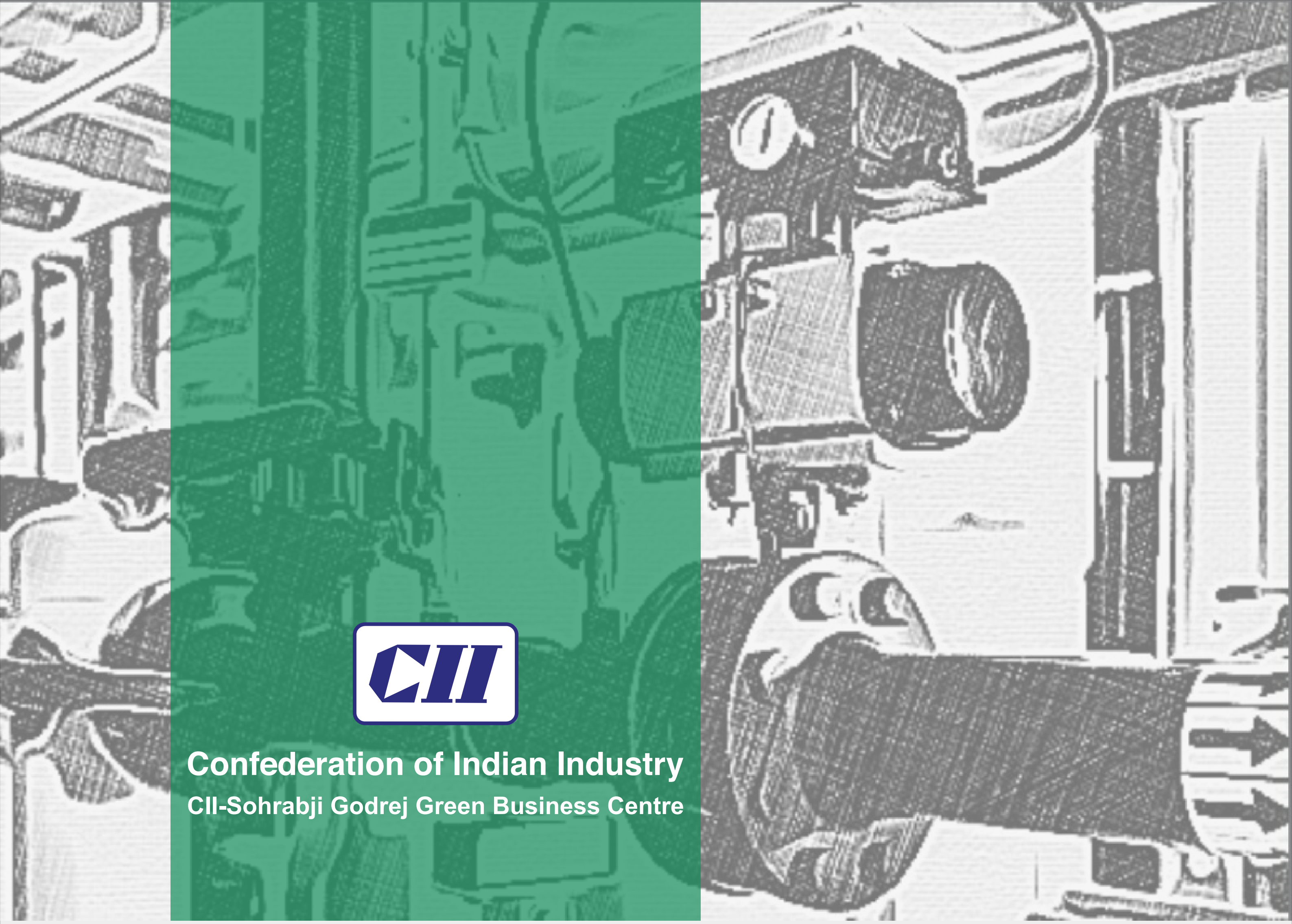


Confederation of Indian Industry

CII-Sohrabji Godrej Green Business Centre

ENERGY EFFICIENCY IN COMPRESSED AIR SYSTEM

Published by
Confederation of Indian Industry
CII-Sohrabji Godrej Green Business Centre
Survey # 64, Kothaguda Post
R.R. District, Hyderabad 500 032 India

FOREWORD

Energy Efficiency is of paramount concern in today's industrial sector; not to forget, increasing global temperatures, sustainable economic growth, and industrial competitiveness. The time is now to adopt innovative and sustainable methods, and step up efforts to improve energy productivity levels, whilst ensuring a healthy and competitive economy.

Energy efficiency is often used as a tool to cut down operating costs for manufacturing a product. Although organisations are aware of its positive implications in contributing to sustainable businesses, it is yet to realise its potential, owing to the present market conditions and institutional barriers.

Compressors & compressed air systems is one such industry utility with significant untapped potential. It is, of course, one of the substantial energy consumer in industry, irrespective of the size or the type of product manufactured, ranging between 10-40% of industry's electrical consumption. There is a definite need to reduce energy costs by improving energy efficiency in compressors & compressed air systems. In fact, 8-15% of the energy savings potential can be realized with zero-to-minimal investment through demand analysis and optimization techniques, while technology upgradations and system improvements can save 20-50% of energy consumption, depending on the use of compressed air.

The manual on "Energy Efficiency in Compressed Air System" focuses on various aspects of energy saving in air compressors/auxiliaries, and showcases the best technologies, operating practices and case studies. The aim of the publication is to help the industry understand the basic concepts of air compressor, KPIs for assessing compressor performance, and to illustrate various success stories across various sectors to improve energy efficiency.

I really appreciate the efforts and help provided by various technology developers and industries, in sharing their case studies for the manual. Also, my hearty congratulations to the working group who have taken enormous efforts to put together best available technologies and showcase industrial practices, and those who have been resourceful in adding value to the manual.

I am sure that the "Energy Efficiency in Compressed Air System" manual will be of great interest to the utility and energy professionals of the industry, and will help them develop a broader perspective in compressed air systems, and most importantly, strive to become world leaders in Energy Efficiency.

Ravichandran Purushothaman

President, Danfoss India Region

Chairman Designate

Energy Efficiency Council

CII – Godrej Green Business Centre

Acknowledgement

It is our privilege to express our sincerest regards to the working group on "Energy Efficiency in Compressed Air Systems" for their invaluable contribution in leading the initiative from the front.

We are also profoundly grateful to the following organisations for openly sharing the technical information and the case studies provided for the identified best practices:

- Athena Cleantech Pvt. Ltd.
- Atlas Copco
- Bureau of Energy Efficiency
- Compressed Air and Gas Institute
- Godrej & Boyce Mfg. Co. Ltd.
- Instamod Airpipe Pvt. Ltd.
- Kaeser Compressors
- Systel Asia

We would also like to place our vote of thanks for all the interactions and deliberations with the industry, suppliers and sector experts. The whole exercise was a thoroughly rewarding experience for CII.

CONTENTS

List of Figures

List of Tables

INTRODUCTION

This manual is prepared with the objective of helping its readers understand the basic concepts of compressors and compressed air systems. It also provides various insights on energy efficiency, performance assessment measures and commercially available technologies to enhance energy performance of compressed air systems in the industry. This manual helps industry make decisions based on the cost economics and technical feasibility of the identified energy saving opportunities.

Introduction to **Energy Efficiency in Compressed Air Systems**

Compressors are the most common energy consuming utility in any industry. Compressed air finds applications in sectors ranging from small machine shop to larger industries such as cement, power, automobile, aluminium, iron & steel, etc. There are instances when the industry might cease to operate without compressed air, such is its importance. They play critical roles across various sectors in the form of instrumentation equipment (control valves/actuators), powering tools, conveying, automations, spraying, bag filter purging and much more.

With the percentage of energy consumption of compressed air utilities in an industry ranging between 10-40%, there is potential to reduce energy consumption by at least 15-40%, by improving the energy efficiency of compressed air systems.

It is known that the end-use efficiency of compressed air systems is as low as 15-20%, indicating potential losses through compression heat loss, compressed air leakages, inefficient design of layout, and also through usage of equipment such as filters, coolers, valves, nozzles, etc.

Energy efficiency in compressed air systems, hence, could be of great value for all energy professionals in the industry. Improvement opportunities, as shown in Figure 1, can help units in achieving long-term energy savings, and contribute significantly to reducing their CO_2 emissions.

Did you know??

Compressed air is considered as the fourth most commonly used industrial utility after water, electricity, & fuels (coal/natural gas).

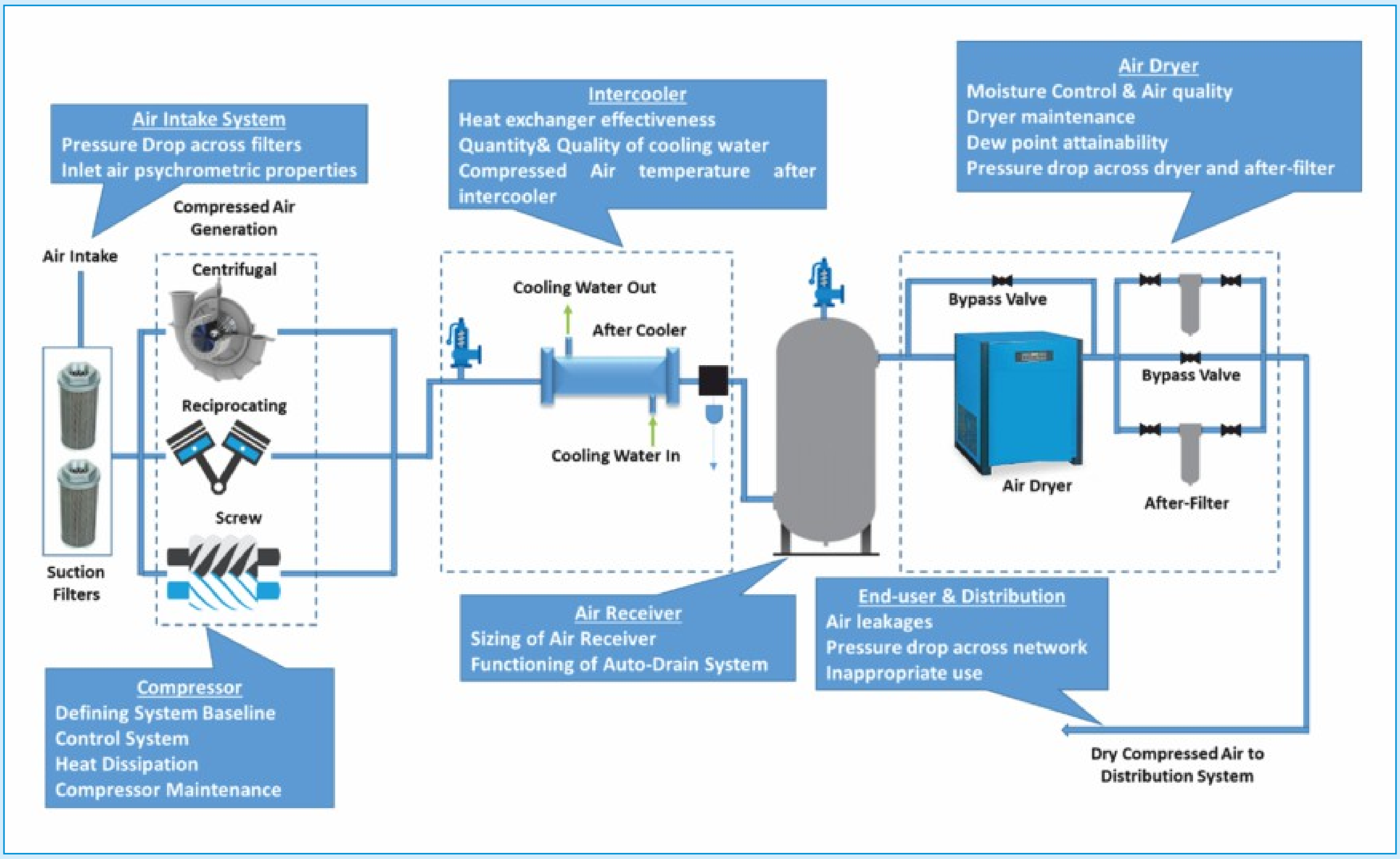


Figure 1: Energy Efficiency performance improvement opportunities

There are, of course, various factors which must be accounted for while designing a compressed air system. Given the dynamic nature of the compressed air systems, factors such as compressor size and numbers, type of control, layout design, air receiver size and numbers, and type of air dryers are equally significant. This not only helps ensures high performance of compressed air systems, but also efficient operation during peak and part demand.

Compressors and compressed air systems presents significant potential for industries to enhance energy efficiency. Yet, the opportunities still remain untapped and unexploited. Therefore, there is a need to create necessary awareness and promote uptake of energy efficient technologies, and develop nation-wide programmes to provide financial assistance for upgrading technologies of compressed air systems. Reinvigorating efforts are needed to bolster the structure of compressed air service market and its associated barriers, in order to accelerate the adoption of latest energy efficient compressed air technologies.

CHAPTER I

COMPRESSED AIR SYSTEM – TYPES, COMPONENTS AND APPLICATIONS

A compressor is a mechanical device that can pressurize compressible fluids/gas from a lower pressure to a higher pressure. However, fans and blowers also perform a similar job. How are they differentiated from each other?

Fans, blowers and compressors are differentiated by the method used to move the air, and by the system pressure they must operate against. As per American Society of Mechanical Engineers (ASME), the specific ratio – the ratio of the discharge pressure over the suction pressure – is used for defining the fans, blowers and compressors.

Table 1: Comparison between Fans, Blowers and Compressors

Equipment	Specific ratio	Pressure rise (mmWC)
Fans	< 1.11	1,136
Blowers	1.11 to 1.20	11,360-2,066
Compressor	> 1.20	---

Basics of Compressed Air System

An industrial compressed air system comprises of various components, including air filters, compressors, prime movers, air quality systems, end-user accessories, distribution network, control systems, etc. The compressor is a device which pressurizes the air from the atmosphere, and this compression requires energy. A prime mover drives the compressor by converting the electrical energy into mechanical energy of the compressor.

The air quality equipment removes moisture and dust from the compressed air so as to ensure effective functioning of end-user equipment. The control system of the compressor regulates the pressure and the flow rate of the compressed air generated. Finally, the distribution network connects the generation and the end-user equipment and transports the compressed air wherever needed.

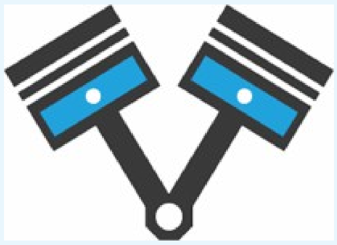
Types & Classification of Air Compressors and Compressed Air Systems

Compressors and their auxiliary systems can be divided into various categories, depending on factors such as volume of compressed air required, generating pressure, quality of air required, etc. The classification of the compressors and their systems are explained below:

Classification of compressors/compression mechanisms

1. Positive Displacement

    a. Reciprocating

    Positive displacement compressors mechanically displace a fixed volume of air in compressed air chamber into a reduced volume. The mechanism comprises of a piston, driven by a crankshaft which is driven by an electric motor. The piston reduces volume of the air trapped in the cylinder, thereby compressing to a higher pressure.

        i. Single Acting

        ii. Double Acting

    b. Rotary

    Air is compressed by two rotating, intermeshing rotors (in some cases one rotor is kept stationery and the other rotates). The action of the rotary screw/lobe can be compared to a reciprocating compressor.

i. Screw Compressor

- Oil-Injected
- Lubricant Free

ii. Scroll

iii. Lobe

2. Dynamic

Dynamic compressors mechanically impart a velocity to the air, through the use of impellers rotating at high speed, in an enclosed housing. The air is forced into a progressively reduced volume.

a. Centrifugal Compressors

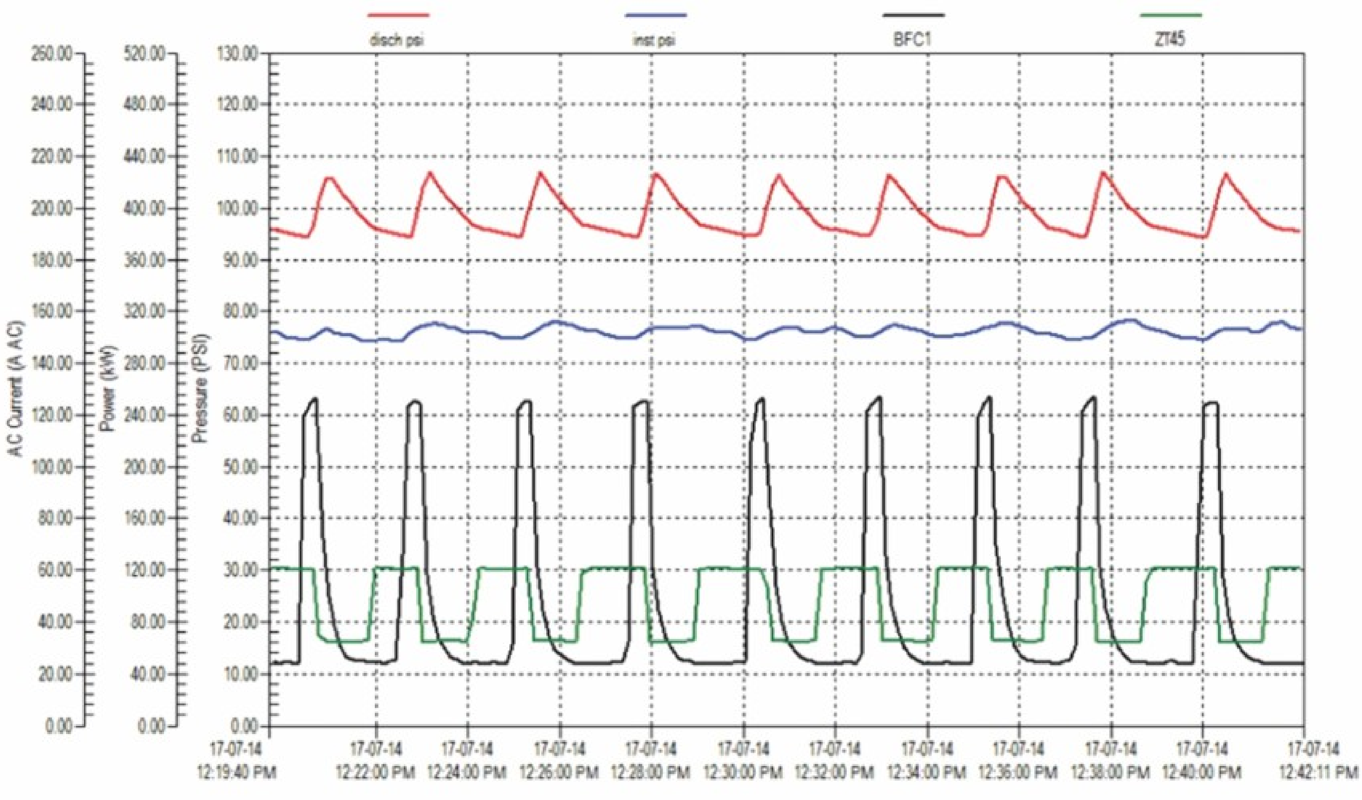
In a Centrifugal compressor, air enters with low velocity, gain kinetic energy from the impeller and velocity rises.

b. Axial Compressors

The axial flow type air compressor is essentially a large capacity, high speed machine, with characteristics quite different from the centrifugal. Each stage consists of two row of blades, one row rotating and the next row stationery. The rotor blades impart velocity and pressure to the gas as the motor turns, the velocity being converted to pressure in the stationery blade.

Control System of compressed air

Matching the supply of compressed air with the demand is necessary to ensure the best performance and efficient operation of compressed air system. While a compressor is installed to cater to the system's demand, a control system modulates the compressor operation to cater to lower demands. The same can be said for controlling the pressure of the compressed air generated by the compressor. In a scenario where multiple compressors are in operation, the control and streamlining of compressor operation becomes more sophisticated.



There are, of course, various types of control systems technologies available today. The type of control systems to be selected depends on the process requirements and are in the form of start/stop, load/unload, variable frequency and variable speed. Therefore, the selection of control system plays a vital role and must be carefully considered to ensure the best performance and efficient operation of the compressed air system.

Lubrication Cooling System

1. Air Cooled Compressors

   It is known that compression of air generates heat, which can be removed by the air-cooled system, which typically consists of a fan, connected as a part of the compressor unit. The fan draws cold air from the atmosphere and takes away the heat from the fins (in case of reciprocating compressor) or heat exchanger (in case of screw compressor).

2. Water Cooled Compressors

   In case of water-cooled compressors, water jackets or heat exchangers are provided to remove the heat. The water circulation is usually provided by a centralized cooling water pump. It is important to note that the quality and quantity of water, and the effectiveness of heat exchanger, play a crucial role in lubricating the cooling system.

In case of water-cooled compressors, the cooling water pumps are designed such that only one pump caters to a series of compressors, which is a common feature in almost all the industries. The pumps are designed keeping in mind that all compressors are operated continuously. But in actual practice, only 50-60% of the compressors are operated. This results in pumping of excess water, leading to higher power consumption.

A Variable Frequency Drive (VFD) for the cooling water pumps can be considered wherever dedicated systems are not possible. This will result in a considerable amount of power savings, as well as good process control.

Table 2: Norms for Cooling Water and pump power Consumption

S. No	Parameter	Capacity	Head/Pressure	Value
1	Water consumption	1,000	7 kg/cm^2	350 LPM
2	Power Consumption	1,000	20 m	2.0 kW

Air quality equipment

1. Inlet air filter

   Filters are used to remove the contaminants – especially dust, oil and moisture – before they could reach the compressor. Some of the filter media used are Ceramics, Sintered Bronze, Boro Silicate glass micro fibre, and activated carbon. The inlet filter on an air compressor is a particulate filter, designed to protect the compressor rather than downstream equipment.

2. Intercooler

   Most designs use two stages of compression with an intercooler between the stages. Air leaving the first stage is passed through an intercooler, where its temperature is reduced as close as possible to atmospheric temperature by cooling water and resulting condensate drained off, before it enters the second stage compression chamber where it is compressed to the desired system pressure.

3. Aftercooler

   Typically, the after cooler removes about 50-60% of water vapour. When the air leaves the after cooler and passes through the compressed air lines, the temperature of the compressed air further reduces. The remaining water vapour in the air starts condensing.

4. Moisture Separator

A moisture separator is a mechanical device designed to remove condensate from an air stream. A moisture separator is typically installed immediately at the downstream of the aftercooler. It should be noted that no moisture separator is 100% efficient and that some condensate most definitely passes through the device.

5. Air Dryers

Adequate compressed air cooling is essential for the proper operation of compressed air treatment equipment. Dryers are normally designed for an inlet compressed air temperature of 38°C.

a) Refrigeration dryer

Refrigeration drying is based on the principle that when the temperature of the compressed air is lowered, the moisture holding capacity is reduced. They are categorized into non-cyclic dryer and cyclic dryer.

b) Adsorption Dryer

In adsorption drying, compressed air is passed through a bed of desiccant material porous in nature where the moisture adheres to the surface. They are further classified into four types:

i. Desiccant heated blower reactivated type

ii. Desiccant heat less purge type

iii. Desiccant heated purge type

iv. Desiccant heat of compression type dryer

c) Deliquescent Type Dryer

The deliquescent desiccant type dryer uses hygroscopic desiccant material, usually salt, which has a high affinity for water.

d) Membrane Type Dryer

Membrane type of dryers has a special membrane that allows the water vapour faster than air stream.

Other auxiliaries

1. Air Receivers

There are various purposes for which an air receiver can be made useful in a compressed air system. They become the source of compressed air during peak demands, which are intermittent in nature. Also, in scenarios where single reciprocating compressors are used, air receivers tend to dampen the pulsation effect and ensure continuous supply of compressed air. Sometimes, in a setup where air dryer is installed after the air receiver, air receivers provide the necessary radiant cooling and assist in condensing some part of the moisture present in the compressed air.

2. Heat Recovery Systems

A large amount of energy supplied to the compressor is expended as heat, resulting in low efficiencies of the compressor system. Heat recovery systems can recover substantial amount of energy from the lubricant, thereby recovering at least 70% of the electrical energy in the form of heat. This heat can be utilized to heat air or water or other process fluids, thereby saving on the energy incurred on combusting fuels.

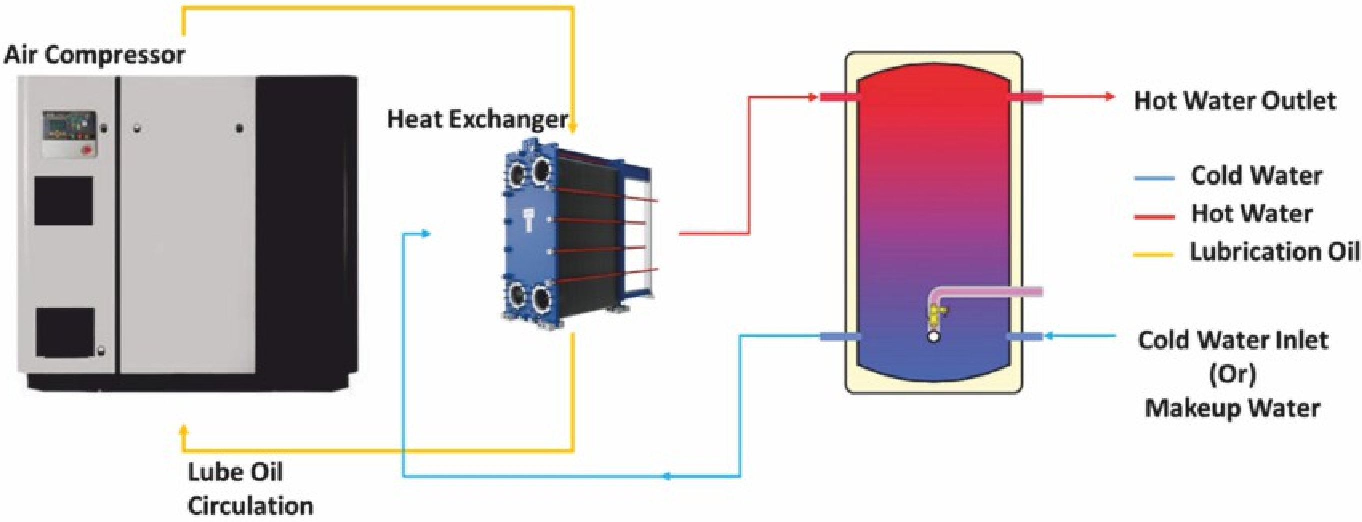


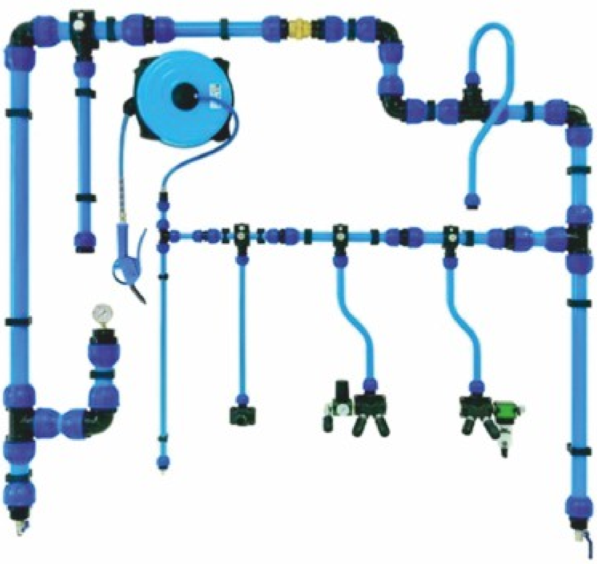
Figure 3: Compressor Waste Heat Recovery

3. Moisture traps and drains

Traps/drains are devices used to remove the condensate from the compressed air and drain it into a collection storage area. In order to minimize the loss of compressed air during condensate removal process, automated condensate traps are used, which are available on various operating mechanisms. They can be timer-based auto drain valves, level sensing-based auto drain valves, float operated drain valves, etc.

A common but inefficient practice in the industry is that the operator leaves the drains cracked open to let the condensate continuously out of the air receiver, which also causes the compressed air to drain along with the condensate. Also, the operators must take proper measures to continuously remove the contaminants obstructing the flow of condensate in these traps.

4. Distribution Network



The distribution system are the ones linking the generation and the end-user of the compressed air system. They comprise of main headers, branches, valves, regulators, hoses, etc. The primary factor which needs to be ensured in a distribution network is the minimum pressure drop, which can be maintained by laying out of pipeline of sufficient diameter and also a loop arrangement of compressed air system.

Another common issue faced by the industry is the air leakages in the distribution network. The distribution network must be aimed to last long and avoid problems due to corrosion, which be eliminated by using aluminium piping.

Applications of Compressed Air

Compressed air is one of the most common resources in industry, used in a large number of applications. Ranging from conveying, tool powering, bag filter purging, actuating, agitating, to control systems, compressed air has a wide range of applications depending on the industrial requirement.

Some of the applications of compressed air utilised in major industrial sectors are tabulated below:

Table 3: Application of Compressed Air Sector Wise

Industry/Sector	Application of compressed air use
Automotive	Power tools, actuation and control, robotic arms, conveying, paint spray, cleaning
Cement	Bag Filters, Air Blasters, Conveying, instrumentation and control, service air, Packing machines
Chemicals	Conveying, instrumentation and control, service air
Food & Beverages	Bottling, Conveying, instrumentation and control, service air, cleaning, vacuum packaging
Engineering/ Manufacturing	Power tools, clamping, actuation, cleaning, spraying, injection moulding, sand blasting
Mining	Tools, hoists, controls and actuation
Pulp & Paper	Conveying, instrumentation and control, service air
Metals	Vacuum degassing, Bag filters, conveying, instrumentation and control, service air
Power	Conveying, instrumentation/actuating and control, service air
Textiles	Agitation, Clamping, Conveying, Loom jet weaving, spinning, instrumentation and control, service air

Did you know??

Compressed air is used in our day-to-day activities, such as filling a tyre, sports equipment (football/ volleyball), air brakes and much more.

ESTABLISHING COMPRESSED AIR BASELINE

Assessing Life Cycle Cost of a Compressor

Air compressor is one of the major utilities in a plant. Depending on the usage in the facility, the energy consumption of air compressor varies from 10-40% of the entire plant consumption. Life cycle cost assessment of the compressor gives an important insight to the plant team on the costs associated in investment, operating and maintenance over the life cycle of the equipment, which can be helpful in making a complex decision.

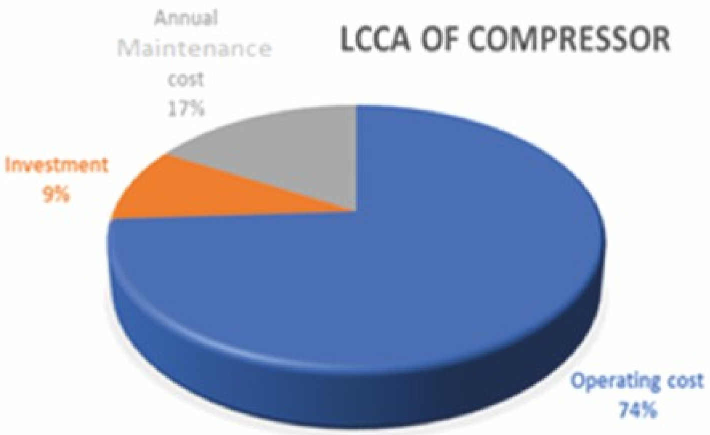


Figure 4: LCCA of Compressor

Evaluating the operating cost of air compressor:

$$\text{Operating cost/annum} = \frac{kW_R \times T \times (\%\, t) \times \text{Unit cost}}{\eta_m}$$

kW_R = Rated Compressor Power

T = total operating hours

% t = percentage time for loading /unloading

η_m = efficiency of motor drive

Scenario A:

For a system requiring 5 bar pressure, a 250 kW (capacity 41.3 m^3/min and rated pressure 7.5 bar) compressor is operating 85% at full load and 15% at part load (consider 20% part load power) is installed. Considering 300 days of operation and unit rate of INR 5/kWh, what would be the life cycle cost of the compressor, considering 10 years of compressor lifetime? The cost of the compressor is INR 30 Lakhs.

Specific Energy Consumption is 6.05 kW/m^3/min

Operating $\text{cost}_{\text{fullload}}$ = 250 kW x 300 days x 24 hrs x 0.85 x INR 5/kWh = **INR 76.50 Lakhs/yr**

Operating $\text{cost}_{\text{Partialload}}$ = 50 kW x 300 days x 24 hrs x 0.15 x INR 5/kWh = **INR 2.70 Lakhs/yr**

Total operating cost per annum = INR. 76.50 Lakhs + INR 2.70 Lakhs = **INR 79.20 Lakhs**

For 10 years of compressor life cycle, cost incurred for energy = **INR 792 Lakhs**

Life cycle cost of compressor = INR 792 Lakhs + INR 30 Lakhs = **INR 822 Lakhs**

For the ease of calculation, the cost incurred for maintenance is not considered for comparison.

Scenario B:

For a similar system requiring 5 bar pressure, a compressor of 43.8 m^3/min capacity & 5 bar rated pressure, is installed. For the similar operating conditions, let us calculate the lifecycle cost of the compressor. The cost of the compressor is INR 70 Lakhs.

Specific Energy Consumption is 4.23 kW/m^3/min

Operating cost $_{fullload}$ = 185 kW x 300 days x 24 hrs x 0.85 x INR 5/kWh = **INR 56.61 Lakhs/yr**

Operating cost$_{Partialload}$ = 37 kW x 300 days x 24 hrs x 0.15 x INR 5/kWh = **INR 1.99 Lakhs/yr**

Total operating cost per annum = INR. 56.61 Lakhs + INR 1.99 Lakhs = **INR 58.60 Lakhs**

For 10 years of compressor life cycle, cost incurred for energy = **INR 586 Lakhs**

Life cycle cost of compressor = INR 586 Lakhs + INR 70 Lakhs = **INR 656 Lakhs**

In comparison to the previous scenario, it can be inferred that the overall savings in the compressor's life cycle cost is **INR 166 Lakhs**. Therefore, while selecting a compressor, primary emphasis must be given to the Specific Energy Consumption of the compressor in accordance to the system requirements.

Establishing a compressed air baseline is as important as selecting a compressor. The various selection criteria that go into analysing the compressed air requirements are the air quality, quantity, pressure requirements, artificial demand and demand pattern of the process. Analysing these five categories helps the user select the size and type of the compressor, select the type and capacity of air dryer, and decide on a possible combination of compressors to operate during non-peak demands and control systems to operate the compressors.

AIR QUALITY

AIR QUANTITY/ CAPACITY

PRESSURE REQUIRED

DEMAND PATTERN

Comparison of Specific Energy Consumption (SEC) of various compressor technologies

The following table illustrates the variation of specific energy consumption of various compressor technologies such as reciprocating, screw and centrifugal machines.

Table 4: Comparing Specific Energy Consumption of different compressor technologies

Parameters	Reciprocating	Centrifugal	Screw (Single Stage)	Screw (Two Stage)
FAD (CFM)	112 m^3/min (3950 CFM) @ 6 bar			
Compressor Power (kW)	620	514	632	580
Specific Power Consumption (kW/m^3/min)	5.53	4.59	5.64	5.18

CHAPTER III

AIR QUALITY

Compressed air leaving an air compressor is not normally of a quality suitable for direct usage. This is due to several factors:

- Atmospheric air at the inlet of air compressor may contain particulate matter, moisture and hydrocarbons. Inlet filters act mainly to remove the particulate matter for protecting compressor and do not contribute to maintaining air quality in downstream.
- The air compressor itself will contribute contaminants in the form of wear particles and compressor oil carry-over.
- The discharge temperature from the compressor may be too high for distribution and use. Cooling after compression results in condensation of moisture vapour and saturated air leaving the aftercooler. Moisture has a harmful effect on pneumatic tools, air operated equipment and processes.

Compressed air quality classes are defined in the ISO 8573-1 standard, the respective classes are shown in the following table:

Table 4: Maximum Particle Size and Concentration of Solid Contaminants

Class	Maximum particle size* microns	Max Concentration** mg/m³
1	0.1	0.1
2	1	1
3	5	5
4	15	8
5	40	10

* Particle size based on a filtration ratio $\beta\mu$ = 20
** At 1 bar (14.5 psia), 20°C (68°F) and a relative vapour pressure of 0.6 (60%).

Table 5: Maximum Pressure Dew point

Class	Maximum pressure dew point (°C)
1	-70
2	-40
3	-20
4	+3
5	+7
6	+10
7	Not Specified

Table 6: Maximum oil content

Class	Max concentration* mg/m³**
1	0.01
2	0.1
3	1
4	5
5	25

*At 1 bar (14.5 psia), 20°C (68°F) and a relative vapour pressure of 0.6 (60%).

** 1 mg/m³ is a weight of oil in a volume of air and is approximately equal to 0.83 ppm by weight.

**Reference ISO Standard & CAGI hand book on air treatment.

Air and its properties affecting the compressor performance

1. Inlet ambient air:

The inlet ambient atmospheric air temperature and pressure has a significant impact on performance of the air compressor.

a. Inlet temperature:

Compressors are installed in a common area, such as a compressor house or room. Proper ventilation or ducting place an important role in maintaining the inlet air temperature in the compressor room. As the inlet air temperature increases, the air density decreases by the following relationship:

For dry air: $\rho = 144 \times P/RT$

ρ = density of air, kg/m^3

P = Pressure of inlet air, bar

T = inlet air temperature, K

R = Universal gas constant for dry air

As the temperature is reduced, the delivered air quantity increases at a much greater rate than power. As a thumb rule, "Every 4°C rise in inlet air temperature results in a higher energy consumption by 1% to achieve equivalent output", as shown in the following table:

Table 7: Effects of intake air temperature on power

Inlet temperature (°C)	Relative air delivery (%)	Power Saved (%)
10.0	102	1.4
15.5	100	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

The following methods can be used for decreasing the air intake temperature:

a) Use of ambient air in place of compressor room air, if the ambient air temperature is cooler than compressor room temperature.

b) Compressor room ventilation: The ventilation of compressor room plays an important role in compressor performance. A dust filter choke, low ambient pressure and high temperature cause the deviation in the compressor performance. Heat load of various equipment in compressor room like compressor, variable speed drives, dryers, cooling fan for motors, etc.

   P = (90-94%) x Shaft power to compressor + Motors drive losses + heat load of the dryer (as per technical data sheet)

   $Q_v = P\,(\text{Heat kW})/1.21 \times \Delta T$

where,

Q_v = quantity of ventilation air (m^3/s)

P = Heat flow in kW

ΔT = Permitted temperature rise

Tips:

- In air cooled compressor ,100% of energy (heat load) to be considered.
- In Water cooled compressor, 10% of energy (heat load) to be considered.
- Ventilation exhaust fan to be placed above the compressor.
- For a compressor room with more compressors, ventilation ducts to be provided. Air velocity in the duct should not exceed 4 m/s.
- In case of insufficient space, install water cooled compressor.

ii. **Inlet Pressure:**

Intake air pressure of compressor depends on the elevation and the pressure drop across intake filters.

a) **Elevation:** Density of air varies directly with atmospheric pressure at the inlet of compressor. Hence, the elevation of the compressor installed plays an important role because the atmospheric pressure varies with altitude. The atmospheric pressure decreases at higher altitudes; hence, the compressor draws more power for the same compressor ratio.

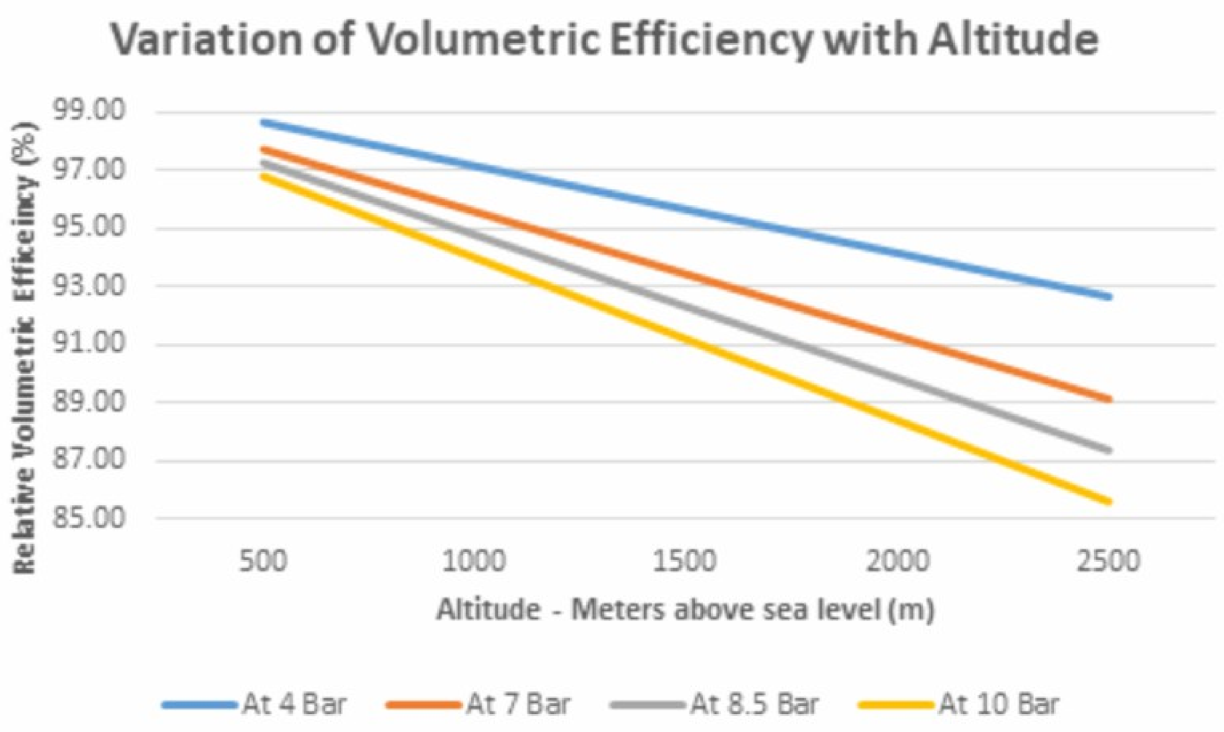


Figure 5: Variation of Volumetric Efficiency with Altitude

Table 8: Effect of altitude in Volumetric Efficiency

Altitude in Meters	Barometric Pressure (milli bar)	Percentage Relative Volumetric Efficiency Compared with Sea Level	
		At 4 bar	At 7 bar
Sea level	1,013	100	100
500	945	98.7	97.7
1,000	894	97.0	95.2
1,500	840	95.5	92.7
2,000	789	93.9	90.0
2,500	737	92.1	87.0

b) Dust free air intake:

Ambient air in compressor room consists of various particulate matter, moisture and hydrocarbons. Inlet air filter are installed at air intake system to protect the compressor. Improper inlet pipe sizing and filter choking create a pressure drop across the filter; hence the density of air will vary before it reaches the suction of air compressor by following relation:

$$\rho = 144 \times (P_{atm} - \Delta p)/RT$$

ρ = density of air, kg/m^3

P_{atm} = Atmospheric Pressure of inlet air at specified location, bar

ΔP = Pressure drop in inlet piping and inlet filter, bar

T = inlet air temperature, K

R = Universal gas constant of air

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% for the same output.

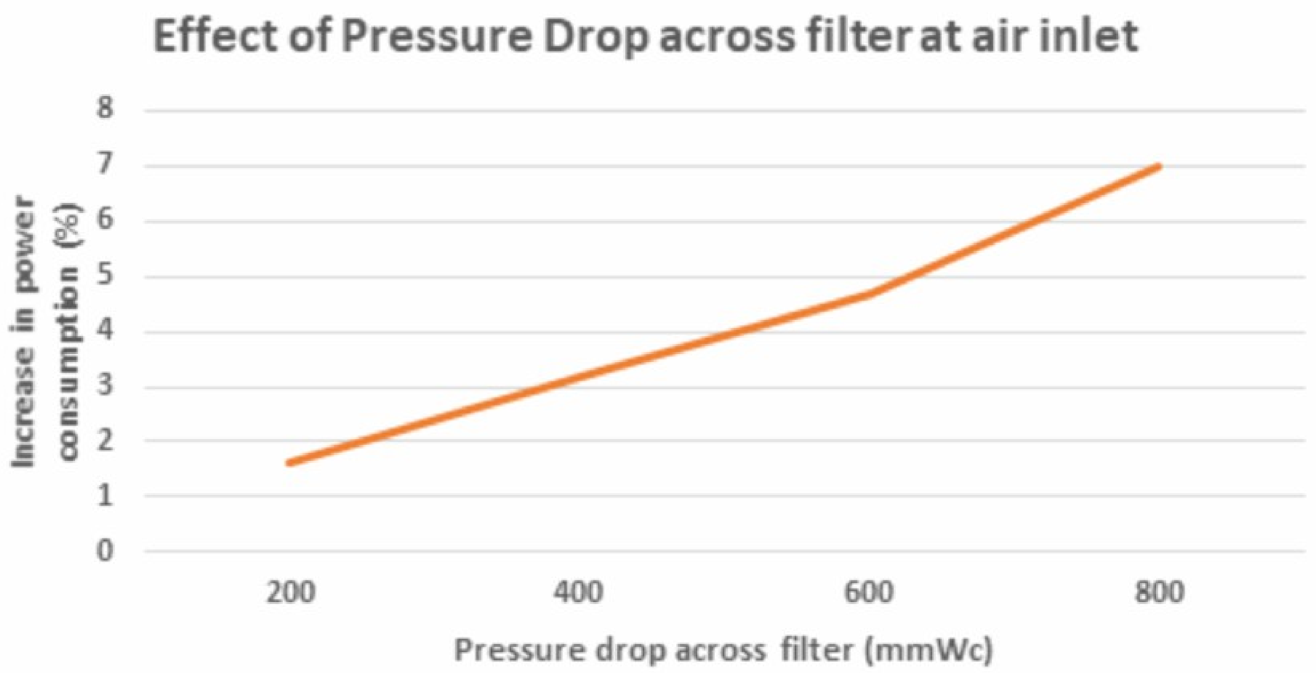


Figure 6: Effect of Pressure Drop across filter at air inlet

iii. **Relative Humidity:**

The atmospheric air has a certain amount of moisture. Relative humidity is the ratio of the actual water vapour partial pressure to the saturation partial pressure at a constant temperature. Relative humidity is dimensionless and normally expressed as a percentage.

Saturated air at a given temperature is the air that contains the maximum amount of water in the form of water vapour. Any excess water vapour will be condensed in the form of water.

The moisture holding capacity of air depends on the ambient temperature. The higher the temperature, the more is the moisture holding capacity of air in the form of water vapour and vice-versa. The moisture-carrying capacity of air increases with a rise in temperature and decreases with increase in pressure. Hence, the compressors need to be sized accordingly, considering the relative humidity at the compressor room.

2. Dew point temperature

The extent of drying compressed air is expressed by the term "dew point". The dew point is the temperature at which condensate will begin to form if the air cools at a constant pressure. The lower the dew point temperature, the drier is the air. Air at -40°C atmospheric dew point means no moisture would condense unless temperature of the air is reduced to less than –40°C, at atmospheric pressure.

Table 9: Moisture content with Atmospheric Dew point

Dew point at atmospheric pressure (°C)	Moisture content (PPM)
0	3,800
-5	2,500
-10	1,600
-20	685
-30	234
-40	80
-60	6.5
-80	0.3

i. Pressure Dew point:

Air outlet from compressor will have high pressure and temperature. The moisture holding capacity of air increases with a rise in temperature and decreases with increase in pressure. Pressure dew point is the dew point of compressed air at working pressure. There is a difference in atmospheric dew point and dew point at high pressure.

Tips:

1. Summer temperatures do not require a very low dew point whereas winter temperatures may dictate a much lower dew point. This will affect the size of the dryer needed, since the same dryer must work in both summer and winter temperatures and humidity conditions.
2. In general, the dew point should be specified -6°C lower than the lowest ambient temperature encountered in order to avoid potential condensation and freezing.
3. Specifying a dew point lower than required for an application can add to the capital and operational costs and is not good engineering practice.
4. It is recommended that ISO 8573-1 be used by end-users, engineers, compressor manufacturers and dryer equipment suppliers.

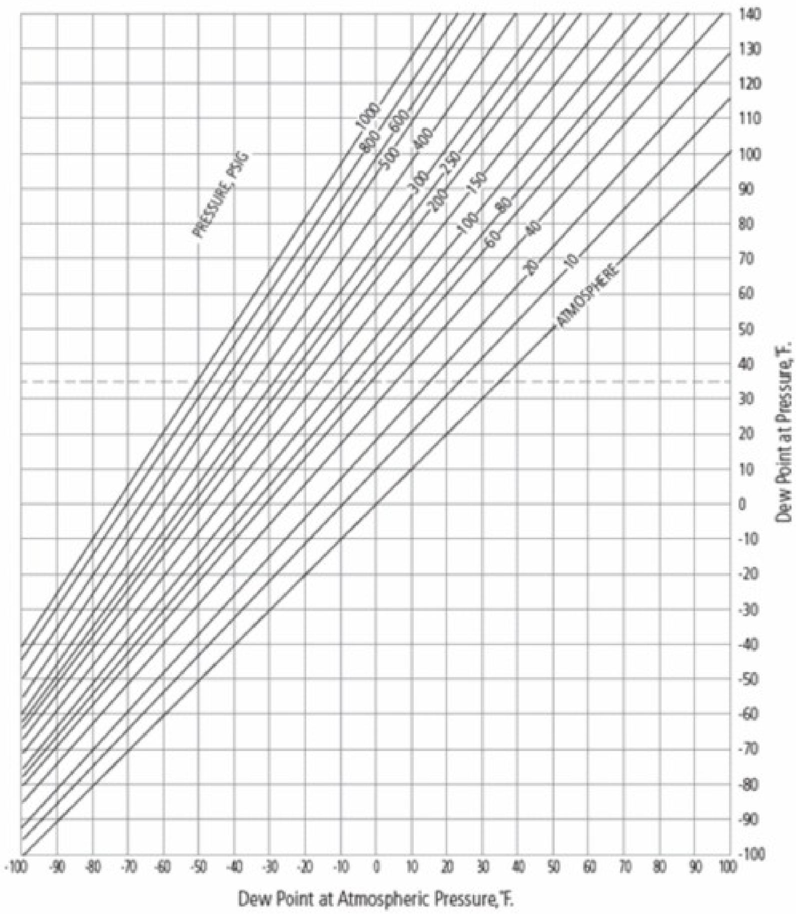


Figure 7: Pressure Dew point

3. Effect of water vapour in compressed air

The compressor compresses the air with a certain amount of water vapour depending on the temperature and relative humidity. When the compressed air is cooled in the after cooler, the water vapour in the compressed air gets condensed, and a significant amount of water is removed. Typically, the after-cooler removes about 50-60% of water vapour.

When the air leaves the after-cooler and passes through the compressed air lines, the temperature of the compressed air reduces further. The remaining water vapour in the air starts condensing.

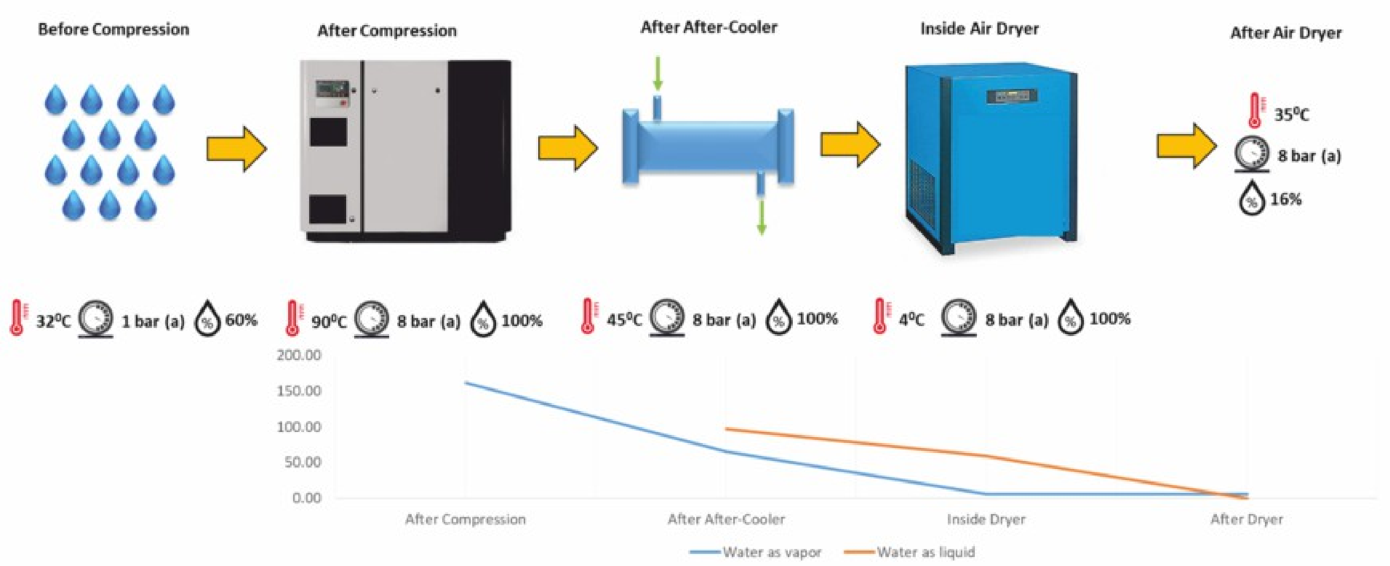


Figure 8: Moisture in Compressed Air system

The effects of water particles in the compressed air are given below:

i. The water particles travel at the same velocity of compressed air and damage the pneumatic valves or instruments at the end user.

ii. Corrosion in the distribution pipe line.

iii. Impaired finishing processes particularly in paint spraying.

2.0 Compressed air Drying

The water vapour in the compressed air has to be removed. This can be achieved by passing the compressed air through the air dryers.

There are two methods of compressed air drying:

i. Refrigeration drying

ii. Adsorption drying

i. **Refrigeration drying**:

Refrigeration drying is based on the principle that when the temperature of the compressed air is lowered, the moisture holding capacity is reduced. By lowering the temperature, the water vapour in the compressed air is condensed and removed. It is a simple mechanical refrigeration system, wherein the dew point is reduced by chilling. They operate at pressure dew point of 2°C to 10°C.

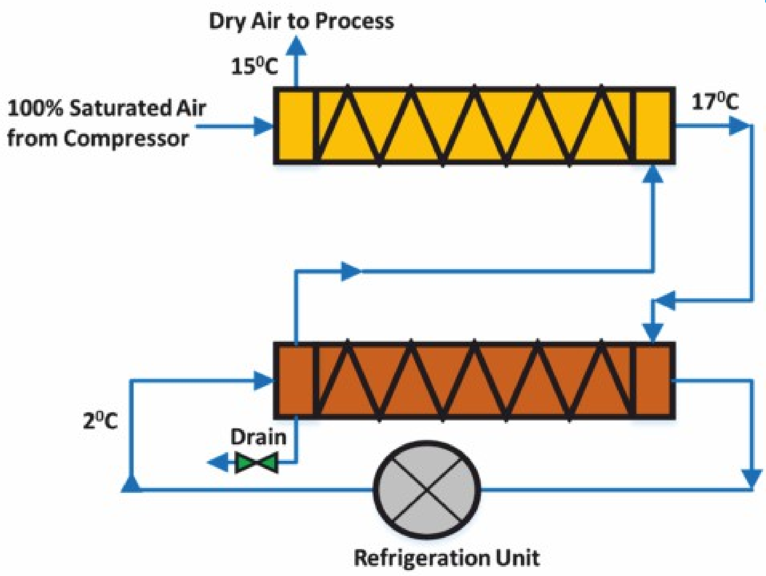


Figure 9: Refrigeration air dryer

The main types of refrigeration air dryers are:

1. Non-cyclic Refrigeration dryer:

   The refrigerant continuously circulates through the system. This is also called direct expansion system, since the hot gas bypass valve or unloader valve is used to control the refrigerant flow for varying compressed air flow and ambient temperatures. This bypass operation keeps a refrigerant compressor in full power operation even when lightly loaded, resulting in poor part-load efficiency.

   - Low initial cost
   - High operating cost

2. Cyclic Refrigeration dryer:

   Cyclic refrigeration dryer uses thermal mass like glycol to store energy. The bypass valve is replaced with thermal mass, which stores energy in a part load condition. The operation of dryer is controlled thermostatically and enables refrigeration cycle to be off in reduced loads.

   - High initial cost when compared to non-cyclic refrigeration dryers
   - Low operating cost
   - Energy efficient

ii. **Adsorption Drying**

In adsorption drying, compressed air is passed through a bed of desiccant material, porous in nature, where the moisture adheres to the surface.

These desiccants have a very large internal surface. Once saturated with moisture, they can be regenerated and reused.

Adsorption dryers can be classified into the following:

a. Desiccant heated, blower reactivated type

b. Desiccant heat less purge type

c. Desiccant heated purge type

d. Desiccant heat of compression type

The operation of the above-mentioned dryer is explained in detail below.

- Desiccant heated blower reactivated type:

  This dryer consists of two pressure vessels filled with desiccants, which has the property to adsorb water. While one vessel is in service, the other vessel will be in regeneration mode. Regeneration involves heating and cooling of the desiccant, before put into use.

  A blower and external heater are used to achieve the regenerating temperature. The operating cost is higher because of the heater (electrical or steam) and also because there is a purge loss of about 1-2% of compressed air. The vessel, which is regenerated, is purged with dry air before it is taken into service. These dryers are normally used for capacities higher than 250 CFM.

- Desiccant heat less purge type

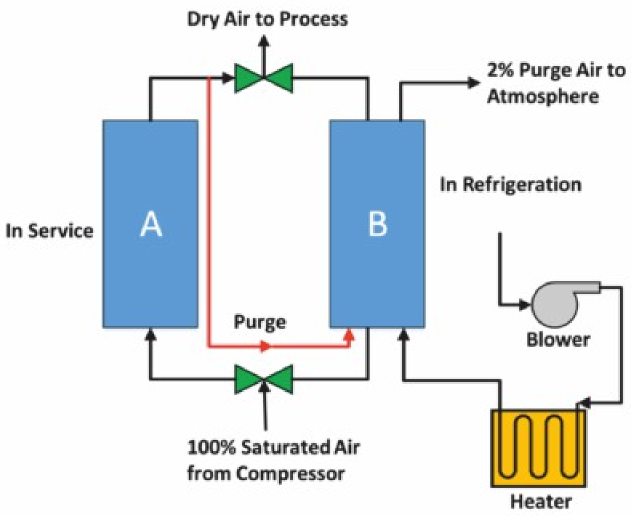


Figure 10: Desiccant heated blower reactivated type dryer

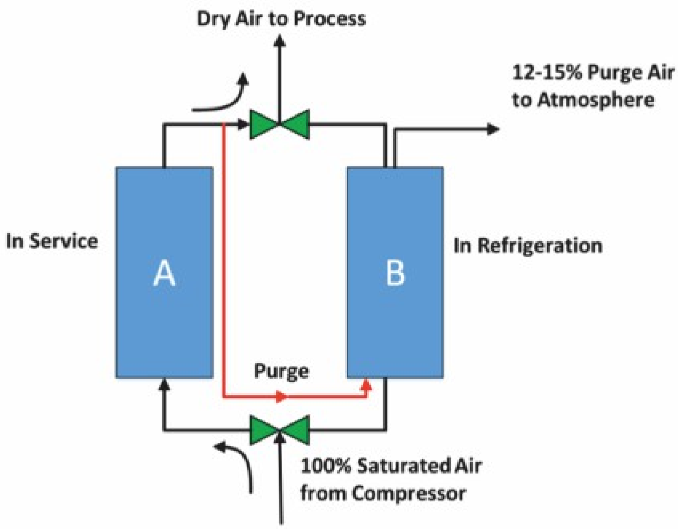


Figure 11: Desiccant heatless purge type dryer

  The operation is very similar to the blower-reactivated type. The difference is that no heating of the desiccant is done. Pure dry air is used for purging through the saturated desiccant. These are used for capacities less than 250 CFM. The operating cost is very high due to purge losses of about 10-12%.

- Desiccant heated purge type

  These dryers heat up the expanded purge air by means of an electric air heater and hence limit the required purge flow to around 8%. This type uses 25% less energy than heatless-type dryers.

- Desiccant Heat of Compression type dryer

  This is a break-through in drying technology where the operating cost is zero or very minimal. HOC dryers are available from 400 CFM to 5,000 CFM capacities. The discharge compressed air, which is at a temperature of 135°C (in the case of reciprocating compressor) is used to regenerate the desiccant. There are no electrical heaters and no purging loss. This makes the dryer very attractive in terms of operating cost. The desiccant can be Activated Alumina or Silica gel depending on the dew point required.

  The dryer consists of two vessels – 'A' and 'B'. Vessel 'A' will be in service for 4 hours. Meanwhile vessel 'B' is reactivated which involves heating for 2.5 hrs and cooling for 1.5 hrs. After this, vessel 'B' is taken into service and vessel 'A' is reactivated. The regeneration cycle consisting of heating and cooling cycle as explained below:

  Vessel 'A' in service, vessel 'B' in heating: Air from compressor enters 4-way valves V2 and V1 and directly to vessel 'B' so as to start the heating process. From vessel 'B', the air through valve V3 and V2 enters after cooler AC1, where it loses some of the moisture. Through V3 again air enters vessel 'A' where moisture is adsorbed by the desiccant and finally leaves through V1 to an after-cooler AC2, where it is cooled to about 35-40°C.

After getting filtered in the after-filter, air goes to process, which is dry to an atmospheric dew point of -40°C. The heating cycle is normally for 2.5 hours.

Vessel 'A' in service, vessel 'B' in cooling: Air from compressor passes through V2, gets cooled in AC1 and enters vessel 'B' through V3. After cooling the desiccant in vessel 'B' air passes through 4-way

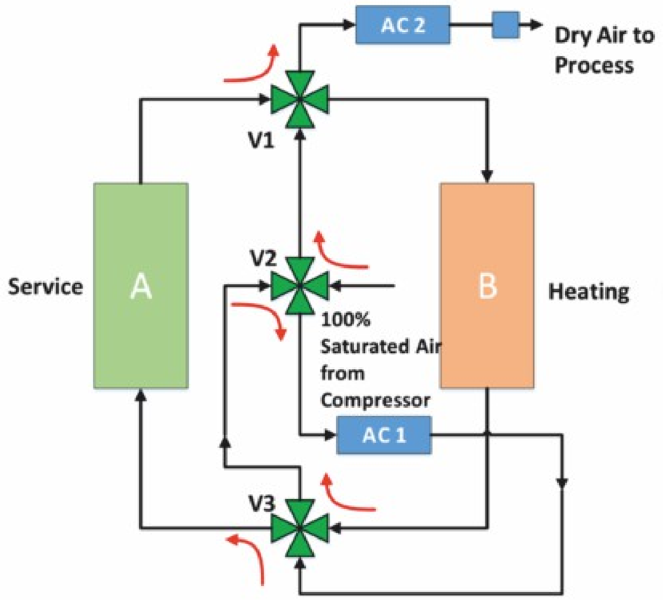


Figure 13: Vessel 'A' in service and Vessel 'B' in Heating mode

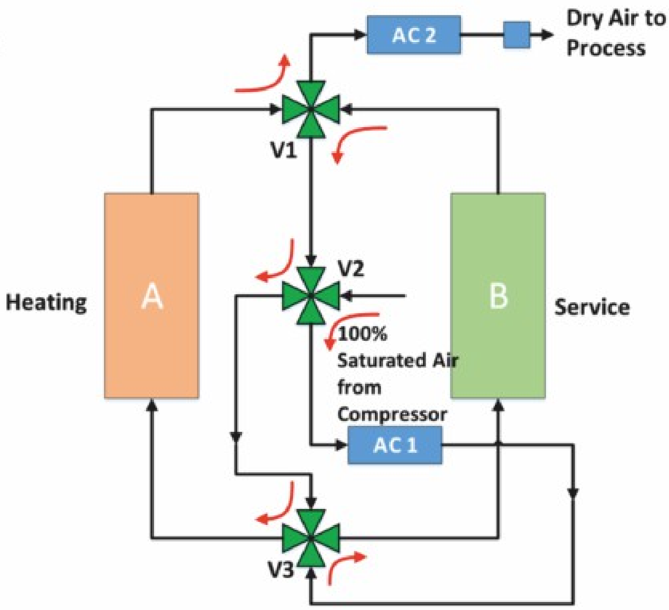


Figure 12: Vessel 'A' in service and Vessel 'B' in Cooling mode

valves V1, V2 and V3 and enters vessel 'A', which is in service.

The air on getting dry, enters After-cooler AC2 via V1, gets cooled to about 35-40°C. This air dried to an atmospheric dew point of -40°C is now ready for use. The cooling cycle is normally for about 1.5 hours.

- Desiccant Selection

Adsorption property is exhibited by some forms of silica, alumina (including bauxite), carbon and certain silicates (molecular sieves). Silica and alumina are used primarily to remove moisture while carbon is used for organic vapours. Molecular sieves can give very low atmospheric dew points, as low as -80°C while activated alumina gives about -40°C.

While using desiccants, it should be noted that attrition (grinding) occurs due to air pressure surges. This desiccant powder is carried away by air because of which after-filters need to be installed before the dry air is taken for use. Molecular sieves have the capacity of adsorbing small molecules of water. Extremely low dew points can be achieved by passing an air stream over molecular sieves. Normally, air is passed through a standard desiccant before it is passed through molecular sieves.

- Desiccant Life

Adsorbing capacity of desiccant materials decreases with age. Contaminants like oil or dust particles will add to this effect. Heat is also one of the factors, which contributes to desiccant ageing. Many manufacturers recommend a desiccant life of three to five years, based on the operating conditions.

The condition of the desiccant should be checked periodically. Any effort to monitor the desiccant condition will give significant benefits in the form of high-quality air, reduced frequency of desiccant change and reduced maintenance cost.

iii. **Single Tower Deliquescent Type Dryers:**

The deliquescent desiccant type dryer uses hygroscopic desiccant material, usually salt, which has a high affinity for water. The desiccant absorbs the water vapour and is dissolved in the liquid formed. The single tower deliquescent desiccant type dryer has no moving parts and requires no power supply. This simplicity leads to lower installation costs. Dew point suppression of -10°C to 10°C below the compressor inlet temperature.

iv. **Membrane Type Dryers:**

Membrane type of dryers have a special membrane that allows the water vapour faster than air stream, reducing the amount of water vapour in the air stream at outlet of the membrane dryer. Typical dew point: -40°C to 4°C. About 15-20% more capacity (CFM) for the same dew point as compared with refrigerant dryer.

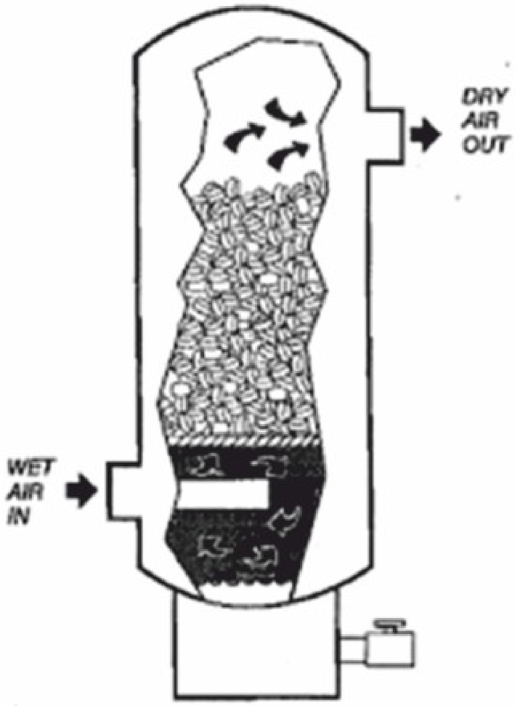


Figure 14: Single Tower Deliquescent Dryer

Figure 15: Membrane Dryer

3. Compressed Air Dryers: Comparison

A comparison of compressed air dryers, as discussed above, is tabulated below:

Table 10: Compressed air dyers Comparison

Type of dryer	Capital cost	Running cost	Dew point °C	Pressure drop	Capacity
Desiccant heatless purge type	Low	High	-40°C	Medium	60 to 900 CFM
Desiccant heated blower reactivated type	High	Medium	-20°C to – 40°C	High	500 to 4,000 CFM or decided by dew point
Desiccant heat of compression	High	Very Low	-20°C to – 40°C	High	400 to 7,000 CFM for lubricated compressor
Refrigeration type dryer	Medium	Low	+3°C	Low	20 to 2,000 CFM
Single tower deliquescent type dryer	Low	Low (but only for once use)	-10°C to 10°C	Low	8.5 to 1,500 CFM
Membrane type	Medium	High	-40°C to 4°C	High	Up to 200 CFM

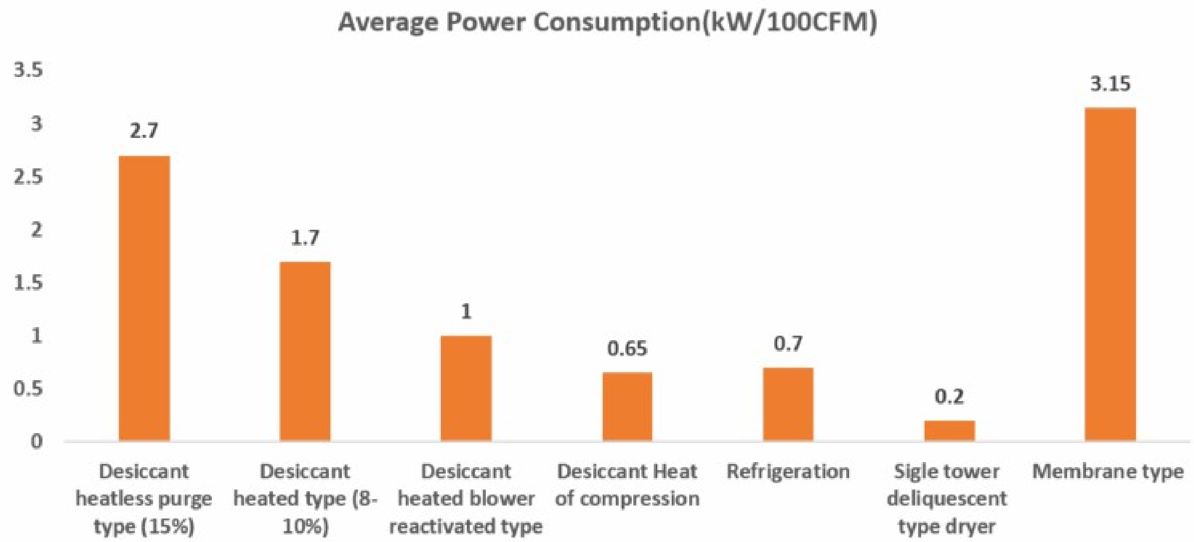


Figure 16: Comparison of Air Dryers

Pressure drop across the compressed air dryer adds to indirect energy cost. The operating pressure of the compressor has to be set considering the pressure loss across the air dryer and the total compressed air requirement.

If the pressure loss across the dryer is higher, accordingly, the operating pressure of the compressor has to be raised and ultimately will result in increased power consumption.

Table 11: Pressure drop across various dryers

Type of Dryer	Pressure loss (PSI)	Purge loss / Extra capacity required (CFM)
Desiccant heatless purge type (15%)	3-5	15% Purge
Desiccant heated type (8-10%)	3-5	8 % Purge
Desiccant heated blower reactivated type	3-5	1-2 % Purge
Desiccant Heat of compression	Less	–
Refrigeration type dryer	3-5	–
Single tower deliquescent type dryer	Less	Used Desiccant material is not regenerative only once
Membrane type	3-5	15-20% More capacity (CFM) for same dew point as compared with refrigerant dryer

In refrigeration type dryers, the design of heat exchangers decides the pressure drop across the dryer. The maximum allowable pressure loss across the refrigeration dryer is 0.2-0.3 kg/cm^2.

In case of adsorption dryers, the pressure drop is affected by the filter used. Improper filters can cause significant pressure drop across the dryer. The maximum allowable pressure drop across the desiccant type dryer is 0.5 kg /cm^2.

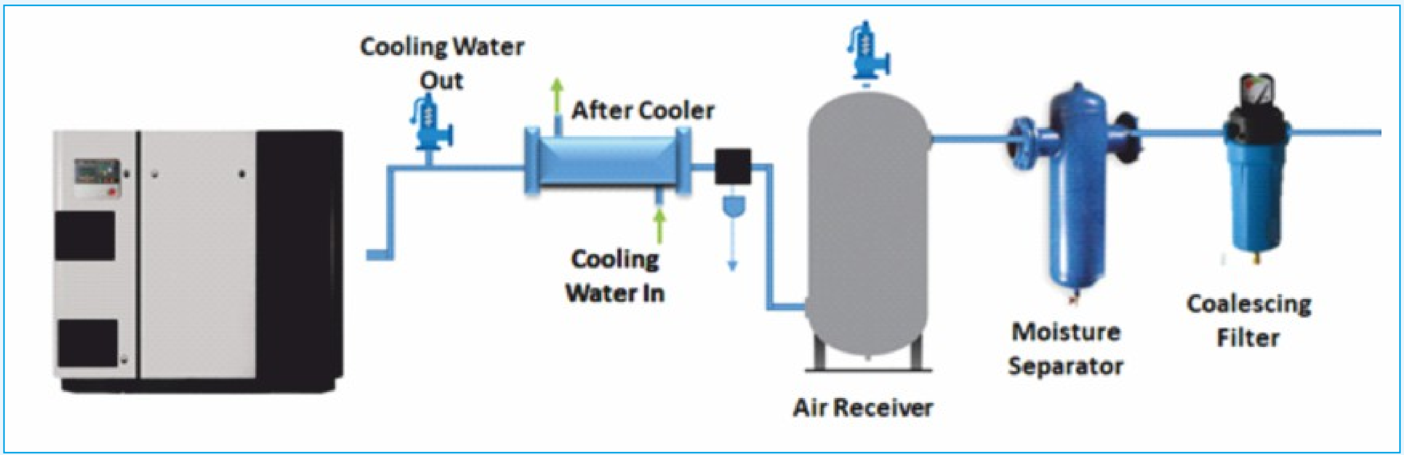
Dryer Application:

Table 12: Dryer applications

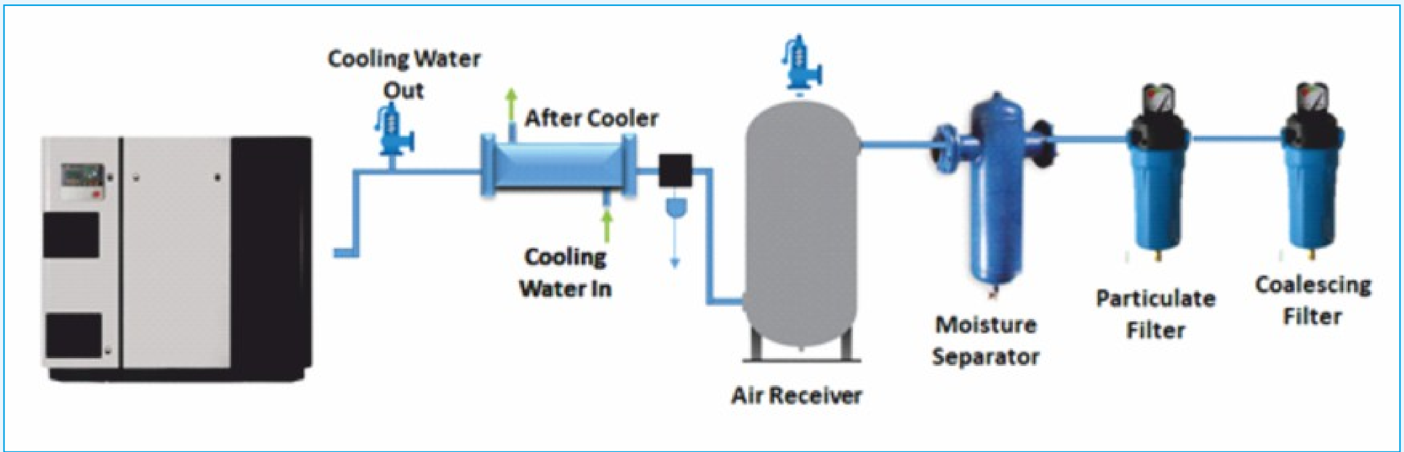
Type of Dryer	Purge loss / Extra capacity required (CFM)
Desiccant heatless purge type (15%)	• Food & Beverage
Desiccant heated type (8-10%)	• Power generation
Desiccant heated blower reactivated type	• Pharmaceuticals Process air
Desiccant Heat of compression	• General pneumatic equipment and pneumatic tools
Refrigeration type dryer	• General pneumatic equipment and pneumatic tools
Single tower deliquescent type dryer	• Industrial plant air • Blast rooms and paint booths • Rail yards • Landfill gas and digester gas • Ready mix, cement, and asphalt plants
Membrane type	• Machine Tool • Measuring Machine • Semiconductor-related Manufacturing Equipment • Powder Coating Food Machinery • Packaging Machine (sealing of film and paper) • General pneumatic equipment and pneumatic tools

4. Air Quality Configuration

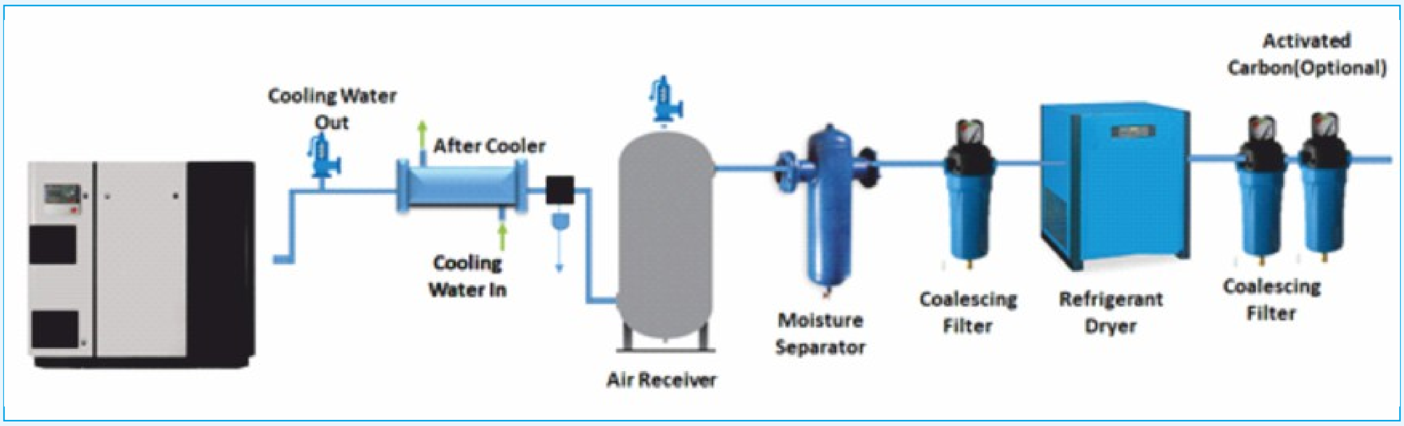
Class (1.-.3) (1 particulate: 0.1 microns, no rating for moisture and Class 3 for hydrocarbons: 1 mg/m^3)



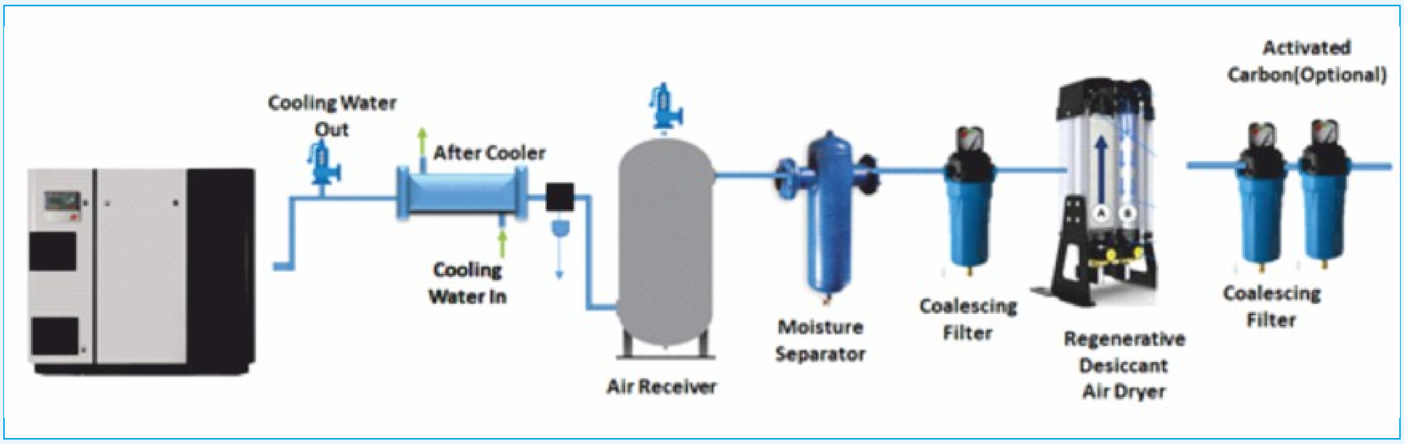
Class (1.-.2) (1 particulate: 0.1 microns, no rating for moisture and Class 2 for hydrocarbons: 0.1 mg/m^3)



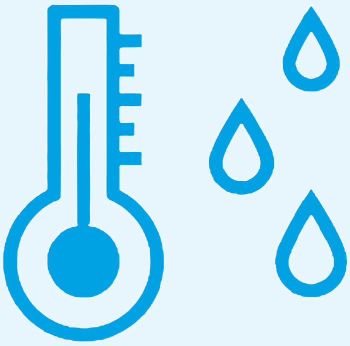
Class (1.4.1) (1 particulate: 0.1 microns, Class 4 for moisture: +3°C and Class 1 for hydrocarbons:0.01 mg/m^3)



Class (1.2.2) (1 particulate: 0.1-micron, Class 2 for moisture: -40°C and Class 2 for hydrocarbons :0.1 mg/m^3)



5. Dryer troubleshooting and dew point reliable measurement



- Dew point control setting plays on operating performance of dryer.
  - If the dew set point is too high, the dryer energy consumption will increase due to more cycles of operation for removal of moisture.
  - If the dew point is too low, the quality of air is not achieved and moisture carry-over is seen in compressed air distribution.
- For maintaining air quality as per ISO 8573-1 with optimum dryer energy consumption, it is important to:
  - Select the right dryer as per ISO 8573-1 air quality class and set dew point as required in process.
  - Install the dew point sensor and have a dew point control logic like dew point depended switching or automatic control.
  - Ensure the sensor operation as desired, since the dew point sensor is vulnerable to damage or contamination from water or oil lubrication.

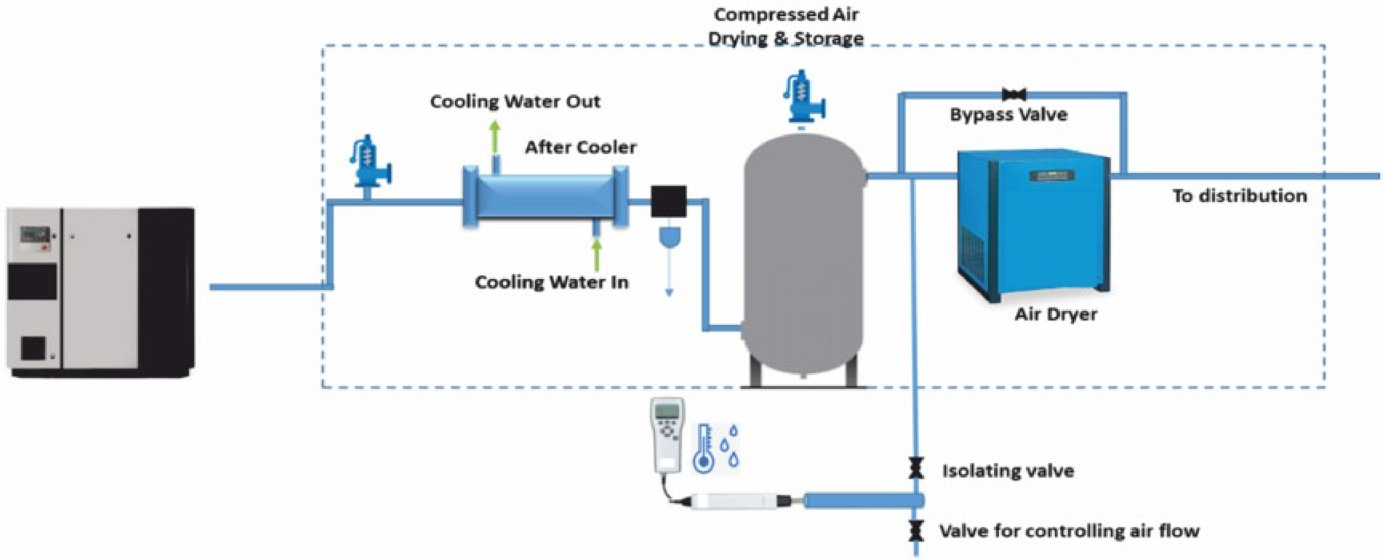


Figure 17: Dew Point measurement

Problems for dryer performance:

- Water presence in the distribution network although dryer set point temperature is maintained.
- Dew point of the dryer properly set as required.
- Operating air flow (CFM) of dryer.
- High dryer inlet temperature due to deterioration in after cooler performance.
- Faulty dew point probe sensor
  - Constant dew point indication
  - Flickering dew point indication
  - Displaying Impossible dry or Wet dew point values
- Condensate drain failure.
- Location of dryer and ambient temperature of dryer room.

Reliable dew point measurement for assessing dryer performance:

Most of the dryer performance problem are related to dew point setting and dew sensor operation. The dew point can be measured using a portable dew point sensor. The following points should be kept in mind before dew point measurement:

- Measuring range of the sensor.
- Understand the pressure characteristics of the dew point instrument.
- Installation of sensor.
- Temperature range of measuring.
- Recommended flow rate of measuring equipment.

CHAPTER IV

COMPRESSED AIR GENERATION

The quantity of air and the pressure requirements are decided by the end-user applications, which possibly form the basis on which to decide the size of the compressor to be selected for generating compressed air. The overall capacity of compressed air is determined by totalling the average consumption of each of the process applications. An additional loading factor is also required to be considered, depending on the process and the maximum demand of compressed air.

Pressure requirements in a given industry vary for different applications. While deciding on the generation pressure of the compressor, we must take into account the pressure drop/lost across dryers, filters, regulators and piping network. As a thumb rule, it must be ensured that for every 800m pipeline length, the pressure drop must not be more than 0.3 bar. Pressure drop is an indication that the necessary amount of pressure is not reaching the end-user and is considered as a shortfall. On the contrary, higher-than-required generation pressure is also considered inefficient. This not only results in increased power consumption of the compressor, but also gives rise to unregulated usage in the form of leakages, increased unloading power, etc.

This chapter deals with basic concepts of various types of air compressors.

Air compressors are mainly classified into two types, based on their construction and operation:

- Positive displacement type
- Dynamic type

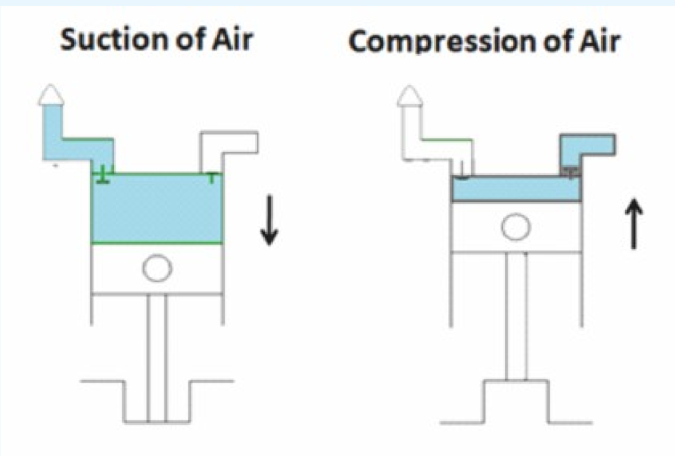
Positive Displacement Type Air Compressors

Positive displacement compressors displace a fixed volume of air in compressed air chamber into a reduced volume. They work on the principle of trapping atmospheric air and reducing the volume by using a solid wall-like piston. Due to the trapping action, they are capable of generating high pressure. They deliver a nearly constant volume, when operated at a fixed speed, while the discharge pressure is determined by the system load conditions. The different types of positive displacement compressors are as follows:

1. **Reciprocating air compressors:**

   Compressed air is generated by the "to & fro" movement of the piston in the compression chamber (just like an IC engine). Each movement compresses a fixed quantity of free air at a specific pressure; the construction operation of single acting reciprocating compressor is as follows:

   Operating Principle:



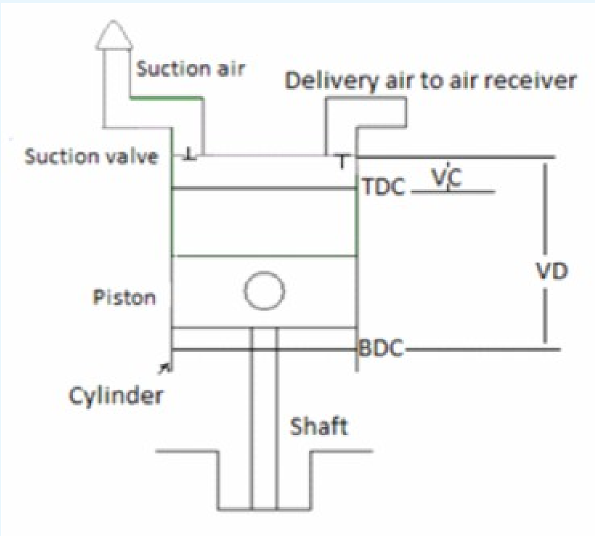


Figure 18: Reciprocating Compressor

TDC: Top Dead Center; **BDC**: Bottom Dead Center
VC: Clearance Volume; **VD**: Displacement Volume

According to the type of construction, reciprocating compressors can be further classified as single stage, double stage, single acting, and double acting compressors.

Types of compression:

Polytropic: PV^n = Constant

n = 0, for isobaric process

n = 1, for iso thermal process

n = K, for isentropic

$K = C_p/C_v$

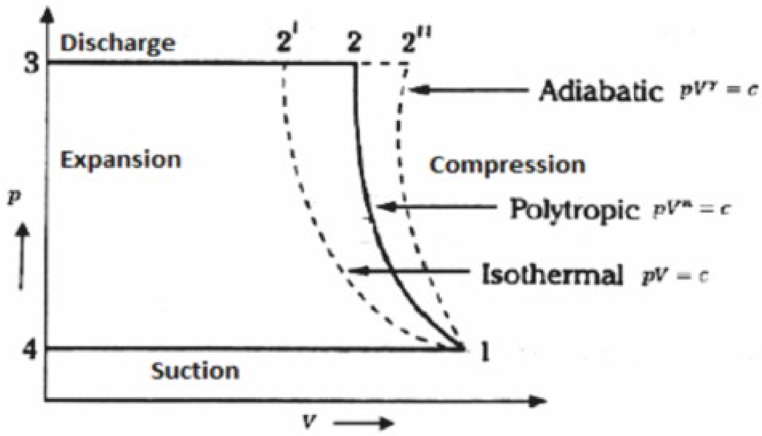


Figure 20: Types of Compression

Basic Fundamentals of Work done in Single Acting Reciprocating Compressor:

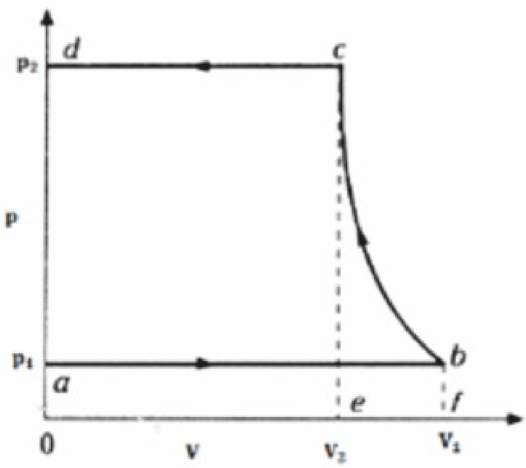


Figure 21 : PV diagram without Clearance Volume

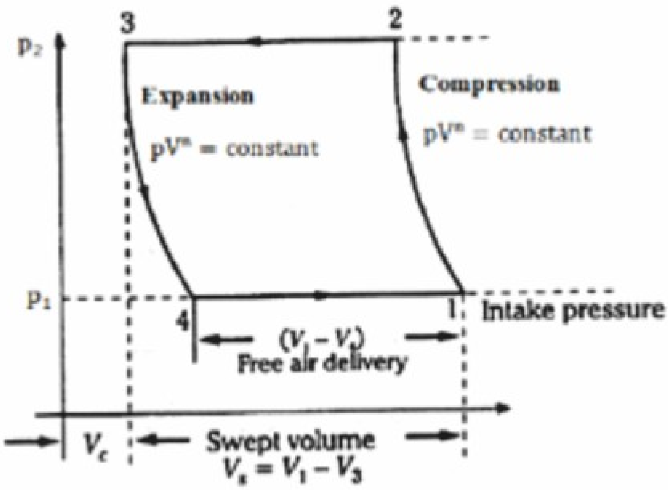


Figure 22: PV diagram with Clearance Volume

Work done: Without V_C

$W_{ISO} = (P_2/P_1)* V_1 * \ln(P_2/P_1)$

$W_{adiabatic} = (\Upsilon/(\Upsilon-1)) *(P_2V_2-P_1V_1)$

$W_{Polytrophic} = (n/(n-1)) *(P_2V_2-P_1V_1)$

Work done: With V_c

$W_{polytropic} = (n/(n-1))*P_1*(V_1-V_4)*[(P_2/P_1)^{(n/n-1)}-1]$

Where:

Υ(Specific heat ratio) = 1.4 for air

n = polytropic constant

P_2 = outlet pressure (kPa), P_1 = Inlet pressure (kPa)

V_2= Final Volume (m^3) after compression

V_1= Initial Volume (m^3) before compression

V_1-V_4 = Free air delivery

Isothermal Efficiency = $\frac{\text{Isothermal work done (kW) x 100}}{\text{Actual measured Input Power}}$

Isothermal work done (kW) = $W_{ISO}/38.7$

Volumetric Efficiency = $\frac{\text{Free Air delivered } (m^3/min) \text{ x 100}}{\text{Compressor displacement } (m^3/min)}$

Compressor Displacement = $\Pi/4 \times D^2 \times L \times S \times \chi \times n$

Where:

D = Cylinder bore, metre

L = Cylinder stroke, metre

n= no of cylinders

S = Compressor speed rpm

χ= 1 for single acting and

2 for double acting

2. **Double stage reciprocating compressor:**

The vertical type air compressors are suitable for applications ranging between 50-150 CFM, and the horizontal balance type is most suited for applications ranging from 200-5,000 CFM. If the pressure increases, the temperature of air rises. Hence, the motor has to work more. Therefore, single stage compressors are not used for higher pressure. For the generation of higher pressure, multistage compression is used with intermediate cooling system to improve efficiency.

- Single stage – 2 to 8.5 kg/cm^2
- Double stage – 8.5 to 12 kg/cm^2
- Multistage - >12 kg/cm^2

The schematic representation of double stage reciprocation is given in the figure below:

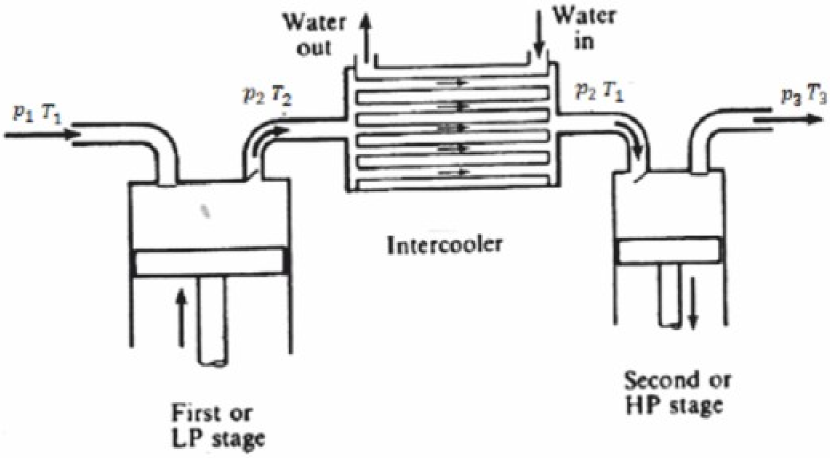


Figure 23: Double stage Reciprocating compressor with Water cooled intercooler

Basic Fundamentals of Work done in Double Acting Reciprocating Compressor:

Work done in LP stage:

W_{Lp} = $(n/(n-1))*P_1*V_1*[(P_2/P_1)^{(n/n-1)}-1]$

Work done in HP stage:

W_{Hp} = $(n/(n-1))*P_2*V_2*[(P_3/P_2)^{(n/n-1)}-1]$

Total Work Done

W = $W_{Lp} + W_{hp}$

If Intercooler is perfect them T= Constant

(Minimum power operation)

$P_1V_1 = P_2V_2$

$P_2 = SQRT(P_1*P_3)$

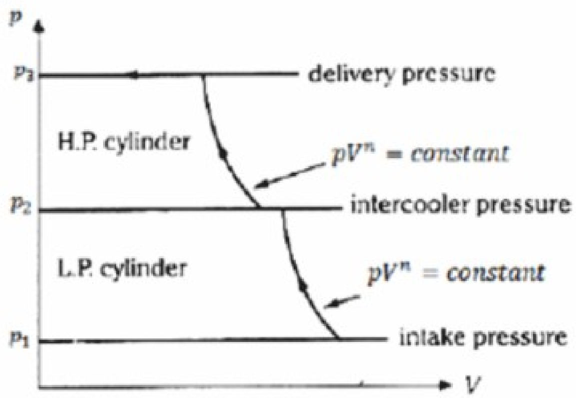


Figure 24: PV Diagram for Double stage reciprocating compressor

Lubricated Reciprocating compressor:

Lubricated reciprocating compressor uses splash or pressure lubrication. The compression rings and oil control rings are made of cast iron.

Oil-free Reciprocating compressor:

These do not have any lubrication fed in the cylinders. Piston rings and rod packing usually are of PTFE (Polytetrafluoroethylene) based materials, carbon, or other synthetic materials, which can operate without added lubrication.

3. **Duplex:**

A duplex reciprocating machine is one that has two pumps mounted on the same tank with an alternator to switch the load from one pump to the other, or switch on both pumps if demand requires. Duplex machines offer some distinct advantages over simplex machines. First, since some duplex machines are dual power source, they can provide backup air by allowing one pump to provide air if the other pump goes down. Second, duplex machines allow for oversizing a machine without wasting energy or extra maintenance costs.

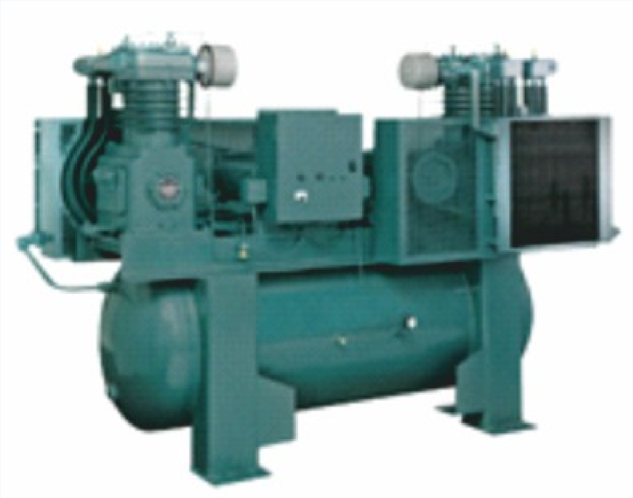


Figure 25: Duplex Compressor

Rotary air compressor:

Air is compressed by two rotating, intermeshing rotors (in some cases one rotor is kept stationery and the other rotates). The action of the rotary screw/lobe can be compared to a reciprocating compressor. The different types of rotary type air compressors are schematically given in the figure below:

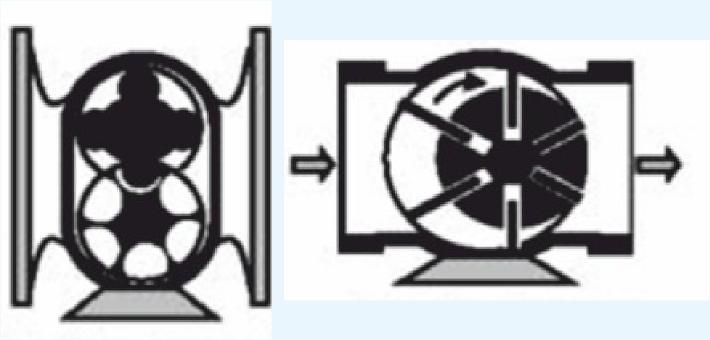


Figure 26: Rotary Compressor

4. **Screw Compressors:**

Rotary Screw compressor consists of two helical screw rotors in casing where the inlet air is compressed. The two rotors form a male (helical lobes) and female (helical groves) coupling. Male motor is rotated with prime mover, the air enters the space between the lobes, and due to the rotation of screw element air get trapped between the lobe and casing. As the rotation continues, the lobe rolls over the grove, and the space for the air is further reduced. Reduction in air volume increases the pressure of air.

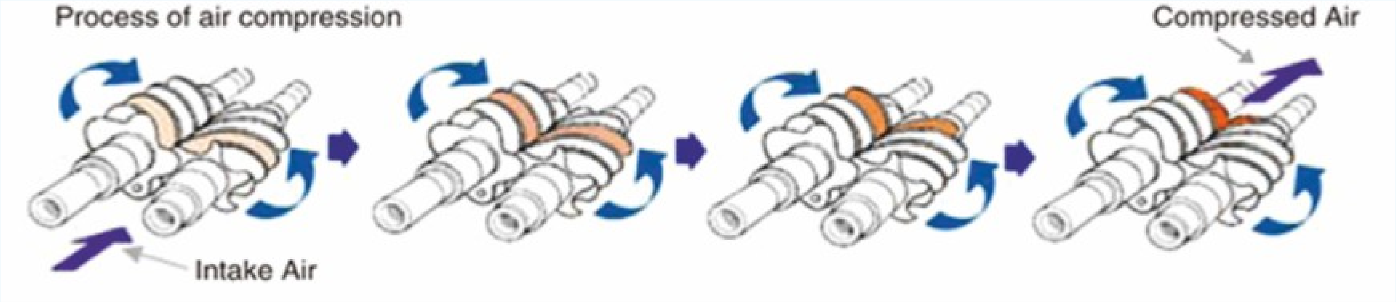


Figure 27: Compression cycle in Screw compressor

The capacity and volume of screw compressor is determined by length and diameter of rotors.

- The longer the rotor, the higher is the pressure discharged.
- The larger the diameter, the greater is the capacity.

Rotary screw compressors are available in different types, depending on:

- Lubrication – Oil Injected, Oil free.
- Stages – Single Screw, Twin screw.
- Cooling system – Water cooled and air-cooled.

Oil Injected Screw compressor:

In oil injected screw compressor, synthetic hydrocarbon oil of ISO 100, 150 or 220 viscosity is injected into the compression chamber, and basically acts like:

- Lubrication for bearing, other moving parts.
- Remover of the heat generated in the compression process.
- Seal to the internal clearance.

Manufacturers design oil system with carryover of 5 ppm, hence it is to be separated using oil filter (10 micron) before use. Recommended oil changes are for every 8,000 operating hours. Oil injected screw compressors are available in the range of 100 to 1,000 cfm, and discharge pressure of up to 10 bar.

Heat from the oil injected is removed through radiator type oil and air heat exchanger or water-cooled heat exchangers.

Oil-free Rotary Screw Compressor:

These are especially designed compressors without oil injection. There are two types available – dry-type and water-injected type. In dry type, the rotors movement is not allowed to touch. Since there is no medium to remove heat, they are deigned in two stages with inter and after cooling system. Dry type is available up to 20,000 cfm and 15 bar pressure.

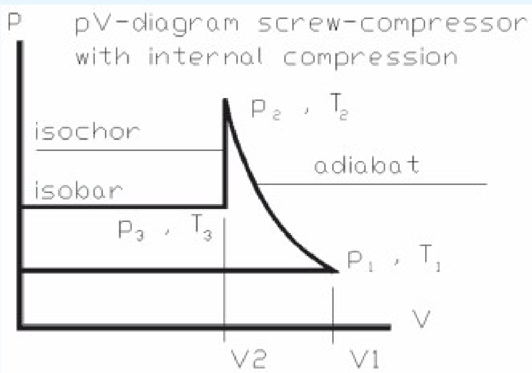


Figure 28: PV Diagram for Screw Compressor

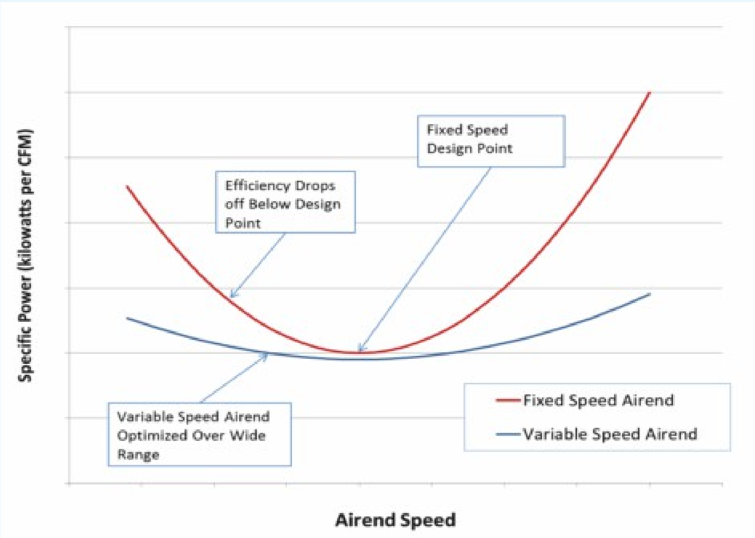


Figure 29: Variation of Specific Power for Fixed speed and Variable Speed

Capacity Control of Positive Displacement Compressor (Reciprocating/Screw)

Start / Stop Control	• **It is the simplest control** • **Pressure switch senses the operating pressure and switches off the motor once the set pressure is reached.** • **Pressure switch is fixed or adjustable between upper and lower pressure setting.** • **Best suitable for compressor lower than 30 Hp.**
Load /Unload Control	**Unload**: Pressure switch senses the signal when the upper pressure setting is reached, it sends signal to close inlet valve (maintaining low flow), resulting in low power requirement. • Compressor operates idle and consume power, which is considered to be inefficient and a wastage of energy. **Load**: when the pressure drops below lower set point, the inlet valve is opened and compressor generate required pressure.
Inlet valve modulation control	• This control enables compressor to match demand • Done by regulating valve that senses pressure and send a proportional signal to close the inlet valve, thereby reducing the pressure. • Inlet valve modulation can be done from 100% to 40%
Auto Dual control	• This control is combination of start/stop and load /unload control. • The timer senses the unload operation and after the set delay it will send signal to stop the compressor.
Variable Displacement control	• Has spiral, slide or turn valve. • Built into the compressor casing to control output to match demand. • Rising discharge pressure causes the valve to be repositioned progressively. • This reduces the effective length of the rotors by allowing some bypass at inlet and delaying the start of compression.
Variable Speed Drive Control	• This control provides automatic adjustment of the operating speed of the motor drive and compressor. • Allows output of compressed air to match air demand during periods where demand is irregular. • In many applications the use of variable speed saves energy over fixed speed systems that might start and stop, or unload to accommodate differences of air usage.

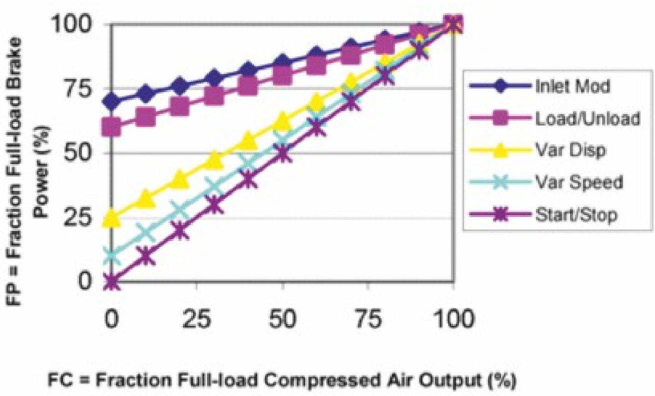


Figure 30: Capacity Control vs Specific power

Dynamic Air Compressors

Dynamic compressors mechanically impart a velocity to the air, through the use of impellers rotating at high speed, in an enclosed housing. The air is forced into a progressively reduced volume. The volumetric flow will vary inversely with the differential pressure across the compressor. The dynamic types of air compressors are classified into:

Centrifugal air compressors:

The centrifugal air compressor consists of an impeller, mounted on a shaft and positioned within a housing, consisting of an inlet duct, a volute and a diffuser. The schematic of a centrifugal compressor is given below.

Parts of centrifugal compressor:

Inlet: The inlet to the centrifugal compressor is a pie or inlet gain vanes. The inlet air passed through the pipe and reaches the impeller.

Impeller: Impeller rotates with high speed transfer energy of the drive to air causing the rise of static pressure and temperature with rise in velocity.

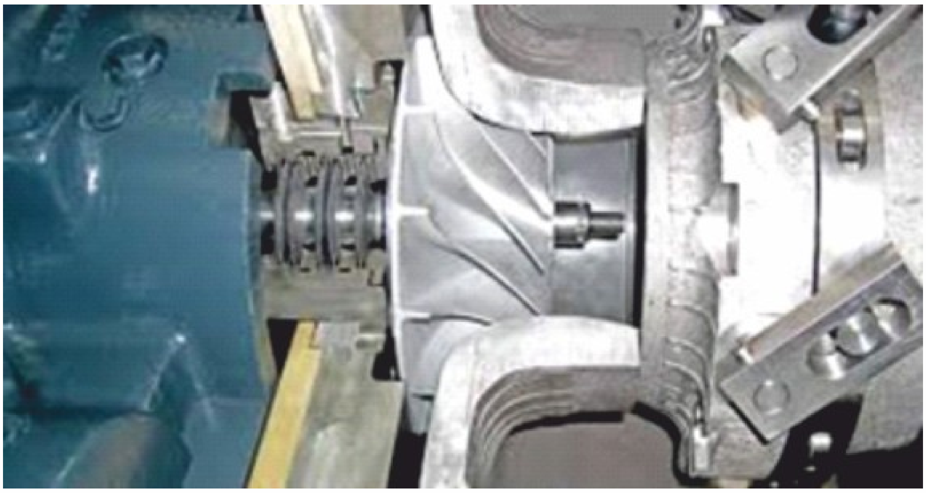


Figure 31: Centrifugal Compressor with Impeller

Depending on the design, impeller is classified into:

Figure 32: shrouded (Open) Impeller

Figure 33: Shrouded (Closed) Impeller

Figure 34: 3D Impeller

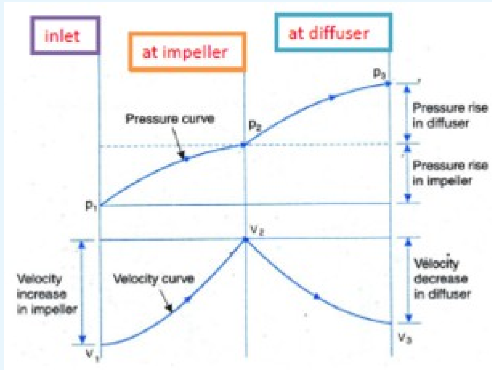
Figure 35: 2D Impeller

Table 13: Comparison between Shrouded and Unshrouded Impeller

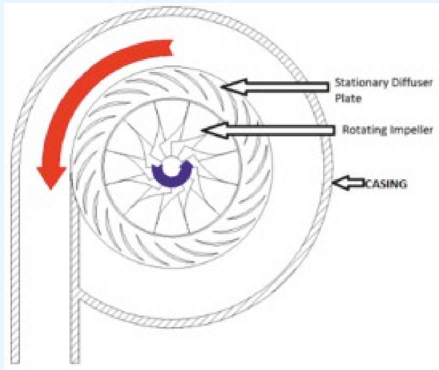
Parameters	Shrouded	Unshrouded
Velocity	Lower Tip speed	Higher Tip speed
Pressure generation	Low	High
Pressure ratio	3:1	10:1
Losses due to tip leakages	Low	High
Efficiency	High	Low (when compared to shrouded)

Diffuser:

In centrifugal compressor, air enters with low velocity gain kinetic energy from the impeller and velocity rises. The increased velocity air enters the diffuser, it converts the high velocity air from impeller to low velocity but increases the pressure. Hence, the discharge pressure of air is developed due to a rise in pressure in the impeller stage, and next in diffuser stage, as show in the figure.



Casing : The collector of a centrifugal compressor can take many shapes and forms. When the diffuser discharges into a large empty chamber, the collector may be termed a Plenum. When the diffuser discharges into a device that looks somewhat like a snail shell, bull's horn or a French horn, the collector is likely to be termed a volute or scroll. As the name implies, a collector's purpose is to gather the flow from the diffuser discharge annulus and deliver this flow to a downstream pipe. Either the collector or the pipe may also contain valves and instrumentation to control the compressor.



How does centrifugal compressor operate?

A centrifugal compressor works like any other centrifugal equipment and its characteristic curve looks like the one given below. The head vs flow characteristic of a centrifugal compressor is shown for the variation in the inlet guide vane.

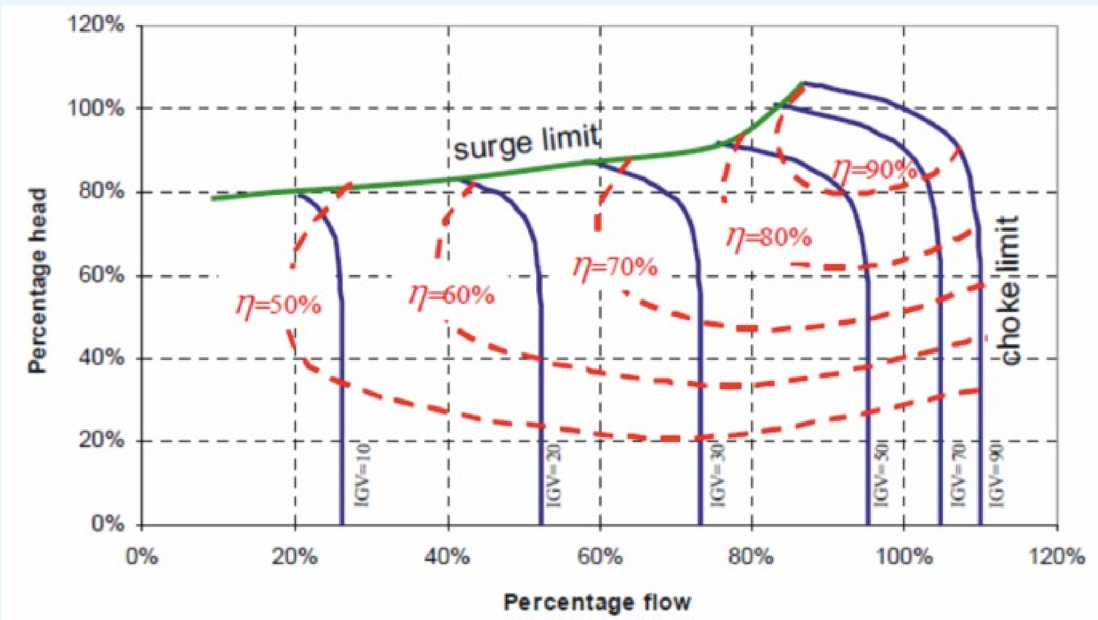


Figure 36: Characteristic curve of a centrifugal compressor

The surge and choke limit of a centrifugal compressor is the region in which the centrifugal compressor should not be operating, and operating in above choke and stall limit may result in some harm to the compressor. The isentropic efficiency curves are also shown in the characteristic curve. The efficiency of the centrifugal compressor drops as the inlet guide vane is further closed. If the centrifugal compressor is run at rated pressure, the possibility of controlling the quantity of compressed air is lowered due to the surge limit. Therefore, in order to safely operate the compressor at part load, the operating pressure of the compressor is lowered than the design based on the requirement.

Did you know?? The centrifugal compressor operates at low specific norms at base load. Base load is nothing but the minimum compressed air demand at which the system continuously consumes and the demand does not drop below this level.

The specific energy consumed by the centrifugal compressors is around 0.12 kW/CFM (Machine power considered). The difference in design and operating powers of the compressors is due to the part load operation of compressor with inlet guide vane, considering efficiencies of the motor of compressed air, and operating at lower pressure than design pressure.

Capacity Control of Centrifugal Compressor

Centrifugal technology is based on dynamic compression, in which air is drawn between the blades of a rapidly rotating impeller, and accelerates to high velocity. The air is then discharged through a diffuser, where the kinetic energy is transformed into static pressure.

They have a characteristic curve of rising pressure as capacity decreases; hence their capacity is limited between surge and stone wall through a controlled combination of inlet control device and unloading valve.

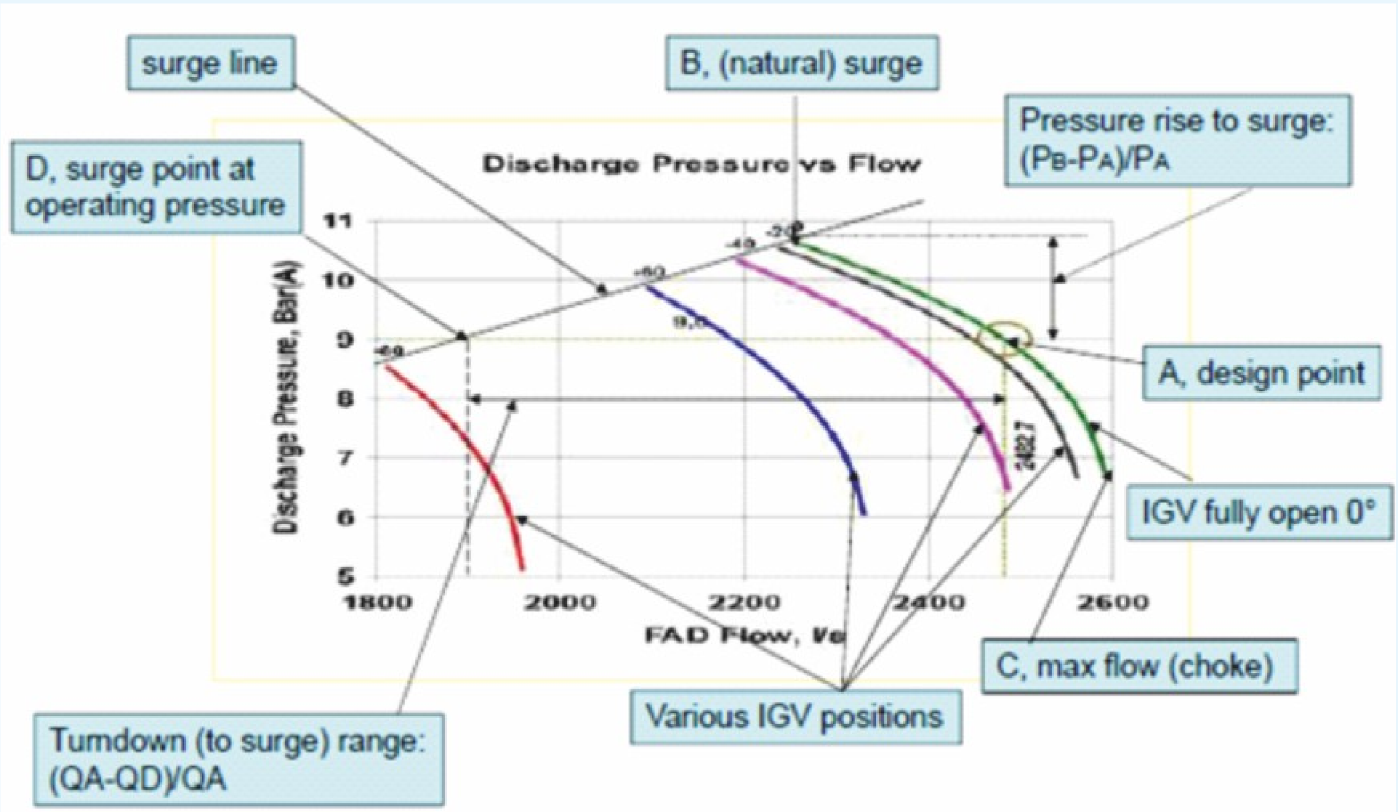


Figure 37: Performance curve of Centrifugal compressor

Turndown (to surge) range: The relative difference between the maximum flow at the design point and minimum flow before the blow off (at the surge line point).

As shown in above figure:

Turndown (to surge) range: $(Q_A-Q_D)/Q_A$

Capacity control of Centrifugal compressor:

The capacity control depends on the demand that is:

1. Within Turndown ratio (Auto Dual Control).
2. With lower demand (Constant Pressure Control).

Tip: Turn down ratio is an important parameter for energy efficient operation of centrifugal compressor, minimum turndown percentage should be considered at design stage to avoid blow-off operation.

1. Auto Dual Control:

- The standard regulation is achieved by inlet butterfly valve (IBV), or inlet guide vanes (IGVs) and controller. After reaching discharge pressure set point, the IBV or IGVs will modulate the compressor inlet to maintain constant discharge press over the control (B→C) range.
- At the minimum throttle point ©, the IBV or IGV stops closing, allowing the discharge pressure to rise to the unload set point. At this moment, the compressor will unload, IBV or IGV will close, and an unloading valve fully opens.
- The compressor remains in the unloaded condition until its demand rises.
- If the compressor remains at unload for fixed period, the unit may configure to power down and stop. The controller will automatically restart and load in response to the system pressure falling to the load set point (A).

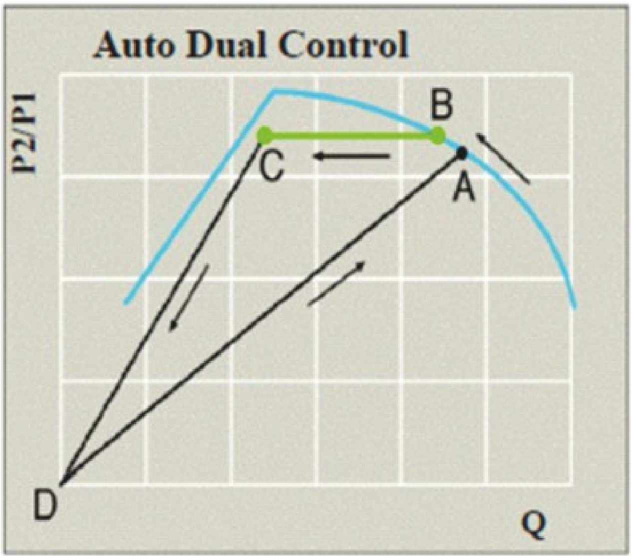


Figure 38: Demand within Turn down ratio

2. Constant Pressure Control:

- This regulation uses (IBV) or (IGV), modulating Unloading valve (UV) and controller. After reaching discharge pressure set point, the IBV or IGVs will modulate the compressor inlet to maintain constant discharge press over the control (A→B) range.
- At the minimum throttle point (B), the IBV or IGV position is fixed and the UV starts modulating, thereby maintaining a constant pressure over the full operating range (A→C).
- User can programme the maximum modulating point of unloading valve, thereby saving power. This type of control is designed for control of air output at constant pressure.

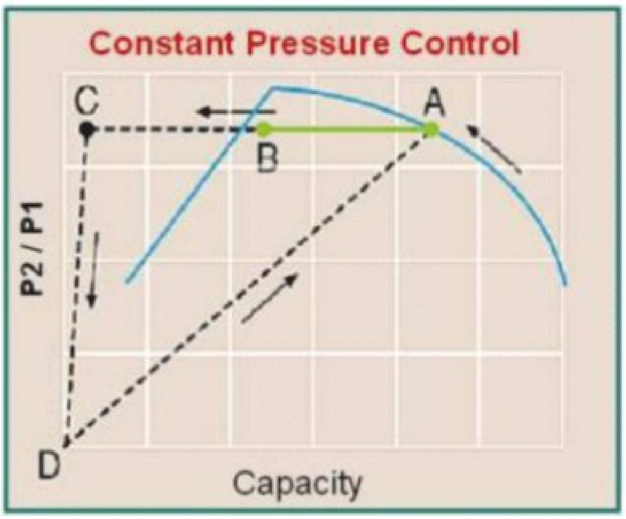


Figure 39: Constant Pressure Control

Ambient Conditions' Effect on Centrifugal Compressor

Centrifugal is dynamic and highly sensitive to ambient conditions.

Inlet Pressure:

The inlet temperature of the air has an impact on the density of the air at the intake of the compressor, and will influence the kinetic energy transferred by the blades to the air. Increased density at lower intake temperatures will result in a higher free air delivery (CFM) and also higher power consumption of the compressor.

Lower Temperature:

- Increases the surge pressure.
- Increases the maximum capacity (weight flow) at a given discharge pressure.
- Increases power consumption (horsepower)

Higher Temperature:

- Decreases the surge pressure.
- Decreases the maximum capacity (weight flow) at a given discharge pressure.
- Decreases power consumption (horsepower).

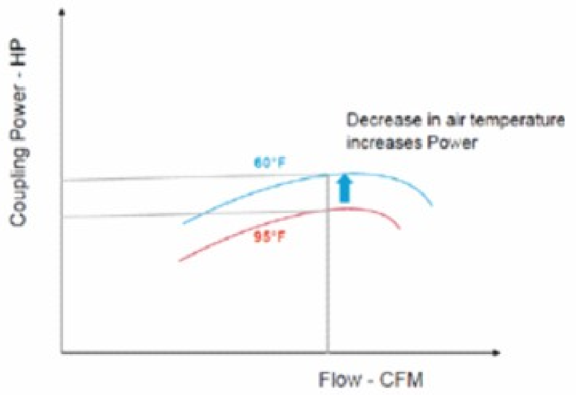


Figure 40: How inlet temperature affects power

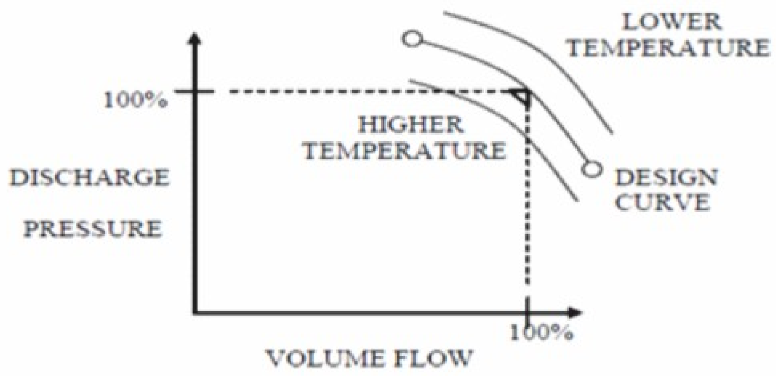


Figure 41: Effect of temperature in performance curves

Inlet Pressure

A decrease in inlet pressure will reduce the density of the air at the compressor intake. As with higher temperatures, it will result in lower free air delivery and power. Changes in inlet pressure can be caused by fouled inlet filters or changing barometric pressure.

Lower Inlet Pressure:

- Decreases the discharge pressure along the entire curve
- Decreases the maximum capacity (weight flow)
- Decrease the power consumption (due to reduced weight flow)

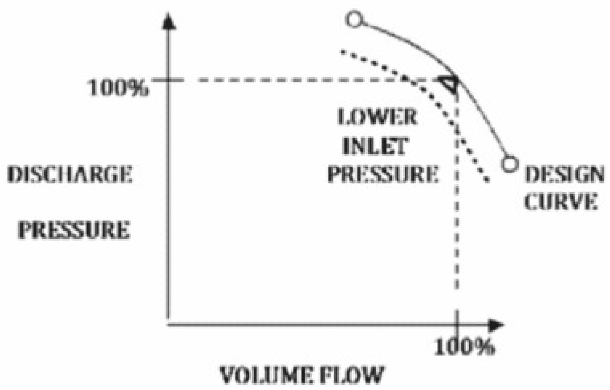


Figure 42: Effect of Pressure in performance curves

Relative Humidity (RH):

An increase in relative humidity (RH) reduces flow and power, and a decrease in RH will increase flow and power. The addition of water vapour to the air makes air humid and reduces the density of the air.

A higher relative humidity will:

- Decreases the discharge pressure at surge
- Decreases the maximum capacity (weight flow)
- Decreases the flow at which surge occurs
- Decreases power consumption (horsepower)

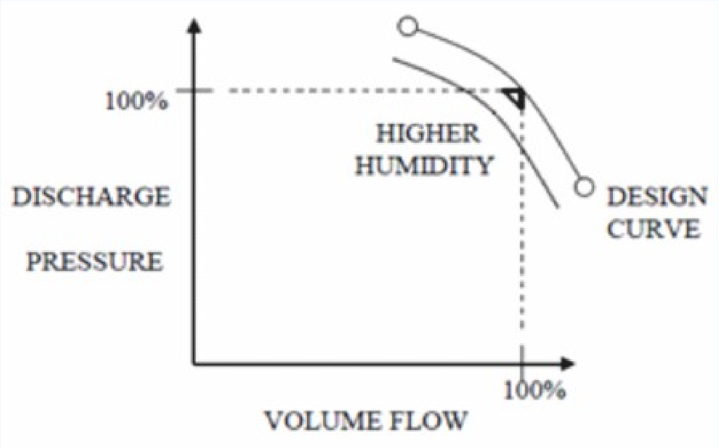


Figure 43: Effect of Relative Humidity in performance curves

Cooling water temperature:

The cooling water temperatures will affect the intake temperatures to the second stage and any further stages, if present. Colder water increases flow and power, and warmer water reduces flow and power.

A lower cooling water temperature will:

- Increases discharge pressure.
- Increases maximum capacity (weight flow).
- Increases power consumption (horsepower).

While, a higher cooling water temperature:

- Decreases discharge pressure.
- Decreases maximum capacity (weight flow).
- Decreases power consumption (horsepower).

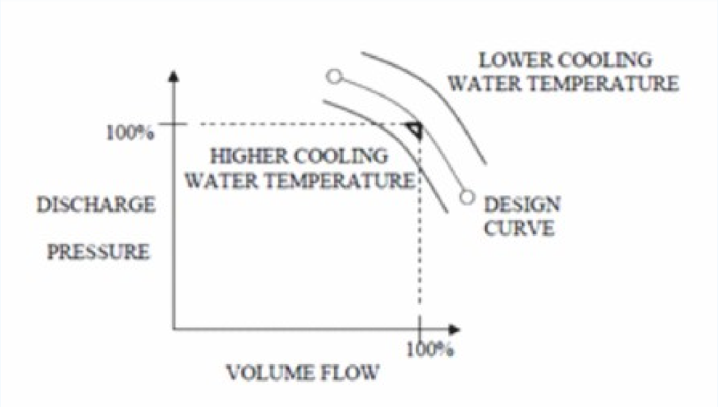


Figure 44: Effect of Cooling Water temperature

1.2.1 Axial flow air compressors

The axial flow type air compressor is essentially a large capacity, high speed machine, with characteristics quite different from the centrifugal. Each stage consists of two row of blades, one row rotating and the next row stationery. The rotor blades impart velocity and pressure to the gas as the motor turns, the velocity being converted to pressure in the stationery blades.

1.2.2 Roots compressors

This is really a blower and is generally limited to a pressure of 1 bar in ingle stage and a pressure of 2.2 bar in two stage combination.

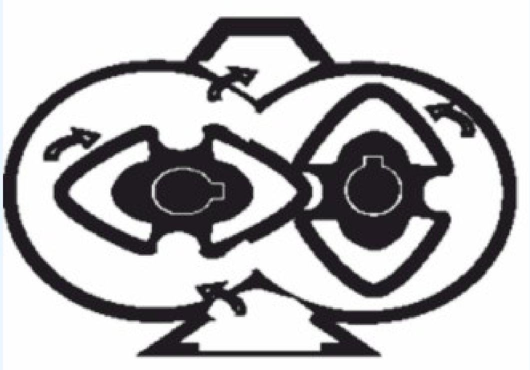


Figure 45: Axial Compressor

Table 14: Selection Criteria for Compressor

Type of Compressor	Capacity (m3/hr)		Pressure (bar)	
	From	To	From	To
Roots blower Compressor	100	30,000	0.1	1
Reciprocating				
• Single /Two Stage	100	12,000	0.8	12
• Multi Stage	100	12,000	12.0	700
Screw				
• Single Stage	100	2,400	0.8	13
• Two Stage	100	2,200	0.8	24
Centrifugal	600	300,000	0.1	450

CHAPTER

V

PERFORMANCE ASSESSMENT OF AIR COMPRESSORS

Over a period of time, the performance of compressors and compressed air systems deteriorates. This could be due to various reasons, such as **poor maintenance, wear & tear, use of poor-quality lubricants, etc.**

The reduction in performance of air compressors leads to increase in overall power consumption, installation of additional compressors, and increase in cost of compressed air. Hence, a periodic check on the performance of compressors is required to ensure rated compressed air delivery, operating efficiency and specific power consumption.

The compressed air leakage level has to be periodically monitored. The increase in leakage level leads to increased energy loss. The leakage level in the plant can be monitored by carrying out a leakage test. In this chapter, the leakage test procedure is discussed in detail.

1. Performance test

The following parameters are determined by carrying out the performance test on the compressors:

Free air delivery (FAD)

Free air delivery is the quantity of compressed air delivered by the compressor at ambient pressure.

Volumetric efficiency

Volumetric efficiency is the ratio of the actual free air delivered to the compressor swept volume.

Specific power consumption

Specific power consumption of the compressor is the ratio of actual power consumption to the quantity of free air delivered.

After carrying out the performance test, the actual performance of the compressor has to be compared with the design values. Suitable measures could be taken to improve the operating efficiency.

i. Measurement of free air delivered by the compressor

The quantity of free air delivered by the compressor can be measured by any of the following two methods:

a. Nozzle method

The compressor receiver is connected with a specially designed nozzle. The compressor is put into operation and the compressed air is discharged to atmosphere through the nozzle. Sonic flow sets in the nozzle throat for a particular ratio of upstream pressure to the downstream pressure.

When the pressure in the receiver is kept constant for a particular period of time, the compressed air delivered by the compressor is equal to the quantity of airflow through the nozzle. The airflow through the nozzle can be calculated from the known characteristics of the nozzle.

The testing arrangement is shown in the fig.

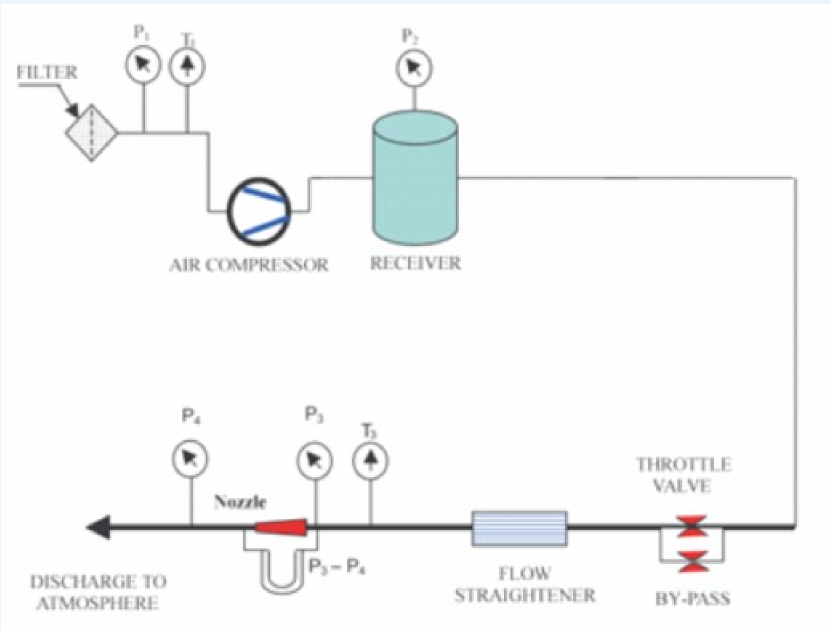


Figure 46: Performance assessment with Nozzle

The compressor discharge is connected to a receiver. In the receiver outlet, a suitable nozzle is installed for flow measurement. Before the nozzle, a straightener and a control valve are installed. Straightener is used to ensure streamlined airflow, and the control valve is used to set the pressures at the inlet to nozzle.

The nozzle used for the flow measurement has to be selected based on the installed capacity of the compressor. As per IS standard IS 10431: 1994, the recommended nozzle dimensions for flow measurement for various capacity of compressors is given below:

Table 15: Nozzle vs Capacity

Nozzle size	Capacity m^3 / hr
6	3-9
10	9-30
16	27-90
22	60-170
33	130-375
50	300-450
80	750-2,000
125	1,800-5,500
165	3,500-10,000

The experiment can be carried out for different discharge pressure of compressors. The discharge pressures can be 40%, 60%, 100% and 110% of normal operating pressure of compressor.

Start the compressor and discharge the compressed air to the atmosphere through the nozzle. It should be ensured that the pressure drop through the throttle valve should be equal to or twice the pressure beyond throttle.

Once the system is stabilized and the pressure in the receiver is maintained constant for a period of time, the following measurements have to be carried out.

The quantity of free air delivered by the compressor can be calculated using the following formula:

$$\text{Free air delivered } Q_f = k \times \Pi \times d^2 / 4 \times T1 / P1 \times \frac{2\,(P3-P4)\,(P2 \times Ra)^{1/2}}{T3}$$

Where

K - Coefficient of discharge of nozzle as per IS standards

D - Diameter of the nozzle m

R_a - Gas constant 287.1 J/kg k

P1 - Absolute inlet pressure kg/cm^2

T1 - Inlet temperature K

P2 - Absolute pressure in receiver kg/cm^2

T3 - Absolute temperature before nozzle kg/cm^2

P3 - Absolute pressure before nozzle kg cm^2

S - Speed of the compressor in rpm

P3 - P4 - Differential pressure across the nozzle kg/cm^2

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

$$\text{Compressor swept volume} = \frac{\Pi \times D^2 \times L \times S \times n \times N}{4}$$

D - Diameter of the cylinder in m

L - Stroke length in m

S - Compressor speed in rpm

n - Number of cylinders in compressor

N = 1 for single acting compressor and 2 for double acting

$$\text{Specific power consumption} = \frac{\text{Actual power consumption}}{\text{Measured free air delivered}}$$

b. Free air delivered measurement using Pump-up test method

The pump-up test method is the simplest method of estimating the capacity of the compressor in the shop floor itself. The free air delivered can be measured by the plant team themselves without using any sophisticated measuring instruments.

The compressor to be tested and a known volume of receivers have to be isolated separately from the main line. Totally empty the compressed air receiver and close the outlet valve of the receiver. Also, it should be ensured that there is no condensate water inside the receiver and the drain valve is also fully closed.

Start the compressor and note down the time taken for raise in pressure in the receiver to the normal operating pressure (P2) from the initial pressure (P1). The same exercise can be repeated three times.

The free air delivered by the compressed air can be calculated using the following formula:

$$\text{Free air delivered by the compressor} = \frac{P_2 - P_1}{P_{atm}} \times \frac{V}{T} \; Nm^3/min$$

P2 - Final pressure in the receiver kg/cm^2

P1 - Initial pressure in the receiver kg/cm^2

Patm - Atmospheric pressure kg/cm^2

V - Volume of compressed air storage m^3

T - Time taken to build up pressure from P1 to P2 in minutes

While estimating the volume of compressed air storage, the volume of after-cooler and the volume of pipeline from the after-cooler to the receiver should be included along with receiver volume.

Also, since the compressed air temperature at discharge is higher than the ambient temperature, the free air delivered has to be multiplied by the following correction factor.

$$\text{Correction factor} = \frac{T_{atm} + 273}{T_1 + 273}$$

Where

T1 - Temperature of compressor at discharge

T_{atm} - Ambient temperature in °C

iii. Compressed Air Leakage test

The leakage test has to be periodically carried out to estimate the compressed air leakage in the plant. The leakage test has to be carried out when there are no compressed air users in operation.

Run the compressor and pressurize the system to the normal pressure. Once the system reaches the normal operating pressure, the compressor will get unloaded.

If there are no leakages inside the plant, the compressor should remain in the unload condition and should not get loaded again. But, in actual practice, due to compressed air leakages, the system pressure will come down and the compressor will go to load mode.

The loading and unloading of the compressor indicate the compressed air leakage inside the plant. Note down the load/unload time (take at least three readings).

The compressed air leakage can be estimated using the formula given below:

$$\text{The system leakages} = \frac{\text{Load time x Compressor Capacity}}{\text{(Load time + Unload time)}}$$

$$\text{\% leakage} = \frac{\text{Air leakage x 100 (of air compressor capacity)}}{\text{Compressor capacity}}$$

iv. Cost of compressed air leakages

For efficient operation, air compressors have an on-load and an off-load pressure setting. The differential between these two settings should not be allowed to exceed 10% of the maximum pressure setting. Hence, the pressure drop due to air leakage play is a key factor for energy savings.

The cost of compressed air leakage at 7.0 bar pressure is given below:

Table 16: Cost of Compressed air through Orifice

Orifice size(mm)	Energy loss(kW)	*Cost of air leakage(INR / year)
0.8	0.2	8,000
1.6	0.8	32,000
3.1	3.0	120,000
6.4	12.0	480,000

**Based on INR 5/kWh; 8,000 operating hours; air at 7.0 bar pressure*

v. Leak Management System

One of the best methods of arresting leakages is through the implementation of Red Tag System. This is the simplest and most effective means, wherein the operator/site official is responsible for seeking the location of compressed air leakage, ties the red tag on to the leakage area, and notifies the concerned department to arrest/repair the leak. The maintenance team arrests the leakage at the next available opportunity. This system ensures proper logging of the air leak and swift action takes towards arresting the leakage.

However, the red tag system is only a minor portion of the leak management system. There are various steps to be followed to implement a successful leak management system.

Step 1 ***Know your baseline***	The first and foremost step of the leak management system is to establish the current operating demand of compressed air. This can be estimated by understanding the loading pattern of the compressors along with the corresponding free air delivered. This essentially forms the basis for leak management.
Step 2 ***Carry out leakage test***	The procedure to carry out leakage test has already been explained in the previous section. It is necessary to quantify the amount of compressed air leakage, which can be used as a baseline to compare and assess the effectiveness of the leakage management.
Step 3 ***Estimate monetary value of air leakage***	This includes two components. First is the monetary loss of energy due to air leakage, which illustrates the severity of air leakages. Second is the amount of resources required to be allocated to effectively arrest all the identified leakages. This could include costs incurred in replacement of pipeline, damaged regulators, filters, valves, etc.
Step 4 ***Physical identification & documentation***	The compressed air line must be inspected for physical damages causing air leaks. While conducting the survey, the red tags can be used to highlight the leakage area. There is a variety of leak detection instruments available in the market for identification of air leakages. It is also important to document/log the specification of the leakage and the necessary resources required for arresting them.
Step 5 ***Arresting/Repairing leakage***	Bigger leaks are easier to identify, and arresting them should be the maintenance team's first priority. The maintenance team must cross-verify with the list of leakages logged by the operation team, just to ensure all leakages are tracked and necessary action has been taken.
Step 6 ***Compare with baseline***	The final step of the leak management system is to compare the results of implementing the leak-arresting exercises. This can help the industry compare and contrast the effectiveness of the leak management system. Repeat the leakage test and compare the percentage of leakage now. An effective system illustrates lower leakage percentage than the baseline.

Air leakage is a common issue faced by every industry. It is continuous and recurring, and industries must take immediate actions towards arresting the leakages. The leakage test must be conducted periodically (recommended quarterly/semi-annual) and the leak management system must be implemented effectively. Industries with a very successful leak management system have achieved leakage percentage of less than 5%, which can be considered as an industry which is efficient in operation.

Lastly, it is important to remember that an effective leak management system induces efficiency, reliability, and cost effectiveness to any compressed air system, irrespective of the type of industry.

Figure 47: Red tag System for Compressed air leakage Reduction

CHAPTER

VI

RECEIVER DESIGN AND SIZING

An adequate air receiver should be provided for the compressed air system. Listed below are some of the main functions of compressed air receivers.

- Provide additional cushion to take care of sudden compressed air demand, in excess of the installed compressor capacity from the plant.
- Maintain steady pressure to meet the plant requirement.
- Since the receiver serves as a reservoir, it prevents frequent loading and unloading of the compressor.
- In addition, the receiver precipitates some of the moisture present in compressed air. Otherwise, the moisture will be carried over to the air dryer, which will lead to additional load on the drier.

The minimum receiver capacity can be calculated for certain applications. At the same time, experience in similar industry and judgment based on the operating condition of the plant shall be considered in selection of receiver capacity.

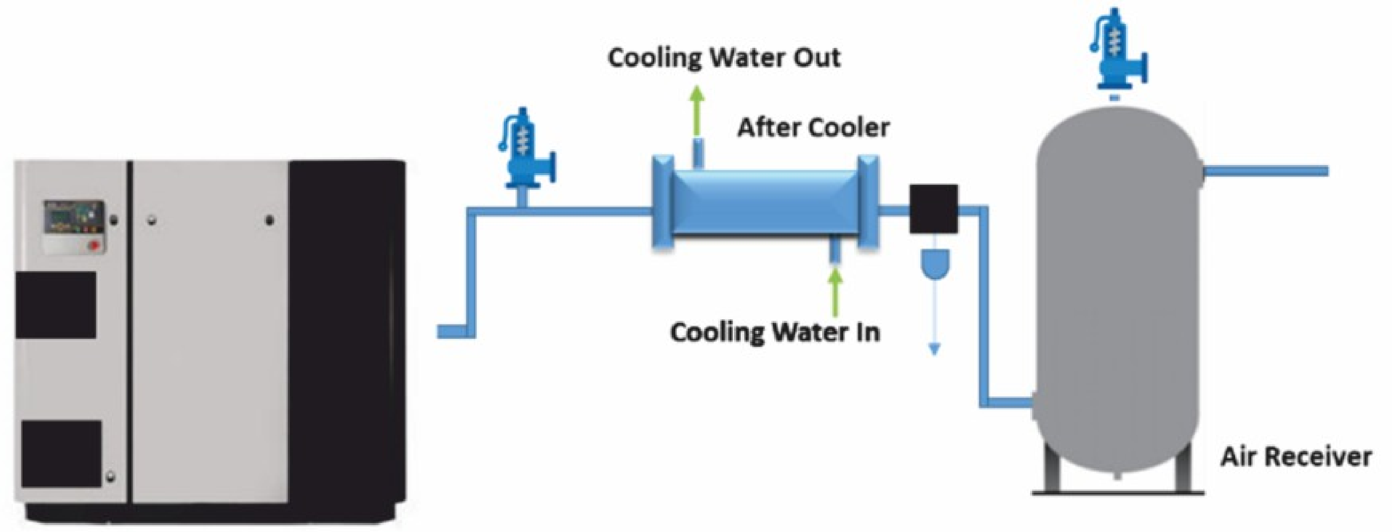


Figure 48: Receiver Design

The size of receiver can be calculated as follows:

$$V = \frac{T*(Q)*P_{atm})/}{(P_1-P_2)}$$

V = volume of the receiver m^3

T = Time allowed (minutes) for pressure drop P1 – P2 to occur.

C = Air demand, cfm of free air

P_a = Absolute atmospheric pressure, psia

P_1 = Initial receiver pressure, psig

P_2 = Final receiver pressure, psig

For reciprocating compressor:

As per IS 7938-1976, the air receivers can be selected based on the following thumb rule.

Volume of air receiver in M^3 = $1/10^{th}$ of flow rate in m^3/ min to $1/6^{th}$ of flow rate in m^3/min

The above thumb rule for designing the receiver varies with the type of compressor, its capacity control and air supply/demand requirement.

Effect of receiver sizing on specific energy consumption of the lubricant-injected oil screw compressor:

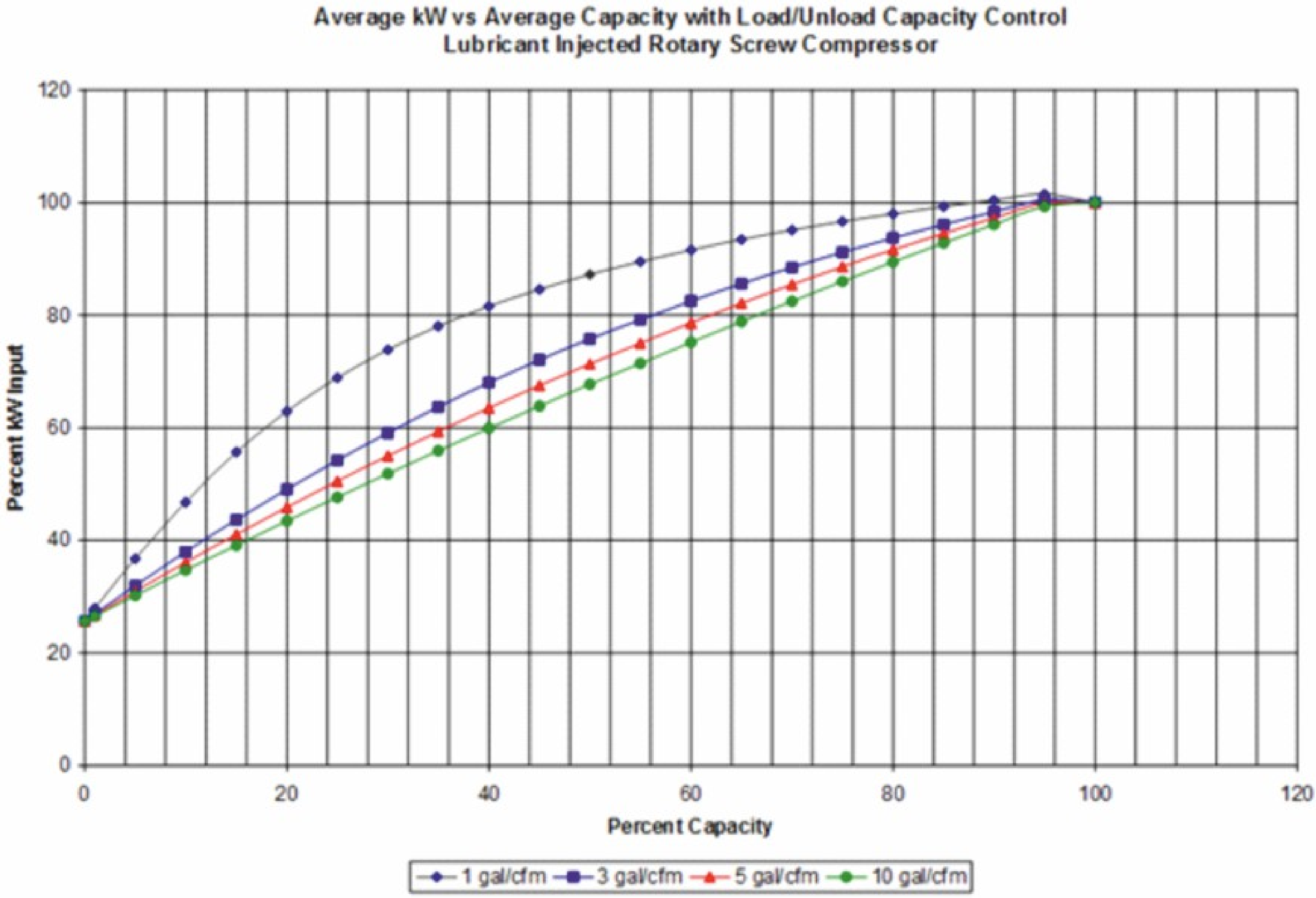


Figure 49: Average KW vs Receiver capacity for Load /unload operation of oil Screw compressor

Receiver volume for:

V1 : 1gal/cfm = 1/10th of the flow rate in M^3/min

V2 : 3 gal /cfm = 1/6th of the flow rate in M^3/min

V3 : 5 gal /cfm = 1/2nd of the flow rate in M^3/min

V4 : 10 gal /cfm = flow rate in M^3/min

Pressure band:	Δp= 10 psi
Time allowed for drop:	T= 40 sec

From the above graph, it is clear that lubricated oil screw compressor consumes 80% of the power for delivery.

Table 17: Specific Energy of Lubricated Screw Compressor in Load /unload control for Various Receiver Capacity

Parameters	V1	V2	V3	V4
Flow (% of full load)	39%	55%	62%	65%
Power consumed (% of full load)	80%	80%	80%	80%
Specific Energy (kw/cfm) w.r.t. full load kw/cfm	2.05	1.45	1.29	1.23

CHAPTER

VII

COMPRESSED AIR PLANT LAYOUT AND DISTRIBUTION

The design of compressed air plant layout and distribution of compressed air plays a significant role in the total energy consumption. While selecting the compressed air layout and distribution, at the design stage, it should be ensured that the pressure drop in the system is very minimal, so that the minimum operating pressure set point for the compressor can be maintained.

i. Plant Layout

Compressed air layout can be of two types, such as centralized compressor system and decentralized compressor system. Suitable compressed air system can be selected based on the plant. Each system has its own advantages.

The location of the compressors, suction pipe work and discharge pipe work are vital in configuring the plant layout.

ii. Selection of plant layout

Centralized and decentralized compressor layouts have their own advantages and disadvantages. The selection would vary from plant to plant.

In a centralized compressor system, all the compressors are located in a single house. This provides greater cost effectiveness in process plants.

Decentralized compressor system is more suitable for engineering industry having multiple production lines and requiring compressed air at different pressures. The compressors are dedicated to the individual production lines and operated at the pressure matching with the plant requirement.

For instance, if a compressor is located indoor in a centralized compressor room, the compressed air system is protected from the weather, allows for easy access for maintenance and maximizes plant floor space. However, centralized compressed air systems usually require additional space to provide adequate ventilation and additional piping to reach the user end, which can increase pressure drops.

The decentralized air layout allows for compressors to be located closest to the largest air users and reduces pressure drop through the airlines. However, this configuration can also result in noise and heat complaints inside the plant.

iii. Location of compressors

Ideally, compressors should be located where they can induct clean, dry and cool air. One of the major issues related to the compressor location is the ambient temperature.

The compressed air system exposed to extremely high temperatures can result in higher specific power consumption, unscheduled shutdowns, increased maintenance and decrease in lubricant life.

Ventilation is equally important for all compressors regardless of type of cooling.

At design stage, it is important to plan for proper ventilation and access to compressor location. Locations exceeding temperature of 45oC should be avoided. A free space of about 1 m around the compressor needs to be provided for maintenance, and another 1 m for motor starter access panel.

Addressing the issue of ventilation at the design stage can help in increasing the life of the compressor, lubricating oil and the coolant.

The following points should be considered while locating the compressors.

- Low humidity to reduce water entrainment.
- Adequate ventilation especially for air cooled unit.
- Minimum suction piping.
- Minimum of bends.

a) **Suction pipe work**

The suction pipe work plays an important role in terms of improving the operation and performance of the compressor. The following points should be considered while designing the suction pipe work for air compressor installations.

- The piping should be kept short to avoid excessive condensation and pressure loss.
- A high efficiency filter should be fitted to collect particulate matter. Generally, filters with dry disposable elements are suitable.
- Sufficient access should be provided for inspection and cleaning of filters. The intake silencer fitted with filter should be located upstream of the silencer to minimize the effect of pulsation.
- The piping should be large enough to avoid excessive energy losses. For every 25 m bar pressure lost at the inlet, the compressor efficiency is reduced by approximately 2%.

b) **Discharge pipe work**

The following points have to be considered while designing the discharge pipe work for the compressor:

- Discharge piping should be full bore, i.e., the size of the compressor outlet. Pipe work should fall in direction of flow towards the air receiver and after cooler.
- The air receiver should be located close to the air compressor and the pipe work should be as short as possible.
- Safety valve should be fitted for positive displacement compressors normally, it is set to release when the line pressure exceeds the operating pressure by 5-10%.

iv. Compressed air Distribution

Compressed air layout should be selected, to minimize the length of piping between the air compressor and the farthest user of compressed air user.

In systems with a large distribution network, it is preferable to have compressor centrally located, to minimize the length of piping between the compressor and the farthest end in the plant.

Some common layouts used are shown in Fig below:

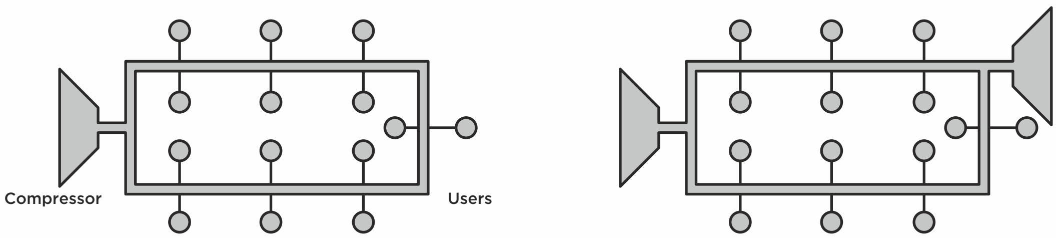


Figure 47 : Loop Grid Compressed air distribution

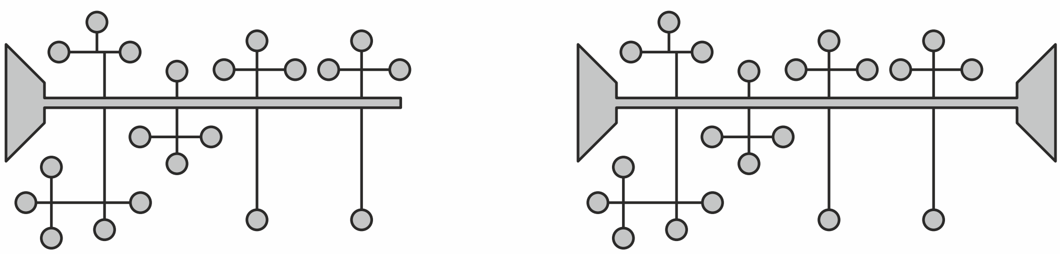


Figure 46: Branch Grid Compressed air distribution

Out of these four headers, loop header is the most desired and energy efficient layout to minimum pressure drop. In some cases, where there is a minimal usage of compressed air at farthest ends, a dedicated small capacity compressor can be installed.

The following points should be considered for the distribution pipe work.

- The drainage points should be installed with the aid of equal 'T's. Due to sudden change in direction of flow, these fittings assist the separation of water drops from the air.
- The pipe work should fall in the direction of flow. The gradient can be kept at approximately 1 in 100.
- Distribution branch connections should be taken from the top of the main to reduce water entrainment in the air.
- Drain traps should be provided at all low points.
- The drain traps should be protected from the ingress of foreign matter by installing a strainer.
- The drain traps in the main line can be installed at every 30-40 m for effective water removal.
- Install pressure gauges in various sections of the entire distribution system for monitoring the pressure in different sections of the network.
- The number of joints and bends in the distribution network should be minimum possible. Further to minimizing the joints, it should be ensured that joints are welded, instead of flexible or screwed joints wherever possible. This facilitates in minimizing the leakages and pressure drop.

v. Estimation of cost of pressure drop in exiting system compressed air pipelines

Reduction in pressure drop in compressed air pipelines help reducing the distribution pressure. The compressor discharge pressure setting can be reduced to the extent to reduction in pressure drop.

$$C_{PD} = [(P_d/P_d)^{0.56} - (P_d - \Delta P)/P_s)^{0.56}] * SP * Q_{air} * R * N$$

Where

C_{PD} = Annual cost of pressure drop due to compressed air

Pd = Discharge pressure of compressor, kg/cm^2a

Ps = Suction pressure of compressor, kg/cm^2a

SP = Specific power consumption of compressor, $kW/(Nm^3/h)$

Q_{air} = Air flow rate, Nm^3/h

Dp = pressure drop in kg/cm^2

R = Cost of power, Rs/kWh

N = Annual operating hours

Estimation of Cost Savings by larger diameter:

Estimate of cost of power consumption due to pressure drop by changing over to new size can be made as below.

$$C_{PD\text{-}NEW} = C_{PD}(D_{old}/D_{new})^5$$

Where

D_{old} = existing diameter, mm

D_{new} = New diameter, mm

Savings due to new pipe = CPD - CPD-new

The longest permitted length in the pipe network for a specific pressure drop can be calculated using the following equation:

$$L = \frac{\Delta P \times D^5 \times P}{450 \times Q^{1.85}}$$

Where

l = overall pipe length (m)

ΔP = permitted pressure drop in the network (bar)

p = absolute inlet pressure (bar(a))

qc = compressor Free Air Delivery, FAD (l/s)

d = internal pipe diameter (mm)

Table 12: Cost for New Pipes

Diameter, mm	Thickness mm	Weight KG	Piping costing Rs/m	Cost of erection Rs/m	Total cost Rs/m
100	6	10	1,000	1,000	2,000
150	6	15	1,500	1,500	3,000
200	8	20	2,000	2,000	4,000
250	8	31	3,100	3,100	6,200
300	10	45	4,500	4,500	9,000
500	10	75	7,530	5,000	12,530
1000	15	150	15,000	10,000	25,000

*** Reference data from BEE CODE ON PIPING*

vi. Determining Proper Piping Sizes:

$$A = \frac{7.87 \times Q \times P_a}{V \times (P_d + P_a)}$$

Where

A = Cross – Sectional area of the pipe bore, in2.

Q = Flow rate, ft3/min free air.

P_a = Prevailing atmospheric absolute pressure, psia.

P_d = Compressor discharge gauge pressure (or line pressure), psig.

V = Design pipe velocity, m/sec

Did you know??
Recommended Value of Velocity in compressed air pipe line is 6 to 9 m/sec

Minimum pressure drop in the distribution 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.

Table 12: Typical pressure drop due to smaller pipe diameter for 100CFM flow

Pipe nominal bore(mm)	Pressure drop (bar) per 100 meters
40	1.80
50	0.65
65	0.22
80	0.04
100	0.02

Compressed Air requirement for various Pneumatic tools

Description of Pneumatic Machine	Free Air Consumption at 6.0 3 0.5 bars cfm	Description of Pneumatic Machine	Free Air Consumption at 6.0 3 0.5 bars cfm
Drilling Machine for		**Internal Vibrator, Internal diameter**	
6 mm holes in steel	13	62 mm	39
9 mm holes in steel	16 to 21	75 mm	53
13 to 20mm holes in steel	26 to 32	112 mm	71
22 to 25mm holes in steel	35 to 42	140 mm	88
32 mm holes in steel	45 to 62	**Rock drills Drifter drill (Cradle mounted)**	
38 mm holes in steel	53 to 56	75 mm	131
50 mm holes in steel	57 to 65	88 mm	169
75 mm holes in steel	65 to 86	100 mm	201
Wrenches (rotary type) for		**Wagon drill with**	
7 mm nuts	5 to 9	100 mm drifter	222
9 mm nuts	16 to 18	88 mm drifter	184
13 to 25 mm nuts	26.48 to 35	**Carving**	
22 to 25 mm nuts	35 to 42	Medium dressing	11
Wrench impact for nuts up to		Roughing and Bushing	14
20 mm	21	Stone surfacer, for large blocks	32
32 mm	39	Spike puller, per spike	4
Wrench, Tapping	16	**Cement Gun**	
Saw, 150 mm dia	21	Small	106
Air chuck or Arbor	0.1 per operation	Medium	169
Sump Pump (400 to 1000 LPM)	53 to 128	**Internal Vibrator, Internal diameter**	
Air Press	0.24 per operation	62 mm	39
Air Motors		75 mm	53
Upto 1 kw	1.20 to 1.35 per KW	112 mm	71
Over 5 kw	1.00 per KW	140 mm	88
Air Cylinder	0.15 per meter tonne of lift	**Rock drills Drifter drill (Cradle mounted)**	
Shuttering vibrators		75 mm	131
3 kg	6	88 mm	169
4.5 kg	11	100 mm	201
6 kg	16 to 21	**Wagon drill with**	
Concrete Compactor	6 to 10	100 mm drifter	222
Coal cutter, percussive		88 mm drifter	184
62 mm	106	**Hand hammer drill (Jack hammer)**	
88 mm	152	14 kg weight	53
100 mm	191	17 kg weight	67
Drill Sharpener		22 kg weight	79
Small	53	30 kg weight	95
Large	127	Plug drill	32

Description of Pneumatic Machine	Free Air Consumption at 6.0 3 0.5 bars cfm	Description of Pneumatic Machine	Free Air Consumption at 6.0 3 0.5 bars cfm
Forging Hammer (Power)		**Sinker Drill**	
50 Kg	64	75 mm	141
150 Kg	138	88 mm	169
250 kg	201	**Stopping Drill**	
500 kg	339	Light	71
1000 kg	565	Heavy	132
Concrete Breaker		Dustless dry drill	0
35 to 40 kg weight	58 to 77	88 mm	191
25 kg weight	48	75 mm	127
15 kg weight	32	Underwater drill	88 to 95
Pile driver	64	Auger drill, for coal	79
Spike Driver	64	Grinders, 6" and 8" wheels	50
Stone Tool for		Grinders, 2" and 2 1/2" wheels	14-20
Lettering and light	6	File and burr machines	18
Forging Hammer (Power)		Rotary sanders, 9" pads	53
50 Kg	64	Rotary sanders, 7" pads	30
150 Kg	138	Sand rammers and tampers	
250 kg	201	1 " x 4" cylinder	25
500 kg	339	1 1/4" x 5" cylinder	28
1000 kg	565	1 1/2" x 6" cylinder	39
Concrete Breaker		Chipping hammers, weighing 10-13 lb	28-30
35 to 40 kg weight	58 to 77	Heavy	39
25 kg weight	48	Weighing 2-4lb	12
15 kg weight	32	Nut setters to 5/16" weighing 8 lb	20
Pile driver	64	Nut setters 1/2" to 3/4" weighing 18 lb	30
Spike Driver	64	Sump pumps, 145 gal (a 50-ft head)	70
Stone Tool for		Paint spray, average	7

Description of Pneumatic Machine	Free Air Consumption at 6.0 3 0.5 bars cfm	Description of Pneumatic Machine	Free Air Consumption at 6.0 3 0.5 bars cfm
Lettering and light	6	Varies from	2 to 20
Carving		Bushing tools (monument)	15 to 25
Medium dressing	11	Carving tools (monument)	10 to 15
Roughing and Bushing	14	Plug drills	40-50
Stone surfacer, for large blocks	32	Riveters, 3/32″-1″ rivets	12
Spike puller, per spike	4	Larger weighing 18-22 lb	35
Steel drills, rotary motors		Rivet busters	35-39
Capacity up to 1/4″ weighing 1 1/4-4 lb	18-20	Wood borers to 1″ diameter weighing 4 lb	40
Capacity 1/4″ to 3/8″ weighing 6-8 lb	20-40	2″ diameter weighing 26 lb	80
Capacity 1/2″ to 3/4″ weighing 9-14 lb	70	**Steel drills, piston type**	
Capacity 7/8″ to 1″ weighing 25 lb	80	Capacity 1/2″ to 3/4″ weighing 13-15 lb	45
Capacity 1 1/4″ weighing 30 lb	95	Capacity 7/8″ to 1 1/4″ weighing 25-30 lb	75-80
		Capacity 1 1/4″ to 2″ weighing 40-50 lb	80-90
		Capacity 2″ to 3″ weighing 55-75 lb	100-110

CHAPTER VIII

TROUBLESHOOTING COMPRESSOR AND COMPRESSED AIR SYSTEMS

Troubleshooting Screw Air Compressor Problems

1. *Compressor is not starting*

When you press the start button but nothing happens, either there is an electrical problem, or the compressor has been tripped on a safety device.

It is recommended to:

- Check supply power.
- Check for errors on display.
- Check emergency stop is out.
- Check and reset the overload relay.

If it is a new installation, check the phase sequence.

2. *Compressor shuts down on high-temperature*

If the compressor trips on over temperature, it could be due to any of the following reasons:

- Ambient temperature is too high or not enough ventilation.
- Too low oil level.
- Wrong type of oil.
- Dirty oil cooler.
- Thermostatic valve not working.
- Dirt/obstruction in oil lines.

3. *Compressor runs but will not load*

A screw compressor can run loaded ('pumping air') or unloaded ('idle'). The inlet/loading valve opens and closes according to air demand. The inlet valve is controlled by a solenoid valve that supplies control air to the inlet/loading valve.

- Check electrical power to solenoid valve.
- Check solenoid valve coil and solenoid valve operation.
- Check working of inlet/loading valve.

4. *Low capacity / not enough pressure*

If the compressor is running at low capacity or there is not enough pressure at the receiver (generation end), check that there is not a very high air demand, or air leak somewhere.

If the capacity of the air compressor is too low, check for the following:

- Does the inlet valve fully open?
- Check differential pressure over oil separator. Replace separator when necessary.
- Check if inlet filter is clean.
- Check and replace compressed air filters (if installed).

5. *Safety valve blows / too high pressure*

If the compressor does not unload, check if the pressure switch is correctly set and working. Check inlet valve and loading solenoid for good operation.

If the safety valve is located before the oil separator, check differential pressure of oil separator

6. *Oil in compressed air*

Oil in compressed air can have various causes:

- Oil separator old/saturated.
- Scavenge line plugged.
- Running temperature too high.
- Oil level too high.
- Wrong type of oil used.
- Minimum pressure valve not working.

7. *Water in compressed air*

Water is a natural by-product of air compression. There will always be water in compressed air, unless it is removed. Check the condensate trap for good operation. There should be water coming out every few minutes. If the manual drain is opened up, there should be only small quantity of water coming out. Check the dew point in case a compressed air dryer is installed.

8. *Compressor overload relay trips*

Check the current draw with a current clamp meter.

If the motor draws excessive current:

- Check the isolation of the motor windings. Should be in the mage-ohms (you need an isolation tester/high voltage ohm meter for this).
- Check the voltage when the compressor is running. If the voltage drops significantly when the compressor starts/runs, you have a bad connection somewhere. Check all relays, fuses and electrical connections.
- Check if all phases are present

If the motor draws its normal current, but still trips on overload, replace the overload relay with a new one (they are known to sometimes become too sensitive when they get old).

Troubleshooting Reciprocating Piston Compressor Problems

1. *Compressor is dead - nothing happens*

If nothing happens (no sounds, no click), it is most probably an electrical problem. Check the following:

- Power supply – check if there is power and all fuses are ok.
- Pressure switch – check the setting on the pressure switch and the actual pressure in the tank. Check the electrical connections on the pressure switch. Most pressure switches can be operated (tested) by pushing on the lever. Does the compressor start?
- Low oil level or high temperature safety switch – bigger compressors have safety switches for low oil level and/or high (overload) temperature. They will prevent the compressor from starting. Sometimes they have a reset button.

2. *Compressor is making noise*

Check where the noise is coming from. Check if everything is fixed tight. Look for loose belts, loose bolts, loose pulleys. Are the rubber damping feet still ok? If the sound comes from the compressor itself, check the oil level first. If the sounds appear or disappears at a certain level, check the inlet/outlet valves, piston rings. If it is a knocking type sounds, you may have a problem with your main bearings or connecting rod bearings.

3. *High oil consumption / low oil level*

- Check for Oil leak
- High oil carry over indicates oil in compressed air

Look for the leak. Common points are the drain valve/plug and the shaft seal.

4. *Oil in compressed air*

This can have a lot of causes.

- Oil level too high. When the oil level drops to normal levels, oil carry-over will stop.
- Wrong oil. Oil with a too low viscosity, or not suitable for reciprocating piston compressors (do not put 15W40 motor oil in your air compressor.)
- Running temperature too high. A higher temperature will lower the oil viscosity (it becomes thinner), which results in more oil carry-over
- Worn piston rings or wrongly installed.
- Worn cylinder surface.

5. *Compressor not building pressure and air blowing out of the inlet filter*

The inlet check valves/plates are broken, worn or dirty. At the up-stroke, air is pushed back through the inlet filter, instead of to the next stage/air receiver. Pressure builds up very slowly (low capacity). Either the compressor is not pumping at full capacity, or there is a big leak somewhere. First, check for air leaks. If nothing is found:

- Check inlet/outlet valves (inside compressor head)
- Check head gasket
- Check inlet air filter

6. *Compressor cannot start (but tries hard).*

If your compressor is unable to start, there could be a problem with your unloader valve. When the compressor stops, the unloader valve blows down the pressure in the exhaust pipe of the air compressor. This is to make sure that the compressor is able to start up again. If the pressure remains in the exhaust pipe, the air pushes down on the compressor piston and the motor is unable to get it moving.

7. *When compressor is stopped, air is leaking out of the unloader valve/pressure switch*

There is nothing wrong with your unloader valve or pressure switch. The problem is with the check-valve on the air receiver. The unloader valve blows-off the exhaust pipe of the air compressor. The check valves make sure that the air in the air receiver stays in the air receiver.

8. *High cylinder temperature.*

Can be any of the following:

- High ambient temperature
- Broken cylinder head gasket
- Leaking/broken/dirty intake/exhaust valves

9. *Water in compressed air*

Water is a normal by-product of air compression. The air receiver should have a drain valve. Drain the drain valve until all the water is out. In case of an automatic drain valve, check if it is working properly. Thermal relay/overload relay trips could be either an electrical problem or a mechanical problem. Check with a current clamp meter how much amps the motor draws. Compare to nameplate data. Check the voltage. If the voltage is too low, it can result in overload/overheating. Also, check the voltage when the compressor is running.

Oil and oil filter changes (Compressor running in dusty environment)

Everybody knows the importance of oil and oil filter. Take the example of a car: it needs some fresh oil and a new oil filter every now and then. The compressor manual will state when this should happen.

But it is experienced that a lot of compressors run in dusty and dirty conditions. A lot of dirt and dust will enter the compressor.

The dust not only causes dirty coolers and overheating. It will eventually enter the air compressor. It contaminates the oil. It wears down the screw element. It clogs up the oil filter and the oil separator. And, it ends up in the compressed air system and compressed air filters.

This dust will shorten the lifetime of compressor components such as compressor element screws and bearings (which is the heart of any compressor!). Also, the oil separator exposes the risk of oil in the compressor air.

A breakdown of the screw element will mean a long compressor down time for a plant. An oil separator could also collapse or become non-functional. It basically sends all the compressor oil into the compressed air system.

Recommendation: In case of a dusty environment, change the oil and filters more often than is indicated in the manual. For example, if the manual says every 4,000 hours, then change it every 2,000 hours.

Figure 52: Screw Compressor Dusty and dirty

Running at high temperatures

The biggest problem for a compressor is overheating. Compressing air generates a lot of heat, and all this heat has to be removed. If the temperature rises too high, it will seize and completely destroy the screw element. Generally, compressor has a warning and a shutdown alarm for high temperatures, so that won't happen anytime soon. But it is generally observed in so many compressors running for weeks and months near or at their 'warning' temperature. Usually, the warning pops up at 110°C and the shutdown at 120°C.

Running at high temperatures will not instantly destroy the compressor but it will slowly damage it. At high temperatures, the compressor oil degrades much more quickly. It will form a thin layer of 'varnish' or 'lacquer' on the inside of each and every part that comes into contact with the compressor oil. This includes the screw element, check valve/oil stop valve, separator filter, oil cooler and oil hoses. Its cooling capacity will decrease and your compressor will run even hotter.

Figure 50: Separator Filter Choked

Figure 49: oil cooler, inter and after coooler

This varnish looks like a reddish glow on the metal surface. It is almost impossible to remove. The only way to remove the varnish is to chemically clean it, which is quite expensive. So, replacing the cooler (and other parts) is often the cheapest solution.

Generally, the compressor has a high temperature alarm and a shutdown alarm. We can run the compressor just below the shutdown temperature, but that does not mean it is good for the compressor. If we cannot lower the temperature by installing extra ducting or ventilation, the only solution is to change the oil more frequently.

Recommendation:

- Don't run the compressor at too high temperatures for a long period of time.
- Keep coolers clean.
- Change oil more quickly. If the normal interval is 4,000 hours and the compressor run at 100+°C, change it every 2,000 hours.
- Or, if the plant has many or very big compressors, then it is useful to take an oil sample every 1,000 hours and have it analysed.

Water in the compressed air

It is surprising to believe the amount of water an air compressor produces each and every day. The water is naturally in the ambient air that is sucked in by the compressor. Because of the large amounts of ambient air that a compressor needs to produce compressed air, there is a lot of water in the compressor air. This water is removed by compressed air dryers and condensate traps.

There are many cases where the compressed air receiver is filled with water (volume of water as compared to receiver volume is significant) such that when manual drain valves are operated, it discharges water continuously for a longer period. Sometimes, this important activity in the plant is not checked. This means that the pneumatic equipment of a plant is basically running on water instead of compressed air. Water in the compressed air will not only directly running your compressed air tools, equipment or products. It will also damage the inside of the compressed air piping, creating a rusty, dirty compressed air piping system. Not only operational & maintenance costs increase but also replacing it could become a high investment job.

Scenario:

One plant used the compressed air mainly to open and close instrument valves, bag filter operation. They had the usual setup: 2 big air compressors installed (one was standby), each with a separate air dryer and some compressed air filters. All connected to a 10,000 litre (10 m^3) air receiver.

It was noticed that there was a lot of water in the compressor oil and in the condensate drain. It was decided to check and drain the main air receiver. As expected for a condensate drain, a lot of water flushed out. Almost half of the air receiver was completely filled with condensate water as was the piping between the compressor and the receiver and part of the piping system towards the air users. Those users operated on water, not compressed air. It was noticed that all dryers and condensate traps were working correctly.

But, they had made one mistake: all drains were connected together to a main line. This 'main line' had a small diameter and was simply dirty and clogged. Nobody had checked this system or drained the condensate. Some simple daily or even weekly checks will end many of the common compressed air problems.

Basic instruments for assessing compressor performance

In order to carry out performance assessment of compressor, it is necessary to understand the preliminary data or measurements which are required to be carried out. The energy audit measurement equipment required for assessing compressed air systems performance are shown below:

Electrical Measuring Instruments – Power Analyzer: These are instruments for measuring major electrical parameters of compressor in both load & unload such as kVA, kW, PF, Hertz, kVAr, Amps and Volts.

Infrared Thermometer: This is a non-contact type measurement which when directed at a heat source directly gives the temperature read out. This instrument is useful for measuring hot spots in furnaces, surface temperatures, etc.

Leak Detectors: Ultrasonic instruments are available which can be used to detect leaks of compressed air and other gases which are normally not possible to detect with human abilities.

Dew point measurement : This equipment is used to pressure dew point temperature of the compressed air at the air dryer. This indication of dew point illustrates the moisture content present in the compressed air after the air dryer.

Pressure Transmitter: Pressure transducer is a device which converts sensed pressure value to an analogue signal of 4-20 mA. Pressure transmitter plays and vital role in data logging and control of compressor. The capacity control done by master controller /HMI/PLC is based on the set value and operating pressure is sensed by Pressure transmitter.

Online Flow Meter: A flow meter is a device used to measure the quantity of air flow; the flow meter converts the measurement flow into analogy signal. On the basis of the principle of flow measurement types, the types of flow meters available include positive displacement, electromagnetic, mass flow, and vortex. The analogy signal from flow meter is connected to data logger or management system for monitoring.

Portable Air Flow Meter: Portable air flow meter uses constant temperature difference method of measuring gas(air). They operate either by introducing a known amount of heat into the flowing stream and measuring an associated temperature change or by maintaining a probe at a constant temperature and measuring the energy required to do so. So there is a certain relationship between heating power rate P, difference of temperature ΔT and mass flow Q as below: $P/\Delta T = K1 + K2\,F(Q)K^3$

K1 , K2, K3 constants depends on the medium.

Best Practices for Compressor Management System

It is not uncommon that many plants ignore low-cost best practices and then end up investing a lot more in operating and maintaining the air compressor system. So, here are some common mistakes to be avoided:

Ignoring daily and weekly maintenance

Air compressors are often forgotten about until a problem appears. Many problems with air compressors gradually built up, they do not always just appear out of nothing. It is recommended to visit the compressor daily (or at least 2-3 times a week) and check all basic maintenance points. It is to be noted that many plants follow routine or preventive maintenance but the end result is cleaning of machines. This should be avoided, instead thorough check up is required.

A checklist as illustrated in the figure must be made and must also be ensured that timely maintenance follow-ups are conducted to ensure proper maintenance of the air compressor and the compressed air systems.

Not keeping records

A history of your compressor is very useful when troubleshooting problems. It is a good idea to note down the most important things every week for example. And, keep records of each and every maintenance done on the compressor: what was changed, where there any problems, what oil was used, etc.

Here are the main things to keep records of:

- Running hours (loaded/unloaded).
- Outlet pressure.
- Ambient temperature & element outlet temperature.
- Dew point temperature of air dryer.
- Was condensate drained from all drains? How much water came out?
- Is compressed air clean and free from water, oil, rust, dirt?
- RPM or speed/capacity percentage (if VFD installed).

	Daily	Weekly	Monthly	Quarterly
Check Oil Level	✓			
Drain Moisture from Tanks	✓			
Inspect Air Filters	✓			
Check for noise/vibration	✓			
Inspect Belt Guard	✓			
Check for air/oil leaks	✓			
Clean exterior of compressor		✓		
Tighten/Retorque Bolts		✓		
Check belt tension		✓		
Check safety valve condition		✓		
Change compressor oil			✓	
Clean/change air filter			✓	
Perform FAD/pump up Test			✓	✓
Check control systems			✓	
Perform Air Leak test				✓
Check condensate drains				✓

Air Compressor Log Sheet - Compressor A/B/C/D *Month ....*

To be entered by operator at 09:00 hrs *Year ....*

Date	Running Hour	Loading Hour	Units consumed	Element Temp.	DP across air filter	Oil Pressure	Oil Temp.
Day 1							
Day 2							
Day 3							
Day 4							
Day 5							
Day 6							
Day 7							
Day 8							
Day 9							
Day 10							
Day 12							
Day 13							
Day 14							
Day 15							
Day 16							

Figure 51: Best Practices

It is recommended to fill in the above list at least once every shift.

To better manage multiple and big compressors, industries are adapting Internet of Things (IoT) technologies to help predict and detect maintenance needs. For example, a compressor can be serviced before it fails, thus avoiding downtime. A major responsibility of plant personnel is to minimise unplanned downtime that stops production. This can drive a lot of preventive maintenance (PM) to make sure equipment does not breakdown. At regular intervals, service engineers run diagnostics, grease parts, and swap out components that wear down, whether they need to be replaced or not.

An alternative is to implement predictive maintenance, which uses data analytics to promptly identify the onset of equipment failure, thereby allowing a reduction in PM frequency and duration, PM man hours and spare parts usage. IoT makes it easier for equipment manufacturers/users to send operational data to the cloud (or private data centres), where it can be thoroughly analysed to better understand how the equipment is functioning. Equipment can send information about its health, like if it is running hot, vibrating a lot, under loading or running just fine. When this data is monitored and analysed, equipment issues can be detected, and operated optimally.

Checklist for Energy Efficient Compressed Air System

- Suction temperature of compressor in compressor room should low or at par with ambient out door temperature.
- Inlet filter should not be in choked. Differential pressure across the inlet filter should be 100mmWc (0.01 kg/cm^2).
- In reciprocating compressors, to check the efficient operation of intercooler, air temperature after intercooler should be "ambient temperature +10°C"
- In water cooled compressor, the cooling water temperature ΔT = 5 to 8°C.
- Loading and unloading counter to be noted down.
  - % unloading should be in the range of 10% to 20%.
- FAD test to be conducted quarterly, to understand actual generation of compressor.
- Power measurement to be done and kW/CFM, KPI to monitored on daily basis.
- % Unload power should be with prescribed limits of OEM specification.
- Dryer dew point temperature should be monitored on periodic basis.
- Pressure drop across dryers should be greater than 0.3 kg/cm^2
- Pressure drop from generation to distribution end should be less than 0.8 kg/cm^2.
- Install VFD in the existing compressor if % Unloading is greater than 20%
- Percentage leakage should be maintained between 8 to 10%.

Not knowing your real compressed air requirements

It costs to compress air and to dry and clean it. The easiest way is to save on compressed air costs is to reduce the pressure. Every 1 bar (15 psi) pressure reduction can result in energy savings of approximately 6% for an average industrial compressor. The generation pressure should be optimised considering the user requirement and pressure drop due to compressed air system.

Therefore, water-removal filters, oil-removal filters, air dryers, etc., should be used only if required. It is not just the cost of the filters, other components, etc., but every filter creates a pressure drop in the system. Without this pressure drop, you can lower your compressor's pressure set points.

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

Table 20: Typical Power Savings through Pressure reduction

Compressors must 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. 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.

Establish a compressed air efficiency-maintenance programme

What would happen if the compressor stops due to breakdown? The production can directly get affected or even the system has to shut down if stand – by compressor is not there (even if it is there but not available due to maintenance etc.) If the compressor is stopped due to breakdown beyond repair then either it is required to have space and a connection for a rental compressor or buy a new one, either way production is stopped or runs at low load. It is advised to establish a compressed air efficiency-maintenance programme. Start with an energy audit and follow-up, then make a compressed air efficiency- maintenance programme a part of your continuous energy management programme.

Adequate training must be given to in-house engineers and operators on compressor and compressed air system on how to operate compressors efficiently, how to maintain and quickly address compressor basic problems. Most compressor problems are relatively easy and quick to fix.

Some of the most common problems faced in the operation and maintenance of a compressor are discussed below:

Overheating Compressor

The process of compression generates heat, which must be removed continuously, else the internal temperature of the compressor will increase. Therefore, oil takes care of extracting the heat from the compressors.

- Periodic maintenance of coolers
- Check Thermostatic valve
- Avoid jamming of coolers
- Ensure free circulation of cooling oil

Oil Carry-Over

Compressed air mixes with oil during compression, which needs to be separated to avoid carry-over into the compressed air system. Oil-injected rotary screw compressor has an oil-separation system which uses centrifugal force and a filter to separate oil and air.

- Ensure proper functioning of oil-separation system
- Check separator filter
- If necessary, replace oil separator

Compressor not 'loading'

Screw compressors can run both 'loaded' and 'unloaded'. When running unloaded, the motor is running, but the air-inlet is closed, so the compressor is not pumping any air. To avoid frequent start/stop of motor, load/unload configuration allows the motor to keep running, controlled by a 'solenoid valve'

- Ensure proper functioning of solenoid valve
- Thoroughly check for instrumentation errors resulting in the failure of solenoid valve
- If necessary, replace the solenoid valve

Compressor Inlet Air

Clean and cooler air means less work is required to produce line pressure. Ideally, the air intake should be located in a clean, dry, shaded area outside the building, at least six feet from the ground. Intake ducts should deliver minimum pressure drop at full capacity.

- Ensure proper exhaust of hot air away from the compressors
- Make sure the air inlet to the compressor is clean and as cool as possible
- Avoid pressure drop at the inlet of the compressor

Lubricator

Air-line lubricators provide lubrication to devices run by compressed air. Typically, a lightweight oil, easily carried by the air, helps operational efficiency.

- Ensure sufficient level of oil in the compressor
- Keep the oilers full and replace oil that appears to be milky or dirty.

Piping

Regardless of what we do to maintain our compressor, if we are not maintaining our piping system, the system becomes ineffective. All air/water inlet and discharge pipe works are affected by vibration, pulsations, temperature, pressure, corrosion and chemical resistance.

- Ensure there is no moisture or oil carry-over into the compressed air pipeline
- Periodically maintain respective air drying systems and oil separation units
- Replace pipeline which are affected by corrosion.

Routine Compressor Maintenance

The following are typical recommended minimum maintenance procedures for air-cooled reciprocating compressors; water-cooled, double-acting reciprocating compressors; lubricant-injected rotary compressors; lubricant-free rotary compressors; and centrifugal compressors. The plant team can use it as a reference and develop tailored maintenance schedule and practices specific to their plant.

Daily/Weekly	Monthly	Semi-Yearly/Yearly
Routine Maintenance for Air-Cooled Reciprocating Compressors		
• **Maintain lubricant level between high- and low-level marks on bayonet gauge. If lubricant is contaminated, drain and replace.** • **Drain receiver tank, drop legs and traps in the distribution system.** • **Give compressor an overall visual inspection and be sure safety guards are in place.** • **Check for any unusual noise or vibration.** • **Check lubricant pressure on pressure lubricated units. Maintain 18-20 psig when compressor is at operating pressure and temperature. HP compressors should maintain 22-25 psig of lubricant pressure.** • **Check for lubricant leaks.** • **Be certain pressure relief valves are working.** • **Clean the cooling surfaces of the intercooler and compressor.** • **Check the compressor for air leaks.** • **Check the compressed air distribution system for leaks.** • **Inspect lubricant for contamination and change if necessary.** • **Clean or replace the air intake filter. Check more often under humid or dusty conditions.**	• Check belt tension. • Change lubricant (more frequently in harsher environments). • Check lubricant filter on pressure lubricated units (more frequently in harsher environments). • Torque pulley-clamp screws or jam-nut.	• When synthetic lubricant is used, lubricant change intervals may be extended to every 1,000 hours or every 6 months, whichever occurs first. • Inspect compressor valves for leakage and/or carbon build-up. If excessive sludge build-up exists inside the crankcase, clean the inside of the crankcase as well as the screen. Never use a flammable or toxic solvent for cleaning. • Inspect the pressure switch diaphragm and contacts. Inspect the contact points in the motor starter.

Routine Maintenance for Water-Cooled, Double-Acting Reciprocating Compressors		
• Check compressor lubricant level in crankcase and cylinder lubricator and, if necessary, add to level indicated by sight gauge. **• Check cylinder lubrication feed rate and adjust, as necessary.** **• Check lubricant pressure and adjust as necessary to meet specified operating pressure.** **• Check cylinder jacket cooling water temperatures.** **• Check capacity control operation. Observe discharge pressure gauge for proper LOAD/UNLOAD pressures.** **• Drain control line strainer.** **• Check operation of automatic condensate drain trap (intercooler and aftercooler).** **• Drain condensate from discharge piping as applicable (drop leg and receiver).** **• Check intercooler pressure on multi-stage machines, and refer to manufacturer's manual if pressure is not as specified.**	• Check piston rod packing for leaks and for blow by at gland. Repair or replace as necessary per manufacturer's manual. • Inspect lubricant scraper rings for leakage. Replace as necessary per manufacturer's manual. • Inspect air intake filter. Clean or replace as necessary. • Drain lubricant strainer/filter sediment. • Lubricate unloader mechanism per manufacturer's manual. • Check motor amperes (amps) at compressor full capacity and pressure.	• Perform valve inspection per manufacturer's manual. • Inspect cylinder or cylinder liner, through valve port, for scoring. • Change crankcase lubricant, if required. • Clean crankcase breather, if provided. • Change lubricant filter element. • Remove and clean control air filter/strainer element. • Check all safety devices for proper operation. • Perform piston ring inspection on non-lubricated design. Replace as necessary per manufacturer's manual. • Remove and clean crankcase lubricant strainer

Routine Maintenance for Lubricant-Injected Rotary Compressor		
• **Monitor all gauges and indicators for normal operation.** • **Check lubricant level and top off as necessary.** • **Check for lubricant leaks.** • **Check for unusual noise or vibration.** • **Drain water from air/lubricant reservoir.** • **Drain control line filter.** • **Weekly** • **Check safety valve operation.**	• Service air filter as needed (daily or weekly if extremely dusty conditions exist). • Wipe down entire unit to maintain appearance. • Check drive motor amps at compressor full capacity and design pressure. • Check operation of all controls. • Check operation of lubricant scavenger/return system. Clean, as necessary.	• Take lubricant sample. • Change lubricant filter. * • Periodically/Annually • Go over unit and check all bolts for tightness. • Change air/lubricant separator. • Change air filter. • Lubricate motors per manufacturer's instructions. • Check safety shutdown system. Contact authorized service person.

Routine Maintenance for Lubricant-Free Rotary Screw Compressor		
• **Observe various control panel displays and local gauges to check that normal readings are being displayed.** • **Observations should be made during all expected modes of operation (i.e., full-load, no-load, different line pressures, and cooling water temperatures).** • **Essential readings of operating conditions should be verified and any necessary adjustments made.**	• Check/change lubricant charge and filter element. • Check/change air filter element. • Check/change sump-breather filter element. • Check/clean control line filter element. • Check/clean condensate drain valve. • Check condition of shaft coupling element and tightness of fasteners. • Measure and record vibration signatures on compressor, gearbox, and motor (optional). • Annual rebuilding of the inlet valve is normally recommended.	• Operate/test all safety devices. • Check/clean heat exchangers. • Check/clean blowdown valve. • Check operation of balancing switch/valve assembly. • Check/clean water regulating valve. • Check/clean check valve. • Check/clean galvanized inter-stage pipe work. • Check condition of isolation mounts under compressor unit and motor. • Check/clean strainer and check valve included in lubricant pump suction line, inside lubricant sump.

Routine Maintenance for Centrifugal Air Compressors		
• **Record operating air inlet, inter-stage and discharge pressures and temperatures.** • **Record cooling water inlet and outlet pressures and temperatures.** • **Record lubricant pressure and temperatures.** • **Record all vibration levels.** • **Check air-inlet filter differential pressure.** • **Check proper operation of drain traps.** • **Drain control air filter.** • **Check for leaks, air, water, and lubricant. Repair and clean as necessary.** • **Check lubricant sump level and adjust as necessary.** • **Check drive motor for smooth operation and record amps.**	• Check lubricant filter differential pressure. Replace element as necessary. • Check lubricant sump venting system. Replace filter elements as necessary. • Check operation of capacity control system. • Check operation of surge control system. • Check main-drive motor amps at full-load operation. • Check automatic drain traps and strainers. Clean and/or replace as necessary.	• Check air-inlet filter and replace element as necessary. • Take oil sample for analysis. Replace lubricant as necessary. • Inspect intercooler, aftercooler, and lubricant cooler. Clean and/or replace as necessary. • Inspect main drive motor for loose mounting bolts, frayed or worn electrical cables, and accumulated dirt. Follow manufacturer's recommendations, including lubrication. • Inspect main drive coupling for alignment and required lubrication. • Inspect gearbox for loose mounting bolts, vibration, unusual noise or wear and axial clearances per manufacturer's manual. • Check impeller inlets and diffusers for signs of wear, rubbing or cracking. • Check control panel for complete and proper operation. • Check all control valves for proper operation. • Check all safety devices for proper settings and operation. • Inspect check valve; replace worn parts. Keep all components/accessories clean and follow all recommended safety procedures.

Disclaimer : Please verify with the OEM manual in case if there is any specific recommendation from OEM and perform trouble shooting.

CHAPTER IX

LATEST TRENDS IN COMPRESSED AIR SYSTEMS

1. Aluminium Piping for Compressed Air Distribution

Air pipeline forms an integral part of the compressed air system, as it connects the generation and the distribution to the end-users of compressed air. Therefore, the selection that goes into consideration of pipeline material plays an important role.

MS piping is the most commonly used material in almost every industry. But it does have its limitations. To start off, the resistance of MS pipe to corrosion was lesser than compared to aluminium material. In circumstances when there are contaminants carried over into the MS pipeline, there is possible build-up over time. Technically, MS piping gets oxidized relatively faster than aluminium due to particles such as oil, water, etc. This further results in turbulent flow in the pipeline, which increases the pressure drop across the compressed air system. This in turn forces the operator to compensate for the loss in pressure and operate the compressor at a higher pressure, thereby consuming more amount of energy.

Figure 57: Aluminum piping

Aluminium piping finds success stories in automobile industries due to its advantages over conventional piping. A contrast between the MS piping, stainless steel piping and aluminium piping is illustrated below:

Table 23: Comparison of Aluminium piping with Carbon and SS Piping

Parameters	Carbon/MS Piping	Stainless Steel Piping	Aluminium Piping
Installation Time	Slow	Slow	Quick
Modifications	Hard	Hard	Easy
Modification Time	Long	Long	Short
Inner Roughness	1.9Qm	1Qm	0.2-0.4 Qm
Pressure Loss	Relatively large	Relatively large	Short
Leakage	10-30%	5-10%	Negligible
Long Term Corrosion	High	Normal	Very Low
Impact on air quality	Big	Small	No
Initial Investment	Low	High	High
Operating cost	Relatively High	Relatively High	Low
Weight	Relatively Heavy	Relatively Light	Light

In practical terms building an organization with wastage prevention, energy efficiency and scalability is the key for sustainable competitiveness in today's scenario. On the initial note the savings from properly designed compressed air production & distribution system is immense. We aspire to be your partner for the same.

The following are the features of Aluminium piping system

Feature	Description
Zero Leakages	The pipe and fittings are made of Aluminium, and the system ensures that there are no leakages from the piping and the components translating into a 10 years zero leak guarantee.
Corrosion resistant	The Pipe material has been engineered so as to counter the common problem of corrosion which results in scaling and porosity resulting in pressure drop and leakages.
Minimum Pressure Drop	Minimal pressures drop by the virtue of long lasting internal smooth surface (RA value: 0.3 Micron) of the pipe resulting in laminar flow as compared to the turbulent flow of the mild steel pipe material. This results in huge energy savings (6% per Bar of Δp).
Modular System	Aluminium Piping system is modular & scalable to keep up with industry's expansion plans and layout changes. Reusable fittings ensure Flexibility of piping layout and higher return on investment.

Description of the project

In a garment manufacturing company, the total power consumption for compressed air is 85 Lakhs per annum, who have installed traditional (GI) piping since 10 years. A feasibility study was conducted on their piping system and initial analysis indicated 35% energy saving potential.

The complete piping layout was modified to the modular aluminium piping system against traditional realized almost 30% of the power. The entire project took one month to complete.

Benefits

Details	Description	Value
Energy savings	energy reduction, Monetary benefit (Rs Lakhs)	30%, Rs.32,15,000 (62kw saving)
Other Savings, Benefits	Maintenance	Nil
Investment	Rs Lakhs	Rs.26 Lac
Payback	Months	15 months
Replication Potential	% of plants in the sector can opt for this technology	80%
Emissions reduction potential	Higher	

Other Benefits

- 100% leak free.
- No maintenance.
- 10 years guarantee for the products.
- ROI: Less Than 24 months.

Challenges faced during Implementation

- Shutdown required for replacing piping in compressor room.
- Mounting supports

Supplier Contact details for the project	
Name	Mr. Rajesh Natarajan
Designation	South India – Deputy Sales Manager
Contact number	+91-9677524417
Email – ID	rajesh.natarajan@airpipe.in
Address for communication	INSTAMOD AIRPIPE PRIVATE LIMITED 709, Shahpuri Tower,C-58, Janakpuri,New Delhi-110058 , +91 11 4953 5588

2. Supply Side & Demand Side Management of Compressor with Industry 4.0

Artificial demand is a common problem faced by every industry. Artificial demand is nothing but additional volume of compressed air required due to the unregulated use by the end-user. Fluctuating air pressure is caused by intermittent use of multiple pneumatic equipment, thereby affecting compressor performance. A sudden air demand causes pressure drop at the point of use. Air Compressors detects it only when it travels upstream through the distribution network. The response is to Load a Compressor or increase in speed by VSD in case of positive displacement Compressors and open the IGV in case of volumetric displacement Compressors, to meet the demand.

After the Compressor responds, it actually takes a while for the entire air system to attain the desired pressure. To overcome this lag in response time between Demand & Supply, compressed air system is maintained at higher level of pressure to meet the sudden demand, leading to "Artificial Demand" translating into inflated energy bills.

An engineering sector requires compressed air in various processes of engines & generator manufacturing. The daily energy consumption of Air Compressors was nearly 11,500 kWh/day. The plant team decided to reduce Air Compressors' energy consumption by cutting down artificial air demand, optimize the flow, stabilize compressed air pressure as well as automatically control the Air Compressors based on demand.

The details of the compressors installed in the plant is tabulated below:

#	Make	Model	Type	Qty	Motor, kW	Capacity, CFM
1	Atlas Copco	ZR132	Oil-free Screw	3	132	850
2	Atlas Copco	ZR132VSD	Oil-free Screw VSD	1	132	800
3	Hitachi Elgi	NH-135-7	Oil-free Screw	2	135	870
4	Hitachi Elgi	OF-265-7	Oil-free Screw	1	275	1659

The typically trend of the fluctuations in pressure is illustrated in the figure below:

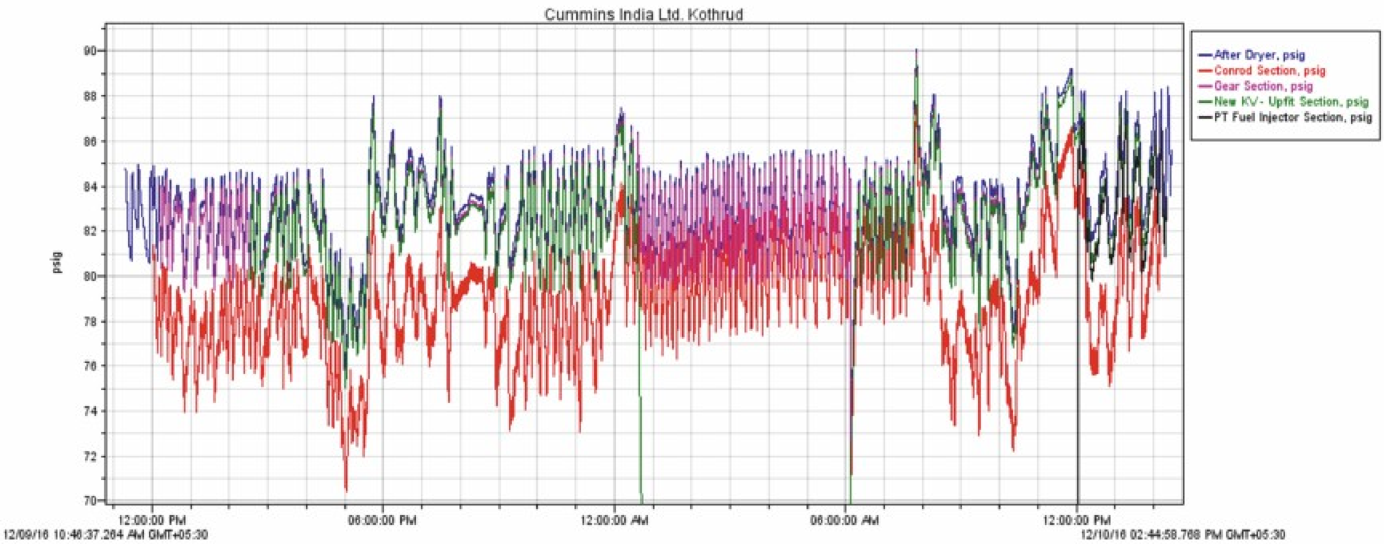


Figure 59: Demand Pattern

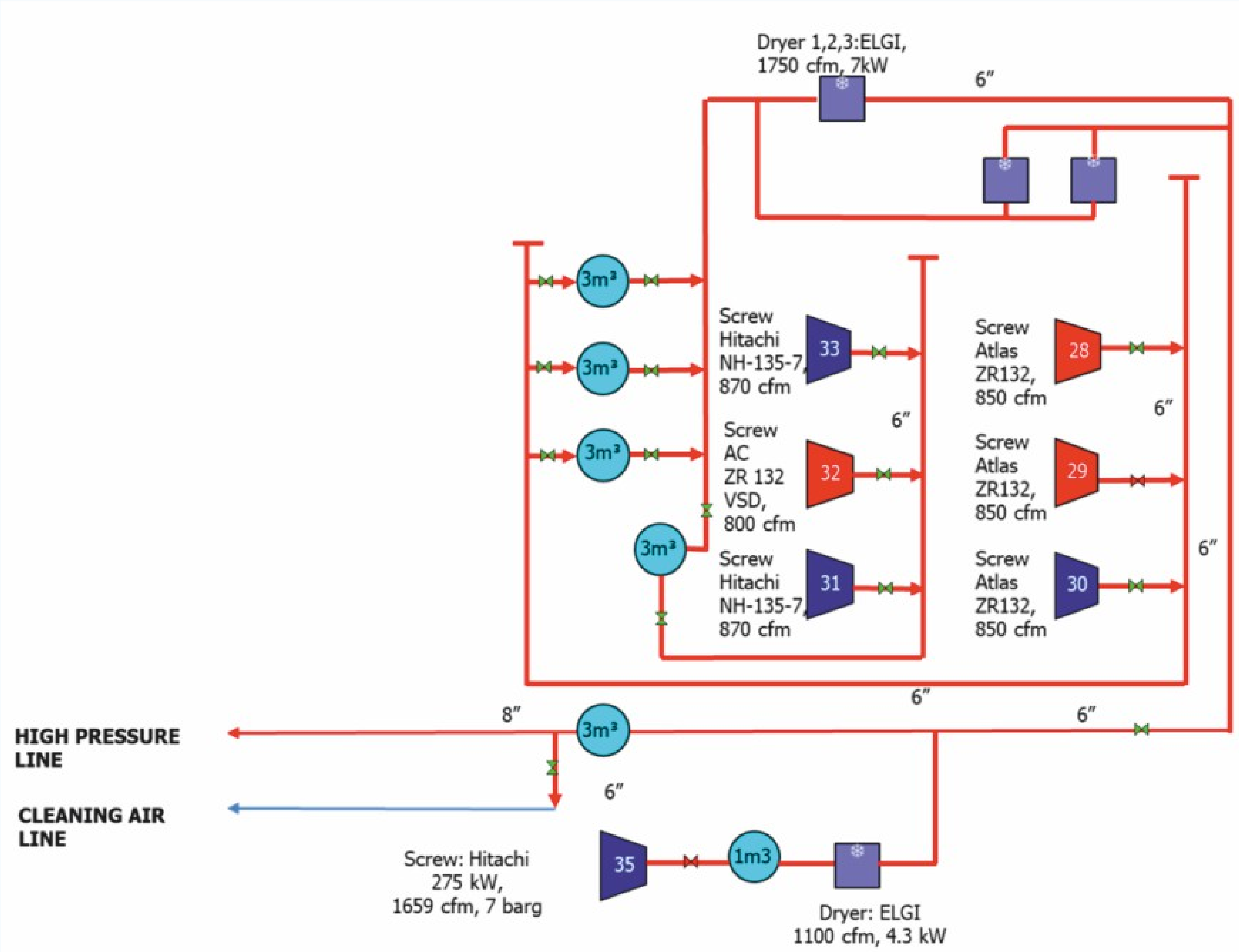


Figure 60: Compressed Air Layout of the plant

It was observed that pressure in the compressed air system was varying from 5 bar to 6.3 bar, which resulted in high artificial demand leading to increased energy consumption of Air Compressors.

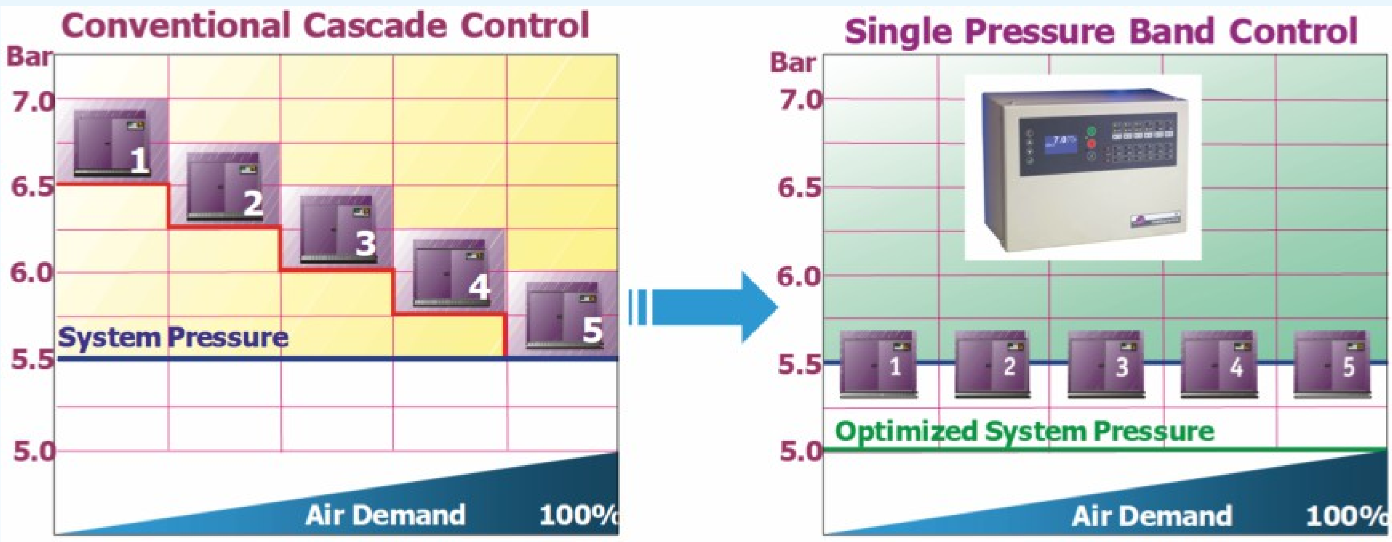
About the technology:

Demand Side Management Systems – reduces artificial demand by controlling the air flow & pressure being delivered to the plant. It is designed specifically to operate at an intermediate point of the compressed air system i.e. on the downstream side of the air treatment equipment and upstream side of the main piping distribution system. It creates useful storage by introducing a controlled differential pressure across an upstream receiver and itself. This storage isolates the Compressors from demand side fluctuations. Peaks are dealt with releasing the stored reserve energy instead of additional horsepower, facilitating the Compressors to run on reduced load. It also provides air at a controlled differential and optimum pressure to the plant, which reduces the mass of air consumed by pneumatic equipment, tools & amount of leakages, which ultimately result in the reduction in energy consumed by Air Compressors.

Supply Side Management Systems – Conventionally, in a multiple Air Compressor system, the capacity control is achieved through individual band of cascaded Pressure settings. In case of fixed speed Compressors, Load & Unload pressure bands are individually set through Pressure Switch or Microprocessor Controller on each Air Compressor. Similarly, in case of variable speed Compressor, the RPM modulation Pressure is set for capacity control.

Thus, depending upon the experience & skills of the Compressor Room Operators, different combination of Air Compressors is run on day to day basis. However, this results in multiple pressure bands, depending upon which Compressors are set to meet the base load demand and which to meet the variable or trim load demand.

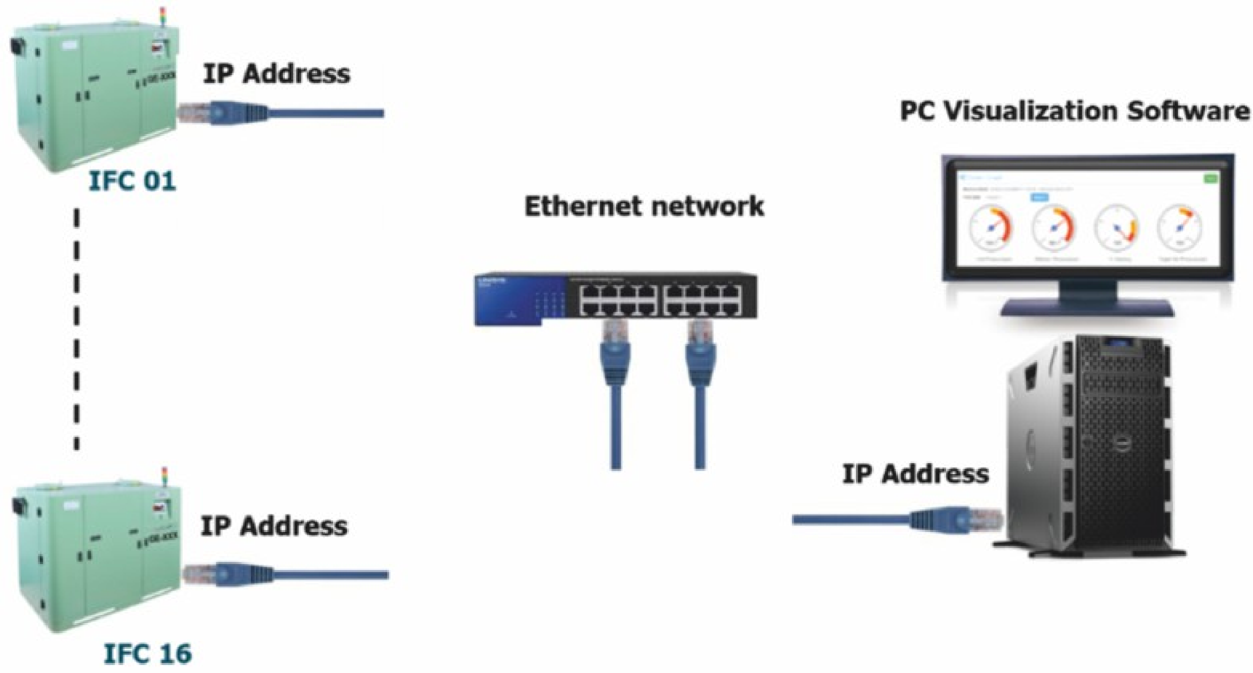
The Supply Side Control System manages up to 12 numbers of positive displacement (Screw / Reciprocating) Compressors of any brand & type, operating in a common compressed air network. ICC manages the fixed speed Compressors with Load / Unload capacity control and the variable speed drive (VFD) Compressors with RPM control. It is programmed for flow capacity and type of control of each Air Compressor at site during its commissioning.



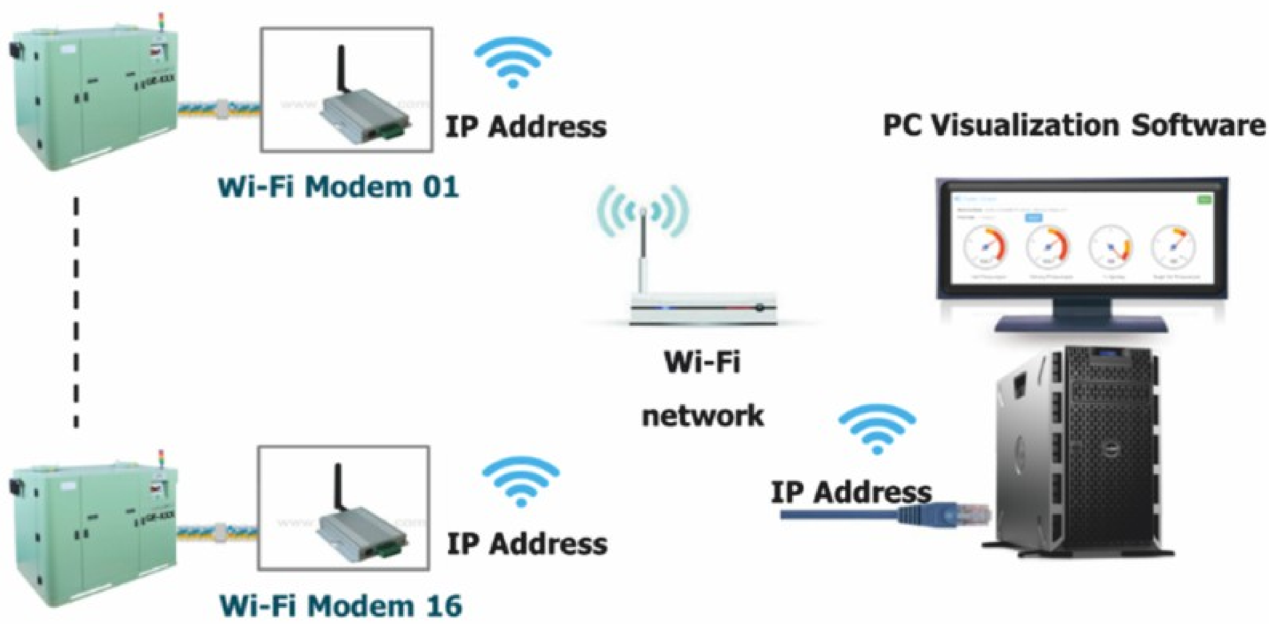
With accurate detection of air demand variation, a continuous feedback is provided to the internal control logic to select the best suited combination of Air Compressors to meet the air demand in a single target pressure control philosophy resulting in complete control of Air Compressors without human intervention. Additionally, this also results in efficient compressor usage & optimization by using the most efficient combination to suit a given demand.

Industry 4.0 – The Demand and Supply Side Controller is Industry 4.0 ready with RS-485, Ethernet, GPRS Modem, Wi-fi Modem for remote monitoring & control through PC.

- System Architecture For Wired Communication through Ethernet connection



- System Architecture For Wireless Communication through WiFi



The demand side and supply side controller is applicable in all manufacturing or process industry using compressed air; such as Automobiles, Cement, Electronics / Semiconductor, Engineering, Food & Beverages, Forging, Pharmaceuticals, Steel, Textile, Tyres and others.

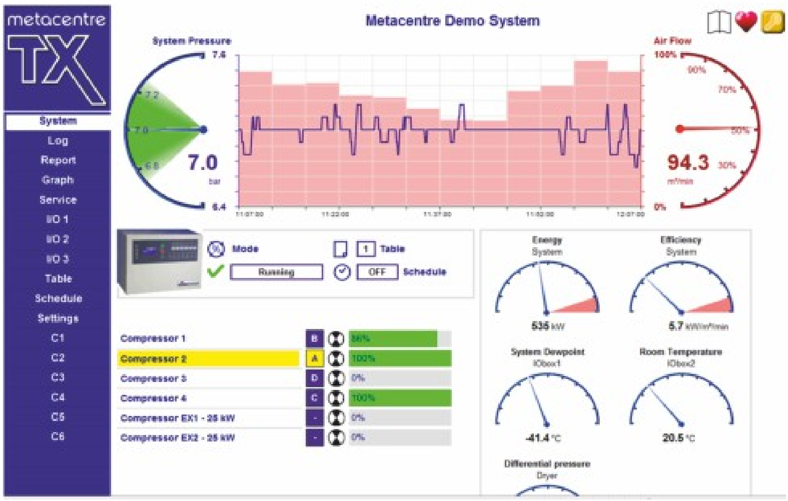
Remote PC Visualization & Monitoring of Air Compressors with Supply Side Management:

Remote PC visualization & monitoring of air the Air Compressors provides information such as online pressure trend at Compressor Room, status of individual Air Compressor, percentage load on every Air Compressor and overall system efficiency, etc.

Benefits:

The installation of demand side management has various benefits:

- Saves energy by reducing the additional loading caused due to artificial demand.
- Separates the demands fluctuations between the peaks and lows.
- Reduces the overall leakages in the plant.
- Maximizes the usefulness of air storage.
- Ensures consistency in delivery to downstream end-users.
- Is compatible with any compressor manufacturer.



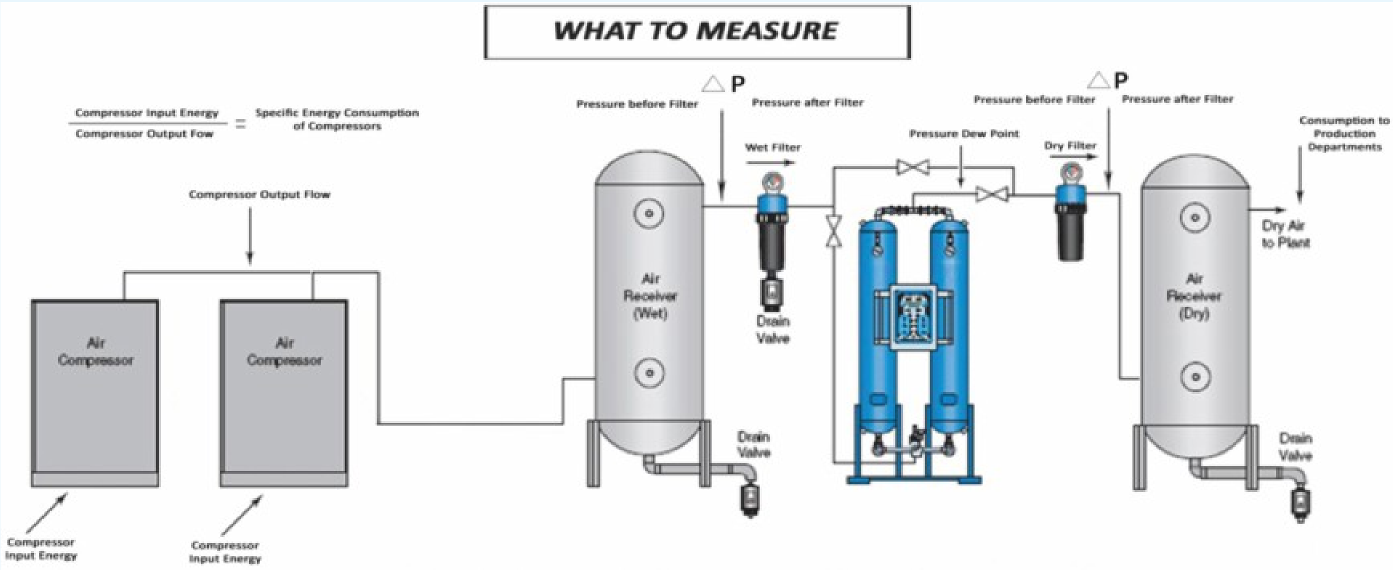
This combination of Supply & Demand Side Management Control Systems was estimated to provide energy saving of 14% and constant pressure to the Shops within +/- 1 psig (0.07 barg). The overall energy savings achieved is Rs 54 Lakhs, incurring an investment of Rs 40 Lakhs. The simple payback of the project was 9 months.

Supplier Contact details for the project	
Name	Godrej & Boyce Mfg. Co. Ltd.
Person to be contacted	Kiron C. Pande
Designation	Associate Vice President & Business Head
Contact number	+91-9820348824
Email – ID	casene@godrej.com; kcp@godrej.com
Address for communication	Automation & Energy Management, Electricals & Electronics Division, Pirojshanagar, Vikhroli, Mumbai 400079. India

3. Smart Monitoring System for measuring compressed air

While most of the end users measure the compressor's power consumption, the compressor's output flow remains unmeasured leading to factual errors in their assumptions about their compressor's specific energy consumption. The ambient conditions coupled with the inefficiency and tolerance factors that are built into a compressor can take a toll on its energy consumption and in times may increase the specific energy consumption even up to 30% of the compressor's claimed efficiency.

Hence consistent monitoring of a compressor's power consumption and discharge flow is the key to maintaining the supply side efficiency. Further a well-designed system should define the key performance indicators like flow, power, pressure, dew point and should be measured at the right locations to understand the overall system dynamics as shown below.



The supply side of the system when improperly aligned with the demand side will result in over compensation of system pressures and will increase artificial demand and related problems like,

- Higher air demand
- Higher leak rate
- Higher repair intervals and costs
- Higher energy bills
- Higher cost per product produced
- Less profits

An automotive component manufacturing plant was consuming almost 1300 CFM from 2 of their rotary screw compressors of capacity 850 CFM (132 kW) and 450 CFM (75 kW) respectively. On papers, these compressors were showcasing a specific energy consumption of 0.16 kW/CFM. The factory, in their efforts of reducing their consumption to 600 CFM, installed a smart monitoring system to measure the total volume of compressed air generated and consumed at different production departments. The smart monitoring system, when installed revealed that both the compressors put together were generating only 1120 CFM as against their rated capacity of 1300 CFM but were consuming close to 220 kW. Hence, the actual specific energy consumption of these compressors were at 0.196 kW/CFM, an increase of over 18 % from the manufacturer's claims.

Extensive service and maintenance were carried out at these compressors and the result, the specific energy consumption was reduced to 0.17 kW/CFM and the factory was able to realise a power savings of over 537 kWh per day.

On the demand side: The measurements also revealed that the assembly and curing departments were consuming close to 800 CFM as against their actual demand of nearly 300 CFM. The painting booth was also consuming close to 320 CFM as against the actual demand of only 50 CFM. With these data in hand, the factory optimised the operating pressures of the machines thereby eliminating artificial demand and saved close to 150 CFM and further reduced a volume of 350 CFM by repairing leakages.

The smart monitoring system was installed at this factory in 2015 and even after 4 years the factory continues to maintain the savings achieved and even has lowered their consumption to 560 cfm as against the post project consumption of 620 CFM. The factory also saved close to 60% in their spares costs since it avoided the purchase of huge spares which are usually listed out by external leak survey agencies during their surveys.

The RoI for this project for implementing the smart monitoring system was just under 6 months.

Supplier Contact details for the project	
Name	Systel Energy Solutions (India) Pvt Ltd
Person to be contacted	Mr Hidhay
Designation	Managing Director
Contact number	+91-9843128715
Email – ID	hidhay@systel.asia

4. Heat Recovery System for Air Compressors

It is a known fact that the end-user consumption is only 10-15% of the total energy used by an industrial air compressor. While some losses are avoidable in the form of leakages, distribution losses, and operation and maintenance practices, a major contributor to the loss is the heat dissipated through the lubrication oil during compression. The overall energy consumption, utilisation and losses are illustrated in the figure below:

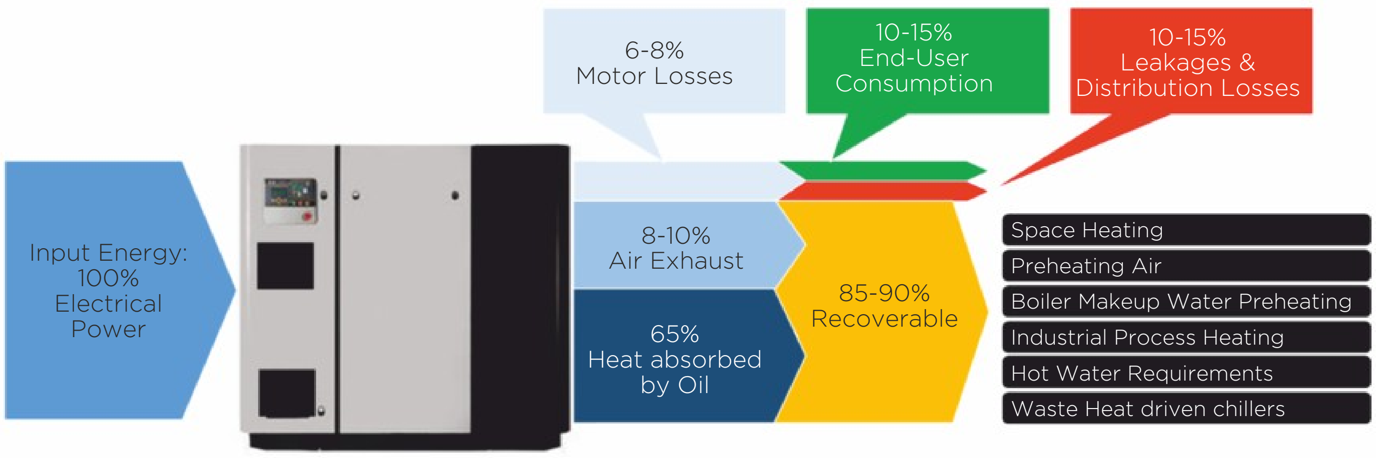


Figure 53: Heat recovery From air compressor

In order to understand why the heat is generated in an air compressor, we need to look at the laws of thermodynamics. During the compression process, the increase in the pressure of air increases the temperature, which is removed by the lubrication oil. This is necessary to ensure proper lubrication of the compression element, while also contributing to cool the compressed air. An added benefit is the improvement in air compressor equipment life and machine reliability.

As much as 85-90% of this heat can be recovered and made useful for various applications such as space heating, water/air preheating, process heating, etc. The remaining heat is unrecoverable in the form of heat carried away by compressed air or as heat radiated to the surrounding ambient environment.

Heat recovery technologies can help lower industry's energy costs incurred on heating systems which uses various energy sources such as natural gas, coal, or even electrical heating. This not only reduces the operating costs of the process, but also improves the energy efficiency levels of the industry.

On a commercial standpoint, heat recovery systems have an attractive payback, considering the purview of various dependent factors such as amount of heat rejected, loading on the compressor, demand for heat recovery applications, cost of alternative energy source, age and efficiency of existing technologies, etc.

About the technology:

The heat generated by the compression process is absorbed by the lubrication oil. Heat exchangers (e.g. plate type or shell & tube) are used for transferring the heat to the process fluid. As illustrated in the figure below, the water is pumped through the plate type heat exchanger, and heat from the lubricating oil is transferred to the water. The effectiveness of the heat exchanger is dependent on the area available for heat exchange, availability of heat, heat transfer coefficient of the heat exchanger and the properties (mass flow rate, density, specific heat, etc.) of the fluid to which heat is exchanged. The hot water, whose density is lower, rises to the top of the water storage tank, and the cold water at the bottom of the tank is circulated to the heat exchanger for gaining heat.

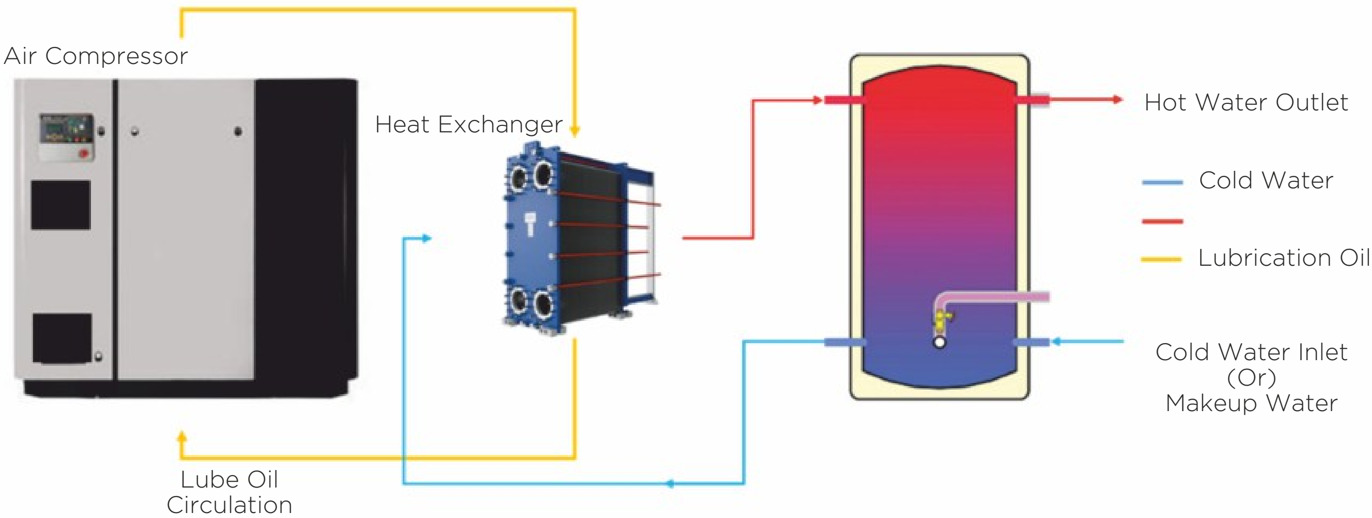


Figure 54: Block diagram for heat recovery

A similar system can also be designed for heating of air and obtain a temperature gain as high as 30°C, depending on the available heating capacity (kW) and the usable volume of heating air (m^3/hr). The energy saving potential obtained is the direct reduction in the fuel utilised for heating air or water to increase the sensible heat.

Implementation of waste heat recovery from air compressor results has resulted in cost savings of Rs 6.95 Lakhs, incurring an investment of Rs. 10.00 Lakhs. The simple payback for implementing the project was 17 Months.

5. Compressed Air System, Industry 4.0, & IOT

Internet of Things (IoT) is considered to be the primary driver of Industry 4.0. It is what we use to create "smart factories". Simply speaking, IoT enables all the equipment to communicate with each other by continuous monitoring, data collection, analysis and manage compressed air products.

Wouldn't it be easier and interesting to analyse all performance-based KPIs on the smartphone? Raw data from the compressed air system is processed into useful information to asses the performance of compressor, which helps optimize the overall operation of the compressed air system.

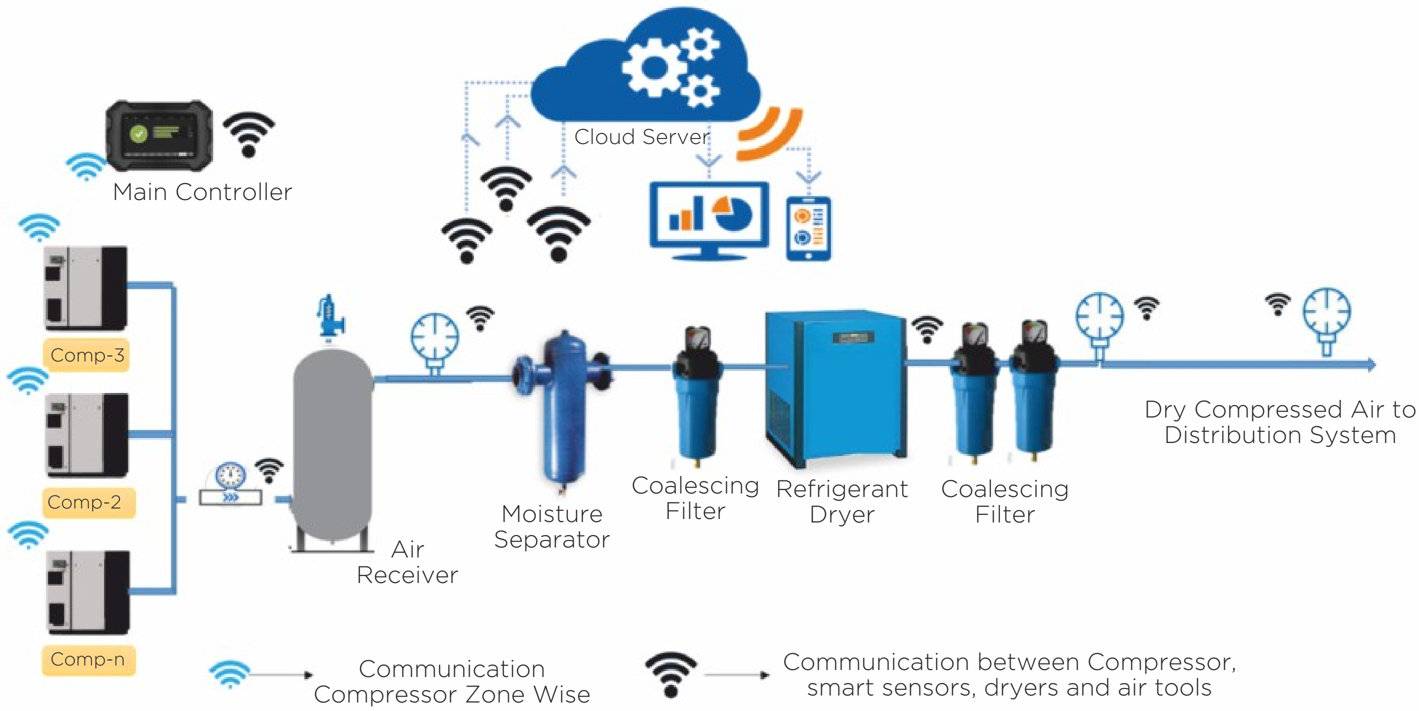
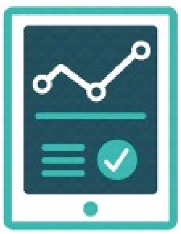


Figure 55: Industry 4.0 and IOT architecture in Compressed air system

Zone-wise compressor communicates to the master controller and the master controller decides the supply-side operation of the compressor, and sends the information to the cloud. The real-time analytics is processed in the cloud from information receive from the master controller of compressor, smart sensors, auxiliaries and air tools use. The processed analytic is useful for KPIs for compressor performance, analysing the real time leakage, flow requirement in each section, pressure drop. Thus, energy saving can be achieved through preventive strategy from the KPIs.

So, Industry 4.0 in the compressed air system can be useful in three distinct ways:



Smart Control & Optimization

- Evaluate and store SEC (kW/CFM) of all compressors.
- Operate the most efficient compressors.
- Analyse the compressed air demand.
- Sequence operation of compressors as per demand.
- Optimise and automate the operation of compressors.

Predictive Maintenance & Condition Monitoring

- Uses analytical techniques to reduce compressor downtime.
- Gather data related to condition monitoring without disturbing normal compressor operation.
- Condition monitoring of compressors includes imbalances, bearing issues, compression element issues, lack of lubrication, oil contamination, etc.
- PM reduces downtime, improves productivity, and improves equipment life & quality of operation.

Remote Monitoring

- Know the status of compressor operation – even on your smartphone.
- Control and optimization of operation – with the touch of a button.
- Consistency in data collection and analysis.
- Make more fully informed decisions.

6. **kVAr Compensation at Load-end for Air Compressors**

Inefficiencies are inherent in the electrical infrastructure in most, if not all facilities. These are mostly on of account of I^2R losses as the infrastructure is spread over a large area. Other causes of these inefficiencies are multiple termination points, oversizing of motors and voltage imbalances.

A kVAR compensator provides significant benefits by reduction of real energy (KW) consumption of 3%-5%, lower electric demand and a smaller carbon footprint. These savings are tangible and can be measured, verified and documented.

This technology is a customised power factor optimisation unit for individual loads designed to achieve maximum efficiency. KVAR units are designed to sense and supply reactive current locally and reduce reduces the current drawn from the meter across the infrastructure, thus maximising the savings on I2R losses.

Figure 66 kVAr sizing methodology

Figure 67 kVAr controller

Sizing kit is used to fix the kVAr requirement of motor and reactive power is pulled locally at the load end by the kit.

Advantages of KVAr Controller:

- KVAR provides energy savings of 4-10%.
- Direct and accurate input of reactive power on the load.
- Reduces the motor temperature thus extending its life.
- No maintenance is required.
- Transforms a conventional motor into to an efficient motor.
- Improves Power Factor.
- Reduces distribution losses across the infrastructure that translates into cost savings.
- Improves voltage regulation due to reduced voltage drop.
- Reduces carbon footprint.

In a leading manufacturer of pharmaceutical ingredients, a study was conducted with an objective to understand the site's operations and electrical infrastructure. The study inferred that that major power consumption was on account of Chiller & Brine Compressor Motor.

The kVAR compensation units were installed to optimize the motor loads in real time on the 350 TR chiller motor and realized energy savings of 4% on the chiller motors. Smart energy meter was connected to the isolated feeder for the chiller motor. Measurement & Verification (M&V) was successfully completed by logging the data for two weeks without kVAR compensation & subsequent two weeks with the kVAR compensation.

Table 24: Case Study of kVAR Controller on Compressor

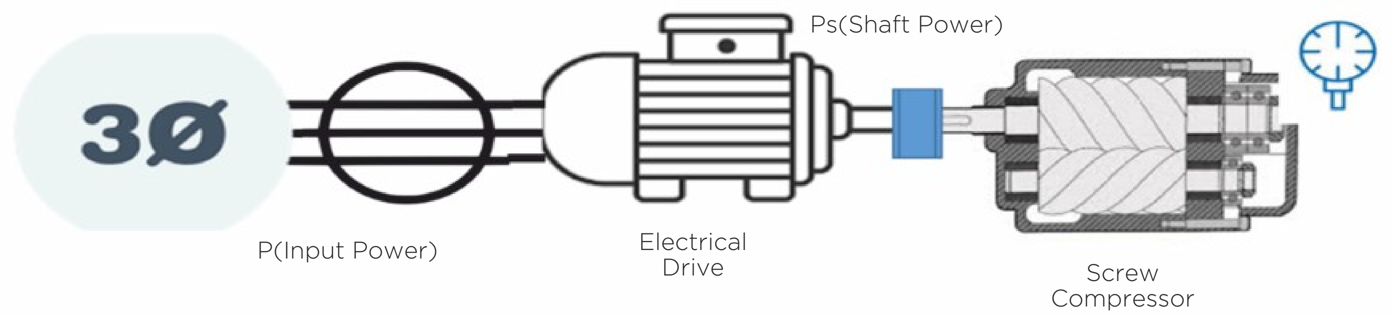
Details	Description	Value
Energy savings	1.32 Lakh kWh units of energy saved	INR 8 Lakhs Saved Per Year
	per year by implementing KVAR.	
Other Savings, Benefits	Reduced maximum demand	
Investment	Rs 10 Lakhs plus GST extra as applicable	
Payback	15 months	
Replication Potential	The technology can be replicated across any industry which is operating with low operating power factor at the drive end	
Warranty	Five Years from the date of Installation	

Supplier Contact details for the project	
Name	Athena Cleantech Private Limited
Person to be contacted	Mr. Sanjeev Reddy
Designation	Sales Head
Contact number	+91-9440259863
Email – ID	sanjeev@cleantech.com.sg
Website	www.cleantech.com.sg www.kvar.com
Address for communication	Plot No.03, Sri Sai Nest, New Bowenpally, Secunderabad - 500011

7. Energy Efficiency Motors (IE-4 Class)

Electrical motor plays an important role in compressor operation. The efficiency of electrical motor is an important parameter determining the input power (shaft power) to compression cycle. The more efficient the electrical motor, the lesser will be the losses and the better will be the operating compressor norms.

As IEC 60034-30-1
- IE1: Standard Efficiency
- IE2: High Efficiency
- IE3: Premium Efficiency
- IE4: Super Premium Efficiency



$$\eta\text{(Motor Efficiency)} = \frac{\text{Ps(Shaft power)}}{\text{P(Input Power)}}$$

Figure 62: Electrical Motor

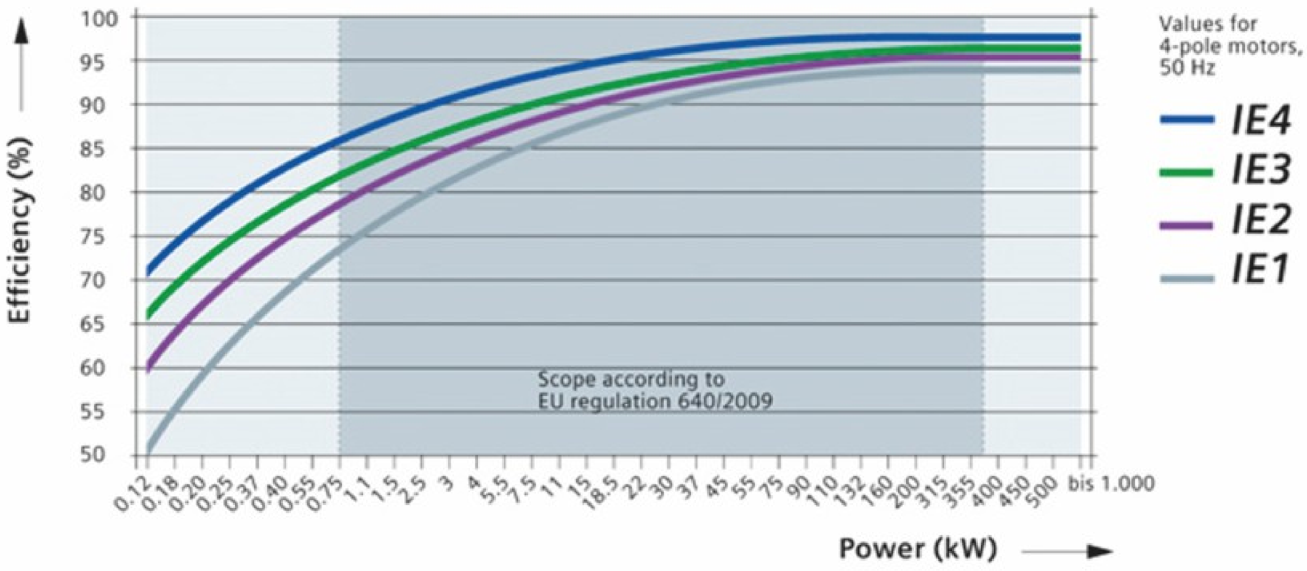


Figure 63: Efficiency classes IE1-IE4 according IEC 60034-30-1

To promote energy efficiency and reduce carbon emissions, the Government of India has phased out the use of IE1 efficiency class (standard motor) as per the Gazette of India dated 18th January 2017, called "Minimum energy performance standards for line operated 3-phase induction motors in India shall be IE2 class applicable from 1st Oct 2017".

Energy Efficient Motors:

- Increasing the mass of rotor conductors/ conductivity
- Precision air gaps to reduce current requirements
- Improved winding and lamination design to minimise power consumption
- Flat efficiency for loading between 50 to 100%

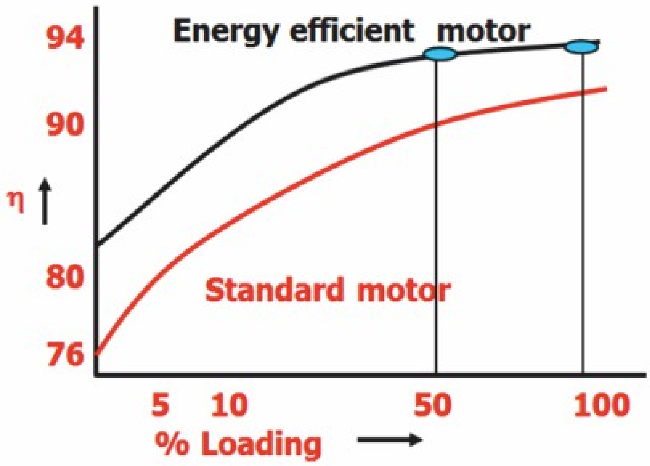


Figure 64: Efficiency Vs % loading

Benefits of IE4 Motors over other motors:

1. Low losses when compared to IE3/IE2
2. Energy savings
3. TCO2 reduction
4. Increased life due to less heating
5. More compressed air for less power.

8. Transvector Nozzle for Cleaning & Service Air Applications

Applications of service air for cleaning and de-dusting clothes is a common but unsafe and expensive practice in the industry.

Compressed air is used for unwanted usages like cloth cleaning during the brake time/shift changes, component cleaning, etc. Considering diameter of the hose pipe of 0.5" to 1", we can estimate the amount of compressed air utilised. This, in fact is constituted as artificial demand, which will induce additional loading on to the air compressor.

Therefore, transvector nozzles find applications in such instances, which can reduce the air consumed by conventional hoses.

Transvector Nozzle

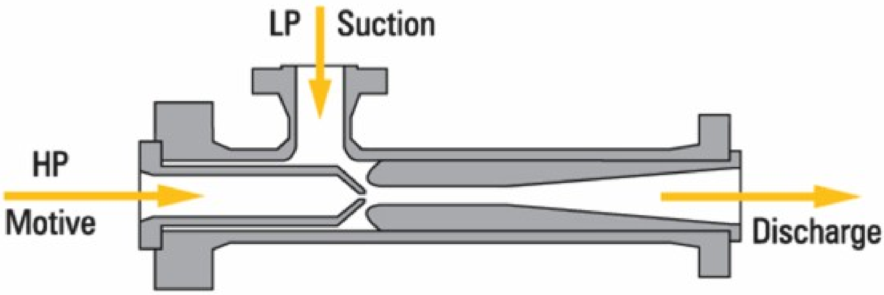


Figure 65: Transvector Nozzle

It works based on ejector principle. The operating principle of the ejector is that the pressure energy in the motive fluid (in this case, the compressed air) is converted to velocity energy by an adiabatic expansion in the converging/diverging nozzle (the transvector gun). Due to the pressure drop of the motive fluid, it will create a low-pressure zone before the mixing chamber. Due to the low-pressure zone, the suction fluid (in this case, the ambient air) will start to move toward it and mix with motive fluid in the mixing chamber. In mixed fluid, enter the diverging portion of the ejector where its velocity energy is converted into pressure energy. Thus, a mixture of compressed air and ambient air is delivered at discharge end at an intermediate pressure. The intermediate pressure and quantity of ambient air depends on the design of nozzle.

Advantages of Transvector Nozzles:

The installation of transvector nozzles will have the following advantages:

- Ability to suck in atmospheric air along with air jet.
- Reduces air consumption by up to 50%.

9. Cogged Flat-belt Drive Instead of V-belt Technology

All the reciprocating compressors utilise V-belt drives for power transmission. Use of V-belts is known to cause some energy losses. There is a power transmission loss of about 5-7% when the V-belts 'WEDGE IN' and 'WEDGE OUT' of the grooved pulleys.

The latest trend in the industry is to use synthetic flat belt drives or cogged belts in place of the V-belt drives. These belts have the following advantages:

* Non-hygroscopic – prevent elongation due to moisture absorption.

* Ensure better grip on the pulley.

* Energy savings of at least 5-7%.

Figure 68: V-belt Vs Flat Belt

Also, proper preventive care must be taken to ensure proper alignment between the drive and driven equipment.

The small bending cross-section of the flat belt causes little bending loss and only slight deformation work (flexing work). This fact, together with even running and the absence of pulley wedge effects, leads to a higher flat belt efficiency as opposed to the open-flank, toothed V-belt, in spite of the fact that the toothed V-belt referred to herein is the most efficient among the various types of V-belts.

Measurements taken at the Federal Corporation for Material Research and testing in Berlin (BAM) in this context showed the following relationships:

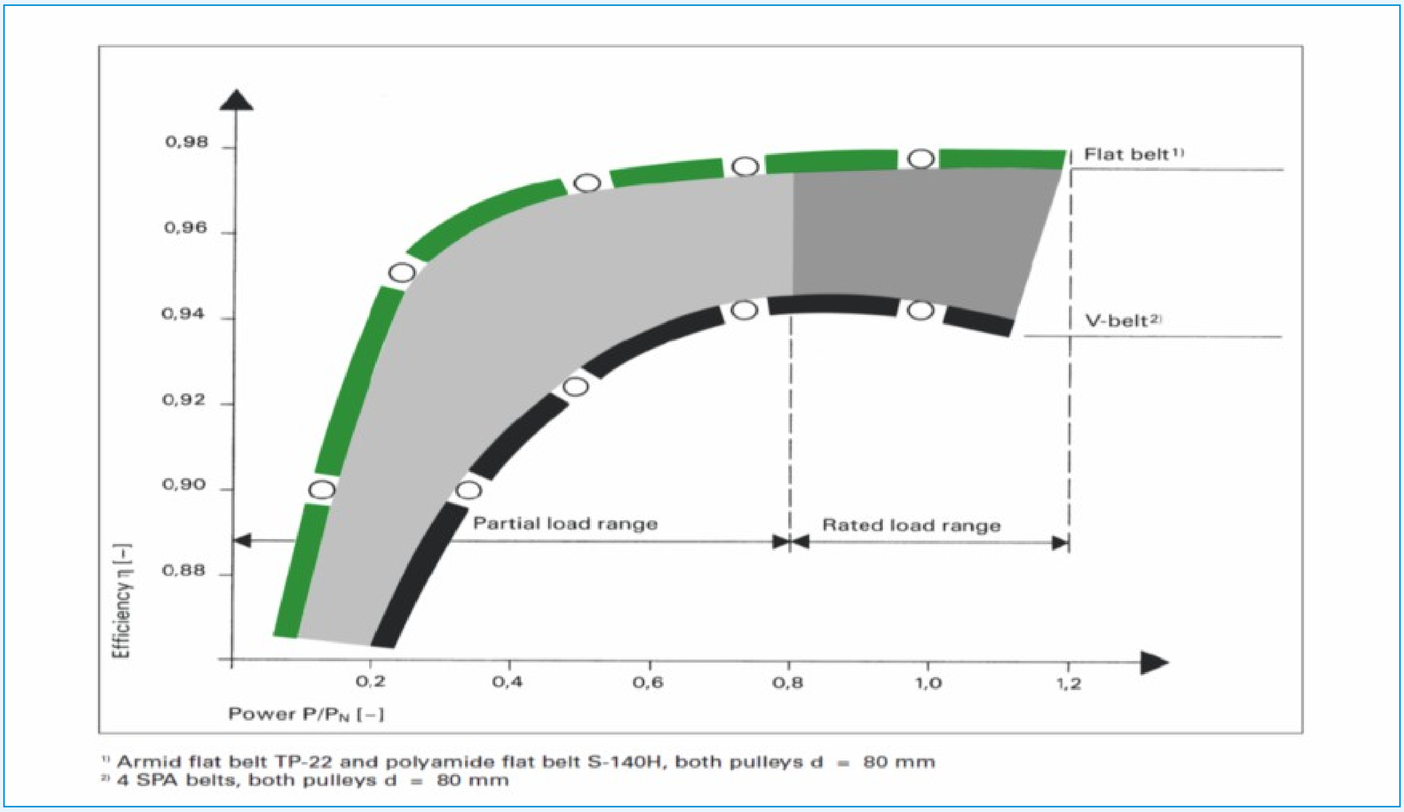


Figure 69: Efficiency Vs Loading

This illustration shows significantly higher flat belt efficiency across the entire operating range than that of the narrow V-belt. The maximum efficiency attained by the flat belt is 98%.

As the load decreases, there is an increasingly marked difference in efficiency in favour of the flat belt, which is about 3.5% in the rated load range, and may be as high as 10% in the partial load range.

Flat belts keep their uniform high-tension force throughout their service life and thus need little maintenance, whereas V-belts have to be checked and re-tensioned from time to time. In other words, once a flat belt drive has been correctly installed, it is maintenance-free (apart from usual control checks) and guarantees constant power transmission during its entire service life.

Instead of changing the pulley completely, to save on the cost of the pulleys, some companies have filled in the v-groves of the pulleys with resins.

a) During this process, the dynamic stability of the pulleys gets affected, leading to bearing failures when used even for a short time. Moreover, there is an increase in transmission losses and slippage occurrence because of the misalignment.

b) Also, filling the pulley groves and subsequent usage will actually increase the rpm of the driven equipment by 2-4%. This will result in increased shaft power requirement of the driven equipment to the extent of 6-12%, over shadowing the benefit of transmission efficiency improvement. This is the most common diagnosis found in the failed attempts of conversion of V-belts to flat belt drives.

The plant team converted the V-belt drives into flat belt drives for the list of identified compressors first in a phased manner.

REPLACE EXISTING COMPRESSORS WITH ENERGY EFFICIENT COMPRESSORS

A power plant requires a large volume of compressed air for instrumentation and service air. Service air applications include ash conveying and regular cleaning applications. The compressed air requirement varies with capacity of plant, i.e., CPPs or IPPs.

The following case study is typical IPP, where five compressors are installed to cater to the compressed air requirements in the plant. The rated capacity of each compressors is 87.6 m^3/min. Three compressors are installed for instrument air requirement (one operating and two stand-by) and two for service air requirement. The layout of the compressors is illustrated below:

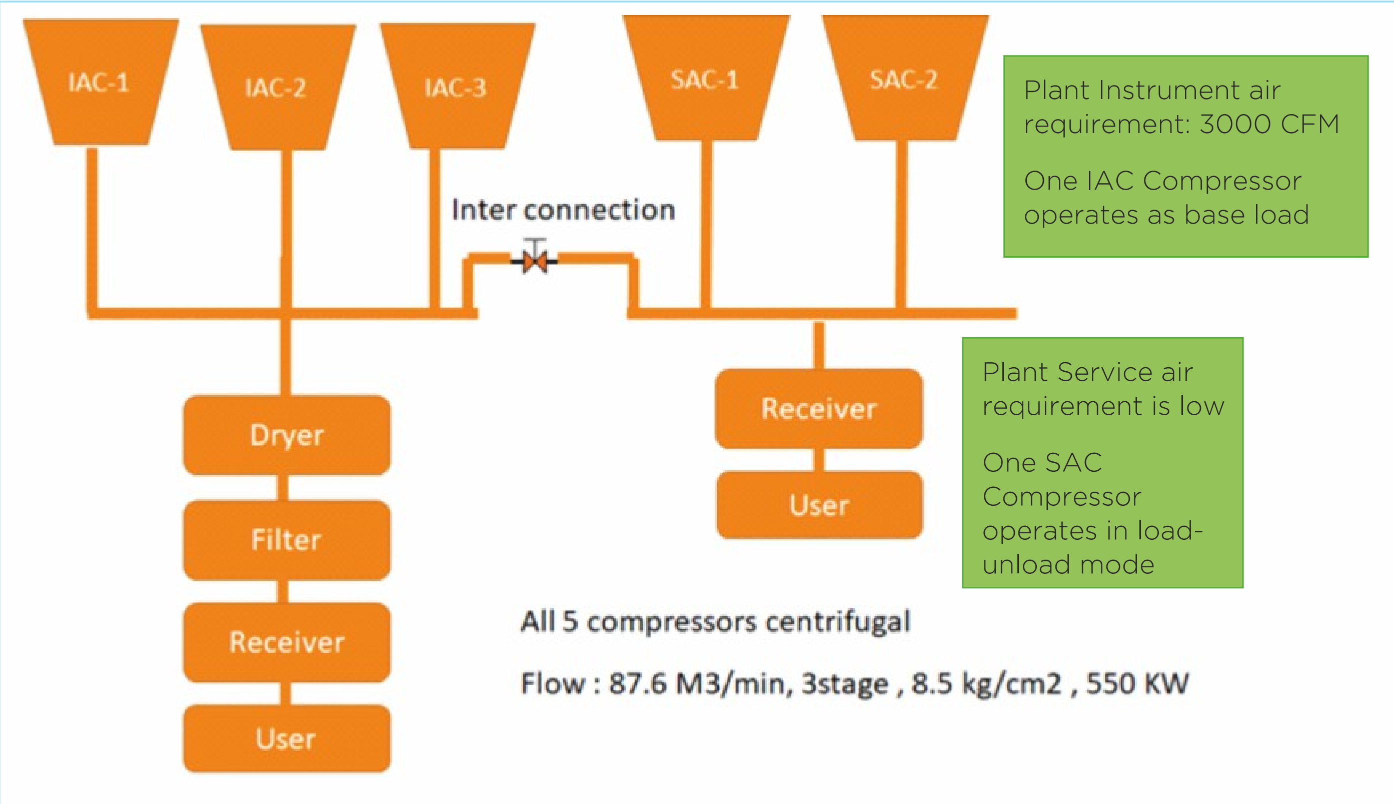


Figure 65: Centrifugal Compressor Installation in Power plant

A detailed assessment of the instrument air and service air compressors are studied to derive the specific energy consumption (kW/CFM) of each compressors. The results of the compressor performance assessment revealed the following:

Compressor Reference	Avg. Pressure (Operating)	Set pressure	IGV Position	By pass Valve Position	Power Consumed	FAD Results	kW/CFM
IAC-1	7.12	7.05	72%	0	498	2875	0.17
SAC-1	7.12	7.05	52%	20	429	332.1	1.5

To avoid unload operation of SAC compressor , the Service air demand for various load studied

- **For BTG:**
  - AHP cleaning- 3-4 kg/cm^2
  - Cleaning purpose –3-4 kg/cm^2
  - For Similar type of Capacity 300MW x2 -350 CFM
- **For DFDS System Air requirement:**
  - Compressed air requirement depends on the cycle time of FLS, type of nozzles used and number of systems installed
  - Approximate consumption 360 CFM

Total service air requirement is 700 CFM and is observed to be highly fluctuating in nature.

The plant team, after analysing the demand and its loading pattern, considering a buffer capacity of 300 CFM, installed a 160 kW, oil free screw compressor with VFD, of 1,016 CFM capacity, for service air demand, thereby achieving power savings of 200 kW.

The annual cost savings by replacing the existing compressors with energy efficient compressor is Rs 38.4 Lakhs. The investment incurred for energy efficient compressors is Rs 55 Lakhs, with a simple payback of 17 Months.

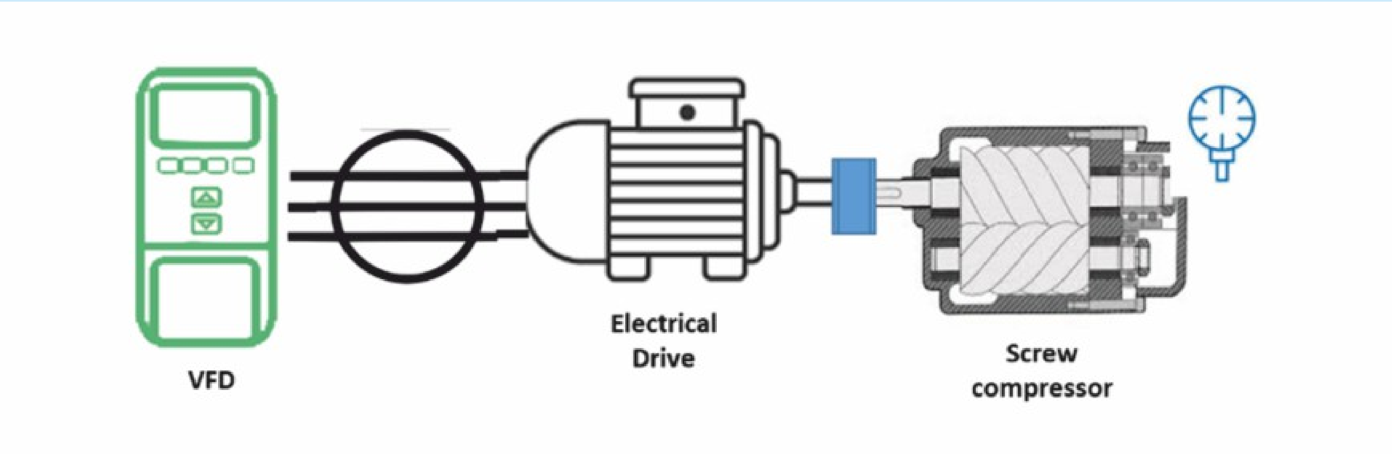


Figure 66: Screw Compressor with VFD

CASE STUDY 2 UTILISE SCREW BLOWERS INSTEAD OF COMPRESSED AIR FOR POT COOLING

A typical aluminium smelter consist of a series of aluminium smelter pot through which aluminium is obtained through redox electrolytic reaction of alumina.

The plant has centralized 9 HP centrifugal compressors of which 7-8 compressors are being operated based on the compressed air demand of the plant. Total HP compressed air consumption was estimated to be 54,920 CFM.

The following applications have been identified as users of HP compressed air in the plant:

1. Potline air consumption – 46,586 CFM
   a. Pot cooling lines – 95 numbers (current), which can increase by up to 140 numbers in summers
   b. Typical air consumption in one line – 70 CFM, total compressed air usage for cooling ~ 7000 CFM
   c. Alumina point break feeding
   d. Fume Treatment Plant – for bag filter purging
   e. Bulker unloading
2. Carbon plant air consumption – 4042 CFM ~ 0.5 compressors
3. Cast House air consumption – 2011 CFM ~ 0.25 compressors
4. Pressure Vessel – 2279 CFM ~ 0.28 compressors (alumina bags unloading)

Figure 67: Compressed air usage in pot cooling

The following are the pressure requirements in various sections:

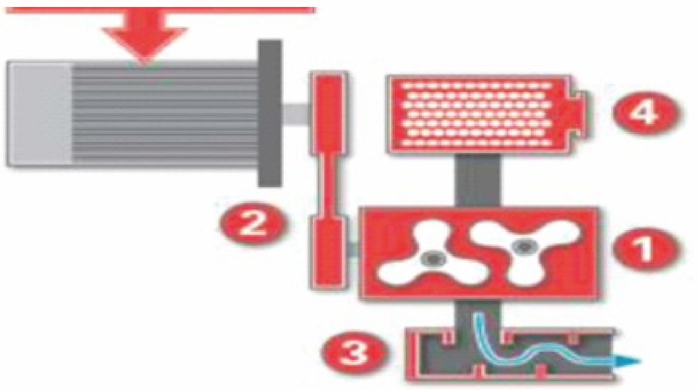
1. Pot cooling: 1200 – 1500 mmWC (cooling requires flow not pressure)
2. FTP Bag Filter Purging: 3 – 3.5 kg/cm^2
3. Bulker unloading: 3 – 3.5 kg/cm^2
4. Pressure Vessel: 3 – 3.5 kg/cm^2
5. All remaining areas: 4-5 kg/cm^2

Plant team observed from the above though Pot line cooling consumes 1200 – 1500 mmWC of air, while compressed air of 5 Kg/cm^2 is being used for pot cooling air is 7000 CFM (95 points).

In summers this requirement rises to as high as 10,000 CFM. There exists significant potential to reduce compressed air consumption by utilizing screw blowers instead of compressed air for pot cooling.

Screw blower technology:

Power Input



Working

4-1 : air enter the suction chamber

1-2 : Internal compressor of air between screw elements

2-3 : Discharged air.

Specific norms of screw blower: 0.03 KW/CFM

Figure 68: Screw Blower

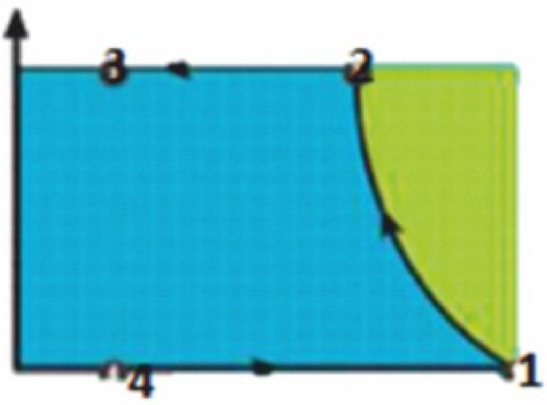


Figure 69: P V -Diagram

The plant team installed two screw blowers of 5,000 CFM (10,000 CFM) for pot cooling activity. This resulted in stoppage of one HP compressor. The overall energy savings achieved by the plant was 67.2 Lakhs kWh/year.

The annual cost savings by utilizing screw blowers for pot cooling is Rs 235 Lakhs. The investment incurred for screw blowers is Rs 120 Lakhs, with a simple payback of 7 Months.

CASE STUDY 3 UTILIZE LP COMPRESSORS FOR ALUMINA BAG UNLOADING, BAG FILTER PURGING AND BULKER UNLOADING

In a aluminium smelter plant, the following applications were overserved to be operating at various pressures requirements:

1. FTP Bag Filter Purging: 3 – 3.5 Kg/cm^2
2. Bulker unloading: 3 – 3.5 Kg/cm^2
3. Pressure Vessel: 3 – 3.5 Kg/cm^2
4. All remaining areas: 4-5 Kg/cm^2

It can be inferred that the applications such as alumina unloading (pressure vessel), bulker unloading and FTP bag filter purging are utilizing high pressure compressors. These applications can be operated with a low pressure compressor. The total compressed air requirement in these areas consumes operation of 1 High Pressure compressor.

There exists significant opportunity to utilize low pressure compressors in these areas to reduce the overall power consumption in the compressed air section.

Also, it was observed that Low-pressure compressors are being utilized for around 5-7 hours for rack unloading. And for the remaining period of time, LP Compressor were operated for the above-mentioned areas, which resulted in switching off 1 HP compressors for 17-19 hours a day.

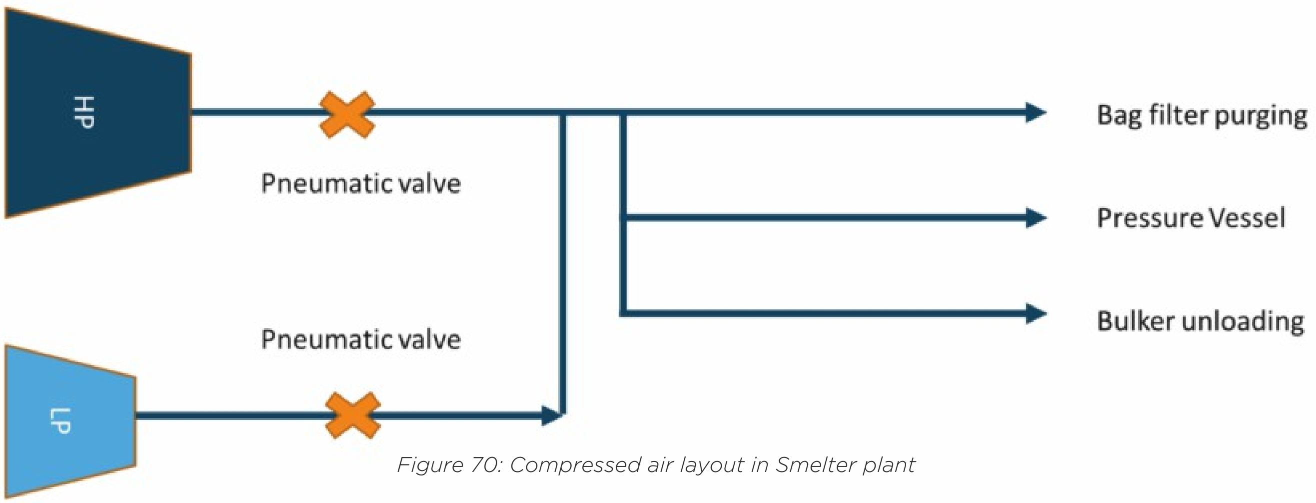


Figure 70: Compressed air layout in Smelter plant

The annual cost savings by utilizing LP compressors is Rs 104 Lakhs. The investment incurred for LP compressors is Rs 60 Lakhs, with a simple payback of 7 Months.

CASE STUDY 4 INTELLIGENT FLOW CONTROLLER (IFC) FOR THE PLANT COMPRESSOR NETWORK

In a 1200 MW (4 x 300 MW) power plant, it was found that the demand of compressed air was found to be fluctuating and power consumed by the compressors also increased due to the artificial demand.

The pressure study of the existing compressor network revealed that:

1. Out of 6 Nos. Atlas Copco ZR355 Instrument Air Compressors 3 Nos. of compressors operate to fulfil the plant requirement & the remaining are stand by. Of the three operating compressors, two operate at base load and one on part load.

2. The Modulating Compressor is loading and unloading between 7.0 to 7.5 bar.

Therefore, an Intelligent Flow Controller (IFC) for power plant compressor network was installed by the plant for reducing the instrument air losses and energy consumption of the compressors. To control this fluctuation, two IFC's, one at plant instrument air receiver outlet and the other at service air receiver air outlet were installed.

Now the air generation fluctuation pattern with IFC control at

1. Instrument Air IFC outlet pressure is 95 psig (6.5 bar) within +/- 0.2 psig.

2. Instrument Air IFC outlet pressure is 79 psig (5.4 bar) within +/- 0.3 psig

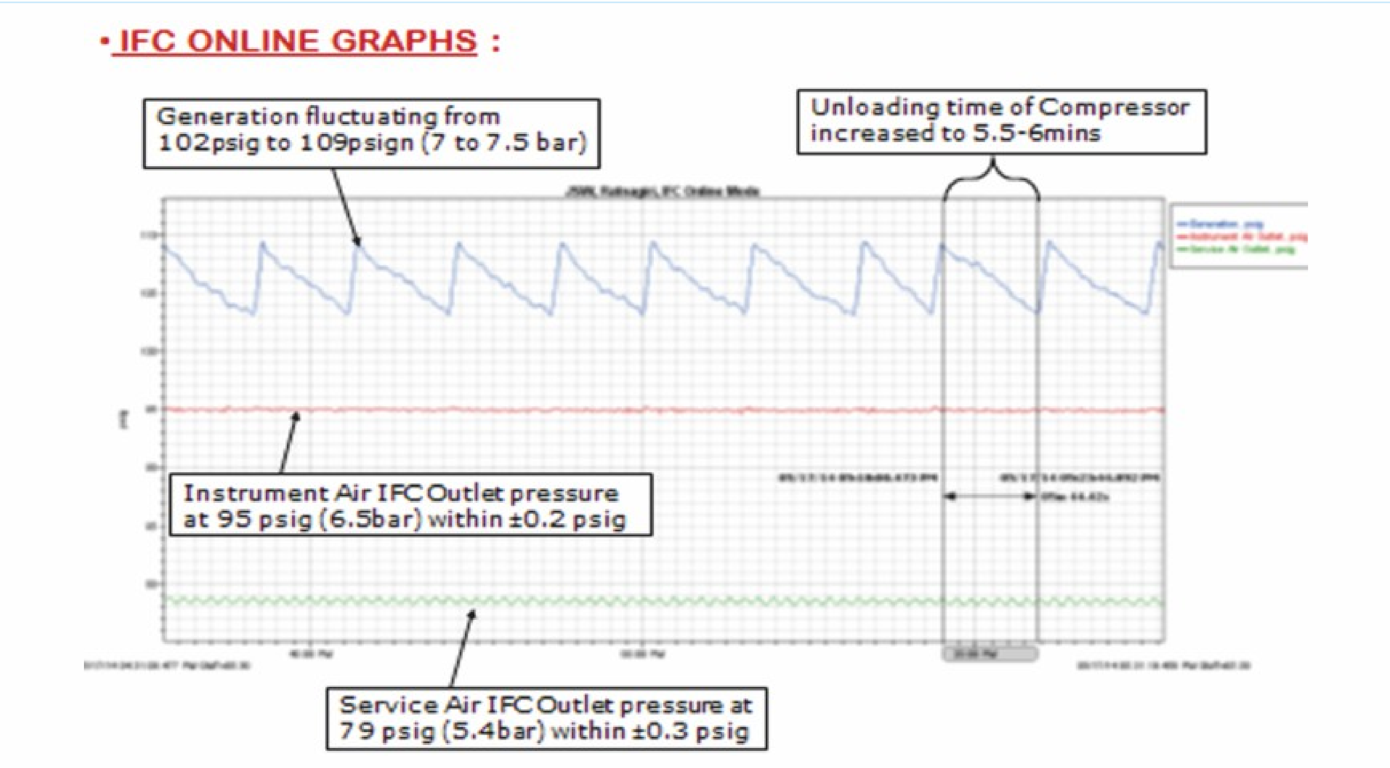


Figure 71: IFC Operation

Implementation of IFC control system resulted reduction in air generation fluctuation, by maintaining constant air pressure output at receiver outlet of Instrument and Service air.

The annual cost savings by installing an intelligent flow controller for the compressed air network is Rs 19.2 Lakhs. The investment incurred for energy efficient compressors is Rs 20 Lakhs, with a simple payback of 13 Months.

CASE STUDY 5 SEGREGATION OF HP & LP COMPRESSED AIR REQUIREMENT

In a hospital, three oil-free 45 CFM/ 11 kw reciprocating compressor are installed of which two are operating, and one in standby condition. A schematic arrangement and application of compressed air is illustrated in the figure below:

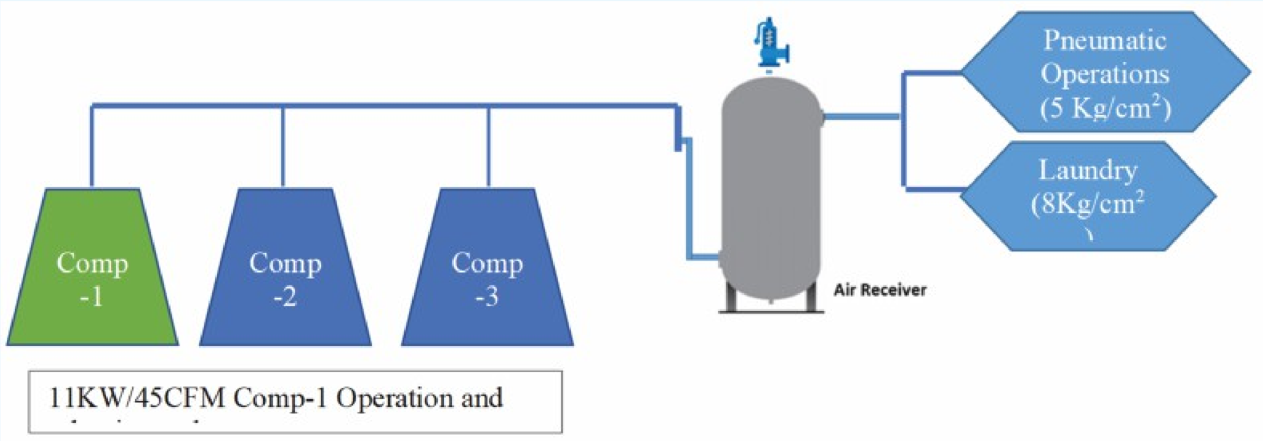


Figure 72: Compressed air layout in Hospital

- Switched on at 6 kg/cm^2
- Switched off at 8 kg/cm^2
- Entire system is maintained with pressure of 8 kg/cm^2

Pressure Vs Power Consumption

It is a known fact that at higher pressure, the power consumption of the compressor also increases. In any industry, the compressor is selected for the high-pressure requirement, though there are both high pressure and low pressure users.

While calculating the average compressed air consumption of the plant, the total requirement of Low Pressure (2.5 to 4.0 bar) and High Pressure (above 4.0 bar) compressed air has to be estimated. If any, say LP or HP air constitutes more than 30% of the average compressed air consumption, then a separate compressed air system is considered to be an energy efficient choice than operate the compressor at higher pressure for all applications. However, the segregation of HP & LP compressed air user has many advantages.

They are:

- Reduces the leakages proportionally, as the leakage levels are high at higher pressures.
- Reduces the overall operating cost. Say a 20 % reduction in pressure results in 20% reduction in power consumption of the compressors. Moreover, the wear & tear of the compressors are less at low pressures.

Hospital team identified significant potential to segregate the high-pressure users and low-pressure users and meeting the LP requirements using dedicated compressors for laundry press machine. Already a HP compressor is available, which can be used for laundry press application. The operating pressure of the entire centralized system was reduce in steps by 2 Kg/cm^2.

New set points

- Compressor are Switched on at 5 kg/cm^2
- Switched off at 6 kg/cm^2

The annual cost savings by segregating LP and HP compressed air requirements is Rs 0.64 Lakhs. Implementation of the project does not require any investment.

CASE STUDY 6

INSTALL STORAGE TANK FOR COMPRESSED AIR SYSTEM

In a cement plant, nine receivers are installed at pyro section and cement mill area out of which

- Four receivers at cement mill/ packing plant area
- Five receivers at pyro section
- Approximately 16.5 m^3 of receiver storage volume

An air receiver tank is an integral and important part of any compressed air system. In a compressed air system, a receiver tank provides the following benefits:

- The receiver tank acts as a reservoir of compressed air for peak demands.
- The receiver tank will help remove water from the system by allowing the air a chance to cool.
- The receiver tank minimizes pulsation in the system caused by a reciprocating compressor or a cyclic process downstream.
- To act as a second heat exchanger

Advantages of Air receiver

- They reduce cycle counts,
- They allow you to lower the pressure on your compressor because of stored energy,
- The stored air approaches the dryer at a lower temperature, thus increasing the efficiency of the dryer

To determine storage capacity required, the following table is referred by plant team:

- Installed additional receiver at User side generation side before and after dryer
- Approx. five nos. of 2m^3 receiver storage volume can be considered

Norm		
	kW	**m3**
	2400 kW	**100 m3**
Cemet Mill/PP Area	692	29
Pyro Section	315	13
	Total Reciever Vol.	**42**
As per BEE guidebook guidelines		
	min 1/10th	**max 1/6th**
Pyro	6	9
Cement Mill	8	14
	Total Reciever Vol.	**24**

The annual cost savings resulted by installation of storage tank is Rs 1.90 Lakhs. The investment incurred for the storage tank is Rs 3 Lakhs, with a simple payback of 19 Months.

CASE STUDY 7	REPLACE CENTRIFUGAL COMPRESSOR WITH AN ENERGY EFFICIENT CENTRIFUGAL COMPRESSOR

A pulp & paper plant operates 3 compressors i.e. one centrifugal compressor of 3800 CFM and 2 screw compressor of 1040 CFM each. The plant compressed air demand at any time is estimated to be approximately 4500 CFM. The compressed air is required for various pneumatic instrument and process requirement in the pulping, paper making and CPP section. The operating pressure at the common header is 6 bar.

The Centrifugal Compressor operating data is given below:

Specifications	Value	Units
Flow	2570	CFM
Power	558	kW
Specific Power	0.22	kW/CFM @ 6 bar
Volumetric Efficiency	68%	
IGV Position	100% Open	

Plant team installed an energy efficient centrifugal compressor with specific power consumption of 0.13 kW/CFM since the present specific power of the compressor is very high and the volumetric efficiency of the compressor is also very low. The specific power at present condition is 0.22 kW/CFM which is at higher side. An energy saving potential of 0.09 kW/CFM is achievable by replacing the existing compressor with energy efficiency centrifugal compressor. In addition, the volumetric efficiency will also improve thereby reducing the current CFM output requirement from the other screw compressor operating in line with the Centrifugal compressor to meet the demand.

The compressed air generation is reduced from the screw compressor will be 1229 CFM which in turn lead to savings in energy since the specific power of the centrifugal compressor is better than screw compressor.

Specifications	Value	Units
Flow	2570	CFM
Power	558	kW
Specific Power	0.22	kW/CFM @ 6 bar
Volumetric Efficiency	68%	
New Compressor		
Flow	3800	
Specific Power	0.13	kW/CFM @ 6 bar
kW Savings	223.90	kW
Net Savings	88.7	Rs Lakhs
Savings from reduction in Load From Screw Compressor	36.88	kW
Net Savings	14.60	Rs Lakh
Total Savings	103.27	Rs Lakh
Investment Required	150	Rs Lakh
Simple Payback Period	17.43	Months

The total annual cost savings by replacing the existing centrifugal compressors with energy efficient compressor is Rs 103.27 Lakhs. The investment incurred for energy efficient compressors is Rs 150 Lakhs, with a simple payback of 17 Months.

CASE STUDY 8

INSTALL NEW LOW-PRESSURE COMPRESSOR FOR FLYASH CONVEYING

In a cement plant, plant team conducted detailed study on the compressors utilized for supplying compressed air for fly ash conveying through the bulker unloading system.

For fly ash conveying in power plant, 2 nos. screw compressors are installed out of which one is running and one is on standby.

- Rated Capacity: 10.19 m^3/min @ 7.5 bar (HP Compressors)
- Average Operating pressure: 4.5 bar

Compressor Name	Running hours	Loading hours	Loading %	Unloading %
FA 1	7688	4503	58	42
FA 2	7979	5306	66	34

However, it was observed that, for bulker unloading, the consumption was regulated to 3 bar using a PRV. Nevertheless, the compressor was consuming energy to compress air up to 4.5 bar. Due to limitations of maintaining minimum pressure of 4.5 bar in the compressor, the plant team were unable to operate the compressor below 4.5 bar.

It was observed that

- Good potential to reduce the generation pressure
- Industry standard for fly ash conveying is at 3.0 kg/cm^2 bar – 0.08 kW/CFM

There is good potential for reducing the SEC of the compressors by replacing the existing compressor with new energy efficient LP compressor and isolate existing fly ash conveying system from other compressed air users, if any.

The annual cost savings resulted by installation of LP compressor for FA unloading is Rs 11.00 Lakhs. The investment incurred for the compressor is Rs 15.00 Lakhs, with a simple payback of 17 Months.

CASE STUDY 9 INSTALLATION OF ELECTRIC OPERATED HOIST INSTEAD OF PNEUMATIC OPERATED HOIST IN FETTLING SHOP

In an automobile plant, a study was done on compressors & compressed air system to identify the possible energy saving opportunities.

The plant team identified more than 20 nos. of pneumatically operated hoist installed in fettling shop. The required compressed air pressure is 6.0 kg/cm^2. Also, at many locations compressed air leakage was found to be significantly high in the compressed air distribution network connected to hoist.

When compressed air is utilized for pneumatic applications, from compressed air generation to end-use many energy transformations take place. i.e. (electrical energy to compressed air and then compressed air to mechanical energy)

In each stage of energy transformation, due to inefficiency of individual equipment certain amount energy is lost. This can be eliminated if electrical energy is directly utilized for producing mechanical work.

Pneumatic operated hoist more costly than electrical operated hoist. Pneumatic operated hoist consumes nearly 3 kW of electric power whereas electric operated hoist consumes nearly 0.75 kW of electric power for same size. Also electrical operated hoist required less maintenance as compared to pneumatically operated hoist. One disadvantage of using of electric operated hoist in sluggishness in response.

Plant team installed electric operated hoist in place of pneumatically operated hoist in phase manner and achieved significant reduction in overall compressed air consumption.

Figure 73: Pneumatic & Electric Hoists

The annual cost savings resulted by replacement of pneumatic hoists with electric hoists is Rs 40.00 Lakhs. The investment incurred for the electric hoists is Rs 30.00 Lakhs, with a simple payback of 9 Months.

CASE STUDY 10 OPTIMALLY UTILIZE THE COMPRESSOR DEPENDING UPON THE REQUIREMENT

In a textile industry, a screw compressor 600 CFM capacity is in continuous operation. Majority of compressed air users are pneumatic instruments, pneumatic valves and actuators. In addition to the above-mentioned users, compressed air is also utilized to remove the yarn whenever there is a yarn breakage.

During normal operation the quantity of compressed air requirement in the plant is about 100 CFM. But, whenever there is a yarn breakage, there is a sudden increase in quantity of compressed air requirement, which is as high as 500-550 CFM.

Since the compressed air requirement during normal operating condition is much lower than the installed capacity majority of time the compressor is getting unloaded. During unloading there is no useful work done by the compressor. The unload power consumption is used only to overcome the internal frictional losses.

Hence substantial energy saving can be achieved by minimizing / avoiding unloading of the compressor.

The operating parameters of the compressor during normal operating condition are as below.

Loading time %	Unloading time %	Load power kW	Unload power kW
17	83	108	38

The following measures have been taken up to minimize the unloading of the screw compressor.

- A reciprocating compressor of capacity 125 CFM was installed to meet the compressed air requirements during the normal operating condition.
- The screw compressor was kept as standby and given automatic starting facility based on the system pressure.
- Whenever the system pressure falls due to sudden use of compressed air for yarn removal, the screw compressor automatically started to meet the compressed air requirement.

A new reciprocating compressor was bought exactly to meet the actual compressed air requirement. The set point for automatic starting of the screw compressor was given slightly lower than the load pressure of the reciprocating compressor.

The plant team did not face any major problem during implementation. The project was completed within a week time.

Benefits:

The unload power consumption of the screw compressor was totally eliminated and resulted in substantial energy saving. The annual cost savings resulted by installation of project is Rs 7.44 Lakhs. The investment incurred is Rs 1.50 Lakhs, resulting in a simple payback of 3 Months.

CASE STUDY 11 REPLACE OLD INEFFICIENT COMPRESSOR WITH NEW EFFICIENT COMPRESSOR

Over a period of time the compressor operating efficiency comes down and the quantity of free air delivered reduces due reasons such as poor maintenance, wear and tear etc.

If the operating efficiency of the compressor is low the specific power consumption (kW/CFM) increases and hence the cost of compressed air increases.

Although, the quantity of free air delivered, operating efficiency and the specific power consumption of the compressor can be determined by carrying out a performance test, the specific power consumption increases by 25 - 30 % as compared to a new efficient compressor, it makes economic sense to replace the compressor with new efficient compressor.

In one of the cement industry a reciprocating compressor of capacity (Free air delivered) 34.32 m^3 / min was in operation. The normal operating pressure is 6.0 kg/ cm^2. Performance test was carried out and results are as follows:

- Actual free air delivered - 26.08 m^3 / min
- Specific power consumption - 6.82 kW/ m^3 / min

The specific power consumption was observed to be very high. Typically for reciprocating compressor the specific power consumption at an operating pressure of 6 kg / cm^2 would be about 5.5 kW/ m^3 / min.

The plant team did not face any major problem during implementation of the above project. The project was implemented in two weeks.

The performance of the compressor has to be monitored by carrying out performance test atleast once in 6 months. Any increase in specific power consumption is an indication of inefficient operation.

The reason for increase in power consumption should be identified and attended during regular maintenance.

There was a significant reduction in specific power consumption and hence the cost of compressed air. A reduction in specific power consumption of 1.2kW/m^3/min was achieved by replacing existing screw compressor with energy efficient screw compressor.

The annual cost savings resulted by installation energy efficient screw compressors is Rs 6.28 Lakhs. The investment incurred for the storage tank is Rs 6 Lakhs, with a simple payback of 12 Months.

CASE STUDY 12 INSTALL VARIABLE FREQUENCY DRIVE FOR THE SCREW COMPRESSOR WITH FEED BACK CONTROL

In cases where the installed capacity is more than the compressed air requirement, the compressors usually tends to operate in load-unload mode. During unloading, there is no useful work done, the power consumption is used to overcome only the internal frictional losses.

In screw compressors the unload power consumption can be eliminated by installing variable frequency drive with feedback control. The pressure sensor provided at the discharge side of the compressor continuously senses the pressure and sends signals to the variable frequency drive.

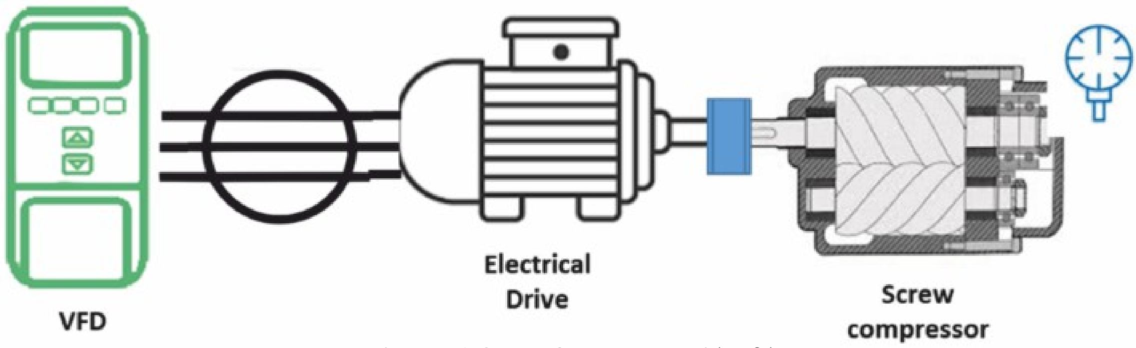


Figure 74: Screw Compressor with Vfd

The variable frequency drive varies the speed of the compressor to maintain the same set pressure and the unload power consumption of the compressor can be totally eliminated.

The other advantages of installing variable frequency drive are as follows:

- Using the variable frequency drive the operating pressure can be precisely controlled. There is no need to maintain a bandwidth as maintained in case of load / unload control. This leads to reduction in average operating pressure of the compressor and hence reduction in power consumption.
- The leakage in the compressed air system is proportional to the operating pressure. Since there is a significant reduction in operating pressure and hence significant reduction in leakage level.
- In addition, by using the variable frequency drive the V/F ratio for the motor can be precisely maintained. This leads to marginal improvement in operating efficiency of motor.

Previous status

In one of the process industry 4 nos of screw compressors of capacity 500 CFM each are in operation for supplying compressed air. Of the four compressors, three compressors are fully loaded and one compressor was partly loaded.

The compressor was loaded at 6.0 kg/cm^2 and unloaded at 7.0 kg/cm^2. An average operating pressure of 6.5 kg/cm^2 was maintained.

The unloading percentage of the compressor was about 50% of the operating time. The unloading power consumption of the screw compressor was about 27 kW.

The screw compressor, which was partly loaded was installed with variable frequency drive with feedback control. The unloading power consumption of the screw compressor was totally eliminated.

The operating pressure of the compressors was precisely set at 6.0kg/cm^2. Since the overall system pressure is reduced and reduction in power consumption is achieved in all the compressors.

When all compressors are in operation and connected to a common receiver, installation of variable frequency drive for one screw compressor is sufficient. This will take care of the fluctuation in compressed air requirement of the entire system.

For standby compressors, the VFD can be installed with change-over contactors, so that whenever change of compressor is required the VFD control can be changed to the compressor in operation.

The annual cost savings resulted by installation of VFD for screw compressor is Rs 10.83 Lakhs. The investment incurred for installation of VFD is Rs 12.00 Lakhs, with a simple payback of 14 Months.

CASE STUDY 13 REPLACE COMPRESSED AIR WITH BLOWER AIR FOR AGITATION IN EFFLUENT TREATMENT PLANT (ETP)

In effluent treatment plant, generally the agitation is carried out by supplying compressed air. The compressed air is tapped from the main header at normal operating pressure of 5.0-6.0 kg/cm^2.

For agitation, only the volume of air flow is the criteria not the pressure. The maximum pressure requirement is not more than 0.5 kg /cm^2. The effective agitation can be achieved by using blower air.

The comparison between the specific power consumption of compressed air and blower air is given below.

- Compressed air-16 kW/ 100 CFM
- Blower air-2 - 4 kW/ 100 CFM

Hence significant energy saving can be achieved by replacing compressed air with blower air for agitation applications.

In one of the engineering industry compressed air is utilized for the agitation application.

The compressed air is taken from the main header, which is at a pressure of 5.5 kg/cm^2. A control valve is utilized for controlling the pressure and supply compressed air to match with the requirement.

The quantity of compressed air utilized for agitation application is about 50 cfm.

A positive displacement blower of following specifications was installed.

- Capacity - 50 CFM
- Pressure - 0.5 kg/cm^2

Therefore, compressed air was replaced with blower air for agitation applications.

Figure 75: Air blower appilication in agitation plant

The annual cost savings by replacing compressor with blower for agitation is Rs 1.26 Lakhs. The investment incurred for new blowers is Rs 0.50 Lakhs, with a simple payback of 5 Months.

CASE STUDY 14 UTILIZE ELECTRICAL TOOLS IN PLACE OF PNEUMATIC OPERATED TOOLS BACKGROUND

Use of pneumatic tools is quiet common in engineering industry. Pneumatic tools require compressed air at a pressure of 5.5 – 6.0 kg/ cm^2. When compressed air is utilized for pneumatic applications, from compressed air generation to end-use many energy transformations take place. i.e (electrical energy to compressed air and then compressed air to mechanical energy)

In each stage of energy transformation, due to inefficiency of individual equipment certain amount energy is lost. This can be eliminated if electrical energy is directly utilized for producing mechanical work.

The theoretical estimation reveals that use of compressed air is about 25% costlier than direct use of electrical energy for producing mechanical work.

Previous status

In one of the engineering industry about 40 pneumatic grinders were utilized for the grinding application.

Compressed air at a pressure of 6.0 kg/cm^2 was being utilized for the pneumatic grinders.

Energy saving project

All the 40 numbers of pneumatic grinders are replaced with the electrical grinders. This has resulted in substantial energy savings.

While utilizing the electrical equipment for the grinding applications, the safety aspects have to be taken into consideration.

The project can be taken up in a phased manner for large installations. The plant team did not face problem in implementing the project. The project was implemented in a phased manner in two months time.

Figure 76:Pneumatic Grinder

Figure 77: Electrical Grinder

The annual cost savings resulted by replacing pneumatic tools with electric tools is Rs 6.50 Lakhs. The investment incurred for electric tools is Rs 11.00 Lakhs, with a simple payback of 21 Months.

CASE STUDY 15 REPLACE DESICCANT HEATER DRYER WITH HEAT OF COMPRESSION TYPE DRYER

In conventional desiccant dryers electrical heaters are utilized for heating the desiccant. In addition to the electrical heating, compressed air is utilized for purging and removal of moisture from the desiccant. Due to these two, a significant amount of energy is wasted.

Heat of compression dryer is a break-through in drying technology where the operating cost is zero or very minimal. Compressed air, directly from compressor discharge, which is at a temperature of 135°C (in the case of reciprocating compressor), is used to regenerate the desiccant. There are no electrical heaters and no purging loss. This makes the dryer very attractive in terms of operating cost.

The desiccant can be Activated Alumina or Silica gel depending on the dew point required. HOC dryers are available from 400 CFM to 5000 CFM capacity.

Figure 78: HOC Dryer

A process industry had an Adsorption type, heater reactivated dryer of capacity 50 m^3/min. The heater capacity for reactivation was about 32 kW. This apart, the dryer had a purge loss of about 10 %.

The plant team has replaced the heater reactivated adsorption type dryer with heat of compression type dryer.

Use of electrical heater has been avoided and there is no compressed air purge loss.

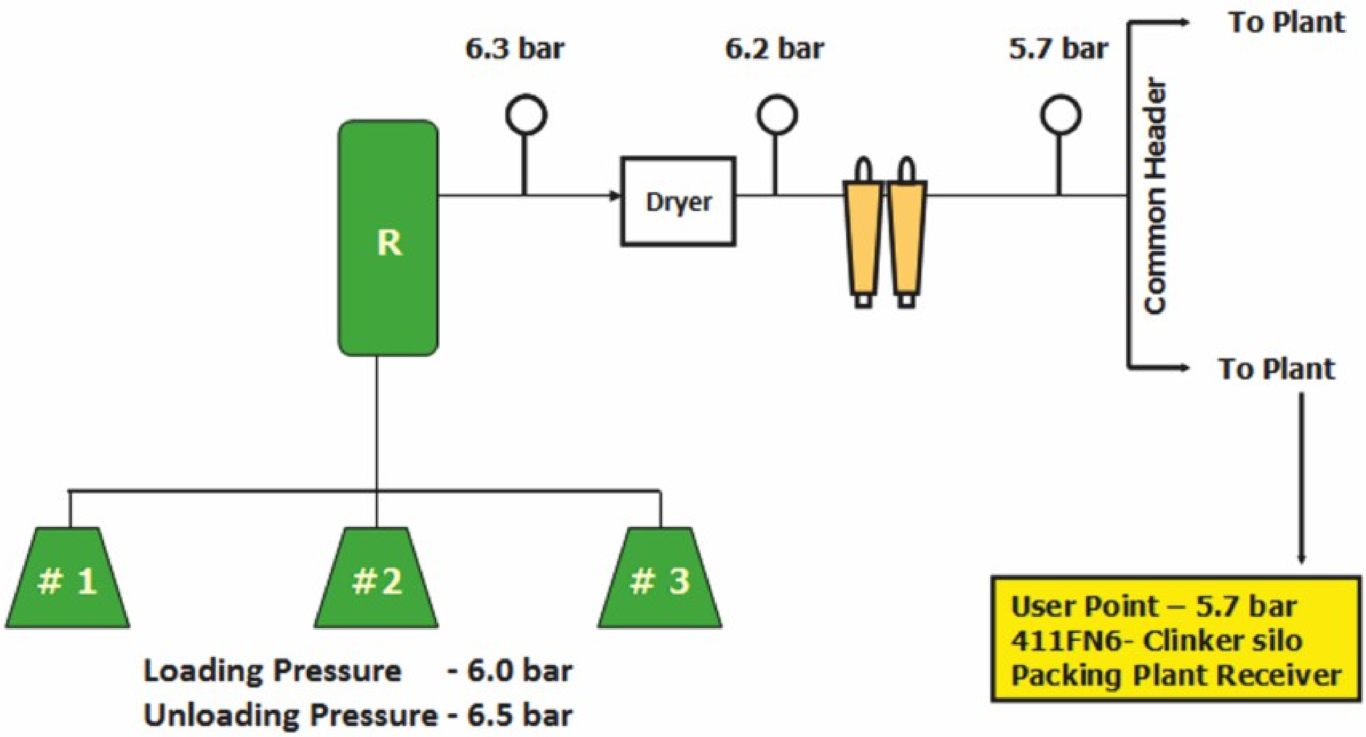
The following points have to be considered while selecting the HOC dryer for the drying application.

- Select the desiccant depending on the required dew point, life of desiccant and cost.
- If temperature (at the discharge of the compressor) of air is less than 135°C as in the case of screw compressors / centrifugal compressors, additional heaters are required for regeneration of desiccant.
- Since air carries some dust, two After-filters need to be installed, one being a stand-by.

The annual cost savings resulted by replacing desiccant dryer with HOC dryer is Rs 7.04 Lakhs. The investment incurred for HOC Dryer is Rs 14.85 Lakhs, with a simple payback of 25 Months.

CASE STUDY 16 REDUCE THE PRESSURE DROP ACROSS THE FILTER & OPTIMIZE THE PRESSURE SETTING OF THE COMPRESSORS

In a textile industry, three compressors are installed in the plant in which one compressor is operated for normal operation. The compressed air first goes to a receiver, then to dryer and through the filter to the end-user. The schematic diagram is shown below.



It was observed that the pressure drop across the generation point and common header is 0.6 bar. On taking a trial to bypass each component between the receiver and common header and the following conclusions are made.

- Pressure drop across dryer – 0.1 bar
- Pressure drop across filter – 0.5 bar

Considering that the design pressure drop across the filter should being maximum 0.1 bar, this indicates 0.4 bar additional pressure drop across the filter. It was also observed that the compressed air is passed through the dryer even though the dryer is not in operation which has resulted in additional 0.1 bar drop.

From the common header to the farthest user point the pressure drop is negligible which indicates the absence of line loss in the system. All the users of compressed air in the system are operating at a pressure of 5.7 bar.

Therefore, necessary maintenance of the filter was carried out and the dryer which is not in operation was also bypassed. This will result in pressure at the user end to be at 6.2 bar.

The plant team then reduced the pressure setting of the compressors so that the header pressure is maintained at 5.5 bar, with a pressure setting of Loading / unloading pressures @ 5.5/5.8 kg/cm^2. This resulted in a direct power saving as compressor operating power is proportional to the generating pressure.

The annual cost savings resulted by reducing pressure drop across air dryer is Rs 2.20 Lakhs. No investment is required for implementation of the project.

CASE STUDY 17 UTILIZE BLOWERS IN PLACE OF COMPRESSORS FOR SILO/HOPPER AERATION

Present Status

In a cement industry, one reciprocating compressor in operated for the purpose of aeration in a blending silo. Upon studying the compressors used for aeration, the following observations were made by the plant team:

- Operating pressure : 0.8 bar
- Operating flow : 1766 CFM
- Operating kW: 120 kW
- Operating SEC: 0.06 kW/CFM

Moreover, the various pressure requirements during the process were also observed based on the gauge pressure and are as follows:

- Maximum Pressure: 1.5 bar
- Minimum Pressure: 0.4 bar
- Average Pressure: 0.8 bar

Typically, in applications such as silo aeration the volume of air plays an important role than the pressure, whose requirements can be taken care by a blower of 0.8 bar pressure.

A significant energy saving potential was realized by installing an energy efficient centrifugal blower in place of the compressor with design specifications as mentioned below:

- Design Pressure: 1.5 bar
- Design Flow: 1800 CFM
- Design Power: 112 kW

The running specifications for the same blower at the 0.8 bar pressure are mentioned below:

- Designed Flow: 1800 CFM
- Designed kW: 70 kW
- Designed SEC: 0.04 kW/CFM

The rated power consumption for the blower is 70 kW for the same operating conditions in comparison to 120 kW by the compressor, thereby achieving energy saving of 50 kW.

The annual cost savings resulted by utilizing blowers for silo aeration is Rs 24.00 Lakhs. The investment incurred for installation of blowers is Rs 45.00 Lakhs, with a simple payback of 23 Months.

CASE STUDY 18 UTILIZE A DEDICATED LOW PRESSURE COMPRESSOR FOR KILN BAG HOUSE PURGING APPLICATION

A comprehensive study was done on compressors & compressed air system in a cement plant to identify and segregate compressed air applications of high pressure and low pressure.

A high pressure screw compressor is operated for the purpose of kiln bag house purging application. It was observed that the pressure requirement near the user was regulated to < 3.0 bar while the generation pressure from the compressor is 6.7 bar.

The reduced pressure is to extend the life of the bag house. The compressed air line from the compressor to the bag house was also studied; it was observed that the PRV was installed in the line for reducing the generation pressure to the optimum user pressure. The compressor consumes more energy to generate high pressure which is later being reduced to a low pressure of 3.0 bar at the user after the PRV. So the work done in generating high pressure is wasted by employing the PRV as the pressure requirement is less.

Due to an inherent limitation of a screw compressor (rated pressure of 7 bar) to operate less than 4.5 bar, the plant team connected the kiln bag house purging line with the main plant header and used a PRV to regulate the pressure to 3 bar.

A new low pressure compressor was operated dedicatedly for kiln bag house purging. The PRV in the line was bypassed and the average pressure delivery from the new LP compressor was set at 3 bar. The specifications of the new LP compressor are as follows:

- Compressed air Flow : 400 CFM
- Maximum Pressure : 3.5 bar

The annual cost savings resulted by utilizing LP screw compressor for bag house purging is Rs 17.20 Lakhs. The investment incurred for installation of LP Compressor is Rs 33.00 Lakhs, with a simple payback of 23 Months.

RULES OF THUMB

POWER AND INSTALLATION

- For every horsepower, a compressor delivers 4-5 CFM (m^3/hr), at 100 psi (7 bar) pressure.
- A 50 HP air compressor can produce up to 45 litres of water per day (with only 8 running hours daily).
- Air receivers should be sized about 15 litres capacity for each CFM of compressor capacity. That's 9 litres per m^3/h in metric units. For example, a small 200 CFM compressor needs a $3m^3$ air receiver.

COSTS AND ENERGY SAVINGS

- Reduction of 1 Kg/cm^2 air pressure (8 Kg/cm^2 to 7 Kg/cm^2) would result in 9% input power savings.
- Compressed air leak from 1 mm hole size at 7 kg/cm^2 pressure would mean power loss equivalent to 4500 kWh per year.
- Compressed air leakage quantity can be as low as 8-10%
- Optimum pressure drop between generation and end user point can be less than 0.5 bar
- Maintaining intercooler performance can save 7% power on compressor
- Every 4°C rise in inlet air temperature of compressor results in a higher energy consumption by 1% to achieve equivalent output.
- Recommended compressed air outlet temperature after intercooler is ambient temperature +20°C
- Minimum quantity of Cooling Water required (in litres per minute) is 2.85 m^3/min for a single stage compressor operating at 7 bar pressure
- Transvector nozzles can reduce power and save compressed air up to 50%. A two stage reciprocating air compressor is about 15% more efficient compared to a single stage unit.

TEMPERATURES

- The typical discharge temperature of a rotary screw compressor (before aftercooler) is: 80°C
- The typical discharge temperature of a single stage reciprocating compressor is: 135°C
- The typical discharge temperature of a two stage reciprocating compressor is: 120°C
- In rotary screw compressors, every 10°C above 95°C reduces the compressor oil life by 50%

GLOSSARY

Absolute Pressure	Pressure which is zero-referenced against full vacuum. It is the sum of gauge pressure (Pg) and atmospheric pressure (Patm).
Absolute Temperature	Temperature measured with reference to absolute zero in Kelvin.
Absorption	The process by which a desiccant melts and changes to liquid phase by absorbing the condensed moisture in the compressed air.
Actual Capacity	Quantity of air/gas actually compressed and delivered under rated conditions. Also referred as Free Air Delivery (FAD). Indicated as acfm.
Adiabatic Compression	Increase in the internal energy of air through external work done (by compressor) without any exchange of heat with the air.
Adsorption	The process by which a desiccant with a highly porous surface attracts and removes the moisture from compressed air.
Aftercooler	Heat exchanger used to reduce the temperature of the discharged compressed air. Cooling is usually done by supplying cooling water into the heat exchanger.
Air Cooled Compressor	Compressor cooled by forced air convection by using exhaust fans
Air Receiver	Vessel used for storing air/gas under pressure.
Atmospheric Pressure	The ambient pressure measured for a specific location (varies based on temperature, altitude or weather).
Automatic Sequencer	A programmed schedule to sequence the operation of compressors based on required variables (pressure, flow, etc.)
Booster Compressor	Machine used for compressing air/gas from an initial pressure (above the atmospheric pressure) to a higher pressure.
Capacity	Quantity of air flow delivered by the compressor under specified conditions, measured in cubic feet per minute (CFM) or cubic meter per second (m3/s).
Check Valve	Device which allows air to flow only in one direction.
Clearance	Volume of cylinder on the working side of piston minus the volume displaced per stroke of the piston.
Compressed Air	Air, which is reduced in volume by increase in pressure, so as to utilize the internal energy of the air to perform required work.
Compression Efficiency	Ratio of theoretical power to the power transferred to the air/gas delivered by the compressor.
Compression Ratio	The ratio of absolute discharge pressure to the absolute suction pressure
Compressor Cycle	The transition of a compressor from one mode of operation to another, i.e., load to unload, idle running, or modulating
Compressor Cycle Time	The amount of time taken for a compressor to complete one cycle
Constant Speed Control	System installed to match the air supply and air demand by controlling the speed of the compressor to control the load
Cut-In pressure	The pressure at which the compressor switches from unload to load operation
Cut-Off pressure	The pressure at which the compressor switches from load to unload operation

Degree of Intercooling	The degree of temperature reduced by the intercooler in comparison with the inlet of the air compressor
Demand Air	The quantity of air required at any particular instant of time for the operation of an equipment, process, or plant
Desiccant	A hygroscopic substance, which has a tendency to absorb moisture from air, therefore used as a drying agent.
Dew Point	The temperature at which the moisture in air begins to condense.
Discharge Pressure	Pressure of air produced by the compressor at the discharge, under specific conditions and given instant of time.
Discharge Temperature	Temperature of air at the discharge of the air compressor.
Displacement	The swept volume per unit time by the pistons in a reciprocating air compressor, expressed in CFM.
Dry Buld Temperature	Temperature of air measured by a thermometer which is freely exposed to air.
Filters	Device to remove or separate the particulate matter, moisture or other particles from air.
Free Air	Quantity of air delivered to a certain point at a specific condition, which is converted back to ambient conditions.
Full Load	Air compressor operating at full speed and delivering maximum air flow.
Gauge Pressure	Pressure which is zero-referenced against ambient air pressure, which is determined using instruments or gauges in a process. Expressed as psig or kg/cm^2 or bar.
Inlet pressure	The pressure at the inlet of the air compressor.
Intercooling	Heat exchanger used to reduce the temperature of the compressed air between the stages of compression.
Isentropic Compression	Refer to Adibatic Compression
Isentropic Efficiency	Ratio of work input to the isentropic process to the actual work input at the same inlet and outlet pressures.
Isothermal Compression	Process of compression in which the temperature of air/gas remains constant
Isothermal Efficiency	Ratio of theoretical work done under isothermal conditions to the actual work transferred to the air/gas during compression.
Leak	Unintended loss of compressed air to the ambient atmosphere through damaged pipelines, instruments, etc.
Load Factor	Ratio of average compressor load over a specific period of time to the rated power of the compressor.
Load/Unload Control	Control mechanism which allows the compressor to load according to demand, or at no load while running the driver at constant speed.
Mechanical Efficiency	Ratio of the power transferred as internal energy to air/gas to the brake horse power of the compressor.
Modulating Control	Control mechanism which allows the compressor to vary demand by varying the inlet proportional to the demand.

Multi-Stage Compressor	Compressor having two or more stages operating in series.
Perfect Intercooling	The condition when the temperature of compressed air leaving the intercooler is equal to the temperature of the air entering the compressor.
Performance Curve	Curve illustrating the discharge pressure and inlet capacity to indicate the performance of the compressor.
Pneumatic Tools	Tool which utilize compressed air for operation.
Polytropic Compression	Process of compression in which the pressure and volume is expressed by the equation "PVn = constant"
Polytropic Efficiency	Ratio of the polytropic energy transferred to air/gas to the brake horse power of the compressor.
Positive Displacement	Compression taking place by reduction of air/gas volume, in a closed space, by displacement of mechanical linkage.
Pressure	Force per unit area, measured by psi or kg/cm^2 or bar.
Pressure Drop	Loss of pressure in the compressed air system or across any component in the system caused by friction or restriction to the flow of compressed air.
Pressure Range/Band	Difference between the cut-in and cut-out pressure of the air compressor.
Rated Capacity	Volume of air flow at rated pressure and at specific conditions.
Reciprocating Compressor	Compression mechanism which uses reciprocating motion of the piston to compress air.
Relative Humidity	Ratio of partial pressure of water vapour in air to the vapour saturation temperature of water at the same dry bulb temperature.
Shaft	Transmission element used to transfer power from prime mover to the compressor.
Specific Gravity	Ratio of specific weight of air or gas to that of the dry air at the same pressure and temperature conditions.
Specific Humidity	The weight of water vapour present in an air vapour mixture per unit weight of dry air
Specific Power	Performance indicator used to indicate the amount of energy consumed to generate one unit of compressed air at particular pressure.
Standard Air	Air at 1 bar (14.5 psi), 20°C (68°F) and 0% relative humidity, as defined by ISO standards.
Start/Stop Control	Control system to match the supply and demand of compressed air.
Valves	Device to regulate or direct the flow of compressed air.
Volumetric Efficiency	Ratio of actual CFM delivered to the displacement of the compressor.
Water Cooled Compressor	Compressor cooled by water through jackets or heat exchangers
Wet Bulb Temperature	Temperature read by a thermometer covered in a cotton wick (known as wet bulb thermometer) over which the air passed.

References

1. Guidebook on Electrical and Compressor by Bureau of Energy Efficiency (BEE), Government of India.

2. Manual on Compressors and Compressed Air Systems, CII – Sohrabji Godrej Green Business Centre, 2010

4. Technical Publications on Air Compressor , auxiliaries and distribution system by Compressed Air Gas Institute (CAGI)

5. Improving Compressed air System Performance, Compressed Air Challenge.

6. Compressed air energy reference guide, CEATI

7. Understanding Centrifugal Compressor Capacity control, CAGI Technical notes

8. How Inlet compressor Effect Centrifugal Compressors, CAGI Technical notes

9. ATLAS COPCO COMPRESSED AIR MANUAL, 8th edition.

10. Dew Point in Compressed Air-Vaisala Application note

About CII

The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering industry, Government, and civil society, through advisory and consultative processes.

CII is a non-government, not-for-profit, industry-led and industry-managed organization, playing a proactive role in India's development process. Founded in 1895, India's premier business association has around 9000 members, from the private as well as public sectors, including SMEs and MNCs, and an indirect membership of over 300,000 enterprises from around 276 national and regional sectoral industry bodies.

CII charts change by working closely with Government on policy issues, interfacing with thought leaders, and enhancing efficiency, competitiveness and business opportunities for industry through a range of specialized services and strategic global linkages. It also provides a platform for consensus-building and networking on key issues.

Extending its agenda beyond business, CII assists industry to identify and execute corporate citizenship programmes. Partnerships with civil society organizations carry forward corporate initiatives for integrated and inclusive development across diverse domains including affirmative action, healthcare, education, livelihood, diversity management, skill development, empowerment of women, and water, to name a few.

India is now set to become a US$ 5 trillion economy in the next five years and Indian industry will remain the principal growth engine for achieving this target. With the theme for 2019-20 as 'Competitiveness of India Inc - India@75: Forging Ahead', CII will focus on five priority areas which would enable the country to stay on a solid growth track. These are - employment generation, rural-urban connect, energy security, environmental sustainability and governance.

With 66 offices, including 10 Centres of Excellence, in India, and 11 overseas offices in Australia, China, Egypt, France, Germany, Indonesia, Singapore, South Africa, UAE, UK, and USA, as well as institutional partnerships with 355 counterpart organizations in 126 countries, CII serves as a reference point for Indian industry and the international business community.

Contact Details:

Mr. P.V. Kiran Ananth

Principal Counsellor

CII-Godrej GBC

Ph: +91 40 4418 5152

Email: kiran.ananth@cii.in

The Mantosh Sondhi Centre

23, Institutional Area, Lodi Road

New Delhi 110 003 (India)

T: +91 11 45771000 / 24629994-7

F: +91 11 24626149

E: info@cii.in

W: www.cii.in

Confederation of Indian Industry