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Optimisation of the energy performance of compressed air production, distribution and use systems

1. Overview of the situation

1.1. Operation and dimensioning

Following a series of 20 compressed air diagnoses and pre-diagnoses carried out in animal feed plants, it emerged that in 70% of the plants audited this system offered a potential energy saving of 30% or more.

Maintenance of the compressed air production, distribution and use system in the majority of plants, has been relatively neglected. Only the periodic maintenance recommended by the compressor manufacturer is conducted satisfactorily (either internally or externally) on the whole.

In most cases, specific attention is paid to this system, but only when:

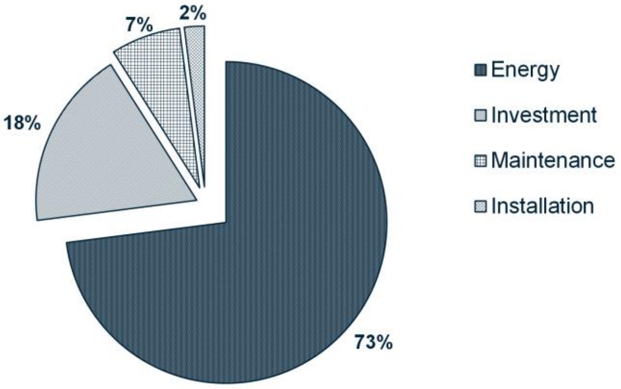
- there is a problem with its operation (a malfunction, air quality problem, etc.)
- the compressed air system reaches saturation point for production.

In the latter case, the most common response is to install a compressed air system with a greater capacity than the existing one, without previously seeking to optimise the existing system (a reduction in air leaks, installation of a buffer tank, optimising air user settings, etc.).

In almost all cases, dimensioning of a compressed air system is carried out in an empirical manner, most often resulting in the over-dimensioning of systems and, therefore, excess electrical energy consumption.

However, as demonstrated by the following graphic, the cost of electrical energy as a proportion of the total operating costs (investment + operation) of a compressed air system is very high.

Example of the relative proportion of costs for a compressed air production system (manufacturer's data) for a compressor with an output of 75 kW producing air at 7 bar for an operating period of 40,000 hours (i.e. approximately 6 to 7 years).



1.2. Electricity consumption of compressed air production systems

A compressed air production system consumes an average of 2.3 kWh of electricity per tonne of feed processed. The consumption recorded by TECALIMAN varies between 0.7 and 6.2 kWh / tonne processed depending on the site audited.

The proportion of electricity consumption by a compressed air production system in relation to the total electricity consumption of a livestock feed plant varies between 2% and 11.8% (depending on the site audited by TECALIMAN).

The cost of the electrical energy consumed by a compressed air production system may vary between 17.5 and 280 hundred Francs per tonne of feed processed (assessment based on the purchase prices of energy obtained within the framework of TECALIMAN's energy performance monitoring for the year 2000).

Compressed air is convenient, safe, “clean” and instant but expensive energy.

Overall, it should be borne in mind that 1 kWh of compressed air applied by air users, is approximately equivalent to 10 kWh of electricity consumed by the production system, i.e. efficiency of 10 %.

The remaining 90% of the energy is dissipated partly in the form of heat, air leaks, pressure losses, etc.

2. Units used to characterise the flow of compressed air

Air flow is commonly measured in cubic metres per hour (m^3/h).

Compressed air flow is expressed on the basis of the pressure and temperature of the compressed air in question.

For this reason, compressed air flow is most commonly expressed under standardised temperature and pressure conditions.

For example, the compressed air flows cited by compressor and dryer manufacturers are, in most cases, provided for an air temperature of 20°C and pressure equivalent to atmospheric pressure.

It is extremely common to use the normal cubic metre per hour (Nm^3/h) as the compressed air flow unit. In this case, compressed air flow is provided for a pressure equivalent to atmospheric pressure and for a temperature of 0°C.

3. Characterisation of the energy performance of a compressed air system

A system's energy performance is characterised by its specific energy consumption (Cs), where

$$Cs = \frac{\text{Electricity consumed (Wh)}}{\text{Volume of compressed air produced or consumed (m}^3\text{ or Nm}^3\text{)}}$$

Common units for this ratio: Wh/m^3: or Wh/Nm^3

Specific energy consumption can be defined at 3 distinct points of the compressed air network:

- Downstream of the compressed air production system, where it represents the electrical energy consumed by the production system in relation to the quantity of air produced by this system,
- Downstream of the compressed air drying system, where it represents the electrical energy consumed by the production and drying systems in relation to the quantity of compressed air supplied to the distribution network,
- Upstream of compressed air users, where it represents the electrical energy consumed by the compressed air production and drying systems in relation to the quantity of compressed air actually consumed by all users.

The optimum specific consumption of a compressed air system equates to the specific consumption obtained at the compressor when the latter is producing its normal air flow (at a given pressure).

Example 1:
A Compressor drawing power of 53.1 kW to produce an air flow of 482 Nm^3/h, at a pressure of 7 bar, has optimum specific consumption of:

53100 Watt / 482 Nm^3/h = 110 Wh/Nm^3

4. Factors influencing the electrical energy consumption of a compressed air system

4.1. Factors associated with the production of compressed air

4.1.1. Compression techniques

Compressors can be classified on the basis of: compression technique, number of compression stages, flow range, type of cooling, type of lubrication, etc.

The compressors encountered in the animal feed industry use a volumetric compression technique.

This compression is obtained by reducing the space containing the air taken in at atmospheric pressure. It is characterised by the compression ratio, which equates to:

$$\frac{\text{Absolute Pressure of the Compressed Air Expelled at the System's Outlet}}{\text{Absolute Pressure of the System's Intake Air}}$$

Pressure is expressed in bar

Consequently, for a compressed air flow produced constantly, the electrical energy drawn by the system increases as the compression ratio increases.

This compression technique is divided into 2 major families:

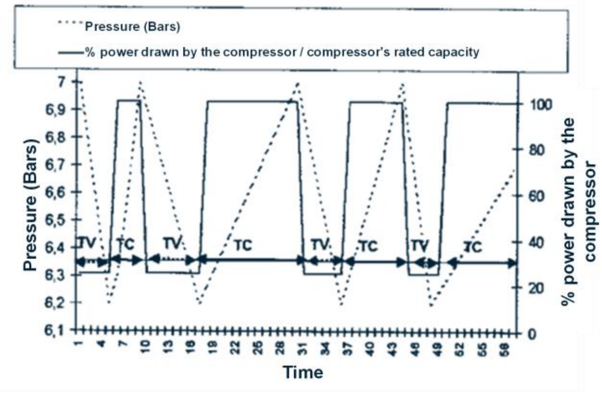
- rotary compressors: lubricated rotary screw compressors represent 80 to 85 % of applications in animal feed plants, with rotary vane compressors representing 10 to 15 % of applications. (There are also rotary lobe compressors, spiral compressors, etc.)
- reciprocating compressors: piston compressors represent less than 5% of applications

4.1.2. Types of compressor control

4.1.2.1 The different types of control

For lubricated rotary screw compressors, there are 3 different types of control:

- **All or Nothing *(ToR in French)*:** A pressure switch adjusts the compressor's operation (full load, idling or complete stop) in order to keep the network pressure between a high value and a low value (see the cycle presented below). This type of control must always be accompanied by a properly dimensioned air reserve in order to deal with consumption peaks and to prevent complete compressor operating cycles (loaded operation + idling) that are too short.



In the above graphic: Tc is the operating time at full load of the compressor and Tv is its operating time when idling.

- **Gradual (or modulating):** this type of control enables stable pressure to be maintained across the network, provided that the air flow drawn by the plant remains at, approximately, between 60 and 100% of the system's nominal flow. This type of control is often consumes more energy than the 2 other types of control.

- **Electronic Speed Variation (ESV)** obtained using a variable frequency drive. This type of control enables the power drawn by the compressor to be adjusted to the air flow drawn by the network. It has the advantage of guaranteeing stable operating pressure within the network (+/- 0.1 bar). The main drawback, compared to other types of control, is the financial investment, which is far greater.

  NB: Compressors controlled by ESV are not available from all manufacturers and in all power ranges.

Only the first 2 types of control are available for rotary vane compressors.

4.1.2.2 **Choosing the type of control**

Specific energy consumption should be the main criterion when choosing the type of control. This is not currently the case.

As explained above, in order to achieve optimum specific consumption for the compressor or compressors installed, it is necessary to produce an air flow that is as close as possible to the nominal flow for this (or these) compressor(s).

Comparison between All or Nothing and ESV control:

For a lubricated rotary screw compressor, all or nothing control will be more attractive (i.e. lower specific consumption) if the air flow produced is between 80 and 100% of its nominal flow. For a compressed air flow produced below 80% of the compressor's nominal flow, ESV control will be more attractive in terms of energy. The threshold of 80% is approximate and depends on the machines compared.

However, given the difference in the value of investment between a compressor with all or nothing control and ESV control, only a technico-economic study enables the ROI (return on investment) period for this difference in investment to be defined. The ROI period is determined on the basis of the average air flow to be supplied to the network, the average specific consumption obtained for the different compressors and types of control examined, as well as the purchase price of electricity.

4.1.3. Dimensioning a system

An over-dimensioned compressed air system is a source of excess energy consumption.

This is particularly true for compressors with all or nothing type control and modulating control.

For a compressor with all or nothing control (the vast majority of systems), specific consumption depends on the compressor's load commitment level (which depends on the flow produced). The lower the load commitment level, the higher the specific consumption.

Example 2:
Based on the same compressor as for example 1 and assuming an average load commitment level of 38%, the specific consumption downstream of the compressor is equal to:

$$= 156 \text{ Wh/Nm}^3$$

i.e. specific consumption greater than 42% of the optimum specific consumption (see example 1).

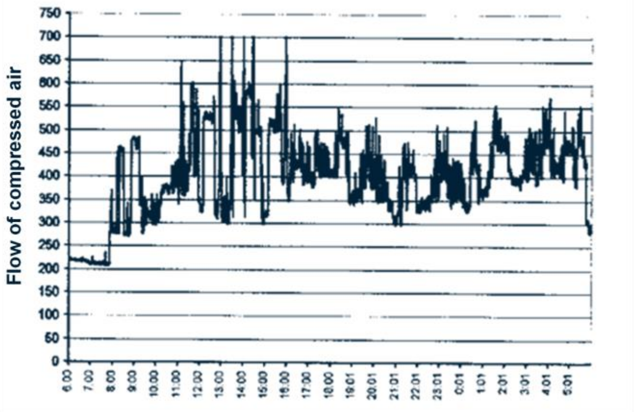
A correctly dimensioned compressed air system must cope with variations in network air drawing, but must also produce (as far as possible) an average air flow that is as close as possible to the nominal flow (to achieve specific consumption that is as low as possible).

It should be borne in mind that, in order to optimise dimensioning of a compressed air system:

- it is possible, in certain cases, to smooth out certain network air drawing peaks by installing properly dimensioned air tanks.

- it may be appropriate to re-evaluate the settings (operating period, pressure, etc.) for large air users.

- it is highly advisable to be in possession of the profile for the air flow drawn by the network (like the example below and originating from a TECALIMAN measurement campaign).



- it is possible to cascade the production of several compressors in order to satisfy the network's air requirement.

4.1.4. Production pressure

The production pressure for compressed air must be suited to the needs of users, whilst incorporating the network's pressure losses.
It should be noted that a decrease in the production pressure for compressed air of 1 bar results in a reduction in the system's specific consumption of around 7%.
A large number of the systems inspected had the potential to reduce production pressure by 0.5 to 0.7 bar.
Therefore, it is important to re-evaluate these settings.

4.1.5. Compressors' operating periods

Apart from in exceptional circumstances, operating compressors at weekends, or more generally during lengthy plant stoppages, is a serious mistake and, as a result, should be prohibited.

4.1.6. The quality of intake air

Clean (free of dust) and dry intake air, which is as fresh as possible, guarantees that the production system will demonstrate good energy efficiency.
Consequently, a rise of 10°C in the temperature of intake air reduces the compressor's energy efficiency by 3.5 %.
For these reasons, it is important to have a properly designed compressed air area (air inlet, filtration, hot air extraction, etc.).

4.2. Factors associated with compressed air drying and processing techniques

4.2.1. Drying techniques

4.2.1.1 Refrigeration drying

This technique enables a dew point of +2 to +3°C to be obtained (i.e. water content of 5.6 to 6.8 mg of water per m^3 of compressed air). Of the 2 drying techniques presented, it has the advantage of being the most energy-efficient and requiring the least investment.

4.2.1.2 Adsorption drying with excess air and no heat

This technique enables a dew point that is far lower than that obtained using the refrigeration technique and, therefore, water content per volume of compressed air that is also lower, to be obtained. The dew point obtained may vary from –20°C (i.e. water content of 0.88 mg of water per m^3 of compressed air) to much lower temperatures.
This drying technique is the most energy-intensive. In effect, it consumes 15 to 20% of the dyer's nominal compressed air flow in order to regenerate the alumina used to dry the air.

4.2.1.3 Adsorption drying using heat (internal or external)

This technique:

- enables equivalent and even lower dew points to be obtained than with the excess air and no heat technique.
- is more energy-efficient than the previous solution, but basically, the financial investment is greater.

4.2.2. Choosing a dryer

The choice of dryer or dryers must take account of:

- the quality of air dictated by:
  - the nature of users,
  - the network's structure (external pipes, etc.),
  - the plant's geographic location.
- the possibility of combining different drying techniques, in order to meet the specific requirements of certain users or even to comply with seasonal constraints relating to the quality of compressed air
- its/their energy consumption
- the amount of investment required.

Specific energy consumption in terms of drying is equal to:

$$Cs = \frac{\text{electrical energy in Wh consumed by the compressor + dryer}}{\text{Volume of compressed air produced – Volume of air used by the dryer}}$$

Example 3:
Based on example 2 and assuming that the dryer installed uses adsorption drying with excess air and no heat and that it has a nominal flow of 600 Nm^3/h (the dryer's air consumption is presumed to be equal to 15% of the nominal flow), the specific consumption downstream of the dryer is equal to:

$$= 307 \text{ Wh/Nm}^3$$

i.e. specific consumption of above:
- *179 % of the optimum specific consumption (see example 1)*
- *97 % of the specific consumption in operation (see example 2).*

NB:
The operating pressure and temperature of the compressed air to be processed, as well as the ambient temperature, have an influence on the stability of the "nominal" dew point of a dryer.
For this reason, to properly dimension a dryer in relation to the flows of compressed air to be processed, it is essential to take account of the extreme operating values for operating pressure, compressed air temperature and ambient temperature.

4.2.3. Filter separators

It is important to limit the number of filter separators and their levels of filtration to those that are strictly necessary. In effect, this type of filter generates pressure losses of the order of 0.2 to 0.3 bar, which results in excess electrical energy consumption by the system of 1.5 to 2%.

4.3. Factors associated with distribution

4.3.1. Compressed air leaks

The various compressed air diagnoses conducted by Tecaliman in animal feed plants reveal that it is common to find leak rates representing between 20 and 60 % of the flow drawn by the plant. In order to be considered satisfactory, the leak rate must not exceed 10 to 15%.

In the absence of measures to regularly trace air leaks, leak rates often represent between 45% and more than 60% of the flow drawn by the plant.

Specific consumption in terms of distribution is equal to:

$$Cs = \frac{\text{Electrical energy consumed (Wh)}}{\text{Volume of compressed air produced – Volume of air leaks}}$$

The greater the leak rate, the higher the specific consumption by users.

Example 4:

Based on example 3 and assuming a leak rate for compressed air from the system of 30%, specific consumption for use is equal to:

= 440 Wh/Nm^3

i.e. specific consumption of above:

300 % of the optimum specific consumption (see example 1)

182 % of the specific consumption in operation (see example 2)

4.3.2. Network pressure losses

These are defined as being the drop in pressure between the air production system's outlet and a specific user of compressed. If the pressure losses are significant, they will involve increasing the production pressure (and hence an increase in consumption) to satisfy users' pressure requirements. It should be noted that air leak rates increase with pressure.

It is vital that, when designing the primary network, it is broadly dimensioned to deal with future extensions.

4.4. Factors associated with compressed air users

The nature of the user and each user's settings have a direct effect on their air consumption.

Industrial cleaning systems are the main family of compressed air users. However, it is common to see 2 cleaning systems installed on 2 identical filters in the same plant, processing relatively similar products, with different settings, without it being possible to identify the reasons behind these different settings.

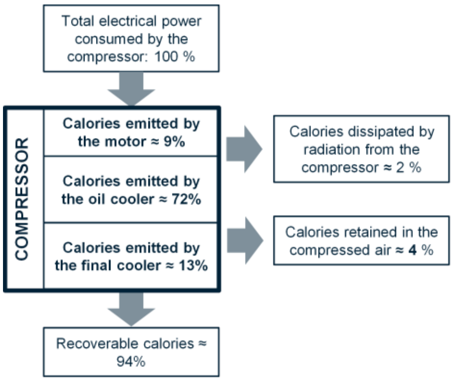
Example of settings for an industrial cleaning system for a 15m^2 *filter with 1.5m bags.*

	Setting 1	*Setting 2*	*Setting 3*
Relative pressure (bar)	*4.5*	*4*	*4*
Interval(s)	*25*	*25*	*35*
Duration (ms)	*200*	*110*	*110*
Air consumption (Nm³/h)	*23*	*10.3*	*7.4*

⇨ *There is a ratio of 3:1 between extreme compressed air consumption levels.*

5. Recovery of the heat dissipated by compressors

5.1. Heat balance for a compressor



5.2. Recovery of calories to preheat a boiler's feedwater

5.2.1. Operating principle

The following diagram outlines the operating principle.

An oil/water heat exchanger is placed within the compressor on the hot oil circuit. This heat exchanger is known as a "feed" or "safety" heat exchanger designed to prevent the risk of the water being contaminated with oil.

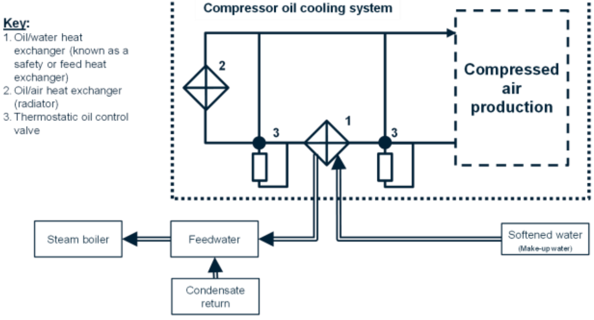
On the oil circuit:

Two thermostatic oil control valves, placed upstream and downstream of the heat exchanger, enable the oil cooling operation to be optimised. Consequently, when there is no need for the production of hot water, the oil is directed towards the oil/air heat exchanger (which cools the oil).

On the water circuit:

The heat exchanger must be placed downstream of the softener in order to protect the heat exchanger against the risks of scaling.

The water network downstream of the heat exchanger must be insulated



5.2.2. Technical feasibility

This depends primarily on 2 factors:

- the compressor's make. In effect, not all compressor manufacturers produce oil/water heat exchangers. To prevent operating problems, it is highly advisable to install a heat exchanger of the same make as the compressor.
- the distance between the compressor's location and the boiler room.

5.2.3. Conceivable energy savings

The potential achievable energy savings depend on a number of factors:

- The initial temperature of the water in the feedwater,
- The compressor's commitment level (the compressor's time operating under load/total operating time),
- The compressor's rated capacity,
- The flow of water drawn by the boiler.

6. Conclusions

To optimise the specific consumption of a compressed air production, drying and distribution system, it is necessary to have a picture of the plant's compressed air requirements, which is as accurate as possible (profile of the flow of compressed air drawn).
Energy performance is assessed on the basis of:

- the specific consumption of the compressed air system (ratio: electrical energy in Wh consumed /m^3 of compressed air produced)
- the system's leak rate
- the dimensioning of the compressed air production system in relation to the plant's compressed air requirements
- the volume of the air reserves available within the network
- the load commitment level of the compressor or compressors
- the compressor's production pressure
- the design of the compressed air area
- the nature and dimensioning of the air dryer (in particular the suitability of the air dryer's technology for the nature of its users)
- the economic and energy benefits of pre-heating the boiler feedwater by recovering the heat available from the compressor
- and the specific aspects of each system. Consequently, it may be necessary to examine the quality of compressed air (moisture content), pressure losses on the network (specifically between the production system and a large user as far as possible from the compressor), the consumption of the largest users, etc.

When doing so, a compressed air diagnosis is a tool that enables an inventory of the existing situation to be carried out and improvement measures to be defined. It should be noted that these diagnoses are subsidised by the ADEME (the French Environment and Energy Management Agency).
These diagnoses also enable operators to review the financial opportunity to outsource the production of compressed air (purchase compressed air by the m^3).
To successfully conclude this review, it is necessary to conduct a technical and financial assessment of the system's operation (over several years). Based on this assessment, industrial operators must define these requirements in terms of outsourcing (response time in the event of a failure, air quality, etc.) in order to produce an invitation to tender and draw up a supply agreement.
The feasibility of outsourcing the production of compressed air basically depends on the plant's annual consumption of m^3 of compressed air.
Outsourcing is a way of guaranteeing a periodic review of the compressed air system's energy performance, as far as the billing flowmeter. In effect, the operator's margin for savings depends, in part, on the differential: the plant's purchase price of electricity compared with the selling price per m^3 of compressed air.