Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 39 (2012) 204 – 211

Procedia Engineering

www.elsevier.com/locate/procedia

XIIIth International Scientific and Engineering Conference "HERVICON-2011"

Estimating Potential Energy Savings in Compressed Air Systems

Ryszard Dindorf[a], a*

[a]Kielce University of Technology, Aleja Tysiąclecia Państwa Polskiego 7, PL- 25314 Kielce, Poland

Abstract

Compressed air is typically one of the most expensive utilities in an industrial facility. While designing energy saving compressed air systems various methods are applied to reduce energy losses and minimize energy consumption. The compressed air systems require the complex approach towards rational energy consumption by effective production, distribution and application equipment of the compressed air. As a first step towards identifying applicable energy savings an inventory of compressed air system and major system operating parameters should be established. On the basis of the data collected, the basic indicators of compressed air system performance can be calculated or estimated: specific power, annual energy cost, cost of compressed air, compressed air leaks, pressure drop in a system.

Keywords: Compressed air systems; energy saving.

1. Introduction

The Motor Challenge Programme (MCP) aims at drawing attention to the energy savings potential that exists in the various motor driven systems, including: compressed air systems, pumping systems, ventilation systems, refrigeration and cooling systems, motor drive systems [1]. The MCP is a voluntary commitment scheme launched by the European Commission at the beginning of 2003 to activate European companies to implement energy efficiency measures for motors. Transforming electrical into mechanical power, electrical motors are central devices in modern industrial production. Moving drivers, fans, compressors and pumps these motors are essential for assuring the continuous creation of a

* Corresponding author. Tel.: +48-4134481; fax: +48-4134481.
E-mail address: dindorf@tu.kielce.pl.

doi:10.1016/j.proeng.2012.07.026

multitude of products and services important to our life such as food, beverages, cars, furniture, textiles, consumer electronics, water and energy supply. Motor driven systems account for 30 % of electricity use in the European Union and for 60 % of industrial electricity use constituting therefore a major and relevant area for energy efficiency improvements. Many studies showed that the potential for energy savings is substantial. By the end of 2009, the MCP comprised a total of 93 companies coming from a surprising wide range of industrial sectors with the focus on production and processing originating from 16 countries in the European Union [2]. Only a handful came from service related sectors. The largest groups of MCP partners came from food production (13%), metal and steel (12%) and water supply (9%). Micro and small sized companies were in the minority, whereas the largest proportion was either medium or large size companies. In total all MCP measures resulted in an estimated annual energy saving of 183 300 MWh and savings of 87 250 tons of carbon emissions per year, which represents an estimated 0.02 % reduction of the total energy consumption in EU 27's industry.

2. Potential energy saving in compressed air system

Energy saving opportunities are present everywhere in compressed air systems, it just takes minimal effort to recognize where energy can be saved [3], [4], [5]. However, it takes concerted efforts to ensure that these energy savings can be maintained. The higher the pressure used in compressed air system or application equipment, the more cost goes into producing this pressure. With the raising price of worldwide crude oil prices, energy costs are expected to increase. Reduction of energy consumption equals to less overall operating cost of factory. There are also environmental concerns as regards the release of carbon dioxide (CO_2). The less energy consumed means less CO_2 emission to the atmosphere which is damaging the environment we live in.

Energy savings in compressed air systems are possible in production and treatment of compressed air, compressed air networks, end use devices, overall system design and operation. Compressed air systems consist of following major components: intake air filters, inter-stage coolers, after-coolers, air-dryers, moisture drain traps, receivers, piping network, filters, regulators and lubricators and pneumatic tools and equipment (see Figure 1).

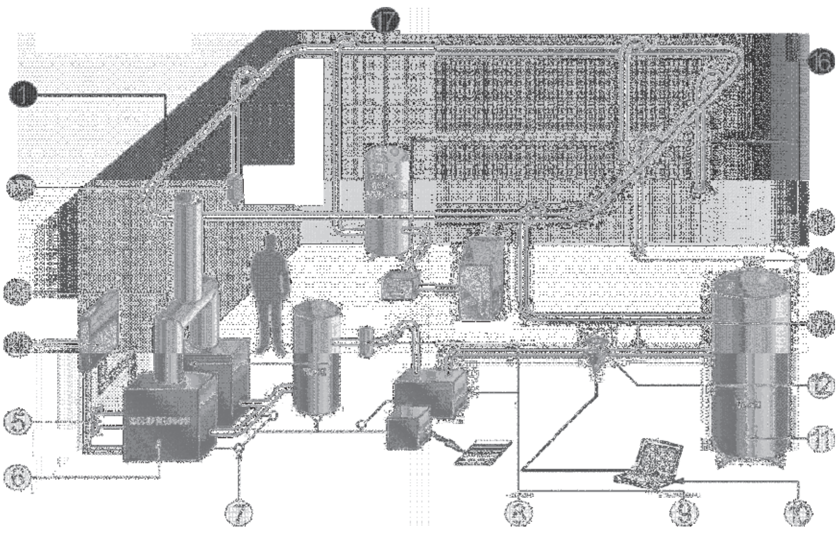

Fig. 1. Compressed air system (Source: European study "Compressed Air Systems in the European Union")

The places were specified on Figure 1 in the formation of the compressed air in which the potential possibilities of decrease of the waste of energy exist:

1. Increase the diameter of the pipes; reduce the length of the network; loop the network; limit elbows (12%). Repair leaks periodically – 15 to 50% of the air production flows through the leaks (20%).

2. Install a system with several pressure values (multi-pressure systems or networks), separate or connected to each other (with the use of local over compressors). Reducing 1 bar pressure provides an energy savings of 8%.

3. Install a heat economizer: upgrading in the process or heating of premises (60%), 90 % of the electrical energy consumed by a compressor is converted to heat. In practice, 60% of this heat can be recovered and used.

4. Mount for instance an automatic control of the compressed air production via a variable speed compressor or an automatic control of all the compressors according to the needs. Average 15 % savings with an automatic control (from 5 to 35 %).

5. Reduce the air inlet temperature: 1% consumption savings are obtained every 3 degrees.

6. Replace compressors with new and better machine(s) with lower specific energy consumption (e.g. more compression stages) more suitable to the requirements of the system (7%).

7. Use “leak-loss free” condensate traps. A high-performance network allows for a maximum pressure loss of 0.5 bars throughout the line.

8. Enhance and check pressure regulating valves, filters, lubricators, driers and condensate traps (2%).

9. Dry off and filter air moderately as needed. Too long drying or too fine filtering leads to unnecessary overconsumption (6%).

10. Make regular recordings with due follow-up and control (e.g. indicators).

11. Design properly storage capacities to allow operation with higher output of compressors and to avoid unexpected switchings on or off.

12. Install control equipment such as flowmeters and air meters, current meters, pressure gauges.

13. Replace leak generating equipment parts (e.g. hoses).

14. For cleaning, use preferably vacuum cleaners which need less energy than blow nozzles or air guns (40%).

15. Do not provide machines with compressed air when they are off (switching-off of the network via a solenoid valve). Switch off the network of machines when they are off (e.g. via automatic solenoid valve).

16. Divide the network into areas with pressure controls or appropriate isolation valves. Close the network areas when not used.

17. Place storage capacities next to machines with high variation of the air required

3. Methods to calculate the cost of compressed air

A typical industrial compressed air installation consists of three main parts: the compressed air production plant, the distribution system and application equipment (Fig. 2).

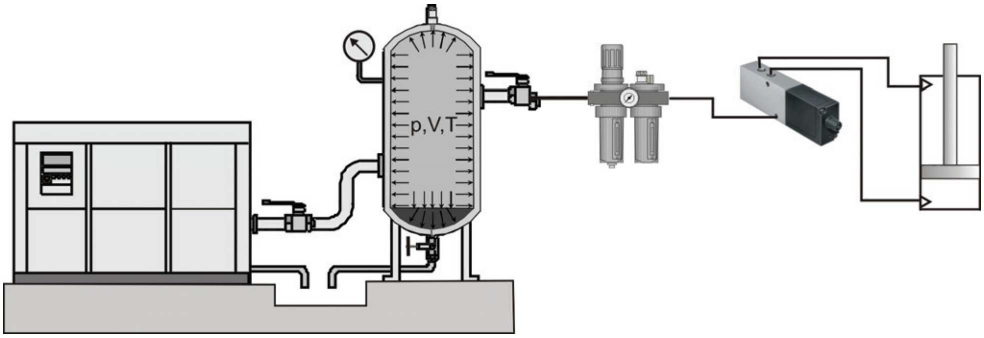

Fig. 2. Compressed air installation

A compressor is powered by an electrical drive. Atmospheric air is drawn through a dust filter and compressed by a factor of up to ten times. Freshly compressed air is hot and contains moisture concentrated from the natural humidity of the atmosphere. Processing takes place through an after-cooler and water-separator before the air passes to an air receiver for storage. Main and branched lines distribute compressed air throughout an industrial site. The main causes of energy waste are leaks, pressure drops, over pressurization, misuse of jets and poor compressor management. Compressed air is an energy carrier difficult to control because it is expensive (0.6 to 3 cents per Nm^3) and it has a high improvement potential of around 25% of possible energy saving on an average.

Methods to calculate the cost of compressed air differ, depending on the type and control settings of each compressor in a system. The following calculations will provide a guide for estimating costs of compressed air.

3.1 Determine the average power draw

In order to calculate the cost of operating a reciprocating compressor, its average power draw must first be calculated:

- **On/Off control**

On/off control is frequently used by small reciprocating compressors. In this type of control, the compressor turns itself off and draws no power as long as the discharge pressure remains above a specified level. This is the most energy-efficient type of control since the compressor runs at maximum efficiency when compressing air and turns off when not compressing air. The following equation determines the average power draw for on/off control [6]:

$$P_A = \frac{P_L \times t_L}{t_L + t_{UL}}, \tag{1}$$

where: P_A – average power draw (kW), P_L – power consumption during loading (kW), t_L – total time while loaded (hrs), t_{UL} – total time unloaded (hrs).

- **Load/Unload control**

With load/unload control, the compressor runs fully loaded, producing compressed air at maximum efficiency until the discharge pressure reaches the upper activation pressure setting, which causes the compressor to unload. When unloaded, the compressor no longer adds compressed air to the system, but the motor continues to run. Typically, unloaded power draw is 20 to 30 percent of loaded power draw. The following equation is used to determine the average power draw for load/unload control [6]:

$$P_A = \frac{P_L \times t_L + P_{UL} \times t_{UL}}{t_L + t_{UL}}, \tag{2}$$

where: P_A – average power draw (kW), P_L – power consumption during loading (kW), P_{UL} – power consumption during unloading (kW), t_L – total time while loaded (hrs), t_{UL} – total time unloaded (hrs).

3.2. Determine the FAD

On of way of determining the Free Air Delivery (FAD) of the compressor is by Pump Up Method – also known as receiver filling method [7]. Although this is less accurate, it can be adopted where the elaborate nozzle method is difficult to be deployed. The Free Air delivery q_{FAD} in m^3/h is calculated as follows:

$$q_{FAD} = \frac{V\,(p_2 - p_1)}{p_N\, t} \times \frac{T_1}{T_2}, \tag{3}$$

where: V – storage volume which includes receiver, after cooler, and delivery piping in m^3, p_N – normal pressure in kPa, p_1 – initial pressure after bleeding in kPa, p_2 – final pressure after filling in kPa, T_1 – initial temperature in K, T_2 – final temperature in K, t – time taken to build up pressure from p_1 to p_2 in hours.

3.3. Determine the specific energy consumption

The power consumption in kW to the free air delivery in m^3/h or the energy consumption in kWh to the volume in m^3 delivered at ambient conditions is determined as specific energy consumption (*SEC*) in kWh/ m^3:

$$SEC = \frac{P_A}{q_{FAD}}\ . \tag{4}$$

For example, at a pressure of 0.7 MPa, the *SEC* should be:

- between 0.085 kWh/Nm^3 and 0.11 kWh/Nm^3 which is a very good ratio,
- between 0.11 kWh/Nm^3 and 0.13 kWh/Nm^3 which is an acceptable ratio,
- above 0.13 kWh/Nm^3, the ratio indicates a problem in the system.

3.4. Determine the carbon dioxide (CO_2) emission ratio

The carbon dioxide (CO_2) emission ratio is defined as the quantity of the carbon dioxide (in kg) generated during the production of 1 m^3/h of the compressed air:

$$EMR = EF \times SEC\ , \tag{5}$$

where: *EMR* – dioxide carbon emission ratio in kgCO_2/m^3/h, *EF* – emission factors from electric energy (carbon dioxide emission intensity), in European Union *EF* = 0,435 kg CO_2/kWh amount.

3.5 Determine the annual energy costs

Calculate the annual energy consumption of the current system:

$$EC = P_A \times H\,, \tag{6}$$

where: EC – annual energy consumption (kWh/yr), P_A – average power draw (kW), H - annual operating hours (hrs/yr).
Once the average power draw is known, the calculations determining the annual energy cost to operate a compressor are the same for all compressor types:

$$AEC = EC \times ER\,, \tag{7}$$

where: AEC - annual energy costs (€/yr), ER - energy rate (€/kWh).

3.6. Determine the leakages

For compressors that have on/off controls or load/unload controls, there is an easy way to estimate the amount of leakage in the system. This method involves starting the compressor when there are no demands on the system (when all the air-operated end-use equipment is turned off) [8]. A number of measurements are taken to determine the average time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will cause the compressor to cycle on and off as the pressure drops due to air escaping through the leaks. Total leakage rate (LR) in percentages can be calculated as follows:

$$LR = \frac{t_{on}}{t_{on} + t_{off}} 100\,, \tag{8}$$

where: t_{on} – on-load time in minutes, t_{off} – off-load time in minutes.
The actual free air (leakage) q_L in m^3/h in the compressed air installation is calculated from:

$$q_L = q_{FAD} \times LR/100\ . \tag{9}$$

Leakage can be estimated in systems with other control strategies if there is a pressure gauge downstream of the receiver [8]. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains and piping. The system is started and brought to the normal operating pressure (p_1). Measurements should then be taken of the time (t) it takes for the system to drop to a lower pressure (p_2), which should be a point equal to about one-half the operating pressure. Volumetric leak flow rate q_L in m^3/h can be calculated as follows:

$$q_L = \frac{V \times (p_1 - p_2)}{p_a \times t} \times k\,, \tag{10}$$

where: V – reservoir volume in m^3, p_1 – normal operating pressure in kPa, p_2 – lower pressure in kPa, p_a – atmospheric pressure in kPa, t – time in hours, k – multiplier corrects leakage to normal system pressure, k=1.25.
Power losses P_{Los} in kW due to leakage in compressed air installation:

$$P_{Los} = q_L \times SEC = q_{FAD} \times LR/100 \times \frac{P_A}{q_{FAD}} = P_A \times LR/100 \, . \tag{11}$$

Annual energy losses (EL) in kWh/yr due to the annual leakage in compressed air installation:

$$EL = P_{Los} \times H_L \; , \tag{12}$$

where: H_L – annual leakage in hours.

The cost of the annual energy losses (CEL) in €/yr due to the annual leakage in compressed air installation:

$$CEL = EL \times ER \; . \tag{13}$$

Compressed air system maintenance is particularly important to avoid excessive loss through leaks:

- Leaks not only waste energy but also cause pressure drops that adversely affect the operation of air-using equipment and tools (reduces production efficiency).
- Leaks are responsible for considerable waste, frequently up to 40 to 50 % of consumption.
- 15% leakage is considered to be an acceptable rate.

3.7. Determine the pressure reduction

Air pressure should be the minimum required for the end use application. This can be determined by investigating the pressure required by equipment and tools. In some cases, isolated pieces of equipment require significantly higher pressure. Redesigning individual items or installing a second compressor to service these items may be more cost-effective. Some sites are divided into high and low-pressure networks. If it is not possible to separate items that require lower air pressure than the main supply, pressure regulators can be fitted to prevent over supplying the end use. For larger systems with numerous take-off points, a ring main is the preferred layout. Ring mains supply air to equipment from two directions halving the velocity and reducing the pressure drop. Ring mains also allow isolation valves to be incorporated for servicing without interrupting other equipment. For simple systems where the point of use and supply are relatively close together, single lines are more suitable. Pressure reduction can be calculated as follows [9]:

$$PR = \frac{(p_z / p_a)^{1-k/k} - (p_r / p_a)^{1-k/k}}{(p_z / p_a)^{1-k/k} - 1} = \frac{(p_z / p_a)^{0.286} - (p_r / p_a)^{0.286}}{(p_z / p_a)^{0.286} - 1} \, , \tag{14}$$

where: PR - pressure reduction, p_z – final pressure in kPa, p_r – reduced pressure in kPa, p_a – atmospheric pressure in kPa, k - the ratio of specific heat (adiabatic process), for air k=1.4.
To calculate the cost reduction due to reduced pressure drop:

$$ES = EC \times (PR \times 0.08), \tag{15}$$

$$ECS = ES \times ER. \tag{16}$$

where: ES – annual energy savings in kWh/yr, ECS – annual energy cost savings in €/yr.

Compressing to a higher pressure, and then bleeding down to a lower level wastes energy. Energy consumption increases rapidly as a function of pressure. Reducing final pressure by 0.1 MPa reduces energy costs by 15%. For every 50 kPa (0.5 bar) reduction in pressure drop on average 3% of electrical power required by the compressor is saved. A pressure drop always occurs during the transmission of air from the compressor to the point of use. Cost of pressure drop fails as pipe diameter increases. Piping costs also rise as a pipe diameter is increased to reduce pressure drop. A compromise between pressure drop and pipe diameter costs is needed for achieving cost efficient piping.

4. Conclusions

Compressed air is typically one of the most expensive utilities in an industrial facility. As a result, potential savings opportunities are aggressively sought out and identified. Once identified, projected energy savings must be calculated in order to justify the cost of implementing the savings opportunity. It is important to calculate projected energy and cost savings as accurately as possible. Unfortunately, savings are frequently overestimated because the methods used to estimate savings neglect to consider important factors such as compressor control and type, storage, and multiple compressor operation. There are three important reasons why it is worth investing time and effort in reducing compressed air costs: it will save energy and money by identifying and eliminating waste; it will improve the reliability and performance of the compressed air system; it will reduce environmental impact through reduced electricity consumption and consequent lower carbon dioxide (CO_2) emissions.

References

[1] *The European Motor Challenge Programme. Compressed Air Systems Module.* European Commission. Directorate-General Energy and Transport. Brussels, (2003).

[2] Bertoldi P., Elle M.: *The European Motor Challenge Programme Catalogue 2003 to 2009.* European Commission, DG JRC, Institute for Energy. Brussels, (2009).

[3] Dindorf R.: *Energy saving control of pneumatic system* (in Polish). Pneumatyka, No. 2, (2007).

[4] Dindorf R.: *Estimate opportunities of energy savings in compressed air systems.* (in Polish). Energetyka, No. 1, (2010).

[5] Dindorf R.: *Energy savings opportunities in compressed air systems* (in Polish). Napedy i Sterowanie, No. 10, (2010).

[6] *Estimate Your Compressed Air Cost. US DOE - Industries of the Future Workshops Supplemental Worksheet.* Illinois Industries of the Future Program. Chicago USA.

[7] Bhatia A.: *Compressors and Compressed Air Systems.* Continuing Education and Development, Inc. NY USA.

[8] Marshall R.: *Compressed Air System Leaks. Best Practices to Compressed Air.* Compressed Air Challenge. US DOE.

[9] Kaya D, Phelan P, Chau D, Sarac HI.: *Energy conservation in compressed-air systems.* International Journal of Energy Research, No. 26, (2002).