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**CERTIFIED INDUSTRIAL ENERGY PROFESSIONAL
CIEP TRAINING PROGRAM
FOR INDUSTRIAL ENERGY SPECIALISTS**
KRISHNAJI PAWAR, LEED AP BD+C, GSAS CGP, ISO 14001:2015, GCP
ENERGY SPECIALIST CURRICULUM



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**COMPRESSED AIR SYSTEMS
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WHAT SHOULD YOU LEARN



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

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.

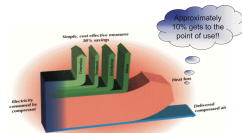


Figure 3.1 Sankey Diagram for Compressed Air System

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.

COMPRESSOR TYPES

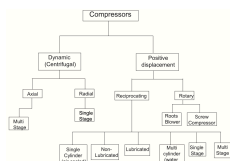


Figure 3.2 Compressor Chart

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.

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.

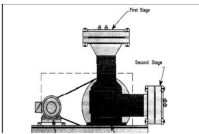


Figure 3.3 Reciprocating Compressor

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

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.

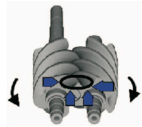


Figure 3.4 Screw Compressors

✓ 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.

✓ The most common rotary air compressor is the single stage helical or spiral lube 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.

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.

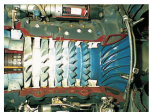


Figure 3.5 Axial Compressor

✓ 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.

GENERAL SELECTION CRITERIA FOR COMPRESSORS

Type of Compressor	Capacity (m ³ /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

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.

COMPRESSOR PERFORMANCE +

Isothermal Efficiency

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

$$\text{Isothermal power (kW)} = \frac{P_1 \times Q_1 \times \ln(P_2/P_1)}{1000}$$

P_1 = Absolute inlet pressure kgf/cm²
 P_2 = Absolute delivery pressure kgf/cm²
 Q_1 = Free air delivered m³/hr.
 $\ln$ = 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.

$$\text{Volumetric efficiency} = \frac{\text{Free air delivered (m}^3/\text{min)}}{\text{Compressor displacement (m}^3/\text{min)}} \times 100$$

Volumetric Efficiency

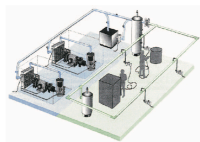
$$\text{Compressor Displacement} = \frac{\pi \times D^2 \times L \times S \times Z \times n}{4}$$

D = Cylinder bore, metre
 L = Cylinder stroke, metre
 S = Compressor speed rpm
 Z = 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 in kW/volume flow rate, for different compressors that would provide identical duty.

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

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°C 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 (°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.

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"

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

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)

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

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°C
50	27.60
80	45.00
100	68.22

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.

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, intercoolers 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.

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.

TABLE 3.6 EFFECT OF INTER-STAGE COOLING ON SPECIFIC POWER CONSUMPTION OF A RECIPROCATING COMPRESSOR - ILLUSTRATION

Details	Inlet Air Cooling	Perfect Cooling (Free Air)	Cooling Water Cooling
First Stage inlet temperature °C	21.1	21.1	21.1
Second Stage inlet temperature °C	30.6	21.1	15.5
Capacity (Cfm/hr)	15.5	15.6	15.7
Shaft Power (kW)	96.3	75.5	74.2
Specific energy consumption (kWh/tonne)	4.8	4.4	4.7
Percent Change	+ 5.1	Reference	- 2.1

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).

It can be seen from the Table 3.6 that an increase of 5.6 °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.

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, stabilisation pressure, orifice constant, etc.

COMPRESSOR CAPACITY ASSESSMENT +

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.

Calculate the capacity as per the formulae given below :

$$\text{Actual Free air discharge} = Q = \frac{P_1 - P_2}{P_1} \times \frac{V}{T} \times \text{Min}^{-1}$$

Where

- P_1 = Final pressure after filling (kg/cm² a)
- P_2 = Initial pressure (kg/cm² a) after bleeding
- P_3 = Atmospheric Pressure (kg/cm² a)
- V = Storage volume in m³ which includes receiver, after cooler, and delivery piping
- T = Time taken to build up pressure to P_1 in minutes

The above equation is valid when 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_1 °C is higher than ambient air temperature say T_2 °C (in isothermal case), the FAD is to be corrected by a factor $(273 + T_2) / (273 + T_1)$.

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 .

EXAMPLE

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	: 7.79 + 0.4974 = 8.287m 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 ² A
Time taken to build up pressure	: 4.021 minutes
Compressor output m ³ /minute	: $\frac{(P_2 - P_1) \times \text{Total Volume}}{\text{Atm. Pressure} \times \text{Pumpup time}}$
	: $\frac{(7.03 - 0.5) \times 8.287}{1.026 \times 4.021} = 13.12 \text{ m}^3/\text{minute}$

Capacity shortfall with respect to 14.75 m³/minute rating is 1.63 m³/minute i.e., 11.05%, which indicates compressor performance needs to be investigated further.

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°C 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.

CHECKLIST FOR ENERGY EFFICIENCY IN COMPRESSED AIR SYSTEM

- ✓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.

CHECKLIST FOR ENERGY EFFICIENCY IN COMPRESSED AIR SYSTEM

- ✓ 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.
- ✓ 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



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