MINISTRY OF EDUCATION

UNIVERSITY OF PETROSANI

DOCTORAL SCHOOL

DOCTORAL FIELD: MINES, OIL AND GAS

Eng. Danci Marius Daniel

DOCTORAL THESIS

CONTRIBUTIONS TO IMPROVING THE ENERGY EFFICIENCY OF PNEUMATIC EQUIPMENT APPLICABLE TO THE MINING INDUSTRY

Scientific leader:

Univ. Prof. Dr. Eng. RADU SORIN MIHAI

Petroșani

2024

1. RESEARCH METHODOLOGY. ACTUALITY, NEED, IMPORTANCE

The high share of energy consumption for the production of compressed air in the mining industry underlines the opportunity to improve the efficiency of the production and consumption of compressed air. Pneumatic energy is one of the most expensive sources of energy, and the share of the EU's industrial energy consumption for the production of pneumatic energy is quite high, being approximately 10%, which highlights the importance of approaching the topic in the doctoral thesis.

Within the 17 Sustainable Development Goals (SDGs), four essential goals can be highlighted for the practical application of the notion of sustainable development, goals that relate to energy, environment and society.

Through its content, this doctoral thesis addresses the following aspects of the four objectives.

Objective 7, which refers to clean energy and affordable prices, focusing especially on target 7.3, namely, by 2030, doubling the global rate of improvement in energy efficiency, by developing algorithms and methods for calculating the energy efficiency of industrial systems and proposing measures aimed at achieving target 7.3.

Achieving Objective 9 Building resilient infrastructures, promoting sustainable industrialization and encouraging innovation, requires achieving a competitive and sustainable industrialization, under the conditions of strengthening the circular economy. In order to achieve this objective, increasing the energy efficiency of industrial systems, through the proposed innovative solutions, promotes innovation and sustainable industrialization.

The work also addresses the objective of Objective 11 with an emphasis on target 11.6 - by 2030, the per capita reduction of the negative impact on the environment in cities, including by paying special attention to air quality and the management of municipal and other waste, considering that increasing energy efficiency, especially in industrial processes and installations, has a major impact on reducing the consumption of fossil fuels and therefore reducing polluting emissions. Consequently, given the large share of industry in energy consumption at the national and global level, the increase in energy efficiency will significantly reduce the impact on the environment and increase the performances for the energy - environment components.

Regarding Objective 13 - Climate action, it is directly influenced by increasing energy efficiency, given the fact that an energy efficient industry will produce much reduced CO2 emissions, thus contributing to reducing the impact on the climate. The synthetic formulation of the major objective for the practical application of the concept of sustainable industrial development can be stated as follows: the maximization of useful effects under the conditions of minimization of resource consumption.

This can be achieved by increasing the energy efficiency of industrial processes which directly leads to a reduction in fossil fuel consumption and therefore environmental impact. On the other hand, the implementation of innovative measures in order to increase the energy efficiency of the processes and industrial facilities analyzed can lead to the valorization of RES, this can facilitate the development of new businesses around these centers, businesses that can benefit from energy at a competitive price, work which will positively affect regional development, by creating new jobs.

Taking into account the above specifications and analyzing the energy efficiency of various industrial installations, the doctoral thesis developed, through the established theme and content,

aims to propose and analyze some feasible solutions to frame the explored system in the concept of sustainable energy by reducing energy consumption and consequently also the consumption of fossil fuels, considering that, for now, fossil fuels have a significant weight in the production of electricity.

1.1. - Theme

Improving the energy efficiency of pneumatic equipment with applicability in the mining industry.

1.2. – Specific objectives

The purpose and justification of the completion of the doctoral thesis refers to the desire to provide some solutions to the challenges faced by the mining industry in Jiu Valley, but this research can be applied in any other field where pneumatic energy is used, such as for example in the pneumatic transport of detergents, the transport of powders, etc.

The main challenges relate to:

- finding local solutions capable of mitigating the effects of the increase in energy prices by making the pneumatic system more efficient considering the high energy consumption for the production of compressed air;
- analyzing options for improving the energy efficiency of the pneumatic energy production and distribution system;
- possibilities of efficient utilization of the secondary energy resources available as a result of the production of compressed air;
- protecting and improving the quality of natural capital while improving the conditions for human and social capital by reducing emissions as a result of increasing the efficiency of processes and reducing the consumption of fossil fuels.

In order to suggest a series of options to respond to the challenges highlighted above, the doctoral thesis pursues the following objectives:

- making a synthesis of the current global and EU energy context;
- making a synthesis regarding the current state of solutions for the production, transport and use of compressed air;
- the realization of some algorithms and calculation methods for the realization of energy balances and the analysis of the possibilities of making pneumatic systems more efficient;
- validation of calculation methods by carrying out various case studies, based on experimental determinations in various industrial pneumatic systems;
- reduction of energy consumption and greenhouse gas emissions in helical compressors with oil injection;
- simulation based on a numerical calculation program of the influence of some functional parameters on some quantities related to the energy efficiency of the pneumatic energy generators;
- the development of numerical calculation programs that quantified the energy performances of helical compressors, compressor fans and pneumatic networks.

- proposing solutions to increase the energy efficiency of pneumatic systems in order to verify and justify the inclusion of the proposed measures in the concept of efficient, competitive and innovative energy.

1.3. – Research hypothesis

Based on the documentary study, and the information discovered regarding the topic of the thesis, we made an inventory of the solutions to respond to the previously stated challenges.

After selecting the systems that fit the sustainable energy criteria, in the work I focused on:

- analysis of the current energy context highlighting the role of pneumatic energy and the general problems regarding the use of compressed air in the mining industry
- carrying out a study on the conceptual framework for the production of compressed air in the mining industry, with the analysis of the main production solutions, namely: piston compressors, turbo compressors and helical compressors;
- the creation of mathematical models and calculation breviaries for determining the energy efficiency of the previously listed compressors;
- carrying out a comparative critical analysis of the compressors used in the mining industry;
- making a calculation algorithm and mathematical model for the mining pneumatic network;
- experimental determinations in order to validate the mathematical models made;
- analysis of the actual/optimal energy balances obtained and the proposal of innovative solutions regarding the increase of energy efficiency;

1.4. Data collection techniques

For data collection and information processing, the following will be used:

- characteristic parameters existing in the prospectuses of the analyzed installations and data from the literature for similar installations;
- the quantities measured and monitored "in situ" at the systems that are the subject of the case studies;
- verification of energy indicators to establish the opportunity to apply the proposed solutions.

2. THESIS STRUCTURE

The thesis contains of: introduction, five chapters, table of contents and bibliography, presented in 132 pages, 20 tables, 73 figures and 54 bibliographic references.

In **Chapter 1**, entitled “THE USE OF COMPRESSED AIR IN THE MINING INDUSTRY”, according to the current European and global energy context is presented, the role of pneumatic energy in the current energy context, as well as a detailed presentation of the general issues regarding the use of compressed air in the mining industry.

Chapter 2, dealing with the topic “CONCEPTUAL FRAMEWORK OF COMPRESSED AIR PRODUCTION IN THE MINING INDUSTRY”, carries out a detailed analysis of piston compressors, turbochargers and scroll compressors. Their constructive parameters are

highlighted and the main connections, that allow the creation of a mathematical model to calculate their operation, are established.

The content of **Chapter 3**, entitled “POSSIBILITIES OF ENERGY OPTIMIZATION OF MINING PNEUMATIC NETWORKS”, proposes a mathematical model of pneumatic networks, addressing both the part of the algorithm for traversing a pneumatic network in the correct sequence of component elements and the mathematical modeling of discrete elements of pneumatic networks and namely pipes and various local resistances.

Chapter 4,”CASE STUDIES”, is focused on the presentation of case studies carried out in order to validate the developed mathematical models. 5 relevant case studies for this purpose of the thesis are presented: the evaluation of measures capable of increasing the energy efficiency of compressors used in mining; reducing energy consumption and greenhouse gas emissions in oil-injected screw compressors; the power range of the compressors used in the mines of Jiu Valley, development of the energy balance for the INGERSOLL RAND – SSRM 250 LV compressor assembly and the energy balance for the Atlas COPCO G.A. compressor assembly. 250W and benchmarking; calculation of the compressed air network from E.M. LONEA based on a numerical calculation program. There are presented detailed calculation briefs for the calculation of exergetic balances, as well as tables with experimentally determined data necessary to perform the calculations. The results are presented in the form of tables and diagrams, in terms of value and percentage, and detailed analyzes of the real and optimal energy balances are carried out in order to establish measures to increase the energy efficiency of the studied pneumatic equipment.

Based on the analyzes carried out and the results obtained in the previously presented chapters, within **Chapter 5**, “CONCLUSIONS AND PERSONAL CONTRIBUTIONS” are highlighted. This chapter includes the general conclusions, personal theoretical and practical contributions, future opportunities and perspectives, including current performance, solutions to increase performance, future options to ensure the sustainability of the pneumatic energy production and distribution system, and concludes with the limits of the research.

Unique aspects treated in the work:

- the systematization and synthesis of some aspects regarding the production and distribution of compressed air;
- designing numerical calculation programs for pneumatic energy users and for the network;
- comparative presentation of the performance of different compressed air production systems;
- comparison of energy and exergetic performance indicators for different types of compressors made by different companies;
- the presentation of concrete case studies, based on "in situ" determinations.
- realization of real hourly and optimal energy balances based on developed mathematical models;
- detailed analysis of energy-exergetic balances and the proposal of solutions to increase energy efficiency.

3. PERSONAL CONTRIBUTIONS

3.1. Theoretical contributions

- making a synthesis regarding the general problems of using compressed air in the mining industry;
- constructive parameters of the helical compressor were presented;
- comparative analysis of the various possibilities of actuation of different tools, highlighting the advantages and disadvantages of using pneumatic actuation.
- analysis of the share of energy consumption with the production of compressed air within the energy consumption of mining operations, with the highlighting of specific consumptions.
- the creation of mathematical models for the operation of the helical compressor, based on which an energy-exergetic balance can be performed to highlight energy losses.
- creating a mathematical model for calculating the energy-exergetic balance of the pneumatic network.

3.2. Practical contributions

We carried out experimental determinations in order to validate the mathematical model and draw up the energy-exergetic balance for helical compressors and pneumatic networks.

We have carried out two case studies on the operation of the helical compressor in real conditions.

Case studies on reducing energy consumption and greenhouse gas emissions in oil-injected scroll compressors were designed.

Real hourly exergy balances related to KAESER ESD 375 compressors were made; KAESER DSDX 305, the effects of heat recovery in the previously mentioned helical compressors being quantified.

We approached a case study, used to energetically justify the opportunity to replace old compressors, with many hours of operation, with two compressors equipped with heat recuperators and compressed air dryers, being determined: the Carnot factor, the amount of heat given up, the exergy harnessed , useful heat, exergy supplied by the grid, increase in energy use efficiency, annual compressor operating time, annual energy savings, GHG production. The performed calculations have the role of justifying the installation of heat exchangers on compressors in pneumatic systems. Based on the calculations performed, the effects of the introduction of dryers were also quantified.

Synthetic presentation of 11 types of helical compressors operating in the mines of Valea Jiului, for which we made a calculation of the significant energy performances based on our own calculation algorithm, after which we designed 9 distinct graphs that highlight the evaluation of the effects of changing the operating parameters of the compressor.

We performed the energy comparative study of two different types of compressors from different manufacturers;

We performed an analysis regarding the optimal supply scheme for a mine equipped with compressors produced by various manufacturers;

We drew up the energy-exergetic balance of the compressor and performed the analysis of the real and optimal energy balance.

They were highlighted in the tables and visualized in the diagram, the ratio between the significant performances of the compressors:

- the difference between the power accessible to compressed air users (maximum compressed air power) and the power required for air compression (polytropic compression power);
- the difference between the thermal power of the compressed air and the exergetic equivalent available in the recovered heat.

We analyzed the effect of changing different parameters on the performance of the screw compressor.

The proposal of some feasible technical-organizational measures based on the comparative energy analysis of the energy performances of the studied helical compressors.

Realization of a canonical form of a pneumatic network in order to algorithmize the calculations, in order to approach it with the help of a numerical calculation program for the calculation of the total and available mass flow based on the 2 limit situations.

Calculation of energy performance indicators in all characteristic points based on mathematical relationships from specialized literature.

Finding a solution to increase the energy efficiency in the transport of compressed air by feeding the main network through 2 distinct points (well with skip and well aeration Jieţ) related to the 2 compressor stations in order to assimilate the mains, with diameters φ 325 and φ 200, with a collector - distributor, which ensures a constant pressure in the connection points of the distribution network.

4. FUTURE OPPORTUNITIES AND PROSPECTS

The realization of the mathematical model of the helical compressor, its validation allows in the future the calculation of energy-exergy balances for compressors operating in some enterprises from other industrial branches. The conclusions of the energy-exergetic balance allow the extrapolation of the results and the measures required to increase the energy efficiency in the case of other helical compressors operating in various industrial branches.

The creation of the mathematical model of the pneumatic network and its validation through experimental determinations allows the realization of the energy-exergetic balance in a short time, and therefore, in case of unsatisfactory results, the operative identification of the losses and the taking of measures to remedy the situation.

The extrapolation of the results in the case of other types of networks allows taking measures to make compressed air systems more efficient by applying organizational measures based on the experience of other users and synthesized in the thesis.

5. LIMITATIONS OF THE RESEARCH

In conclusion, the proposed research objective was achieved following the application of appropriate methods for evaluating the energy performances of helical compressors.

The quantitative and qualitative analyzes in the paper can be used as a foundation for future research if the following limitations are considered:

- the analyzes were carried out for the types of helical compressors existing in the mining operations in Jiu Valley, a fact that requires experimental determinations to be carried out for other types of compressors as well.
- the need to carry out an analysis for the other components of the pneumatic system in order to further reduce the demand for pneumatic energy, thus achieving important savings in terms of electricity costs.