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To cite this article: Mykhailo Kirsanov *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1348** 012060

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# The use of secondary heat resources during the accumulation of compressed air in closed mining workings

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**Abstract.** The article considers the possibility of energy accumulation in mining workings in order to reduce the consumption of fossil organic fuel by the mining enterprise itself. For this purpose, the authors propose to accumulate compressed air in closed mine workings using secondary heat resources to generate additional electricity. The energy management of mining enterprises can be equipped with freon steam turbines which implement the Rankine thermodynamic cycle to obtain additional electricity from secondary heat. To measure the efficiency of the process, the air must be compressed isothermally. The compression must be carried out in several stages, and the air must be cooled after each stage. Taking into account the development of energy storage technologies in the form of compressed air in specially prepared closed mining workings, the required air pressure can be from 70 to 90 at. The article assesses the possibility of using a secondary heat resource during air compression at mining enterprises. It is shown that the use of freon steam turbines during the accumulation of compressed air in underground pressure accumulators increases the subsequent production of electricity during the operation of the air turbine by 7.6% during the day.

## 1. Introduction

Over the past decade and a half, a notable trend has emerged within the mining industry, engineering sector, and energy domain. These industries rely on equipment and raw materials sourced from preceding stages of production and processing, and they exhibit substantial reliance on organic fossil fuels. In addition, restrictions on the consumption of fossil fuels are becoming increasingly stringent, and more attention is paid to the harmful environmental impact of their use [1]. Within the mining industry, the dual role of both producing and consuming organic fuel is evident. Consequently, a practical task arises to explore technological advancements and engineer equipment specifically aimed at decreasing the industry's organic fuel consumption. This task can be solved by using secondary energy resources more efficiently.

Secondary energy resources are formed as a by-product of mining and processing technologies [2]. In the mining industry, a substantial amount of secondary energy resources is available in the form of secondary heat resources, which can be used to generate additional electricity due to their useful processing. There are various ways of using secondary heat resources. In mining enterprises, these heat resources are mainly related to mine water, ventilation air, the heat of the rock in the middle of a



wasted bank or in the dump of the coal enrichment process, and the heat of the compressed air of the mine pneumatic systems [3-7].

One of the ways of using secondary heat resources is to process them in heat pumps into the heat of a higher temperature potential for the needs of the mining enterprise itself or the surrounding areas. However, the amount of heating and cooling needs is seasonal. In addition, the operation of the heat pumps to increase the temperature potential of secondary heat resources requires electricity consumption. These costs can be significant if large volumes of secondary heat resources are used. Therefore, it is appropriate to use technical solutions for the generation of additional electrical energy at the expense of secondary heat resources produced at mining enterprises [8].

In addition to heat pumps, there is another way to increase the efficiency of the mining enterprise's energy complex at the expense of secondary heat sources. It is to include in its composition of the equipment, which carries out gas dynamic and heat exchange processes in gas turbines to implement the Rankine thermodynamic cycle [9-11] with additional generation of electric energy. The main advantage of the Rankine thermodynamic cycle with a working substance from the class of freons is the possibility of its application for the use of secondary heat of various parameters and under different conditions due to the selection of the appropriate freon [12].

The amount of secondary heat resources related to the heat of compressed air of mine pneumatic systems is quite significant. Here, it is necessary to consider the systems of electrical energy accumulation through compressed air accumulation in closed mining workings [13]. At mining enterprises, electric and pneumatic energy are used for the extraction of minerals, for the production of which an electric drive is required. Today, the operation of electric machines has a fairly high level of perfection, but it still has reserves for increasing efficiency. In most enterprises of the mining industry of Ukraine, piston, centrifugal and screw compressors are used for the production of pneumatic energy [14]. In the process of compression, the air heats up. Therefore, the process should be carried out isothermally to increase the efficiency when compressing air. For this purpose, air compression should be done in several stages, and the air should be cooled after each compression stage. The required compressed air pressure varies in a wide range. If we take into account the recent development of the technology of accumulating electrical energy in the form of compressed air in specially prepared closed mine workings [14], in this case, the required pressure in the underground gas accumulator (pa) is 70-90 technical atmosphere (at).

The research aims to evaluate the possible potential of a secondary heat resource during air compression at mining enterprises.

## 2. Methods

To achieve the set research purpose, methods of analysis and generalization of the results of known theoretical and experimental studies, mathematical modelling based on the fundamental laws of mechanics and thermodynamics were used. A proven algorithm for solving a system of nonlinear algebraic equations was used.

To use the heating value of compressed air and estimate the value of this secondary energy resource, we assume a three-stage compression based on the required pressure level. We focus on the average pressure value of 80 at, which is equal to 7.85 MPa. Then, according to the principles [14] of choosing rational values of the compression stage by the number of stages, the compression value relative to the atmospheric pressure  $p_0$  of air for one stage is determined by the equation

$$\varepsilon_1 = k \sqrt{\frac{p_a}{p_0}} = 4.263. \quad (1)$$

where  $k$  is the number of compression stages.

Air compression with heat extraction is a polytropic process. In order to compile a table of air heating by compression stages and estimate the quantity of secondary heat, which can then be used then to vaporise the working substance before feeding it to the gas turbine for additional electricity

generation, it is necessary to calculate the parameters of the polytropic process for each compression stage of the defined three-stage process.

For the first stage of compression, we determine:

- the specific technical work per 1 kg of air

$$L_{c1}(n_1) = \left( \frac{n_1}{n_1 - 1} \right) \cdot R_{\mu a} \cdot T_0 \cdot \left( \varepsilon_1^{\frac{n_1-1}{n_1}} - 1 \right), \quad (2)$$

where  $n_1$  is the index of the polytropic process at the first stage of air compression,  $R_{\mu a} = 286.9 \text{ J/(kg}\cdot\text{K)}$  is the gas air constant:

$$R_{\mu a} = \frac{R_{gu}}{\mu_a}, \quad (3)$$

where  $R_{gu} = 8.314 \text{ J/(mol}\cdot\text{K)}$  is the universal gas constant,  $\mu_a = 0.029 \text{ kg/mol}$  is the molecular weight of air,  $T_0$  is the initial temperature of atmospheric air, K;

- air temperature after compression

$$T_1 = T_0 \cdot \left( \varepsilon_1^{\frac{n_1-1}{n_1}} \right); \quad (4)$$

- the index  $n_1$  of the polytropic process for the first stage of air compression based on the first law of thermodynamics

$$C_{v,a} \cdot \left( \frac{n_1 - \gamma_a}{n_1 - 1} \right) \cdot (T_1 - T_0) = (-0.41) \cdot L_{c1}(n_1), \quad (5)$$

where  $C_{v,a}$  is the heat capacity of air at constant volume,  $\text{J/(kg}\cdot\text{K)}$ ,  $\gamma_a = 1.4$  is the index of the isentropic process for air.

In equation (5), it was assumed that the cooling heat of the compression stage of the compressor is 41 per cent of the specific technical work  $L_{c1}$  according to equation (2). The first term in the fraction numerator in (5) corresponds to the heat received in the heat exchanger from the compressed air heated after the compressor and transferred to the vaporization of the working substance for the gas turbine. Thus, equations (2), (4), and (5) form a system of algebraic equations for calculating the specific technical work  $L_{c1}$  of the compressor, the temperature  $T_1$  of the air after the first stage of compression and the index  $n_1$  of the polytropic process for this stage of compression.

Since the value of  $\varepsilon_1$  for one degree of compression is set by equation (1), the value of the index  $n_1$  of the polytropic compression process depends on the percentage of cooling heat of the compression stage of the compressor from its specific technical work  $L_{c1}$ . From the solution of system (2) – (5), we find the parameters  $L_{c1}$ ,  $T_1$ ,  $n_1$  [10]. For the second stage of compression, we write the same equations (2) – (5) considering the stage number's designations.

The specific technical work of the second stage:

$$L_{c2}(n_2) = \left( \frac{n_2}{n_2 - 1} \right) \cdot R_{\mu a} \cdot (T_0 + 3) \cdot \left( \varepsilon_1^{\frac{n_2-1}{n_2}} - 1 \right), \quad (6)$$

where  $n_2$  is the index of the polytropic process at the second stage of air compression.

Air temperature  $T_2$  after the second stage of compression

$$T_2 = (T_0 + 3) \cdot \left( \varepsilon_1^{\frac{n_2-1}{n_2}} \right). \quad (7)$$

The index  $n_2$  of the polytropic process for the second stage of air compression based on the first law of thermodynamics:

$$C_{v,a} \cdot \left( \frac{n_2 - \gamma_a}{n_2 - 1} \right) \cdot (T_2 - T_0 + 3) = (-0.415) \cdot L_{c2}(n_2), \quad (8)$$

where "0.415" is the coefficient of heat utilization of the specific technical work of compression of the stage.

The temperature difference is necessary for effective heat exchange. Therefore, in the equations for the second degree of compression, it was assumed that the initial temperature would be 3° higher than  $T_0$ . Equations (6) - (8) form a system of algebraic equations for calculating the specific technical work  $L_{c2}$  of the compressor, the temperature  $T_2$  of the air after the second compression stage and the index  $n_2$  of the polytropic process for this compression stage. Since in equations (6) - (8), the initial temperature before the second stage of air compression has changed,  $n_2$  is slightly different from  $n_1$  for the first compression stage.

For the third stage of compression, we do not give the equations because they coincide with equations (6) - (8), considering the designations of the degree number. However, the coefficient of heat utilization of specific technical work of the third compression stage has to be equal to "0.43". In the equations for the third stage of compression, it is also assumed that the initial temperature for the third stage is also 3° higher than  $T_0$ .

If the three-stage air compression process is carried out in a closed mine working at night for 8 hours, it is necessary to determine the volume of this underground battery based on the available capacity of secondary (or renewable) energy sources. We estimate the value of this capacity at 9 MW. When choosing this value, we assume that the wind energy park of the mining enterprise can contain 18 wind electric generators, each with a minimum industrial capacity of 500 kW. When filling a closed mine working, the pressure change is more significant than the critical one most of the time because the required filling pressure is 90 at.

Thus, the speed of air in the pipeline is equal to the local speed of sound. For air supply  $G_a$  (kg/s), we can use the well-known equation [14] for filling the capacity in the critical mode

$$G_a = 0.685 \cdot \left( \frac{\pi \cdot d^2}{4} \right) \cdot \left( \frac{p_a}{\sqrt{R_{\mu a} \cdot T_0}} \right), \quad (9)$$

where  $d$  is the inner diameter of the supply pipeline, m;  $p_a$  – filling pressure of the mine working, Pa.

We find the required volume of closed mining working based on the available capacity resource for accumulation. When air is supplied according to (9) at night for 8 hours, the mass of air accumulated in the closed mining working (kg) is:

$$M_a = G_a \cdot 8 \cdot 3600. \quad (10)$$

Then, follow the equation of state of air as a thermodynamic substance,

$$p_a \cdot V_a = M_a \cdot R_{\mu a} \cdot T_0, \quad (11)$$

we determine the required volume  $V_a$  of mining working:

$$V_a = 8.354 \cdot 10^4 \cdot \pi \cdot d^2 \cdot \sqrt{T_0}. \quad (12)$$

To equations (4) and (7), we need to add another condition related to the available  $N_a$  capacity of secondary (or renewable) energy sources. The value of this power should be equated to the total electrical power of three-stage air compression when it is pumped into the mine working

$$N_a = G_a \cdot \eta_c \cdot (L_{c1} + L_{c2} + L_{c3}), \quad (13)$$

where  $\eta_c$  is the efficiency of compressors, determined according to the type of compressor and their passport data.

To find a solution to the given systems of equations, a proven algorithm for solving a system of nonlinear algebraic equations was used [15].

### 3. Results and discussion

After solving the system of equations (6) – (8), we find the parameters  $L_{c2}$ ,  $T_2$ ,  $n_2$ . The system of equations for the third stage coincides with (6) – (8). By solving the equations of the system for the third stage using Newton's method [15], we find the relevant values of  $L_{c3}$ ,  $T_3$  and  $n_3$ . The solution of system (9), (12), and (13), which is obtained by the same method, gives us the air supply  $G_a$ , the required volume of mining working and the diameter of the air supply pipeline, according to the available capacity of secondary energy sources.

Thus, a system of equations has been formed for determining the parameters of the secondary heat resource during three-stage air compression, as well as a system of equations for finding the air supply  $G_a$ , the required volume  $V_a$  of the mining working and the diameter  $d$  of the pipeline in accordance with the available capacity of secondary energy sources.

To carry out specific calculations, we estimated the value of the power of secondary resources of the mining enterprise at 9 MW. The solution of the systems of equations was found using Newton's method for solving systems of nonlinear equations [14]. The parameters of the polytropic three-stage compression process and other thermophysical parameters of the process were found. The results of the calculations are presented in the table 1.

**Table 1.** Parameters of three-stage air compression.

Number of compression stage	Pressure, MPa	Initial temperature, °C	Temperature after compression, °C	Index of the polytropic process
1	0.432	20	101	1.203
2	1.841	23	104	1.201
3	7.848	23	102	1.194

Usually, the index of the polytropic process for cooling compressors is in the range of 1.17-1.2. When solving equations (9) - (13), the volume of the underground compressed air accumulator was 5336 m<sup>3</sup>, and the diameter of the pipe supplying the compressed air was 34 mm. The supply of compressed air to the underground battery and its consumption  $G_a$  through compression stages of compressors was determined by the diameter of the supply pipe (34 mm). According to expression (9), the air consumption was 17.31 kg/s.

When compressed air is cooled sequentially through three compression stages, it can be obtained heat (from 1 kg of air):

$$q_1 = C_{pa} \cdot (T_1 - T_0) + 0.41 \cdot L_{c1}, \quad (14)$$

where  $C_{pa}$  is the heat capacity of air at constant pressure, J/(kg·K).

$$q_2 = C_{pa} \cdot (T_2 - T_0 + 3) + 0.415 \cdot L_{c2}, \quad (15)$$

$$q_3 = C_{pa} \cdot (T_3 - T_0 + 3) + 0.43 \cdot L_{c3}. \quad (16)$$

The cooling heat per 1 kg of compressed air after the compression stage consists of the cooling heat of the compressor and the air after the stage to the initial temperatures in accordance with table 1. The heat (14) - (16) of 1 kg of compressed air at its flow rate  $G_a$ , which is 27.05 kg/s according to our calculations, forms the heat output is

$$N_{tc} = G_a \cdot (q_1 + q_2 + q_3) \quad (17)$$

and has a value of 7.2 MW.

Due to this thermal power, it is possible to organize the evaporation of working substances that have a low value of global warming potential in accordance with modern international requirements for the use of the vapour of these working substances in heat exchange and gas dynamic processes in gas turbines for additional electricity generation.

#### 4. Conclusions

Accumulation of compressed air in closed mines at the expense of secondary heat resources with subsequent activation of air pressure for the production of additional electrical energy increases the efficiency of mining enterprises. In order to generate additional electricity at the expense of secondary heat, it is proposed to include freon steam turbines implementing the Rankine thermodynamic cycle in the energy complex of mining enterprises.

The analysis of the results of the research on the use of the heat of air compression showed that the use of freon steam turbines in the accumulation of compressed air in underground pressure accumulators increases by 7.6% the subsequent generation of electricity during the day during the operation of the air turbine.

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