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Cost Effectiveness Analysis of Pressure Regulation Method on Pneumatic Cylinder Circuit

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Abstract – *Decreasing of operating pressure in compressed air systems leads to improving of overall energy efficiency. In this paper, the focus is on the pressure reduction at the point of use. There are many methods for the pressure reduction realization but there are no exact data about the efficiency obtained for those methods and associated costs. We have identified four different methods for pressure reduction in the pneumatic circuits. Based on the conducted experiments, the diagrams of compressed air savings as a function of decreased pressure level in the pneumatic cylinder are proposed. Decreasing supply pressure for pneumatic cylinder is the most cost effective but has a number of limitations. Reduction of supply pressure in front of the actuator can be applied only when the cylinders are oversized and that is limited number of cases. If it is not possible to apply this method and cylinder is working without load in one stroke, three other methods are available. Characteristics of each method are discussed and the cost effectiveness of each method, based on obtained experimental results, is given.*

Keywords – cost effectiveness, energy efficiency, pneumatic cylinder, pneumatic system, pressure regulation.

1. INTRODUCTION

The compressed air systems are reliable, safe and very well suited for performing numerous functions, but their economic efficiency is rarely taken into account. They represent a significant energy carrier in industry, business systems and public sectors and that is why the compressed air installations are considered as the fourth in the order of significance, just after electrical energy, oil and gas, and water [1].

However, unlike the first three, the compressed air is the only resource produced on-site, which enables its users the complete supervision over the entire process. Unfortunately, direct measurement of the consumed air is not an established practice; this can also be said about calculations of thus created costs. In cases of improper design and use, it can make unnecessary costs for the company.

An adequately designed, properly realized and well-maintained compressed air system can save a lot of money every year. Besides, increasing the reliability will decrease the risks of production disruption while ecological effects will be improved as well as the influence on human health. Good quality and reliability of these systems are accomplished with good system management [2], [3]. This enables significant savings of the consumed energy, prolonged component's life cycle, more reliable system operation and lowered system operation costs. The potentials are great for reducing energy consumption in compressed air systems, and they can be realized with small to medium investments [4]. Users should be supported to analyze the energy costs with the procedures that should be easy to use [5], [6]. There are significant issues that influence the overall increase in energyefficiency of the compressed air systems, which are explained in greater detail in [2], [7]-[10].

The system operation depends on the properties of each element but even more on the design of the entire system. It is very advisable to first identify priorities for optimizing compressed air use at an industrial site without compromising the production yield [11]-[13].

The following technical measures have been identified as one that can improve the functioning of a compressed air system [9]:

- Improvement of compressed air preparation: reduction of pressure and energy lost in processes of drying and filtering; optimization of filtering and drying as a function of consumer needs [14];
- Overall system design, including the systems with multiple pressure levels;
- Reduction of pressure losses due to friction in the pipes and tubes;
- Air leakage reduction [15], [16];
- Reduction of operation pressure;
- Optimization of certain devices that consume compressed air: application of more efficient, better adjusted devices or, in some cases, replacement of compressed air with an electrical drive;
- Recycling of used compressed air [17]-[19], etc.

Judging by the findings of numerous studies, the stated measures can increase energy efficiency of the pneumatic systems with the most frequent period for ROI of less than three years [2], [9], [20]. Besides that, the proposed diagrams could be used for the estimation of utilities or maintenance costs.

1.1 Designing the Overall System

The primary goal of a proper system design is to adjust the pressure, quantity and quality of compressed air to the needs of different users at their points of use. It can be a complex task, in cases when different end users have different or varying consumption needs. One

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example of the problems arising in systematic design is dilemma: one or multiple pressure levels within a system. Typical systems are designed to deliver the air according to the highest pressure and quality required by an end user. This approach can cause unnecessary expenses of energy if only a small portion of consumers requires air prepared in such a way. The alternative solutions may be to build a system that delivers lower pressure and installs pressure amplifiers for those consumers that requires higher pressure or to provide and install dedicated compressor at the places of application for devices that require higher pressure.

1.2 Optimization of Devices that Consume Compressed Air

Many devices that consume compressed air can be used in a more energy efficient manner. The optimization of devices that consume compressed air is one aspect of systemic approach to designing a compressed air system. The optimization can be achieved by replacing the existing components with more energy efficient ones, by installing additional elements, or better use of the existing components.

1.3 Reduction of Operating Pressure

Compressed air systems should be operated at the lowest functional pressure that meets production requirements. Higher pressures increase leakage, and thereby the loss of energy. In many compressed air systems, increase of operating pressure is used to compensate for the lack of capacity due to the leakage. However, higher the pressure, higher the leakage, while the unregulated consumers use more compressed air, and thus more energy. Applications requiring compressed air should be checked for any excessive pressure and any duration longer than necessary. They should be regulated, either by production line sectioning or by pressure regulators on the equipment itself [21]. Tools that do not require operating at system pressure should use a lower pressure delivered by some way of pressure reduction. Case studies show an average payback period for reducing pressure to the minimum required for compressed air applications of about three months [22]. Each bar of the pressure increase is followed by an increase in electrical energy consumption required to compress the air in a range between 5% and 8% or, the standard rule of thumb is that reducing pressure settings by 13 kPa will reduce energy consumption by 1% [21], [23].

Approximated costs are often required for planning systems costs for development, production or life cycle [12], [21]. For industrial engineer faced with the necessity of energy efficiency improvement, but not at any price, it is vital to make connection between available methods of pressure reduction, there saving potential and other characteristics with investment costs of each method. A proper approach would be to identify the most significant energy-intensive compressed air cylinders and possible strategies to reduce the energy requirement [24]. However, what are the real (measured) values for the effects of pressure reduction inside the pneumatic system at the point of use of compressed air?

In this paper, we are identifying four methods used for pressure reduction at the point of use – before the pneumatic cylinders, and examining their possibilities for improving of energy efficiency as well as their cost effectiveness.

2. PRESSURE REDUCTION ON PNEUMATIC CYLINDERS

There are several possible methods for increasing energy efficiency by reducing the operating pressure on pneumatic cylinder:

- reducing pressure, in both, operating and return stroke, see Figure 1(b);
- reducing pressure in the stroke without load, see Figure 2 and Figure 3;
- different lower pressure levels in extracting and retracting stroke, see Figure 4.

Those methods will be discussed in more details in next chapters.

2.1 Method I

The most usual way for pressure reduction is to reduce supply pressure on the pneumatic cylinder, see Figure 1(b). Instead of standard supply of pneumatic cylinder like in Figure 1(a), the pressure regulator is added in supply line in front of directional valve. Decreasing supply pressure leads to improving of the overall energy efficiency. Besides that, maintenance costs became lower due to less wearing out of cylinders and other production devices. However, it is necessary to keep in mind that supply pressure cannot be too low. Otherwise, if the force and speed of piston movement is decreased too much, process characteristics and operating regime could be seriously disrupted. Generally, application of this method is limited only to situations when the cylinder is bigger than needed and has load in both movement directions. Cylinder bigger than needed can be applied because of either improper design of pneumatic system (over dimensioning) or due to some other reasons: request for standardization, request for robustness, less sensitiveness to buckling, lower maintenance costs, smaller number of spare parts, etc. This method is the simplest one and it does not require any dedicated equipment but it is possible to apply only in previously mentioned conditions.

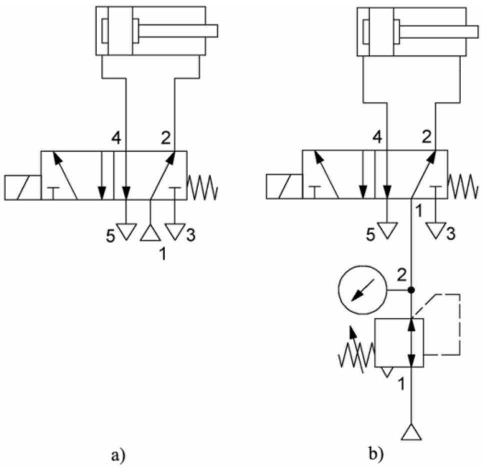

Fig. 1. Pneumatic circuit (a) without and (b) with pressure regulator

Decreasing the supply pressure only in stroke without load also enables decreasing of compressed air consumption (CAC). Pressure reduction in stroke without load is possible to achieve in different ways. Three of them are usual:

- with pressure regulator and non return valve in by pass line (Figure 2) – method II;
- with pressure regulator and quick exhaust valve (Figure 3) – method III;
- with reversible directional valve and two pressure regulators (Figure 4) – method IV.

2.2 Method II

The most usual way for pressure reduction in stroke with no load is to put pressure regulator with non return valve in by pass line in the supply line for the no load stroke of the pneumatic cylinder, see Figure 2. This pneumatic circuit has to provide reduced pressure for the no-load stroke, what is done with the pressure regulator and not restricted way for the exhausted air during load stroke, what is done with non-return valve.

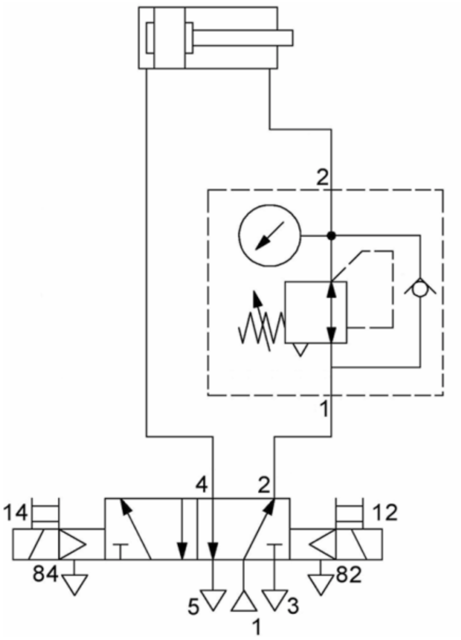

Fig. 2. Pneumatic circuit with pressure regulator and non return valve in by pass line.

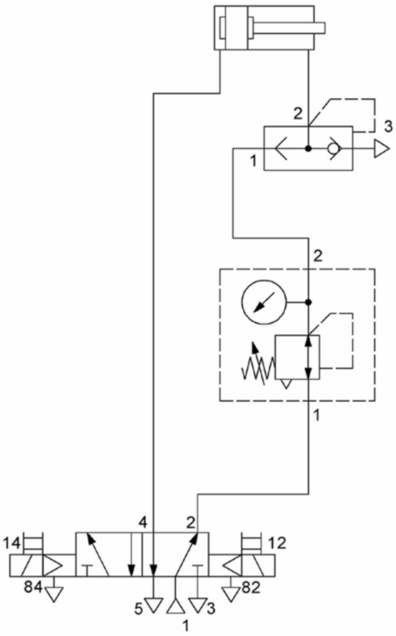

Fig. 3. Pneumatic circuit with pressure regulator and quick exhaust valve.

This method is suitable when the cylinder is of proper diameter according to the force and velocity requirements but has load only in one direction. It requires dedicated pressure regulator with non return valve in by pass line although it is possible to use standard pressure regulator and check valve and connect them in the same way.

2.3 Method III

Method presented in Figure 3 is suitable when the cylinder is of proper diameter according to the force and velocity requirements, has load only in one direction and there is the requirement to increase the speed of cylinder moving under the load. It requires, beside pressure regulator, the quick exhaust valve in the same supply line. Due to the quick exhaust valve, there is no need for non return valve in by pass line so the standard pressure regulator can be used.

This method is very similar to method II but enables higher velocity in stroke with load. Due to the additional element (quick exhaust valve) in supply line for no load stroke, it has somewhat different characteristics concerning effects of pressure reduction.

2.4 Method IV

Method presented in Figure 4 can be used for pressure regulation in one stroke only or, with additional pressure regulator as depicted in Figure 4, for different pressure regulation in retracting and in extracting stroke. It is particularly suitable for cases where the pneumatic cylinder is over dimensioned and there is load only in one stroke. It requires directional valve with possibility of reverse flow. Additional restriction is that this directional valve is used in such a way that has only one exhaust port what can be inappropriate in some cases of velocity reduction.

3. EXPERIMENTAL INVESTIGATIONS

In order to obtain quality data for the judgment about cost effectiveness of identified methods, an experimental set-up has been realized.

3.1 Measuring Instruments

CAC was measured with the FESTO AirBox portable laboratory, encompassing the consumption of the double acting cylinder FESTO DSNU-20-50 with monostable, electrically actuated valve for cylinder control. The AirBox ascertains CAC based on characteristic flow rate values and acquires pressure values through sensors.

The AirBox is placed in front of control valve. Compressed air flows past a surface that is continuously heated. The flowing air absorbs thermal energy from the warm surface. A temperature sensor quantifies the variation in temperature that represents a specific airflow. The measurement variation of the AirBox has been determined to be less than 100 mbar for pressure measurements at measuring frequency of 100 Hz [25]. Pressure was also measured with this instrument. For measurement is used thin-film metal pressure sensor with measuring range from 0 to 10 bar (gauge) and accuracy of ±1% of the measuring range (full scale).

3.2 Experimental Conditions

The ambient temperature during the testing was 20±2°C. The temperature of the compressed air was 26±3°C. The entire pneumatic installation as well as the measuring equipment were in the evaluation environment for approximately 24 hours and thus were assumed to be in a thermally stable state.

4. METHODOLOGY

One measurement encompassed 100 working cycles consisting of one extracting and one retracting stroke of pneumatic cylinder at one level of pressure. Each measurement was conducted ten times and repeated at different pressure levels. Same set of measurements were done for each identified method for pressure reduction. In order to minimize the effect of random errors the mean value of ten measuring cycles was calculated as well as its standard deviation.

CAC was measured in normalized liters (FAD) for each method of pressure reduction and at different pressure levels. Pressure is always given as gauge pressure except in Figure 5 since it is given as the direct output of measuring device.

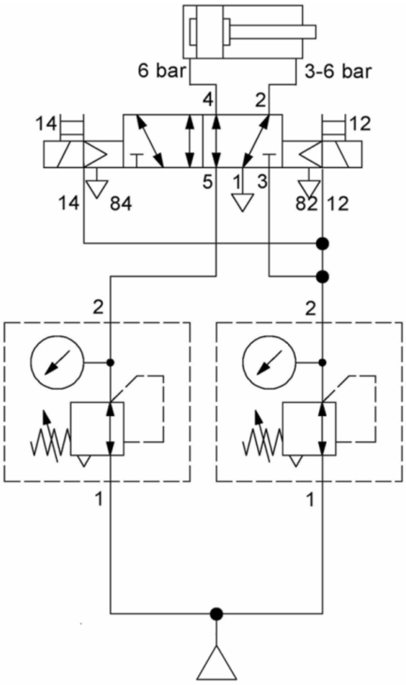

Fig. 4. Pneumatic circuit with reversible directional valve and pressure regulators.

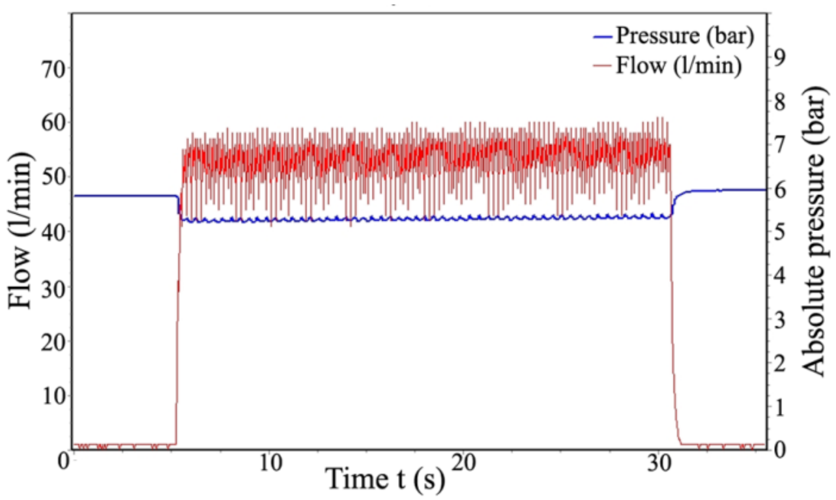

Fig. 5. Example diagram of compressed air consumption of double acting cylinder DSNU-20-50 for 100 working cycles and pressure of 5 bar (gauge).

Table 1. CAC and savings for method I.

Pressure bar (gauge)	100 working cycles		
	Compressed air consumption, Q (l)	Savings (%)	
		Relative to previous pressure level	Cumulative comparing to 6 bar pressure
6 bar	26.93	0	0
5 bar	22.57	16.1	16.1
4 bar	19.17	15.0	28.8
3 bar	16.10	16.0	40.2

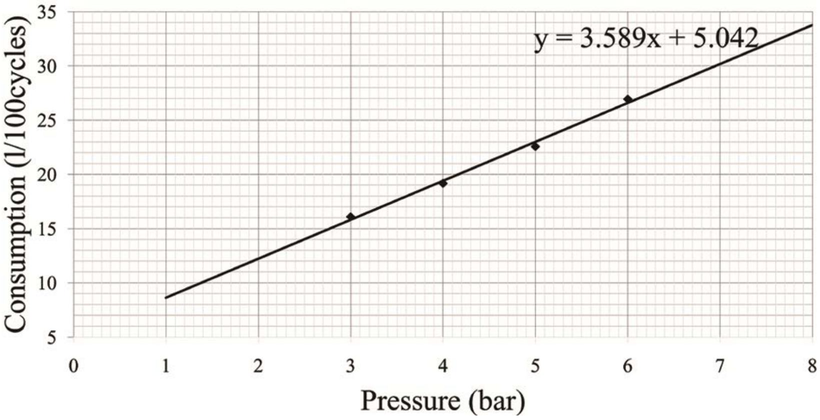

Fig. 6. Trend line of CAC for method I as a function of pressure level in pneumatic cylinder.

Table 2. CAC and savings for method II.

Pressure bar (gauge)	100 working cycles		
	Compressed air consumption, Q (l)	Savings (%)	
		Relative to previous pressure level	Cumulative comparing to 6 bar pressure
6 bar	28.51	0	0
5 bar	27.36	4.0	4.0
4 bar	25.38	7.2	10.9
3 bar	23.63	6.8	17.1

An example diagram of CAC for examined cylinder, for the method I and for defined experimental conditions and pressure of 5 bar (gauge) is presented in Figure 5. With integration of surface below the function line (red line), the CAC is calculated.

Starting pressure was 6 bar. This pressure represents the common value for the most industrial applications. Then, pressure was reduced by 1 bar, up to the value of 3 bar. This is the lowest pressure that ensures continuous operation of pneumatic devices, although some equipment can work with lower pressure than that, but not reliable. Obtained results are presented in the following diagrams and tables.

4.1 Decreasing Supply Pressure for Pneumatic Cylinder – Method I

Basic pneumatic circuit with standard double acting cylinder is shown in Figure 1(a), and redesigned pneumatic circuit with added pressure regulator (FESTO LR) is presented in Figure 1(b).

CAC measurements for this case are presented in Table 1. The trend line of compressed air consumption in dependence on pressure level on pneumatic cylinder is calculated and presented in Figure 6. Trend is described by the line equation: $y=3.589x+5.042$. According to the diagram, it can be easily concluded that CAC is in direct proportion to the pressure level.

4.2 Pressure Reduction in Stroke without Load

If the work is done only in one stroke of the cylinder, reduction of pressure in the stroke without the load will decrease the energy consumption. Pressure reduction encompassed CAC measurement of double acting cylinder in retracting stroke without load. Three cases were examined. For each special case, certain pneumatic equipment was added in the pneumatic circuit. According to the diagrams, it can be easily concluded that CAC is in direct proportion to pressure level in no-load stroke.

Experimental results - method II. First experiment encompassed determination of CAC in stroke of the cylinder without load. Pressure regulator (FESTO LRMA), with built in non-return valve in by-pass line, was used for decreasing the supply pressure for piston rod chamber of cylinder. Pneumatic circuit with pressure regulator is shown in Figure 2. Obtained results are presented in Table 2.

The trend line of CAC in dependence on pressure level in stroke without load is presented in Figure 7. This trend is described by the line equation: $y=1.662x+18.74$.

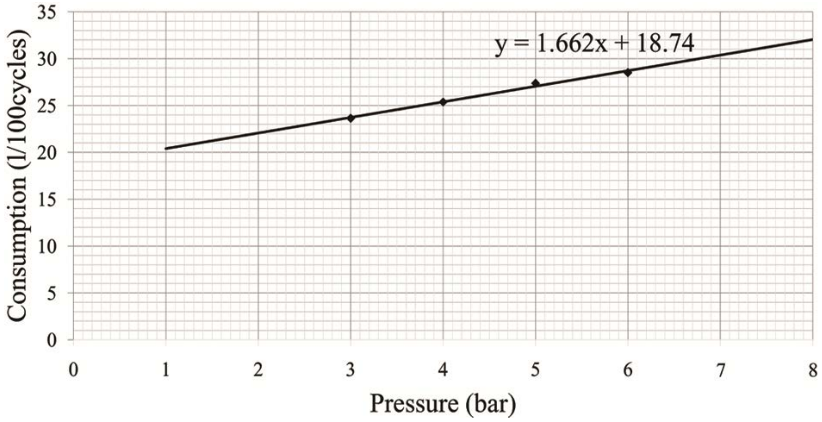

Fig. 7. Trend line of CAC for method II as a function of pressure level in pneumatic cylinder.

Table 3. CAC and savings for method III.

Pressure	100 working cycles		
bar	Compressed air	Savings (%)	
(gauge)	consumption, Q (l)	Relative to previous pressure level	Cumulative comparing to 6 bar pressure
6 bar	28.39	0	0
5 bar	27.41	3.4	3.4
4 bar	25.33	7.5	10.7
3 bar	24.16	4.6	14.9

Experimental results - method III. In the second experiment, the pressure in the stroke of the cylinder without load was decreased using standard pressure regulator FESTO LR. For the flow of compressed air in opposite way, quick exhaust valve FESTO SEU is used, and is positioned after the pressure regulator. Pneumatic circuit with pressure regulator and quick exhaust valve is presented in Figure 3. Obtained results are presented in Table 3. The trend line of CAC is presented in Figure 8. and described by the line equation: y=1.477x+19.,67.

Experimental results - method IV. In the third case, bistable, reversible valve FESTO JMFH-5-1/8-S-B was used for cylinder control and the standard pressure regulator FESTO LR was used for decreasing the pressure. Pneumatic circuit with reversible control valve and pressure regulator is presented in Figure 4. Obtained results are presented in Table 4. The trend line of compressed air consumption is presented in Figure 9. The trend is described by the line equation: y=1.798x+14.86.

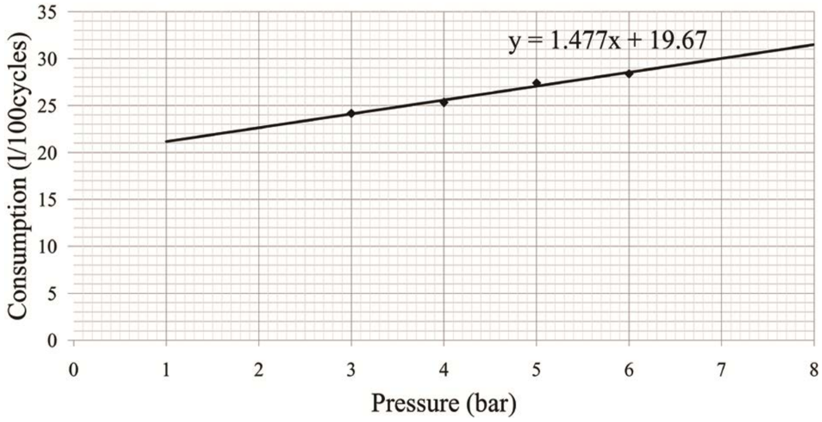

Fig. 8. Trend line of CAC for method III as a function of pressure level in pneumatic cylinder.

Table 4. CAC and savings for method IV.

Pressure	100 working cycles		
bar	Compressed air	Savings (%)	
(gauge)	consumption, Q (l)	Relative to previous pressure level	Cumulative comparing to 6 bar pressure
6 bar	25.23	0	0
5 bar	24.27	3.8	3.8
4 bar	22.52	7.2	10.7
3 bar	19.82	11.8	21.4

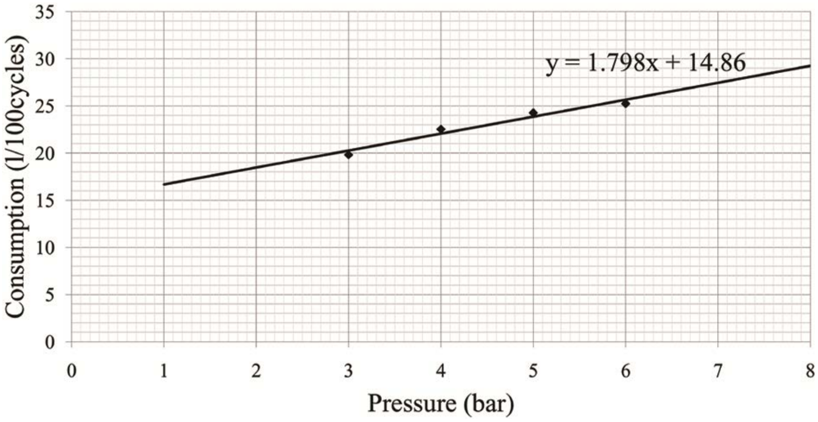

Fig. 9. Trend line of CAC for method IV as a function of pressure level in pneumatic cylinder.

5. COST EFFECTIVENESS

5.1 Cost Effectiveness of Pressure Reduction in both Strokes

Cost effectiveness analysis is done according to the results of compressed air consumption of two cylinders with different diameters and strokes. In the first case, the ratio between investment costs and savings on the cylinder with 20 mm diameter and 50 mm stroke is calculated, based on the data from Table 1 and Figure 6. The ROI for decreasing pressure from 6 to 2 bar is calculated as 7.7 years (Table 5).

ROI estimation is done following the calculation proposed in [26]. The final ROI is obtained as the ratio between extra cost and one year cost saving. Based on the equation y=3.589x+5.042, from Figure 6, the diagram of savings of compressed air consumption as a function of pressure level on the pneumatic cylinder is proposed, see Figure 10.

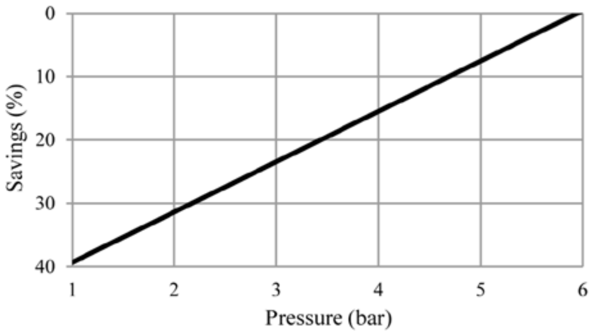

Fig. 10. Savings of compressed air as a function of supply pressure in the pneumatic cylinder.

In the second case, cost effectiveness of cylinder with 125 mm diameter and 1000 mm stroke was analyzed. Based on the catalogue value for compressed air consumption, consumption per cycle was calculated (125 l/cycle). With the data from the diagram of compressed air savings (Figure 10), the ratio of investment costs and savings is determined (Table 5).

Table 5. Cost effectiveness analysis for method I for two different sizes of cylinders.

	DSNU-20-50	DNC-125-1000
Price of 1 m^3 of compressed air (€)	0.02	
CAC per cycle for supply pressure of 6 bar (l/cycle)	0.27	125
CAC per cycle for supply pressure of 2 bar (l/cycle)	0.12	58.75
Number of working cycles per minute (cycle/min)	6	
Effective capacity per year (min/year)	180,000	
Number of cycles per year (cycle/year)	1,080,000	
CAC per year for supply pressure of 6 bar (m^3/year)	291.60	135,000
CAC per year for supply pressure of 2 bar (m^3/year)	129.60	63,450
Difference in CAC per year for 2 and 6 bar pressure (m^3/year)	162	71,550
One year cost saving (€/year)	3.24	1,431
Extra cost (pressure regulator LR) (€)	25	40
Return on investment (years)	7.7	0.028

5.2 Cost Effectiveness of Pressure Reduction in Stroke without Load

Based on the equations y=1.662x+18.74; y=1.477x+19.67 and y=1.798x+14.86, from Figure 7, 8, and 9, the diagrams of savings of compressed air consumption as a function of pressure level in stroke without load are proposed, see Figure 11.

By applying the same methodology, cost effectiveness of previously described pressure reduction in stroke without load for three different cases are presented. Calculations of savings for given pneumatic circuits are given in Table 6.

Based on obtained data, significant differences in realized savings can be noticed for the identified methods of pressure reduction on pneumatic cylinders. For example, by using Method IV saving of 21.4% is realized when applying pressure of 3 bar instead of 6 bar while, using Method III, saving of 14.9% is realized. That means that saving achieved with Method IV is 43.6% greater compared to Method III. On the other side, if it is possible to apply Method I (reduction of supply pressure in both strokes of pneumatic cylinder), it will result with even 88% greater savings compared to Method IV.

Besides, tremendous differences in return on investment can be noticed in dependence not only on applied method of pressure reduction but on the dimension of cylinder, as well. Taking in account that most standard cylinders can be found in a range between Ø8 and Ø320 mm and strokes between two and 2000 mm in this paper are chosen two examples not from the very end of the range (Ø20x50 and Ø125x1000).

As can be seen, the calculation is done for one cylinder. In case of pneumatic circuit with more cylinders, the savings would be more significant.

For example, applying the same Method IV on relatively small cylinder with Ø20 and stroke of 50 mm is giving the ROI of 31 years. Same method applied on the big cylinder (Ø125 and stroke of 1000 mm is giving ROI of only 11.5 days.

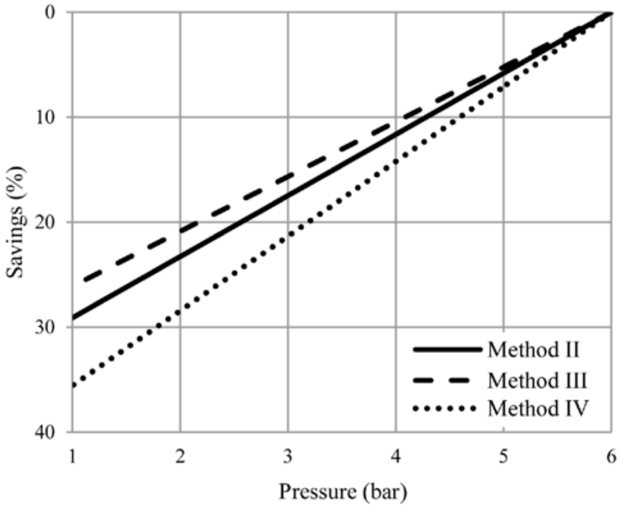

Fig. 11. Savings of compressed air as a function of pressure in stroke without load, with different methods.

Table 6. Cost effectiveness of pressure reduction in stroke without load with different methods and for different cylinders.

	Method II		Method III		Method IV	
	cylinder DSNU-20-50	cylinder DNC-125-1000	cylinder DSNU-20-50	cylinder DNC-125-1000	cylinder DSNU-20-50	cylinder DNC-125-1000
Price of 1 m^3 of compressed air (€)	0.02					
CAC per cycle for supply pressure of 6 bar (l/cycle)	0.29	125	0.26	125	0.24	125
CAC per cycle for supply pressure of 2 bar (l/cycle)	0.22	96.25	0.22	98.75	0.18	90
Number of working cycles per minute (cycle/min)	6					
Effective capacity per year (min/year)	180,000					
Number of cycles per year (cycle/year)	1,080,000					

CAC per year for supply pressure of 6 bar (m^3/year)	313.20	135,000	280.80	135,000	259.20	135,000
CAC per year for supply pressure of 2 bar (m^3/year)	237.60	103,950	237.60	106,650	194.40	97,200
Difference in CAC per year for 2 and 6 bar pressure (m^3/year)	75.60	31,050	43.20	28,350	64.8	37,800
One year cost saving (€/ year)	1.51	621	0.86	567	1.29	756
Extra cost (pressure regulator LR) (€)	35	53	68	144	40	63
Return on investment (years)	23.17	0.85	79.06	0.254	31	0.083

6. CONCLUSION

When industrial engineer is faced with the problem of decreasing energy costs in pneumatic system, one of the most popular measures is reducing the supply pressure for pneumatic cylinders. In that case, it would be very useful to be able to calculate possible savings for different methods of reducing pressure. In this paper is not given any in-depth discussion about the reasons that causes the differences in CAC because the purpose of this paper is to discuss cost effectiveness of the identified methods.

Based on the measurements of compressed air consumption and cost effectiveness analysis presented in this paper, two diagrams of savings are proposed:

- The diagram of compressed air savings as the function of supply pressure for the pneumatic cylinder (same pressure in both strokes of cylinder).
- The diagram of compressed air savings as a function of different pressure in stroke of the cylinder without load, while using different methods for pressure regulation.

Method for pressure regulation given in Figure 1(b) is the most cost effective but has a number of limitations. Reduction of supply pressure in front of the actuator can be applied only when the cylinders are oversized and that is limited number of cases.

If it is not possible to apply this method and cylinder is working without load in one stroke, three other methods are available.

Method for pressure regulation, in no load stroke, given in Figure 2 is the second best according to this investigation with very small difference to the best one. Method for pressure regulation given in Figure 3 ranked as the last one but has some other advantage (velocity improvement) and it is still very cost effective. Method for pressure regulation given in Figure 4 has proved to be best in this investigation among the methods for pressure regulation in no load stroke and can offer additional advantage of differently reduced pressures in both strokes. In that case it is possible to calculate savings using diagram from Figure 10 separately for each stroke.

For every identified measure for increasing energy efficiency is very important to calculate return on investments (ROI) period because it usually represents a major factor for making decisions about investment in such a measure. Namely, each company is defining, as internal policy, which measures should be applied based on, previously defined, acceptable ROI. This period used to be about five years during the stable economy but in recent years, due to economic crises, this period has shortened in many companies on three years. Nowadays, some companies shorten this period on only one year. From the obtained experimental results and thus calculated savings can be clearly seen that ROI for these measures strongly depends, besides the chosen method, on the dimensions of the pneumatic cylinder. Reviewed methods are particularly cost effective when applied on cylinders with bigger diameters and/or strokes. With the obtained results, it is possible to apply most appropriate method for pressure regulation and to calculate possible savings. Obtained diagrams of possible savings can be used, together with prices of described components, to generate a good estimation of ROI for every identified method of pressure reduction.

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