УДК 621.515.004.82

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# EXERGY ANALYSIS OF WASTE HEAT RECOVERY SYSTEMS OF MINE COMPRESSORS

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# ЕКСЕРГЕТИЧНИЙ АНАЛІЗ СИСТЕМ УТИЛІЗАЦІЇ ТЕПЛА ШАХТНИХ КОМПРЕСОРНИХ УСТАНОВОК

**Purpose**. To determine the most perfect system for mine compressor waste heat recovery regarding its thermodynamic properties and identify the elements where the largest exergy losses occur. Conduct comparative analysis between direct heating, heat pump and cogeneration waste heat recovery systems.

**Methodology**. Mathematical modelling of thermodynamic processes occurring in waste heart recovery systems and mine compressors has been applied. Comparative exergy analysis of the mine compressor with waste heat recovery systems has been performed.

**Findings**. The detailed exergy analysis of direct heating, heat pump and cogeneration waste heat recovery technologies used for the mine compressor waste heat recovery has been made. It has been determined that cogeneration waste heat recovery system operating in heating mode has the highest exergy efficiency.

**Originality**. A detailed exergy analysis of the elements of mine compressors with waste heat recovery systems has been made for the first time. The most exergy efficient mine compressor waste heat recovery system has been determined.

**Practical value**. The diagrams of exergy flows which allow determining exergy losses in each element of the mine compressors with direct heating, heat pump and cogeneration waste heat recovery systems have been designed.

**Keywords**: *mine compressor exergy analysis, heat recovery, heat pump, cogeneration technology*

**Introduction.** Air compressor stations which produce air for mining machinery operation and different technological processes are one of the main energy consumers in coal and iron mines. Therefore, the efficiency of mining greatly depends on the efficient production, transmission and consumption of compressed air. It is known that along with the mechanical work produced, mining air compressors release large amounts of energy in the form of waste heat. In a typical compressor cooling system, all the heat produced as a result of a compressor operation is lost to the environment, not only lowering the energy efficiency but also causing the environmental problems such as global warming and heat pollution. The amount of this heat can reach 90% of the total electrical energy consumed by the compressor. Since during the compressor operation the amount of waste heat produced is almost the same as the total amount of waste heat produced, it is reasonable to try to recover this waste heat for power generation or useful heat production.

Moreover, since a great amount of fossil fuel (basically coal) in Ukrainian mines is burned annually in boilers for heating or hot water supply, any measures for the reduction of fossil fuel consumption could bring economic and environmental benefits, increasing the efficiency of mining. That is why waste heat recovery from compressor stations can increase the efficiency of compressed air production, as well as that of mining overall.

**Analysis of the recent research**. Research in the field of mine compressor waste heat recovery have been conducted by G. P. Gerasymenko, V. A. Murzin, Y. A. Tseitlin, V. A. Boiko, V. B. Skripnikov, teams of scientists in the National Mining University, Institute of Technical Physics of Heat, Institute of Technical Mechanics, Institute of Mine Mechanics named after M. M. Fedorov and other leading scientific research and design institutes.

The following ways of waste heat recovery have been suggested: water heating for hot water and heating system; air heating which is supplied to the mine in cold seasons; generating cold using absorption refrigeration machines, and electric power generation [1, 2].

Waste heat recovery for heat and electrical energy generation is considered the most promising one. To obtain high-grade heat energy, direct heating and heat pump technology are used. For electricity generation cogeneration technology, based on the simultaneous generation of heat and electrical energy is used.

An important advantage of using a heat pump along with the mine compressor is closed cooling water circuit, which ensures the absence of scale formation on the surfaces of the heat exchange tubes and leads to a significant increase of overhaul period and lower repair costs of air coolers.

The temperature of the inlet cooling water greatly influences the cost of compressed air production and affects the operation of the heat pump. However, the nature of this influence is ambiguous. On the one hand, the increase in cooling water inlet temperature leads to increasing COP. On the other hand, when the cooling water inlet temperature increases, the compressed air outlet temperature (as a result compression work) also increases. This results in turbo-compressor performance decrease. Therefore, it is important to determine the temperature mode of cooling water circulation loop at which the efficiency of turbo-compressor heat pump system is the highest.

To get electricity, the cogeneration technology based on simultaneous generation of electrical and heat energy is used.

The atmospheric air is compressed by the turbo-compressor and cooled in the air coolers. In order to increase the temperature potential of the waste heat recovered, and to keep the outlet temperature of compressed air within a required range, the implementation of new types of air coolers is suggested. The new types of proposed air coolers consist of two sections: the first section along the air flow is for waste heat recovery and the second one is for the further cooling of the compressed air to the required temperature. To convert the waste heat into power, the power plant working on ORC is used. There are several advantages of using ORC to recover low grade waste heat, including a smaller size, environmental soundness and great flexibility. The main advantage of the ORC is its superior performance in recovering low temperature waste heat. The ORC has become widely practised for generating power from different heat sources such as geothermal, solar, waste, heat of internal combustion engines and gas turbines [3–5].

**Unsolved aspects of the problem.** In-depth quantitative analysis of waste heat recovery systems based on the heat pump and cogeneration technology as well as the technology of direct heating of the transfer agent has being performed by the scientists of Dnipropetrovsk National Mining University [6–8].

Further research in the field of mine compressor waste heat recovery requires a detailed exergy analysis of each system with the establishment of the value of exergy losses in each element of the system and identifying the elements which have the largest exergy losses.

The **objective** of this study is to conduct a comparative exergy analysis between the direct heating of the mine compressor, heat pump and cogeneration waste heat recovery systems.

**Presentation of the main research.** At a given temperature of the cooling water at the inlet to the compressor air coolers $t_{w1}$ (evaporator outlet of the heat pump), the problem of heat pump and turbo-compressor system operation mode calculation is divided into two independent parts. The first part is the turbo-compressor operation mode calculation and the second one is the heat pump operation mode calculation.

As the initial data, an aerodynamic compressor performance curve and air cooler characteristics are used. To recalculate the compressor performance curve under new temperature conditions (which differ from the rated ones), the mathematical model [8] is used. This model is based on the assumption that the compression work of the uncooled sections remains the same at both rated and actual modes provided the actual gas volumetric flow rate also remains constant. In compliance with this assumption, pressure ratio for an $i$–uncooled section at a given inlet air temperature is expressed as

$$\varepsilon_i = \left[ \frac{T_{in\,r}}{T_{in\,a}} \left( \varepsilon_r^{\frac{k-1}{\eta_i k}} - 1 \right) + 1 \right]^{\frac{\eta_i k}{k-1}},$$

where $T_{in\,r}$ is related absolute inlet air temperature for an $i$-uncooled section; $T_{in\,a}$ is actual absolute inlet air temperature; $\varepsilon_r$ is the rating value of pressure ratio for an $i$-uncooled section; $V_i$ is volumetric flow at the entrance to an $i$-uncooled section; $\eta_i$ is polytropic efficiency of an $i$-uncooled section; $k$ is a polytropic compression exponent.

As a result of the turbo-compressor operation mode calculation, the value of outlet cooling water temperature $t_{w2}$ and heat transferred from the compressed air $Q_x$ are considered to be the initial data for heat pump operation mode calculation.

At the given $Q_x$, $t_{w1}$, $t_{w2}$ and the hot water outlet temperature for hot water supply system, the problem of the heat pump operation mode calculation is to determine the parameters of the thermodynamic cycle as well as electrical power rate consumed by the heat pump motor.

The objective of the operating conditions of the heat pump under the given conditions and water temperature, prepared for the hot water system of the enterprise, is to determine the parameters of the thermodynamic cycle as well as electric power consumed by the drive motor of the compressor of the heat pump.

The calculation of operation mode of the turbo-compressor with cogeneration waste heat recovery system was made on the basis of the modelling of operation mode of the turbo-compressor and power plant with ORC.

A certain challenge is to choose an appropriate organic working fluid which can meet all requirements and constraints imposed on the system. The working fluid should exhibit chemical stability at the operating pressure and temperature, environmental friendliness and low toxicity. In addition, it should be non-corrosive, non-flammable, and non-auto-igniting, as well as having good material compatibility. Another characteristic that must be considered during the selection of the organic working fluid is its shape of the saturated curve. With respect to the slope of the saturated curve in the $T$-$s$ diagram, all organic working fluids are divided into three groups: dry fluids have a positive slope; wet fluids have a negative slope; while isentropic fluids have an infinitely large slope. Basically, dry and isentropic fluids are more preferable, since they do not condense when the fluid goes through the turbine. The aim is to extend turbine blade service life by preventing their damage due to working fluid condensation. Since one of the main objectives of this study is to determine the conditions under which the highest value of power is obtained, it is desirable to choose the working fluid whose critical temperature is slightly higher than the temperature of the upper heat reservoir. In this case, the fluid evaporation enthalpy is minimal, and the working fluid flow rate is maximum, which influences the highest value of power output [9, 10].

In view of the aforesaid, the fluid with positive slope of the saturated curve in the *T-s* diagram is used as a working one. For that working fluid $(dT/ds)_{sat} > 0$, where $dT$ is temperature increment; $ds$ stands for entropy increment.

While modelling the stepped character of the low-boiling working fluid, temperature changes are considered during heating and vapour generation in air coolers as well as corresponding temperature changes of the heating air. The inlet temperature of the heating air is determined on the basis of the modelling of the characteristics and operation modes of the uncooled sections of the turbo-compressor.

It is known that exergy efficiency is the main indicator of thermodynamic perfection of thermal installations and systems

$$\eta_{ex} = \frac{E_{\text{out}}}{E_{\text{in}}}$$

and

$$\eta_{ex} = 1 - \frac{\Delta E}{E_{\text{in}}},$$

where $E_{\text{in}}$, $E_{\text{out}}$ stand for exergy power at the inlet and outlet of the system; $\Delta E$ refers to exergy losses.

Exergy power in any section of the flow is determined as a product of the mass flow rate and specific exergy of the flow in a given section, and is calculated by the formula of Louis-Stodola

$$E = me = m[(i - i_0) + T_0(s_0 - s)],$$

where $i$, $s$ are specific enthalpy and entropy of the flow at the given part of the system; $i_0$, $s_0$ are specific enthalpy and entropy of heat transfer system; $T_0$is absolute temperature of the environment.

Exergy losses in a given element of the system are defined as the difference between inlet and outlet exergy flows. For example, for a given heat exchanger, exergy losses occurring while transferring heat from the heating to the heated medium are determined as

$$\Delta E = m_1(e_a - e_b) - m_2(e_d - e_c),$$

where $e_a$, $e_b$ and $m_1$ are specific exergy of the flow of the heating medium at the inlet and outlet of the element and its mass flow rate; $e_c$, $e_d$ and $m_2$ are specific exergy of the flow of the heated medium at the inlet and outlet of the element and its mass flow rate.

Relative exergy efficiency is defined as the ratio of the exergy losses in each element to the total losses of energy in the system $\sum \Delta E$

$$\eta_{ex}^{r} = \frac{\Delta E}{\sum \Delta E}.$$

The study was conducted for K-250-61-5turbo-compressor, widely used at mining enterprises.

Exergy analysis was performed under the following conditions: air temperature was 15 °C and ambient pressure was 0.1 MPa; final air pressure (absolute) was 0.9 MPa; cooling water pumped temperature was 30 °C; temperature of the water pumped to hot water supply system was given as 45 °C.

The thermodynamic properties of the working fluids were calculated by REFPROP 7.0, developed by the National Institute of Standards and Technology of the United States. The ORC simulation was performed using a simulation program written by the author with MathLab.

In [6–8] the schemas were developed, the analysis were conducted and the main energy indexes for heat pump, cogeneration technology and the technology of the direct heating of the heat transfer agent were determined.

For the compressor with a typical cooling system, as well as with the usage of cogeneration technology and the technology of the direct heating electrical energy consumed by turbo-compressor motor and for heat pump the electrical energy consumed by the compressor of the heat pump was considered as input exergy. The sum of the compressed air exergy at the outlet of the compressor, the electrical energy produced (in case of cogeneration waste heat recovery implementation) and the heat energy produced for heat supply system (in case cogeneration, heat pump and direct heating waste heat recovery systems usage) was considered as output exergy.

**Research results**. The main results of the exergy analysis of the mine compressors with different waste heat recovery systems are shown in Table.

The table shows that exergy efficiency reaches the highest value when the ORC power plant operates in the heating mode. For each waste heat recovery system in-depth exergy analyses for every element of the system was performed and exergy diagrams were designed (Fig. 1–3).

**Conclusion and recommendations for further research.** The diagrams show that both heat pump and cogeneration waste heat recovery systems operating in a heating mode have the highest exergy losses caused by irreversibility of heat exchange processes in the evaporator and condenser.

Based on the exergy analysis it has been shown that cogeneration waste heat recovery system operating in a

*Table*

The results of the exergy analysis of mine compressors

| Cooling system | $E_{\text{in}}$, kW | $E_{\text{out}}$, kW | $\Delta E$, kW | $\eta_{ex}$ |
|---|---|---|---|---|
| Typical | 1447.7 | 933.8 | 513.9 | 0.645 |
| Direct heating | 1447.7 | 985.4 | 462.3 | 0.681 |
| Heat pump | 1752.4 | 1092.6 | 659.8 | 0.624 |
| Cogeneration (heat mode) | 1447.7 | 1032.5 | 415.2 | 0.713 |
| Cogeneration (condenser mode) | 1447.7 | 10212 | 426.5 | 0.705 |

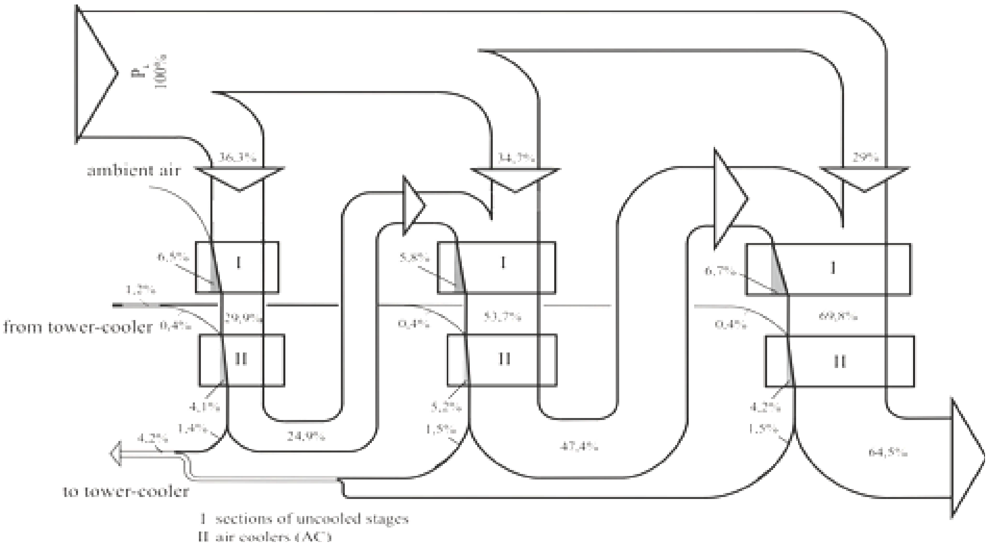


*Fig. 1. Exergy diagram of the compressor with a typical cooling system*

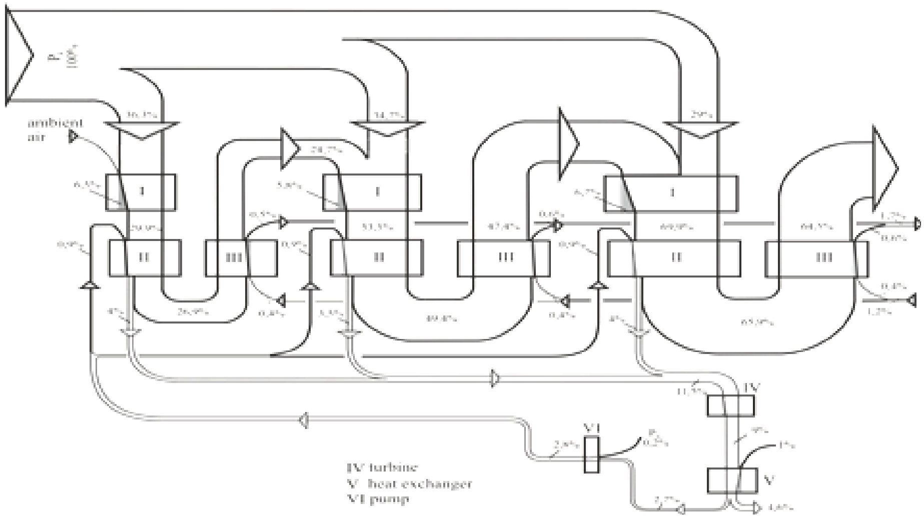


*Fig. 2. Exergy diagram of the cogeneration waste heat recovery system (heating mode)*

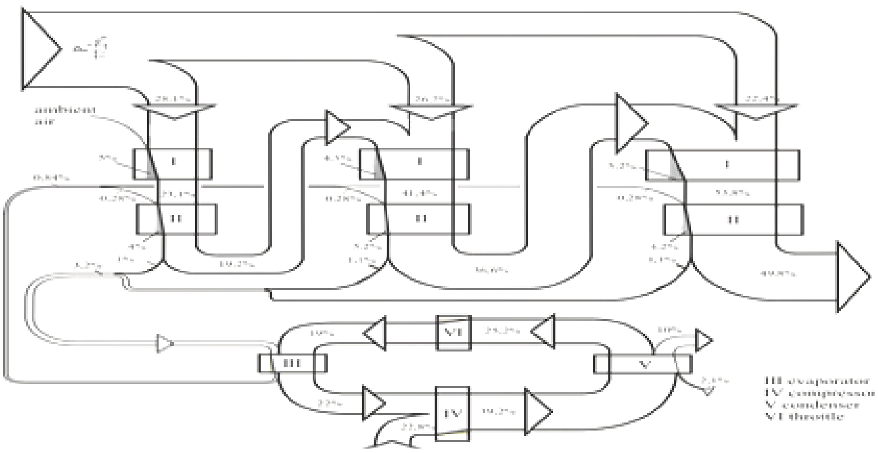


*Fig. 3. Heap pump exergy diagram*

heating mode is the most perfect system of mine turbo-compressor waste heat regarding its thermodynamic properties. It has been shown that in all considered waste heat recovery systems the highest exergy losses occur in heat exchanges.

Another advantage of the cogeneration technology is its flexibility. It makes it possible to generate both heat and electricity according to the mining needs. For instance, in summer time when demand for heat energy is low, the cogeneration waste heat recovery system can work in a power mode. In winter, when demand for heat energy increases, the cogeneration system can run in a eating mode generating mostly heat energy.

To increase the exergy efficiency of heat exchanges of the waste heat recovery systems the additional research is to determine the optimal design and operational parameters of the heat exchanges to be done.

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**Мета.** Визначити найбільш термодинамічно досконалу систему утилізації тепла шахтних компресорних установок і виявити елементи, в яких втрати ексергії найбільші, шляхом проведення порівняльного ексергетичного аналізу теплонасосної, когенераційної технології та технології прямого нагріву.

**Методика.** Математичне моделювання термодинамічних процесів, що протікають у теплоутилізаційних установках і шахтному компресорі при їх спільній роботі. Порівняльний ексергетичний аналіз систем утилізації тепла стиснутого повітря шахтних компресорних установок.

**Результати.** Виконано ексергетичний аналіз теплонасосної, когенераційної технологій утилізації тепла шахтних компресорних установок, а також технології прямого нагріву. Встановлено, що ексергетичний ККД має найбільш високе значення в разі когенераційної утилізації тепла, яке відводиться від стискуваного повітря, при роботі теплосилової установки по теплофікаційному циклу.

**Наукова новизна.** Уперше проведений детальний ексергетичний аналіз елементів систем утилізації тепла шахтних компресорних установок зі встановленням найбільш термодинамічно досконалої технології використання низькопотенціального тепла.

**Практична значимість.** Побудовані діаграми потоків ексергії, що дозволяють визначити втрати ексергії в кожному елементі системи утилізації тепла стиснутого повітря шахтних компресорних установок.

**Ключові слова:** *шахтний компресор, ексергетичний аналіз, утилізація тепла, тепловий насос, когенераційна технологія*

**Цель.** Определить наиболее термодинамически совершенную систему утилизации тепла шахтных компрессорных установок и выявить элементы, в которых потери эксергии наибольшие путем проведения сравнительного эксергетического анализа теплонасосной, когенерационной технологии и технологии прямого нагрева.

**Методика.** Математическое моделирование термодинамических процессов, протекающих в теплоутилизационных установках и шахтном компрессоре при их совместной работе. Сравнительный эксергетический анализ систем утилизации тепла сжатого воздуха шахтных компрессорных установок.

**Результаты.** Выполнен эксергетический анализ теплонасосной, когенерационной технологий утилизации тепла шахтных компрессорных установок, а также технологии прямого нагрева. Установлено, что эксергетический КПД имеет наиболее высокое значение в случае когенерационной утилизации тепла, отводимого от сжимаемого воздуха, при работе теплосиловой установки по теплофикационному циклу.

**Научная новизна.** Впервые произведен детальный эксергетический анализ элементов систем утилизации тепла шахтных компрессорных установок с установлением наиболее термодинамически совершенной технологии использования низкопотенциального тепла.

**Практическая значимость.** Построены диаграммы потоков эксергий, позволяющие определить потери эксергии в каждом элементе системы утилизации тепла сжатого воздуха шахтных компрессорных установок.

**Ключевые слова:** *шахтный компрессор, эксергетический анализ, утилизация тепла, тепловой насос, когенерационная технология*

*Рекомендовано до публікації докт. техн. наук В. І. Самусею. Дата надходження рукопису 21.05.15.*

УДК 622.28 : 624.11

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# GEOMECHANICAL ESTIMATION OF THE EFFECTIVENESS OF SEWER TUNNEL REPAIR BY THE "PIPE IN PIPE" TECHNOLOGY

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# ГЕОМЕХАНІЧНА ОЦІНКА ЕФЕКТИВНОСТІ ВІДНОВЛЮВАНОГО РЕМОНТУ КОЛЕКТОРНИХ ТОНЕЛЕЙ МЕТОДОМ „ТРУБА У ТРУБІ"

**Purpose.** The development of analytical methods for forecasting the stress state of sewer tunnel linings, reconstructed by the "pipe in pipe" technology, including ones in dense urban areas, the use of which allows geomechanical estimation of bearing capacity of the reconstructed facilities in operation in various mining conditions for opening stability to fulfill.

**Methodology.** Obtaining rigorous solutions of the plane elasticity problems using the theory of analytic functions of a complex variable, conformal mapping method, apparatus of analytic continuation of complex potentials that are regular in the half-plane simulating the rock mass through its border, properties of Cauchy type integrals, Faber polynomials and complex series.

**Findings**. A mathematical model of the interaction of a sewer tunnel restored by the "pipe in pipe" technology, with the surrounding rock (soil) mass, as elements of a common deformable system that allows more thoroughly considering the impact of mining and geological conditions, external influences, as well as the basic design parameters of the lining produced due to repairs, on the bearing capacity and strength of the reconstructed underground structure as a whole.

**Originality.** A new approach to evaluating the effectiveness of repairing sewer tunnels, which is based on geomechanical criterion, obtained on a study of the stress state and bearing capacity of three-layer underground construction created by the "pipe in pipe" technology is proposed.

**Practical value**. The development of an algorithm for determining the stress state of shallow collector tunnel linings, restored by the trenchless technology, under the action of various external loads and impacts, as well as while developing a software that enables to make multivariant designs restore sewer tunnel linings, both for research purposes and in practical design.

***Keywords:*** *sewer tunnel, trenchless repair technology, stress state, lining, bearing capacity, design*