GOOD PRACTICE GUIDE 241

Energy savings in the selection, control and maintenance of air compressors

GOOD PRACTICE GUIDE 241

ENERGY EFFICIENCY

BEST PRACTICE PROGRAMME

ENERGY SAVINGS IN THE SELECTION, CONTROL AND MAINTENANCE OF AIR COMPRESSORS

This Guide is No. 241 in the Good Practice Guide series. It provides clear guidance on energy efficient selection, control and maintenance of air compressors and demonstrates the success of implementing Good Practice measures and policies. It allows the reader to assess the energy implications of different compressed air generation and control options and to devise a cost effective maintenance strategy. Case studies are also included which provide practical examples of the savings that can be achieved.

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FOREWORD

This Guide is part of a series produced by the Government under the Energy Efficiency Best Practice Programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

— *Energy Consumption Guides:* (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— *Good Practice Guides:* (red) and *Case Studies:* (mustard) independent information on proven energy-saving measures and techniques and what they are achieving;

— *New Practice projects:* (light green) independent monitoring of new energy efficiency measures which do not yet enjoy a wide market;

— *Future Practice R&D support:* (purple) help to develop tomorrow's energy efficiency good practice measures.

If you would like any further information on this document, or on the Energy Efficiency Best Practice Programme, please contact the Environment and Energy Helpline on 0800 585794. Alternatively, you may contact your local service deliverer – see contact details below.

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1. INTRODUCTION

Compressed air is used in industry for a wide variety of purposes, but it is not free. Air leaving the compressor costs the equivalent of 50 p/kWh, a total of £390 million/year in the UK. This Good Practice Guide shows how to select and maintain plant to bring down the cost of generating compressed air.

Fig 1 shows how energy cost over a ten-year period typically far outweighs the capital and maintenance costs. Installing and maintaining an energy-efficient system is therefore highly cost-effective and small differences in plant efficiency can save far more energy and money than initial differences in capital cost.

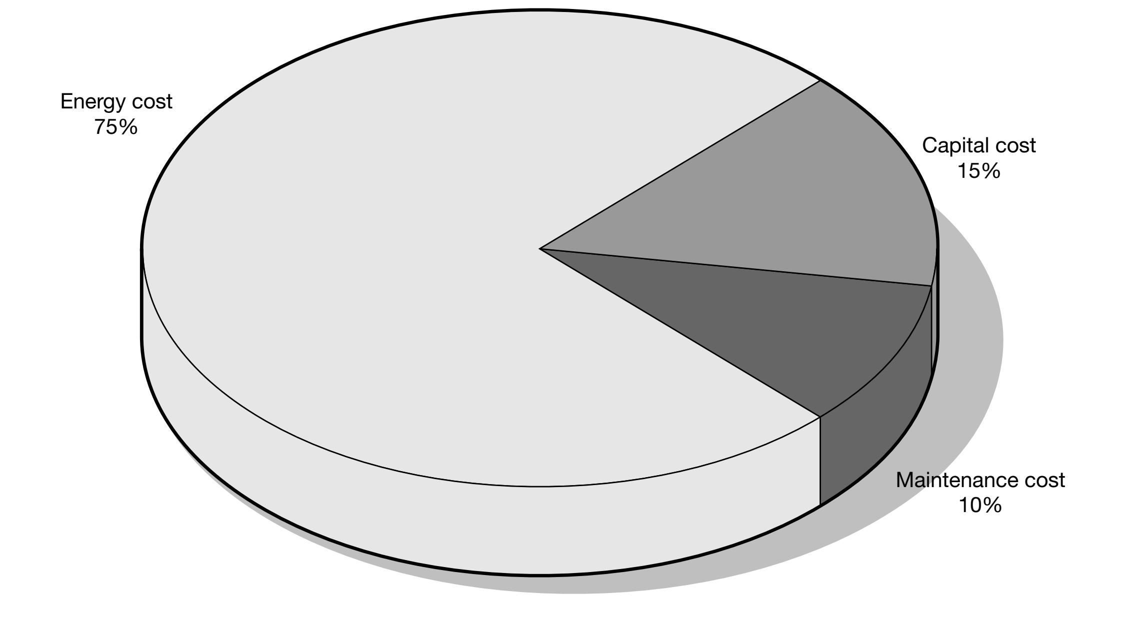

Fig 1 Typical cost of compressed air systems over a ten-year period based on a typical compressor performance of 5 cfm/kW and an electricity price of 5 p/kWh.
Note: cfm - cubic feet per minute

Improved control and maintenance practice not only saves energy costs but can also increase plant life and reduce the risk of costly downtime from compressor failure. These cost savings, while often hard to quantify, can be at least as large as the savings in direct energy costs.

In many cases, more savings can be made where it is economic to recover waste heat and use it for other purposes. Even with the most efficient plant, up to 90% of the input power is lost as heat in the compressor and much of this can be used usefully.

1.1 Energy Saving Opportunities

A typical air compressor installation of 100 kW (605 cfm) operating on a three-shift seven-day system could cost £40,000/year in energy costs. **An approximate cost for compressed air can be calculated assuming a cost of 0.8 p/cfm/hour or £65/cfm/year.**

Savings of up to 20% are possible through good selection, control and maintenance, reducing the energy bill in this typical plant by around £8,000/year. This would also reduce CO_2 emissions by over 400 tonnes/year.

In the extreme case of a 1,000 cfm air compressor costing £40,000 to buy, and running at full load (200 kW) continuously, it would cost as much in energy consumption in the first seven months of use as it did to buy.

1.2 Purpose of This Guide

This Guide explains how the selection, control and maintenance of compressed air plant can improve energy efficiency and reduce running costs.

It allows the reader to assess the energy implications of selecting different compressed air generation plant with various control options and to devise a cost-effective maintenance strategy. Case studies throughout the text provide practical examples of the savings that can be achieved and references are given to other useful publications.

This Guide is as comprehensive as possible but is necessarily general in nature. Users are, therefore, strongly recommended to consult specialists and equipment suppliers at an early stage, before making any final decisions, as each installation has its own particular requirements and energy saving opportunities.

This Guide is aimed primarily at maintenance/plant engineers with a good basic understanding of compressed air plant, but will be also of interest to non-technical managers. It covers stationary compressor installations generating pressures between 5 bar and 14 bar gauge (barg).

Relevant energy saving techniques and achievable savings will vary greatly from site to site - the following data show the level of savings generally found in practice:

- compressor installation - up to 5%;
- compressor selection - up to 10%;
- controls - up to 20%;
- maintenance - up to 10%.

2. ASSESSING THE COMPRESSED AIR REQUIREMENTS OF A SITE

Before deciding on the most appropriate compressed air plant, a thorough assessment of the compressed air requirements of a site is required. This Section identifies the key issues and discusses the following questions:

- What pressure is required? - Section 2.1.
- What air quality is required? - Section 2.2.
- What is the pattern of demand? - Section 2.3.
- What compressor capacity is required? - Section 2.4.
- Where is air required? - Section 2.5.
- Can the waste heat be used? - Section 2.6.

2.1 What Pressure is Required?

Most compressed air tools and equipment can be operated satisfactorily at a pressure of 6.3 barg (90 psig). The average, well-designed, compressed air treatment and distribution system shows a pressure drop of approximately 0.7 bar (10 psi) at the farthest point of distribution. This means that the minimum operating pressure for the compressors should be around 7 barg (100 psig).

Designing and operating a system at unnecessarily high pressures will waste energy and increase running costs[1] (Fig 2).

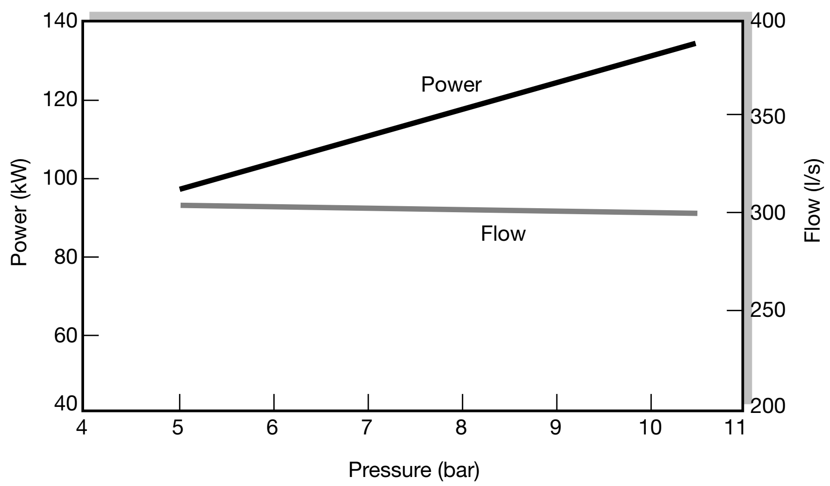

Fig 2 Energy savings by operating at lower pressures

Individual items of equipment are often operating on supply pressures in excess of that required, in which case, savings can be made by installing pressure regulators to keep the equipment supply pressure to the minimum necessary.

For example, equipment used on a fluctuating air supply of 6 - 7 barg, which could operate at 5.5 barg, would save approximately 14% by regulating the pressure locally to 5.5 barg. If the pressure could be reduced to 5.0 barg then savings would be almost 24%. Additionally, any losses arising from leaks in the system would reduce as pressure is regulated downwards.

Supplying an air main at high pressure just to satisfy the pressure requirements of a small amount of equipment should be avoided. This may mean using local boosters or small, high-pressure compressors for some local high pressure needs or even reconsidering the local requirements for compressed air.

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[1] See Good Practice Guide 126, *Compressing air costs*, available from the Energy Efficiency Best Practice Programme, contact the Energy Efficiency Enquiries Bureau, Tel: 01235 436747 Fax: 01235 433066.

2.2 What Air Quality is Required?

Oil-free air compressors are available which produce higher quality air than standard lubricated machines. Although these may cost more initially, the cost of this should be balanced against the additional capital, energy and maintenance costs of separate treatment equipment.

Oil-free screw compressors are more common in larger systems and **lubricated compressors** in smaller systems. Oil-free screw compressors avoid adding oil from the compression process into the supply air and may seem the obvious choice for sensitive applications. However, lubricated compressors have many advantages, as shown in Table 1 and, with the right filters, can produce air of equally high quality (see Good Practice Guide 216).

Table 1 Oil-free versus lubricated compressors

OIL-FREE COMPRESSORS	LUBRICATED COMPRESSORS
Advantages	**Advantages**
• More efficient and thus lower running cost. • May require fewer filters and oil changes. • Longer operational life. • Often preferred when manufacturing sensitive products such as food and pharmaceuticals.	• Considerably lower capital cost. • Simple plant. • Oil provides an important cooling effect. • Lower speeds/temperatures than oil-free compressors.
Disadvantages	**Disadvantages**
• Capital cost is normally greater. • Routine servicing costs are usually higher. • Multi-stage compression necessary to reach higher pressures. • Compressors are more complex.	• More frequent rebuilds. • More filter maintenance and oil changes required. • Greater treatment capital and running costs (due to the pressure drop across filters).

2.3 What is the Pattern of Demand?

The demand for compressed air varies widely from factory to factory depending on what the compressed air is used for. Demand patterns can be relatively constant, stepped or widely fluctuating.

As compressors are most efficient when operating at or near full load, it is more efficient to use a combination of compressors and controls (including variable speed technology) to meet a varying demand than to use one large compressor running at part load for most of the time.

In addition, installing a larger compressor may require a larger standby unit.

However, the lower efficiency of smaller compressors should also be considered (Fig 3). It is therefore essential to have a controlled sequence of switching multiple machines to achieve maximum energy efficiency (see Section 4.2).

Fig 3 shows some demand patterns and how these can be met efficiently with combinations of multiple compressors.

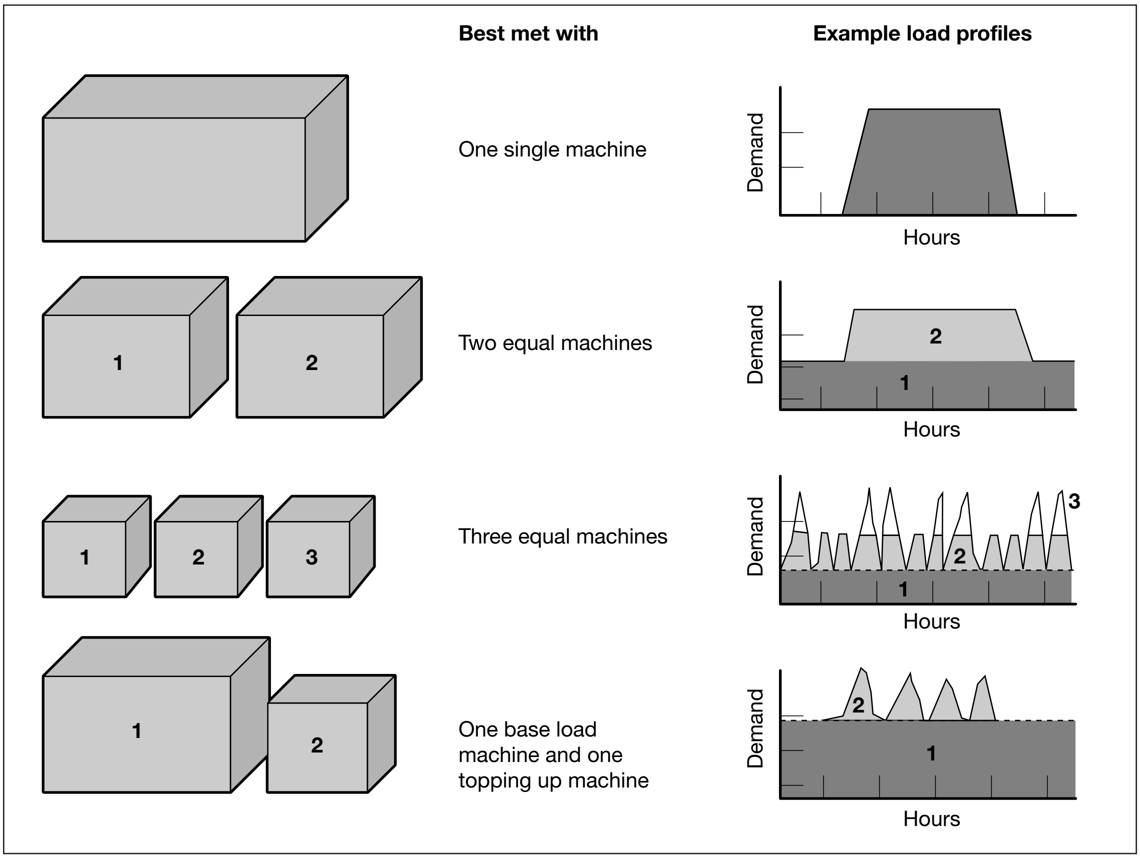

Fig 3 Examples of using multiple compressors to meet different demands

Storage receivers typically store 5 - 10% of the compressor capacity and can be used to smooth peaks in demand and reduce peak loads on the compressor. This avoids excessive cycling and part-load operation - improving energy efficiency and reducing wear on the compressor.

During periods of sudden high demand, an extra receiver near the point of take-off may avoid the need to provide extra capacity.

2.4 What Compressor Capacity is Required?

The main aim is to produce an adequate supply of compressed air at the appropriate pressure and quality. Designers should seek to minimise the demand and then meet it at the lowest cost in the most energy-efficient way possible.

Air compressor efficiency generally increases with size as shown in Fig 4 (overleaf). Nevertheless, the poorer part-load efficiency of compressors means that it is usually more efficient to run a smaller compressor at near full load than a larger one at low load.

In new installations, compressor plant is generally sized by adding all the likely individual loads allowing for simultaneous use for constant demand requirements and using diversity factors for intermittent air users[2]. Ideally, the total capacity would be based on exact knowledge of the equipment or process requirements. If this is underestimated, the compressor plant will be too small and unable to maintain the required pressure in the system. Conversely, if the total air consumption is greatly over-estimated there may be excessive capital investment and reduced efficiency. In existing systems, replacement plant can be sized based on the true measured demand for air (see Section 3.3).

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[2] See British Compressed Air Society's Installation Guide.

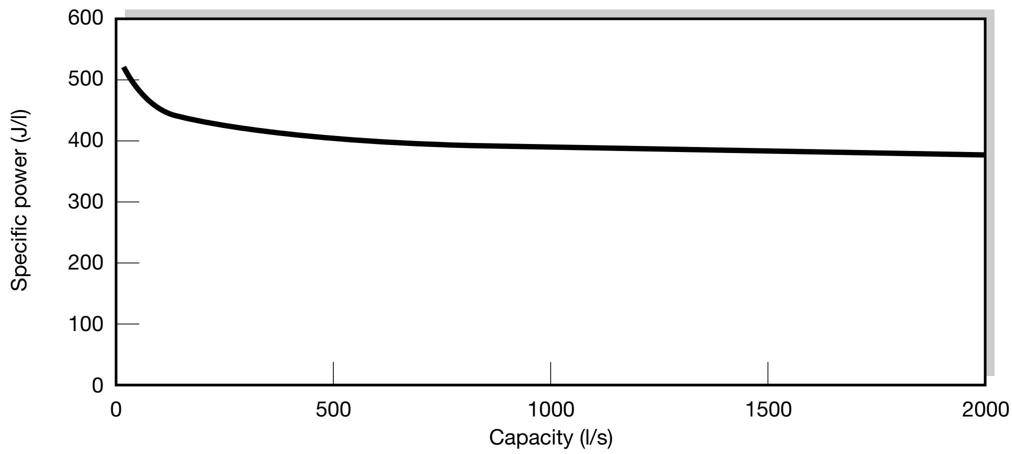


Fig 4 Average compressor full-load specific power consumption and compressor capacity at 7 bar

As modern compressors have high reliability, standby plant requirements should be carefully considered and not guessed. It is good practice to include a standby compressor equal in size to the largest duty machine. However, it is possible to reduce capital costs by opting for smaller standby plant. This depends on the down-time that can be accommodated and/or any mobile units that could be hired.

To ensure energy efficiency, designers should avoid adding excessive or arbitrary 'future changes' or 'standby' margins to the output of the selected compressors. However, when installing new plant, future expansion should always be taken into account by making an allowance for the purchase of an additional compressor at a later date. Increasing compressor capacity presents no problem, provided that the rest of the installation has been planned accordingly.

2.4.1 *Leakage*

Often a significant proportion of a machine's output supplies leaks in the distribution system and this can result in new plant being oversized.

For an installation with a regular inspection and maintenance programme, leakage should not exceed 10% - in most systems leakage is much higher. Compressors should be adequately sized, to allow for the worst case of system leakage.

Over time, leakage will gradually increase and an ongoing leakage reduction campaign is essential. Most tools work only intermittently whereas any leakage, even from a small hole, is both continuous and significant. Major cost savings can be achieved by reducing leakage[3].

2.5 Where is Air Required?

A key issue in planning a compressor installation is whether there should be a central compressor plant or a number of separate compressors near to the main points of use. For replacement plant there may be no practical choice, but for new installations the issues in Table 2 should be carefully considered.

[3] See Energy Consumption Guide 41, Good Practice Guide 126 and Good Practice Case Study 346, *Compressed air savings through leakage reduction and the use of high efficiency air nozzles.*

Table 2 Centralised versus decentralised plant

CENTRALISED SYSTEMS	DECENTRALISED SYSTEMS
Advantages	**Advantages**
• Capital cost per unit output generally falls with increased capacity of centralised plant. • Tends to be better engineered, operating at higher efficiencies, (where load factors are high) and more durable. • Some systems will naturally require centralised plant, e.g. to meet very large volumes. • Lower total installed compressor capacity and, possibly, lower initial cost. • Possibly a higher efficiency, and thus lower running cost, due to larger units. • Energy performance for processes with diverse patterns of use is usually better. • Heat recovery potential may be greater due to larger centralised plant, particularly if hot water is required. • Greater security of supply due to built-in standby of multiple compressors. • Condensate collection simplified by grouping to one system.	• Low capital cost, savings made on minimising the distribution systems. • Systems can be zoned to more closely match the demand patterns. • Can be readily altered and extended. • Output and/or pressure can be varied to suit each particular plant section. • Pipe sizes and lengths can be reduced, thus minimising leakage and cost. • Compressors and/or associated equipment can be shut down during periods of low demand or for maintenance, with only a localised effect. • Heat recovery may be simplified due to individual compressors being close to heat use.
Disadvantages	**Disadvantages**
• Space requirements of centralised plant and distribution systems are significant. • Leakage losses will be greater due to larger distribution network. • Capital cost of distribution systems is high.	• Equipment tends to be less robust with shorter operational life. • Quality of control, maintenance and air quality may be inferior to central plant systems. • Smaller machines tend to be less efficient.

2.6 Can the Waste Heat be Used?

Over 90% of the energy input to air compressors is rejected as heat and there are opportunities for recovering and using much of this otherwise wasted energy (Fig 5).

Where heat can be recovered, it can reduce overall running costs significantly, see Good Practice Guide 238[4]. However, heat recovery is not the main purpose of a compressed air system and it should not affect the operation of the compressor.

Heat recovery is generally most cost-effective when introduced as part of a new or replacement compressor installation and some compressors have special features to make this easier.

For example, a 500 l/s air-cooled compressor could supply roughly 160 kW of heat at between 40 to 50°C. For a site using direct gas-fired space heating, operating 48 hours/week, recovering and using this heat would produce annual savings of approximately £4,000.

[4] See Good Practice Guide 238, *Heat recovery from air compressors.*

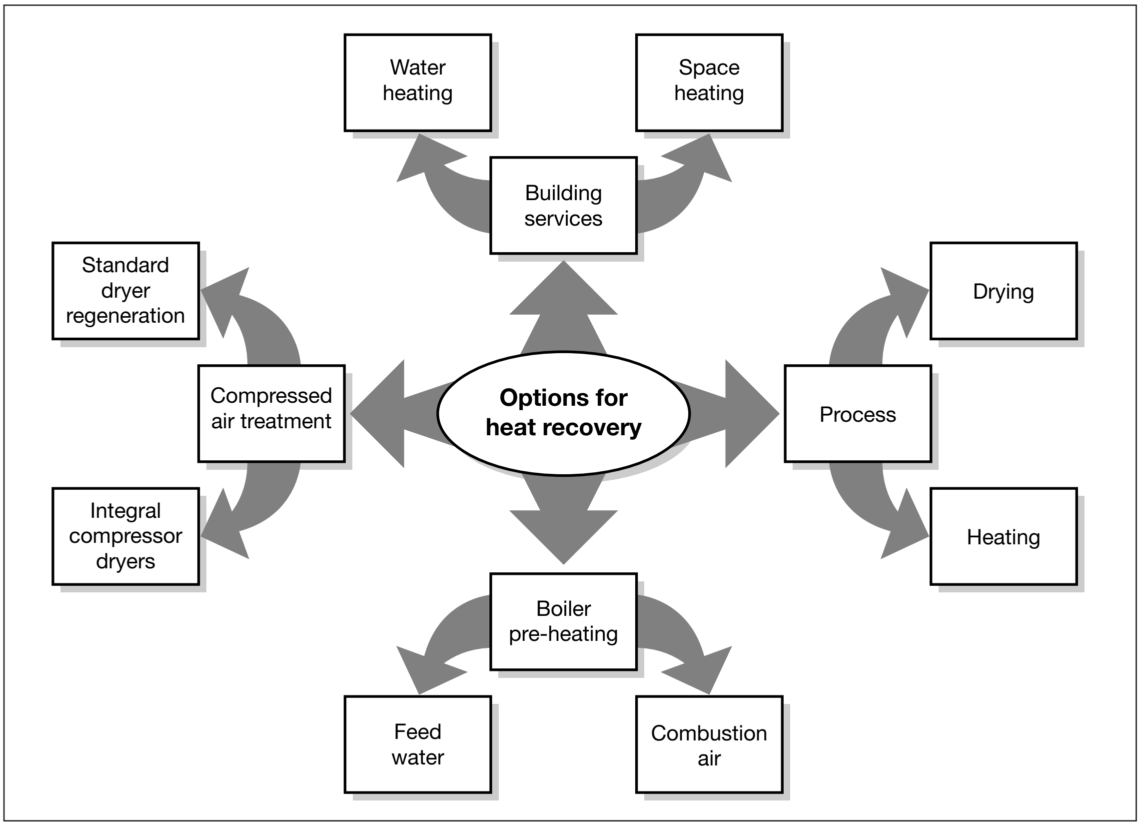


Fig 5 Options for using recovered heat

3. PLANT SELECTION

As soon as the compressed air requirements for the site have been identified, the most appropriate energy efficient plant can be selected.

There are plenty of opportunities to reduce running costs, energy consumption and capital cost at the design stage through good sizing and the most appropriate selection of air compressors. The key issues when selecting plant are covered in the following Sections:

- size of compressors - Section 3.2;
- type of compressor - Section 3.3;
- compressor controls - Section 4;
- maintenance requirements - Section 5;
- possibility of heat recovery - Section 2.6.

3.1 Terminology Used in Specifying a Compressor

There are many different terms that may be used when specifying air compressors. It is important that the specifier is aware of these in order to avoid confusion and also to ensure that proposals can be analysed and compared accurately.

This Section defines many of the terms used throughout the industry.

3.1.1 *Defining Air Flow*

The capacity of a compressor can be expressed in volumetric or mass flow terms, for example:

Table 3 Unit terms used to define compressor capacity

Units	Meaning
cfm	Cubic feet per minute
l/s	Litres per second
m^3/h	Metres cubed per hour
m^3/min	Metres cubed per minute
kg/h	Kilograms per hour

It is also very important to define the conditions that apply to the compressed air when referring to flow rate in terms of:

- pressure;
- temperature;
- humidity - this has a small effect (up to 4%) on the compressor delivery, since water vapour is compressed, but mostly removed, during after-cooling and drying.

Under identical pressure, temperature and humidity conditions, the volumetric flows can be converted as shown in Table 4.

Table 4 Volumetric flow conversion

From	To - multiply by			
	cfm	**l/s**	**m^3/h**	**m^3/min**
cfm	1	0.4719	1.699	0.02832
l/s	2.119	1	3.600	0.06000
m^3/h	0.5886	0.2778	1	0.01667
m^3/min	35.31	16.67	60	1

Standard and Normal Conditions (typically scfm or Nm^3/h) ensure that any air flow specified is related to standardised conditions - not necessarily the inlet conditions of the compressor. Unfortunately, there are various conventions used, so clarification is still advised. Commonly used conditions are shown in Table 5.

Table 5 Standard and normal conditions

	Standard	**Normal**
Pressure (mbarA)	1,013.25	1,013.25
Temperature (°C)	15	0
Relative humidity %	0	0
Density (kg/m^3)	1.225	1.292

Under these conditions, use the following conversion factors shown in Table 6.

Table 6 Conversion factors for standard and normal conditions

From	To - multiply by		
	cfm	**Nm^3/h**	**kg/h**
cfm	1	1.611	2.081
Nm^3/h	0.6209	1	1.292
kg/h	0.4805	0.7738	1

3.1.2 *Defining Compressor Capacity*

The capacity for **reciprocating, rotary vane** and **screw** compressors is typically quoted as:

> **Free Air Delivered (**or **FAD)**. This is the volume at the discharge flange referred back to inlet conditions (that is the inlet volumetric rate of the compressor).

The capacity for **centrifugal** compressors is typically quoted as FAD or as:

> **Inlet Capacity (Icfm, Im^3/h, etc.)**. This is the volume of air passing the inlet flange of the compressor. It is not a good term to use when comparing one machine against another as it does not take into account ‘seal’ losses in the compressor itself.

With centrifugal compressors, manufacturers will normally quote the delivery at high inlet air and cooling water temperatures and low inlet pressure. This is to ensure that the machine meets the required duty when the air density is low.

The compressor delivery under typical site conditions should also be requested from the manufacturer.

Confusion arises when the inlet conditions are considered downstream of inlet filtration, and the compressor discharge pressure is taken upstream of the after-cooler.

In order to allow for a true direct comparison of offers, suppliers should be asked to provide the following information:

REQUEST FOR AIR COMPRESSOR PACKAGE DELIVERY

- Site ambient conditions of:

  air temperature - xx°C,
  pressure - x,xxx mbarA,
  relative humidity - xx%;

  Preferably the averages for the site location

- a discharge pressure from the package (including after-cooler) of - xx.x barg;
- and a cooling water temperature of xx°C (where relevant).

Either:

Please state the package delivery in Nm^3/h (normal conditions being 1,013 mbarA, 0°C, dry).

Or:

Please state the package delivery in scfm (standard conditions being 1,013 mbarA, 15°C, dry).

Example (1 of 3)

A compressor is quoted with a FAD of 500 cfm under manufacturer's inlet condition. With ambient conditions of 1,010 mbarA, 20°C, 60% relative humidity (RH), the compressor will deliver 483 cfm.

3.1.3 *Compressor Power Consumption*

The power consumption should be requested as the **Packaged Compressor (electrical) Power Input** and should include the electrical input to the motor and other auxiliary items (cooling fans, oil pump, etc.). Care should be taken to ensure that the *actual* motor power is provided to ensure that true comparisons can be made (see Appendix).

If shaft power, or nominal motor power, is referred to it excludes these auxiliaries. The electrical input to external units (cooling water pumps, separate after-coolers, etc.) should, also be included when comparing alternatives. For example, it may be relevant in the choice between water-cooled and air-cooled compressors where the cooling fan is integral to the package.

The power consumptions quoted should be relevant to the inlet conditions used in defining the capacity (Section 3.1.1), not those used in the original design of the compressor. This can make a significant difference to the power of all types of compressor, but particularly in centrifugal machines.

Example (2 of 3) In delivering 483 cfm, the Packaged Compressor (electrical) Power Input is 92 kW. (Note: The rated shaft power of the compressor would be 80 kW.)

3.1.4 *Efficiency*

Specific power is the term used to evaluate the capacity versus the power input (i.e. efficiency) at full and part loads. In the following examples, a low specific power figure means a more efficient machine. Use the conversion factors in Table 7.

Table 7 Conversion factors for specific power (efficiency)

From	**To - multiply by**		
	kW/100 cfm	**kWh/100 Nm^3**	**J/Nl**
kW/100 cfm	1	0.6209	22.35
kWh/100 Nm^3	1.611	1	36.00
J/Nl	0.04474	0.02778	1

Example (3 of 3) In delivering 483 cfm, the specific power of the compressor package will be 19.0 kW/100 cfm. (Note: Using the manufacturer's rated shaft power and FAD would give a specific power of 16.0 kW/100 cfm - here the actual efficiency is 19% worse than indicated, excluding tolerances; hence the importance of understanding the terms used.)

3.1.5 *Compressor Test Standards*

Reciprocating, rotary vane and screw compressors should have their performance quoted to CAGI/PNEUROP PN2CPTC2.

Centrifugal compressors should have their performance specified to ASME PTC10 test codes.

Test tolerances are also important when specifying compressors. Manufacturers are allowed a tolerance on the output, the power consumed and the specific power - the amount depends on the capacity of the compressor. These must be stated on all proposals as well as no-load and part-load tolerances (usually different).

3.2 Sizing Compressors

In new installations, compressor plant is generally sized by adding all the likely individual loads and taking into account diversity factors to allow for simultaneous use.

In existing installations, it may be possible to monitor current demand and use this to size replacement plant (see Section 2.4).

Fig 6 shows a typical demand pattern and the key data needed to specify efficient compressed air plant:

- Peak - used to size the total compressor capacity.
- Mean demand - used to calculate operating costs.
- Base load - if working for long hours at base load, then ensure this can be met efficiently (also useful as a measure of leakage).

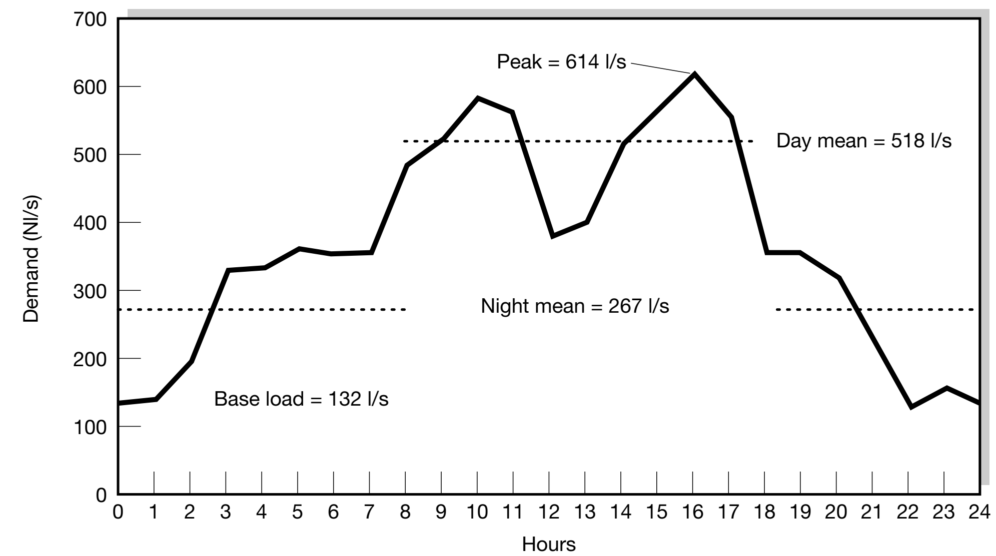


Fig 6 Using a demand profile to size plant

3.3 Selecting Compressors

Fig 7 shows the approximate capacity and pressure limitations of each type of compressor.

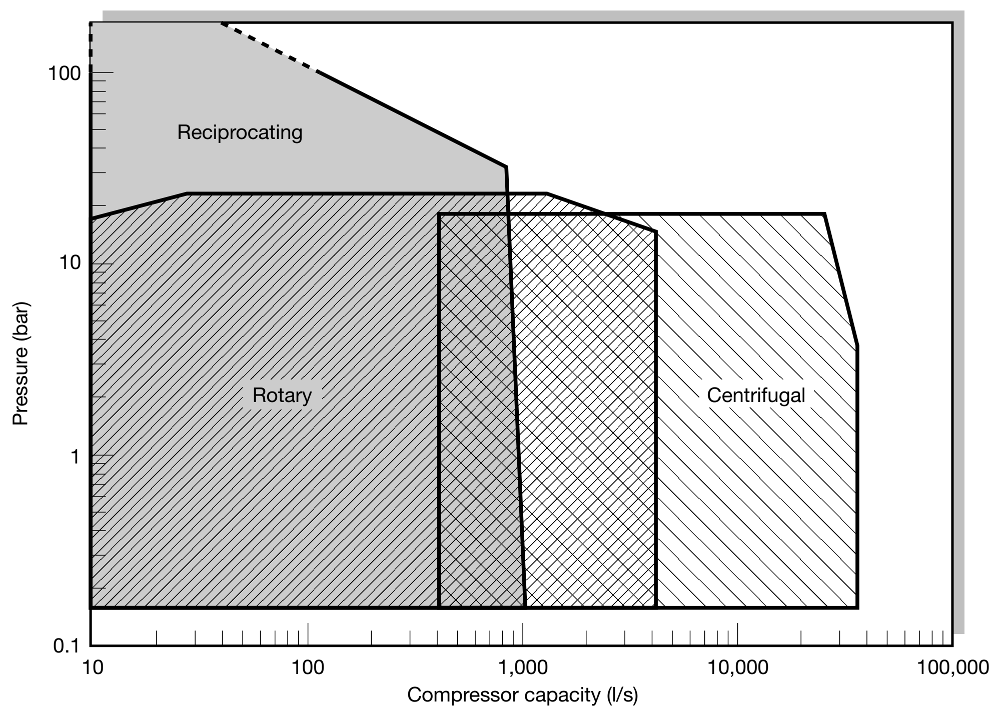


Fig 7 Compressor capacity and pressure limitations

Table 8 (overleaf) shows the advantages and disadvantages of various common types of compressor, in order to aid selection.

Table 8 shows the specific power consumption in particular - which is the key indicator of plant efficiency (see Section 3.1.4). This varies with the size and type of compressor and consultation with the supplier is recommended.

The figures in Table 8 show the in-service efficiency of compressors found on site and not the 'as-new' performance. Further characteristics of common compressor types are shown on the following pages.

Table 8 Comparison of common compressors

Compressor	Lubrication	Cooling	Capacity (l/s)	Specific power at full load (J/l)	Part-load efficiency	Capital cost	Running costs	Maintenance requirements	Air quality	Typical controls	Installation
Reciprocating (piston compressors)	Lubricated	Air	2 - 25	510	Good	Average	Average	Average	Poor	On-line/ Off-line	Average
	Lubricated	Air/Water	25 - 250	425	Good	Average	Average	Average	Poor	On-line/ Off-line	Average
	Lubricated	Air/Water	250 - 1,000	361	Excellent	High	Low	High	Average	On-line/Off-line or step	Complex
	Oil-free	Air	2 - 25	552	Good	Average	Average	High	High	On-line/Off-line or step	Average
	Oil-free	Air/Water	25 - 250	467	Good	Average	Average	High	High	On-line/Off-line or step	Average
	Oil-free	Air/Water	250 - 1,000	404	Excellent	High	Low	High	High	On-line/Off-line or step	Complex
Rotary screw	Oil-injected	Air	2 - 25	510	Poor	Low	High	Average	Average	On-line/ Off-line	Easy
	Oil-injected	Air	25 - 250	446	Good (with variable speed drive)	Low	High	Average	Average	On-line/Off-line + Auto	Easy
	Oil-injected	Air/Water	250 - 1,000	404	Fair	Average	Average	Average	Average	On-line/ Off-line + Modulating	Easy
	Oil-free	Air	25 - 250	429	Good	High	Average	Average	High	On-line/Off-line + Auto	Easy
	Oil-free	Air	250 - 1,000	382	Good	High	Average	Average	High	On-line/Off-line + Auto	Easy
	Oil-free	Air/Water	1000 - 2,000	382	Good	High	Low	Average	High	On-line/Off-line + Auto	Easy
Vane	Oil-injected	Air	2 - 25	510	Poor	Low	High	Low	Poor	On-line/ Off-line + Modulating	Easy
	Oil-injected	Air	25 - 250	446	Fair	Low	High	Average	Average	On-line/ Off-line + Modulating	Easy
Centrifugal	Oil-free	Water	250 - 1,000	446	Good	Average	Average	Average	High	Modulating or Auto Dual	Easy
	Oil-free	Water	1000 - 2,000	382	Excellent	Average	Average	Low	High	Modulating or Auto Dual	Easy
	Oil-free	Water	Above 2,000	361	Excellent	High	Low	Low	High	Modulating or Auto Dual	Average

3.4 Lubricated Screw and Vane Compressors

- Lubricated or oil-injected rotary compressors are usually less efficient than oil-free machines, mainly because oil-injected machines are single-stage machines.
- Oil-injected machines are very reliable, require only routine maintenance and have a long lifetime.
- The specific power of oil-injected machines ranges from 404 - 510 J/l.
- Many users who need quality air use filtration on oil-injected machines because of the lower capital cost of the machinery compared to oil-free machines.
- Filtration on oil-injected machines is less energy efficient than using oil-free compressors, but oil-injected machines are the most popular type of machine for producing standard quality air.
- Rotary oil-injected compressors are being installed in increasing numbers due to their simplicity, ease of installation, low maintenance and low noise levels.
- These machines are highly applicable where space is restricted or there are insubstantial foundations.
- Compression air-end may need inspecting and replacing after 25,000 hours.

Controls

- Oil-injected rotary compressors can be controlled at constant speed via two-step unloading or modulation (see Section 4.2).
- For efficiency reasons, throttled modulation should be used only if the load is over 70% of the compressor capacity.
- Machines are often fitted with both control types and some models can automatically switch from modulation to two-step loading at lower loads.
- Some oil-injected screw machines are available with built-in variable speed drives (see Section 4.1.11) which give the best part-load efficiency along with other benefits.

Heat Recovery

- Heat recovery is usually simple with screw compressors.
- Heat can be recovered from the **cooling water** using a plate or shell-and-tube heat exchanger in the hot return water.
- Heat can also be recovered from **air-cooled machines** via a heat exchanger on the oil cooler.
- In air-cooled machines, the **air flow** leaving the fan can be directed into the building to recover heat for space heating purposes.

3.4.1 *Oil-injected Screw Compressors*

- Capacities from 25 to 1,000 l/s can be served by single-stage oil-injected rotary screw compressors.
- Oil-injected machines are available up to 14 barg discharge pressure.
- The injected oil is used to cool the air as it is being compressed, to seal the compressor air-end.
- 75% of the heat of compression is typically removed in the oil cooler, the remainder by the aftercooler and radiation losses.
- Two-stage machines are becoming available with improved efficiencies.

How They Work

- Two meshing helical rotors rotate in opposite directions. The design of the rotor is such that the free space between them decreases in volume along their axes. This decrease in volume compresses the air trapped between the rotors.

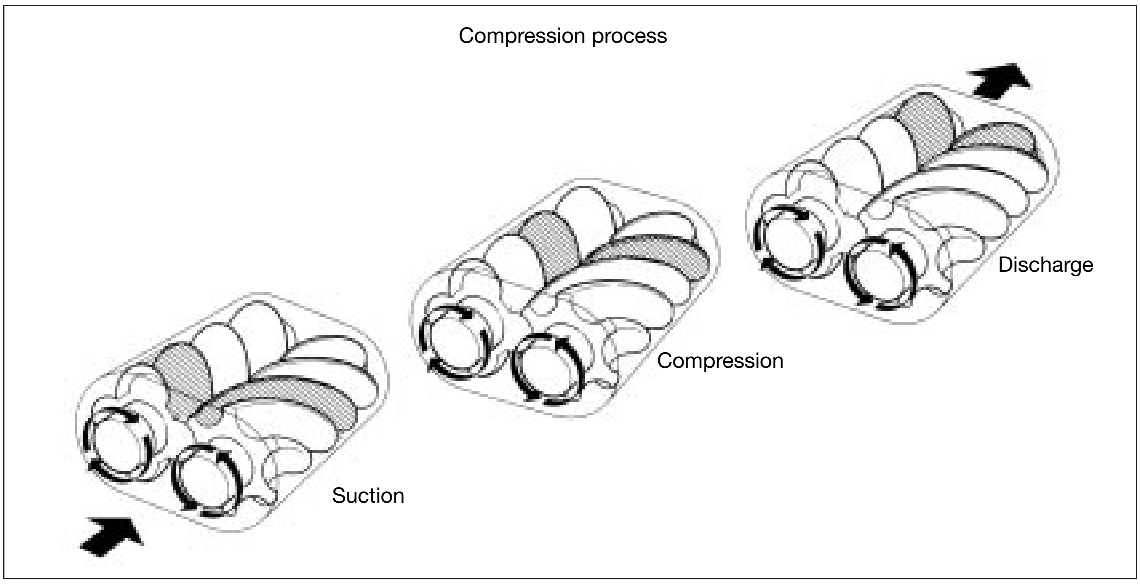


Fig 8 Single-stage oil-injected screw compressor

3.4.2 *Rotary Vane Compressors*

- Capacities from 25 to 250 l/s can be served by single-stage oil-injected rotary vane compressors.
- In the smaller sizes (up to 30 kW), rotary vane machines are very quiet and are used in decentralised locations to generate compressed air at the point of use.

How They Work

The compressor consists of a rotor mounted off-centre in a cylindrical chamber. As the rotor rotates, so the space between adjacent blades decreases from inlet to exhaust.

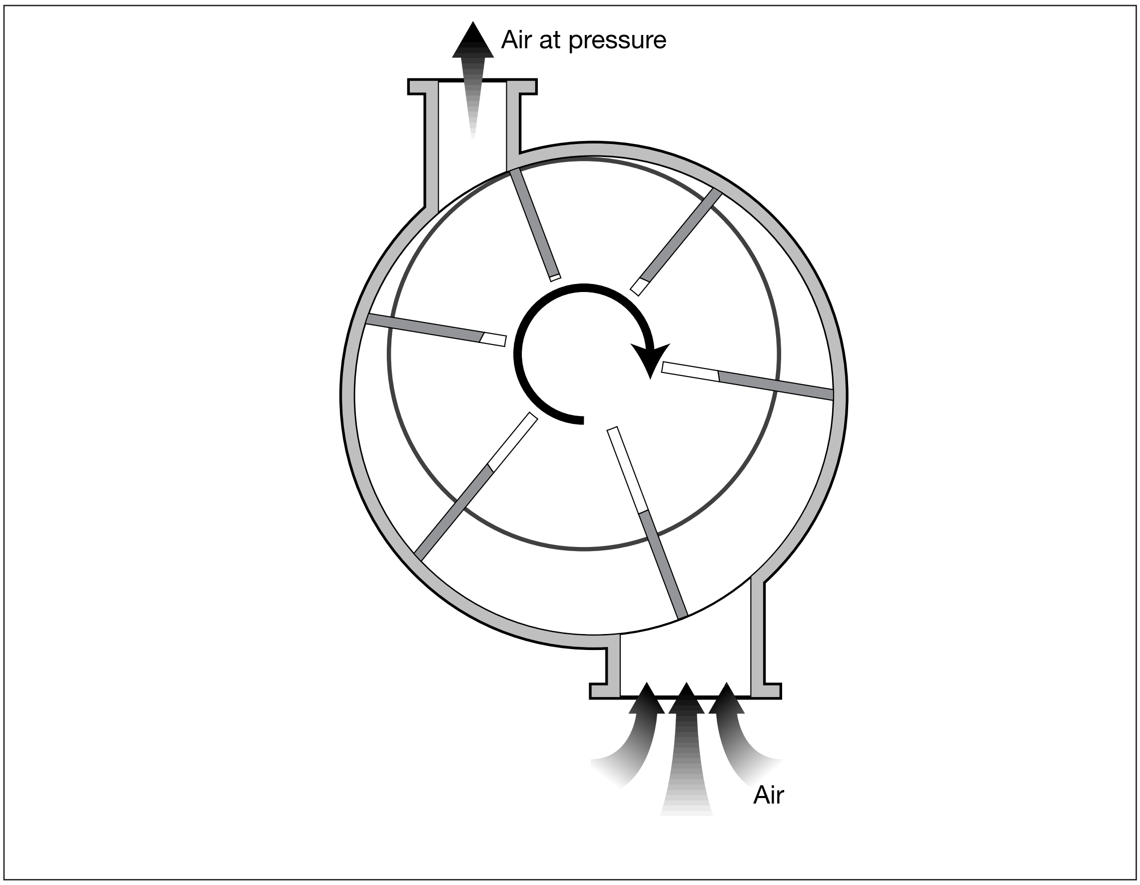


Fig 9 Rotary vane compressor

3.4.3 *Oil-free Screw Compressors*

- These compressors are normally two-stage when required for duties between 5 and 10.5 bar.
- Air-cooled machines are normally available up to 1,000 l/s and water-cooled to 2,000 l/s.
- Below 150 l/s, rotary-toothed, scroll and water-sealed screw compressors are available.
- Non-lubricated rotary compressors are usually more efficient than oil-injected machines, mainly because they are two-stage units.
- They generally have a higher capital cost, but a longer lifetime than lubricated compressors.
- The specific power of oil-free machines ranges from 382 - 429 J/l.
- Oil-free rotary machines are often used when high quality air is required.
- These machines are highly applicable where space is restricted or the foundations are not substantial.
- Compression air-end may need inspecting and replacing after 40,000 hours.
- The female rotors in oil-free compressors are driven separately by gears (unlike lubricated screw compressors where the male rotor directly drives the female rotor).

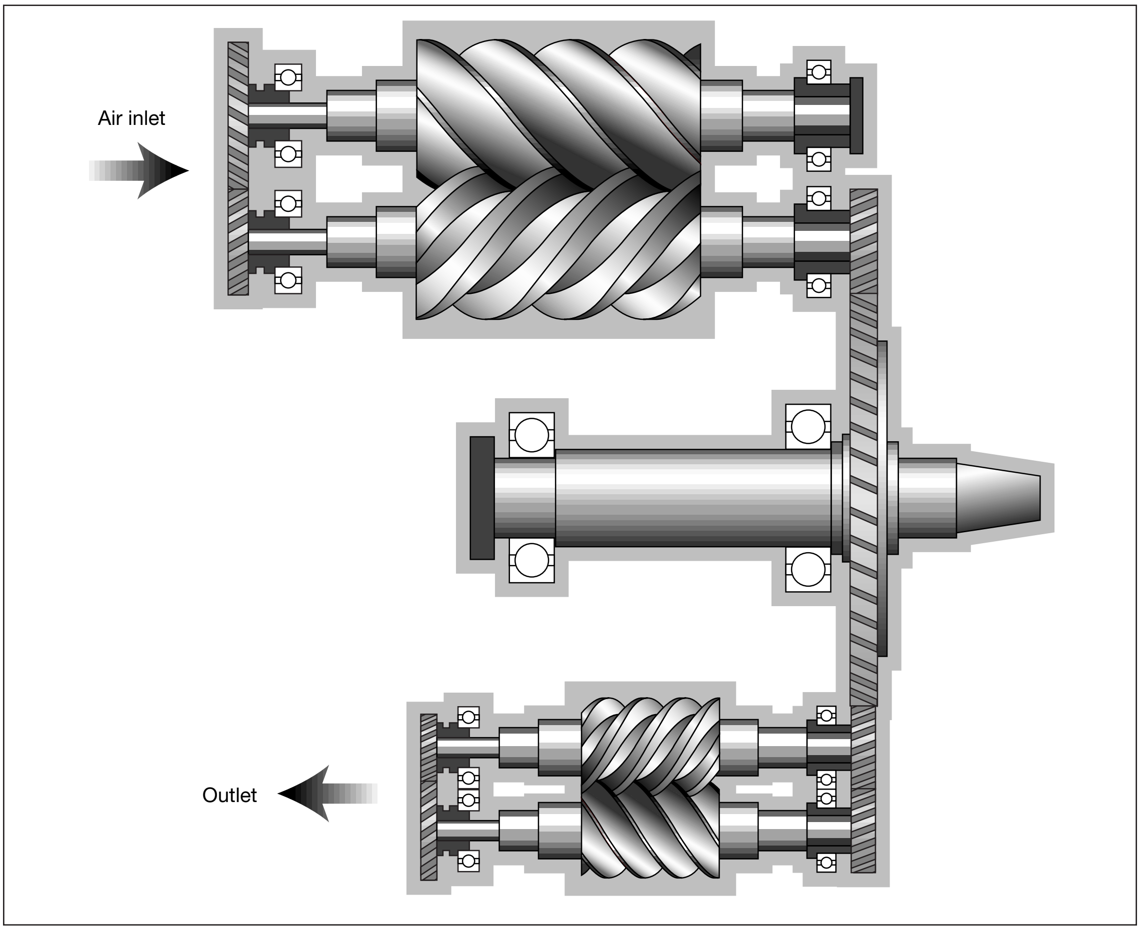


Fig 10 Oil-free screw compressor

Controls

These compressors are usually supplied as two-step unloading (see Section 4.1.2). Some larger models may have an optional modulation control, with two-step unloading at lower loads (see Sections 4.1.5 and 4.1.6).

Heat Recovery

Special oil-free models are available which can produce hot water at over 90°C. These have double pass inter- and after-coolers which ensure the correct cooling, while providing hot water for heat recovery at a higher temperature.

3.4.4 *Centrifugal Compressors*

- Centrifugal machines are available from 250 l/s (450 cfm) to over 10,000 l/s (20,000 cfm).
- They are popular, and energy efficient - particularly where demand is fairly constant, sustained and high volume.
- Specific power ranges from 361 - 446 J/l.
- They are nearly always water-cooled and employ two, three, or four stages of compression. Some configurations include an after-cooler.
- Capacities over 2,000 l/s are usually met by centrifugal compressors.
- For very large capacity requirements (beyond the scope of this Guide), axial flow compressors are usually used.
- Generally, for energy efficiency at full and part load, the more stages of compression, the better.
- The external design conditions, such as site ambient temperatures, have a significant influence on the energy requirements and control range of these compressors.
- These machines are applicable if noise is a consideration in the design.
- As centrifugal compressors are inherently oil-free, they deliver high quality air and discharge air is free from pulsation.
- A well designed and applied centrifugal compressor will often be the lowest cost machine to maintain.

Controls

- Output is normally reduced by modulation to 70% of the design flow (see Section 4.1.6).
- For installations where the demand is sometimes below 70% of design flow, machines with automatic dual control systems should be installed.
- Inlet guide vanes are preferable to inlet throttles as they improve the part-load efficiency and turn-down range.

Heat Recovery

- Heat can be recovered from the water in these machines using a plate or shell-and-tube heat exchanger in the hot return water.
- To maintain best compressor efficiency, the intercoolers must have the coldest and highest quality water possible.

How They Work

- Centrifugal compressors are rotary continuous flow machines in which the rapidly rotating element accelerates the air, pressurising partially in the rotating element and partially in stationary diffusers or blades.
- The acceleration of the air in centrifugal compressors is obtained through the action of one or more rotating impellers.

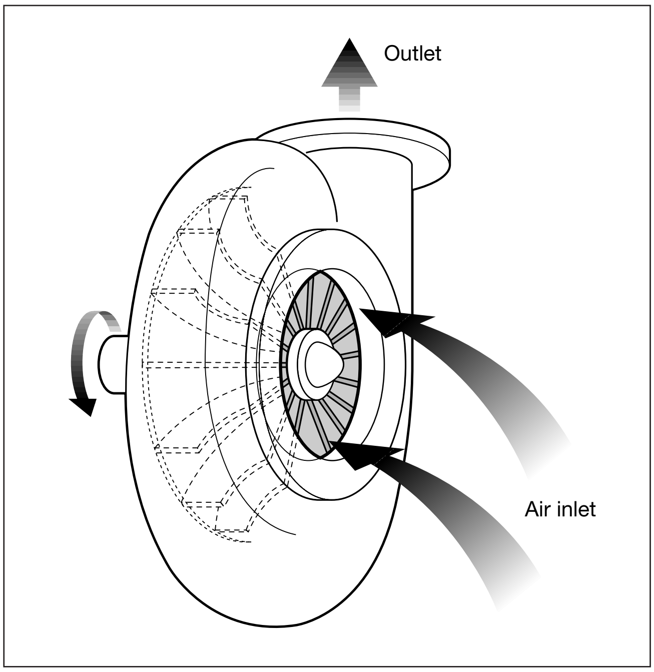


Fig 11 Centrifugal compressor

3.4.5 *Reciprocating Compressors*

- Larger reciprocating compressors can be the most energy efficient type of compressor.
- Specific power of lubricated machines ranges from 361 - 510 J/l.
- Oil-free machines range from 404 - 552 J/l.
- Efficiency decreases rapidly if they are poorly maintained.
- Air-cooled machines run at a higher crank-shaft speed with relatively poor efficiency compared to water-cooled versions.
- Water-cooled machines are the most efficient compressors available in terms of full-load and part-load power consumption.
- In the small size range from 15 to 30 kW, air-cooled units tend to be single- or two-stage, single acting and mounted on an air receiver.
- Above 30 kW they are usually double-acting water-cooled machines either lubricated or non-lubricated.
- This type of compressor is usually the only choice when pressures over 14 bar are required.

Controls

- Common techniques for controlling the capacity of reciprocating compressors are cylinder unloading, on-line/off-line inlet throttling and modulation inlet throttling (see Section 4.2).
- Cylinder unloading can be achieved in a number of ways using suction valves or clearance pocket unloading in various stages.
- On-line/off-line is generally the more efficient for part-load control (see Section 4.2).

Heat Recovery

- In air-cooled machines, the air flow leaving the fan can be directed into the building to recover the heat for space heating purposes.
- In water-cooled machines, opportunities exist for heat recovery via plate or shell-and-tube heat exchangers.

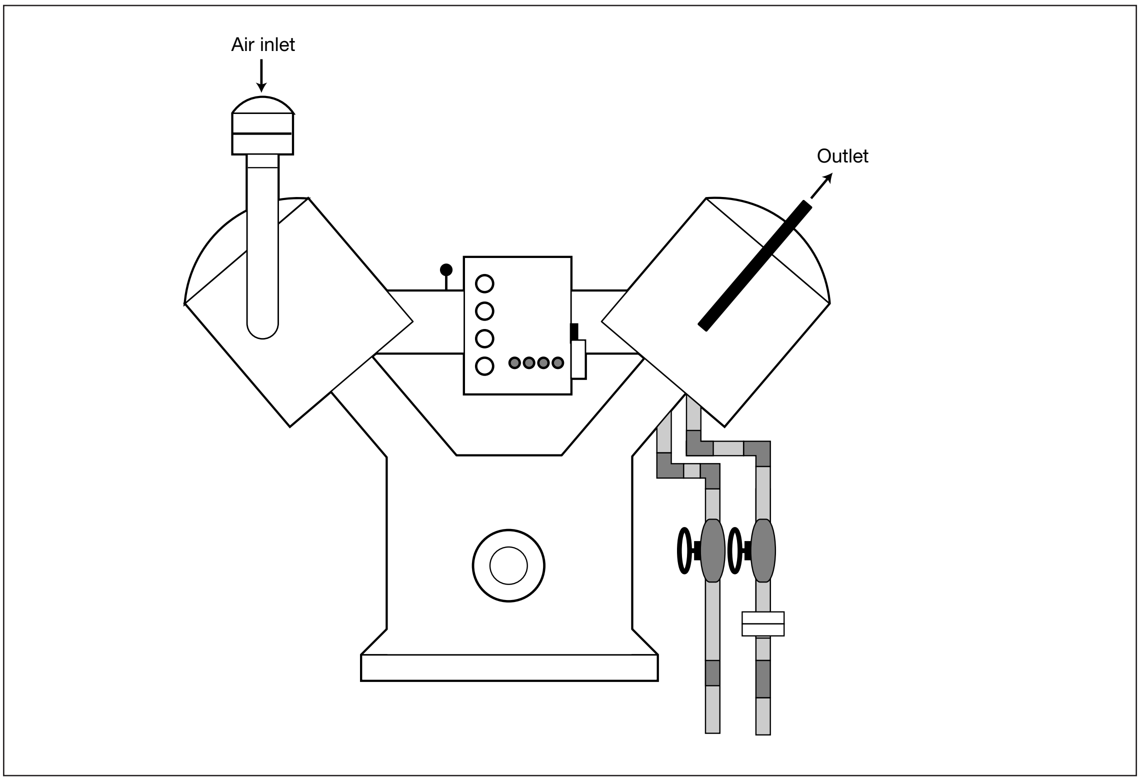


Fig 12 Reciprocating compressor

How They Work

Single acting, single-stage

The machine takes in air at atmospheric pressure and compresses it to the required pressure in a single-stage. Compression takes place only on the uptake of the piston.

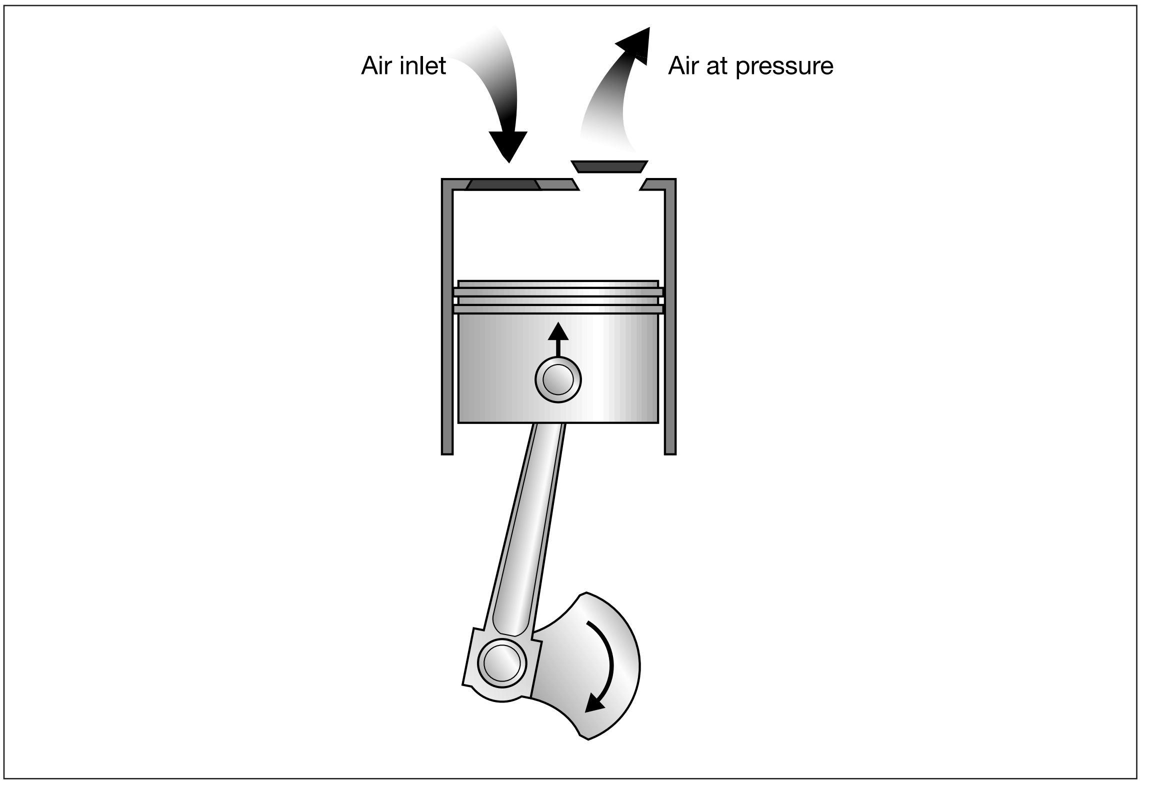


Fig 13 Single acting, single-stage compressor

Double acting, two-stage

The machine takes in air at atmospheric pressure and compresses it in two stages to the final pressure. Both sides of the cylinders are used to compress air.

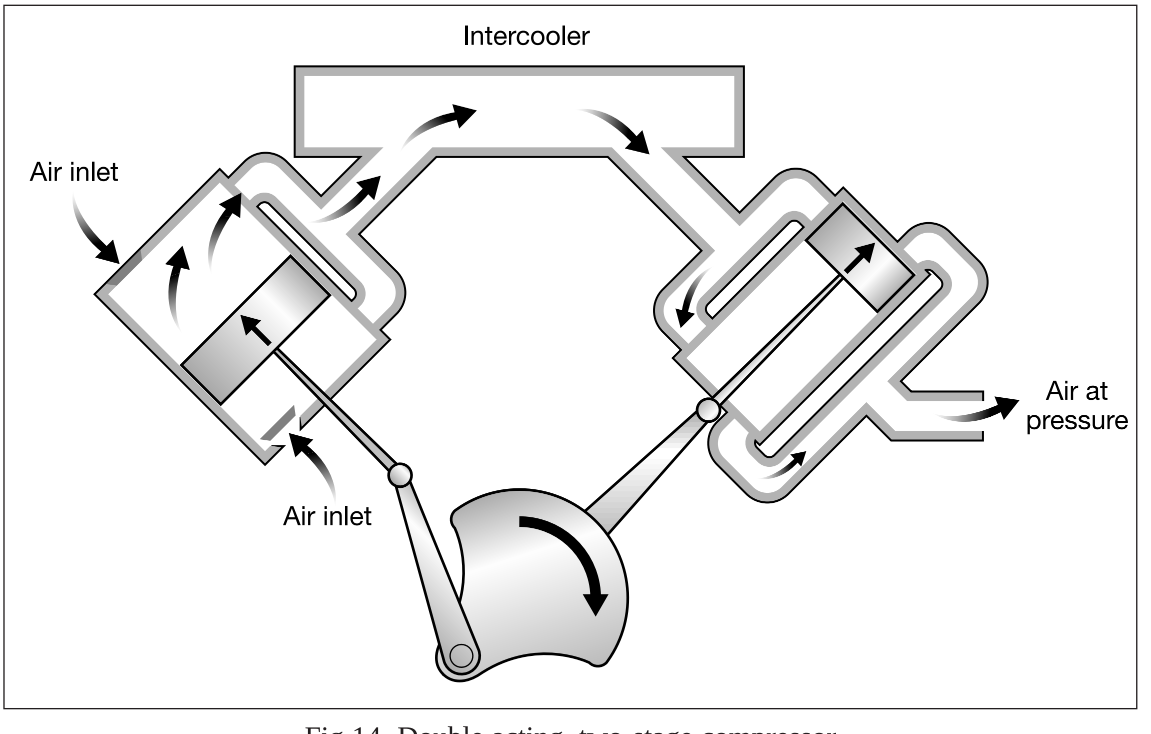


Fig 14 Double acting, two-stage compressor

3.5 Compressor Specification

To ensure that energy efficient compressors are purchased for a given duty, a specification should be written against which qualified suppliers can offer a proposal. Suppliers should be advised that bids will be analysed from an energy efficiency and lifetime cost of ownership viewpoint. **A full worked example of a specification and bid analysis is included in the Appendix.**

A specification should always include the following:

- background information about the site;
- the scope of supply;
- the duty in terms of mean, peak and minimum demand;
- the range of site ambient air temperatures and pressures expected;
- the mean site ambient air temperatures and pressures expected;
- the maximum site cooling air or water temperature expected;
- the height above sea level of the site;
- the standby strategy (see Sections 2.3 and 2.4);
- the minimum pressure required at the usage points;
- the air quality required at the usage points[5];
- the ancillary equipment needed (starters, isolators, local and remote controls, annunciators, and other items;
- the noise level required of all items;
- the hours to be run each week and the number of weeks per year.

Suppliers should also be asked to provide the following information with the proposal:

- the machine configuration offered;
- the unit size in terms of rated output;
- the conditions of air temperature, air pressure, relative humidity (RH) and cooling temperature under which the machine is rated;
- the output of the machine in scfm and/or Nm^3/h (given the mean site ambient air pressure and temperature);
- the number of units offered;
- the air treatment system offered (i.e. type of dryer, number and type of filters);
- the required delivery pressure at the compressor discharge, taking treatment system losses into account;
- the power consumed at the compressor shaft at the required delivery pressure;
- the method of control;
- the part-load power consumptions;
- the cooling system power including all pumps, fans and heaters;
- the actual power of each drive motor;
- the efficiency of each drive motor;
- the total package electrical input power;
- type of test employed;
- tolerances on flow, power and specific power at full and part load;
- full maintenance costs over five/ten years;
- itemised prices.

[5] See Good Practice Guide 216, *Energy saving in the filtration and drying of compressed air.*

Case Study - Armstrong World Industries Ltd, Thornaby

Armstrong World Industries Ltd at Thornaby in Teesside is a leading manufacturer of quality floor coverings. The site was operating two ten-year-old screw compressors that, with the growth of the production facilities, were being run flat-out with no standby. Further increases to the production facilities were also planned. Additional problems were being experienced with the compressor cooling, air quality and pressure drops to production.

Following recommendations from a survey of the system, the compressor station has been completely updated. Three new air-cooled compressors of 950 cfm nominal capacity have been installed. These are operated by an automatic sequencer. Waste heat in the cooling air from the compressors is now ducted into the main production building to supplement the automated heating system during the winter months. The new installation also includes a suitably-sized receiver, filters and a refrigerant dryer. The supply from the compressor house has been upgraded, along with the ring mains around the main production areas.

As a result of the work, the system is considerably more reliable with adequate air pressure and quality for production. The availability of a standby machine provides extra security and reduces mobile compressor hire costs during routine maintenance. In addition, it is estimated that 12% of the compressed air generation costs have been saved through the improved efficiency of the newer compressors. The use of the recovered waste heat is providing further savings.

Case Study - Eternit UK Ltd, Widnes

This roof tile manufacturing plant requires compressed air for both process and instrument purposes. The old compressor station comprised four oil-injected rotary screw compressors of between 270 and 400 cfm capacity. The air was treated by filtration and refrigerant drying. The age and condition of the compressors meant that replacement was imminent.

In order to help justify and design a new system, measurements of the air demand and compressor efficiencies were taken. These identified an energy saving potential of some 50% over current operations.

Knowing the air demand pattern allowed three new compressors to be sized for the differing production levels over the week, thus optimising full-load or near full-load running. A programmable controller ensured that the best sized compressors were operating at any given time. The compressed air treatment was upgraded to desiccant drying, with higher running costs but improved quality, in line with production requirements.

Measurements taken following the new installation have shown a 41% reduction in compressed air generation costs. In addition, there has been a saving in maintenance costs due to the increased reliability of the new system.

4. CONTROL OPTIONS

Most compressors run for much of their lives at less than full output because of the inevitable variation in daily demand. The efficient control of compressors at part-load, and switching them off when not needed, can achieve savings of 5 to 20% in total generation costs. There are three aspects of compressor control to consider:

- individual compressor control - Section 4.1;
- multiple compressor control - Section 4.2;
- control of the whole system - Section 4.3.

4.1 Individual Compressor Control

There are many configurations of air compressor, and many methods of control and group control. The most common forms of control on air compressors are:

- stop/start (small machines only);
- on-line/off-line;
- cylinder off-loading (piston-type only);
- modulating.

With all on/off type controls, installing an air receiver or large capacity piping system can help to prevent the compressor starting and stopping too frequently (i.e. hunting). One disadvantage of this system is that the load/unload cycle has to be controlled over a pressure differential of around 0.5 barg.

The part-load efficiency curves shown in this Section (Figs 15 - 20) show the increasing specific power generation for generating compressed air as the demand falls. Fig 15 graphically shows the increase.

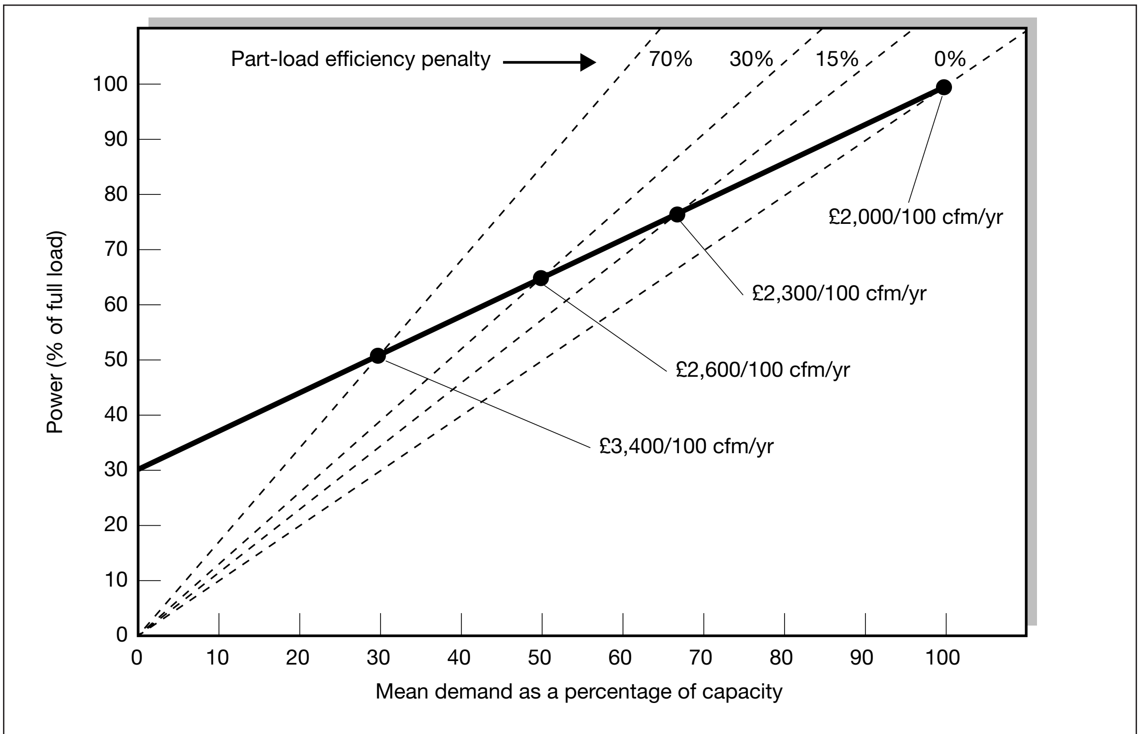


Fig 15 The cost of poor part-load efficiency - example of a rotary compressor under on-load/off-load control

4.1.1 *Automatic Stop/Start (Reciprocating, Vane and Screw)*

On a small compressor of less than 10 l/s, the compressor's motor is switched off when there is no demand. When it is on, it operates with constant power consumption when at the rated pressure. When it is off, the power consumption is zero. This approach is inherently efficient and represents the ideal part-load efficiency characteristic. However, it can also have problems in meeting part-load demands due to frequent switching on/off of the compressor. Therfore, this is not employed on larger machines.

4.1.2 *On-line/Off-line Control (Reciprocating, Vane and Screw)*

Many reciprocating, vane and screw compressors are operated using an on-line/off-line or two-step principle. When actually compressing air they operate near their rated power, but when the compressed air requirements are met, the compressors continue to run but are 'off-line'. Typical part-load operation using on-line/off-line control is shown in Fig 16. The machines actually only operate at full-load or no-load. Fig 16 shows the average power requirement at particular loads, e.g. 10 minutes on, 10 minutes off is a 50% load factor. The low load when 'off-line' means that it is possible to gain further power savings by connecting the motor in star during this time[6].

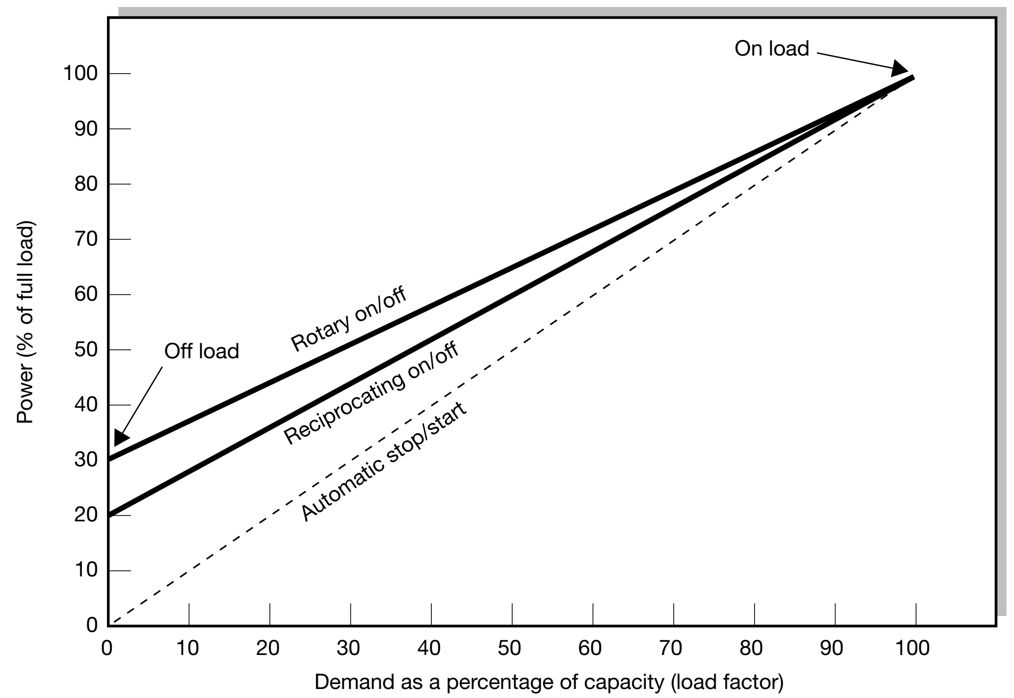


Fig 16 Part-load operation using on-line/off-line control

The compressor is controlled by completely closing a valve in the air inlet pipe or, with some reciprocating machines, holding the suction valves off their seat to provide the off-line effect when system pressure is at the top set-point. The machine will come back on line at the low set-point.

This can be very economical in reciprocating machines since the cylinders can pump down to vacuum conditions - giving an off-load power consumption of around 20% of full load.

With **rotary lubricated vane** and **screw compressors** the lubricant injection system is usually kept pressurised. This uses more off-load power (about 30 - 40% of full load) when motor losses are taken into account.

On-line/off-line inlet throttles on **oil-free screw compressors** are very similar to that described above. Most oil-free screw compressors are two-stage, allowing the first stage to be throttled and the air circulating through the second stage returned to the inlet having been cooled in a

[6] See Good Practice Case Study 267, *Permanent star running of a lightly loaded motor.*

secondary cooler. This reduces the off load power to less than that of lubricated rotary screw compressors.

Automatic shut-down controls - automatically switch off the motor when it runs unloaded for a user defined period, typically 15 - 20 minutes, and restarts the machine on demand for compressed air. The maximum number of starts per hour is specified by the motor manufacturer, typically 3 to 4 times per hour, and the minimum run-on time should not be reduced below that specified.

The part-load performance of a machine under this type of control lies between that of the reciprocating on/off and the automatic stop/start. The use of soft starters enables the motor to be switched on and off more frequently, enabling larger energy savings to be made by reducing the 'off-load' running time.

4.1.3 *Clearance Pocket Unloading in Three to Five Steps (Reciprocating Only)*

A proportion of the air at outlet pressure can be fed to internal pockets built into the cylinder castings, which equal a half or a quarter of the machine's capacity. By sequential filling of the pockets, rather than letting the compressed air into the system, the machine becomes part-loaded. The energy in the pressurised air is not lost because it helps the piston on its return stroke, although there are some efficiency losses. The part-load characteristics are similar to those shown for the reciprocating on/off control in Fig 16 although this method is slightly less efficient.

4.1.4 *Modulating - by Turn Valves (Oil-injected Screws Only)*

Compressor displacement is varied by rotating a helical control valve which opens bypass ports to return excess air to the inlet port. In practice, it is found to have similar efficiency to on-line/off-line control. However, this system does enable close pressure control within 0.1 barg over the modulating range.

4.1.5 *Modulating - by Inlet Throttles (Reciprocating, Vane and Screw)*

Reciprocating, vane and screw compressors can be controlled using a modulating inlet throttling valve. With this method, a variable aperture valve is allowed to partly close the inlet pipe as the system pressure rises to reduce the output of the machine. It has the advantage of keeping within a very close pressure differential.

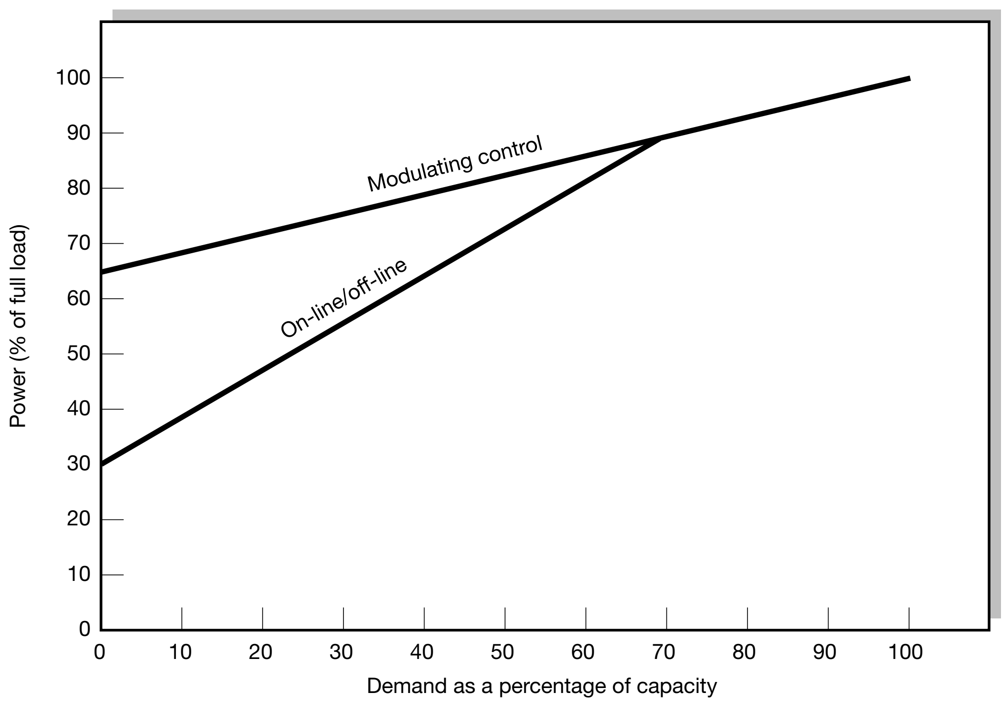


Fig 17 Part-load operation of modulating controls

As throttling continues, the inlet pressure reduces and the compression ratio increases. The power requirements at low part-loads are much higher than on/off control, as shown in Fig 17.

As the compression ratio increases, the air temperature at the discharge increases. To avoid problems, modulation is not allowed past around 50% load - when the power being drawn can be as high as 75%. Throttling the output in this way is less efficient than on-line/off-line control and so should only be used for highly loaded compressors.

On oil-injected screw compressors the oil removes the excess heat. This allows modulation to a much lower load, although not very efficiently.

4.1.6 *Modulating - by Inlet Throttles with On-line/Off-line Control (Reciprocating, Vane and Screw)*

This selects modulating or on-line/off-line control to ensure modulating control is not used below 70% load. A variation of this system allows manual selection of one or other of the control modes.

4.1.7 *Modulating - by Suction Valve Unloading (Reciprocating Only)*

The action of suction valves can be extended with variable timing devices during the opening period of the valves. This allows almost step-less control from no-load to full-load.

4.1.8 *Modulating - by Inlet Throttles with Atmospheric Bypass (Centrifugal Only)*

Dynamic compressors have to be carefully designed to ensure surge will not occur on days of high temperature and low pressure. Surge, shown in Fig 18, involves a sudden reversal of air through the compressor and must be avoided during normal operation. The full-load power requirement will increase on days of higher density intake.

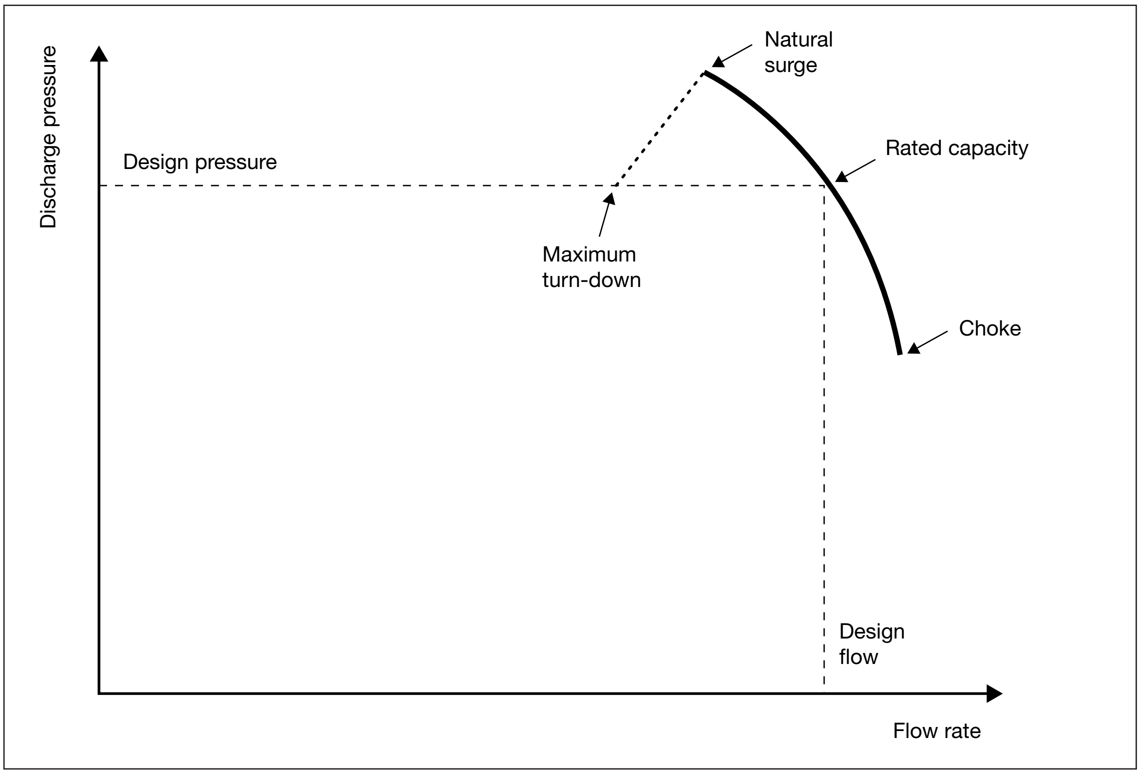


Fig 18 Full-load performance of centrifugal compressors

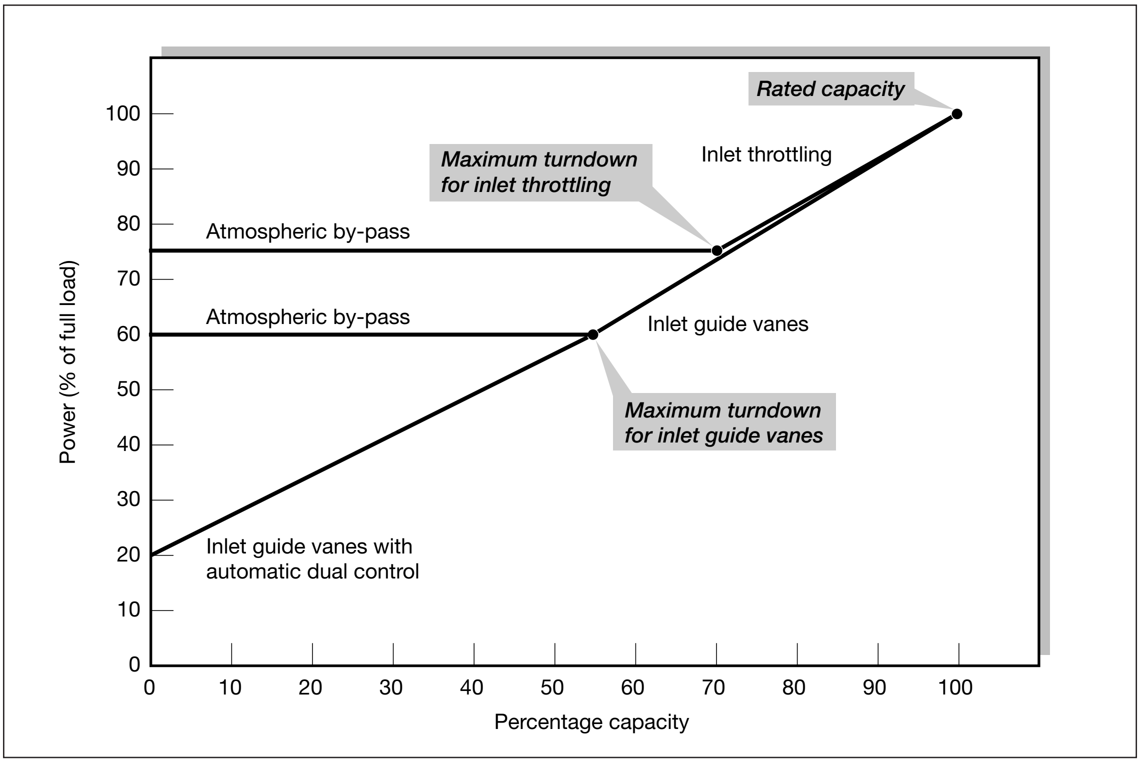


Fig 19 Part-load operation of centrifugal compressors

The part-load efficiency of centrifugal machines is a function of the aerodynamic design and can vary greatly. Fig 19 shows the effect of part-load operation of centrifugal compressors using different controls.

Throttling the inlet of centrifugal compressors provides a different effect to that of reciprocating and screw compressors. It reduces the weight of the air flowing up to the first-stage impeller with a reduction in the power being absorbed.

The limit of this control is when the pressure-increasing capability has been reduced to the point where the natural surge pressure is close to the operating pressure. This is known as the point of maximum turndown (see Fig 19). Below the point of maximum turndown, an atmospheric bypass valve opens allowing a proportion of the pressurised air to be vented to the atmosphere.

This method of control is energy efficient over the modulation range - from about 70% of output up to full load. Over this range, the power consumed is reduced almost in line with the flow, and the pressure is held at a very close differential of around 0.1 bar. Below the point of maximum turndown, the surplus air is bypassed to the atmosphere and this is very wasteful.

4.1.9 *Inlet Guide Vanes with Atmospheric Bypass (Centrifugal Only)*

Inlet guide vanes change the angle of attack, and hence flow, of the air onto the impellers. Guide vanes are preferable to inlet throttles as they improve the part-load efficiency and turn-down range, particularly at off-design inlet conditions.

4.1.10 *Automatic Dual Control (Centrifugal Only)*

To avoid wasting pressurised air in centrifugal machines due to bypassing, automatic dual controls can be used to sense the point of maximum turndown and then close the inlet valve and off-load the machine. This reduces considerably the power being consumed. One disadvantage of automatic dual control is that the pressure differential is increased to about 0.5 bar during light load running.

4.1.11 *Variable Speed Control*

Variable speed control is a newer method of compressor control that provides efficient operation over a wide range (down to around 20%) by closely matching output to demand. It can be fitted to reciprocating, rotary vane and screw compressors. In multiple installations, variable speed control is only necessary on the final or 'top-up' compressor, which will normally be 'floating'.

The cost of purchasing a compressor with integral variable speed control is much more attractive than retrofitting the controls, as the gearbox, belt drive and other controls are not needed. Retrofitting variable speed control is possible, but care should be taken to ensure adequate lubrication at low speeds and to avoid running at resonant frequencies.

Variable speed control provides close system air pressure control - lowering the mean pressure, for example, by 0.5 bar will save 3% of the energy consumed.

Variable speed compressors are designed for greater part-load efficiency and so should only be used in applications where they will be running for long periods at part load. At full load, the additional small losses in the control electronics can mean that they are slightly less efficient than conventional compressors and so should never be used as a base load compressor.

If the machine is configured in such a way that it experiences frequent periods of no demand, the integral soft-start allows frequent shut-downs and makes further energy savings (see Section 4.1.2).

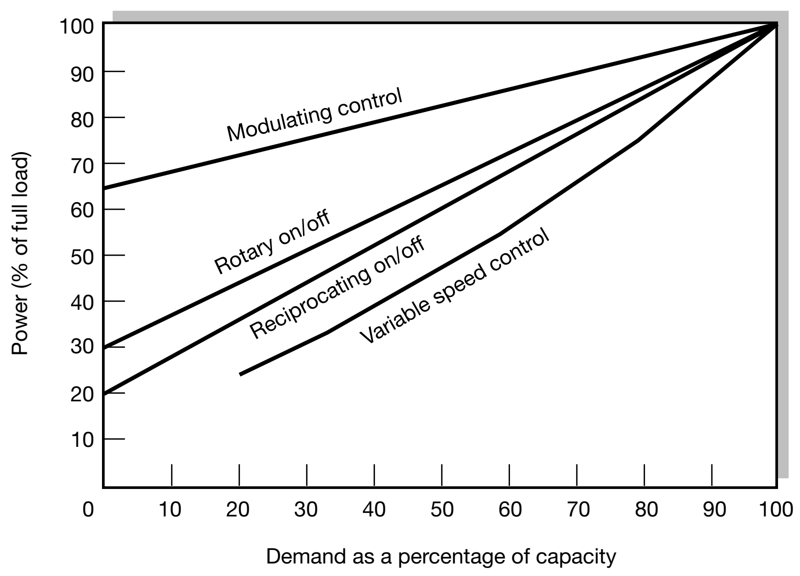


Fig 20 Part-load operation using a variable speed drive compared to other types

Compressors with variable speed control are available with both conventional AC induction motors, inverter variable speed drive, and with the much newer switched reluctance motor and drive.

4.2 Multiple Compressor Control

Most installations are made up of more than one compressor, allowing spare capacity for maintenance and better matching of demand. Automatic sequence controls can select the best combinations to match the demand based on pressure or, in some cases, flow measurement. The sequence can be rotated to equalise wear on individual compressors and it is also possible to avoid using the most inefficient machines. Many forms of automatic control exist for optimising the operation of multiple installations and the two most common control methods are described opposite.

4.2.1 *Cascade Pressure Control*

This simplest form of control is based on mechanical pressure switches which bring in more machines as the pressure falls. The pressure switch or transducer is usually located in the plant room. More responsive control is obtained if it is placed at the far end of the air distribution network. However, care should be taken to ensure that the compressor discharge pressure is not unnecessarily high due to pipework and treatment pressure drops.

Fig 21 shows the ‘lead’ No. 1 machine set at the highest pressure for the low demands. As the demand increases, the pressure will fall, bringing the second machine on line, and then the next, until the maximum demand rate for all four compressors is reached.

Each compressor requires a pressure band (ΔP1) for its load and unload set-points, shown as 0.5 bar in Fig 21. This band must be sufficient to prevent excessive cycling, a factor governed by the compressor size and receiver capacity. The pressure offset between the individual compressor bands (ΔP2) is again governed by the site installation. This offset needs to be kept to a minimum, but should be sufficient to prevent two or more compressors loading or unloading together.

Generation pressures cannot be varied according to demand, and so the higher pressure at low demand means higher energy consumption. Care must also be taken to ensure that the pressure settings are within the limits of the compressor capability.

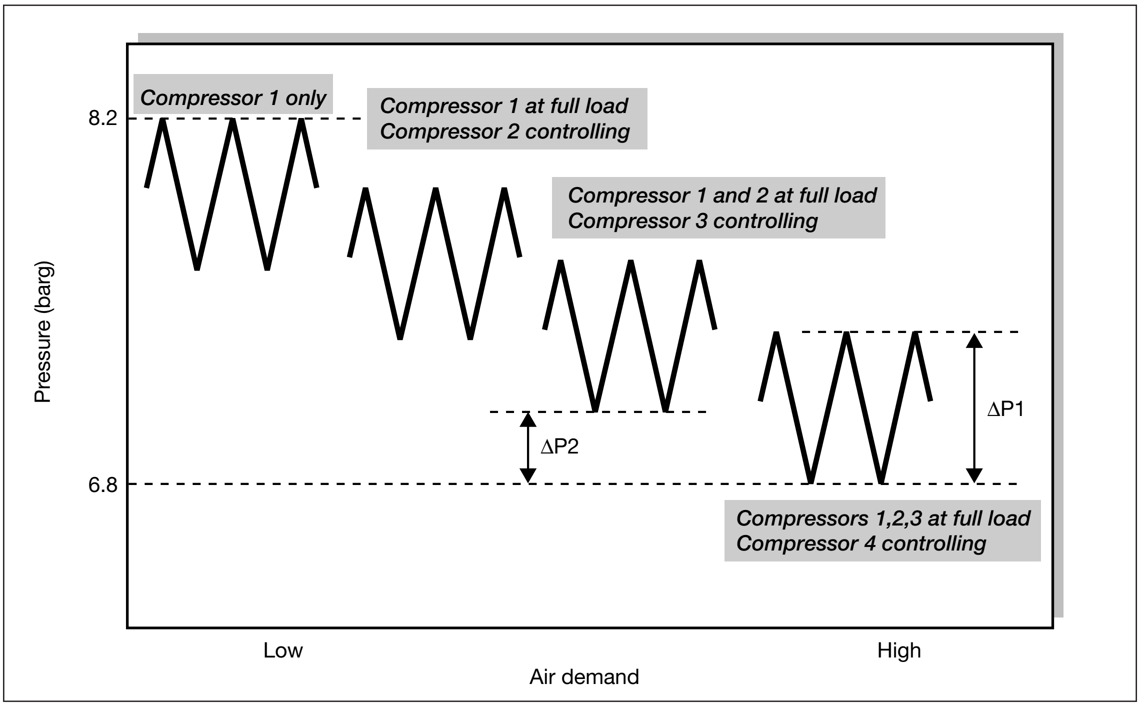


Fig 21 Cascade pressure control typical situation

4.2.2 *Electronic Controls*

Electronic controls can be used for sequence control based on a combination of pressure and demand-related signals. This avoids the need for sequential set pressures for individual machines, and eliminates the wide pressure control band inherent in cascade control (ΔP1 in Fig 22, overleaf).

Avoid fixed pressure settings. This allows generation pressures to be varied according to demand. Pressure can be lowered at the weekend and during the evening.

Monitoring the rate of change in pressure allows the controls to predict how long it is likely to be before a compressor is needed again and hence shut off the compressor completely, avoiding no-load running losses.

Some systems allow the pressure differential to be controlled automatically to calculate the most economic range for the load at the time of reaching the top of each pressure cycle. Too narrow a band will lead to frequent cycling, whilst a wide band will incur the penalties of cascade sequencing. Close control of the pressure differential using microprocessor-based controls and reduced system pressure, when acceptable, can provide energy savings as shown in Fig 22.

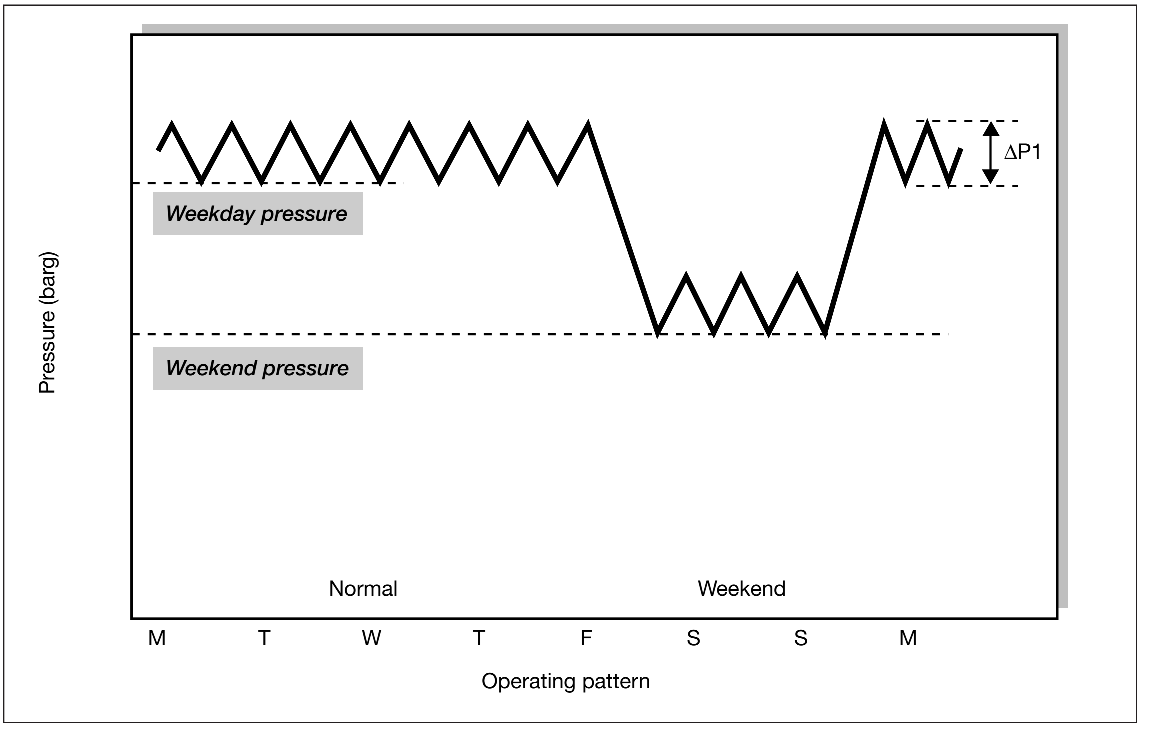


Fig 22 Reducing the pressure to suit site requirements using electronic controls

4.3 Overall System Control

System controls vary widely in complexity. In general, the more complex control systems provide greater flexibility and savings but often require careful commissioning. All systems require some degree of monitoring to ensure ongoing correct operation, and linking the controls to a Building Management System is an ideal way of achieving this.

4.3.1 *Simple Controls*

- The system may also require relatively simple zone controls to allow parts of the system to be shut down when not in use. Note that any control system adopted should be discussed with the compressor supplier to ensure that it is suitable and does not compromise any warranties or service agreements.
- A simple **time switch** is the most basic form of fixed time control which can be used to turn the plant off when not required in order to save energy.

Good Practice Case Study 136 - *Cost and energy savings achieved by improvements to a compressed air system*

As part of the programme to reduce the cost of compressed air at Creda's Stoke-on-Trent works, solenoid valves were fitted to isolate sections of pipework when not in use. The investment of £8,000 in these solenoid valves and associated pipework rationalisation led to energy savings worth £4,600/year.

4.3.2 *Integrated Controls*

Integrated controls may be part of the Building Management System and control the compressors and zones. Integrated controls can also be used to monitor plant operation, air demand, electricity consumption, etc, and can indicate when plant requires maintenance based on plant operation hours or condition monitoring.

Alarms can also be used to highlight plant faults or out of limit conditions. These provide useful management information and can often give an early indication of underlying problems. Fig 23 shows a typical installation of an integrated control system.

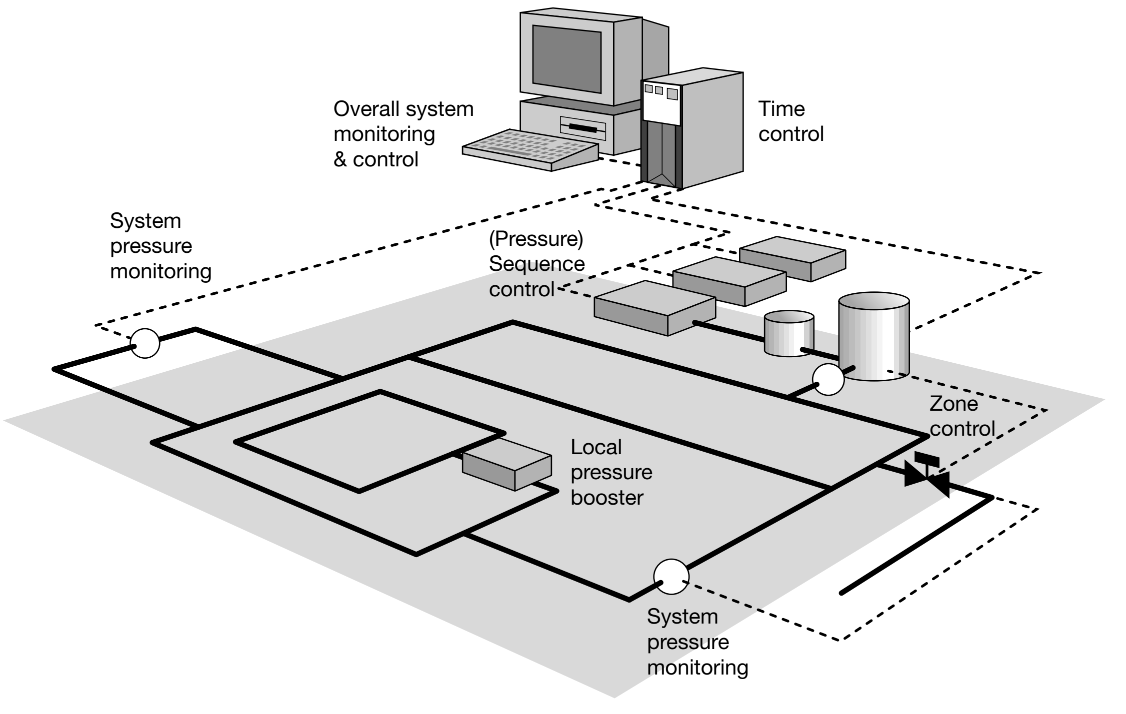


Fig 23 Typical installation of an integrated control system

Good Practice Case Study 137 - *Compressed air costs reduced by automatic controls*

Compressed air costs have been reduced by Land Rover through the introduction of an integrated automatic control system. Overall pressure control, compressor sequencing and time controls were installed giving an energy cost saving of £24,000/year. This also highlighted a site leakage problem, leading to further savings of £24,000/year.

Case Study - Viaton Industries Ltd, Brassington, Derbyshire

Viaton Industries specialises in the manufacture of micronised fillers for industry and the blending of iron oxide pigments used in the manufacture of a wide variety of building materials. The Company also offers a comprehensive contract grinding and micronising service. At its minerals division site, 7 bar compressed air is used for a variety of process and instrument purposes.

There were two air systems for the site. An elderly piston compressor served one part of the plant and modern oil-injected, rotary screw compressors the other. The requirement for compressed air changed over time and a review of the systems was needed to provide adequate standby capacity and ensure efficient operation.

The review included establishing, by measurement, the efficiency of the site compressors and measuring the air demand of the two systems. It was found that the reciprocating compressor was considerably more efficient than the smaller, single-stage screw machines, although its part-load efficiency was poor.

The two systems were linked and the operating strategy changed to run the reciprocating compressor on base load, with the smaller units being used to match demand changes. This change provided a potential saving on the annual compressed air costs of 19.8%, with a payback within one year. The saving was achieved through more efficient generation and reduced part-load running of the separate systems. In addition, the need to purchase additional capacity for standby duty was avoided.

Following the implementation of the strategy, the production demand has increased, all within the capacity of the revised system.

Case Study - British Aerospace Airbus Ltd, Broughton

The British Aerospace site near Chester manufactures the wings for the Airbus and sub-assemblies for the 125 Executive Jet. The 7 bar compressed air for the site is generated by six reciprocating compressors of 2,500 cfm nominal capacity and a screw compressor of a similar size. Five of the reciprocating compressors are located in a central station, with the other two machines feeding the system from remote locations.

The compressors were controlled on a traditional pressure switch cascade system, which provided two energy saving possibilities:

1. Each of the reciprocating compressors had five-step loading (off load, $^1/_4$, $^1/_2$, $^3/_4$ and full load). Consequently, the pressure settings for the lead machine were considerably higher than for the seventh. This caused low pressure problems if two of the base load compressors were being serviced and the seventh was required. In addition, for much of the time, the pressure was higher than needed.

2. The compressors did not have an automatic start/stop facility, and often five were running when only two were required.

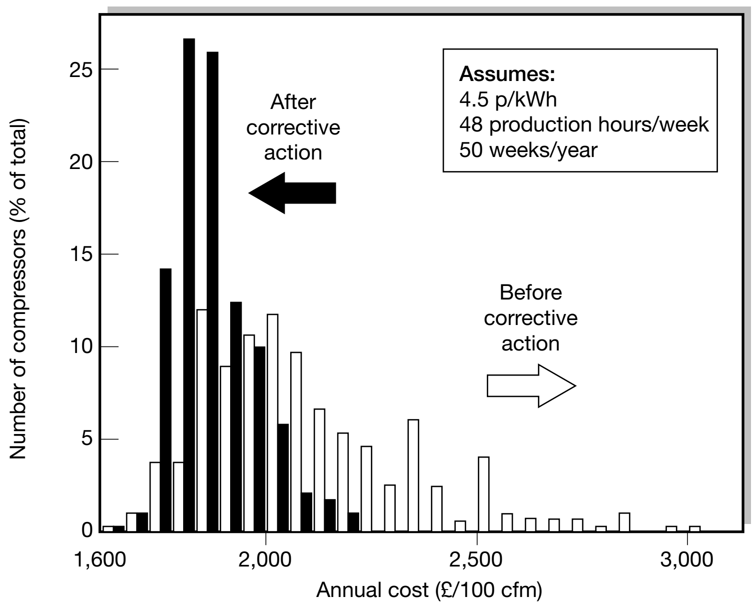
In order to optimise the efficiency of the plant, the Company has invested in a modern, microprocessor-based control system. This has realised the energy saving potential, providing a consistent pressure to meet production requirements and eliminating unnecessary off-load running. Other benefits include improved monitoring of the system and sequence rotation of the compressors.

The system has achieved annual energy savings of between £40,000 and £50,000, which have paid for the system within the first year.

5. MAINTENANCE

Achieving long-term reliability and energy efficient operation through good maintenance is a vital aspect of all compressed air installations. The running hours of the plant and the loads on the machines both have a profound impact on the level and cost of maintenance.

It is a false economy to ignore maintenance on any type of compressor. It is recommended that manufacturers, or their accredited agents, are used for service work and that genuine spare parts are used. An apparently cheaper component, such as an incorrectly designed replacement discharge valve, costs more in the long-term due to the detrimental effect that it has on compressor efficiency.



Tests carried out on over 300 typical 7 barg compressors show that average energy savings of around 10% can be made through simple improvements to compressor efficiency, many being low cost maintenance actions. The results of these tests are summarised opposite and Energy Consumption Guide 40 provides further details.

Fig 24 Savings made by making simple improvements to compressor efficiency

Maintaining ancillary equipment is also important in ensuring the energy efficiency of the whole system. A more detailed discussion of air treatment equipment is provided in Good Practice Guide 216, *Energy saving in the filtration and drying of compressed air*.

5.1 Planned Preventive Maintenance

Maintenance tasks generally fall into two main categories, planned preventive maintenance and reactive or breakdown maintenance.

Maintenance duties might also include plant operation and the installation of new services and equipment. The activities of maintenance staff, or contractors, can have a major impact on energy use in several areas:

- servicing plant and equipment to maintain optimum efficiency;
- repairing faults that cause direct energy wastage;
- implementing energy efficiency measures;
- condition or time based maintenance;
- monitoring plant performance.

5.2 Using Maintenance Contractors

Deciding whether to use a contractor for maintenance involves several factors. Some of the advantages and disadvantages are shown in Table 9.

Table 9 Advantages and disadvantages of contract and direct labour

CONTRACT LABOUR	DIRECT LABOUR
More competitive price.	More difficult to assess costs.
More flexible workforce with wide skills.	Fixed workforce and fixed skills.
May not be able to respond to all emergencies.	Always available to respond to emergencies.
Contract needs to be monitored.	In-house supervision required.
Specialist training and tools included.	Need to provide specialist training and tools.

Compressed air plant can also be installed, operated and maintained by **contract energy management** (CEM) companies, or as a **managed air system** by a compressor supplier. This can include shared savings or energy supply contracts.

New Practice Final Profile 92 - *Supplying compressed air by contract energy management*

When air compressor plant at Rhone Poulenc's Gloucester factory needed replacing, the capital and running costs were paid for under an energy services agreement. Rhone Poulenc now purchases compressed air on a pay-as-used basis with the energy services company having an incentive to maintain a high generating efficiency, and Rhone Poulenc responsible for reducing leakage and other wasteful practices. Rhone Poulenc has made energy cost savings of £9,000/year and has avoided the capital cost of the new plant. In addition, the Company is able to concentrate on its core business and leave the care of the compressed air plant to the energy services company.

5.3 Maintenance Issues

5.3.1 *Routine Maintenance Checklists*

Maintenance procedures should always be carried out in accordance with the manufacturer's instructions. Table 10 summarises the most important maintenance requirements for different types of compressor, with typical time intervals. Specific maintenance schedules should be drawn up for individual machines.

Section 3.4 shows some advantages and disadvantages of various machines in respect of their maintenance requirements.

Reciprocating compressors, particularly the oil-free type, suffer the most from lack of maintenance in terms of efficiency. If, for example, a 500 l/s demand was served by a poorly maintained, oil-free reciprocating compressor, compressor efficiency would deteriorate from 400 J/l to 450 J/l over a 12-month period, adding over £2,000 to the annual running costs. The efficiency of rotary vane and screw machines does not deteriorate so rapidly.

Centrifugal compressors, having few moving parts and comparatively large clearances, will maintain their efficiency over longer periods. The inlet air filters, cooling water system and the inter-coolers must be rigorously maintained or efficiency will fall off rapidly.

Table 10 Maintenance checklist

Maintenance activity:	**Lubricated screw compressor**	**Oil-free screw compressor**	**Lubricated reciprocating compressor**	**Oil-free reciprocating compressor**	**Rotary vane compressor**	**Refrigerant type air dryer**	**Desiccant type air dryer**	**In-line filters**	**Air receivers**
Visual check for leaks and damage	A	A	A	A	A	A	A	A	A
Check indicator readings	A	A	A	A	A	A	A	A	A
Top up lubricators			A						
Drain condensate and check traps	A	A	A	A	A	A		A	A
Check water flow	A*	A*	A*	A*	A*				
Check top-up lubricating oil	B	B	B	B	B				
Check suction filter	B#x	B#x	B#x	B#x	B#x				
Check tension of drive belts	B#x	B#x	B#x	B#x	B#x				
Check/adjust cylinder lubricators			B*						
Check purge silencers are clear							B		
Check cooler fin and cabinet filter cleanliness	C*	C*	C*	C*	C*	C*			
Change lubricating oil	Dx+	Dx+	Dx+	Dx+					
Change/clean oil filters	Dx+	Dx+	Dx+	Dx+	Dx+				
Clean scavenge filter	Dx								
Clean water strainers	D*	D*	D*	D*	D*	D*			
Clean coolers internally	D	D	D	D	D	D	D		
Check operation of controls/instruments	D	D	D	D	D	D	D		D
Grease motor bearings	D*	D*	D*	D*	D*				
Check big end bearings and bolt torques		D*x	D*x						
Strip/clean suction and delivery valves		D*x	D*x						
Check and clean governor and filter		D*x							
De-carbon inside cylinder, valve pockets and pipes		D*x	D*x						
Check piston ring gaps		D*x	D*x						
Check function and set point of protection devices	E	E	E	E	E	E	E	E	E
Check electrical cabling/components	E	E	E	E	E	E	E		
Clean condensate separators	E*	E*	E*	E*	E*	E*			
Leakage test	E	E	E	E	E	E	E	E	
Check purge flow							E		
Change air/oil separator	E/F#+								
Change desiccant							F#x		
Compression assembly refurbishment	25,000 hrs	40,000 hrs	12,000 hrs	9,000 hrs	25,000 hrs				

KEY **Typical Frequency**

A Daily
B Weekly or every 50 running hours whichever occurs first
C Monthly or every 250 running hours whichever occurs first
D Six monthly or every 2,000 running hours, whichever occurs first
E Annually or every 4,000 running hours whichever occurs first
F Bi-annually or every 8,000 running hours whichever occurs first

Notes

* If applicable
# Depending on site conditions
x If required by manufacturer's instructions
+ Depending on oil used

5.3.2 *Compressor Plant Condition Monitoring*

Monitoring reliability, availability and maintenance costs is a key part of any maintenance strategy. Monitoring equipment performance will help to identify malfunctions and provide a more accurate prognosis of maintenance requirements. In turn, this should provide energy saving through optimum utilisation of the machines and a reduction in no-load running.

To maintain high efficiencies, health checks should include:

Reciprocating compressors

- cylinder head temperatures;
- first and other stage inlet and outlet temperatures and pressures;
- final discharge temperatures;
- cooling medium on and off temperatures;
- noise and vibration;
- hours run on and off load;
- oil and air leaks and any abnormalities.

Oil-injected rotary vane and screw compressors

- inlet and outlet temperatures and pressures;
- final discharge temperatures;
- separation system pressure drops;
- scavenge system;
- cooling medium on and off temperatures;
- noise and vibration;
- hours run on and off load;
- oil and air leaks;
- oil carry-over and any abnormalities.

Oil-free rotary screw and rotary tooth compressors

- first and second stage inlet and outlet temperatures and pressures;
- final discharge temperatures;
- cooling medium on and off temperatures;
- noise and vibration;
- hours run on and off load;
- oil and air leaks and any abnormalities.

Centrifugal compressors

- first and other stage inlet and outlet temperatures and pressures;
- final discharge temperatures;
- cooling medium on and off temperatures;
- stage vibration;
- noise and general vibration;
- hours run on and off load;
- oil and air leaks and any abnormalities.

Individual compressor controls

- correct operation of control valves;
- correct operation of auto stop/start facilities.

Multiple compressor controls

- pressure band analysis;
- sequence patterns and off-load running times.

Cooling systems

Correct operation of:

- cooling towers and water treatment;
- make-ups and spray drift;
- heat dump radiators;
- pumps sets;
- air inlet and discharge ducting (restrictions and location).

5.4 Options for Refurbishing Plant

It can be more economical to refurbish air compressors than replace them. In this case, it is recommended that the manufacturer or authorised agent is contacted.

5.4.1 *Reciprocating Compressors*

Double acting water-cooled machines are often well worth refurbishing, provided the design is still current and spare parts are readily available. Refurbishment can include changing the capacity and modernising the controls. However, single or double acting air-cooled machines of up to 250 l/s capacity over 20-years-old are probably not worth extensive refurbishment. These machines were not particularly efficient when new and there have been no developments to add to their efficiency.

> **Good Practice Case Study 277 - *Refurbishment of a compressed air system***
>
> Beatson Clark had been experiencing problems with the reliability of its compressed air supply due to the poor efficiency of the compressors. An initial review of the system recommended the purchase of some new compressors. However, instead it spent £44,000 having some much older machines refurbished, giving a total payback period through energy and maintenance savings of 1.3 years.

5.4.2 *Lubricated Rotary Compressors*

Since there has been rapid development in this class of machine over the last 25 years, refurbishment is unlikely to be worthwhile.

5.4.3 *Oil-free Rotary Compressors*

Some machines may benefit from improvements that have been made over last ten years - depending on the manufacturer. The gearbox and drive arrangements can be retained and the latest compression air-end, coolers and controls can be retrofitted to enhance the energy efficiency for a proportionally lower cost compared to the cost of purchasing a new machine.

5.4.4 *Centrifugal Compressors*

Manufacturers of these compressors have made huge improvements in energy efficiency over the last 15 years. It is possible to fit a 30-year-old machine with the latest aerodynamics in terms of the impellers and diffusers, and the latest controls such as inlet guide vanes, and electronic positioners and monitoring systems. This has greatly improved the efficiency at full and part load in several cases, at a fraction of the price of a new machine.

5.4.5 *Motor Repairs*

If the motor fails, it may be appropriate to have it repaired rather than replaced. This must be through a quality repair shop in order to minimise the additional energy losses that can be incurred by poor repair practice[7].

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[7] See EEBPP/AEMT Good Practice Guide, *Repair of motors to minimise energy losses*, available from the Association of Electrical and Machinery Trades at 177 Bagnall Road, Basford, Nottingham, NG6 8SJ. Tel 0115 978 0086.

Good Practice Case Study 233 - *Energy and cost savings from air compressor replacement.*

When an increase in production meant that additional compressed replacement air was required at the J H Ashworth and Sons yarn factory in Hyde, Cheshire, an independent report on the existing air compressors was commissioned. As a result, rather than just buying another compressor to meet the additional demand, the existing small compressors were replaced with a single larger and much more efficient machine. It is now meeting a 25% increase in compressed air demand with only a 6% increase in electricity usage.

Case Study - Alcan Smelting, Lynemouth

Alcan's Lynemouth smelter uses large amounts of compressed air for process and instrumentation purposes. The air is generated by six oil-free reciprocating compressors in a central compressor house.

The original maintenance strategy was to carry out a short service and inspection at 4,000 hours followed by a full service at 8,000 hours. After discussions with the compressor service company, it was decided to change the maintenance strategy to a single full service every 6,000 hours. This reduced the overall number of services per machine from eight to six over a 24,000 hour period, providing a large saving in maintenance costs, as well as giving an improvement in machine performance.

When running under the original maintenance strategy, the compressors were all performance tested during a survey of the compressed air system in 1990. This revealed an average free air delivery of 1,697 cfm and specific power consumption of 18.9 kW/100 cfm at 100 psig. Repeat tests in 1996, when running under the new strategy, revealed an improvement in average output to 1,775 cfm, with an efficiency of 19.0 kW/100 cfm at an increased pressure of 110 psig. This is equivalent to a rate of 18.2 kW/100 cfm at 100 psig.

Based on a measured site demand of 7,300 cfm, this has given an annual saving in running costs in excess of 315,000 kWh. Alcan produces its own power at a very low rate however, at a typical cost of 4.3 p/kWh the savings would be in excess of £13,500/year. This is all in addition to the savings in maintenance costs.

Case Study - National Power plc, Drax Power Station

The National Power site at Drax in Yorkshire is the largest coal-fired power station in Europe. Compressed air is used at a variety of pressures for a range of process and instrument applications. One such application is the automatic boiler control (ABC) on the six boilers. Three of the boilers, units 4 to 6, are each supplied from three oil-free screw compressors of approximately 340 cfm capacity (nine compressors in total), with waste heat recovery dryers.

As part of the ongoing review of energy use at the site, an investigation into the efficiency of these three systems was undertaken to determine any areas for improvement. The performance of the compressors was found to be poor in terms of delivery (78% of rating typical) and efficiency (average 52% more costly than expected).

The compressors had been serviced by a company other than the manufacturer or approved agent. Following the above findings, the service contract has been changed to the manufacturer and now includes a major overhaul of the compressors.

Repeat performance tests of the machines following this work have shown considerable efficiency improvements, and increased the available capacity. The energy saved by undertaking the overdue service requirements has highlighted the false economy of poor servicing.

APPENDIX

SPECIFYING AND ANALYSING QUOTES FOR AN AIR COMPRESSOR INSTALLATION - WORKED EXAMPLE

The example given in Section 3.2 showed how a demand which varied over a 24-hour period varied from 132 l/s to 614 l/s at 7 barg. The mean demand is given as:

- daytime mean - 518 l/s (for 10 hours/day);
- night-time mean - 267 l/s (for 14 hours/day).

An allowance for potential growth of 20% is required, giving a capacity requirement of 740 l/s plus standby. In this case, two units of 370 l/s will ideally meet the demand, as shown in Fig 25, together with a third standby unit.

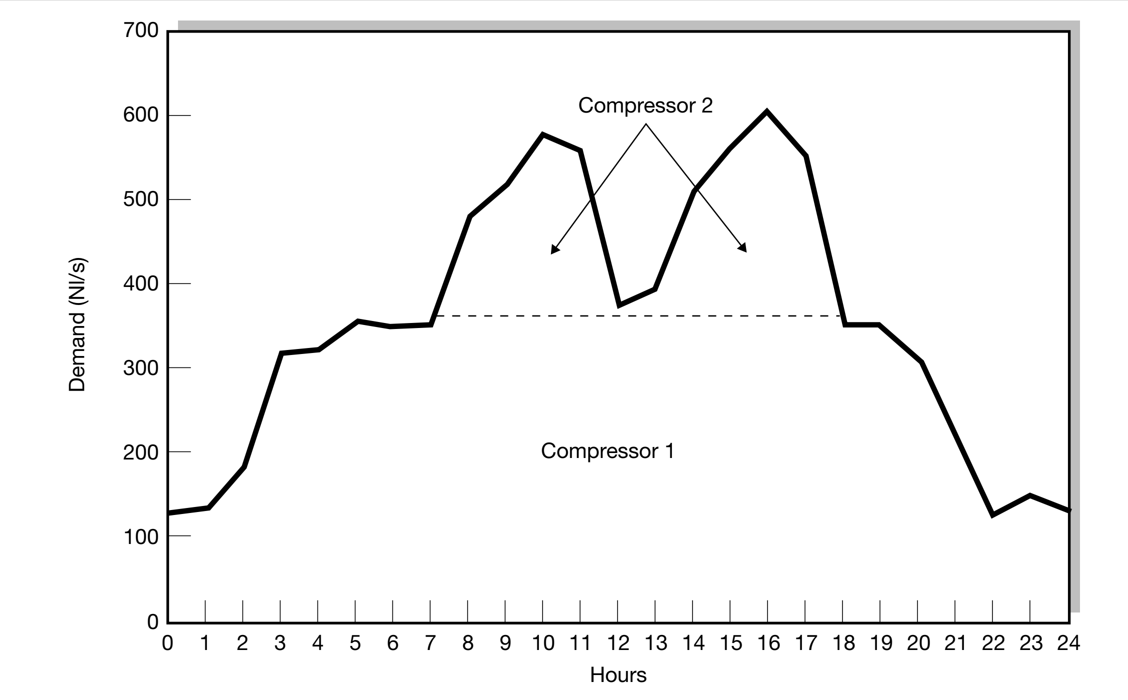

Fig 25 Demand met with two compressors

A typical specification for this duty would be as follows:

Background

Compressed air is an essential service and is required for a variety of instrumentation and process uses at the light assembly plant. The air is used for 24 hours per day, five days per week and 50 weeks per year - the typical demand pattern is shown above. The company is to purchase new air compressors to replace some ageing air-cooled reciprocating machines. The operating strategy is to provide two machines to cover the duty and one standby unit.

Scope of Supply

Proposals are invited for three off electrically-driven, air-cooled, lubricated packaged compressors sized for a minimum 370 l/s each. General purpose oil and water removal filters and refrigerated air dryers are to be provided to meet the air quality required. New air receivers with condensate recovery and clean-up systems are also to be provided. Air is to be used at 6.2 barg throughout the factory. An electronic control system is to be included which will ensure that only the minimum number of machines are on line to meet the duty.

The machines are to be installed in a purpose-built compressor house in which the new equipment is to be housed. The existing feeding air main and factory mains are adequately sized at full demand and the pressure drop from downstream of the air dryer to the far end of the piping network is 0.5 bar (6.7 barg minimum required from the compressor house).

The Site Conditions are:

electrical supply	-	400V/3Ph/50Hz;
site air temperatures	-	-5°C to +35°C;
site air pressures	-	985 to 1027 mbarA;
ancillaries needed	-	starters, isolators and local controls;
noise level	-	75 dBa at 1 metre from the compressors;
electricity cost	-	5 p/kWh.

Please quote the compressor delivery performance in litres/second related to 'Normal' conditions (1,013 mbarA, 0°C, dry), given the mean site ambient of:

- 1,007 mbarA;
- 12°C;
- 60% RH.

The actual rating of the main drive motor (including any service factor) should be given.

Bid Analysis

The specifier should write a bid analysis after receiving detailed proposals from selected suppliers. Use a form similar to Table 11 to compare the compressor proposals.

The total costs are highlighted in Fig 26 (overleaf), showing the importance of energy as a proportion of lifetime costs of ownership. The method used to calculate the energy costs is shown in the example on page 42. Over a ten-year period the energy and maintenance costs become very significant.

From this analysis it should be simple to select the most appropriate system based on:

- energy efficiency;
- running costs;
- maintenance cost (including future availability of parts);
- capital cost;
- installation cost.

Further analysis of the bid is required to check the equipment proposed for each site and any ancillary equipment.

Table 11 Bid analysis

	SUPPLIER A	SUPPLIER B	SUPPLIER C
SUMMARY OF EQUIPMENT OFFERED			
Compressor configuration	Oil-injected screw	Lubricated piston	Oil-injected screw
Output in Nl/s	385	390	380
Package input power at full load kW	140	135	150
Specific power J/Nl	364	359	395
Package input power at no load kW	35	31	57
Number of units	3	3	3
Noise level dBa	72	84	74
Discharge pressure bar	7.5	7.7	7.9
Treatment system	Fridge dryer + filters	Fridge dryer + filters	Fridge dryer + filters
Treatment system pressure drop bar	0.8	1	1.2
Method of control	2-step	2-step	Mod + auto
ANALYSIS OF RUNNING COSTS			
Elec. kW to meet daytime demand (one full load, one part-load - see Figs15 - 20)	211	207	251
Elec. kW to meet night-time demand (one part-load - see Figs 15 - 20)	108	106	134
Electrical kWh per week	18,110	17,770	21,930
Annual cost of energy	£45,275	£44,425	£54,825
Maintenance cost for five years	£40,000	£58,000	£40,000
Energy cost for five years	£226,375	£222,125	£274,125
Running cost over five years	£266,375	£280,125	£314,125
Capital cost	£120,000	£130,000	£110,000
Cost of ownership over five years	£386,375	£410,125	£424,125

Note that the above is an example of bid analysis only. Actual performance characteristics of the different types of compressors will vary.

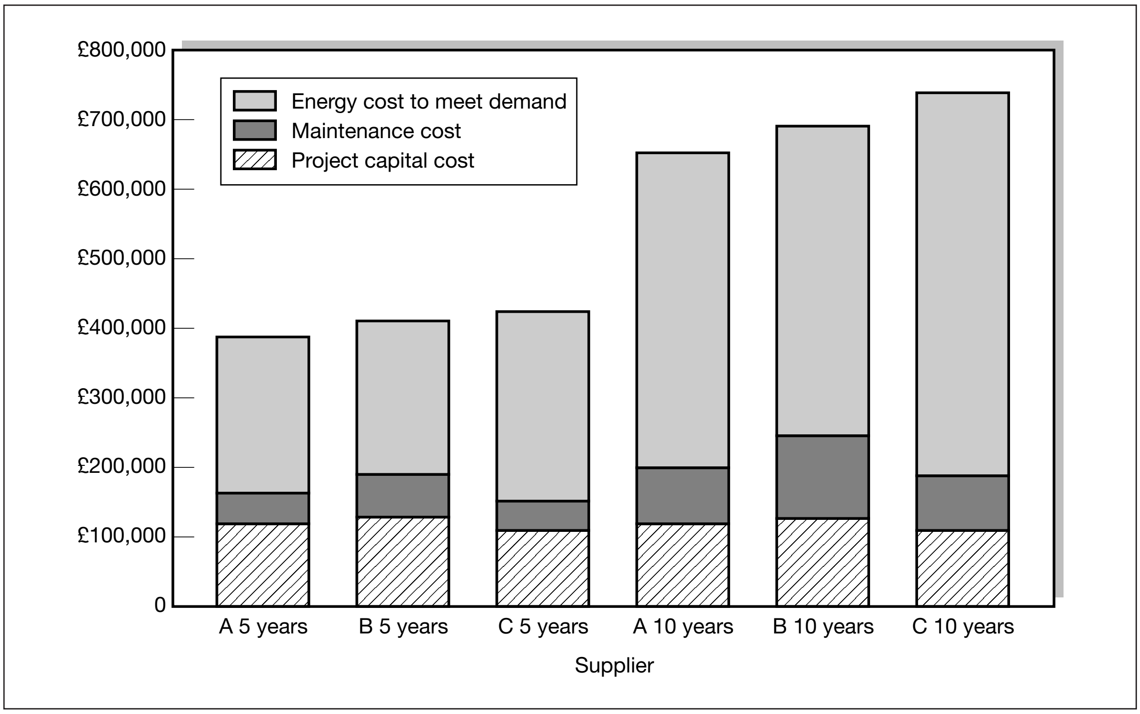

Fig 26 Calculation of Energy Costs

Calculation of Energy Costs - Example

Daytime demand = 518 l/s mean

For supplier A, compressor load $= \frac{518 \text{ l/s}}{385 \text{ l/s}} = 1.35$

Total compressor power consumption:

Compressor 1 (full load) = 140 kW

Compressor 2 (35% load) = 35 kW + 35% (140 kW - 35 kW) = 70.7 kW

Compressor 1 and 2 = 212 kW

Weekly daytime electricity use

5 days x 10 h/day x 212 kW = 10,600 kWh

In a similar way, the weekly night time electricity use is 7,596 kWh

Total weekly electricity use is 18,196 kWh

Total annual cost of electricity is:

50 weeks x 5 p/kWh x 18,196 kWh/week = £45,490 p.a.

The Government's Energy Efficiency Best Practice Programme provides impartial, authoritative information on energy efficiency techniques and technologies in industry, transport and buildings. This information is disseminated through publications, videos and software, together with seminars, workshops and other events. Publications within the Best Practice Programme are shown opposite.

Further information

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Energy Consumption Guides: compare energy use in specific processes, operations, plant and building types.

Good Practice: promotes proven energy efficient techniques through Guides and Case Studies.

New Practice: monitors first commercial applications of new energy efficiency measures.

Future Practice: reports on joint R & D ventures into new energy efficiency measures.

General Information: describes concepts and approaches yet to be fully established as good practice.

Fuel Efficiency Booklets: give detailed information on specific technologies and techniques.

Energy Efficiency in Buildings: helps new energy managers understand the use and costs of heating, lighting etc.