SHIP Egypt

Session 10

Compressed Air

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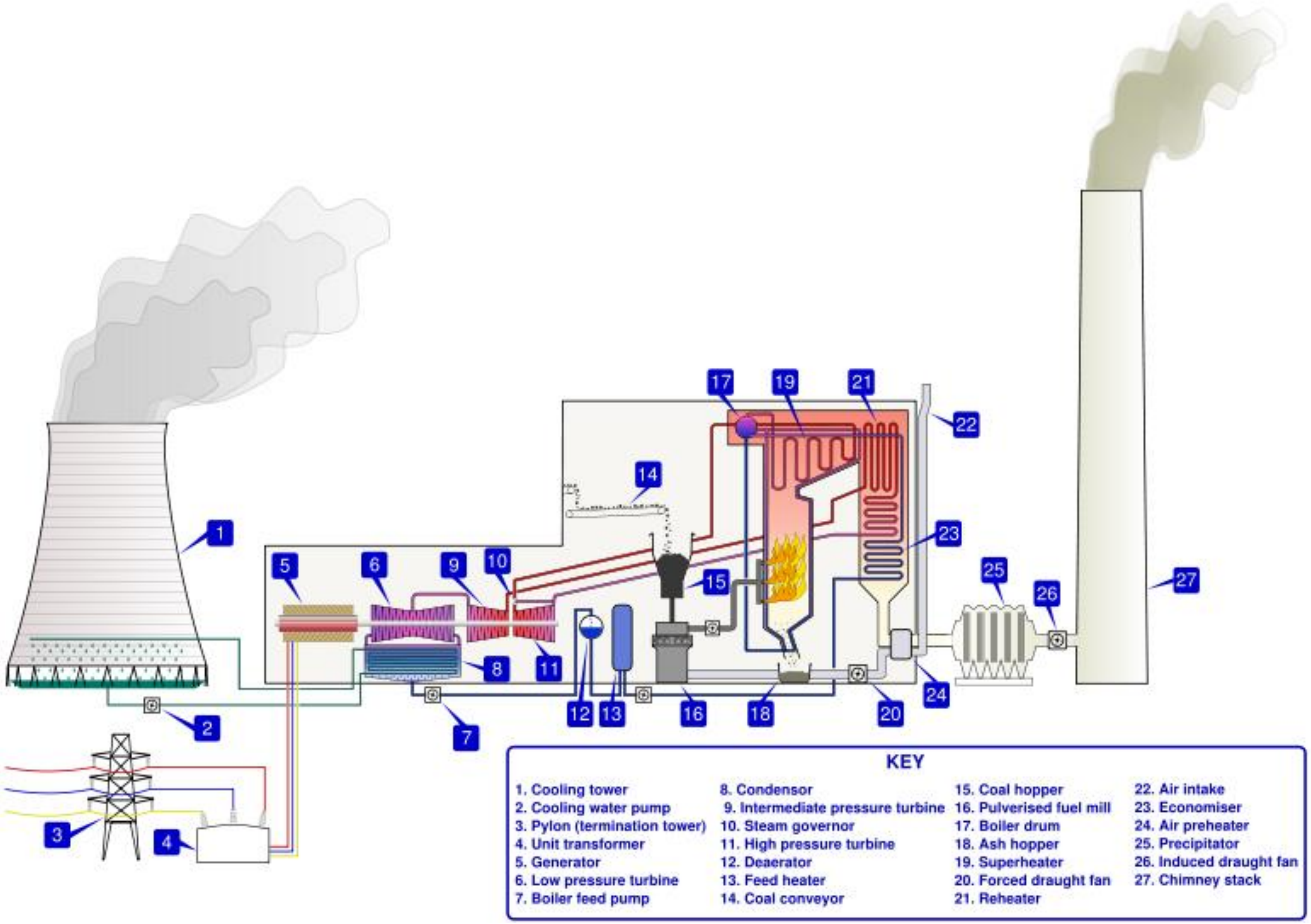
Industrial sectors uses of compressed air

Industry	Example Compressed Air Uses
Apparel	Conveying, clamping, tool powering, controls and actuators, automated equipment
Automotive	Tool powering, stamping, control and actuators, forming, conveying
Chemicals	Conveying, controls and actuators
Food	Dehydration, bottling, controls and actuators, conveying, spraying coatings, cleaning, vacuum packing
Furniture	Air piston powering, tool powering, clamping, spraying, controls and actuators
General Manufacturing	Clamping, stamping, tool powering and cleaning, control and actuators
Lumber and Wood	Sawing, hoisting, clamping, pressure treatment, controls and actuators
Metals Fabrication	Assembly station powering, tool powering, controls and actuators, injection molding, spraying
Petroleum	Process gas compressing, controls and actuators
Primary Metals	Vacuum melting, controls and actuators, hoisting
Pulp and Paper	Conveying, controls and actuators
Rubber and Plastics	Tool powering, clamping, controls and actuators, forming, mold press powering, injection molding
Stone, Clay, and Glass	Conveying, blending, mixing, controls and actuators, glass blowing and molding, cooling
Textiles	Agitating liquids, clamping, conveying, automated equipment, controls and actuators, loom jet weaving, spinning, texturizing

Typical energy production processes



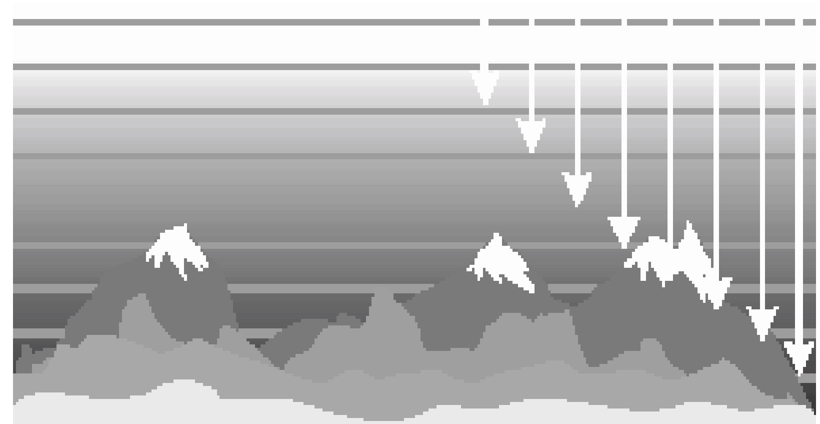
Energy production process

- Typical types of energy:
  - Heat
    - Hot water
    - High or low pressure steam
  - Electricity
    - Compressed air

Fuels: solid, liquid, gases → combustion process → energy

Physical and Chemical Properties of air

- Atmospheric pressure at sea level:
  - 1,013 [bar] = 760 [mm/Hg]



- Overpressure
  - 1 [m³] at an overpressure of 7 [bar] means that 1 [m³] of air is compressed at an overpressure of 7 [bar] (= 8 [bar] absolute pressure) and has 1/8 of its initial volume

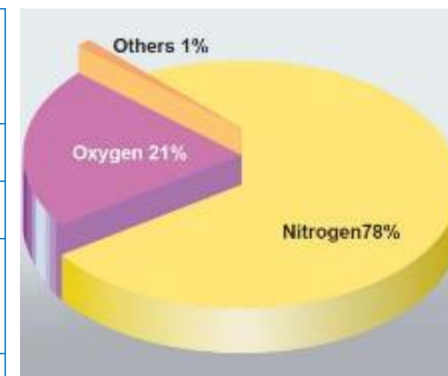
Absolute pressure 8 bar
pressure gauge

Overpressure
pressure 0 bar

Compressed air in industry

- Air is a colorless, odorless and tasteless gas mixture.
- It is a mixture of many gases, but is primarily composed of oxygen (21%) and nitrogen (78%).
- This composition is relatively constant, from sea level up to an altitude of 25 [km].
- General composition of air.

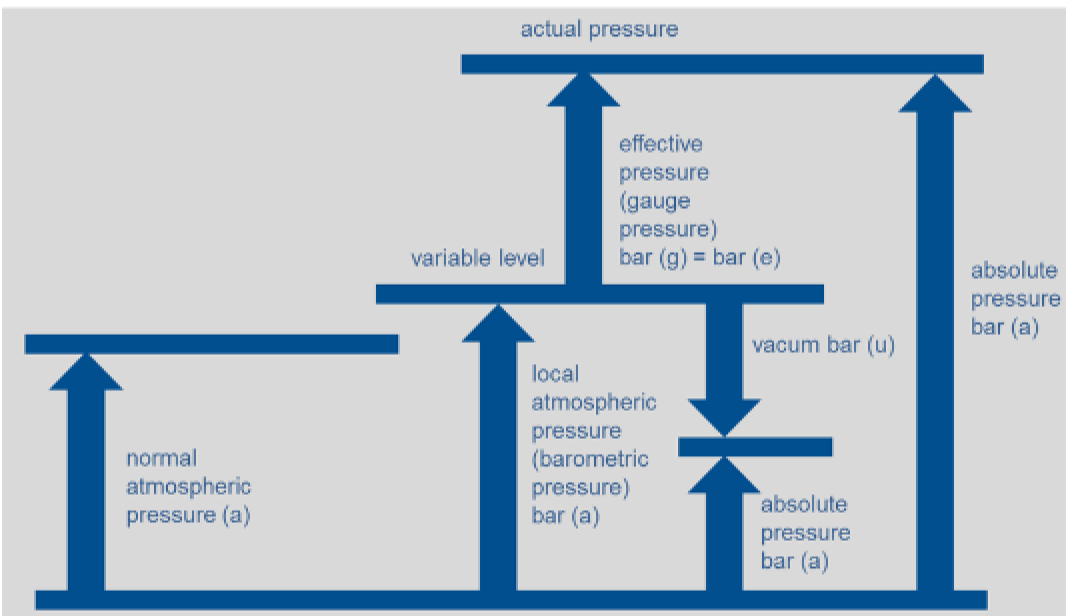
No.	Gas	Volume (%)	Mass (%)	Molecular weight(kg/kmol)	Molecular weight in air
1	Nitrogen	78,03	75,46	28,015	21,880
2	Oxygen	20,99	23,19	32,000	6,704
3	Carbon dioxide	0,03	0,05	44,003	0,013
4	Hydrogen	0,01	0,0007	2,016	0,000
5	Monatomic gases(Ar, Rn, He,Kr, Ne)	0,94	1,30	39,943	0,373

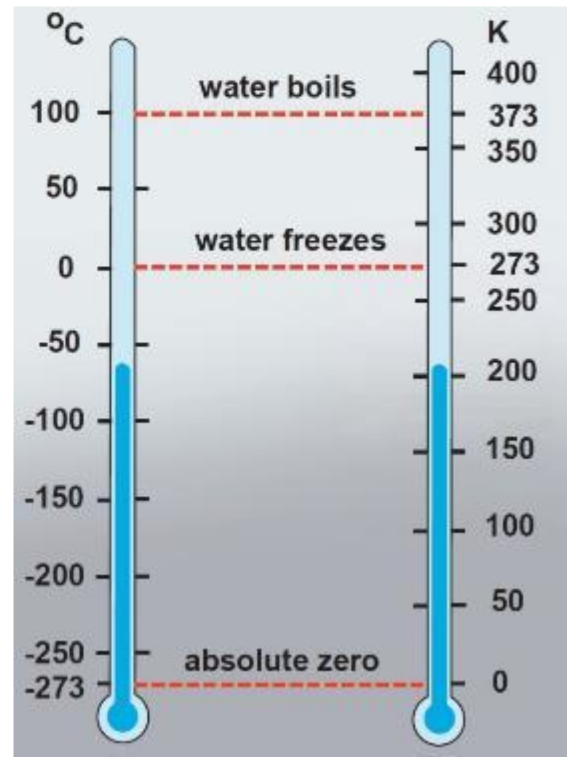


Parameters of air: temperature , pressure , humidity.

- Most pressure gauges register the difference between the pressure in a vessel and the local atmospheric pressure. Therefore to find the absolute pressure the value of the local atmospheric pressure must be added.

  - ⇨ T = t + 273.2
    - t = absolute temperature [°K]
    - T = centigrade temperature [°C]





zero pressure (perfect vacum)

Moist air

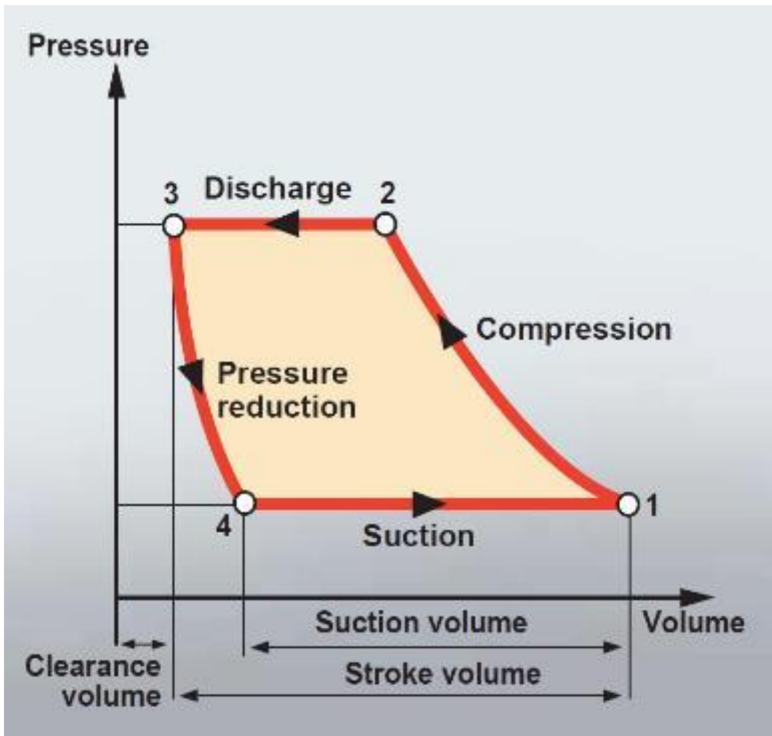
- Air can be considered a mixture of dry air and water vapor. Air that contains water vapor is called moist air, but the air's humidity can vary within broad limits. Extremes are completely dry air and air saturated with moisture. The maximum water vapor pressure that air can hold increases with rising temperatures. A maximum water vapor pressure corresponds to each temperature.
- Air usually does not contain so much water vapor that maximum pressure is reached. Relative vapor pressure (also known as relative humidity) is a state between the actual partial vapor pressure and the saturated pressure at the same temperature.
- The dew point is the temperature when air is saturated with water vapor. Thereafter, if the temperature falls, the water condenses. Atmospheric dew point is the temperature at which water vapor starts to condense at atmospheric pressure. Pressure dew point is the equivalent temperature with increased pressure

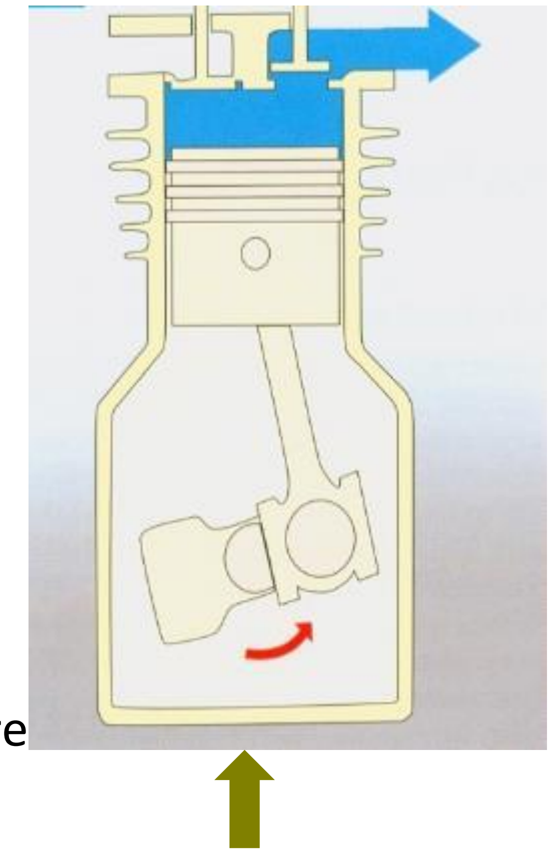
Moist air

- Relative humidity
  - Relative humidity is the ratio of the partial pressure of water vapor in an air-water mixture to the saturated vapor pressure of water at a prescribed temperature.
  - Partial pressure is the hypothetical pressure of gas if it alone occupied the volume of the mixture at the same temperature (according to the Dalton's law).
  - Relative humidity has no unit and it contains between 0 and 1, normally expressed as percentage (100%=1). When relative humidity equals 0 it means that air is dry, if the relative humidity is 1 the air is saturated. When relative humidity equals 1, cooling the air causes the water vapor condensation.
    Unit: ϕ % .
- Absolute humidity
  - Absolute humidity is the amount of water vapor in the air.
    Normally expressed as g/Nm^3 of air.

Compression cycles (theory)

- The p/V diagram shows the process without losses, with complete filling and emptying of the cylinder





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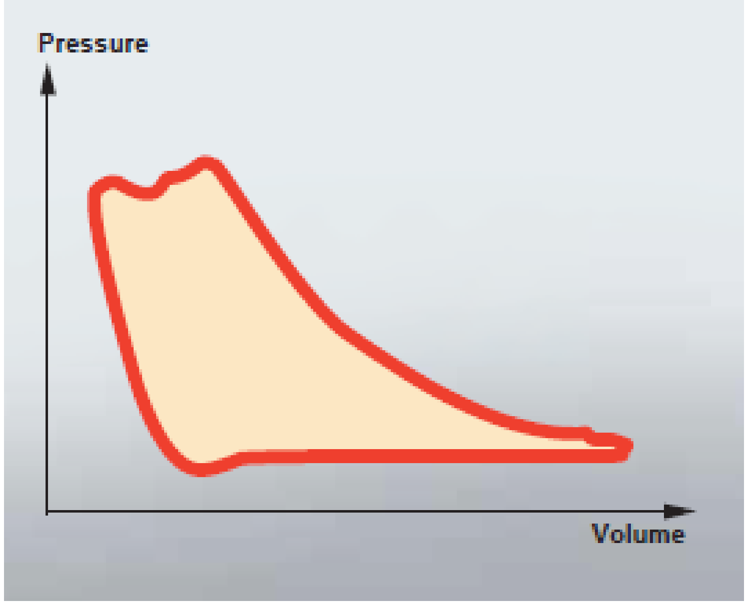
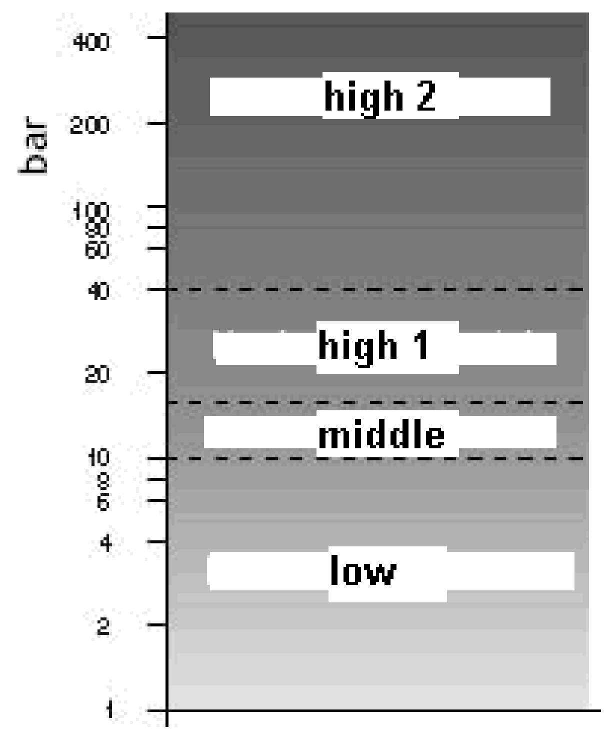
Compression cycles (real)

- A realistic p/V diagram for a piston compressor. The pressure drop on the inlet side and the overpressure on the discharge side are minimized by providing sufficient valve area.



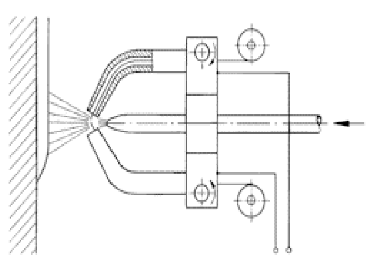
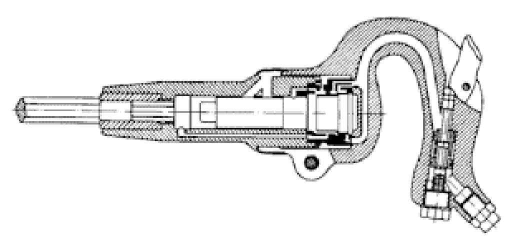
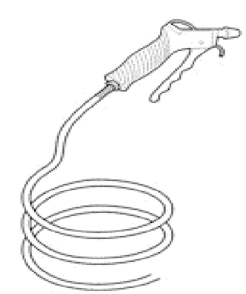
Compressed air in industry

- High pressure 2:
  - ⇨ Tightness testing, power plants, lathe equipments, oxide compression.
  - ⇨ Compressor: piston compressors
- High pressure 1:
  - ⇨ Tightness testing (pipes), plastic boxes forming
  - ⇨ Compressor: piston compressors, screw compressors.
- Middle pressure:
  - ⇨ Heavy vehicles tires, specialized mechanical devices.
- Low pressure:
  - ⇨ The most popular usage in industry
  - ⇨ Compressor: piston compressors, screw compressors.

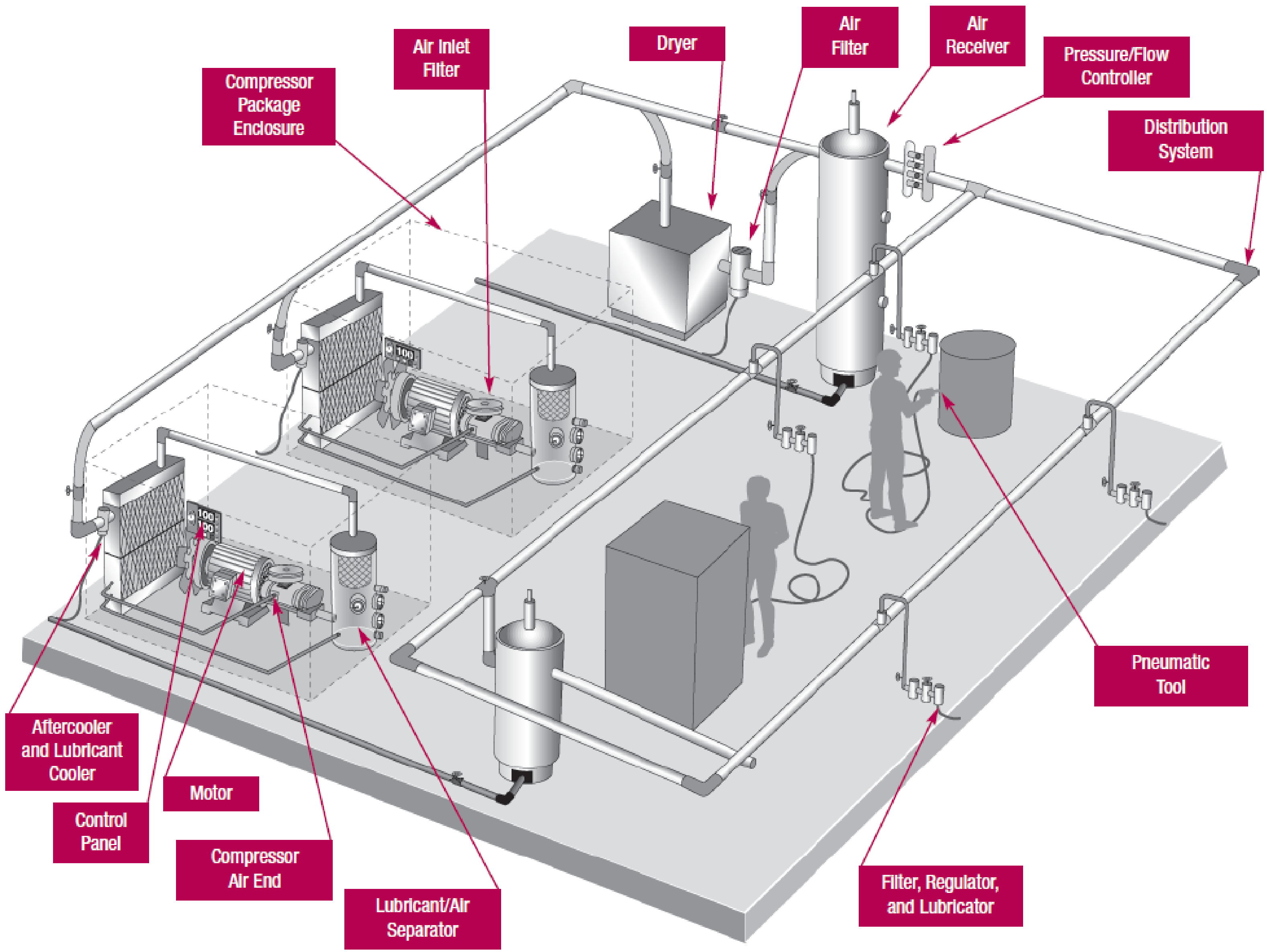


Compressed air in industry

- The business sectors that use the most compressed air include:
  - Drive and transport (to-and-fro motion in actuators, pneumatic mass transport),
  - Machines and devices supply (pneumatic hammers and wrenches)
  - Sprayers supply (painting, varnishing),
  - Purging and drying elements during the treatment (spray guns, drying jets).
  - Pneumatic control systems
  - Non-returnable packages production
  - Electric power devices

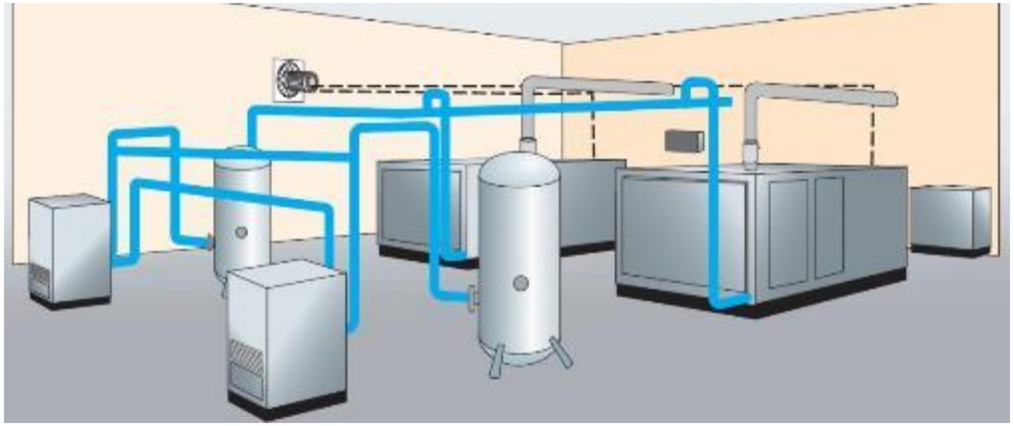




Compressed Air Systems



Placement and design

- The compressed air plant should be installed to facilitate distribution system routing in large installations with long piping. Service and maintenance can be facilitated by installing the compressed air plant near auxiliary equipment such as pumps and fans; even a location close to the boiler room may be beneficial.
    - It is important that the compressor installation has a layout that is service friendly and flexible to accommodate future expansion. The minimum area at service points in front of the machine electrical cabinets should be
      1200 mm



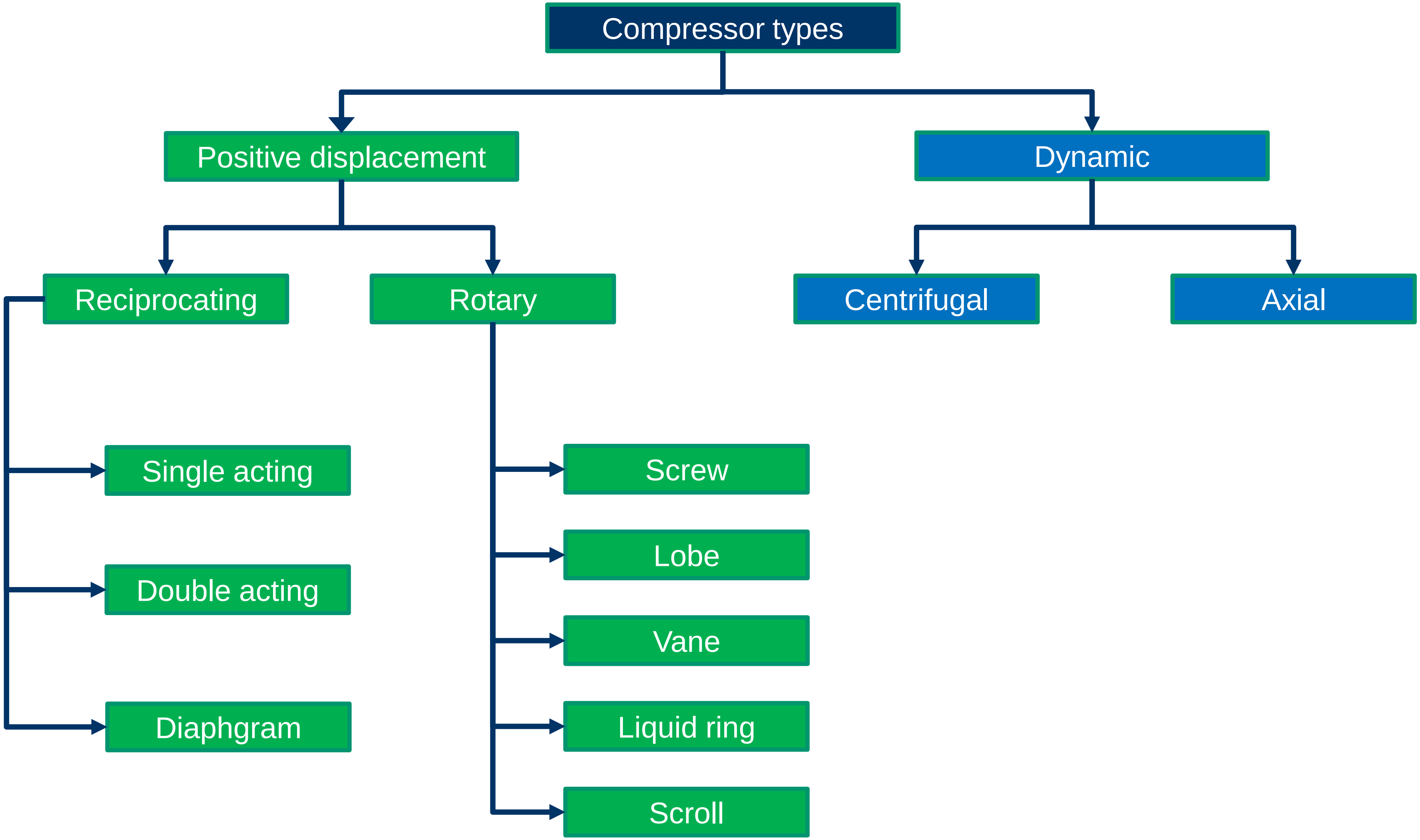
Compressed air distribution

- Inadequate compressed air distribution systems will lead to high energy bills, low productivity and poor air tool performance. Three demands are placed on a compressed air distribution system: a low pressure drop between the compressor and point of consumption, a minimum of leakage from the distribution piping, and efficient condensate separation if a compressed air dryer is not installed.
- The best solution involves designing a pipe system as a closed loop ring line around the area in which air consumption will take place. Branch pipes are then run from the loop to the various consumer points. This provides uniform compressed air supply, despite heavy intermittent usage, as the air isled to the actual point of consumption from two directions.
- This system should be used for all installations, except if some points of large air consumption are located at a great distance from the compressor installation. A separate main pipe is then routed to these points

Two basic principles of compression

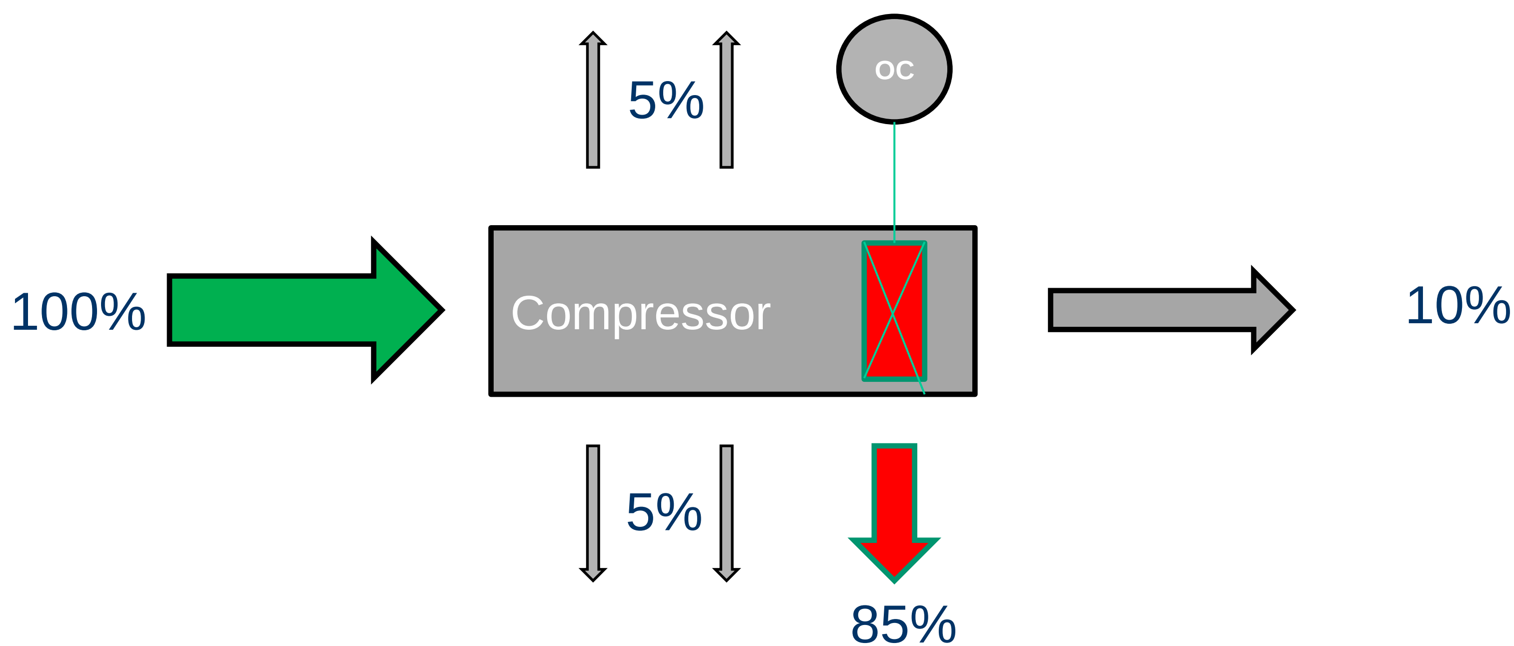
- There are two generic principles for the compression of air (or gas):
  - **Positive displacement compressors** include, for example, reciprocating (piston) compressors, orbital (scroll) compressors and different types of rotary compressors (screw, tooth, vane). In positive displacement compression, the air is drawn into one or more compression chambers, which are then closed from the inlet. Gradually the volume of each chamber decreases and the air is compressed internally. When the pressure has reached the designed build-in pressure ratio, a port or valve is opened and the air is discharged into the outlet system due to continued reduction of the compression chamber's volume.
  - In **dynamic compression**, air is drawn between the blades on a rapidly rotating compression impeller and accelerates to a high velocity. The gas is then discharged through a diffuser, where the kinetic energy is transformed into static pressure. Most dynamic compressors are turbocompressors with an axial or radial flow pattern. All are designed for large volume flow rates

Methods of compressing gas (air)



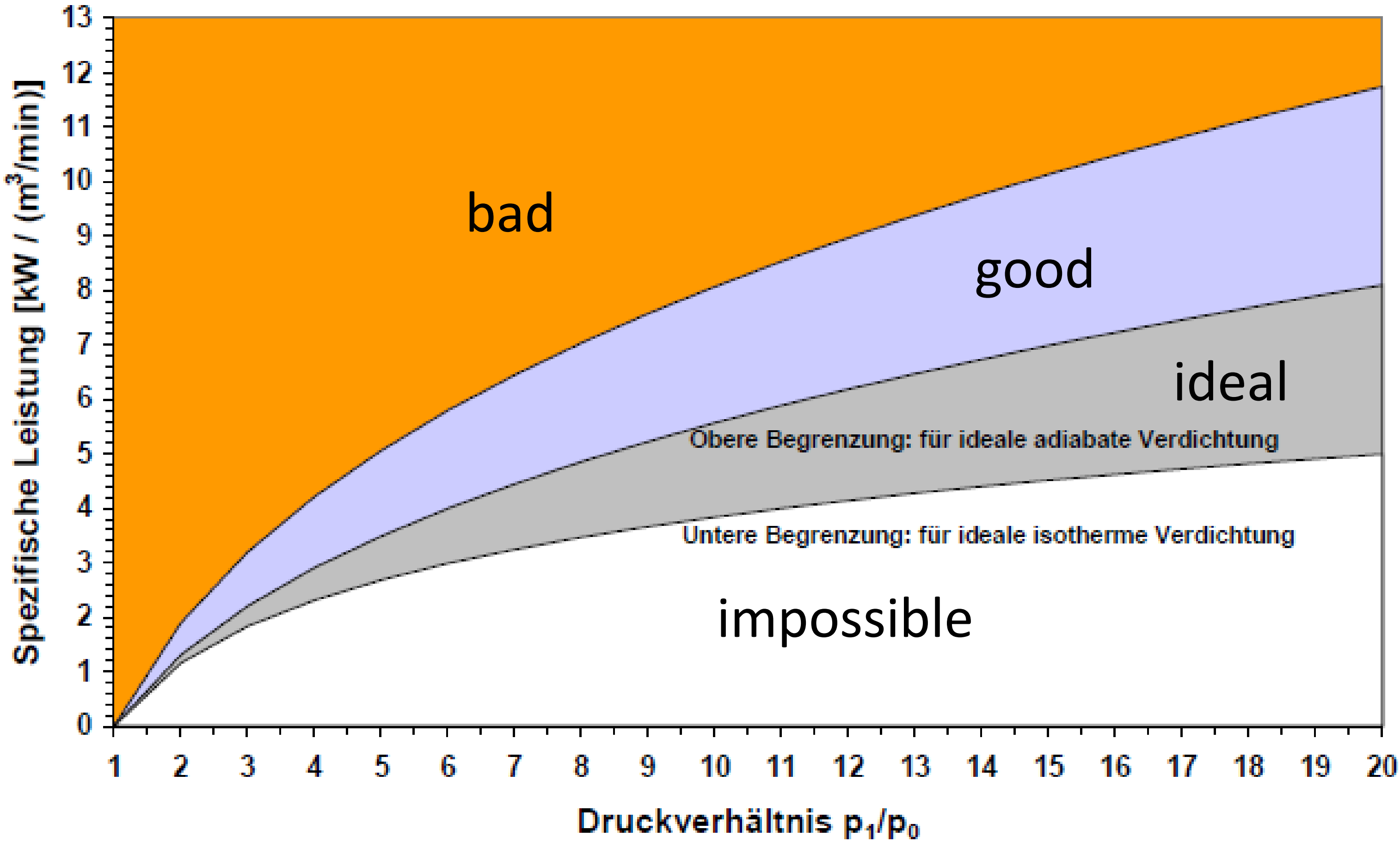
The process of compressing air is wasteful

- The supplied electrical energy is converted in the following scale:
  - Approximately 10% is compressed to the air energy, and the remaining 90% to heat, ~ 85% of which can be recovered in a heat exchanger (oil cooler)
  - Remaining ~ 5% of the energy is radiated as heat to the environment.



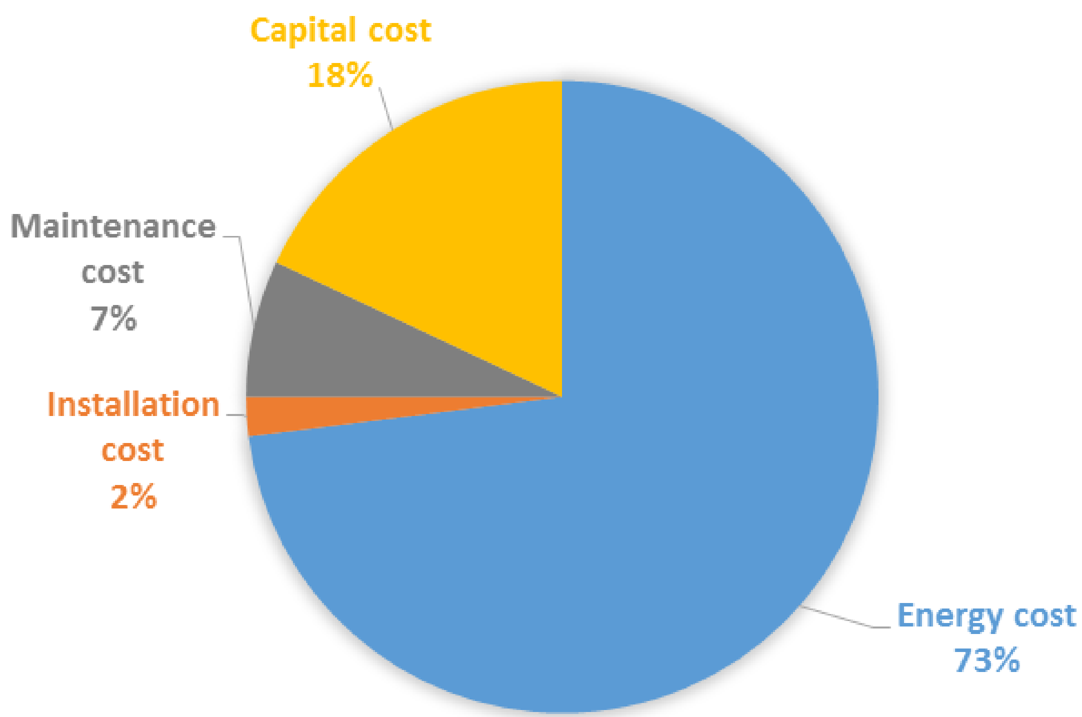
Benchmark for energy performance

- 8 kW/m³/min = 0.133 kWh/m³



Compressor costs

- Compressor costs over a ten-year life in compressed air production



Equipment - Compressed air receiver

- Standard volume:
  - Up to 30% m^3/min flow volume compressors
- Benefits of increasing the capacity of air receiver:
  - Reduction of the operating pressure range
  - Reduction of the number of cycles of load / no load

Treatment of compressed air

- Drying compressed air
  - All atmospheric air contains water vapor: more at high temperatures and less at lower temperatures. When the air is compressed the water concentration increases.
  - For example, a compressor with a working pressure of 7 bar and a capacity of 200 l/s that compresses air at 20°C with a relative humidity of 80% will release 10 liters/hour of water in the compressed air line. To avoid problems and disturbances due to water precipitation in the pipes and connected equipment, the compressed air must be dried. This takes place using an after-cooler and drying equipment.
  - The term “Pressure Dew Point” (PDP) is used to describe the water content in the compressed air. It is the temperature at which water vapor condenses into water at the current working pressure. Low PDP values indicate small amounts of water vapor in the compressed air.

Compressed air distribution

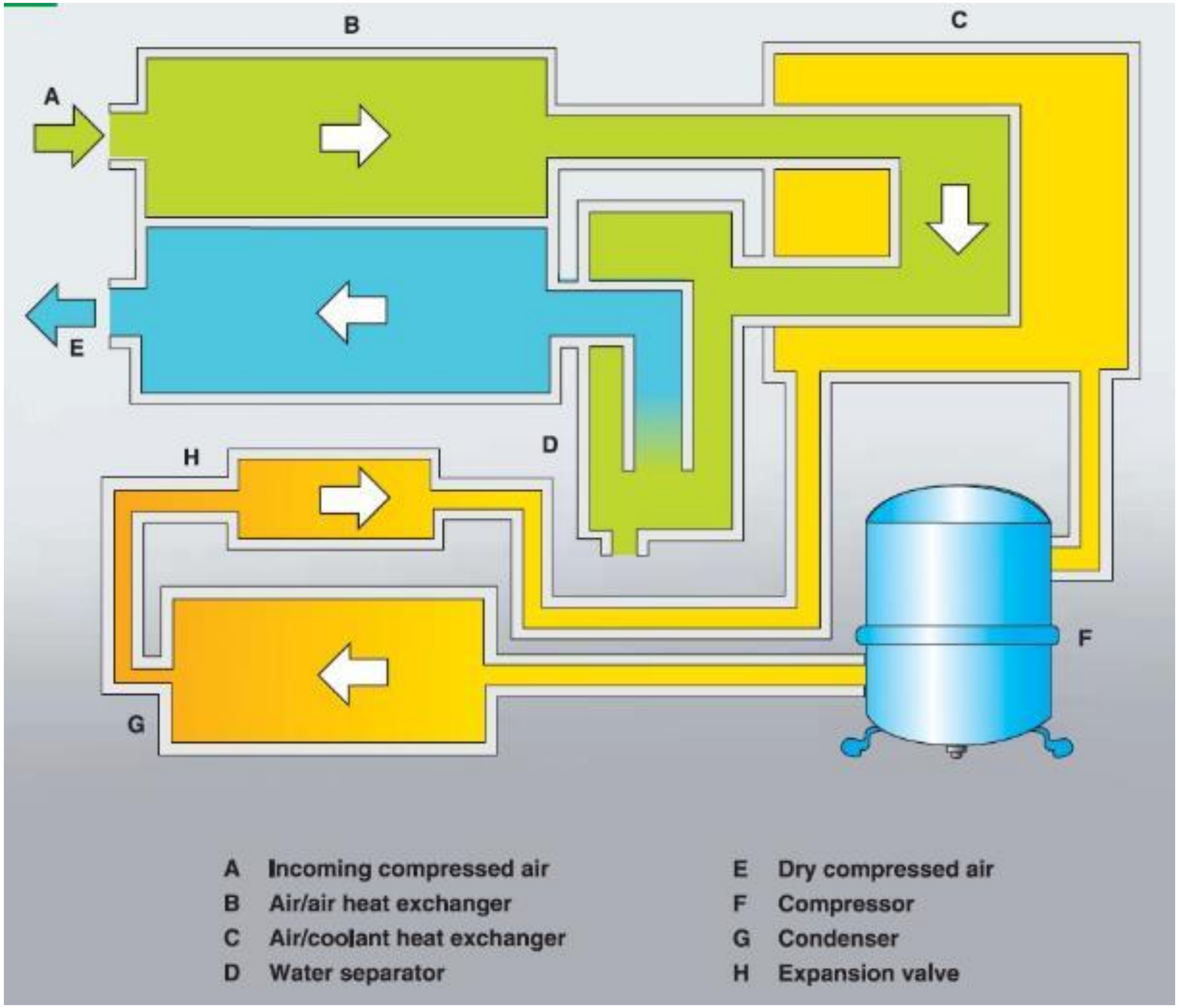
- The principles for air distribution are:.
  - Air receiver - one or more air receivers are included in each compressor installation
  - Design of the compressed air network - the starting point when designing and dimensioning a compressed air network is an equipment list that details all compressed air consumers, and a diagram indicating their individual locations
  - Dimensioning the compressed air network - The pressure obtained immediately after the compressor can generally never be fully utilized because the distribution of compressed air generates some pressure losses, primarily as friction losses in the pipes
  - Flow measurement - strategically placed air flow meters facilitate internal debiting and economic allocation of compressed air utilization within the company. Compressed air is a production medium that should be a part of the production cost for individual departments within the company

Treatment of compressed air

- After-cooler
  - An after-cooler is a heat exchanger that cools the hot compressed air to precipitate the water that otherwise would condensate in the pipe system. It is water-cooled or air-cooled, is generally equipped with a water separator with automatic drainage and should be placed close to the compressor.
  - Approximately 80–90% of the precipitated condensation water is collected in the after-cooler's water separator. A common value for the temperature of the compressed air after passing through the after-cooler is approx. 10°C above the coolant temperature, but can vary depending on the type of cooler. An after-cooler is used in virtually all stationary installations. In most cases, an after-cooler is built into modern compressors.

Treatment of compressed air

- Operational principle of refrigerant drying



Treatment of compressed air

- Overcompression
  - Over-compression is perhaps the easiest method for drying compressed air. Air is first compressed to a higher pressure than the intended working pressure, which means that the concentration of water vapor increases. Thereafter the air is cooled and the water is separated as a result.
  - Finally, the air is allowed to expand to the working pressure, and a lower PDP is attained. However, this method is only suitable for very small air flow rates, due to its high energy consumption.

Treatment of compressed air

- Refrigerant dryer
  - Refrigerant drying means that the compressed air is cooled, which allows a large amount of the water to condense and be separated. After cooling and condensing, the compressed air is reheated to around room temperature so that condensation does not form on the outside of the pipe system.
  - This heat exchange between ingoing and outgoing compressed air also reduces the temperature of the incoming compressed air, and as such reduces the required cooling capacity of the refrigerant circuit.
  - Cooling the compressed air takes place via a closed refrigerant system. Smart steering of the refrigerant compressor via intelligent control algorithms can significantly reduce the power consumption of modern refrigerant dryers. Refrigerant dryers are used for dew points between +2°C to +10°C and have a lower limit, which is the freezing point of the condensed water

Energy flow for pneumatic tools

100 % Input

10 % motor losses

25 % compression losses

20 % start up and stopping time

5 % air drying, filtering

20 % pressure drop, reduction valves

5 % leakage

5 % conversion losses

5 % useful power at pneumatic tool

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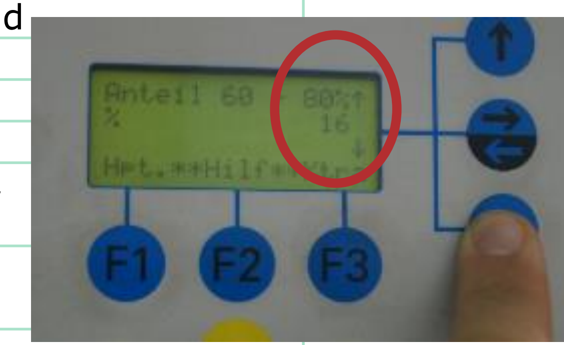
Data collection

	Comp 1 (Main)	Comp 2 (Sub)
Name	Atlas Copco; GA15-7,5	Atlas Copco; GA11FF
Base-Part-Peak Load use	Base load	Peak load
Capacity [kW]/Liter	15 kW	11 kW
Year of construction	1993	2013
Production flow [m³/min] / [l/s]	43 l/s	35,8 l/s
Power at full load [kW] (incl. Side units)	19,5 kW	15,9 kW
Power when idle [kW] (incl. Side units)	5,6 kW	5,2 kW
Power at stopp	<100W, timed 6-10 min	
Full load hours	n.a.	255
Part load hours	n.a.	489
Total hours	2000	744
Pressure band: On [bar] off [bar]	6,5-7,5	6,7-7,2
Pressure drop due to air treatment (Optional)	3-stage filter	3-stage filter
Type of compressor	Screw compressor with oil injection 4-5mg/m³ oil in air	Screw compressor with oil injection 4-5mg/m³ oil in air
Air dryer	Atlas Copco dryer FX 6 (A5)	Atlas Copco GA11FF integrated
Year of construction	2015	2013
Air dryer capacity	0,844 kW	0,52 kW
Heat recovery	HX above vents	HX in next room



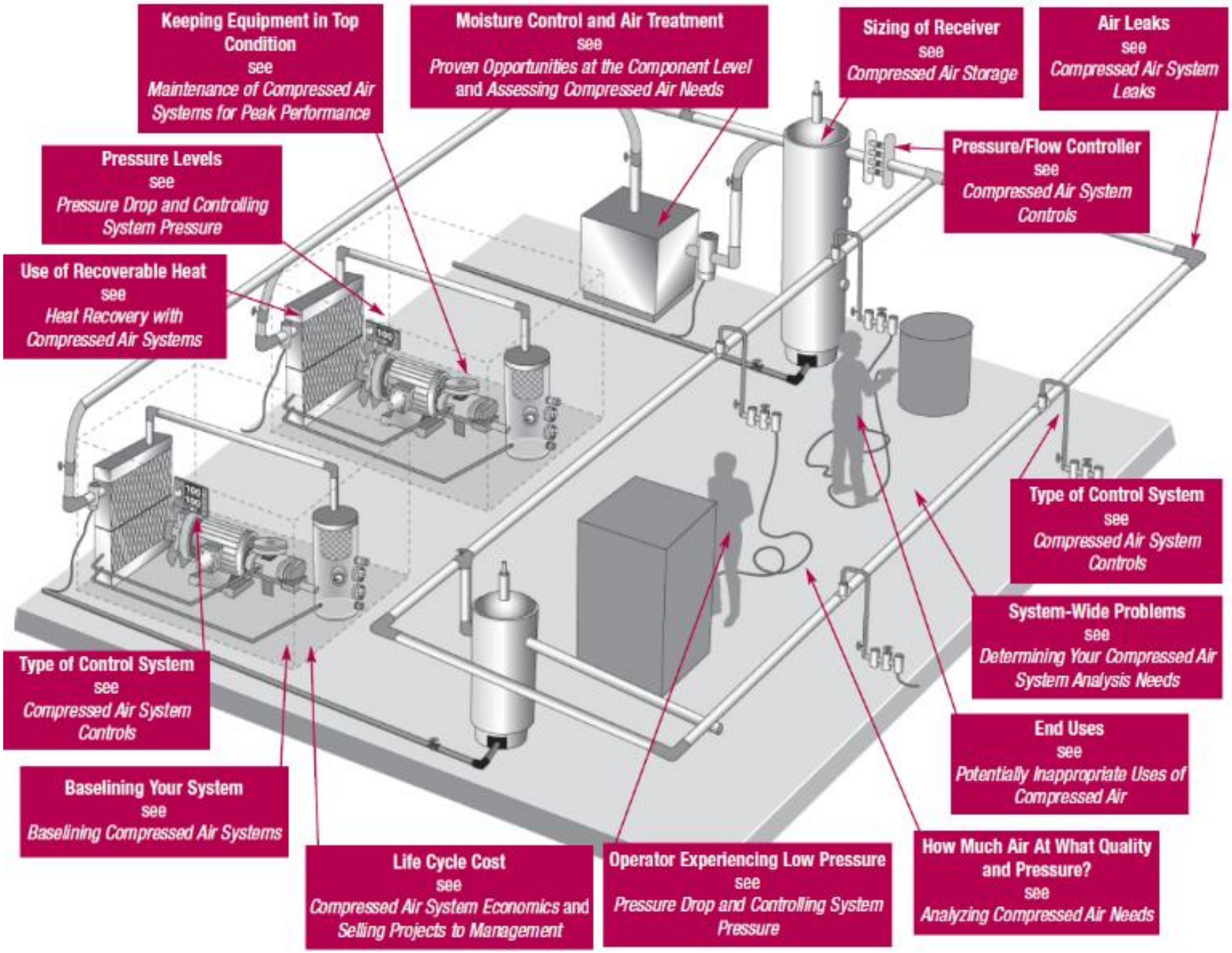
Collecting data - source

Compressor #	01	02	03	04
Location	Mixing Lab	Molding Deptt	Radiator Deptt	Suction Deptt
Type	Screw	Piston	Piston	Piston
Make	MITSUI SEIKI	Fauiji	-	-
Rated Power (hp)	15.0	2.0	10.0	30.0
Max Pressure (psi)	150.0	100.0	150.0	150.0
Set Operating Pressure (bar)	8.0 – 9.0	4.5 – 5.0	2.6 – 4.4	7.0 – 9.0
Running Hours	47613.47	-	-	-
Loaded Time (Hrs)	Continuous	On Demand	69, 67 sec	160 sec
Unloaded Time (Hrs)	-	-	140, 140 sec	66 sec
% age Loading	100	-	50	70
Suction Air Temp. (°C)	35	-	35	35
Drain Status	Manual	Manual	Manual	Manual
Dryer (Make, Type)	No	No	No	No
Usage Point Pressure (bar)	7.6 (110 psi)	4.0	4.0	5.0
Current Status	Running	Running	Running	Running
Line from Compressor	1" line to tank	8mm line to tank	1" line to tank	1.25" line to tank
Line out from Tank	8mm line to Mixing Lab	8mm line to Preformer m/c	Two 8mm line to Mandrills	Three different lines from tank to deptt

Collecting data – usage points

Department	Machines	Required Pressure (bar)	Reach Pressure (bar)
Mixing Lab	2- Kneader m/cs	110 psi	130 psi
Molding Department	1-Preformer m/c	4.0	5.0
	For Parts Pulling	Air guns are using	
Radiator Department	1-Mandrill Insertion	5.0 psi	4.0
	1-Knitting m/c	5.0 psi	4.0
	1-Outer m/c	5.0 psi	4.0
	1 Air gun for screwing	No Gauge	4.0
Suction Department	1-Expender m/c	6.0	9.0
	1-Mandrill Insertion	2.0 – 3.0	9.0
	1-Delivery Outer m/c	50 psi	9.0
	1-Pad Printer	5.0	7.0
	2-Vulcanizing m/cs	No Gauge	8.0
	1-Straight Extruder	5.0	8.0

Performance opportunities



Low hanging fruits

- Reduction of working time
- Reduction of pressure level
- Change of air-intake
- Minimizing leakages
- Sectionizing the pipe system
- Operational control
- Substitution of the demand for compressed air
- Heat recovery
- Maintenance

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Substitution of demand for compressed air

- It is easy to use (no problems with leaks, safe, ..)
- But due to poor efficiency of compressors, compressed air is the most expensive form of energy
- So replacement of compressed air applications with similar others is the goal

Methods of humidifying air:	Energy used per m3 water laid:
Compressed air based humidifying:	30 – 200 kWh/m3
High pressure humidifying:	1 – 15 kWh/m3

Typically the saving potential by substituting compressed air is about 70 %.

Substitution of demand for compressed air

- Use electric tools instead of pneumatic tools
  - ⇨ Saving potential 10-20 %
- Use electric or hydraulic drives for linear or rotational traction
  - ⇨ Saving potential 90 %
- Don‘t use compressed air for cleaning
  - ⇨ Dust is only moved to another location, but not removed
  - ⇨ Vacuum cleaner
- Bubblers, mixers and others to be replaced with electric devices
- Blowing and cooling may be replaced with small fans

Reduce operating time of the grid

- Compressed air system is under pressure all time
- Also in periods where the industry closed

→ operating hours: 8760 h

- Time control: closing from 20:00 til 6:00 = minus 10 h/d

→ operating hours: 5110 h

Why is it often not so simple?

What can we do?

Reduce pressure level

- Is the pressure of the compressors all the same?
- Is the pressure adjusted to your required pressure level at the point of use?
  - ⇨ Often, this is not the case. Mostly because of ignorance.

Typically:

- Δp = - 1 bar → ΔE_{compr} = - 6 - 8 %
- Δp = -0.3 bar → - 4 % leakage rate
- If the difference between the pressure demanded and at the compressors is more than 1.3 bar – action is needed.

Typical pressure levels for consumers

⇨ Cleaning (ex. Air pistol)	3 bar
⇨ Tools	6.3 bar
⇨ Process machines with less	depends, but often they work perfectly

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Reduce pressure level

- Reduction from 8.5 to 9 bar down to 6.5 bar (for the tool) + 1.3 bar (for distribution losses), finally 7.3 to 7.8 bar

Compr.	Power	Running time	Energy
Loaded	59 kW	3,000 hrs	177,000 kWh
Un-loaded	25 kW	500 hrs	12,500 kWh
			189,500 kWh

	Pressure level:
Existing conditions:	
Compressor pressure level:	8,5 – 9,0 bar
Demand at the machine	6,5 bar
New condutions:	
Compressor pressure level:	7,3 – 7,8 bar

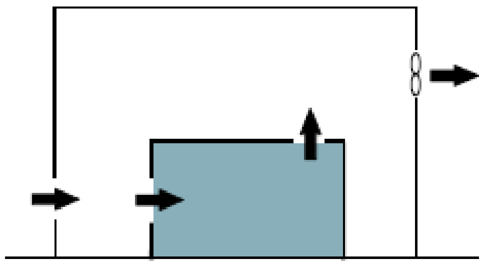
- By using the load curve (data sheet) we find that the specific enery consumption for the compressor at 9 bar is 0.121 kWh/m³, and at 7.8 bar it is 0.111 kWh/m². A reduction of about 8 %
- → 15 MWh saved, 0 €$ invest

Change of air intake

- Compressor performance and energy consumption depends also on

Temperature of the intake air.

*π: $\Delta T = 3\ K$ → 1 % change of energy consumption



Example:

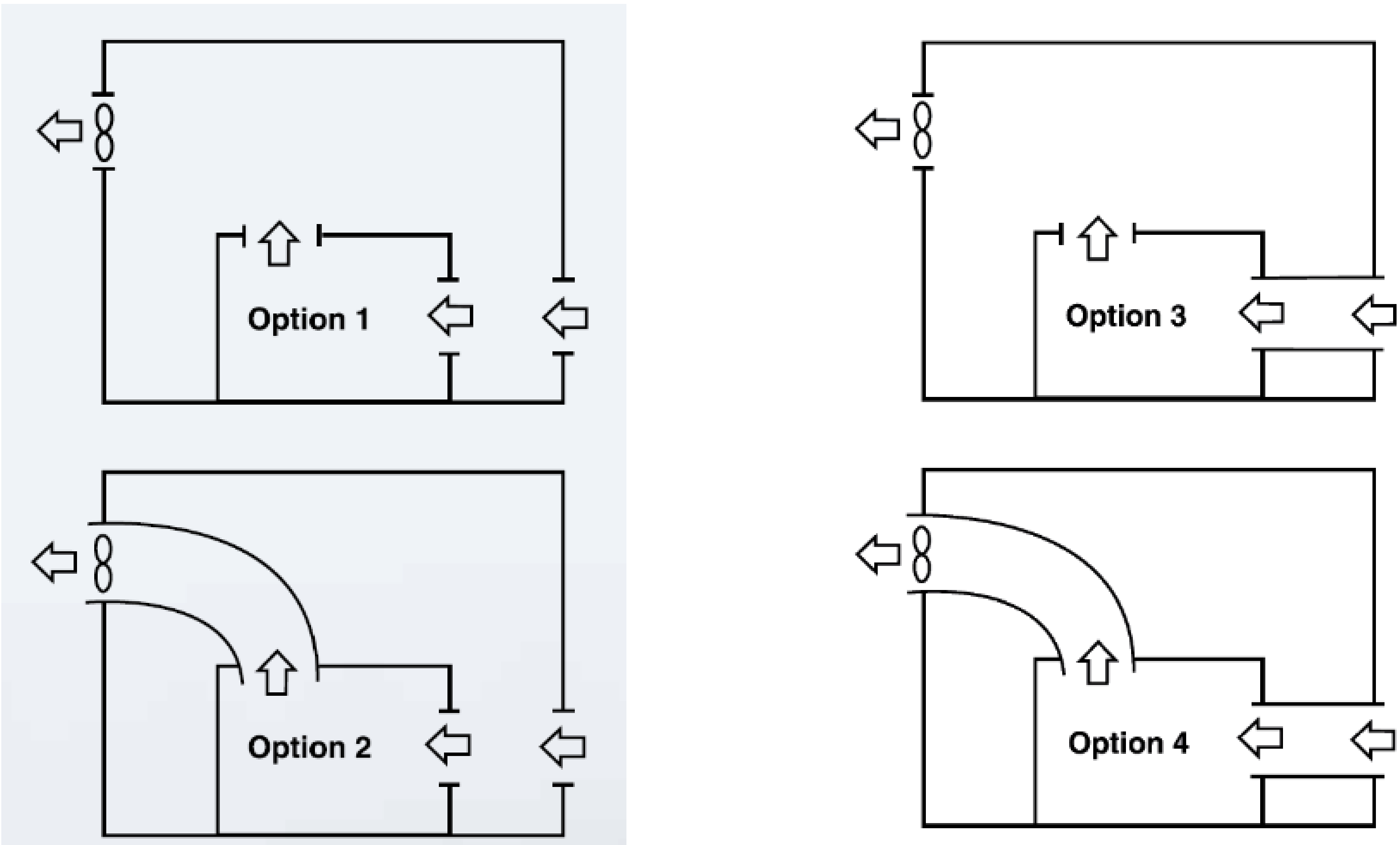
$P_{el} = 59\ kW$ $t = 3000$ hours

$T_{air\ supply} = 40\ °C$

By using air from the outside through a flue the air intake temperature can be reduced by 8 K.

$E_{savings} = P * t * (8\ K / 3\ K)) = 59\ kW * 3000\ h * 2.6\ \% = 4720\ kWh$

Examples of different ventilation solutions



Source: Atlas Copco

Leakages

+ Leakages can often are 10 - 30 % of compressed air systems consumption
+ At night (or other off times) the compressor should not be running more than 1 out of 12 hrs.

Leak size	Energy	Cost
mm	kWh	€/yr
1	3800	380
3	35,000	3,500
5	96,000	9,600
10	380,000	38,000
		Base: 8,000 h/a, 7 bar, 0,1 €/kWh

Minimizing leakages

- It is impossible not to have leaks in a compressed air system
- But leaks mean loss of energy!
- If you leakage rate is more than 5 % of produced air – a leakage search & repair mission is needed
- Leakage rate is determined by measurement:
  - Load and unload effect, kW
  - In 30 minutes: the running time loaded and unloaded
- Choose a period where there is no production (evening, weekend)
  - Load effect: 59 kW
  - Unload effect: 15 kW
  - **Load time: 6 minutes out of 30 minutes → leakage rate of 20 %**
  - Total running time: 3000 hrs
  - Actual leakage rate: 20 % of (59-15) kW * 3,000 hrs = 26,400 kWh
  - Obtainable leakage: 5 % of (59-15) kW * 3,000 hrs = 6,600 kWh

  SAVING **19,800 kWh**

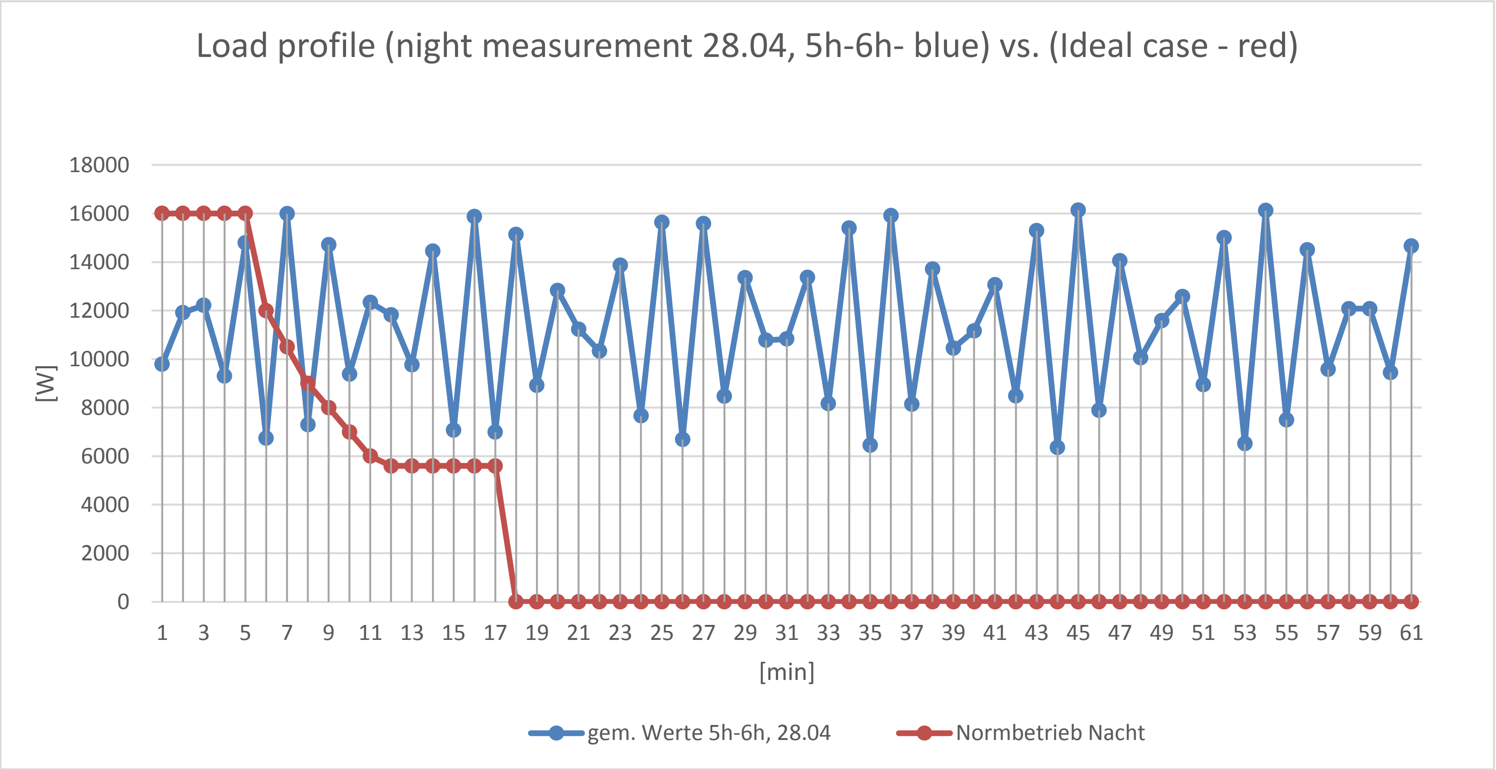
Leak reduction

- The sources of leakage are numerous, but the most frequent causes are:
  - Manual condensate drain valves left open.
  - Failed auto drain valves.
  - Shut-off valves left open.
  - Leaking hoses and couplings.
  - Use of jubilee clips that develop leaks.
  - Leaking pipes, flanges and pipe joints.
  - Strained flexible hoses.
  - Leaking pressure regulators.
  - Air-using equipment left in operation when not needed.

Leak reduction

- There are three main ways to check for leaks:
  - Listen – run the compressor without using any air tools or equipment. Make sure that there is as little background noise as possible and then walk slowly around the system listening for hissing or rasping sounds. Check all joints, flanges and valves carefully.
  - Look – make up a simple solution of soapy water. Run the system without using air tools or equipment. Apply the solution to all pipework (especially joints) and then look to see where it bubbles up, indicating air leakage.
  - Detect – hire or purchase ultrasonic leak detection equipment from the compressed air system supplier.

Off-time measurement



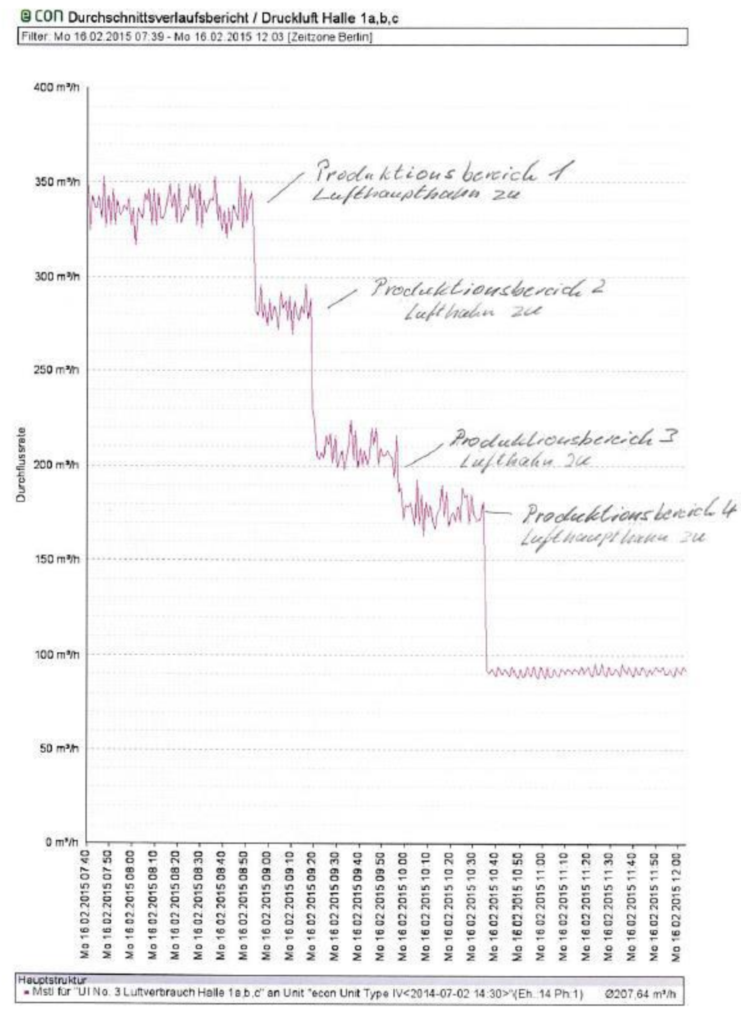
Partial switch down

- Switch off of users
- Partial switch down of production area
- Monitoring of air feed rate, capacity o

on-off intervals

→ Monitor remaining air demand

→ Rank production areas



Leakage find & repair mission

- Experience shows that the likelihood of leaks is greater, the closer one gets to the end user.

Proceed with the leakage detection as follows:

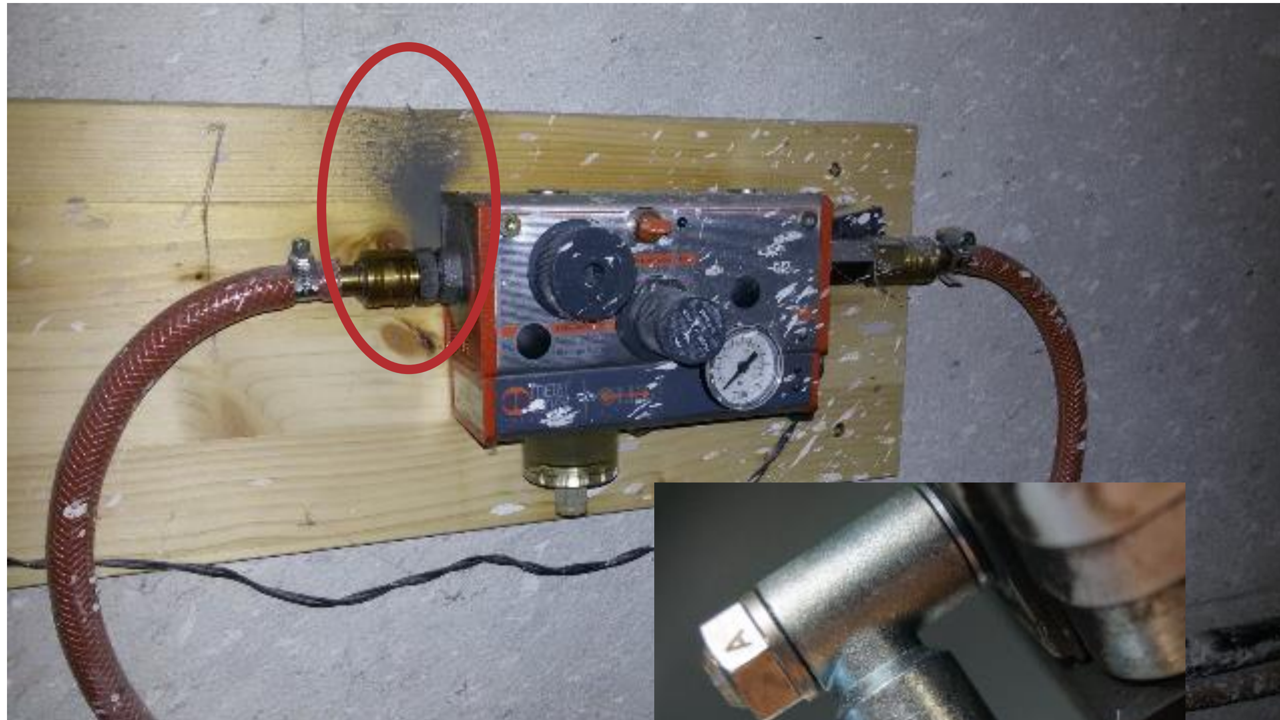
- Check with the **ultrasonic measuring** systematically the pipeline and the compressor, dryer, tank, steam traps and filters for leaks.
- Check especially carefully unions, couplings, and branches of the pipeline network.
- Do not forget the ports of machinery and equipment.
- **Mark detected leaks** clearly visible - for example, with bright colored adhesive labels.
- To ensure that during the subsequent elimination no leak is forgotten.

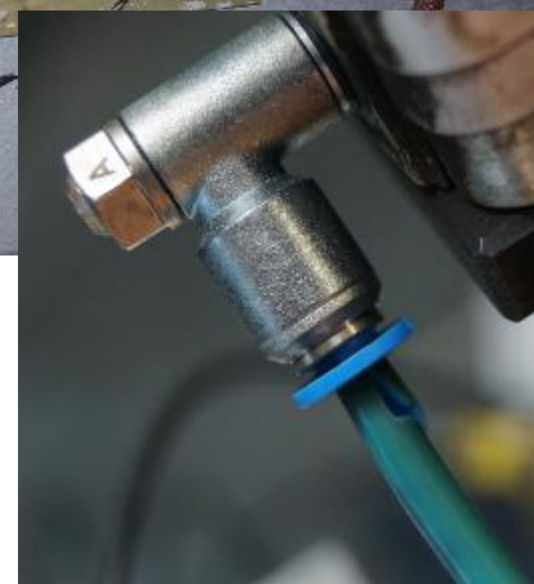
Eliminate the identified and marked leaks in the system as follows:

- Glands: tighten loose screws and replace old, leaky glands.
- O-rings: use proper O-rings correctly and replace any damaged O-rings.
- Coupling plug nipple: Replace.
- Hose clamps: Tighten or replace.
- Hoses: replace brittle, leaking pipes (for example, glassy PVC tubing) or shorten them.
- Valve or cylinder: let the valve or the cylinder repair or replace by the skilled artisan.
- pneumatic components: replace the seals.
- Maintenance units: Replace sealings or replace at all

Leakages – search & repair mission

Leakages – search & repair mission





Leakages – search & repair mission

Sectionizing the system

- Sectionizing is relevant if:
  - A few machines need high pressure and the rest of the system is driven at the past/lower pressure level
  - Only a few items needs compressed air when the industry does not operate
    - Compressed air motors for stirring primers and adhesives
- During an energy audit the following conditions need to be examined:
  - Is it possible to close off when production sections are not operating → Install manual or automatic valves
  - Is it possible to use a smaller compressor for off-production time
  - Is it possible to use reduction valves

Sectionizing the system

- A huge compressor delivers compr. Air to a few fire shutters in periods without production
- To calculate the energy saving potential by using a smaller compressor the following measuring is needed:
  - Load and unload effect, kW
  - In 30 minutes the running time @ load and unload
- You also need the compressor output in m²/min, which is normally is plate data or on the controller

Load effect	Un-load effect	Running time (load/unload)	Compressor output	Running team
59 kW	25 kW	1.5 min/6.5 min	8 m³/min	2000 h/a
Average effect	31 kW	Average output	1.5 m³/min	be able

	Average effect	Running time	Energy
Actual setup	31 kW	2,000 h	62,000 kWh
New setup	11 kW	2,000 h	22,000 kWh
		Enery Saving	40,000 kWh

Operational control

- Improve control parameters
  - Δp for on/off pressure above 1 bar and below 0.5 bar
- Load factors: should be at least 70 %
- for peak load compressors the goal is 90 %
- If unload fraction is 20-50 % action is required.
  - Replace time controlled condensate drains with electronic level controlled ones.

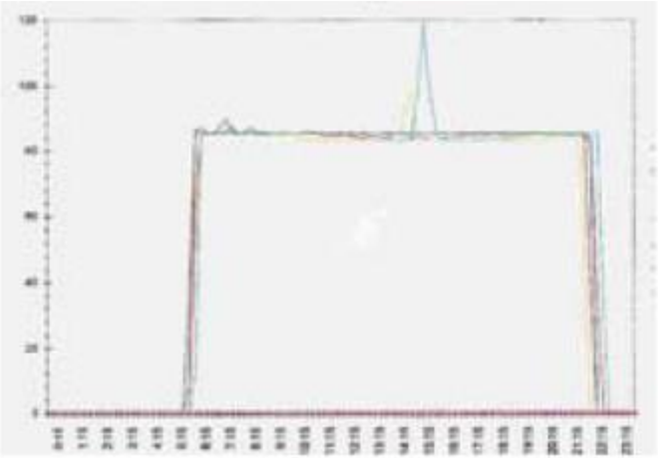
Operational control

- If the demand for compressed air is sufficiently high the stock of compressors can be either one big or a couple of small compressors.
- By a relative constantly demand for compressed air one compressor dimensioned for the need will be preferred
- By variations in the demand several compressors well regulated to the actual demand are recommended.

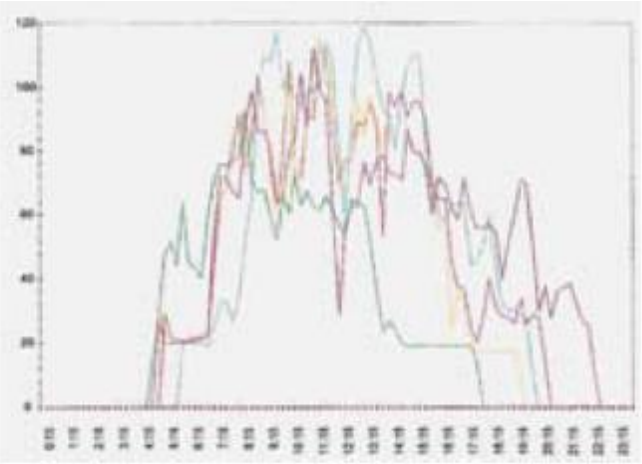
Control and regulation systems

- Regulation in general
  - Frequently, applications require constant pressure in the compressed air system. This, in turn, requires that the compressed air flow from the compressor center in order to be regulated. There are a number of flow regulation methods available, depending on the type of compressor, acceptable pressure variations, air consumption variations and acceptable energy losses.

Unload condition



Minor fluctuation of demand

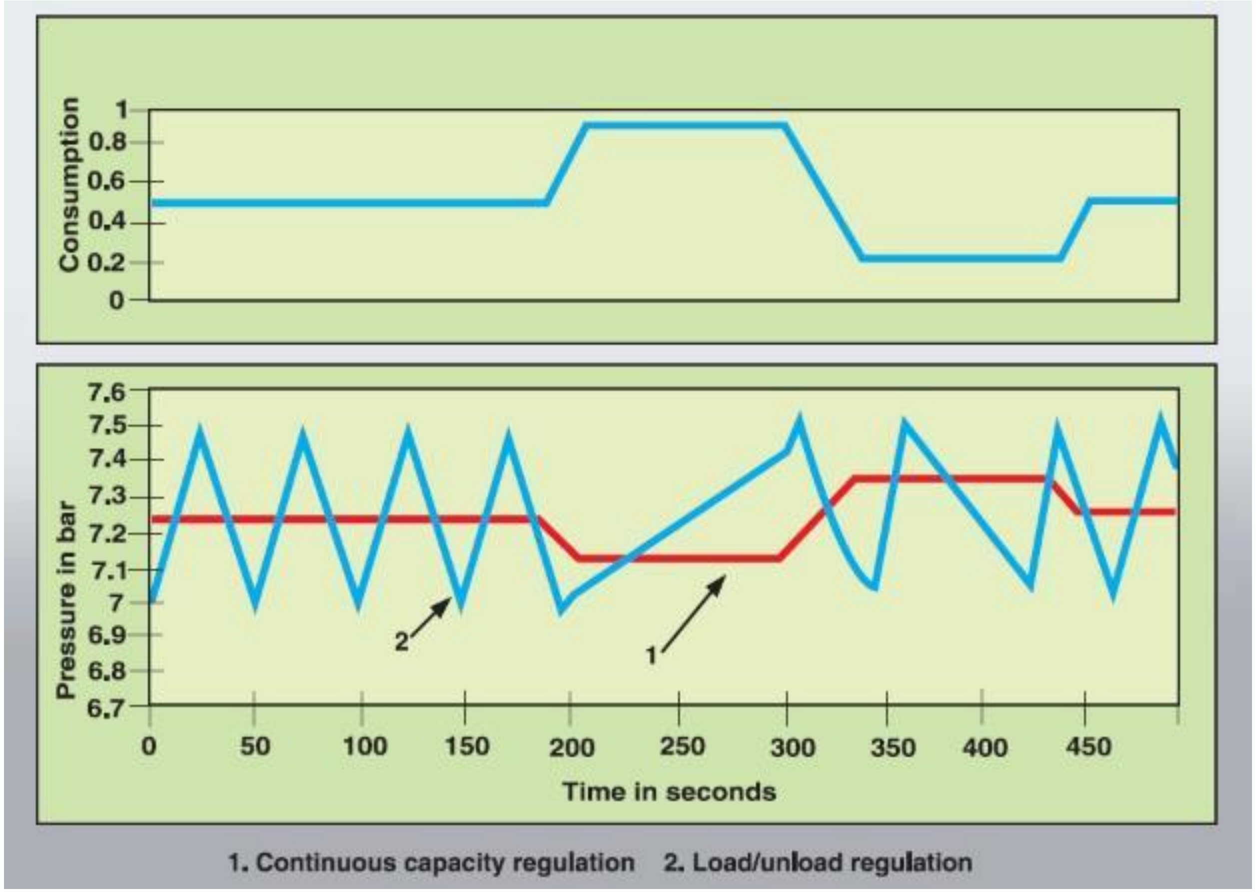


Huge fluctuations: frequent unload operation

Very common

Control and regulation systems

- Two main groups of regulation systems:



Control and regulation systems

- Two main groups of regulation systems:
  - **Continuous flow rate regulation** involves the continuous control of the drive motor or inlet valve according to variations in pressure. The result is normally small pressure variations (0.1 to 0.5 bar), depending on the regulation system's amplification and its regulating speed.
  - **Load/unload regulation** is the most common regulation method and involves the acceptance of somewhat larger variations in pressure between two limit values. This takes place by completely stopping the flow rate at the higher pressure (off-loading) and resuming the flow rate (loading) when the pressure has dropped to the lowest limit value. Pressure variations depend on the permitted number of load/unload cycles per time unit, but normally lie within the 0.3 to 1 bar range

Control and monitoring

- General
  - Regulation systems are becoming more advanced and fast-paced development offers a variety of new solutions. Relay systems have been replaced by programmable equipment (PLC), which, in turn, is currently being replaced by product-adapter systems based on microcomputers. These designs most often aim to optimize operations and costs.

Control and monitoring

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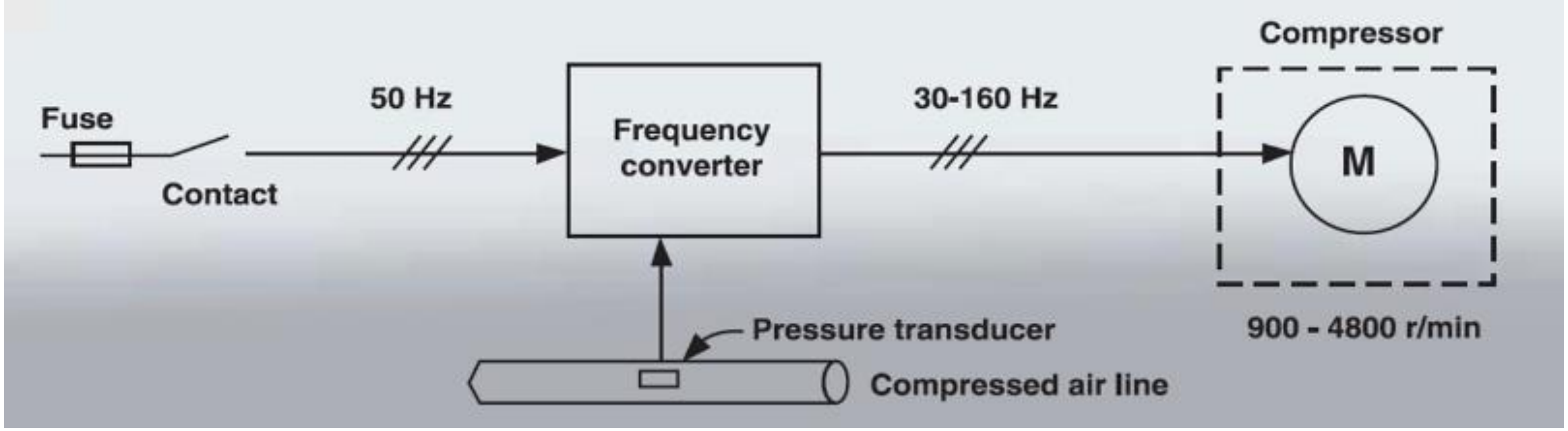


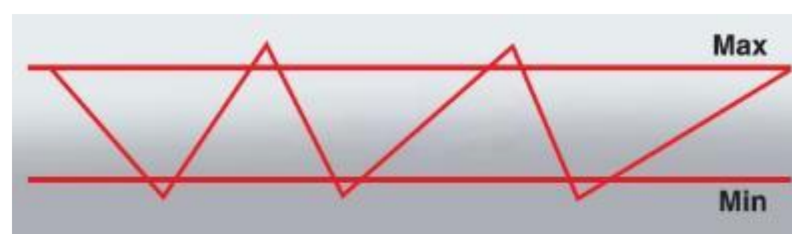
Control and monitoring

- Regulation principles for different compressors eg.:
  - Regulation principles for displacement compressors:
    - Pressure relief
    - Bypass
    - Throttling the inlet
    - Pressure relief with throttled inlet
    - Start/stop
    - Speed regulation
    - Variable discharge port
    - Suction valve unloading
    - Load–unload–stop
  - Regulation principles for dynamic compressors
    - Inlet regulation
    - Outlet regulation
    - Load–unload–stop
    - Speed regulation
- Controlling compressors according to these principles requires a regulation system that can be used either for an individual compressor or an entire compressor installation.

Control and monitoring

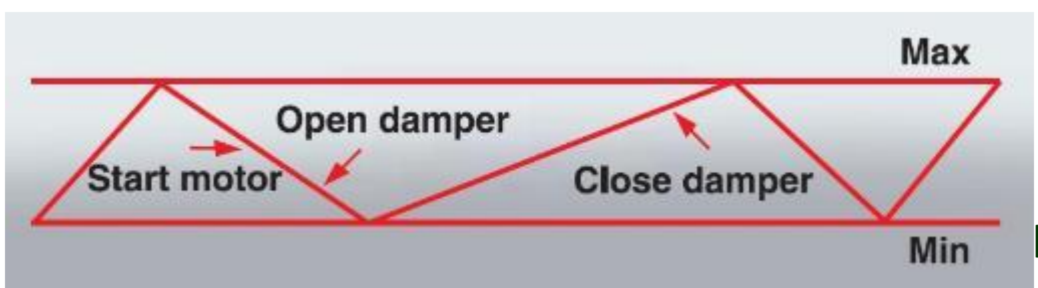
- Load–unload–stop
  - Traditional control, now common on smaller compressors, uses a pressure switch placed in the compressed air system that has two selectable values: one for the minimum pressure (= loaded) and one for maximum pressure (unloaded). The compressor will then work within the limits of the set values, for example, within a range of 0.5 bar. If the air requirement is very small, the compressor runs predominantly in off-loaded (idling) mode.
  - The length of the idling period is limited by a timer (set, for example, to 20 minutes). When the set time period elapses, the compressor stops and does not start again until the pressure has dropped to the minimum value.
  - The disadvantage of this method is that it offers slow regulation.

Pressure band, Min–Max, within which the compressor operates:
"Min" = load,
"Max" = off-load.



Control and monitoring

- Load–unload–stop
  - ⇨ A further development for this traditional system is to replace the pressure switch with an analogue pressure transducer and a fast electronic regulation system.
  - ⇨ Together with the regulation system, the analogue transducer can sense how quickly the pressure in the system changes.
  - ⇨ The system then starts the motor and controls the opening and closing of the damper at the right time. This methods offers quick and accurate regulation within ± 0.2 bar.



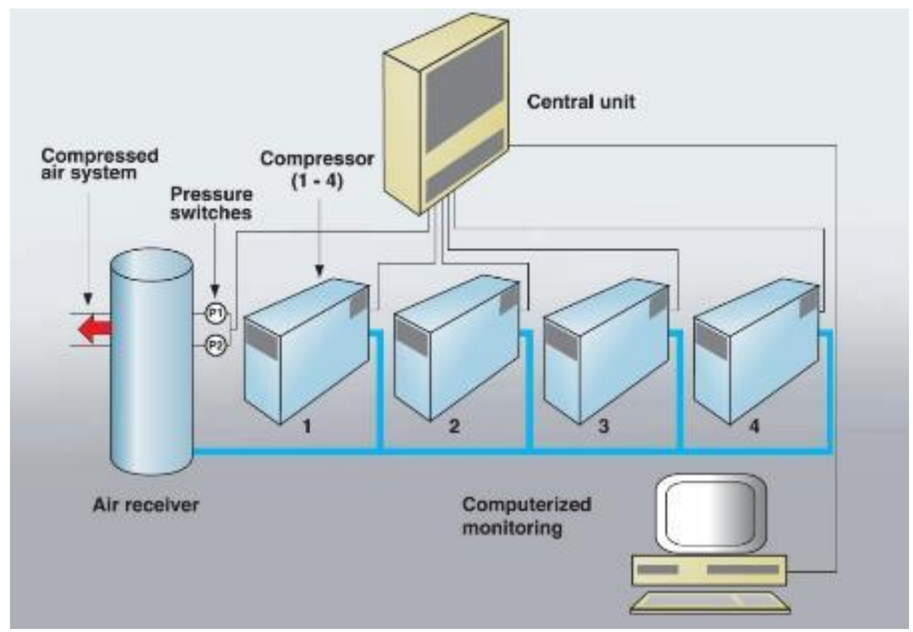
- ⇨ he motor, starter and regulator at "the right time".

Data monitoring

- All compressors are equipped with some form of monitoring equipment to protect the compressor and prevent production downtime.
- The transducer is used to sense the current condition of the installation. Information from the transducers is processed by the monitoring system, which gives a signal to an actuator, for example.
- A transducer for measuring the pressure or temperature often consists of a sensor and a measurement converter. The sensor senses the quantity to be measured.
- The measurement converter converts the sensor’s output signal to an appropriate electrical signal that can be processed by the control system
  - Temperature measurement
  - Pressure measurement

Data monitoring – central control

- Central control in association with compressors usually signifies relatively intelligent control systems. The basic demand is to be able to maintain a predetermined pressure within tight limits and to provide economic operation for the installation. To achieve this, the system must be capable of predicting what will happen in the system, while at the same time sensing the load on the compressor.

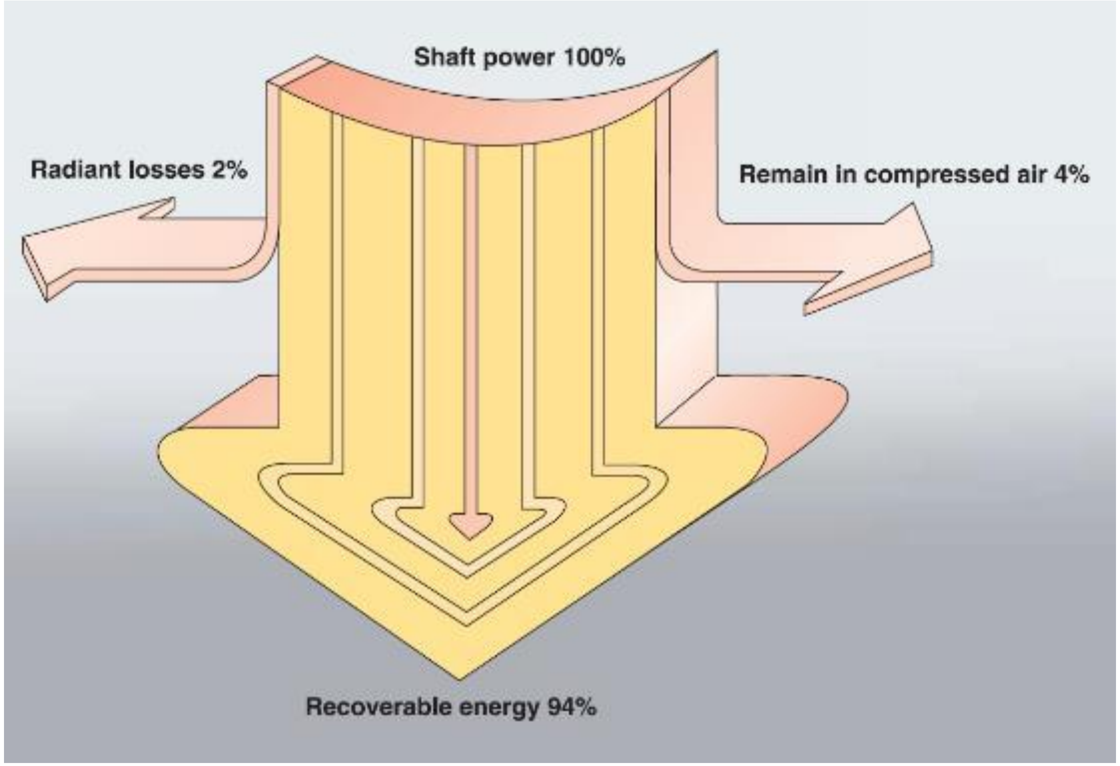


Energy recovery

- When air is compressed heat is formed. Before the compressed air is distributed into the pipe system the heat energy is extracted, and becomes waste heat. For each compressed air installation, the issue of sufficient and reliable cooling capacity for the installation must be addressed. Cooling can take place either by means of the outdoor air or a cooling water system that uses municipal water, stream water or process water in an open or closed system.
- Many installations that produce compressed air offer significant and frequently unutilized energy saving possibilities in the form of waste energy recovery. In large industries, energy costs can amount to 80% of the total cost of compressed air production. As much as 94% of the energy supplied to the compressor can be recovered, for example, as 90° hot water from oil-free screw compressors.

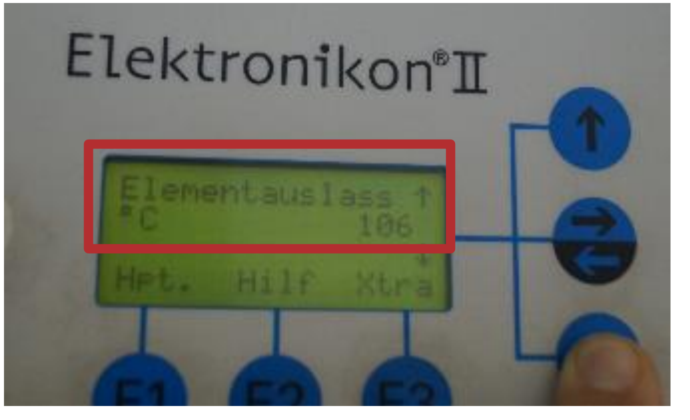
Energy recovery

- As heat is the unavoidable by-product of compression, energy can be recovered in the form of hot water from the compressor cooling system.



Heat recovery

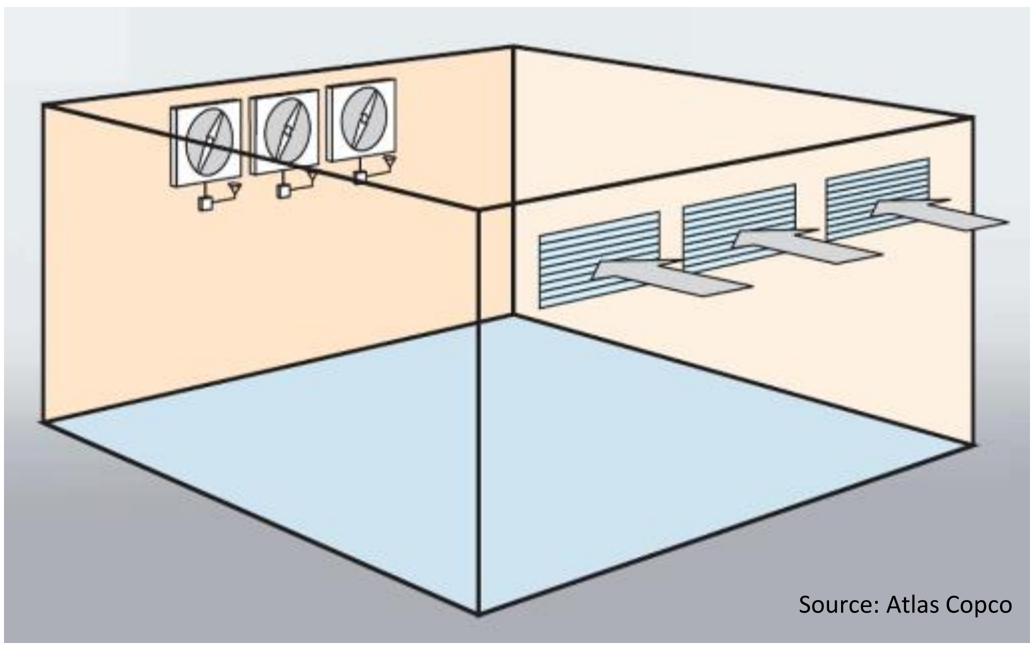
- Heat recovery systems can reuse 85 % of the losses of a compressor
- Heat recovery systems are dependent on:
  - ⇨ Heating energy demand of the company
  - ⇨ Simultaneity of the compressor operation and the heat demand
  - ⇨ Spatial proximity to the compressor: Heat distribution / heat consumers
  - ⇨ Temperature level of waste heat must be sufficient for heat consumers
  - ⇨ Screw compressors are suited best for heat recovery
- Air cooled compr.: 80 – 90 % is useable, at 60-70 °C
- Water cooled compr: 50 – 60 % is useable, at higher temper. levels



Load effect:	Load time:	Heat recovery:	Saving:
59 kW	3.000 hours	0,85	150.000 kWh

Compressor room ventilation

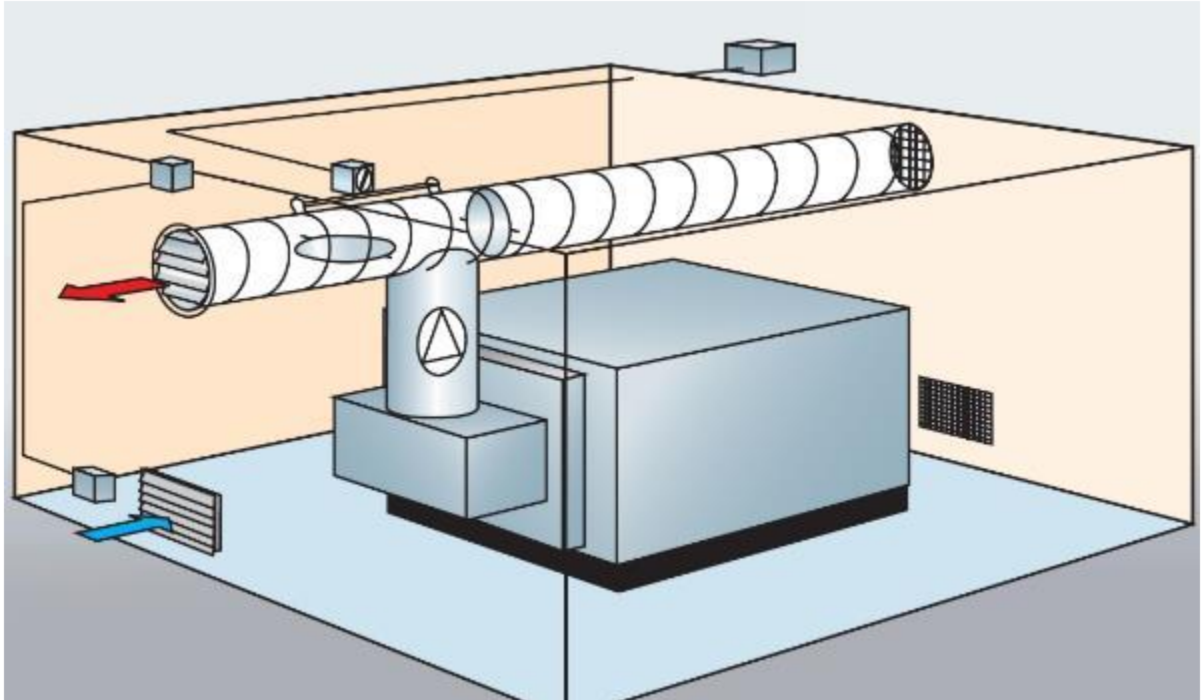
- Heat in the compressor room is generated from all compressors. This heat is let off by ventilating the compressor room. The quantity of ventilation air is determined by the size of the compressor and whether it is air or water cooled.
  - ⇨ System with several thermostat-controlled fans, which together can handle the total ventilation requirement.



Source: Atlas Copco

Energy recovery

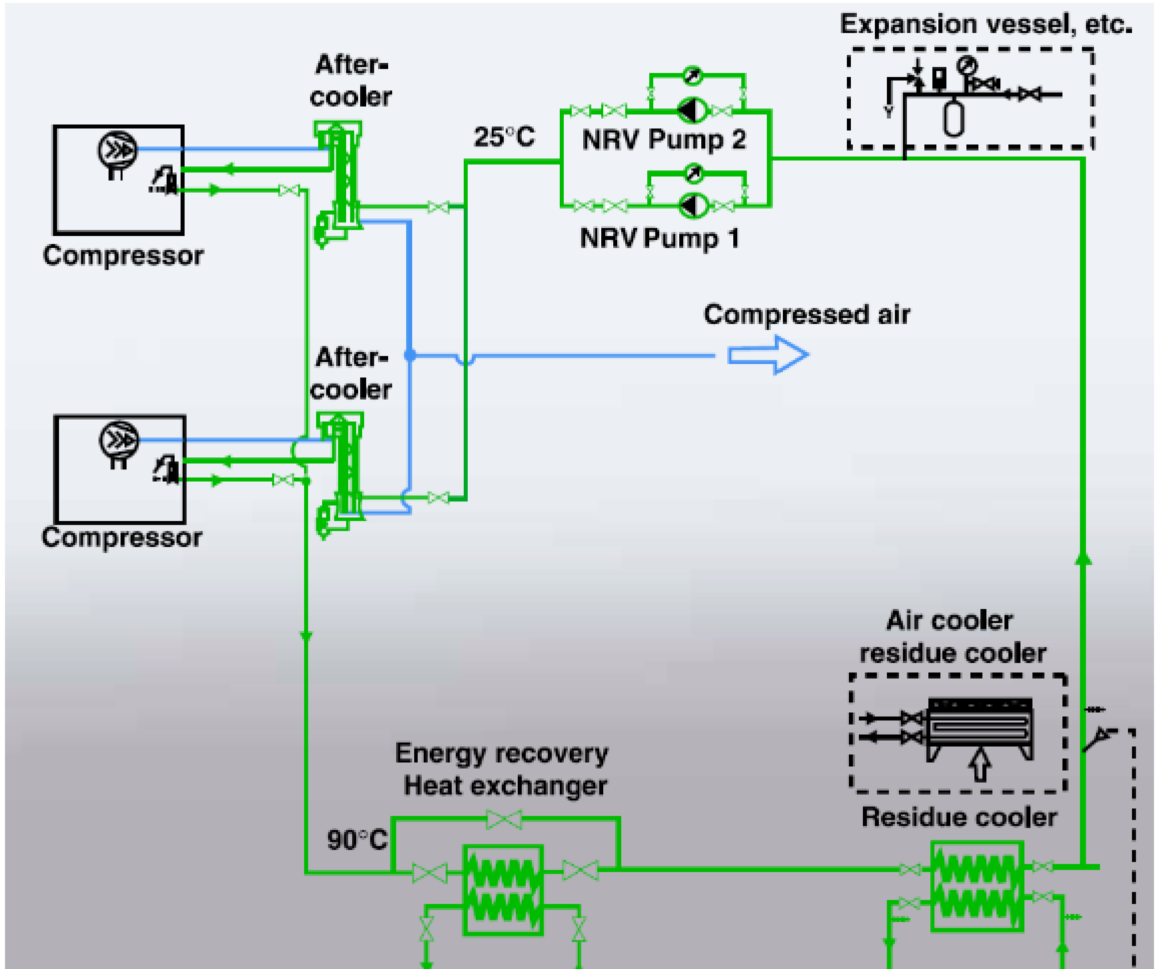
- Energy recovery from an air-cooled compressor.



Source: Atlas Copco

Heat recovery from water cooled compressors

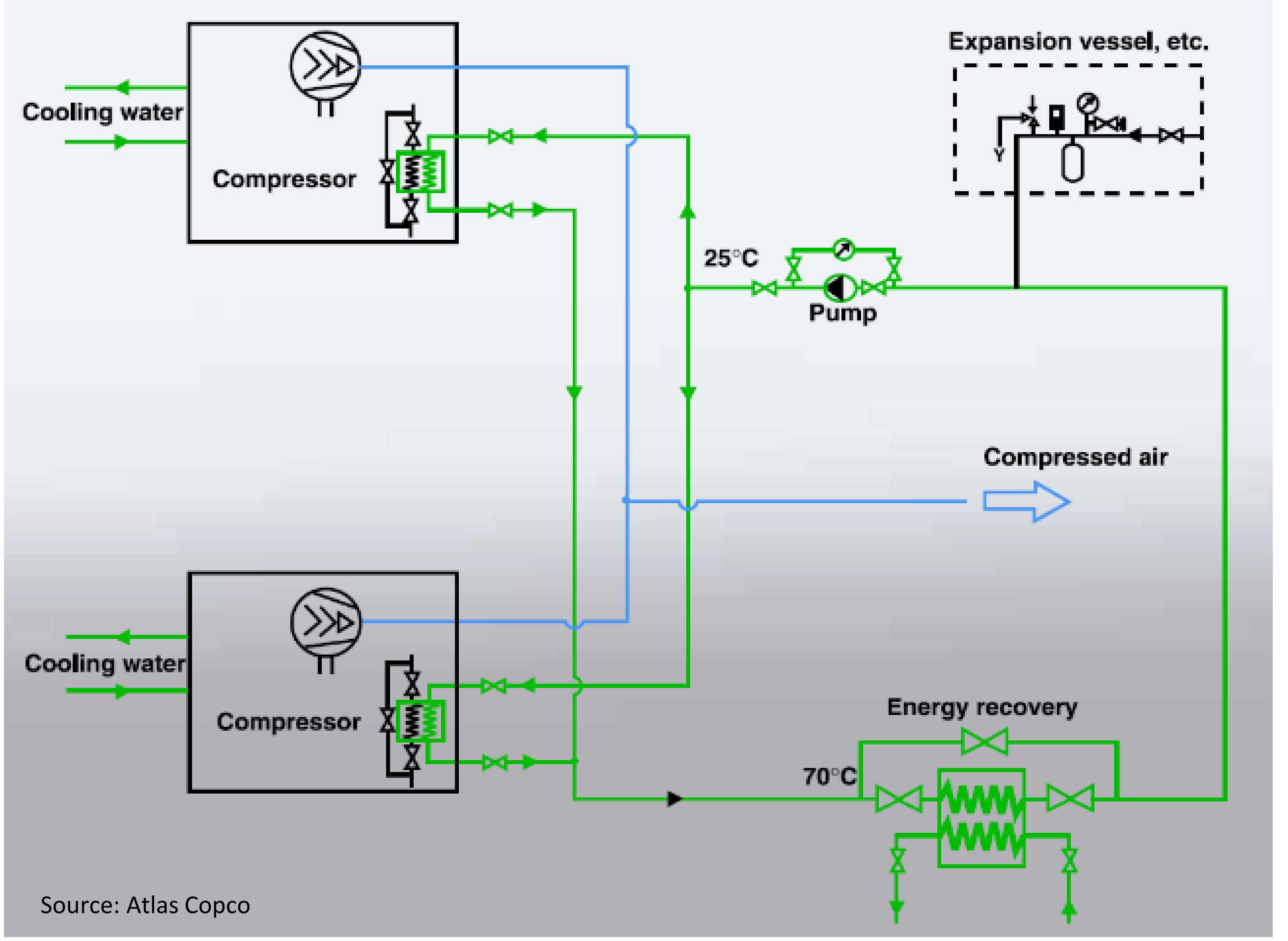
- Oil free screw compressors



Source: Atlas Copco

Heat recovery from water cooled compressors

- Oil lubricated screw compressors



Source: Atlas Copco

Heat recovery – internal heat exchanger

Source: Kaeser

Heat recovery toolbox

by Kaeser

http://www.kaeser.co.ke/Online_Services/Toolbox/Heat_recovery/default.asp


Source: Kaeser

Calculating Heat Recovery

Calculating the recoverable heat of a rotary screw compressor

Please use a decimal point and not a comma to indicate the decimal place!
The blue rows indicated contain results.

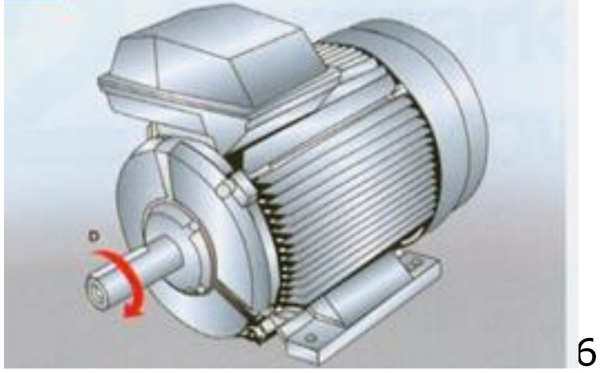
- (●) SI - Units
- ( ) US - Units

- (●) Space heating with hot exhaust air
- ( ) Water heating

Motor power output at working pressure	0	kW
Motor efficiency	0	%
Load hours per day	0	h
Motor power consumption	0	kW
Useable energy per full load hour	0	kWh
Heating period per year	0	days
Price heating oil	0.70	$/l
Calorific value of heating oil	9.8	kWh/l
CO_2 emissions heating oil	2.8	kg CO_2/l
Central heating efficiency	90	%
Savings	0	$/year
	0	kWh/year
	0	kg CO_2/year
Price natural gas	0.75	$/m³
Natural gas calorific value	10.2	kWh/m³
CO_2 emissions natural gas	2	kg CO_2/m³
Central heating efficiency	105	%
Savings	0	$/year
	0	kWh/year
	0	kg CO_2/year

Electrical installation

- Motors
  - For the most part, three-phase squirrel cage induction motors are used for compressor operations. Low voltage motors are generally used up to 450 – 500 kW, whereas for higher power, high voltage motors are the best option.
  - The motor protection class is regulated by standards.
  - The dust and water jet-resistant design (IP55) is preferred over open motors (IP23), which may require regular disassembly and cleaning.
  - In other cases, dust deposits in the machine will eventually cause overheating, resulting in shortened service life. Since the compressor package enclosure provides a fi rst line protection from dust and water, a protection class below IP55 may also be used.

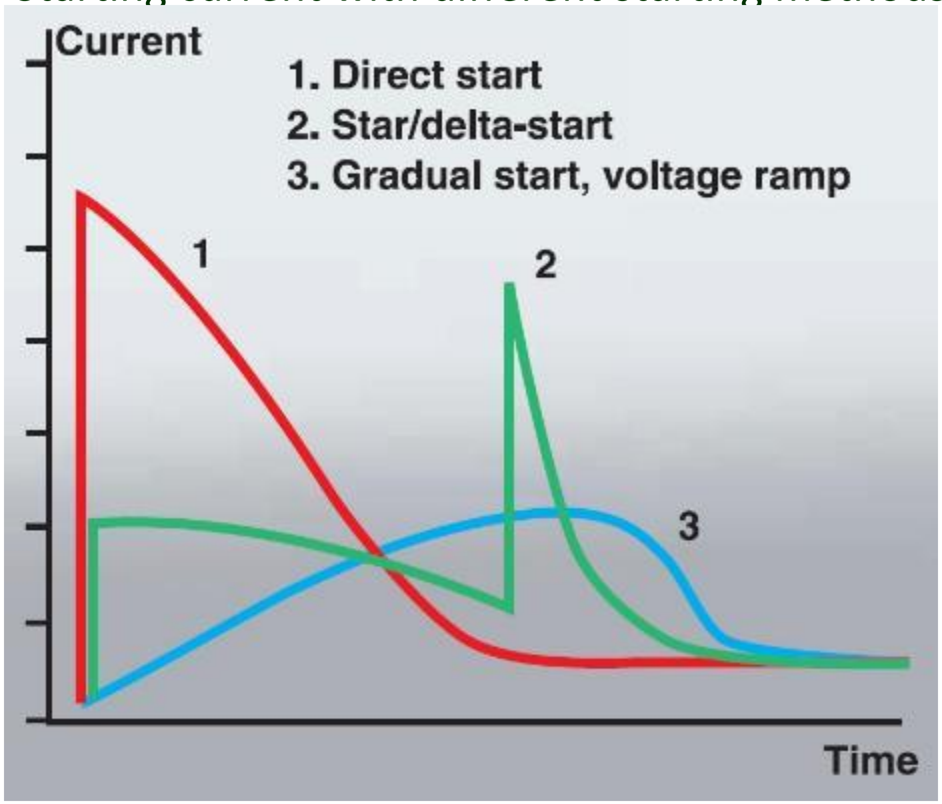


Electrical installation

- Starting methods
  - The most common starting methods are:
    - Direct start
      - Direct start is simple and only requires a contactor and overload protection. The disadvantage it presents is its the high starting current, which is 6–10 times the motor's rated current, and its high starting torque, which may, for example, damage shafts and couplings.
    - Star/delta–start
      - The star/delta–start is used to limit the starting current. The starter consists of three contactors, overload protection and a timer. The motor is started with the star connection and after a set time (when the speed has reached 90% of the rated speed), the timer switches the contactors so that the motor is delta-connected, which is the operating mode
    - Soft start.
      - Soft start (or gradual start), which can be an alternative start method to the star/delta–start, is a starter composed of semiconductors instead of mechanical contactors. The start is gradual and the starting current is limited to approximately three times the rated current

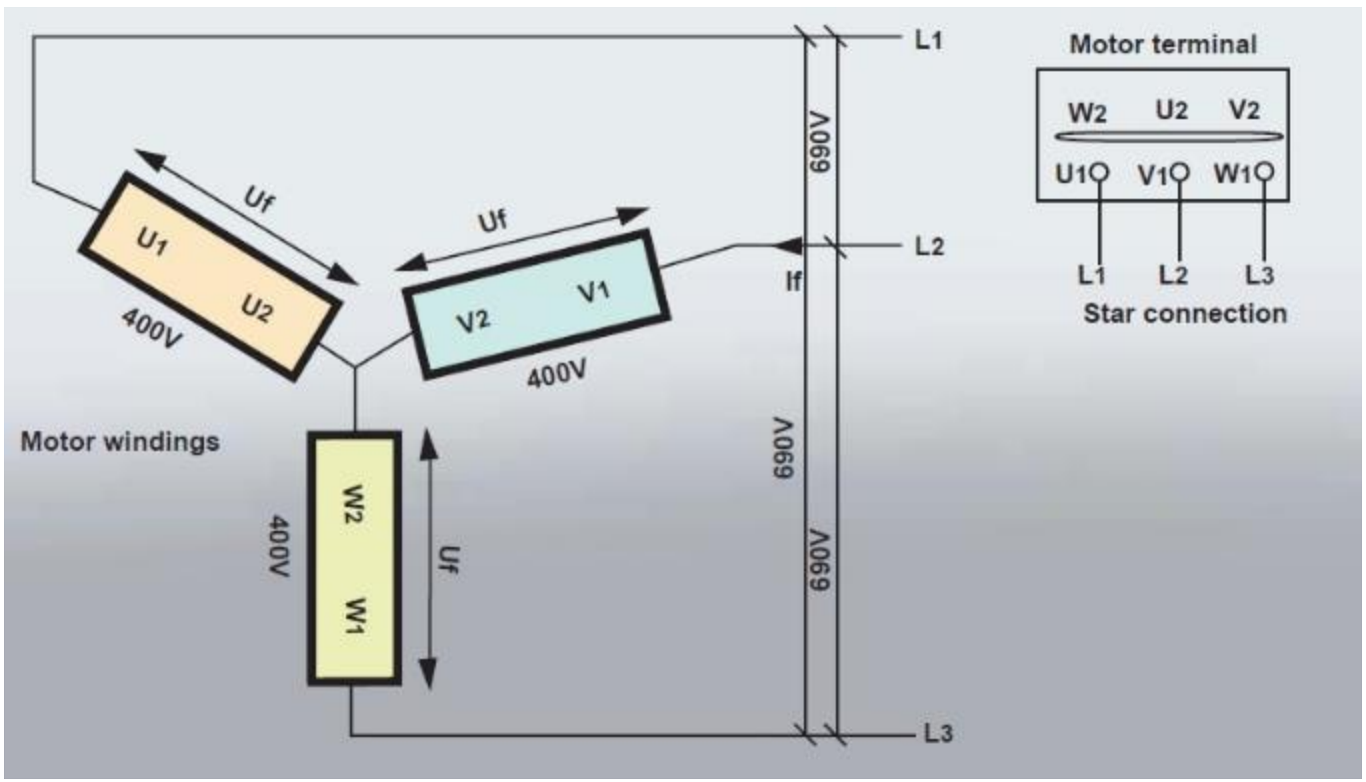
Electrical installation

- ➢ Starting methods
  - ⇨ Starting current with different starting methods



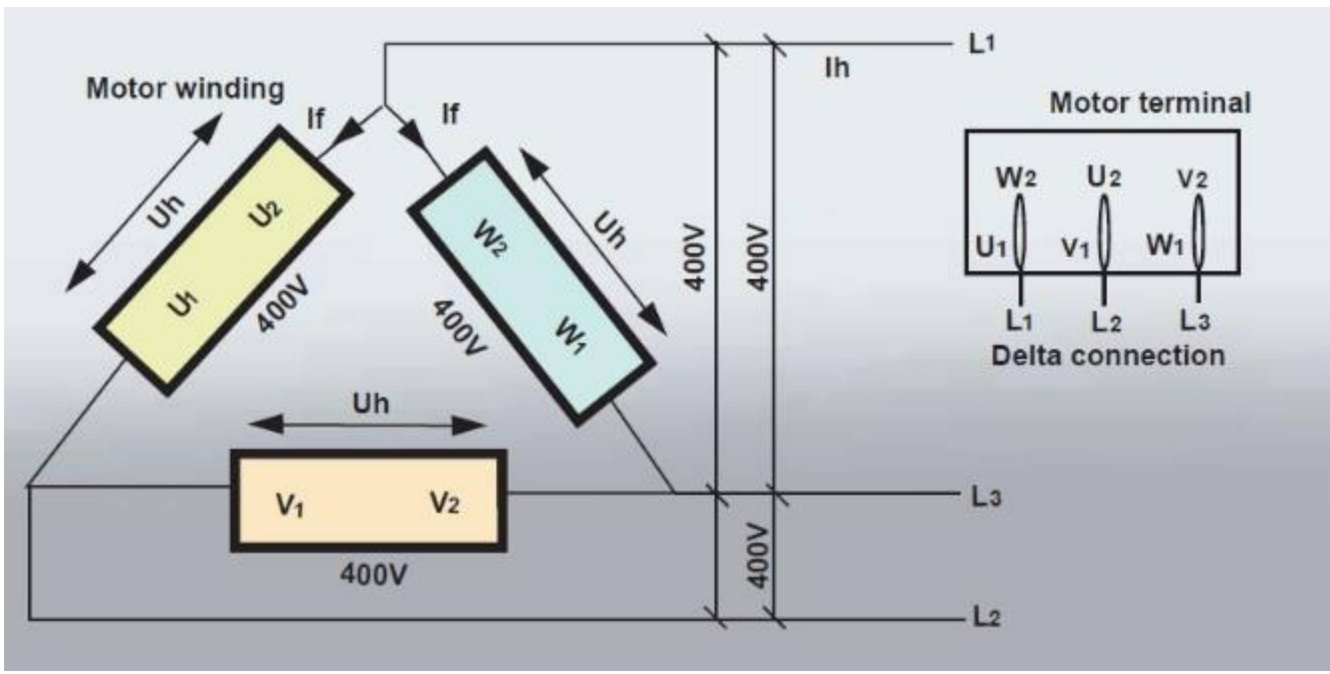
Electrical installation

- Starting methods
  - The motor windings connected in a star configuration, and how the connection strips are placed on the star-connected motor terminal. The example shows the connection to a 690V supply



Electrical installation

- Starting methods
  - The motor windings connected in a delta configuration, and how the connection strips are placed on the delta-connected motor terminal. The example shows the connection to a 400V supply.

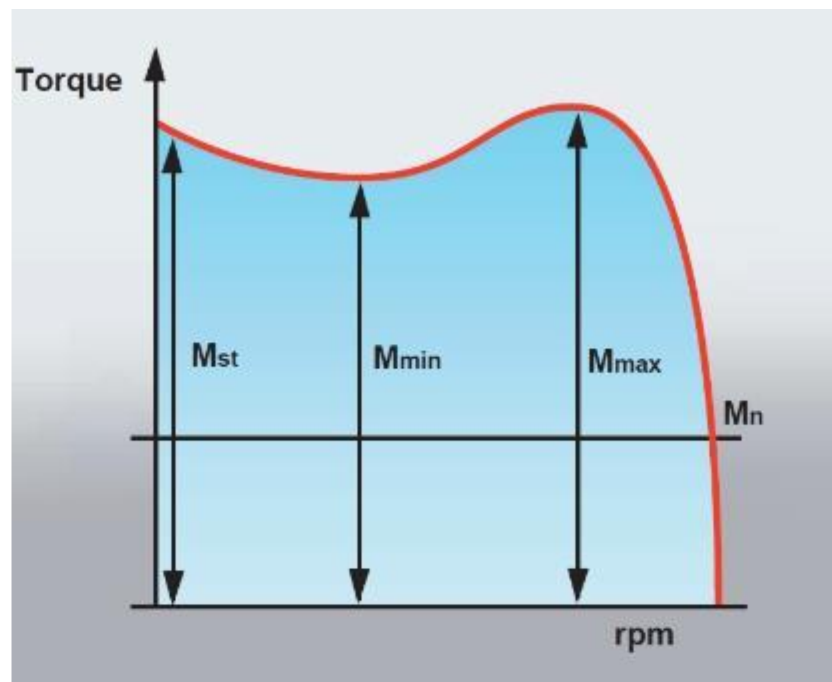


Electrical installation

- Torque
  - An electric motor's turning torque is an expression of the rotor turning capacity. Each motor has a maximum torque. A load above this torque means that the motor does not have the capability to rotate. With a normal load the motor works significantly below its maximum torque, however, the start sequence will involve an extra load.
  - The characteristics of the motor are usually presented in a torque curve.

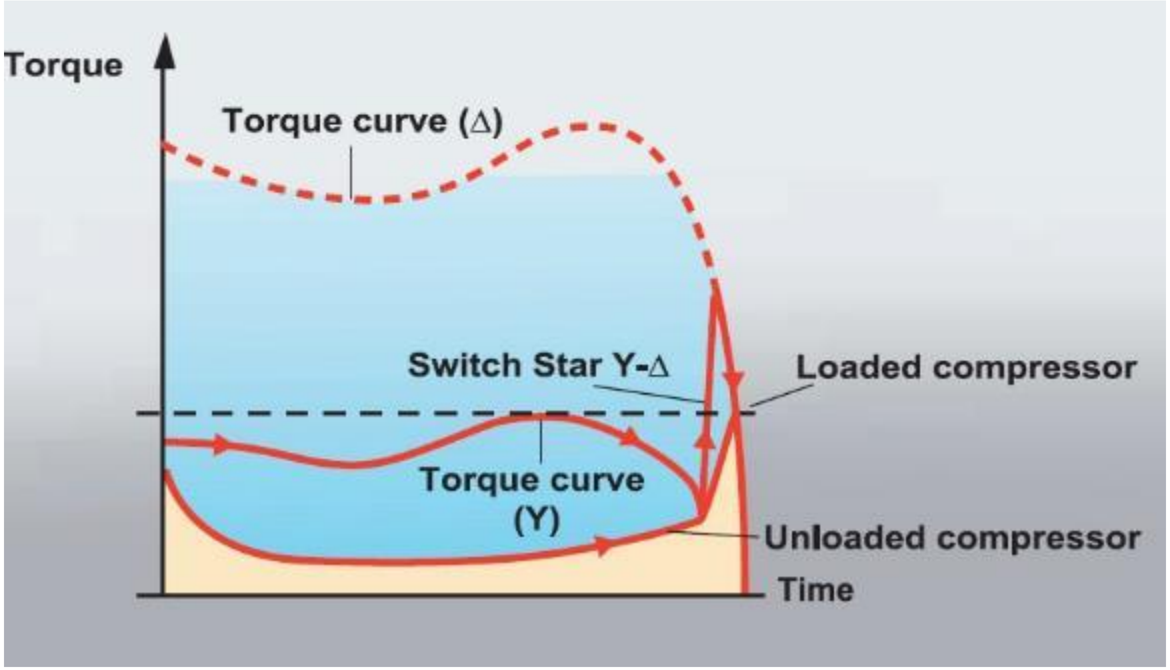
Electrical installation

- Torque
  - The torque curve for a squirrel cage induction motor.
  - When the motor starts the torque is high.
    - M_{st} start torque
    - M_{max} max torque ("cutting torque")
    - M_{min} min. torque ("saddle torque")
    - M_n rated torque



Electrical installation

- Torque
  - The torque curve for a squirrel cage induction motor. A star/delta started induction motor torque curve combined with a torque demand curve for a screw compressor. The compressor is unloaded (idling) during star operations. When the speed has reached approx. 90-95% of the rated speed the motor is switched to the delta mode, the torque increases, the compressor is loaded and finds its working point



Standards and regulations

- Standards are referred to frequently by legislators as a way of creating uniform market impacts. Standards may be produced, issued and maintained by standardization organizations on national, supranational (European) and international levels, but equally by specific trade associations focusing on specific industrial sectors (the petroleum industry, compressed air industry, electronics industry etc.).
- Standards produced by the International Organization for Standardization (ISO) may be converted into national standards by the ISO member countries at their discretion. Standards produced by the CEN (European Committee for Standardization), are developed for use by the 30 national members, and conversion into national standard may be mandatory in the case of harmonized standard

Standards and regulations

- Pressure equipment safety
  - EU Directive 87/404/EC, Simple pressure vessels
  - EU Directive 97/23/EC, Pressure Equipment, referring to the following standards:
    - EN 764-1 to 7, Pressure equipment
    - EN 286-1 to 4, Simple, unfired pressure vessels designed to contain air or nitrogen

Standards and regulations

- Environment
  - EU Directive 2000/14/EC, Outdoor Noise Emission, referring to the following standards:
    - EN ISO 3744:2009, Determination of sound power levels of noise sources using sound pressure – Engineering method
    - EN ISO 2151:2004, Noise test code for compressors and vacuum pumps – Engineering method
    - EU Directive 2004/26/EC, Emission standard for non-road engines – Stage III levels implemented from 2006 to 2013, Stage IV as from 2014

Standards and regulations

- Electrical safety
  - EU Directive 2004/108/EC, Electromagnetic compatibility, referring to the following standards:
    - EN 61000-6-2:2005, Electromagnetic compatibility (EMC) - PART 6-2: Generic Standards – Immunity for Industrial Environments
    - EN 61000-6-4:2006, Electromagnetic compatibility (EMC) - PART 6-4: Generic Standards – Emission standards for Industrial Environments
    - EU Directive 2006/95/EC, Low Voltage Equipment, referring to following standards:
    - EN 60034- Part 1 to 30, Rotating Electrical Machines – Rating and Performance
    - EN 60204-1:2009, Safety of Machinery – Electrical Equipment of Machines – Part 1: General Requirements
    - EN 60439-1:2004, Low-voltage switchgear and control gear assemblies – Part 1: Type tested and partially type tested assemblies

Standards and regulations

- Standardization
  - ISO 3857-1:1977, Compressors, pneumatic tools and machines - Vocabulary - Part 1: General
  - ISO 3857-2:1977, Compressors, pneumatic tools and machines - Vocabulary - Part 2: Compressors
  - ISO 5390:1977, Compressors - Classification

Appendix: Types of air compressors

Types of air compressor

- Dynamic compressors
  - In a dynamic compressor, the pressure increase takes place while the gas flows. The flowing gas accelerates to a high velocity by means of the rotating blades on an impeller. The velocity of the gas is subsequently transformed into static pressure when it is forced to decelerate under expansion in a diffuser. Depending on the main direction of the gas flow used, these compressors are called radial or axial compressors

Types of air compressor

- Positive Displacement compressors
  - In all displacement compressors the enclosed volume expands to a maximum and then decreases, i.e. the volume is reduced. As the volume is compressed, the pressure is produced (internal compression). When the compression pressure in the tank exceeds the back pressure in the air receiver (pressure vessel) or the main air distribution ducts (the compressed air), the pressure valve opens (reciprocating compressors) or the compressed air flows at a constant pressure to the main air distribution ducts (built in rotary screw compression ratio). Displacement compressors do not respond to installation conditions (air pressure, height above sea level, humidity and temperature).

Types of air compressor

- Typically industrial systems operate at pressures of 600-1,000 [$kPa_{(g)}$] (6-10 [$bar_{(g)}$]) using a packaged rotary air compressor (such as a rotary screw or rotary sliding vane) or a reciprocating/piston compressor.
- For applications with high flow requirements at these pressures, centrifugal type compressors are often used
- 1 [bar] = 100 [kPa] = 750,03 [mmHg]

Types of air compressor

- Packaged rotary air compressor
  - The packaged rotary air compressor is the most commonly used type, as it has the lowest capital cost with relatively low noise levels, simple installation and low maintenance costs. The most widely used of these throughout industry is the rotary screw air compressor as it has proved to be reliable and generally only requires a routine maintenance schedule. It also provides the widest range of products to choose from. These machines are available in lubricated and oil-free versions.

Types of air compressor

- Typically, the power rating of single-stage rotary screw compressors range from 2.2 kW to over 400 kW, with the more energy efficient two stage rotary screw compressors ranging from 75 kW to 900 kW.
- Rotary sliding vane compressor models range from 1.1 kW to 75 kW. These machines are very quiet and easy to install in decentralized systems and laboratories.

Types of air compressor

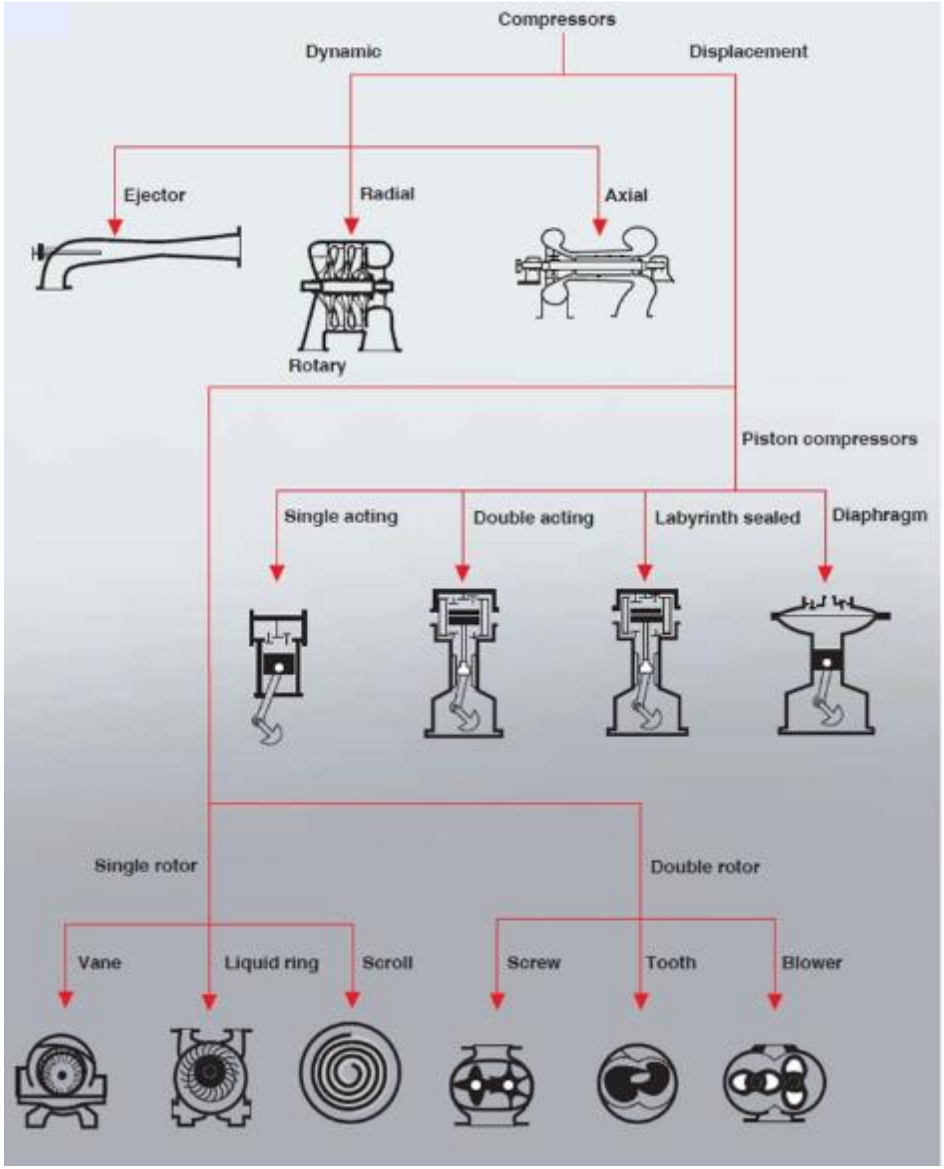
- There are still many heavy duty industrial double acting, two stage, water cooled reciprocating piston compressors, in service, with sizes up to and over 450 kW.
- While these often provide equal, or better, specific energy consumption to that of rotary compressors, they can suffer from reduced performance levels as parts begin to wear therefore, extensive maintenance and overhaul are needed to overcome this potential reduction in performance.

Types of air compressor

- As a result, reciprocating compressors can be costly to maintain by comparison to packaged units. They are also expensive and noisy with foundations often required to site medium to large-sized units, which can add significantly to installation costs. However, reciprocating compressors are still the main machine used for high pressures applications from 30 to 400 bar and for special gases.

Types of air compressor

- Most common compressor types, divided according to their working principles



Types of air compressor

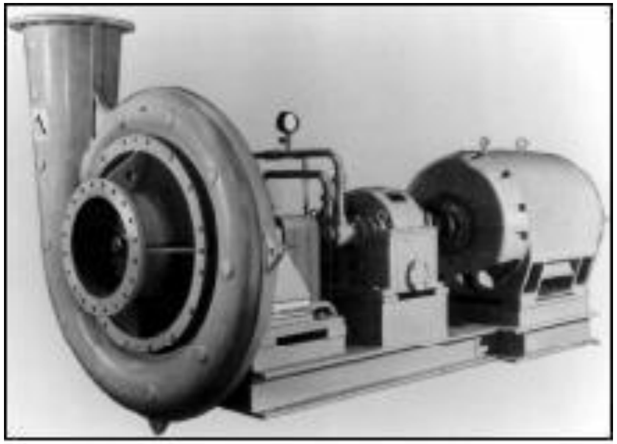
- In applications requiring a high volume of air, centrifugal compressors are often used. Although available with a flow rate from around 200 litres/s, this type of compressor is no more efficient than the rotary screw unit until flow rates of around 1,000 litres/s are needed. In this case the centrifugal compressor begins to dominate the market because of unrivalled energy efficiency and inherent oil free design

Types of air compressor

- Centrifugal compressors
  - Centrifugal compressors use a rotating disk or impeller in a shaped housing to force the gas to the rim of the impeller, increasing the velocity of the gas. A diffuser (divergent duct) section converts the velocity energy to pressure energy.
  - They are very widely used for continuous, stationary service in industries such as petroleum refineries, chemical and petrochemical plants, natural gas processing plants and many other industrial facilities.
  - Their applications can range from 100 hp (75 [kW]) to thousands of horsepower. With multiple staging, centrifugal compressors can achieve extremely high output pressures greater than 10,000 psi (69 [Mpa]).
  - Since compression generates heat, the compressed gas has to be cooled between stages. The inter-stage coolers may result in some partial condensation of the gas and the condensed liquid is removed in vapor-liquid separators.

Types of air compressor

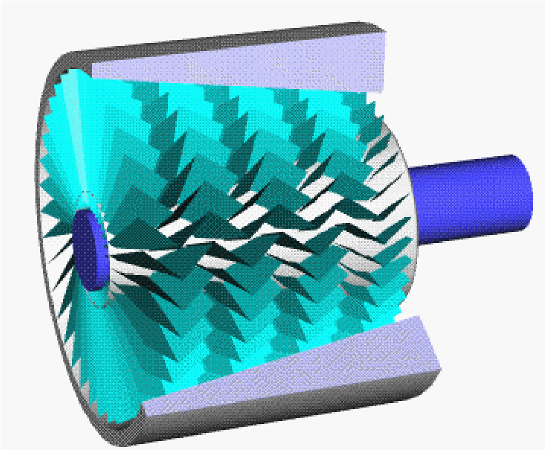
- Centrifugal compressors
  - Many large snow-making operations (like ski resorts) use this type of compressor. They are also used in internal combustion engines (as superchargers and turbochargers), in small gas turbine engines and as the final compression stage of medium sized gas turbines.



Single-stage centrifugal compressor (left) driven by electric motor (right) using gearbox (center). Gas enters compressor through flanged opening at left center and discharges from flange at upper left corner.

Types of air compressor

- Axial-flow compressors
  - Axial-flow compressors are dynamic rotating compressors that use arrays of fan-like airfoils to progressively compress the working fluid. They are used where there is a requirement for a high flows or a compact design
  - Axial compressors can have high efficiencies; around 90% polytropic at their design conditions. However, they are relatively expensive, requiring a large number of components, tight tolerances and high quality materials. Axial-flow compressors can be found in medium to large gas turbine engines, in natural gas pumping stations, and within certain chemical plants.



Types of air compressor

- Reciprocating compressors
  - Reciprocating compressors use pistons driven by a crankshaft. They can be either stationary or portable, can be single or multi-staged, and can be driven by electric motors or internal combustion engines.
  - Small reciprocating compressors from 5 to 30 horsepower (hp) are commonly seen in automotive applications and are typically for intermittent duty.
  - Larger reciprocating compressors well over 1000 hp are still commonly found in large industrial and petroleum applications.
  - Discharge pressures can range from low pressure to very high pressure (>5000 psi or 35 MPa).
  - In certain applications, such as air compression,multi-stage double-acting compressors are said to be the most efficient compressors available, and are typically larger, noisier, and more costly than comparable rotary units.

Types of air compressor

- **Rotary screw compressors**
  - Rotary screw compressors use two meshed rotating positive-displacement helical screws to force the gas into a smaller space.
  - As the screws rotate, the gas is drawn into the inlet port and fills up the space between the screws. The compression begins when the end of a male thread blocks the end of a female thread. The volume available between the compressor body and these two threads then progressively decreased during rotation. When this volume merges into the delivery outlet of the compressor, compressed gas is discharged from the compressor.
  - Screw compressors are typically used for continuous operation in commercial and industrial applications and may be either stationary or portable. Their applications range from 3 hp (2.24 [kW]) to over 500 hp (375 [kW]) and from low pressure to very high pressure (>1200 psi or 8.3 [Mpa])

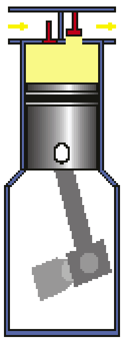
Types of air compressor

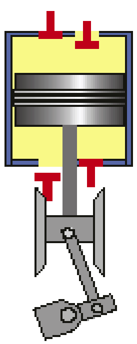
- Compressor with oil injection.
  - Precisely metered quantities of oil are continuously injected from the cooling oil to the compression chamber, which has three functions: cooling, sealing, lubrication. Oil receives and immediately dissipates heat generated during compression. It also seals the gap between the body of the compressor and compressing element (piston, a pair of rotors, with screws) and lubricate the bearings of the rotors.
  - The mixture of air and oil flows from the compression member directly to the tank oil separation. Changes in direction and reductions of the flow velocity are used to precipitate the motor oil from the compressed air, the effectiveness is more than 99%. After passing through the oil separator cartridge external the air to be compressed for use, contains a minimum residue oil about 1-3 mg/m^3.

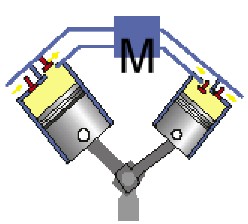
Types of air compressor

- Oil-free compressors.
  - In the oil-free screw compressors air compression process takes place without sealing the space between the compressor shell and compressing element.
  - In some cases, the water injection takes functions of oil.
  - Pressures in oil-free compressors are lower than in oil equivalents.

Types of air compressor



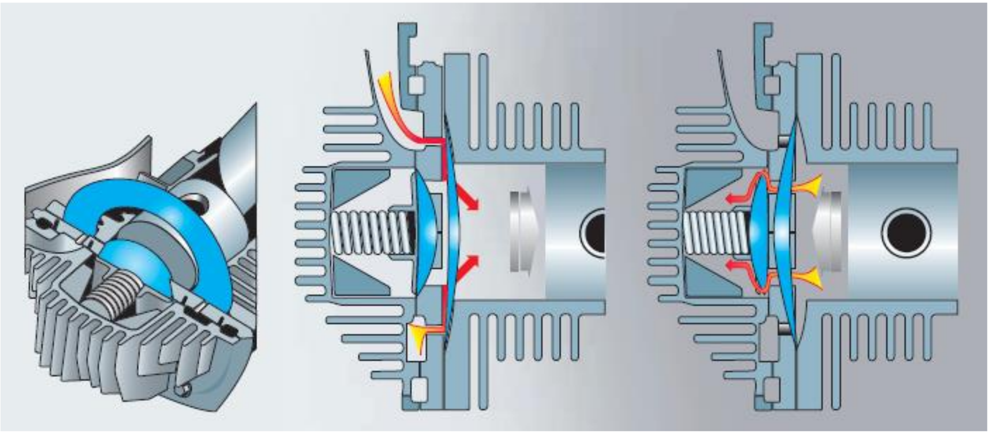


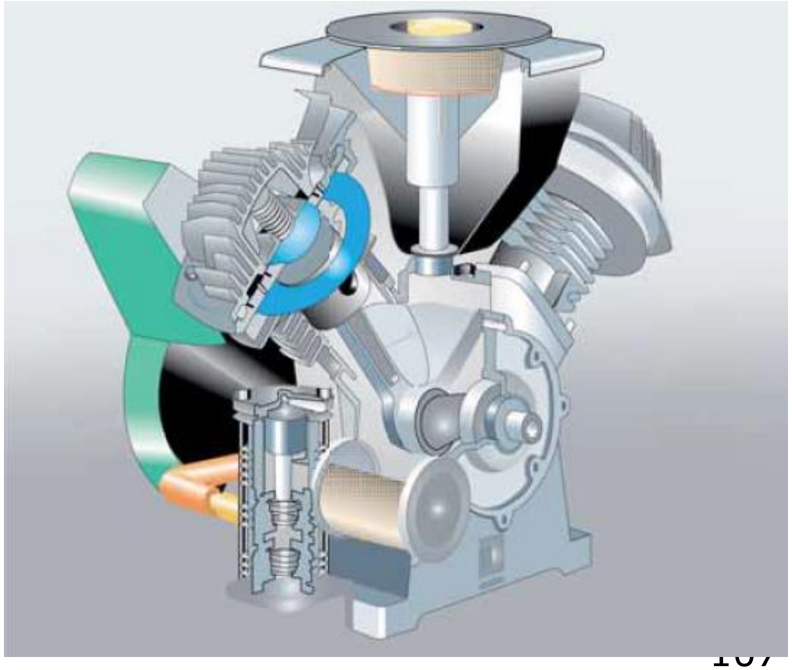


- Piston compressors
  - At the stroke of the crank the piston draws gas (air). When back stroke starts, the inlet valve closes. Then the gas (air) is compressed and pushed out by the pressure relief valve.
  - Single stage compression
    - The compression until the discharge pressure with a single stroke of the piston.
  - Two-stages compression
    - When gas enters the first stage of compression,
    - Is cooled in the intercooler and then compressed to the discharge pressure in the high-pressure cylinder
  - Advantages of piston compressors
    - The ability to compress almost all gases
    - Efficient compression for pressures up to 15 bar size
    - Economical as assist device
  - Disadvantages of piston compressors
    - A large number of wearing parts

Types of air compressor

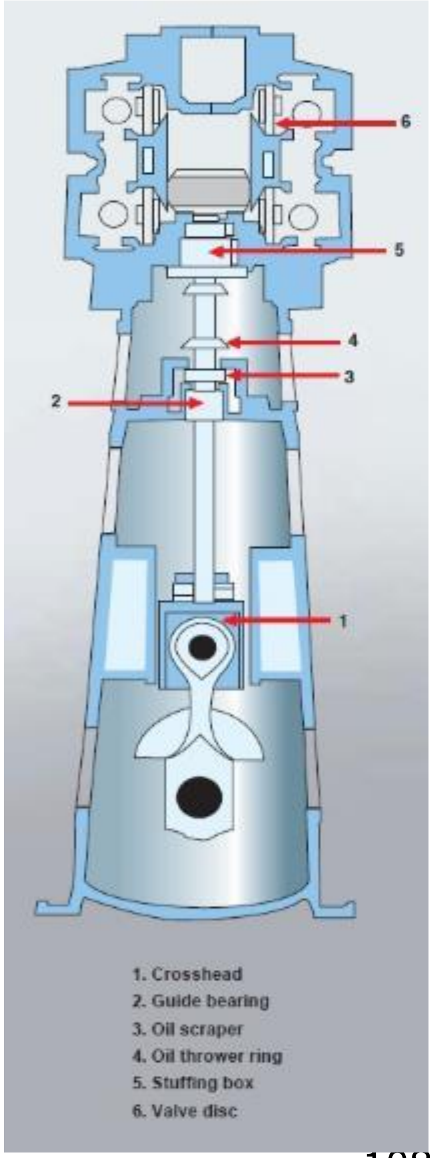
- Piston compressors
  - Piston compressor with a valve system consisting of two stainless steel valve discs.
  - When the piston moves downwards and draws in air into the cylinder the largest disc flexes to fold downwards allowing air to pass.
  - When the piston moves upwards, the large disc folds upwards and seals against the seat. The small disc's flexi-function then allows the compressed air to be forced through the hole in the valve seat





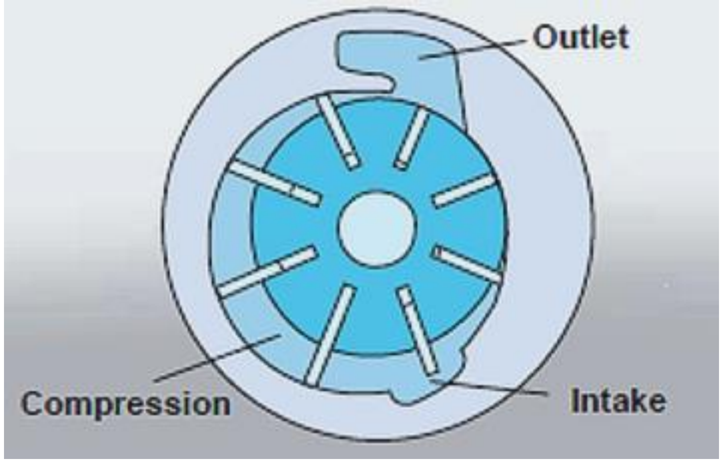
Types of air compressor

- Piston compressors
  - On double-acting, large compressors the L-configuration with a vertical low pressure cylinder and horizontal high pressure cylinder offers immense benefits and has become the most common design
  - Labyrinth sealed, double acting oil-free piston compressor with crosshead



Types of air compressor

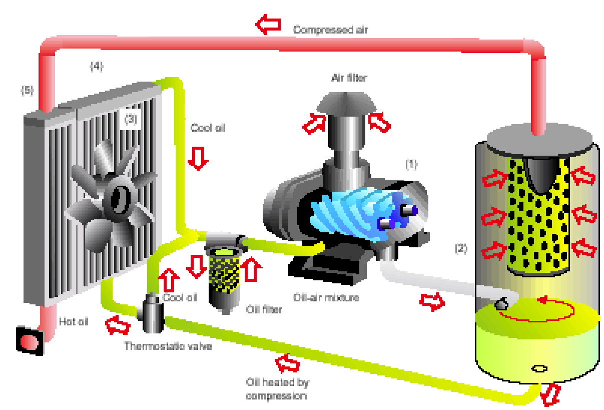
- Positive displacement compressors
  - Vane compressor
    - Advantages:
      - The high mass expense at medium pressure
    - Disadvantage:
      - Large oil consumption



Types of air compressor

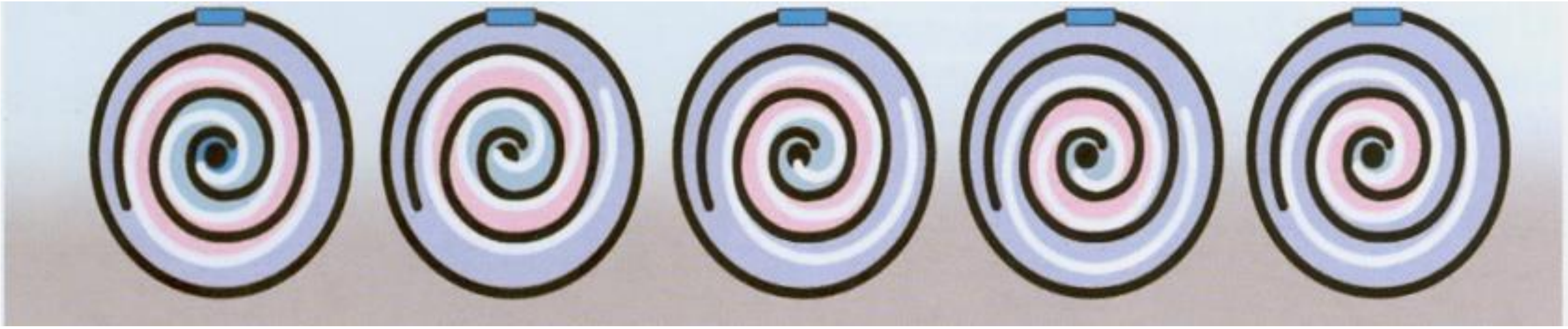
- Screw compressors
  - Screw compressors are effective and comparing with piston compressors, cheap devices
    - Air (1) is driven by an electric motor. The oil is injected during compression to provide sufficient cooling and is separated from the air in the oil separator (2); integrated oil separator cartridge provides outlet almost free from oil.
    - The fan (3) ventilate the compressor unit and cools air when it flows through the oil, the fan also blows the air throught coolers (4, 5).

      The control unit monitors the process of manufacturing compressed air in the prescribed pressure limits. The safety device protects the compressor unit and in case of a failure turns it off automatically.



Types of air compressor

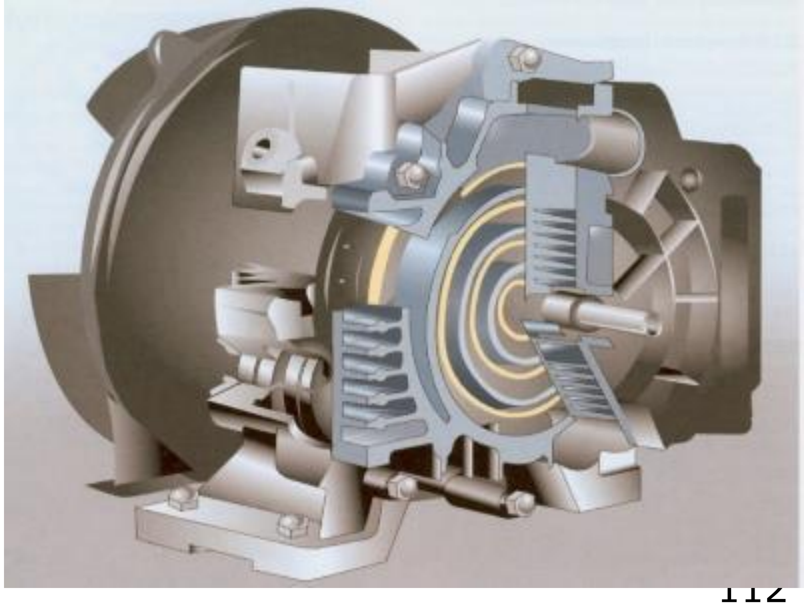
- Scroll compressor
  - Advantages:
    - Constant air flow without pulsation
    - The compression process is relatively quiet without vibrations
    - No amendment of torque, eg. piston compressor
  - Application:
    - Hermetic compressor chillers



Types of air compressor

- Positive displacement compressors
  - A scroll compressor is a type of (usually) oil-free orbiting displacement compressor, i.e. it compresses a specific amount of air into a continuously decreasing volume.
  - The compressor element consists of a stator spiral fixed in a housing and a motor-driven eccentric, orbiting spiral. The spirals are mounted with 180° phase displacement to form air pockets with a gradually varying
volume

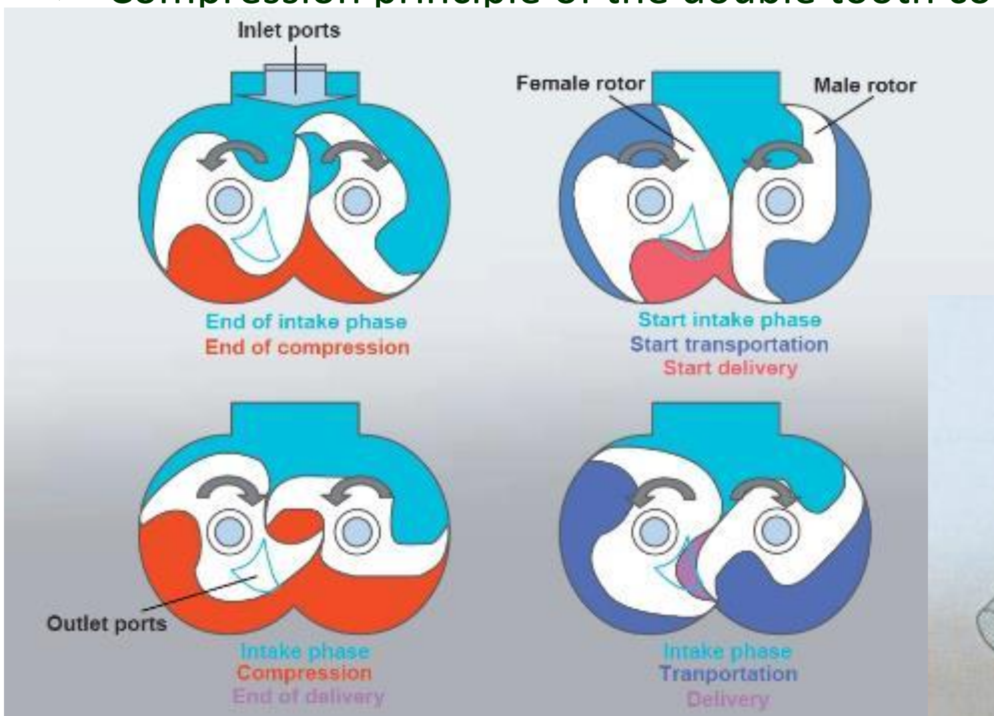
- A scroll compressor cross section

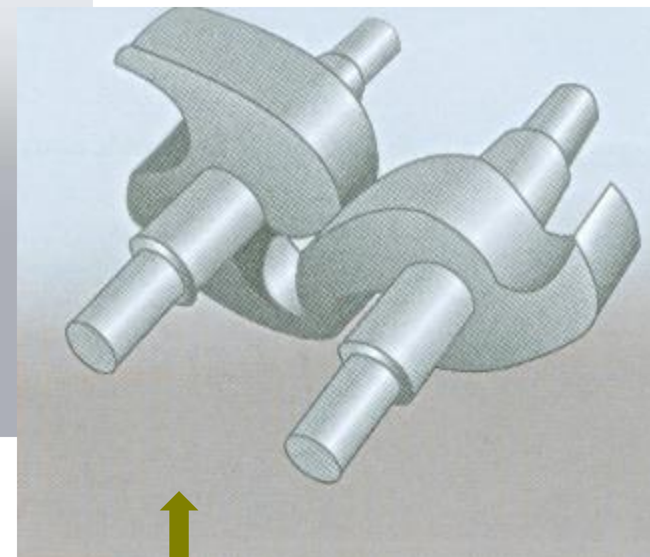


Types of air compressor

➢ Positive displacement compressors

⇨ Compression principle of the double tooth compressor

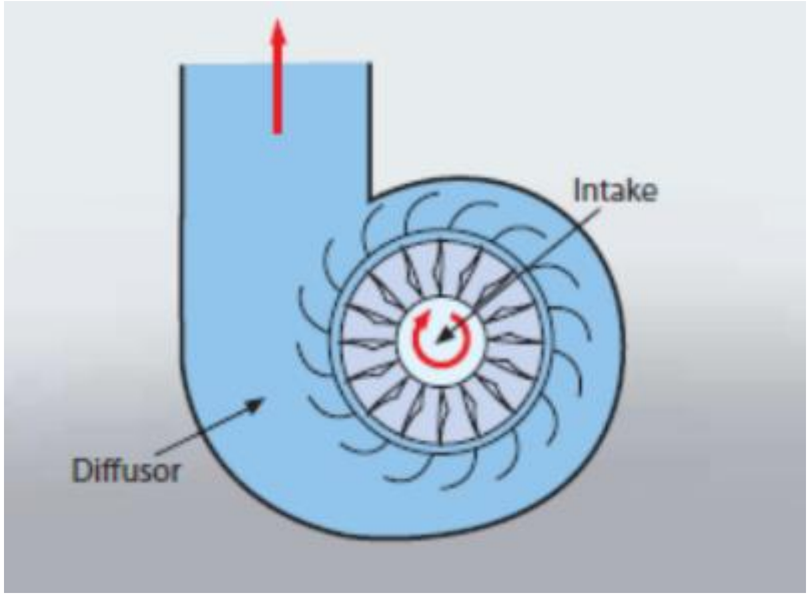




⇨ Rotor set of a double tooth compressor

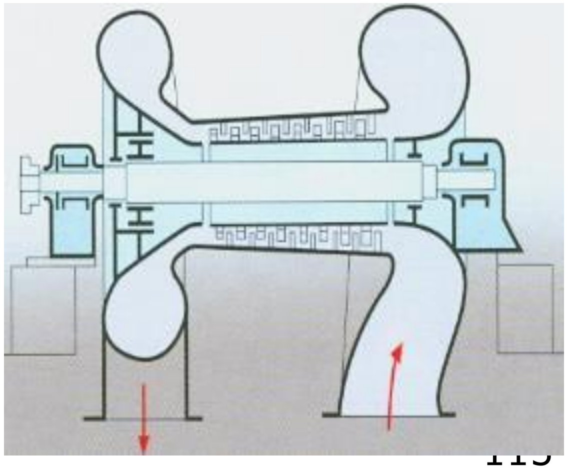
Types of air compressor

- Dynamic compression – fluid-flow machine
  - Converts kinetic energy of the mass flow to gas static pressure.



Types of air compressor

- Axial compressors
  - An axial compressor has axial flow, whereby the air or gas passes along the compressor shaft through rows of rotating and stationary blades. In this way, the velocity of the air is gradually increased at the same time that the stationary blades convert the kinetic energy to pressure. A balancing drum is usually built into the compressor to counterbalance axial thrust.
  - Axial compressors are generally smaller and lighter than their equivalent centrifugal compressors and normally operate at higher speeds. They are used for constant and high volume flow rates at a relatively moderate pressure, for instance, in ventilation systems. Given their high rotational speed, they are ideally coupled to gas turbines for electricity generation and aircraft propulsion.



Other types of compressors.

- Vacuum pumps
  - Machine-stressing from lower pressure to atmospheric pressure.
  - Commonly are multi-stages machines
- Booster compressor
  - Compressor that compresses compressed air to a much higher pressure
  - Used to equalize pressure drop for long installations.
- Pressure intensifiers
  - In e.g. laboratory tests from 7 bar to 200 bar in a single stage cycle

Mobile compressors

Mobile compressors

- Mobile compressors generally are screw compressors with oil injection with a diesel engine
- Small compressors have electric motor
- Oil-free compressors are only used in processing industry , offshore mining.
- Equipped with an integrated air treatment
- Susceptible to weather conditions - moisture
- Note: Susceptible to atmospheric conditions 1% of water in oil shortens the life of the bearing 40%

Mobile compressors

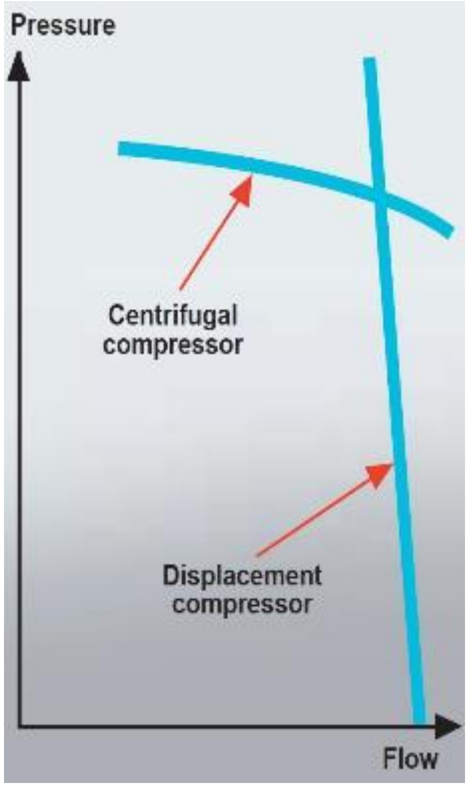
- Available pressure ranges and corresponding applications of mobile compressors

Pressure range	Pressure [bars]	Area of application
Low	7 – 8.6	Contract work
Medium	10 -14	Ground stabilization
High	17 – 20	Drilling and Industrial
Very high	25 – 35	Water and Geothermal well drilling
Ultra high	35 – 350	Deep hole drilling (oil, gas, minerals, geothermal water) as well as pipeline services nitrogen generations

Comparison: turbocompressor and positive displacement

- At constant rotational speed, the pressure/flow curve for a turbocompressor differs significantly from an equivalent curve for a positive displacement compressor.
- Turbocompressor
  - ⇨ Is a machine with a variable flow rate and variable pressure characteristic.
  - ⇨ Is designed for large air flow rates
- Displacement compressors
  - ⇨ Is a machine with a constant flow rate and a variable pressure.
  - ⇨ Provides a higher pressure ratio even at a low speed.

The load curves for centrifugal respective displacement compressors when the load is changed at constant speed



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Session 10

Compressed Air

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