Impact of network expansions on energy losses in compressed air

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Abstract. Compressed air is a very widely used energy medium, used in various fields. It is one of the most widespread, but also one of the most expensive working media used in modern industry. According to studies available in the literature in Australia and the European Union, energy consumption by compressed air systems accounts for about 10% of total industrial energy consumption, while in the United States it accounts for 30% of total electricity consumption. In addition, these systems are one of the least efficient forms of energy - only about 10-30% of the energy generated by the compressor reaches the end point. This is primarily due to a change in the form of energy (e.g. heat), but also leaks in the network and inefficient use. During operation in the compressed air network, pressure losses (linear and local) occur as a result of pipeline construction as well as pressure losses caused by the use of devices and elements responsible for maintaining adequate air quality (local losses) in the network. The pressure drop caused by the pipeline elements will depend on the extent of the network, the diameter of the pipeline, the number of places where there is a change in the direction of air flow (elbows, venturi, etc.). However, the losses caused by the use of treatment elements will depend on the expected air quality (number of filtration stages, appropriate air dryer) as well as on the network operation time (e.g. air filter contamination). The purpose of this study is to determine the impact of compressed air network extensions on energy losses resulting from, among others friction during flow. The values of these losses depend on many parameters such as efficiency, air flow speed, diameter and length of the pipeline. Knowledge about the correlation of these parameters will allow for proper selection of compression devices, as well as for optimal design of the pneumatic network.

1. Compressed air management in industry

Efficient use of energy in industrial plants is one of the main pillars of modern energy policy in Europe. However, the world today is constantly moving steadily towards increasing primary energy consumption. Compressed air is often seen as a cheap and even free energy source. Nothing more wrong. Numerous studies confirm that the industry only uses about 30% of the compressed air produced, the rest is lost due to leaks, inadequate pressure of the prepared air, improper use, etc. Compressed air is one of the most expensive energy utilities used in production plants. Industrial pneumatics often require the highest purity classes. These requirements directly translate into the need to install special driers, filters and separators. This leads to both the increased costs of the investment itself, which is the installation of a compressed air network, but also increases the costs of maintenance and energy [1,2,3]. There is not much information available in the literature on the...
energy efficiency of compressed air networks [4,5,6]. An indicative distribution of the operating costs of the air compressor is shown in Figure 1.

![Figure 1. Cost of compressors operation [1].](image)

Possibilities for energy savings in compressed air installations are primarily associated with reduced energy consumption for compressor drive, compressed air transmission and control of pneumatic systems.

To effectively use compressed air energy, an analysis is needed that should include the following specific tasks:

- taking an inventory of your compressed air systems,
- analysis of the efficiency of the production and use of compressed air,
- an assessment of the applicability of energy saving measures,
- adopting a cost reduction plan by improving energy efficiency,
- preparing a progress report on the implementation of the action plan.

Conducting an audit is therefore necessary in the process of determining the cumulative energy consumption of a production plant. Identifying places that can potentially have an impact on reducing energy consumption is a fundamental task in this situation.

As previously tried to demonstrate compressed air does not belong to cheap energy carriers. Such a great need for energy in the air compression system results from the fact that most of the energy used for compression is dissipated in the form of heat - the air is first heated and then it must be cooled. Often, moisture must also be removed (remove harmful water condensate from the installation), filter dust and deliver it to the place of use. If the installation is extensive, this usually means large losses due to compressed air leaks.

2. Air flow through the installation

When flowing through the network elements, the pressure of the compressed air changes. The selection of the device (usually a compressor) that is responsible for its initial value should therefore be preceded by an analysis of compressed air demand. It is carried out taking into account the required working pressure of the receivers with the admissible minimum marked, increased by pressure losses occurring in the installation connecting the individual receivers.

An integral part of the compressed air network, in addition to the elements producing (sets of compressors) and treatment (filters, driers, separators) air are the elements forming its network structure - installations connecting individual network components. Its main task is air distribution - ensuring technological flow of the factor between individual network elements. Its design (diameter of wires, number of direction changes, connections, etc.) significantly affects the operating parameters of compressed air - especially the pressure value.

In a compressed air system, pressure drops are generated by:

- length of pipelines,
- pipe diameter,
- roughness of the internal surface of the pipeline,
- operating pressure in the network - higher pressure results in higher pressure.

Branches in the compressed air network also cause additional losses, which is why each of these types of elements must be taken into account when calculating energy demand. Most often, each such
element has a specific flow resistance, which is expressed as the length of the straight section. It is also disadvantageous to move the installation components too far, because the distance between the compressor and the receiver generates compressed air losses during transport. In addition, network design with remote components is disadvantageous during network upgrades or renovations. Linear and local losses are another unfavorable factor causing a pressure drop in the compressed air system. Linear losses are usually caused by internal friction. During technological processes, the working medium is transported by pipelines in which the friction effect occurs, as well as the transformation of useful work into heat.

Most linear losses are expressed by the Darcy-Weisbach equation [9]:

$$\Delta p = \lambda \cdot \frac{d \cdot \rho \cdot v^2}{2} \quad (1)$$

where:
- \(d\) - pipeline diameter,
- \(v\) - flow velocity,
- \(l\) - distance of measuring points,
- \(\Delta p\) - pressure difference at points separated by \(l\),
- \(\lambda\) - flow resistance coefficient.

The coefficient of linear losses - friction losses \(Z_T\) is therefore equal to:

$$Z_T = \lambda \cdot \frac{l}{d} \quad (2)$$

The degree of smoothness of the conductor is determined for the correct determination of the friction coefficient \(\lambda\). The nature of the flow should also be remembered because roughness has no effect on linear losses in the stratified flow range (\(Re <2300\)) and then the friction coefficient is calculated according to the formula [9]:

$$\lambda = \frac{64}{Re} \quad (3)$$

For turbulent flows, the coefficient of friction depends on the roughness of the pipes. Local losses also play a very important role in calculating the pressure drop. They are often called local losses and their size depends on the shape and type of additional elements used, such as: elbows, valves, orifices, diffusers and others. The values of local losses are varied and this is due to the construction of additional elements. For elbows, the amount of local losses is mainly due to the geometry of this element, because with the flow of the working medium in the corners and behind sharp angles, there are swirls that cause the dispersion of mechanical energy.

Appropriate design of the compressed air installation allows for minimizing the pressure loss of compressed air, which can significantly affect the value of the energy used to drive the compressors.

3. Impact of compressed air network design solutions on pressure losses in the compressed air network

The main task of the compressed air network is to supply air to the receiver with the appropriate parameters: pressure value and mass flow. These values will be influenced by the network span and design parameters of the fluid transport pipeline. The following study examines various design options for compressed air networks. The impact of pipeline diameter and length on air pressure losses was assessed. The amount of these losses has a direct impact on the energy costs of the compressor station. Minimizing these losses has a positive impact on the company’s economic balance. The original FINCH 2.0 program was used to perform the analysis. It was created in the programming language Delphi 7 and allows the calculation of both pressure losses in compressed air installations and
determines the amount of energy recovered from the air compressor in the installation. It also allows the calculation of linear and local losses in pneumatic installations, depending on additional elements used in the network. A compressed air network of 50-800 m in length (defined as equivalent length taking into account local losses resulting from the need to use pipeline structural elements, e.g. elbows, valves, etc.) and with a diameter of 0.017-0.158 m was analyzed. The next variables were the pressure behind the compressor and performance system. The study did not take into account the change in height of the network in relation to sea level, the type of flow is laminar flow. The material that was used to build the pipeline is aluminum. The results are presented in the form of the charts below.

Graph 1. Dependence of energy losses on flow velocity - pipeline length 50 m.

Graph 2. Dependence of energy losses on flow velocity - pipeline length 100 m.

Graph 3. Dependence of energy losses on flow velocity - pipeline length 150 m.

The diagrams presented above show the dependence of energy loss generated during the air flow through the compressed air network depending on the flow speed, assuming equal network efficiency (the value of this speed depends on the diameter of the pipeline). As the flow velocity increases (and the pipeline diameter decreases), the value of air energy losses increases - the higher the velocity (smaller flow diameter), the more energy must be allocated to overcoming the resistance to movement.
in the pipeline resulting from min. from friction against its walls. Analyzing these graphs, it can also be seen that the energy loss increases proportionally with the length of the pipeline.

Graph 4. Dependence of energy loss on flow velocity - pipeline diameter 0.08 m.

Graph 5. Dependence of energy loss on flow velocity - pipeline diameter 0.02 m.

Graph 4 and 5 show the relationship between energy loss and flow velocity for two extreme values of pipeline diameter 0.02 and 0.08m. The flow rate in this case varies due to the change in system performance. Energy losses increase with increasing flow velocity as well as with increasing pipeline length. A much larger amount of energy to overcome the resulting losses should be allocated in the case of air flow through a smaller diameter pipe (0.02m).

Graph 6. Dependence of energy losses on the pipeline diameter - pipeline length 100m.
The above graphs nu 6 and 7 show the dependence of energy losses on the pipeline diameter for different system performance values and for two different pipeline lengths 100 and 500 m. Based on these, it can be concluded that again the pipeline diameter value has a significant impact on the energy loss value - the smaller the diameter should be used to power the compressor to overcome frictional losses. Network performance also has an impact on this loss - the higher the performance, the greater the loss. Analyzing all the results presented above, it should be stated that both the length and diameter of the pipeline significantly affect the energy consumption of the air compressor, whose task is to create the appropriate pressure required in the technological process.

Selected variants of design solutions subjected to this analysis have been verified in real conditions. The discrepancy of the results obtained in these studies reached values compared to approx. 15% in simulation tests. In the case of energy loss analysis in real installations, component losses (filters, dryer, local starts, etc.) were taken into account, but they were not included in the value of losses. The obtained value of the discrepancy of simulation and real results allows to state that the calculation model adopted in the Finch program correctly reflects actual energy losses.

4. Conclusions
The main task of compressed air installation is to provide air to the final recipient (machine) with appropriate technological parameters. These parameters are primarily pressure, flow rate and quality of compressed air. The structure and degree of filtration of the installation itself will depend on them. Its elements influence the change of factor parameters. The value of this change must be taken into account at the design stage of the compressed air network. Important parameters during this process are the diameter and length of the compressed air network. Appropriate selection of these parameters will allow you to minimize losses, but also allow you to install a cheaper compressor (both in purchase and in operation) with lower energy consumption. Current research shows that system development is expedient, consisting of a comprehensive approach to energy savings during production (compressors, air treatment and preparation stations), distribution (installations and pipelines) and use (drives, machines, devices) of compressed air. Comprehensive control of the compressed air network can be carried out by performing an audit to show the scale of losses of this air. It can be the basis for modernizing the network in order to optimally use the energy contained in compressed air.

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