed rpm
χ	=	1 for single acting and 2 for double acting cylinders
n	=	No. of cylinders

For practical purposes, the most effective guide in comparing compressor efficiencies is the specific power consumption ie kW/volume flow rate , for different compressors that would provide identical duty.

3.4 Compressed Air System Components

Compressed air systems consist of following major components: Intake air filters, inter-stage coolers, after coolers, air dryers, moisture drain traps, receivers, piping network, filters, regulators and lubricators (see Figure 3.6).

- **Intake Air Filters**: Prevent dust from entering compressor; Dust causes sticking valves, scoured cylinders, excessive wear etc.

- **Inter-stage Coolers**: Reduce the temperature of the air before it enters the next stage to reduce the work of compression and increase efficiency. They are normally water-cooled.

- **After Coolers:** The objective is to remove the moisture in the air by reducing the temperature in a water-cooled heat exchanger.

- **Air-dryers**: The remaining traces of moisture after after-cooler are removed using air dryers, as air for instrument and pneumatic equipment has to be relatively free of any moisture. The moisture is removed by using adsorbents like silica gel /activated carbon, or refrigerant dryers, or heat of compression dryers.

- **Moisture Drain Traps:** Moisture drain traps are used for removal of moisture in the compressed air. These traps resemble steam traps. Various types of traps used are manual drain cocks, timer based / automatic drain valves etc.

- **Receivers**: Air receivers are provided as storage and smoothening pulsating air output - reducing pressure variations from the compressor
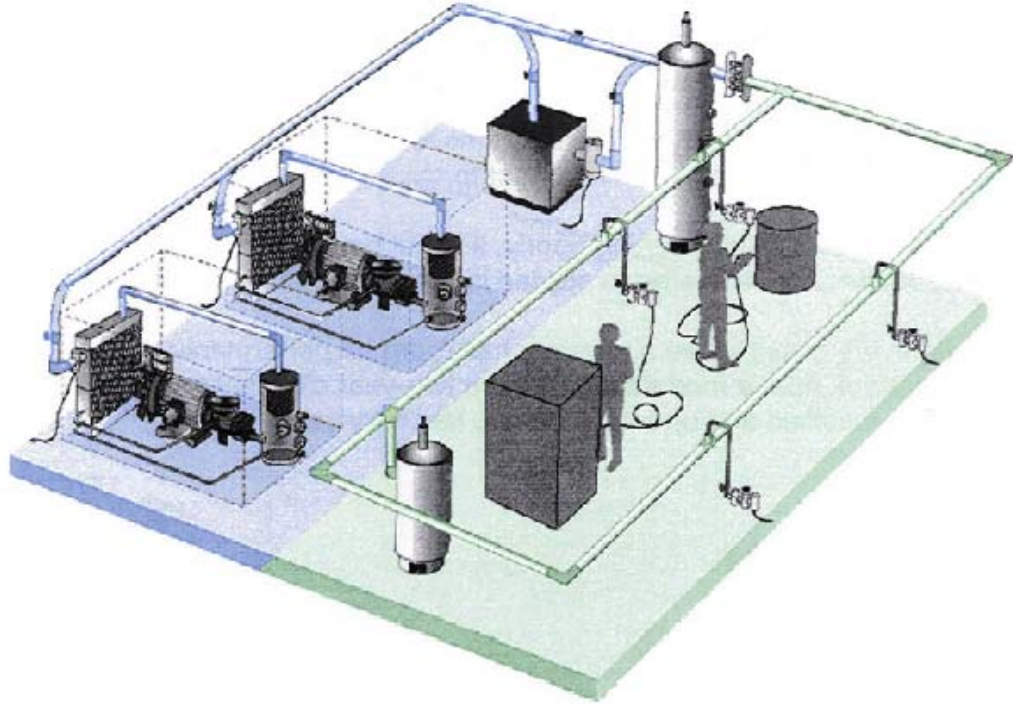
Figure 3.6 A Typical Compressed Air System Components and Network

3.5 Efficient Operation of Compressed Air Systems

Location of Compressors

The location of air compressors and the quality of air drawn by the compressors will have a significant influence on the amount of energy consumed. Compressor performance as a breathing machine improves with cool, clean, dry air at intake.

Cool air intake

As a thumb rule, *"Every 4^0C rise in inlet air temperature results in a higher energy consumption by 1 % to achieve equivalent output"*. Hence, cool air intake leads to a more efficient compression (see Table 3.2).

Table 3.2 Effect of Intake Air Temperature on Power Consumption		
Inlet Temperature (^{0}C)	**Relative Air Delivery (%)**	**Power Saved (%)**
10.0	102.0	+ 1.4
15.5	100.0	Nil
21.1	98.1	- 1.3
26.6	96.3	- 2.5
32.2	94.1	- 4.0
37.7	92.8	- 5.0
43.3	91.2	- 5.8

It is preferable to draw cool ambient air from outside, as the temperature of air inside the compressor room will be a few degrees higher than the ambient temperature. While extending air intake to the outside of building, care should be taken to minimize excess pressure drop in the suction line, by selecting a bigger diameter duct with minimum number of bends.

Dust Free Air Intake

Dust in the suction air causes excessive wear of moving parts and results in malfunctioning of the valves due to abrasion. Suitable air filters should be provided at the suction side. Air filters should have high dust separation capacity, low-pressure drops and robust design to avoid frequent cleaning and replacement. See Table 3.3 for effect of pressure drop across air filter on power consumption.

Table 3.3 Effect of Pressure Drop Across Air Inlet Filter on Power Consumption	
Pressure Drop Across air filter (mmWC)	**Increase in Power Consumption (%)**
0	0
200	1.6
400	3.2
600	4.7
800	7.0

Air filters should be selected based on the compressor type and installed as close to the compressor as possible. As a thumb rule *"For every 250 mm WC pressure drop increase across at the suction path due to choked filters etc, the compressor power consumption increases by about 2 percent for the same output"*

Hence, it is advisable to clean inlet air filters at regular intervals to minimize pressure drops. Manometers or differential pressure gauges across filters may be provided for monitoring pressure drops so as to plan filter-cleaning schedules.

Dry Air Intake

Atmospheric air always contains some amount of water vapour, depending on the relative humidity, being high in wet weather. The moisture level will also be high if air is drawn from a damp area - for example locating compressor close to cooling tower, or dryer exhaust is to be avoided (see Table 3.4)

Table 3.4 Moisture in Ambient Air at Various Humidity Levels	
% Relative Humidity	**Kg of water vapour per hour for every 1000 m^3/min. of air at 30^0C**
50	27.60
80	45.00
100	68.22

The moisture-carrying capacity of air increases with a rise in temperature and decreases with increase in pressure.

Elevation

The altitude of a place has a direct impact on the volumetric efficiency of the compressor. The effect of altitude on volumetric efficiency is given in the Table 3.5.

Table 3.5 Effect of Altitude on Volumetric Efficiency			
Altitude Meters	**Barometric Pressure milli bar***	**Percentage Relative Volumetric Efficiency Compared with Sea Level**	
		At 4 bar	**At 7 bar**
Sea level	1013	100.0	100.0
500	945	98.7	97.7
1000	894	97.0	95.2
1500	840	95.5	92.7
2000	789	93.9	90.0
2500	737	92.1	87.0

* 1 milli bar = 1.01972 x 10^{-3} kg/cm^2

It is evident that compressors located at higher altitudes consume more power to achieve a particular delivery pressure than those at sea level, as the compression ratio is higher.

Cooling Water Circuit

Most of the industrial compressors are water-cooled, wherein the heat of compression is removed by circulating cold water to cylinder heads, inter-coolers and after-coolers. The resulting warm water is cooled in a cooling tower and circulated back to compressors. The compressed air system performance depends upon the effectiveness of inter-coolers, after coolers, which in turn are dependent on cooling water flow and temperature.

Further, inadequate cooling water treatment can lead to increase, for example, in total dissolved solids (TDS), which in turn can lead to scale formation in heat exchangers. The scales, not only act as insulators reducing the heat transfer, but also increases the pressure drop in the cooling water pumping system.

Use of treated water or purging a portion of cooling water (blow down) periodically can maintain TDS levels within acceptable limits. It is better to maintain the water pH by addition of chemicals, and avoid microbial growth by addition of fungicides and algaecides.

Efficacy of Inter and After Coolers

Efficacy is an indicator of heat exchange performance- how well intercoolers and after coolers are performing.

Inter-coolers are provided between successive stages of a multi-stage compressor to reduce the work of compression (power requirements) - by reducing the specific volume through cooling the air - apart from moisture separation.

Ideally, the temperature of the inlet air at each stage of a multi-stage machine should be the same as it was at the first stage. This is referred to as "perfect cooling" or isothermal compression. The cooling may be imperfect due to reasons described in earlier sections. Hence in actual practice, the inlet air temperatures at subsequent stages are higher than the normal levels resulting in higher power consumption, as a larger volume is handled for the same duty (See Table 3.6).

Table 3.6 Effect of Inter-stage Cooling on Specific Power Consumption of a Reciprocating Compressor -Illustration			
Details	**Imperfect Cooling**	**Perfect Cooling (Base Value)**	**Chilled Water Cooling**
First Stage inlet temperature ^{0}C	21.1	21.1	21.1
Second Stage inlet temperature ^{0}C	26.6	21.1	15.5
Capacity (nm^3/min)	15.5	15.6	15.7
Shaft Power (kW)	76.3	75.3	74.2
Specific energy consumption kW (nm^3/min)	4.9	4.8	4.7
Percent Change	+ 2.1	Reference	- 2.1

It can be seen from the Table 3.6 that an increase of 5.5^{0}C in the inlet air temperature to the second stage results in a 2 % increase in the specific energy consumption. Use of water at lower temperature reduces specific power consumption. However, very low cooling water temperature could result in condensation of moisture in the air, which if not removed would lead to cylinder damage.

Similarly, inadequate cooling in after-coolers (due to fouling, scaling etc.), allow warm, humid air into the receiver, which causes more condensation in air receivers and distribution lines, which in consequence, leads to increased corrosion, pressure drops and leakages in piping and end-use equipment. Periodic cleaning and ensuring adequate flow at proper temperature of both inter coolers and after coolers are therefore necessary for sustaining desired performance. Typical cooling water requirement is given in Table 3.7.

Table 3.7 Typical Cooling Water Requirements	
Compressor Type	**Minimum quantity of Cooling Water required (in litres per minute) for 2.85 m^3/min. FAD at 7 bar**
Single-stage	3.8
Two-stage	7.6
Single-stage with after-cooler	15.1
Two-stage with after-cooler	18.9

Pressure Settings

Compressor operates between pressure ranges called as loading (cut-in) and unloading (cut-out) pressures. For example, a compressor operating between pressure setting of 6 - 7 kg/cm^2 means that the compressor unloads at 7 kg/cm^2 and loads at 6 kg/cm^2. Loading and unloading is done using a pressure switch.

For the same capacity, a compressor consumes more power at higher pressures. They should not be operated above their optimum operating pressures as this not only wastes energy, but also leads to excessive wear, leading to further energy wastage The volumetric efficiency of a compressor is also less at higher delivery pressures.

Reducing Delivery Pressure:

The possibility of lowering (optimising) the delivery pressure settings should be explored by careful study of pressure requirements of various equipment, and the pressure drop in the line between the compressed air generation and utilization points. Typical power savings through pressure reduction is shown in Table 3.8.

Table 3.8 Typical Power Savings Through Pressure Reduction				
Pressure Reduction		**Power Savings (%)**		
From (bar)	**To (bar)**	**Single-stage Water-cooled**	**Two-stage Water-cooled**	**Two-stage Air-cooled**
6.8	6.1	4	4	2.6
6.8	5.5	9	11	6.5

The pressure switches must be adjusted such that the compressor cuts-in and cuts-out at optimum levels.

A reduction in the delivery pressure by 1 bar in a compressor would reduce the power consumption by 6 – 10 %.

Compressor modulation by Optimum Pressure Settings:

Very often in an industry, different types, capacities and makes of compressors are connected to a common distribution network. In such situations, proper selection of a right combination of compressors and optimal modulation of different compressors can conserve energy.

Where more than one compressor feeds a common header, compressors have to be operated in such a way that the cost of compressed air generation is minimal.

- If all compressors are similar, the pressure setting can be adjusted such that only one compressor handles the load variation, whereas the others operate more or less at full load.

- If compressors are of different sizes, the pressure switch should be set such that only the smallest compressor is allowed to modulate (vary in flow rate).

- If different types of compressors are operated together, unload power consumptions are significant. The compressor with lowest no load power must be modulated.

- In general, the compressor with lower part load power consumption should be modulated.

- Compressors can be graded according to their specific energy consumption, at different pressures and energy efficient ones must be made to meet most of the demand (see Table 3.9).

Table 3.9 Typical Specific Power Consumption of Reciprocating Compressors (based on motor input)		
Pressure bar	**No. of Stages**	**Specific Power kW/170 m³/hour (kW / 100 cfm)**
1	1	6.29
2	1	9.64
3	1	13.04
4	2	14.57
7	2	18.34
8	2	19.16
10	2	21.74
15	2	26.22

EXAMPLE

Compressor modulation

Assessing compressed air system study for a plant section gave following results. Comment on the results?

- Compressors on line A, B, C, D, E (all reciprocating type)
- Trial observation Summary

Compressor Reference	Measured Capacity CMM (@ 7 kg/ cm²)	'On' Load kW	'Unload' kW	Load Time Min.	Unload Time Min.
A	13.17	115.30	42.3	Full time*	Nil
B	12.32	117.20	51.8	Full time*	Nil
C	13.14	108.30	43.3	Full time*	Nil
D	12.75	104.30	29.8	Full time*	Nil
E	13.65	109.30	39.3	5.88 min.	39.12 min.

*   Compressors running in load conditions and not getting unloaded during normal operations.

Comments:

- For a cycle time of 45 minutes (39.12 + 5.88)

  i)   Compressed air generated in m³

     =   45 (13.17) + 45 (12.32) + 45 (13.14) + 45 (12.75) + 5.88 (13.65)

     =   2392.36 m³

  ii)   Power consumption kWh

     =   45/60 (115.3) + 45/60 (117.20) + 45 / 60 (108.3) + 45/60 (104.3) + 5.88/60 (109.8) + ((39.12) / 60) 39.3

$$= \quad 370.21 \text{ kWh} / 45 \text{ Minutes}$$

iii) Compressed air generation actual capacity on line in m^3

$$= \quad 45 [13.17 + 12.32 + 13.14 + 12.75 + 13.65] = 2926.35 \text{ m}^3$$

a) The consumption rate of the section connected

$$= 2392.36 / 45 = 53.16 \text{ m}^3/\text{minute}$$

b) Compressor air drawal as a % of capacity on line is

$$= \quad [2392.36 / 2926.35] \times 100 = 81.75 \text{ \%}$$

c) Specific power consumption $= 370.21 / 2392.36 = 0.155 \text{ kW/m}^3$

d) Idle power consumption due to unload operation = 25.62 kWh in every 45 minutes cycle i.e., 34.16 kWh every hour.

e) It would be favorable in short term and energy efficient to keep the compressor 'D' in cycling mode on account of lower un-load losses and hence capacity. Speed of the compressor can also be reduced by reducing motor pulley size.

f) A suitable smaller capacity compressor can be planned to replace the compressor with highest unload losses.

g) An investigation is called for, as to why such a large variation of unload power drawn, exists although all compressors have almost the same rated capacity.

Segregating low and high pressure air requirements

If the low-pressure air requirement is considerable, it is advisable to generate low pressure and high-pressure air separately, and feed to the respective sections instead of reducing the pressure through pressure reducing valves, which invariably waste energy.

Minimum pressure drop in air lines

Excess pressure drop due to inadequate pipe sizing, choked filter elements, improperly sized couplings and hoses represent energy wastage. The Table 3.10 illustrates the energy wastage, if the pipes are of smaller diameter.

Typical acceptable pressure drop in industrial practice is 0.3 bar in mains header at the farthest point and 0.5 bar in distribution system.

Table 3.10 Typical Energy Wastage due to Smaller Pipe Diameter for 170 m³/h (100 cfm) Flow		
Pipe Nominal Bore (mm)	**Pressure drop (bar) per 100 meters**	**Equivalent power losses (kW)**
40	1.80	9.5
50	0.65	3.4
65	0.22	1.2
80	0.04	0.2
100	0.02	0.1

Equivalent lengths of fittings

Not only piping, but also fitting are a source of pressure losses. Typical pressure losses for various fitting are given in Table 3.11.

Table 3.11 Resistance of Pipe Fittings in Equivalent Lengths (in metres)										
Type of Fitting	Nominal Pipe Size in mm									
	15	20	25	32	40	50	65	80	100	125
Gate Valve	0.11	0.14	0.18	0.27	0.32	0.40	0.49	0.64	0.91	1.20
Tee 90⁰ long bend	0.15	0.18	0.24	0.38	0.46	0.61	0.76	0.91	1.20	1.52
Elbow	0.26	0.37	0.49	0.67	0.76	1.07	1.37	1.83	2.44	3.20
Return bend	0.46	0.61	0.76	1.07	1.20	1.68	1.98	2.60	3.66	4.88
Outlet of tee globe valve	0.76	1.07	1.37	1.98	2.44	3.36	3.96	5.18	7.32	9.45

Blowers in place of Compressed Air System

Since the compressed air system is already available, plant engineer may be tempted to use compressed air to provide air for low-pressure applications such as agitation, pneumatic conveying or combustion air. Using a blower that is designed for lower pressure operation will cost only a fraction of compressed air generation energy and cost.

Capacity Control of Compressors

In many installations, the use of air is intermittent. Therefore, some means of controlling the output flow from the compressor is necessary. The type of capacity control chosen has a direct impact on the compressor power consumption. Some control schemes commonly used are discussed below:

Automatic On / Off Control:

Automatic On /Off control, as its name implies, starts or stops the compressor by means of a pressure activated switch as the air demand varies. This is a very efficient method of controlling the capacity of compressor, where the motor idle-running losses are eliminated, as it completely switches off the motor when the set pressure is reached. This control is suitable for small compressors.

Load and Unload:

This is a two-step control where compressor is loaded when there is air demand and unloaded when there is no air demand. During unloading, a positive displacement compressor may consume up to 30 % of the full load power, depending upon the type, configuration, operation and maintenance practices.

Multi-step Control:

Large capacity reciprocating compressors are usually equipped with a multi-step control. In this type of control, unloading is accomplished in a series of steps, (0%, 25 %, 50 %, 75 % & 100 %) varying from full load down to no-load (see Table 3.12).

Table 3.12 Power Consumption of a Typical Reciprocating Compressor at Various Loads	
Load %	Power Consumption as % of full load Power
100	100
75	76-77
50	52-53
25	27-29
0	10-12

Throttling Control:

The capacity of centrifugal compressors can be controlled using variable inlet guide vanes. However, another efficient way to match compressor output to meet varying load requirements is by speed control (see Table 3.13).

Table 3.13 Typical Part Load Gas Compression :Power Input for Speed and Vane Control of Centrifugal Compressors		
System Volume, %	Power Input (%) Speed Control	Power Input (%) Vane Control
111	120	-
100	100	100
80	76	81
60	59	64
40	55	50
20	51	46
0	47	43

At low volumetric flow (below 40 %), vane control may result in lower power input compared to speed control due to low efficiency of the speed control system. For loads more than 40 %, speed control is recommended.

Avoiding Misuse of Compressed Air:

Misuse of compressed air for purposes like body cleaning, liquid agitation, floor cleaning, drying, equipment cooling and other similar uses must be discouraged.   Wherever possible, low-pressure air from a blower should be substituted for compressed air, for example secondary air for combustion in a boiler / furnace.

The following Table 3.14 gives an idea of savings by stopping use of compressed air by choosing alternative methods to perform the same task.

- ▪ Electric motors can serve more efficiently than air-driven rotary devices, wherever applicable. The Table gives the comparison of pneumatic grinders and electrical grinders.

Table 3.14 Typical Power Requirements for Pneumatic and Electrical Tools				
Tool	Wheel dia mm	Speed rpm	Air Cons. m^3/h	Power kW
Pneumatic angle grinder	150	6000	102 m^3/h at 6 bar	10.2
Electric angle grinder	150	5700-8600	N.A.	1.95 – 2.90
Pneumatic jet grinder	35	30000	32.3 m^3/h at 6 bar	3.59
Electric straight grinder	25	22900 - 30500	N.A.	0.18

It may be noted that in some areas use of electric tools are not permitted due to safety constraints, especially places where inflammable vapours are present in the environment. It should always be remembered that safety consideration always override energy conservation.

- ▪ In place of pneumatic hoists, electric hoists can be used.

- ▪ Material conveying applications can be replaced by blower systems preferably by a combination of belt / screw conveyers and bucket elevators. In a paper manufacturing facility, compressed air was used for conveying wood chips. The equivalent power consumption was 77 kW. This method of conveying was replaced by blower system consuming only 7 kW, a saving of 70 kW. This has also been widely applied in cement industry where pneumatic conveying has been replaced by bucket and screw conveyor resulting

How air amplifiers work?
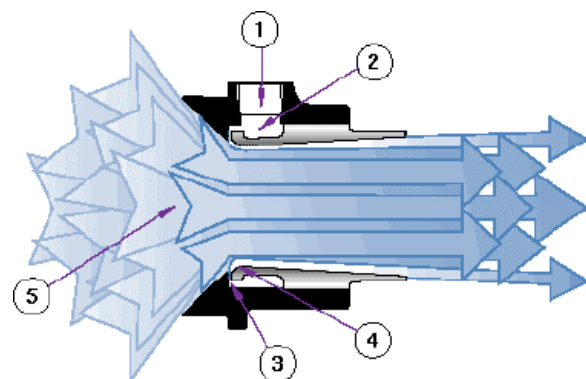
Compressed air flows through the inlet (1) into an annular chamber (2). It is then throttled through a small ring nozzle (3) at high velocity. This primary air stream adheres to the coanda profile (4), which directs it toward the outlet. A low pressure area is created at the center (5) inducing a high volume flow of surrounding air

in significant energy reduction.

- When moving air really is required for an application, often sources other than compressed air can do the job. For applications like blowing of components, use of compressed *air amplifiers (see Figure)*, blowers or gravity-based systems may be possible. Brushes can sweep away debris from work in progress as effectively as high-pressure air. Blowers can be also used for this purpose. Many applications do not require clean, dry, high-pressure and expensive 6 bar or 7 bar compressed air rather, only moving air is needed to blow away debris, provide cooling, or other functions. In these cases, local air fans or blowers may satisfy the need for moving air much economically. If a ¼" hose pipe is kept open at a 7 bar compressed air line for cleaning for at least 1000 hours / annum, it can cost about Rs. 1.0 lakhs / annum. If absolutely necessary, compressed air should be used only with blow guns to keep the air pressure below 2 bar.

- For applications, where compressed air is indispensable for cleaning internal crevices of machines etc., installation of a separate cleaning air header with a main isolation valve may be considered. The main valve should be opened only for a few, well-defined time periods during the whole day; no connections for cleaning should be provided from process or equipment air lines.

- Replacement of pneumatically operated air cylinders by hydraulic power packs can be considered.

- Vacuum systems are much more efficient than expensive venturi methods, which use expensive compressed air rushing past an orifice to create a vacuum.

- Mechanical stirrers, conveyers, and low-pressure air will mix materials far more economically than high-pressure compressed air.

Avoiding Air Leaks and Energy Wastage:

The major opportunity to save energy is in the prevention of leaks in the compressed air system. Leaks frequently occur at air receivers, relief valves, pipe and hose joints, shut off valves, quick release couplings, tools and equipment. In most cases, they are due to poor maintenance and sometimes, improper installations etc.

Air leakages through Different Size Orifices

The Table 3.15 gives the amount of free air wasted for different nozzles sizes and pressure.

Table 3.15 Discharge of Air (M³/Minute) through Orifice (Orifice Constant C_d – 1.0)							
Gauge Pressure Bar	**0.5 mm**	**1 mm**	**2 mm**	**3 mm**	**5 mm**	**10 mm**	**12.5 mm**
0.5	0.06	0.22	0.92	2.1	5.7	22.8	35.5
1.0	0.08	0.33	1.33	3.0	8.4	33.6	52.5
2.5	0.14	0.58	2.33	5.5	14.6	58.6	91.4
5.0	0.25	0.97	3.92	8.8	24.4	97.5	152.0
7.0	0.33	1.31	5.19	11.6	32.5	129.0	202.0

Cost of Compressed Air Leakage:

It may be seen from Table 3.16 that any expenditure on stopping leaks would be paid back through energy saving.

Table 3.16 Cost of Air Leakage		
Orifice Size mm	**kW Wasted**	*** Cost of air leakage (Rs/Year)**
0.8	0.2	8000
1.6	0.8	32000
3.1	3.0	120000
6.4	12.0	480000

* based on Rs. 5 / kWh ; 8000 operating hours; air at 7.0 bar

Steps in simple shop-floor method for leak quantification

- Shut off compressed air operated equipments (or conduct test when no equipment is using compressed air).

- Run the compressor to charge the system to set pressure of operation

- Note the sub-sequent time taken for 'load' and 'unload' cycles of the compressors. For accuracy, take ON & OFF times for 8 – 10 cycles continuously. Then calculate total 'ON' Time (T) and Total 'OFF' time (t).

- The system leakage is calculated as:

% leakage = $T \times 100 / (T + t)$

(or) System leakage (m³/minute) = $Q \times T / (T + t)$

Q = Actual free air being supplied during trial, in cubic meters per minute (cmm)

T = Time on load in minutes

t = Time on unload in minutes

EXAMPLE

In the leakage test in a process industry, following results were observed

Compressor capacity (m^3/minute)	=	35
Cut in pressure, kg/cm^2	=	6.8
Cut out pressure, kg/cm^2	=	7.5
Load kW drawn	=	188 kW
Unload kW drawn	=	54 kW
Average 'Load' time	=	1.5 minutes
Average 'Unload' time	=	10.5 minutes

Comment on leakage quantity and avoidable loss of power due to air leakages.

a) Leakage quantity (m^3/minute) $= \dfrac{(1.5)}{(1.5)+(10.5)} \times 35$

$= 4.375$

b) Leakage per day, (m^3/day) $= 6300$

c) Specific power for compressed
air generation $= \dfrac{188 \text{ kWh}}{(35 \times 60) \ m^3/\text{day}}$

$= 0.0895 \text{ kWh/}m^3$

d) Energy lost due to leakages/day $= 564$ kWh

Leakage Detection by Ultrasonic Leak Detector:

Leakage tests are conducted by a Leak Detector having a sensing probe, which senses when there are leakage in compressed air systems at high temperatures-beneath insulated coverings, pipelines, manifolds etc.

The leak is detected by ultrasonic vibration. Leak testing is done by observing and locating sources of ultrasonic vibrations created by turbulent flow of gases passing through leaks in pressurized or evacuated systems.

Line Moisture Separator and Traps

Although, in an ideal system, all cooling and condensing of air should be carried out before the air leaves the receiver, this is not very often achieved in practice. The amount of condensation, which takes place in the lines, depends on the efficiency of moisture extraction before the air leaves the receiver and the temperature in the mains itself. In general, the air main should be given a fall of not less than 1 m in 100 m in the direction of air flow, and the distance between drainage points should not exceed 30m.

Drainage points should be provided using equal tees, as it assists in the separation of water. Whenever a branch line is taken off from the mains it should leave at the top so that any water in the main does not fall straight into the plant equipment. Further, the bottom of the falling pipe should also be drained.

Compressed Air Filter

Although, some water, oil and dirt are removed by the separators and traps in the mains, still some are always left, which are carried over along with compressed air. Moreover, pipe systems accumulate scale and other foreign matters, such as small pieces of gasket material, jointing compounds etc. Burnt compressor oil may also be carried over in pipe work, and this, with other contaminants, forms a gummy substance. To remove these, all of which are liable to have harmful effects on pneumatic equipment, the air should be filtered as near as possible to the point of use. Water and oil collected in the filter sump must be drained off; because if the level is allowed to build up, it is forced through the filter element into the very system it is designed to protect.

Regulators

In many instances, pneumatic operations are to be carried out at a lower pressure than that of the main supply. For these applications, pressure regulators are required to reduce the pressure to the required value and also to ensure that it remains reasonably constant at the usage point.

Lubricators

Where air is used to drive prime movers, cylinders and valves, they should be fitted with a lubricator. Essentially, a lubricator is a reservoir of oil and has been designed so that when air is flowing, a metered amount of oil is fed in mist form into the air stream. This oil is carried with the motive air, to the point of use to lubricate all moving parts. All lubricators require a certain minimum rate of airflow to induce oil into their stream. It is advisable to install filters, regulators and lubricators as close as possible to the equipment being served.

Air Dryers

There are certain applications where air must be free from moisture and have a lower dew point. Dew point is the temperature at which moisture condenses. This calls for more sophisticated and expensive methods to lower the dew point of compressed air. Three common types of air dryers used are heat-less (absorption), absorption and refrigerated dryers. They produce dry air with -10^0C to -40^0C dew point, depending on the type of dryers. Refer Table 3.17 for moisture content in air and Table 3.18 for typical pressure dew point and power consumption data for dryers.

Table 3.17 Moisture Content in Air	
Dew point at Atmospheric Pressure ^{0}C	Moisture Content, ppm
0	3800
-5	2500
-10	1600
-20	685
-30	234
-40	80
-60	6.5

Table 3.18 Typical Pressure Dew Point and Power Consumption Data for Dryers				
Type of Dryer	Atmospheric Dew Point ^{0}C	First Cost	Operating Cost	Power Cons. For 1000 m^3/hr
Refrigeration	-20	Low	Low	2.9 kW
Desiccant regenerative (by compressed air purging)	-20	Low	High	20.7 kW
Desiccant regenerative (external or internal heating with electrical or steam heater, reduced or no compressed air purging)	-40	Medium	Medium	18.0 kW
Desiccant regenerative (using heated low pressure air, no compressed air loss)	-40	High	Low	12.0 kW
Desiccant regenerative (by recovery of heat of compression from compressed air)	-40	High	Very low	0.8 kW

Air Receivers

The air receiver dampens pulsations entering the discharge line from the compressor; serves as a reservoir for sudden or unusually heavy demands in excess of compressor capacity; prevents too frequent loading and unloading (short cycling) of the compressor; and separates moisture and oil vapour, allowing the moisture carried over from the after coolers to precipitate.

The air receiver should be generously sized to give a large cooling surface and even out the pulsation in delivered air pressure from reciprocating compressor. Simple formulae often quoted for air receiver size is to take a value equal to one minute's continuous output of the compressor. However, this should be considered indicative of the minimum size of receiver.

Another approximation can be to size the receiver volume to be 5% of the rated hourly free air output. Providing an air receiver near the load end, where there is sudden high demand lasting for a short period, would avoid the need to provide extra capacity.

Loss of air pressure due to friction

The loss of pressure in piping is caused by resistance in pipe fittings and valves, which dissipates energy by producing turbulence. The piping system will be designed for a maximum allowable pressure drop of 5 percent from the compressor to the most distant point of use.

Piping layout

Where possible the piping system should be arranged as a closed loop or "ring main" to allow for more uniform air distribution to consumption points and to equalize pressure in the piping. Separate services requiring heavy air consumption and at long distances from the compressor unit should be supplied by separate main airlines. Pipes are to be installed parallel with the lines of the building, with main and branch headers sloping down toward a dead end. Traps will be installed in airlines at all low points and dead ends to remove condensed moisture. Automatic moisture traps used for this purpose are effective only when the air has been cooled and the moisture has precipitated. Branch headers from compressed air mains will be taken off at the top to avoid picking up moisture.

Capacity Utilisation

In many installations, the use of air is intermittent. This means the compressor will be operated on low load or no load condition, which increases the specific power consumption per unit of air generated. Hence, for optimum energy consumption, a proper compressor capacity control should be selected. The nature of the control device depends on the function to be regulated. One of the objectives of a good compressed air management system would be to minimize unloading to the least as unloading consumes up to 30% of full load power.

One way of doing this is to use a smaller compressor.

Decentralized compressors, as against centralized compressors often serve this purpose better by having the option to switch off when air is not need in a particular section/equipment.

If a compressor is oversized and operates at unloading mode for long periods, an economical way will be to suitably change the pulley size of the motor or compressor and reduce the RPM to de-rate the compressor to a lower capacity.

With decreasing cost of variable speed drives, it has become a viable option to maintain constant pressure in the system and to avoid unloading operations by varying the speed of the compressor. However, caution should be taken for operations at very low speeds, since it will affect the lubricating system. This can be overcome by providing a separate lube oil system independent of the compressor.

3.6   Compressor Capacity Assessment

Due to ageing of the compressors and inherent inefficiencies in the internal components, the free air delivered may be less than the design value, despite good maintenance practices. Sometimes, other factors such as poor maintenance, fouled heat exchanger and effects of altitude also tend to reduce free air delivery. In order to meet the air demand, the inefficient compressor may have to run for more time, thus consuming more power than actually required.

The power wastage depends on the percentage deviation of FAD capacity. For example, a worn out compressor valve can reduce the compressor capacity by as much as 20 percent. A periodic assessment of the FAD capacity of each compressor has to be carried out to check its actual capacity. If the deviations are more than 10 %, corrective measures should be taken to rectify the same.

The ideal method of compressor capacity assessment is through a nozzle test wherein a calibrated nozzle is used as a load, to vent out the generated compressed air. Flow is assessed, based on the air temperature, stabilization pressure, orifice constant. etc.

Simple method of Capacity Assessment in Shop floor

> Isolate the compressor along with its individual receiver being taken for test from main compressed air system by tightly closing the isolation valve or blanking it, thus closing the receiver outlet.

> Open water drain valve and drain out water fully and empty the receiver and the pipe line.   Make sure that water trap line is tightly closed once again to start the test.

> Start the compressor and activate the stopwatch.

> Note the time taken to attain the normal operational pressure P_2 (in the receiver) from initial pressure P_1.

> Calculate the capacity as per the formulae given below :

Actual Free air discharge

$$Q \ = \ \frac{P_2 - P_1}{P_0} \times \frac{V}{T} \ \text{Nm}^3 / \text{Minute}$$

Where

P_2 =   Final pressure after filling (kg/cm^2 a)

P_1 =   Initial pressure (kg/cm^{2}a) after bleeding

P_0 =   Atmospheric Pressure (kg/cm^2 a)

V   =   Storage volume in m^3 which includes receiver, after cooler, and delivery piping

T   =   Time take to build up pressure to P_2 in minutes

The above equation is relevant where the compressed air temperature is same as the ambient air temperature, i.e., perfect isothermal compression. In case the actual

compressed air temperature at discharge, say $t_2{}^0C$ is higher than ambient air temperature say $t_1{}^0C$ (as is usual case), the FAD is to be corrected by a factor $(273 + t_1) / (273 + t_2)$.

EXAMPLE

An instrument air compressor capacity test gave the following results (assume the final compressed air temperature is same as the ambient temperature) – Comment?

Piston displacement	:	16.88 m^3/minute
Theoretical compressor capacity	:	14.75 m^3/minute @ 7 kg/cm^2
Compressor rated rpm 750	:	Motor rated rpm : 1445
Receiver Volume	:	7.79 m^3
Additional hold up volume, i.e., pipe / water cooler, etc., is	:	0.4974 m^3
Total volume	:	8.322 m^3
Initial pressure P_1	:	0.5 kg/cm^2
Final pressure P_2	:	7.03 kg/cm^2
Atmospheric pressure P_0	:	1.026 kgf/cm^2A

Compressor output m^3/minute :

$$\frac{(P_2 - P_1) \times \text{Total Volume}}{\text{Atm. Pressure} \times \text{Pumpup time}}$$

$$: \quad \frac{(7.03 - 0.5) \times 8.322}{1.026 \times 4.021} = 13.17 \ m^3/\text{minute}$$

Capacity shortfall with respect to 14.75 m^3/minute rating is 1.577 m^3/minute i.e., 10.69 %, which indicates compressor performance needs to be investigated further.

3.7 Checklist for Energy Efficiency in Compressed Air System

- Ensure air intake to compressor is not warm and humid by locating compressors in well-ventilated area or by drawing cold air from outside. Every 4^0C rise in air inlet temperature will increase power consumption by 1 percent.

- Clean air-inlet filters regularly. Compressor efficiency will be reduced by 2 percent for every 250 mm WC pressure drop across the filter.

- Keep compressor valves in good condition by removing and inspecting once every six months. Worn-out valves can reduce compressor efficiency by as much as 50 percent.

- Install manometers across the filter and monitor the pressure drop as a guide to replacement of element.

- Minimize low-load compressor operation; if air demand is less than 50 percent of compressor capacity, consider change over to a smaller compressor or reduce compressor speed appropriately (by reducing motor pulley size) in case of belt driven compressors.

- Consider the use of regenerative air dryers, which uses the heat of compressed air to remove moisture.

- Fouled inter-coolers reduce compressor efficiency and cause more water condensation in air receivers and distribution lines resulting in increased corrosion. Periodic cleaning of inter-coolers must be ensured.

- Compressor free air delivery test (FAD) must be done periodically to check the present operating capacity against its design capacity and corrective steps must be taken if required.

- If more than one compressor is feeding to a common header, compressors must be operated in such a way that only one small compressor should handle the load variations whereas other compressors will operate at full load.

- The possibility of heat recovery from hot compressed air to generate hot air or water for process application must be economically analyzed in case of large compressors.

- Consideration should be given to two-stage or multistage compressor as it consumes less power for the same air output than a single stage compressor.

- If pressure requirements for processes are widely different (e.g. 3 bar to 7 bar), it is advisable to have two separate compressed air systems.

- Reduce compressor delivery pressure, wherever possible, to save energy.

- Provide extra air receivers at points of high cyclic-air demand which permits operation without extra compressor capacity.

- Retrofit with variable speed drives in big compressors, say over 100 kW, to eliminate the `unloaded' running condition altogether.

- Keep the minimum possible range between load and unload pressure settings.

- Automatic timer controlled drain traps wastes compressed air every time the valve opens. So frequency of drainage should be optimized.

- Check air compressor logs regularly for abnormal readings, especially motor current cooling water flow and temperature, inter-stage and discharge pressures and temperatures and compressor load-cycle.

- Compressed air leakage of 40- 50 percent is not uncommon. Carry out periodic leak tests to estimate the quantity of leakage.

- Install equipment interlocked solenoid cut-off valves in the air system so that air supply to a machine can be switched off when not in use.

- Present energy prices justify liberal designs of pipeline sizes to reduce pressure drops.

- Compressed air piping layout should be made preferably as a *ring main* to provide desired pressures for all users.

- A smaller dedicated compressor can be installed at load point, located far off from the central compressor house, instead of supplying air through lengthy pipelines.

- All pneumatic equipment should be properly lubricated, which will reduce friction, prevent wear of seals and other rubber parts thus preventing energy wastage due to excessive air consumption or leakage.

- Misuse of compressed air such as for body cleaning, agitation, general floor cleaning, and other similar applications must be discouraged in order to save compressed air and energy.

- Pneumatic equipment should not be operated above the recommended operating pressure as this not only wastes energy bus can also lead to excessive wear of equipment's components which leads to further energy wastage.

- Pneumatic transport can be replaced by mechanical system as the former consumed about 8 times more energy. Highest possibility of energy savings is by reducing compressed air use.

- Pneumatic tools such as drill and grinders consume about 20 times more energy than motor driven tools. Hence they have to be used efficiently. Wherever possible, they should be replaced with electrically operated tools.

- Where possible welding is a good practice and should be preferred over threaded connections.

- On account of high pressure drop, ball or plug or gate valves are preferable over globe valves in compressed air lines.

	QUESTIONS
1.	The efficiency of compressed air system is around a) 80% b) 60% c) 90% d) 10%
2.	For instrumentation air needs, which of the following compressors are used: a) Roots blower b) Lubricated screw c) Lubricated reciprocating d) Non-lubricated compressor
3.	Which of the following is not a rotary compressor? a) Roots blower b) Screw c) Centrifugal d) Reciprocating
4.	Which of the following compressors best meet high volume low pressure requirements? a) Reciprocating b) Screw c) Centrifugal d) Lobe
5.	FAD refers to the compressed air discharge a) at ISO stated conditions b) Inlet conditions c) at outlet conditions d) at STP
6.	Isothermal efficiency is the ratio of isothermal power to a) Motor power drawn b) isentropic power c) Shaft power d) theoretical power
7.	Which of the following parameters are not required for evaluating volumetric efficiency of the compressor? a) Power b) Cylinder bore diameter c) stroke length d) FAD
8.	The smoothening of the pulsating output of a reciprocating compressor is helped by a) Receiver b) intercooler c) after cooler d) drain traps
9.	Which of the following does not improve compressor performance ? a) cool air intake b) clean air intake c) humid air intake d) lower elevation
10.	The leak test results show load time of 5 seconds and unload time of 10 seconds. If the compressor capacity is 100 cfm, then the leakage would be a) 33 cfm b) 50 cfm c) 200 cfm d) 66 cfm

11.	In a compressor capacity trial in a plant, following were the observations:
	      Receiver capacity : 10 m^3
	      Initial pressure : $0.2 \text{ kg} / \text{cm}^2\text{g}$
	      Final pressure : $6.0 \text{ kg} / \text{cm}^2\text{g}$
	      Additional hold-up volume : 1.2 m^3
	      Atmospheric pressure : $1.026 \text{ kg} / \text{cm}^2\text{A}$
	      Compressor pump-up time : 4.26 minutes
	      Motor power consumption (avg.): 98.6 kW
	Calculate the operational capacity of compressor & specific power consumption (neglect temperature correction)?

12.	List the factors that affect energy efficiency in air compressors.

13.	What are the methods of capacity control in reciprocating air compressors?
14.	Briefly explain shopfloor method of air compressor capacity assessment.
15.	What are the effects of moisture on compressed air?
16.	Briefly explain the benefits of an air receiver.
17.	A reciprocating V belt driven compressor was found to operating during normal factory operation with the following parameters: Load pressure = 6 bar Unload pressure = 8 bar Load time = 3 minutes Unload time = 1.5 minutes Suggest possible energy saving opportunities on a short-term basis.

REFERENCES

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2. PCRA Publications on Compressed Air System
3. NPC Energy Audit Reports