ENERGY EFFICIENT COMPRESSED AIR FILTRATION
An Experimental Study on the Effect of Filters Selection and Configuration on Pressure Drop

by

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Over the past decades, the industrial sector has been trying to improve the use of resources and the environmental impact they create. Significant work has been done in compressed air systems. However, there is still much room for improvement. The focus of this study is on a new approach to energy efficient compressed air filtration. This approach involves the installation of different filter configurations that enable a lower pressure drop, instead of the conventionally selected filter. The goal is to reduce the pressure drop, while maintaining the same level of air quality. Pressure drop and compressed air quality are taken as key performance indicators that assess the efficiency and sustainability of compressed air system. It has been experimentally proven that compressed air quality classes remain the same for filters with the same grade of filtration, regardless of the number, type, and way of their installation. However, there is a small difference in the case of particulate and coalescing filters. This environmentally friendlier approach provides a win-win situation. The pressure drop is reduced, costs are also reduced, the system operates continuously and more reliably, and the process is more sustainable.

Key words*: compressed air, filtration, energy efficiency, non-energy benefits, sustainability*

Introduction

Population growth and intensive industrial production lead to increased exploitation of natural resources, as well as emissions of pollutants into the air, soil and water [1, 2]. Manufacturers of different goods are making efforts to provide high quality products and services, taking care on environmental protection and sustainable development [3-5]. Production activities and applied energy saving measures must include non-energy benefits, such as sustainability, with the least negative impact on the environment, while minimizing the consumption of natural resources [6, 7], increased reliability in production, extended equipment lifetime, *etc*. [8].

In the industrial sector, about 10% of electricity consumed is spent on compressed air (CA) production [9-11]. Research shows that energy efficiency measures in various CA systems (CAS) are often treated with less importance than they deserve [9, 12, 13], although many of them were considered to be low-cost measures [14, 15]. According to [16] specific energy

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efficiency measures in CAS often face information-related barriers, such as a lack of information on the costs and benefits associated with the measure under consideration.

If we look at the Gralen diagram [17], which represents the ratio between electricity supply and output in the form of useful CA, it is clear that the issue of energy efficiency of the CAS is extremely important. A situation that is often encountered in practice is that manufacturers focus on CAS only when pressure losses begin to interfere with the normal operation of production. It is crucial to measure the CAS energy consumption, as well as the flow of CA in real-time [18]. In this way, spots where different energy saving strategies can be applied can be identified. Some of them are associated with air leaks, others deal with high-efficient motors or try to reduce operating pressure, *etc*. [10, 19-21].

One of the critical places in CAS where problems often occur are filters. Inadequate maintenance of the filter can cause two significant problems: pressure drop and contaminants penetration into the part of the system downstream of the filter.

Filters remove contaminants (solid particles, oil, water, *etc*.) from CA, but at the same time cause a pressure drop [22, 23]. However, a distinction must be made between an acceptable pressure drop (the one we are counting on) and an alarming pressure drop, which indicates that intervention on the filter is required.

In contrast, filters can be used to ensure adequate CA quality, but with less pressure drop [19, 24]. By reducing the pressure drop, the total amount of CA consumed, and thus produced, is reduced. This will shorten the operating hours of the compressor and the amount of electricity consumed, which in turn will lead to less CO_2 in the atmosphere [25, 26].

The aim of this research is to achieve a lower pressure drop during filtration of CA. The conventional method for selecting CA filter includes, firstly, determining the total CA consumption for a particular application, and secondly, choosing the necessary filters. Engineers in most cases choose the appropriate filter from the manufacturers' product catalogue, taking into account only the required air-flow. They select the first filter with a higher air-flow than required. With this, the process of the filter selection ends.

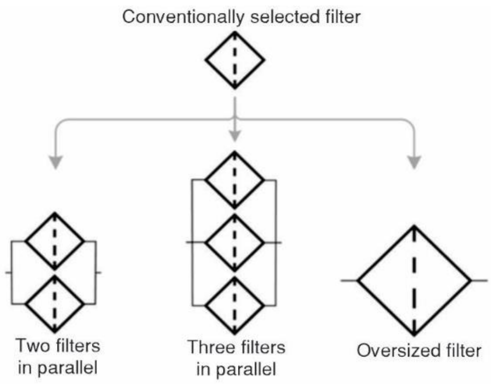

Figure 1. Filters' configurations replacing conventionally selected filter

However, this method can be improved. The proposed approach involves the selection and installation of different filter configurations that provide lower pressure drop, instead of the conventionally selected filter. The goal is to reduce the pressure drop, while maintaining the same level of air quality. This idea was tested on two and three filters installed in parallel, and on a filter with higher capacity than needed, as shown in fig. 1. These filters configurations replace the conventionally selected filter. The pressure drop for all proposed filters' configurations has been determined experimentally.

In addition, the quality of CA after filtration was measured to determine the quality class od CA. Therefore, it has been determined how different filter configurations affect the quality of the CA, *i.e*. does the quality change or remains the same.

The installation of different filter configurations requires extra costs that cannot be ignored. Therefore, an appropriate cost-benefit analysis was conducted.

The same methodology was applied to particulate and coalescing filters.

Materials and methods

The starting point in this study is the diagram of the pressure drop that appears on the filter, as a function of the air-flow, shown in fig. 2 [27]. For an air-flow of 600 Nl per minute, the filter has a pressure drop Δp_1. If we replace this (conventionally selected) filter with two identical filters, placed in parallel, the flow of 600 Nl per minute will be distributed between these two filters, *i.e.* an air-flow of 300 Nl per minute of CA will flow through each of them. During the preparation for this study, we have experimentally confirmed that, in the case of two and three filters installed in parallel, the flow of CA is evenly distributed among them, with a deviation of up to 2%.

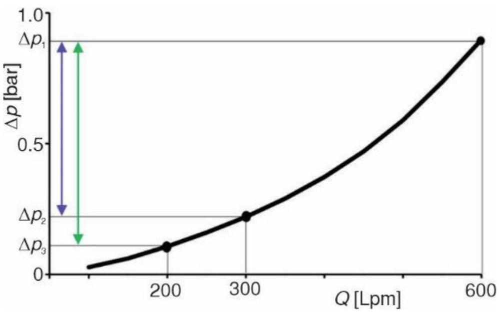

Figure 2. Pressure drop as a function of air-flow (adopted from [27])

With an air-flow of 300 Nl per minute pressure drop Δp_2 occurs. This leads to a significant reduction in the pressure drop of $\Delta p_1 - \Delta p_2$, as shown in fig. 2. In the case of three filters installed in parallel, the air-flow through each of them will be 200 Nl per minute and the pressure drop on the installation would be Δp_3. The total reduction in the pressure drop is $\Delta p_1 - \Delta p_3$, as can be seen in fig. 2.

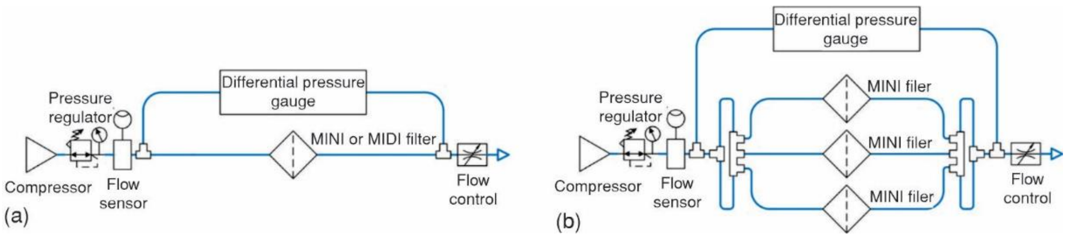

Figure 3. Installation scheme during pressure drop measurement on different filter configurations

In accordance with the basic idea, the pressure drop was measured for different low flow (MINI) and medium flow (MIDI) configurations. The low flow filter (conventionally selected) was replaced by two, and then three parallel filters. Also, the low flow filter has been replaced with a medium flow filter. The installation scheme of the devices during the pressure drop measurement on one filter is shown in fig. 3(a), and on three parallel filters in fig. 3(b). In the case of a parallel installation of two filters, the same installation was used as in the case with three filters, but the middle line was blocked. During the experimental measurements, particulate filters with a grade of filtration of 40 μm and 5 μm, and coalescing filters with 1 μm and 0.01 μm grade of filtration were used.

Measurements were performed with a variation of two parameters: air-flow and pressure. Air-flow has been changed, within the working flow filters, in intervals of 50 Nl per minute from 150-600 Nl per minute (for particulate filters), 150-500 Nl per minute in the case of coalescing filters with a grade of filtration of 1 μm, and from 150-350 Nl per minute for 0.01 μm coalescing filters. Dry CA was used, with pressure variations from 2-6 bar in intervals of 1 bar.

For each of these configurations, in addition to measuring the pressure drop, the quality of the CA after filtration was determined. Quality classes were determined according to ISO

8573.1:2010 [24] procedure. The output values of solid particles, oil and water were measured. This step is very important to check whether the same types of filters (in terms of grade of filtration) in different configurations (two/three filters in parallel or one larger) provide the unchanged class of CA quality.

Experimental equipment

All experimental measurements were performed on two types of filters:

– particulate - LF series: LF-D-MIDI/MINI, with a grade of filtration 40 μm and 5 μm and
– coalescing - LFMB and LFMA series: LFMB-D-MIDI/MINI, with a grade of filtration 1 μm, and LFMA-D-MIDI/MINI, with a grade of filtration 0.01 μm [27].

The pressure drop was measured by an integrated device for remote monitoring of pressure drop on CA filters using two pressure gauges [28]. The CA flow and pressure was measured by FESTO AirBox portable laboratory, a multifunctional device for measuring the air-flow, humidity (dew point), and oil (aerosol, liquid and vapour) in CA [29]. Drager indicator tubes were used to determine the dew point (5/a-P) and oil content (10/a-P and 1/a) in CA [30-32]. The content of solid particles in CA was determined using a HandiLaz Mini particle counter. This device has three measuring channels; 0.3 μm, 0.5 μm, and 5.0 μm, and the maximum air volume during one measurement is 2.83 Nl per minute. HandiLaz Mini was used together with the high-pressure diffuser HDP III [33, 34].

Results

The following section contains the results of the conducted experiments. Due to the large number of results, only data for an operating pressure of 6 bar are presented, as the most common pressure in industrial applications. The results for other tested operating pressures (2-5 bar) are analogous to these.

Pressure drop

Based on the measurements results, some facts are obvious. By increasing the pressure of CA, with a constant air-flow, the pressure drop decreases. By increasing the air-flow, while maintaining a constant pressure, the pressure drop on the filter also increases.

Figure 4(a) presents the results for the tested configurations of particulate filters, with a grade of filtration of 40 μm, at a pressure of 6 bar. As can be seen, the highest pressure drop occurs for a single low flow particulate filter (1×MINI). By placing two identical filters in a parallel installation (2×MINI), instead of one (1×MINI), the pressure drop was significantly reduced. By adding another filter to the parallel installation, the pressure drop is further reduced. However, the cost-effectiveness of the number of filters must be carefully analysed. As can be seen from fig. 4(b), and which is very important for later discussion, the pressure drop curve for a medium flow filter (1×MIDI) is between the curves for 2×MINI and 3×MINI filters installed in parallel. The same results were obtained for other tested pressure levels.

Figure 4(b) shows the results of the tested configurations of coalescing filters, with a grade of filtration of 1 μm and a working pressure of 6 bar. The manufacturer defines the maximum air-flow for this type of filter at 500 Nl per minute. Therefore, the results are presented for a flow range from 150-500 Nl per minute. At first glance, these results look similar to the results of the particulate filters. The trend of decreasing the pressure drop by adding low flow filters to a parallel installation is still evident. It is important to note that the pressure drop on the medium flow filter (1×MIDI) is below the pressure drop curves for 2×MINI and 3×MINI filters in parallel installation. The same results were obtained for other tested working pressures.

Based on the measurement results, it is clear that different types of filters behave differently. Character of pressure drop trends is not the same for particulate and coalescing filters. The difference is in the lowest pressure drop that is achieved. For particulate filters, three parallel low flow filters (3×MINI) provide the lowest pressure drop. In the case of coalescing filters, this is made possible by the use of medium flow filter (1×MIDI), as shown in fig. 5.

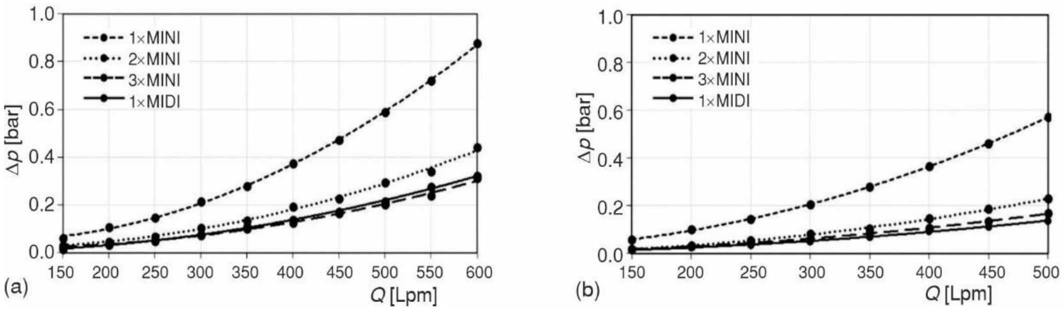

Figure 4. Pressure drop on 40 μm particulate (a) and 1 μm coalescing (b) filters at 6 bar pressure

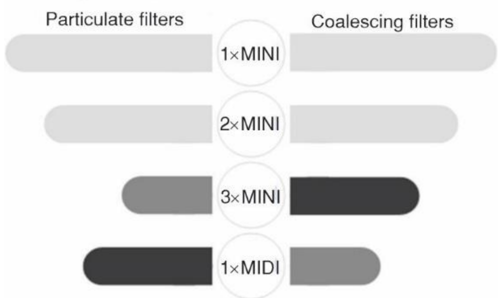

Figure 5. Comparison of achieved pressure drops for tested filter configurations

Compressed air quality

In parallel with the pressure drop measurement, the quality of the CA is measured after filtration, for all filter configurations. The results are presented in tab. 1. The purpose of this measurement was to determine what happens to the quality of CA in case of using different filter configurations. As can be seen in tab. 1, there are certain differences between the measured quality classes of CA and the quality classes specified by the manufacturer. In three of four tested grades of filtration, the concentration of the solid particles was two classes better than that specified by the manufacturer. For particulate filters, the water content also differs from the manufacturer's specification. This can be explained by the fact that the testing of filters was performed in laboratory conditions with considerably cleaner ambient air than in real industrial conditions where filters are mainly used.

In the case of a coalescing filter of 0.01 μm, it cannot be determined exactly whether the CA Class is 1 or 2 for solid particles, due to the limitations of the measuring device. However, it can be said that the CA belongs to one of these two classes. As in the previous cases, there is a deviation of the dew point in the CA. If we take a closer look at the obtained results, the measured dew point for these filters is –10 °C and –9 °C. Class 3 is defined with a dew point ≤–20 °C, and Class 4 with a dew point ≤3 °C. So, the quality of the CA is significantly better than Class 4, but insufficient to classify it as Class 3.

Discussion

The conventional method of selecting a CA filter does not guarantee energy efficient operation of the CAS. The filter selection should be in accordance with the principles of sustainable production [35]. In other words, the pressure drop that occurs on the filter and how it affects the overall characteristics of the system must be taken into account [36]. Learning about

Table 1. Achieved quality classes for tested filter configurations *vs.* manufacturer's specification

	Grade of filtration	Filter configuration	Achieved quality class	Manufacturer specification
Particulate filters	40 μm	1×MINI	5. 5. 4	7. 4. 4
		2×MINI	5. 5. 4	7. 4. 4
		3×MINI	5. 5. 4	7. 4. 4
		1×MIDI	5. 5. 4	7. 4. 4
	5 μm	1×MINI	4. 5. 4	6. 4. 4
		2×MINI	4. 5. 4	6. 4. 4
		3×MINI	4. 5. 4	6. 4. 4
		1×MIDI	4. 5. 4	6. 4. 4
Coalescing filters*	1 μm	1×MINI	3. 4. 3	5. 4. 3
		2×MINI	3. 4. 3	5. 4. 3
		3×MINI	3. 4. 3	5. 4. 3
		1×MIDI	3. 4. 3	5. 4. 3
	0.01 μm	1×MINI	≤ 2. 3. 2	1. 4. 2
		2×MINI	≤ 2. 3. 2	1. 4. 2
		3×MINI	≤ 2. 3. 2	1. 4. 2
		1×MIDI	≤ 2. 3. 2	1. 4. 2

*prefiltration with particulate filter 5 μm

sustainability [37] and encouraging energy saving measures while emphasizing non-energy effects are of great importance for the sustainable development of the production sector [38].

Particulate filters

Based on the experimental results, it can be seen that the use of a single particulate low flow filter (1×MINI) causes the highest pressure drop among all tested filter configurations. The pressure drop on the 1×MINI particulate filter, with a grade of filtration of 40 μm, at an operating pressure of 6 bar and an air-flow of 600 Nl per minute, was 0.88 bar. By replacing this filter with two parallel low flow filters (2×MINI), the pressure drop was reduced by 50% and amounted to 0.44 bar. With the installation of a third low flow filter in a parallel configuration (3×MINI), the pressure drop was reduced by an additional 30%, or about 65% compared to the initial pressure drop, and was 0.31 bar. If one medium flow filter (1×MIDI) replaces the 1×MINI filter, the pressure drop was 0.32 bar, slightly higher than the pressure drop on the 3×MINI, fig. 4(b). The prices of the filters used during the experiments are also shown in fig. 6, and will be used in further discussion.

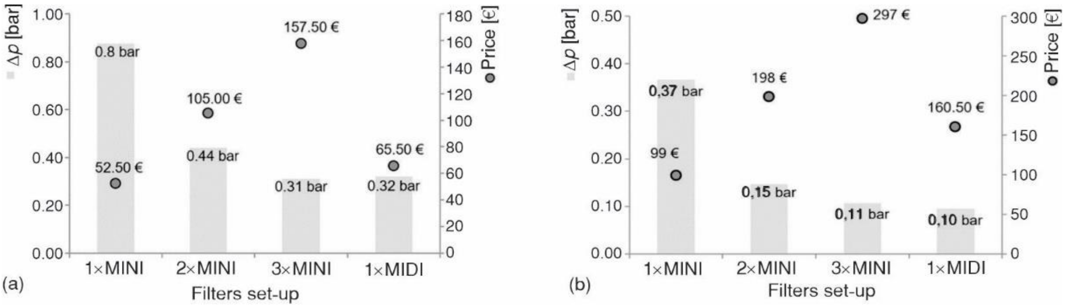

Figure 6. Pressure drop at 6 bar pressure and 600 Nl per minute air-flow and particulate filters prices (a), and at 4 bar pressure and 400 Nl per minute air-flow and coalescing filters prices (b)

In addition to the filters prices, CA filters also have operating costs, because the filter cartridge must be changed regularly. Table 2 provides an overview of the estimated costs of installation and operation costs during the filter lifecycle (10 years), for all tested filter configurations. Installation costs include the cost of the filter itself, connectors mounted on the filter, tubing, and staff costs. Parallel filters include the prices of the necessary fittings and additional tubing. Operating costs during the filter lifecycle include replacement of the filter cartridge, which must be done every 6 months (according to the recommendations of the filter manufacturer), as well as staff costs during replacement.

Table 2. Costs of installation and operation of particulate filter configurations during the projected lifecycle of ten years

	Filter configurations			
	1×MINI	2×MINI	3×MINI	1×MIDI
Total installation costs [€]	**60.90**	**138.60**	**207.90**	**74.30**
Operation				
Year 1 of operation*	11.05	22.10	33.15	18.00
Years 2-10 of operation**	9×22.10	9×44.20	9×66.30	9×36.00
Costs of installation and operation [€]	**270.85**	**558.50**	**837.75**	**416.30**

* Replaceable every 6 months, the first filter cartridge is delivered with the filter, ** replaceable every 6 months

The most common dilemma that arises when using CA filters is: *How long is the lifecycle of the filter cartridge and when should it be replaced?*. In accordance with common practice, filter cartridges are replaced in accordance with the manufacturer's specifications [39]. However, these maintenance activities can be performed in both cost-effective and sustainable ways. For particulate and coalescing filters, the lifecycle of a filter cartridge can be determined by the pressure drop, since the pressure drop is directly proportional to the level of filter contamination. Therefore, the safest way to determine the level of contamination is to measure the pressure drop.

Reducing the pressure drop in the system undoubtedly leads to energy cost savings. An illustration of the savings can be very easily made on the example of a real CAS. If we consider the CAS with an installed power of 200 kW and an operation of 6800 h per year, the annual electricity consumption of the system can be described by eq. (1), and the annual energy costs by eq. (2) [22]:

$$EC = P_A \times H \tag{1}$$

$$AEC = EC \times ER \tag{2}$$

where EC is the annual energy consumption [kWh per year], PA – the average power [kW], H – the annual operating hours [h per year], AEC – the annual energy costs [€ per year], and ER – the energy rate [€/kWh]. At the observed CAS and at the price of 0.1445 €/kWh [40], the annual energy costs are calculated by eq. (3). According to [22], the annual energy savings (ES) due to the reduced pressure drop (Δp) can be calculated by eq. (4), and the annual cost savings (ECS) by eq. (5):

$$AEC = 200\ [\text{kW}] \times 6800\ [\text{h/year}] \times 0.1445\ [\text{€/year}] = 196520\ [\text{€/year}] \tag{3}$$

$$ES = EC \times \Delta p \times 0.08 \tag{4}$$

$$ECS = ES \times ER = EC \times \Delta p \times 0.08 \times ER = AEC \times \Delta p \times 0.08 \tag{5}$$

The estimated annual cost savings (ECS) for the observed CAS, were calculated based on the reduction in pressure drop achieved by the tested filter configurations, and the results are presented in tab. 3.

Based on the calculated installation and operation costs of the tested filter configurations, tab. 2, and the annual cost savings, tab. 3, it is possible to determine the savings that can be achieved during the filter lifecycle (projected to 10 years). These costs are listed in tab. 4.

Table 3. Annual cost savings due to reduced pressure drop of particulate filter configurations

			Filter configurations		
			2×MINI	3×MINI	1×MIDI
EC	Annual electricity consumption	[kWh/year]	1360000	1360000	1360000
AEC	Annual energy costs	[€/year]	196520	196520	196520
Δp	Decrease in pressure drop	[bar]	0.44	0.57	0.56
ER	Energy rate	[€/kWh]	0.1445	0.1445	0.1445
ECS	**Annual cost savings**	**[€/year]**	**6917.00**	**8961.00**	**8804.00**
	Annual cost savings	[%]	3.52	4.56	4.48

Return on investment and savings may vary from manufacturer to manufacturer and application characteristics (operating conditions, operating pressure, air-flow, *etc.*), Therefore, the proposed cost-benefit analysis should be done for each specific application. The usage of over-dimensioned filter should be carefully considered in relation to the flow range in which the filter works efficiently. The minimum filter flow should be less than the required flow for the system.

Table 4. Lifecycle costs of tested particulate filter configurations

	Filter configurations			
	1×MINI	2×MINI	3×MINI	1×MIDI
Installation and operation costs [€]	270.85	558.50	837.75	416.30
Savings per 10 years [€]	–	–69170.00	–89610.00	–88040.00
Total savings per 10 years [€]	**270.85**	**–68611.50**	**–88772.00**	**–87623.70**

Coalescing filters

The lowest pressure drop occurs on the medium flow filter (1×MIDI), as opposed to the three parallel low flow filters (3×MINI) in the case of the particulate filters. If we apply the proposed cost-benefit analysis to the coalescing filters, we get completely different results.

According to the measurement results, for an operating pressure of 6 bar and an air-flow 400 Nl per minute, it can be seen that the use of low flow coalescing filter (1×MINI), with the grade of filtration 1 μm, results in the highest pressure drop of 0.37 bar. By replacing this filter with two parallel filters (2×MINI), the pressure drop was reduced by 60% and was 0.15 bar. By installing a third filter in the parallel connection (3×MINI), the pressure drop was reduced by an additional 27%, or about 70% compared to the initial pressure drop, and was 0.11 bar. If the medium flow filter (1×MIDI) replaces the 1×MINI filter, the pressure drop was 0.10 bar which is slightly lower than the pressure drop on the 3×MINI, as can be seen in fig. 4(b).

Analogous to the calculation of the costs of installation and utilization of the particulate filters, tab. 5, gives the estimated costs of installation and operation costs all tested coalescing filter configurations.

In order to determine which filter setting is optimal, it is best to estimate the possible annual savings, using eq. (5), on the actual CAS. The same CAS as in the previous case was considered, with an installed power of 200 kW and operation of 6800 hours per year. Savings are achieved by reducing the pressure drop, as a result of using different filter configurations instead of the traditionally selected low flow filter. The savings calculation was applied to all tested filter configurations, and the results are presented in tab. 6.

Table 5. Costs of installation and operation of coalescing filter configurations during projected lifecycle of ten years

	Filter configurations			
	1×MINI	2×MINI	3×MINI	1×MIDI
Total installation costs [€]	**107.40**	**231.60**	**347.40**	**169.30**
Operation				
Year 1 of operation*	52.60	105.20	157.80	75.00
Years 2-10 of operation**	9×105.20	9×210.40	9×315.60	9×150.00
Costs of installation and operation [€]	**1106.80**	**2230.40**	**3345.60**	**1594.30**

* replaceable every 6 months, the first filter cartridge is delivered with the filter, ** replaceable every 6 months

Based on the calculated costs of installation and operation of the tested filter configurations and annual savings from tab. 6, it is possible to determine the savings that can be achieved during the filter lifecycle (projected for ten years). These costs are given in tab. 7.

Table 6. Annual cost savings due to reduced pressure drop of coalescing filter configurations

			Filter configurations		
			2×MINI	3×MINI	1×MIDI
EC	Annual electricity consumption	[kWh/year]	1360,000	1360000	1360000
AEC	Annual energy costs	[€/year]	196520	196520	196520
Δp	Decrease in pressure drop	[bar]	0.22	0.26	0.27
ER	Energy rate	[€/kWh]	0.056	0.056	0.056
ECS	**Annual cost savings**	**[€/year]**	**3458.75**	**4087.62**	**4244.83**
	Annual cost savings	[%]	1.76	2.08	2.16

Table 7. Lifecycle costs for coalescing filter configurations

	Filter configurations			
	1×MINI	2×MINI	3×MINI	1×MIDI
Installation and operation costs [€]	**1106.80**	**2230.40**	**3345.60**	**1594.30**
Savings per 10 years [€]	–	– 34587.50	– 40876.20	– 42448.30
Total savings per 10 years [€]	**1106.80**	**– 32357.10**	**– 37530.60**	**– 40854.00**

The situation with coalescing filters is significantly different, as the prices of filters and filter cartridges are quite different from the particulate filters. By adding a filters to a parallel installation, the pressure drop is reduced, but the price rises dramatically. Prices vary from manufacturers to manufacturer, so a cost-benefit analysis must be done carefully for a particular application.

Finally, the question arises as to whether the conventional method of filter selection can be replaced by a more sustainable approach. In addition to technical and economic analysis, additional criteria may be introduced to help engineers make the final decision on the use of filters.

System reliability as a non-energy benefit

In addition to energy savings and energy cost savings, measures to improve energy efficiency in industry can bring a number of benefits. Some of them result in increased reliability of the production system, increased productivity, optimal maintenance, reduced emissions to water, air, soil and waste, *etc*. [41].

As an additional criterion for assessing possible filter configurations, the reliability of a system supplied with filtered CA can be introduced. In the case of a single filter, the reliability of the system is equal to the reliability of the filter itself. If this filter fails, it will lead to a malfunction in the production system in which the filter is installed. The CA distribution system after the filter will be contaminated and a large pressure drop may occur. Costs caused by production delays in many industrial applications can be extremely high.

In the case of two or three parallel filters, malfunction or shutdown of the production system will only occur only if all filters fail, making the system more reliable [42]. From this point of view, a more acceptable option is to install two or three filters in parallel. According to the authors [43], investments and implementation of energy efficiency measures are more likely to be realized if monetary values are added to them. So, take, for example, just one failure of one particulate filter for the observed filter lifecycle of ten years, with an accompanying cost of €10000. Realisation of configurations with several filters installed in parallel ensures grater savings, tab. 8, and at the same time allows continuity of the production process.

Table 8. Lifecycle costs for particulate filter configurations with calculated filter failure

	Filter configurations			
	1×MINI	2×MINI	3×MINI	1×MIDI
Installation and operation costs [€]	270.85	558.50	837.75	416.30
Costs caused by filter failure [€]	10000.00	10000.00	10000.00	10000.00
Savings per 10 years [€]	–	– 69170.00	– 89610.00	– 88040.00
Total costs [€]	**10270.85**	**– 58611.50**	**– 78772.25**	**– 76623.70**

From tab. 9 it can be concluded that the use of a single particle filter (1×MINI), selected by the conventional approach, causes the highest costs. All other tested filter configurations provide significant savings, but the use of three parallel filters (3×MINI) provides maximum savings. If the same cost calculation is applied to coalescing filters, as is presented in tab. 9, it can be seen that the costs vary from configuration to configuration. The most cost-effective option is to install a 1×MIDI filter. But in that case, reliability of the system would be low. So, the optimal solution is to install three coalescing filters in parallel (3×MINI).

Table 9. Lifecycle costs for coalescing filter configurations with calculated filter failure

	Filter configurations			
	1×MINI	2×MINI	3×MINI	1×MIDI
Installation and operation costs [€]	1106.80	2230.40	3345.60	1594.30
Costs caused by filter failure [€]	10000.00	10000.00	10000.00	10000.00
Savings per 10 years [€]	–	– 34587.50	– 40876.20	– 42448.30
Total costs [€]	**11106.80**	– **22357.10**	**27530.60**	– **30854.00**

Conclusions

The CAS should be designed, implemented, and managed to meet user requirements in terms of efficient use. This includes the supply of sufficient CA, in terms of pressure and flow, of appropriate quality. Increasing energy efficiency during its production, preparation and distribution must be a permanent goal. This paper considers pressure drop of CA during filtration. Reducing the pressure drop increases the energy efficiency of CA and reduces the negative impact on the environment by reducing the CO_2 emissions, due to the reduced consumption of electricity by the compressor.

The obtained experimental results confirm that by using a different number of filters, differently installed, it is possible to reduce the pressure drop that occurs through them. The CA quality remains the same for filters with the same grade of filtration, regardless of the number, type and way of their installation. In other words, any filter configuration, within the same grade of filtration, will provide the same quality of CA.

By introducing system reliability, it can be concluded that the installation of three parallel filters gives a win-win situation, for both types of filters, particulate and coalescing. The pressure drop is reduced, costs are reduced, the system operates continuously and reliably, and the process is more sustainable.

The CA filtration can be further improved by replacing the filter cartridges according to the actual level of dirt, instead of replacing the filter cartridge based on the manufacturer's recommendations. The degree of contamination of the filter is determined based on the pressure drop that appears on it, and can be easily measured. Reduced labour needs, reduced maintenance and extended equipment life are ranked among the biggest non-energy benefits in many studies.

These results should encourage engineers not only to use the conventional method of filter selection, but to think and act in a more sustainable way.

The implementation of the achieved results is possible in all industrial applications where there is a CAS.

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