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Functioning Efficiency of the Central Air-Conditioning System on the Selected Example

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INTRODUCTION

Exploitation in Polish mines is associated with many natural and technical hazards (Maurya et al., 2015, pp. 491-498; Szlązak, Obracaj, Borowski, 2005, pp. 243-256). While planning the opening of a new deposit, it is necessary to identify levels of natural hazards and to include them in the fundamental considerations for the conceptual design of extraction (Rozporządzenia Ministra Energii z dnia 23 listopada 2016 r.). Recognising and combating them requires the use of both modern techniques, technologies, equipment and machines, as well as good knowledge and skills combined with an ability to apply it effectively. The increasing depth of exploitation contributes to the increase in the scale of natural hazards. Along with the rise of depth, the amount of methane released into the workings and the temperature of the virgin rock increases, which in turn causes the climate conditions to deteriorate further and the endogenous fire hazard to aggravate (Obracaj, Borowski, 2005, pp. 243-256; Millar, Trapani, Romero., 2016, pp. 721-727; McPherson, 2012, p. 491; Hartman et al, 1997, p. 583).

Exploitation in Polish hard coal mines is carried out at increasing depths, which is associated with deterioration of climatic conditions in underground excavations. Currently, extraction takes place at an average depth of 800 m above sea level (Szlązak, Obracaj, Głuch, 2013, pp. 117-128,). In many mines, the level of extraction reaches below 1000 m (Szlązak, Obracaj, Głuch, 2013, pp. 117-128, Szlązak, Obracaj, Borowski, 2008a, pp. 497-510).The depth of exploitation increases year by year. Co-occurrence of natural hazards may contribute to reducing the safety of conducted works. For this reason, designing and implementing preventive measures becomes of paramount importance. That is why an extensive scientific research is needed to control existing natural hazards.

Ensuring adequate thermal comfort for crews working in mining excavations at great depths requires the use of a properly designed air conditioning system (Szlązak et al. 2009, pp. 253-262, Szlązak, Obracaj, 2017, pp.19-36). It should

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ensure the maximum efficiency of the use of cooling power in mining excavations. The purpose of this article is to illustrate the factors affecting the reduction of air-conditioning system efficiency on a selected example and indicate the possibilities of its improvement. The publication presents the research on the impact of the depth of exploitation and the increase in the virgin temperature of the rock mass on the cooling power needed to ensure appropriate working conditions. Also, the efficiency of an air-conditioning system has been evaluated in a study focused on a selected example.

FACTORS AFFECTING CLIMATIC CONDITIONS

The increase in the depth of exploitation is associated with an increase in the virgin temperature of the rock mass. Figure 1 presents changes in the virgin temperature of the rock mass in the mines of the Upper Silesian Coal Basin. The results presented in the graph show that in some mines the virgin temperature of the rock mass exceeds 50°C.

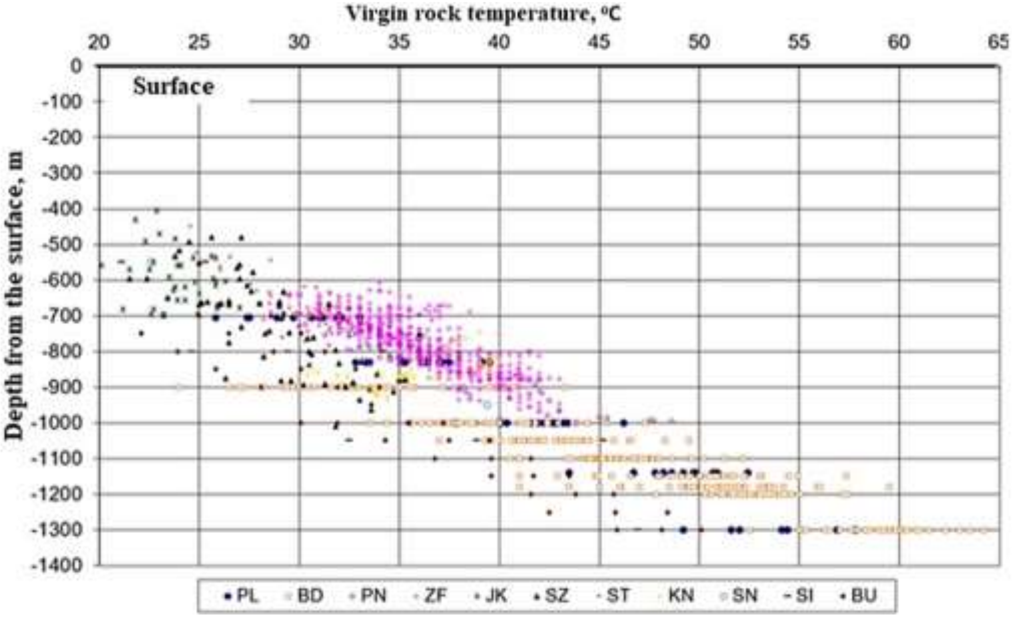

Fig. 1 Changes in the virgin temperature of the rock-mass related to depth in Polish mines

Source: (Szlązak, Obracaj, Swolkień 2018a, pp. 203)

The heat flux is transferred from the exposed rocks through convection, moisture evaporation and radiation (Szlązak, Obracaj, Swolkień 2018a, pp. 203, 2018b, pp. 1-5).

In addition to the virgin temperature of the rock mass, climate conditions in excavations are influenced by the following factors (Rozporządzeniu Ministra Środowiska z 1 lipca 2017 roku w sprawie zagrożeń naturalnych w zakładach górniczych):

- machinery and electromechanical devices installed in the excavations,
- air temperature entering the excavations,
- the time during which the excavation is ventilated,
- the transported output,

- rock oxidation (the thermophysical properties of the oxidising rocks),
- pipelines transporting various media,
- vapours of water present in the excavation,
- changes in the pressure of air passing through excavations.

The state of climatic hazard is also affected by proper planning of underground workings, rational ventilation of workings and organisation of the technological process, and above all, the transport of the mined coal and location of electrical equipment.

High temperature and humidity lead to deteriorating of climatic conditions, which may cause a decrease in such functions of the human body as the ability to perceive, concentrate, attention, and perceptiveness. This detrimental effect of temperature and humidity on the human system is referred to as climate hazard. Therefore, problems related to the design of ventilation and air conditioning of excavations in underground mines are becoming more and more significant. Shortly, further deterioration of climatic conditions in Polish mines should be expected as a result of increased concentration of extraction and reaching deeper levels (Szlązak, Obracaj, Swolkień 2018a, pp. 203).

In 2018, conditions in Polish hard coal mines were so harsh as to justify reducing the daily working hours (WUG, 2018, pp.1-57). The estimated number of employees employed in these excavations during the day was about 8000 (WUG, 2018, pp. 1-57).The improvement of climatic conditions in the most endangered mines is associated with the increasing use of refrigeration equipment. In 2018, central air-conditioning was used in 3 hard coal mines (moves), and group air-conditioning in 7 (WUG, 2018, pp. 1-57). At the end of 2018, approximately 268 cooling devices installed in split, grouped or centralised air-conditioning systems were operating in hard coal mines (WUG, 2018, pp. 1-57).

In copper ore mines (including excavations made in rock salt) in 2018, values of temperature exceeding the norm were recorded in 146 excavations and areas where 6,500 employees were employed (WUG, 2018, pp. 1-57).The central air-conditioning system was used in two copper ore mines.

In 2018 (WUG, 2018, pp. 1-57):

- 159 self-propelled mining machines with air-conditioning worked in Lubin Mining Plant, including:
  - 56 units closed operator cab equipped with air conditioning,
  - 103 units air-conditioned by supplying cooling air (to an open cabin)
- 298 self-propelled mining machines with air conditioning worked at the Rudna Mining Plant, including:
  - 227 units with a closed operator cab equipped with air conditioning,
  - 71 units air-conditioned by supplying cooling air (to an open cabin).
- 243 self-propelled mining machines with air conditioning worked in Polkowice-Sieroszowice Mining Plant, including:
  - 206 units with a closed operator cab equipped with air conditioning,
  - 37 units air-conditioned by supplying cooling air (to an open cabin).

ASSESSMENT OF THE EFFECTIVENESS OF THE AIR CONDITIONING SYSTEM

The central air conditioning system

A centralised air-conditioning system consists of low-pressure and high-pressure water circuits combined with a pressure regulator and high-pressure heat exchangers installed at the bottom of the mine. In centralised air-conditioning systems, water-cooling units are used to cool water that functions as the cooling medium provided to underground workings (Szlązak, Obracaj, Swolkień, 2018a, pp. 1-203; Vosloo, Liebenberg, Velleman, 2012, pp. 328-335; Guo et al, 2015, pp. 649-654, Whillier, 1980, pp. 341-345;Ramsden, Branch, Willson, 2007, pp. 92-98). The *low-pressure circuit* is a pipeline network that distributes water to water coolers. Considering the large area covered by workings in an underground plant, the total length of pipelines can reach several dozens of kilometres. For technological reasons, air coolers in an underground mine are placed at various depths. The water pressure in the *low-pressure circuit* can reach 4 MPa. Figure 2 presents a diagram of the central air conditioning operation.

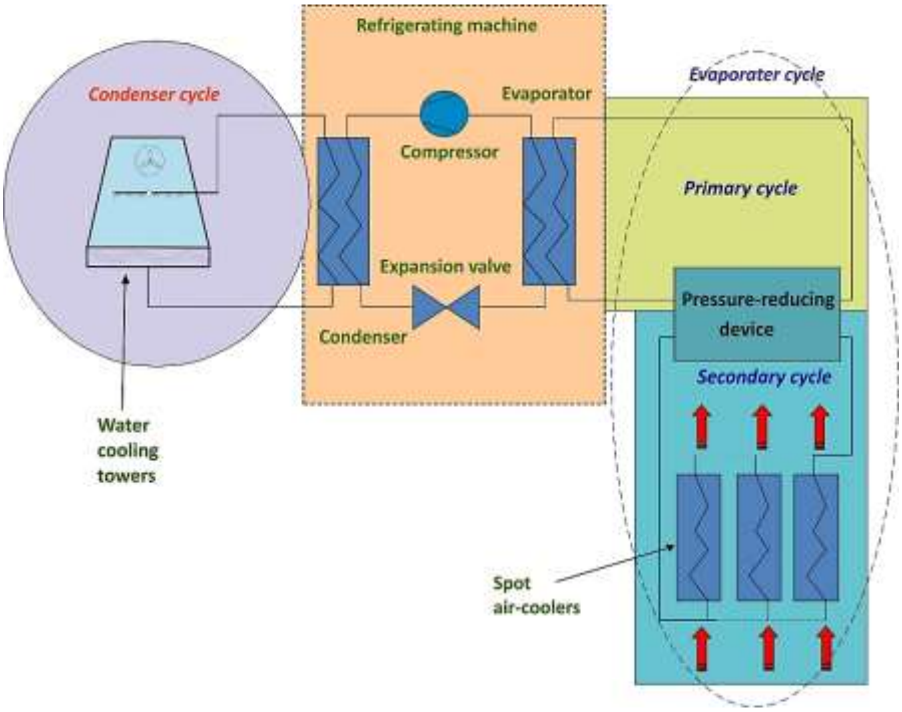

Fig. 2 The functioning scheme of a centralised air-conditioning system
Source: (Szlązak, Obracaj, Swolkień, 2018b, pp. 1-5)

Coolers are deployed in underground workings linked to particular exploitation areas and opening areas. In an underground mine, the number of areas can vary. Also, individual areas are characterised by the changeable cooling load, which makes it necessary to relocate coolers as workings become shorter or new ones are opened.

The pipeline network supplying cooling water is also subject to constant modifications as new pipelines branch off the central line. In turn, these modifications mean that the distribution of water needs to be regulated at all times.

The cooling devices used in mining plants are based on the following components:

- compressor cooling units, driven by electricity
- absorption cooling units, driven by heat energy.

Electric power supplied to a compressor cooling unit is highly efficient, while the heat converted in the boilers of cooling absorption units is waste energy characterised by low efficiency. Considering a large amount of (inefficient) energy needed to generate cooling power, the inclusion of absorption units in an air-conditioning system can be advantageous only when 'free' (low-cost) waste energy of low quality is available.

THE METHODOLOGY OF THE MEASUREMENTS

To evaluate the efficiency of an air-conditioning system, a study was carried out into the functioning of the air-conditioning system in a selected hard coal mine. The study consisted of determining the balance of heat exchange in air coolers and the other components of the mine air-conditioning system. To do so, it was necessary to find out the parameters of the ice water passing through the pipeline network and the parameters of the cooling units.

The research objective outlined above was attained by carrying out the following procedures:

- ➢ measuring the cooling power provided by the central air-conditioning station on the surface
- ➢ measuring the heat flux absorbed in air coolers
- ➢ measuring the water flow rate and evaluating the condition of the pipeline network carrying chilled water
- ➢ evaluating the condition of the installation
- ➢ identifying possible improvements in the functioning of the air-conditioning system.

The heat exchange in membrane coolers is linked to the enthalpy balance of the media passing along both sides of the membrane, the media being the mine air and the cooling liquid. The function of the cooling liquid is performed by ice water supplied and returning via a network of pipelines. The efficiency of this process depends on the parameters of air and ice water at the inlet to the cooler.

Calculating the heat balance of the air coolers and determining the enthalpy had to be preceded by measurements of temperature and air humidity at the inlet and outlet sides of the cooler, and by measurement of volumetric water flow rate (Szlazak, Borowski, Obracaj, 2008a, pp. 497-510, 2008b, pp. 86-96).

To evaluate the efficiency of air cooling, the following values were measured:

- ➢ air temperature as measured by dry-bulb and wet-bulb thermometers at the inlet to the cooler fan
- ➢ air temperature as measured by dry-bulb and wet-bulb thermometers at the outlet of the cooler fan
- ➢ air temperature as measured by dry-bulb and wet-bulb thermometers

between the outlet of the fan and the inlet to the cooler

- average air velocity measured at the cross-section of the outlet of the air cooler and the inlet to the cooler fan
- supply and return temperature of ice water (supplied to and returning from the cooler or a cooling device of immediate application)
- the atmospheric pressure of air in the place where the cooler is installed.

Also, measurements of water flow rate were conducted, and the condition of the pipeline network carrying ice water and cooling water was evaluated, as well as the condition of the system. The study involved coolers with a rated power of 35, 300, 350, 400 kW and units comprising coolers with a power of 200 kW. A diagram of the centralised air-conditioning system in which the measurements were taken is presented in Figure 3.

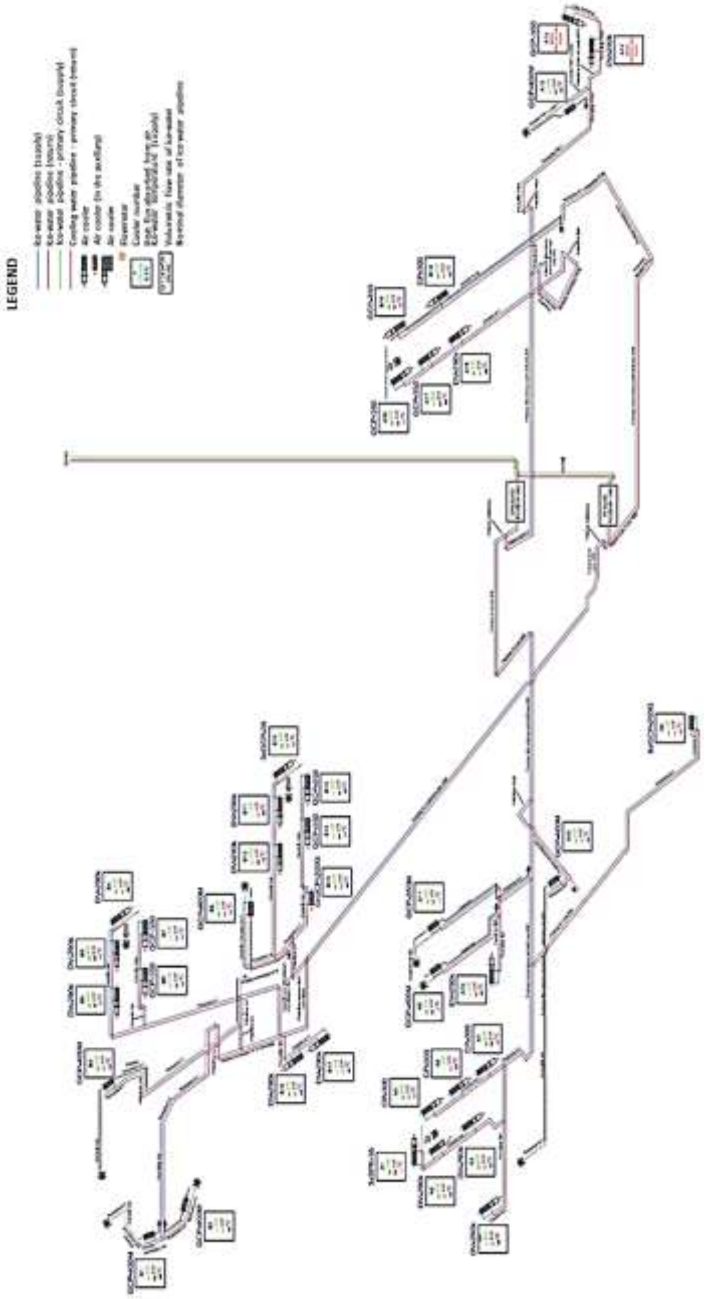

Fig. 3 Diagram of the air-conditioning system

Authors describe the methodology applied in the study in paper Szlązak et al., 2018b (Szlązak, Obracaj, Swolkień, 2018b, pp. 1-5).

RESULTS OF THE CALCULATIONS AND DISCUSSION

Figures 4 and 5 present changes in the chilled water temperature in the secondary circuit recorded in the air-conditioning chambers at level 853 and level 1000.

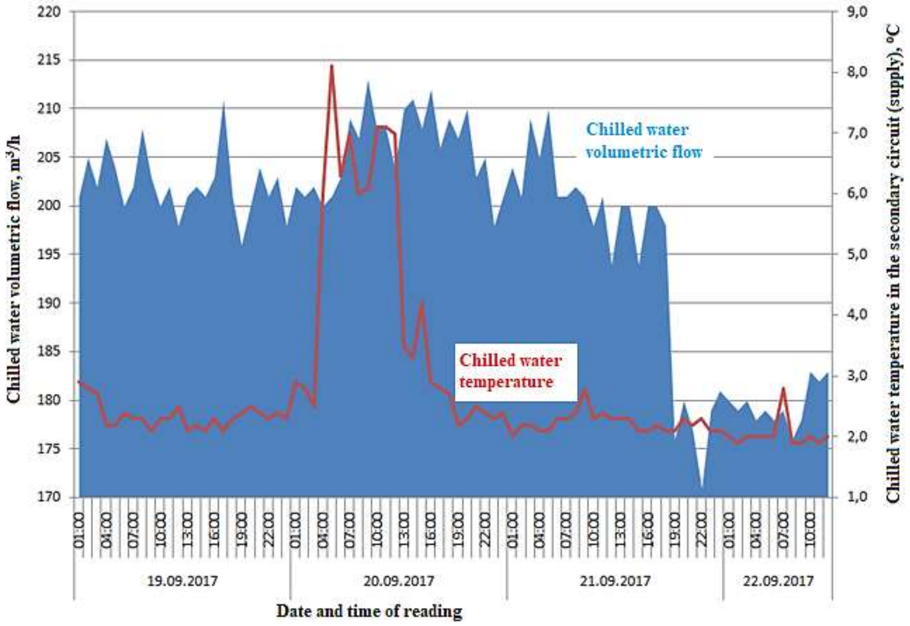

Fig. 4 Chilled water volumetric flow in the secondary circuit at 853

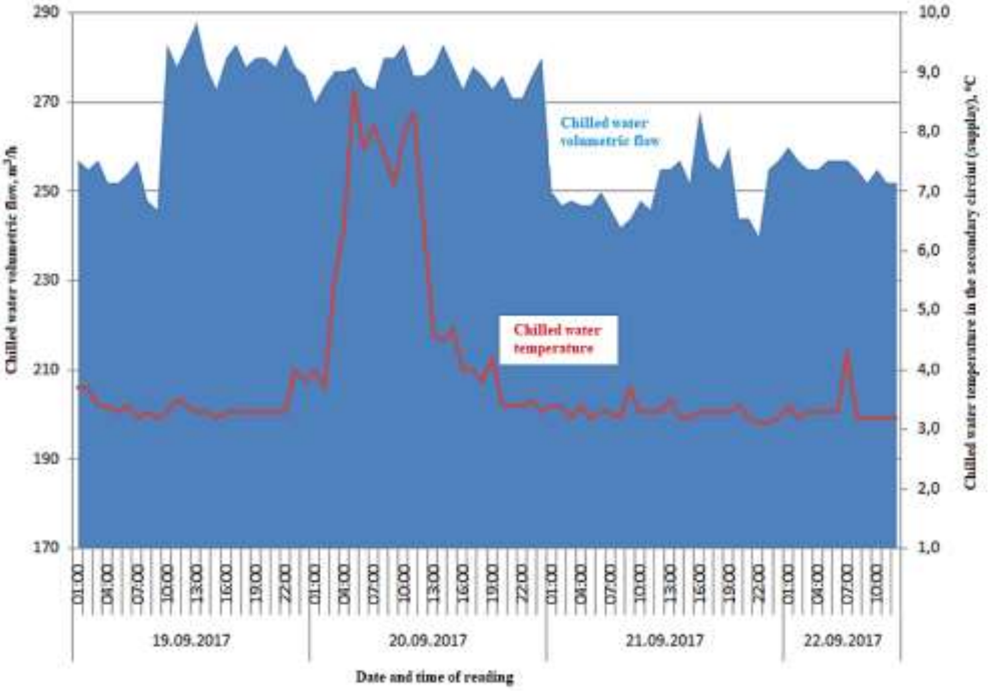

Fig. 5 Chilled water flow in the secondary circuit at 1000

According to the results of readings from measuring devices installed in the central air-conditioning system, during the audit the flow of chilled water in the installation was (readings results during the failure of the compressors in the surface air conditioning station were rejected):

- at the level of 830 from 171 m^3/h to 212 m^3/h (chart in Figure 4.29-196 m^3/h on average),
- at the level of 1000 from 240 m^3/h to 288 m^3/h (chart in Figure 4.30-263 m^3/h on average).

According to the readings of the mine measuring apparatus, the temperature at the entrance to the DRKA-200 chamber (level 853) ranged from 1.9°C to 4.2°C (average 2.3°C). The temperature of the return water to the surface ranged from 12.8°C to 16.0°C (average 13.4°C).

In the air-conditioning chamber at 1000 level, the supply and return water temperatures are recorded according to two meters. According to the readings of the mine measuring apparatus, the temperature at the entrance to the PES-250 chamber (level 1000) ranged from 3.1°C to 5.5°C (average 3.0°C). The temperature of the return water to the surface ranged from 13.1°C to 15.8°C (average 14.0°C). According to the readings of the mine measuring apparatus, the temperature at the outlet of the DRKA-250 chamber (level 1000) ranged from 4.5°C to 6.7°C (average 5.0°C). The return water temperature ranged from 12.2°C to 15.8°C (average 14.0°C).

In consideration of the results presented above, tests on the operation of all coolers connected to the system were carried out. The calculated values of cooling power in the primary circuit of the centralised air-conditioning system on the surface are presented in Table 1, and their distribution is presented in Figure 6. The balance of cooling power in mining workings is presented in Figure 7.

Table 1 Calculated values of cooling power in the primary circuit of the centralised air-conditioning system

Measurement day	Water flow rate, m^3/h	Supply temperature of the water, °C	Return temperature of the water, °C	Cooling power, kW
1 as of 8:15 am	559	2.7	14.2	7500
2 as of 11:05 am	580	2.6	13.2	7160

The calculated maximum total power amounted to 7.5 MW, whereas its degree of utilisation in the workings was below 50% at η = 0.472%.

The study in the air-conditioning system (Fig. 3) has provided evidence that the implementation of air-conditioning systems in mines does not prevent air temperature from exceeding the permitted level of 28°C as measured with a dry-bulb thermometer. Figures 6 to 8 present the results obtained during the study, of the relationship between the cooling power generated by the coolers and 1) the air temperature in the place of installation, 2) the flow rate of water supplied to the cooler, and 3) temperature of water supplied to the cooler. In the diagrams, the areas corresponding to the required parameters of water and air are shaded blue. For the required cooling power to be achieved, both water and air parameters at the inlet have to be within the marked areas.

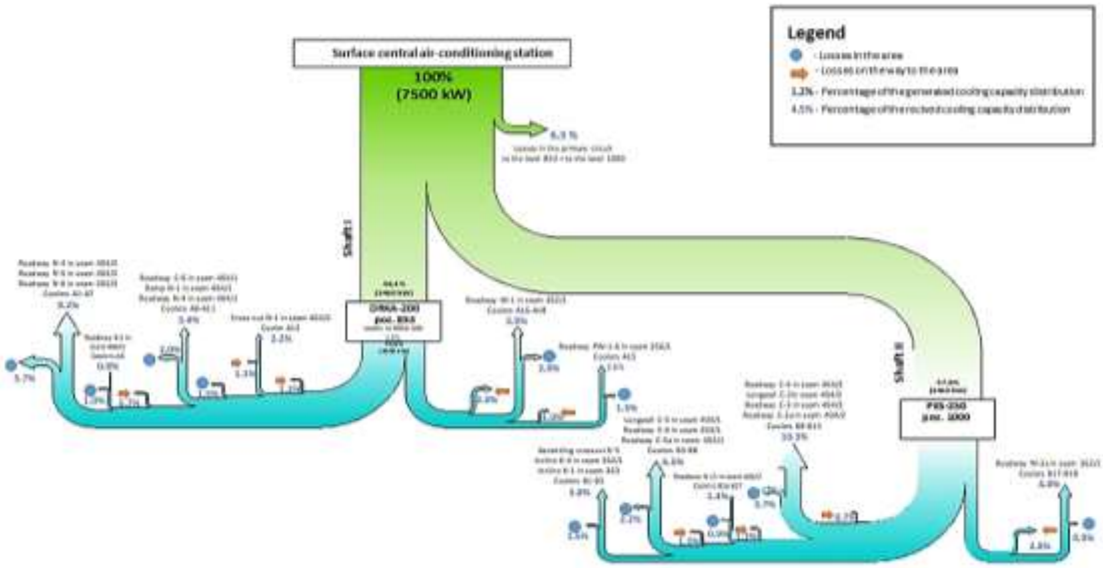

Fig. 6 Sankey diagram of the distribution of cooling power in the centralised air-conditioning system under analysis

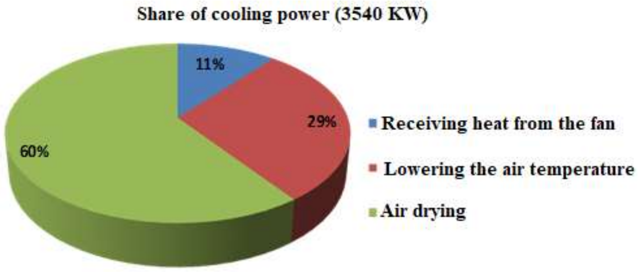

Fig. 7 The utilisation of cooling power

Figure 9 presents the relationship between the reduction of air temperature in the cooler and the relative humidity of air at the inlet to the cooler.

An analysis of the relationships presented in the diagrams has revealed that the maximum cooling power was achieved by a cooler with a rated power of 300 kW at a temperature of 27°C (210 kW, Fig. 8).

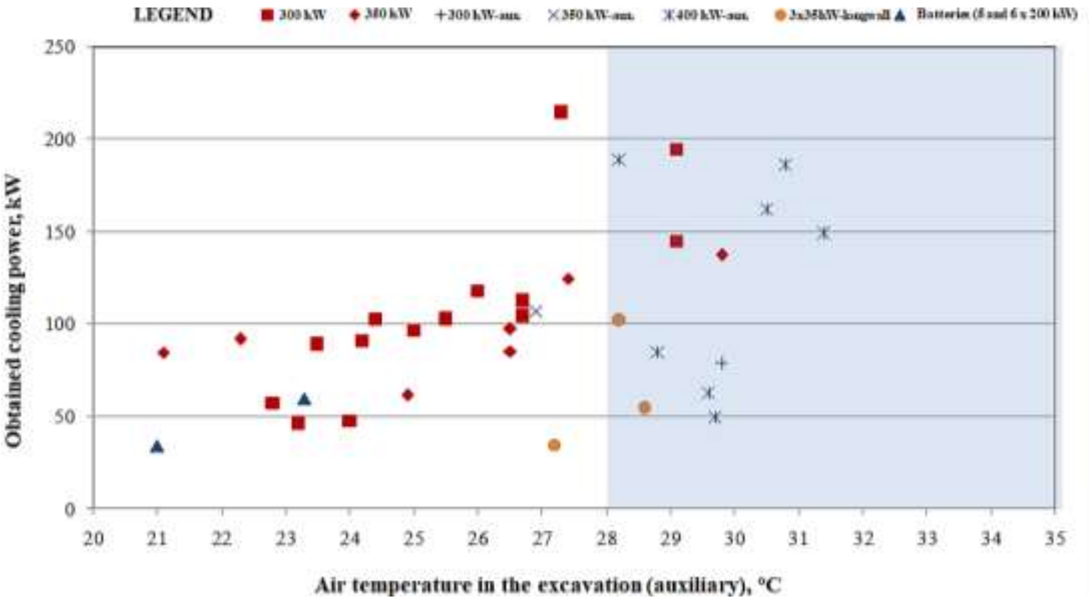

Fig. 8 The relationship between the cooling power of air coolers and air temperature

As for the area of high temperatures (shaded blue), none of the coolers in the study achieved a cooling power above 190 kW. The reduction of cooling power depends to a large extent on the volumetric flow rate of water supplied to the cooler (Fig. 9).

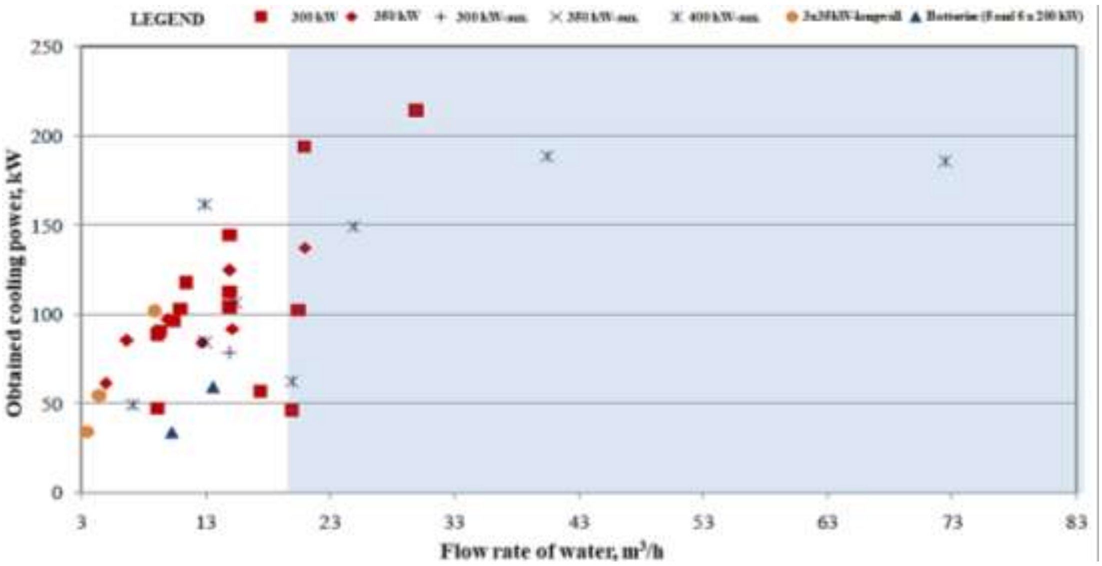

Fig. 9 The relationship between the cooling power of air coolers and the flow rate of supplied water

Most results were obtained for water flow rates ranging from 3 to 23 m^3/h. An increase in water flow rate above 23 m^3/h caused – in the case of coolers with a rated power of 300 kW and 400 kW – a significant rise of the cooling power (210 kW for the cooler with a rated power of 300 kW and 190 kW for the cooler with a rated power of 400 kW). Another factor contributing to the low efficiency of cooling units is the excessive temperature of water at the inlet to the coolers (Fig. 10), which in most cases was above 6.5°.

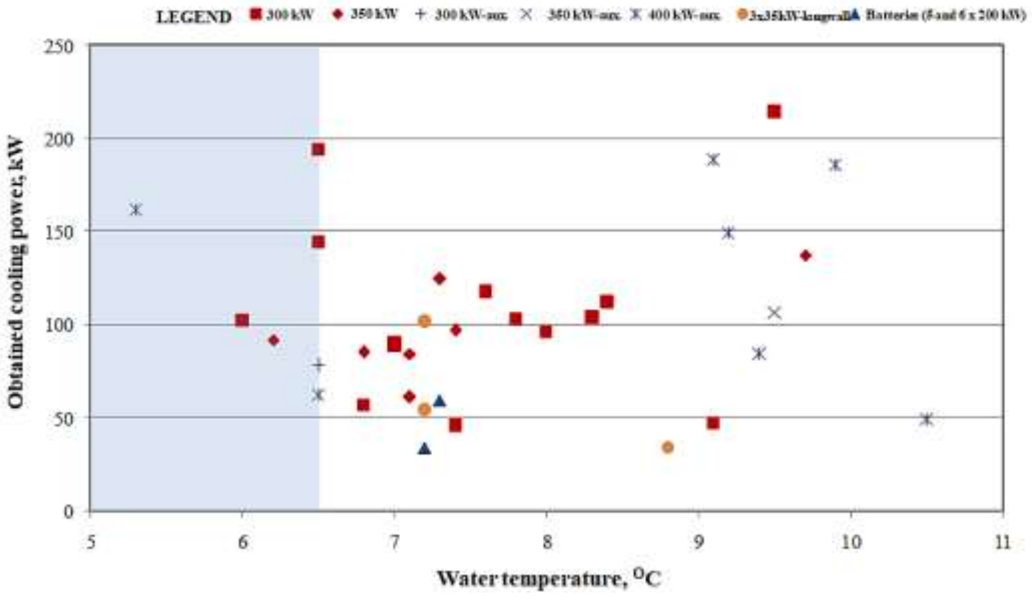

Fig. 10 The relationship between the cooling power of air coolers and water temperature at the inlet to the coolers

An analysis of the relationship between the reduction of air temperature in the cooler and the relative air humidity (Fig. 11) has revealed that in all coolers in the study the fall of temperature – at a relative humidity ranging from 50 to 90% – was between 4°C (the 400 kW cooler at a relative humidity of 89%) and 13°C (the 350 kW cooler at a relative humidity of 72%).

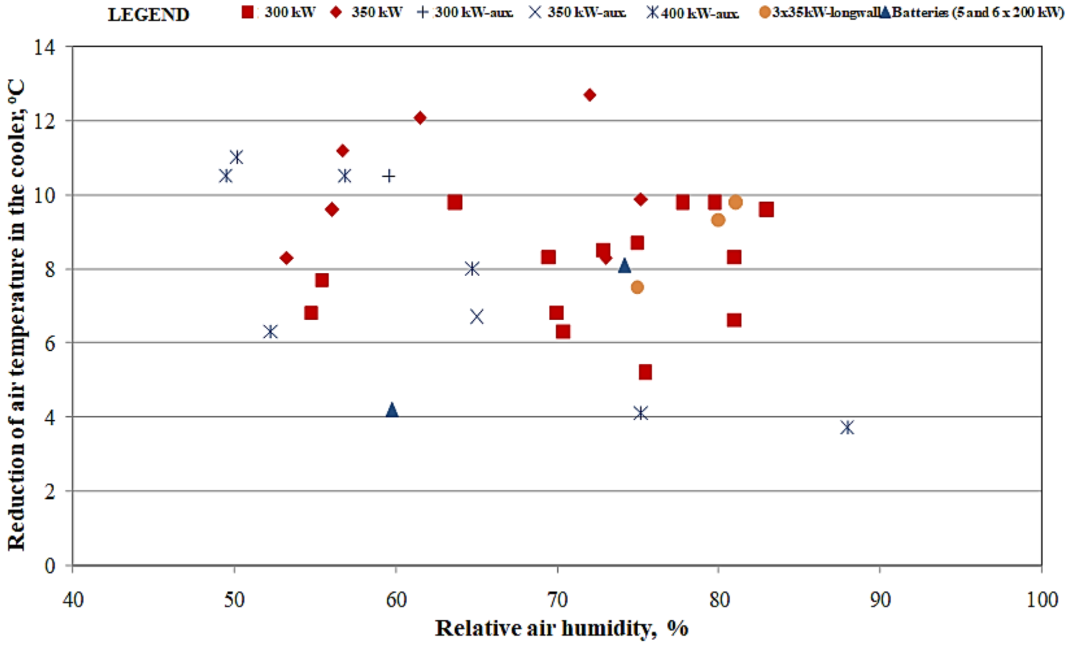

Fig. 11 The relationship between the reduction of air temperature in the cooler and relative air humidity at the inlet to the cooler

A probable explanation of the insufficient cooling of air is that it became dry. The air coolers are responsible for that because apart from reducing the air temperature, they function also as dehumidifiers. When air humidity is high (from 50 to 90%), some of the cooling power is spent on removing water vapour from the air, and only the remainder is used to reduce its temperature. For the same reason, in several cases under investigation, even the fact that a cooler was appropriately placed in an area with high temperatures and functioned with adequate parameters, such as water flow rate or water temperature, the device failed to reduce the temperature in the working to the desired level.

The efficiency of air coolers depends – among other factors – on their construction and the cleanliness of the surfaces exchanging heat. However, the primary cause behind the low cooling parameters is the impossibility to install the coolers in places with the highest air temperatures (Fig. 8), as well as the insufficient flow rate (Fig. 9) and excessive temperature of the water supplied to them (Fig. 10).

Air coolers should be relocated to spots with the highest air temperatures as exploitation fronts and longwall faces advance and should accommodate temporary fluctuations in the parameters of supplied air. Relocating the coolers, however, necessitates introducing frequent modifications in the pipeline network of the cooling system and requires ongoing adjustments in the distribution of ice water. In mining plants, the parametres of water passing through the pipelines are controlled only to a limited degree, which prevents regulating the distribution of water on an ongoing basis. Following the proposed projects of air-conditioning systems, the grouped and centralised air-conditioning systems need to be equipped with flow meters and temperature sensors to monitor water parameters. Monitoring these parameters enables making quicker decisions about the distribution of water or relocating air coolers or main pipelines.

The measured results discussed above indicate that it is imperative not only to expand the existing air-conditioning systems but also to operate them appropriately. A centralised air-conditioning system is designed to withstand the maximum load anticipated as exploitation unfolds. At the stage of construction, the control range for the distribution of ice water is determined, as well as the principles for controlling the distribution of water in the future extensions of the pipeline network. It is often necessary to install a larger number of coolers in a given area and to disable coolers operating in another area. To install more devices, it is necessary to replace ice water pipelines with pipes with a larger diameter. If the reconstruction of the pipelines is not followed by adjusting the distribution of water, the result might be a decreased velocity of water passing through air coolers. Consequently, the efficiency of air coolers is often diminished, and the returning chilled water does not absorb the required heat flux.

The above considerations imply that the cooling power generated by the installed air-conditioning systems is not utilised appropriately and effectively. It is possible to improve the efficiency of a centralised air-conditioning system by researching into:

- possible ways of reducing the costs of air-conditioning and extending the daily working hours in the workings by ensuring adequate climate conditions
- possible improvements in the efficiency of air cooling at longwalls and during preparatory/opening activities conducted at large depths where the virgin temperature of the rocks is high
- increasing the heat flux absorbed in air coolers installed in workings
- improving the efficiency and degree of utilisation of the cooling devices operating in mines with a schedule of audits targeted at reducing electric power consumption.

SUMMARY

The present article aims to demonstrate how certain factors diminish the efficiency of an air-conditioning system on a selected example and to suggest possible improvements.

To evaluate the efficiency of an air-conditioning system, a study was carried out into the functioning of the air-conditioning system in a selected hard coal mine. The study involved coolers with a rated power of 35, 300, 350, 400 kW and units comprising coolers with a power of 200 kW. The obtained results are evidence that the implementation of air-conditioning systems in mines does not prevent air temperature from exceeding the permitted level of 28°C as measured with a dry-bulb thermometer.

An analysis of the results has revealed the following:

- the maximum total power amounted to 7.5 MW,
- its degree of utilisation in the workings was below 50% at $\eta = 0.472\%$
- the maximum cooling power was achieved by a cooler with a rated power of 300 kW at a temperature of 27°C (210 kW)
- in the area of high temperatures, none of the coolers in the study achieved a cooling power above 190 kW
- most values of cooling power were obtained for water flow rates ranging from 3 to 23 m^3/h, i.e. out of the range of valid parametres
- an increase in water flow rate above 23 m^3/h caused a significant rise of the cooling power in the case of coolers with a rated power of 300 kW and 400 kW (210 kW and 190 kW, respectively)
- the temperature of water at the inlet to the coolers was excessive (in most cases it was higher than 6.5°C)
- in all coolers under analysis, the reduction of air temperature in the cooler was unsatisfactory
- at a relative humidity ranging from 50 to 90%, the fall of temperature ranged from 4°C (the 400 kW cooler at a relative humidity of 89%) to 13°C (the 350 kW cooler at a relative humidity of 72%).

The above considerations imply that the cooling power generated by the installed air-conditioning systems is not utilised appropriately and effectively. It is possible to improve the efficiency of a centralized air-conditioning system by conducting research into 1) reducing costs of air-conditioning by ensuring adequate climate conditions in the workings, 2) possible improvements in the efficiency of air cooling at longwalls and during preparatory/opening activities conducted at large depths where the virgin temperature of the rocks is high, 3) increasing the heat flux absorbed in air coolers installed in workings, and 4) improving the efficiency and degree of utilisation of the cooling devices operating in mines with a schedule of audits targeted at reducing electric power consumption.

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Abstract.
One of the particularly significant threats during exploitation is the climatic threat, which is associated with an increase in the overall costs that are allocated to combating it. The rise in the virgin temperature of the rock mass by 1oC increases the demand for the required cooling capacity to be taken from the air. The publication assesses the effectiveness of the air-conditioning installation by testing its operation on a selected example. The assessment of the efficiency of the air-conditioning installation for a selected hard coal mine showed that none of the five tested coolers achieved the maximum assumed rated power. The use of total power (7.5 MW) in mining excavations was less than 50% and amounted to η = 0.472%. The research showed that the main reason for obtaining low cooling parameters is the inability to locate them in the place of the highest air temperatures. The other problem is an insufficient airflow rate of cooling water supplied to the coolers at too high temperature. The above considerations indicated that the cooling power from built-in air- conditioning systems is not properly and effectively used. Improving the efficiency of its functioning is possible by proceeding research that will eliminate the above factors and by using air conditioning equipment, taking into account the periodic audit of their work to reduce electricity consumption.

Keywords: Air conditioning, climate hazard, cooling power