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APPLICATION OF THE GMC-1000 AND GMC-2000 MINE COOLING UNITS FOR CENTRAL AIR-CONDITIONING IN UNDERGROUND MINES

ZASTOSOWANIE GÓRNICZEGO URZĄDZENIA CHŁODNICZEGO GMC-1000 I GMC-2000 W CENTRALNEJ KLIMATYZACJI KOPALŃ PODZIEMNYCH

The paper describes the design and results of operating measurements of the GMC-1000 and GMC-2000 Mine Cooling Units. The first part describes the design of the cooling unit and its key components: the chiller, evaporator, condenser, oil cooler, evaporative water cooler and gallery air cooler. The possibilities of use in central air conditioning systems of underground mines are described. The second part discusses the results of the workstation and operating measurements and determines the coefficients for evaluating the performance of the mine cooling unit.

Keywords: central air conditioning of underground mines, cooling unit, evaporator, condenser, cooling power, counter clockwise cycle

Wraz ze wzrostem głębokości eksploatacji pogarszają się warunki pracy w wyrobiskach podziemnych, a w szczególności warunki klimatyczne związane ze wzrostem temperatury. Przy temperaturach pierwotnych górotworu przekraczających 40°C utrzymanie temperatury w wyrobiskach eksploatacyjnych poniżej wartości 28°C, uznawanej za wartość dopuszczalną ze względu na warunki pracy załogi, wymaga, oprócz zwiększonej wydajności wentylacji wyrobisk, także ich klimatyzacji. Można znaleźć wiele prac dotyczących tych zagadnień. Problemów klimatyzacji i chłodzenia wyrobisk dotyczą między innymi prace: Filka i jego zespołu (1999, 2002, 2004, 2006), Łuska i Nawrata (2002), Kalukiewicza i jego zespołu (2008). W krajowym górnictwie dotyczy to zarówno kopalń węgla kamiennego, jak też rud miedzi.

W większości przypadków konieczność utrzymania wymaganych warunków klimatycznych w rejonie, przy jednoczesnym nacisku na ekonomiczną stronę procesu pozyskiwania kopalin, powodują konieczność stosowania klimatyzacji grupowej przy zastosowaniu urządzeń o dużej wydajności zlokalizowanych na dole kopalni.

W niniejszym artykule omówiono wybrane zagadnienia doboru urządzeń klimatyzacji grupowej na przykładzie urządzenia chłodniczego GMC-1000 i GMC-2000. Konstrukcję urządzenia opracowano w firmie EUROTECH Sp. z o.o. przy współpracy z pracownikami Katedr Maszyn Górniczych Przeróbczych

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i Transportowych oraz Systemów Energetycznych i Urządzeń Ochrony Środowiska Wydziału Inżynierii Mechanicznej i Robotyki Akademii Górniczo-Hutniczej w Krakowie w ramach projektu dofinansowanego przez Ministerstwo Nauki i Szkolnictwa Wyższego.

Górnicze urządzenie chłodnicze jest przeznaczone do chłodzenia powietrza wentylacyjnego w chodnikach wydobywczych kopani podziemnych. Znajduje zastosowanie wszędzie tam, gdzie panują trudne warunki wydobywcze powodowane między innymi dużymi obciążeniami cieplnymi. Wysokie temperatury utrudniają prace górnicze. Powodują konieczność skrócenia czasu przebywania pracowników w rejonach o najwyższych temperaturach. W połączeniu z zapyleniem i wilgotnością stanowią istotny problem przy eksploatacji maszyn i urządzeń ścianowych. Agresywna atmosfera powoduje znacznie szybsze zużycie sprzętu. Problemy te uzasadniają konieczność stosowania systemów chłodzenia powietrza bezpośrednio w rejonach, w których prowadzone jest wydobycie.

Górnicze urządzenie chłodnicze GMC stanowi kompletny system chłodzenia powietrza wentylacyjnego w chodnikach wydobywczych. Realizowane zadania powodują, że system ten musi być rozbudowany pod względem technicznym jak również przestrzennym. Część zadań stawianych przed urządzeniem chłodniczym jest realizowana w znacznej odległości od chodników wydobywczych. Dotyczy to przygotowania wody chłodzącej, która służy do schładzania powietrza w chłodnicach ścianowych. Woda z rejonu jej schładzania przepływa rurociągami do rejonów wydobywczych, gdzie jest wykorzystywana do chłodzenia powietrza. Urządzenie pracuje w układzie zamkniętym. Należy zwrócić uwagę, że system chłodzenia musi spełniać wszystkie wymagania określone przez odpowiednie przepisy górnicze dotyczące zasad eksploatacji i bezpieczeństwa.

Podstawowymi elementami górniczego urządzenia chłodniczego są następujące aparaty (rys. 1): agregat chłodniczy, chłodnica wyparna wody, chłodnica chodnikowa powietrza. Wymienione aparaty są urządzeniami, w których następują przepływy ciepła. Mają one różny charakter w zależności od przeznaczenia danego elementu. Urządzenie chłodnicze jest uzupełnione dodatkowymi elementami, które są niezbędne do jego prawidłowego funkcjonowania. Do grupy tej należą maszyny z układami napędowymi wymuszające przepływy czynników w poszczególnych wymiennikach ciepła. Mamy tutaj wentylatory i sprężarki czynników gazowych oraz pompy do wody jak również cieczy technologicznych. Urządzenie chłodnicze musi być wyposażone w dodatkowy sprzęt i aparaturę kontrolno-pomiarową. Konieczne są filtry do gazu i cieczy. Czujniki przepływu, temperatury i ciśnienia. Schemat górniczego urządzenia chłodniczego z opisem poszczególnych elementów jest pokazany na rysunku 1.

W ramach projektu celowego nr 6 ZR8 2007C/06934 wykonane zostało Górnicze Urządzenie Chłodnicze przeznaczone do klimatyzacji grupowej (centralnej) w kopalniach podziemnych. Konstrukcję urządzenia opracowano w firmie EUROTECH Sp. z o.o. przy współpracy z pracownikami Katedry Maszyn Górniczych Przeróbczych i Transportowych oraz Katedry Systemów Energetycznych i Urządzeń Ochrony Środowiska Wydziału Inżynierii Mechanicznej i Robotyki Akademii Górniczo-Hutniczej w Krakowie. Prototyp urządzenia był badany w WUCH „PZL – Dębica" S.A., następnie przeszedł próby ruchowe w O. ZG „ Rudna". Obecnie kilka egzemplarzy górniczego urządzenia chłodniczego jest eksploatowanych w kopalniach węgla kamiennego. Prototyp urządzenia GMC-1000 miał moc chłodniczą 1000 kW, wykonano również egzemplarz GMC-2000 o mocy chłodniczej 2000 kW. W tabelach 1-3 przedstawiono wyniki pomiarów agregatu GMC-1000 przeprowadzonych na prototypie oraz wyniki uzyskane w czasie eksploatacji w Kopalni Węgla „Rydułtowy-Anna", tabela 4 zawiera wyniki uzyskane w czasie eksploatacji urządzenia GMC-2000 w Kopalni Węgla „Bielszowice". Urządzenie chłodnicze w kopalni „Rydułtowy-Anna" pracuje od lutego 2009.

W trakcie prób, za pomocą regulatora wydajności, zmieniano wydajność sprężarki chłodniczej. Regulator wydajności zapewnia płynną regulację strumienia od 0% do 100%. Ilość sprężanych par czynnika R134a w danej chwili, a tym samym zmianę wydajności sprężarki, uzyskuje się za pomocą sterowanego hydraulicznie suwaka regulacji wydajności.

Temperatura wody lodowej dopływającej do parownika (t_{w5}) była stabilna w trakcie poszczególnych pomiarów, ale specyfika stanowiska nie pozwalała na utrzymanie stałej wartości temperatury dla kolejnych prób. Wynikał stąd rozrzut wartości t_{w5} w granicach 11,1°C do 17,4°C. Kolejną wielkością regulowaną była temperatura parowania t_o (cienienie parowania), która w trakcie pomiarów była zmieniana w granicach –1,4°C do +1,4°C.

Badania eksploatacyjne miały na celu sprawdzenie przydatności agregatu do pracy w warunkach kopalnianych. Poszczególne próby były realizowane przy różnych wartościach nastaw i wielkości wejściowych układu. Brak możliwości ustalenia wartości wybranych parametrów wynikał z faktu przeprowadzania pomiarów w czasie prowadzenia prac wydobywczych w O.ZG „Rudna". Wartości wielkości wejściowych zależały od chwilowego stanu obciążeń i warunków otoczenia.

Temperatura wody lodowej dopływającej do parownika była stabilna w trakcie poszczególnych pomiarów (tylko te były przyjmowane jako reprezentatywne), ale zmieniała się ze względu na współpracę agregatu z działającymi w wyrobisku chłodnicami powietrza. Temperatura t_{w5} zmieniała się w granicach 12,7°C÷19,1°C. Kolejną wielkością regulowaną była temperatura parowania t_o (ciśnienie parowania), która w trakcie pomiarów zmieniała się w granicach –1,1°C÷+1,1°C.

Uzyskane przez górniczą maszynę chłodniczą GMC-1000 i GMC-2000 wartości parametrów pracy na stanowisku badawczym i przy próbach ruchowych potwierdziły przyjęte założenia projektowe. Wartości parametrów założone na etapie projektowania zostały osiągnięte w trakcie badań stanowiskowych. Założona moc chłodnicza wynosiła 1000 kW, w czasie pomiarów udało się osiągnąć moc chłodniczą 1250 kW. Moc ta została osiągnięta przy 100% nastawie suwaka regulującego przepływ czynnika chłodniczego przez sprężarkę i spadku temperatury wody lodowej w parowniku 11,4 K. Wynik ten daje 25% zapas mocy chłodniczej względem mocy chłodniczej nominalnej, spadek temperatury wody lodowej, w tym przypadku, jest mniejszy o 15,5% w stosunku do założonego. Zapas mocy jest większy w stosunku do niedoboru spadku temperatury oznacza to, że możliwe jest osiągnięcie wymaganego spadku temperatury nawet przy mniejszych mocach chłodniczych. Stwarza to możliwość regulacji parametrów pracy urządzenia chłodniczego w szerokim zakresie.

W kilku pomiarach uzyskane temperatury schłodzenia wody były korzystniejsze niż to założono na etapie projektowania GMC. Szerokie przedziały zmienności wartości parametrów stwarzają duże możliwości sterowania pracą górniczych maszyn chłodniczych GMC-1000 i GMC-2000. Osiągnięcie wymaganego stopnia schłodzenia wody lodowej pozwoli na wymagane schłodzenie powietrza w chłodnicy ścianowej.

Rezultaty uzyskane w czasie prób stanowiskowych, ruchowych i eksploatacji w kopalniach pozwalają na stwierdzenie, że górnicza maszyna chłodnicza może być eksploatowana w centralnych układach klimatyzacyjnych kopalń podziemnych.

Słowa kluczowe: centralna klimatyzacja kopalń podziemnych, agregat chłodniczy, parownik, skraplacz, wydajność chłodnicza, obieg lewobieżny

1. Introduction

As the exploitation depth increase, the working conditions in underground mines, especially the climatic ones, worsen mainly because of the increased temperature. With the rock mass original temperatures above 40°C, maintaining the temperature below 28°C, which is considered as the working limit, requires air conditioning in addition to increased ventilation in the headings. There are many papers pertaining to this problem available. The cooling and air conditioning issues are discussed in the works of: Filek et al. (1999, 2002, 2004, 2006), Łusek and Nawrat (2002), Kalukiewicz et al. (2008).

In case of the domestic mining industry, this applies to both the hard coal and cooper ore mines. There is a number of solutions to the air conditioning problem, ranging from individual workplace conditioning, mostly of the operator cabins, to central air conditioning systems, with the cooling medium supplied from a high-power cooling unit located on the surface.

Each of the systems has its advantages and drawbacks while considering such criteria as the cooling power, efficient operating range, investment cost and operating cost, resulting with such factors as the reliability, durability and servicing. The choice of a specific system, and thus the equipment and installation, depends on the local conditions of the mine.

In most cases, the necessity to maintain the required climatic conditions in the working area, bearing in mind the economy of exploitation at the same time, causes the need to utilise a centralised system using high-performance equipment located underground. Due to the place of operation, the equipment has to meet a number of conflicting requirements, for example to be compact enough to allow transport to the site and installation in a specially prepared chamber with standard dimensions and, at the same time, offer high cooling power to achieve the required climatic conditions. Furthermore, it has to ensure a high level of comfort and safety to the crew, which in turn demands possibly high efficiency. Dust, humidity, high temperature and, in many cases aggressive mining atmosphere, also put high demands on the choice of materials and such parameters as the thickness of ducts and tank walls, which determine the durability of the components. Furthermore, the necessity to ensure favourable conditions for heat exchange and minimising the loss in ducting are in conflict with the cost of the equipment and its installation, which is critical for the investment cost of the user.

This paper discusses chosen problems of the selection of central air conditioning equipment based on the example of the GMC-1000 and GMC-2000 cooling units. The unit was designed by EUROTECH Sp. z o.o. in cooperation with the staff from the AGH University of Science and Technology of Krakow Faculty of Mechanical Engineering and Robotics, Department of Mining, Dressing and Transport Machines and Department of Power Systems and Environmental Protection Facilities of Krakow, under the project co-financed by the Ministry of Science and Higher Education.

The unit, intended for use in various conditions in underground mines, meets all stringent standards of explosion protection design ATEX Directive, and the requirements of other directives, such as the Machinery Directive and Pressure Equipment Directive.

2. Mine cooling unit

The mine cooling unit is intended for cooling ventilation air in galleries of underground mines. It can be used wherever difficult working conditions are present, among others, due to high thermal load. High temperatures make mining work difficult. This requires to reduce the working time in the areas with the highest temperatures. In addition to dust and humidity, high temperature poses significant problems in operating the longwall machinery and equipment. Aggressive atmosphere leads to premature wear of components. All those problems require the use of air cooling systems directly in the mining areas.

The mine cooling unit constitutes a complete ventilation air cooling system for mining galleries. The functions performed require the system to be technically complex and space consuming. Most of the functions of the cooling equipment are executed in a considerable distance from the mining areas. This applies to the preparation of cooling water which is used for cooling air in longwall air coolers. From the chilling area, the water is forced with pipelines to the mining areas, where it is used for cooling of air. The unit operates in a closed system. It should be noted that the cooling system has to comply with all the requirements prescribed by the mining regulations regarding the operation and safety.

The main components of the mine cooling unit are the following (fig. 1): the chiller, water evaporative water cooler, gallery air cooler. The components mentioned are devices in which heat flows occur. They are of different types, depending on the application of a given component. The chiller comes with additional components which are necessary for its proper functioning. These include machinery with drive systems for forcing the refrigerant flow in individual heat exchangers. There are ventilators, compressors for gaseous refrigerants, pumps for water and process liquids. The chiller has to be equipped with additional accessories and C&I components. Gas and liquid filters are necessary. Flow, temperature and pressure detectors are also installed. Figure 1 shows the schematic diagram of the mine cooling unit, describing individual parts.

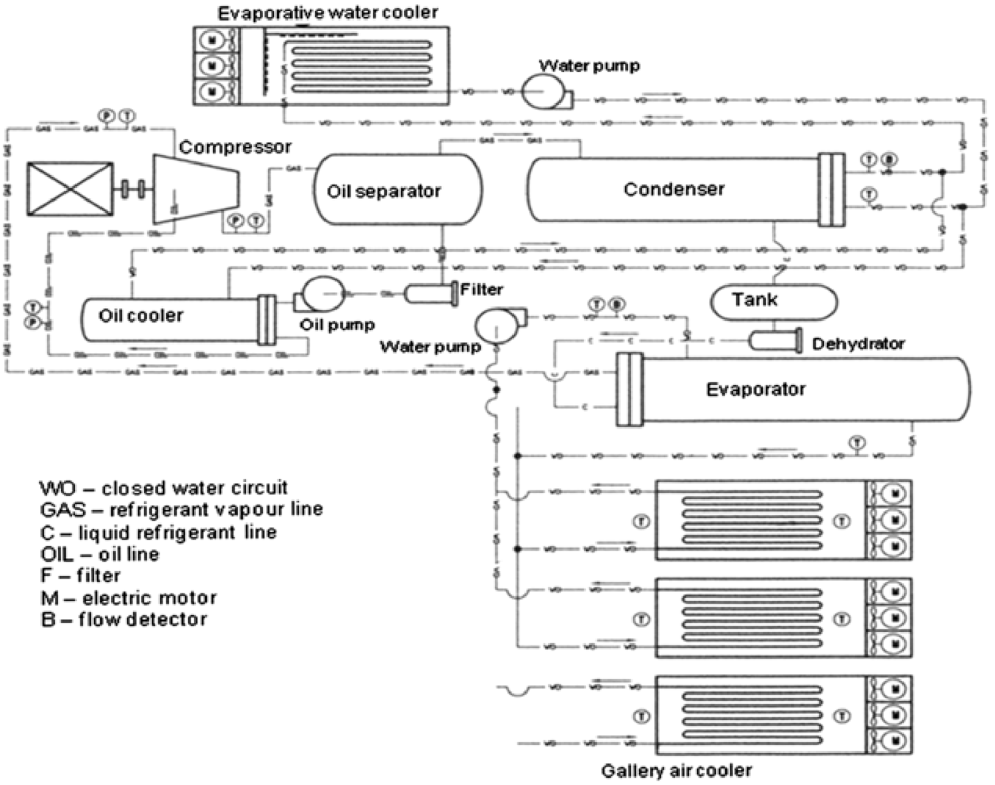

Fig. 1. Mine cooling unit diagram

Chiller is a set of components for generating ice water for the gallery air coolers. The chiller comprises the following devices: evaporator, condenser, oil cooler, oil separator, refrigerant tank, dehydrator, water and oil pumps, compressor, accessories and C&I.

Evaporator. The main part of the cooling unit is the evaporator with heat power output 1100 kW (fig. 2). The refrigerant used is R134a. (The evaporation process is shown as the transformation 4-1 in figure 5) The evaporation process is divided into two stages. The first part of the process is effected in the initial evaporator with heat output 367 kW. In the initial evaporator, the dryness of the medium changes from 0.3 to 0.55. The evaporation temperature is +0.5°C. Water temperature in this process changes from 7.5°C to 3°C. The initial evaporator constitutes the section of the heat exchanger in which the water is finally cooled.

Ultimate evaporation occurs in the end evaporator, in which the R134a refrigerant changes it dryness from 0.55 to 1 and is slightly overheated to +3ºC. Water temperature changes from 16.5°C to 7.7°C. It is the first stage of cooling water used for chilling air in the gallery cooler. The heat output of the end evaporator is 733 kW.

The ODs of individual parts of the evaporator are different. The initial evaporator has a smaller diameter than its end part.

Structural solutions incorporated in individual parts of the evaporator are the same. It is a shell and tube exchanger (figure 3).

Fig. 2. GMC-1000 Cooling Unit

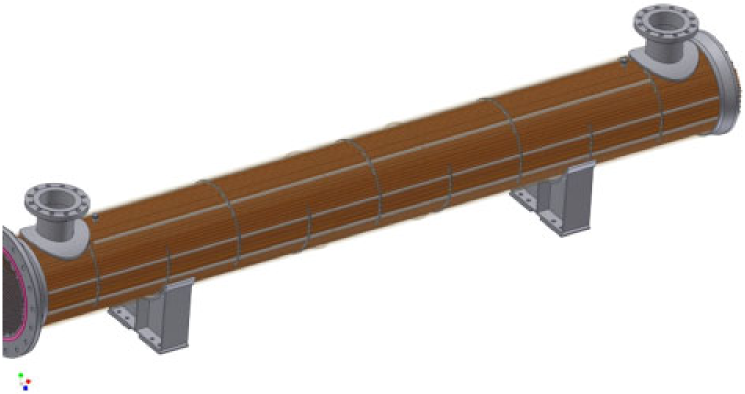

Fig. 3. One of the evaporator sections – evaporator filling with a tubular segment

The R134a refrigerant flows inside the tubes. The water being cooled contacts the tube surfaces while flowing inside the exchanger shell. To ensure longer contact of water with tube surfaces and for increased turbulent flow, there are lateral partitions installed inside the shell. Copper tubes are fixed to the tube plates, which are connected with the manifolds supplied with the refrigerant. Water is forced to the evaporator with the manifolds, through which it flows from or to the shell. In the bottom part of the shell, drain holes are provided for the removal of contaminants and draining the exchanger.

Condenser is the second important part of the cooling unit (fig. 2). In this component, the vapours of the R134a refrigerant are condensed. (The condensation process is shown as the transformation 2-3 in figure 5). The heat involved in the condensation process is transferred to the water. The condenser is a typical shell and tube exchanger used for that purpose. Water cooling the condenser is obtained from the evaporative water cooler. The refrigerant vapours leaving the evaporators are compressed upstream the condenser with the compressor.

The evaporator and condenser are the main heat exchangers in the cooling unit. Proper functioning of the system is ensured by additional components, such as: the oil separator and oil cooler.

Oil cooler. As a result of the compression process, the temperature of the refrigerant and oil increases. The oil serves as the lubricant and cooling medium in the compressor. Hot oil is cooled with the water oil cooler. Water for oil cooling comes from the evaporative water cooler. The water oil cooler is a typical shell and tube exchanger.

The **oil separator** removes oil particles which penetrate into the R134a refrigerant inside the compressor.

The cooling unit is additionally equipped with special components ensuring its proper operation. Other components are the C&I and fittings such as filters, valves etc.

Evaporative water cooler with heat output 1350 kW is intended for preparing water used in the process of condensation of vapours of the R134a in the condenser of the cooling unit and for cooling the oil. It operates in a closed cycle. Heat drawn from the condensation of the refrigerant vapours in the condenser is released to the air blown by the evaporative water cooler. The rate of heat absorption is increased by the evaporation of water sprayed on the tube packs.

The evaporative water cooler comprises a series of profiled tube packs. One pack includes four profiled tubes. Tubes constituting a pack are positioned in such a manner that they create a plane, which comes in contact with air on the outside.

Temperature of the water flowing in the tube packs is reduced with the evaporating spraying stream. To increase the intensity of the dissipated heat, air is forced between the tube packs. The air flows through narrow gaps which are rectangular in section. Small cross sectional area of the air duct allows achieving high velocity of the air flow. This has a beneficial effect on the heat absorption ratio on the air side. Further intensification of the water cooling process is achieved by creating water film on the surface of tubes. It is achieved by means of a specially designed spraying system.

In the spraying system, particular attention should be drawn to the nozzles which disperse a jet of water into a spout of drops. The design of the nozzles ensures achieving drops of a desired size so that they evaporate in the time of flowing through the ducts of individual packs of water tubes. The phase transition is characterised by very high values of the heat absorption ratio, which considerably improves water cooling in the cooler. The air flowing sweeps the steam which is created from the water film covering the tube packs. Air humidity increases in this process. The part of spraying water which has not evaporated from the surface of the tube packs, flows into the trays and is drained back to the sprinkling water tank. The profiled tube packs are connected with the collection manifolds. In the evaporative cooler, copper tubes with diameter 18 mm and wall thickness 1 mm are installed. The tubes are flattened to 15 mm. Air flow is forced with the WLE 800 ventilator with the output of 13 m^3/h.

Gallery air cooler (fig. 4) is designed for cooling ventilation air which is forced to the excavation area. It is placed near the areas of mining works. This means that it can be considerably distant from the cooling unit in which ice water is prepared. For cooling air, the gallery cooler uses water which is chilled in the evaporator of the cooling unit. The heat output of the gallery cooler is 350 kW.

The air cooler design incorporates the solutions utilised in the evaporative water cooler (fig. 4). This design includes the profiled tube packs as well. The output diameter of the copper tubes in the air water cooler is 12 mm, with wall thickness 1 mm. The tubes are flattened to 10.2 mm. The cooler is operated near the area of mining works and thus, it is exposed to adverse effects of contaminants contained in the atmosphere. The sprinkling system of the gallery air cooler is intended to periodically wash the dust accumulated on the surface of tube packs. Air flow through the cooler is forced with the WLE 800 ventilator with the output of 13 m^3/h.

Fig. 4. GCP 350 mine air cooler

3. Cooling cycle of the mine cooling unit

The mine cooling unit operates according to Linde cycle. The cycle, for the R134a refrigerant, is shown in figure 5. The cooling unit operates in the counter clockwise compressor cycle.

The following transformations are performed in the cycle: 1-2 process of compressing the refrigerant vapours in the compressor, 2-3 condensation in the condenser, 3-4 depressurisation of the refrigerant in throttling valves, 4-1 refrigerant evaporation in the evaporator. In the figures, the calculated values of pressures in the condenser and evaporator are shown. The key role in obtaining ice water with the desired specifications has the transformation taking place in the evaporator. The process of the refrigerant evaporation in the evaporator takes place at a constant pressure, hence the unit amount of heat supplied to the refrigerant corresponds to the difference of enthalpy in the points 1 and 4 ($q_o = i_1 - i_4$).

The refrigerant suitable for use with the mine cooling unit is R134a. It belongs to the group of synthetic refrigerants with the formula $C_2H_4F_4$. The R134a refrigerant is absolutely safe to

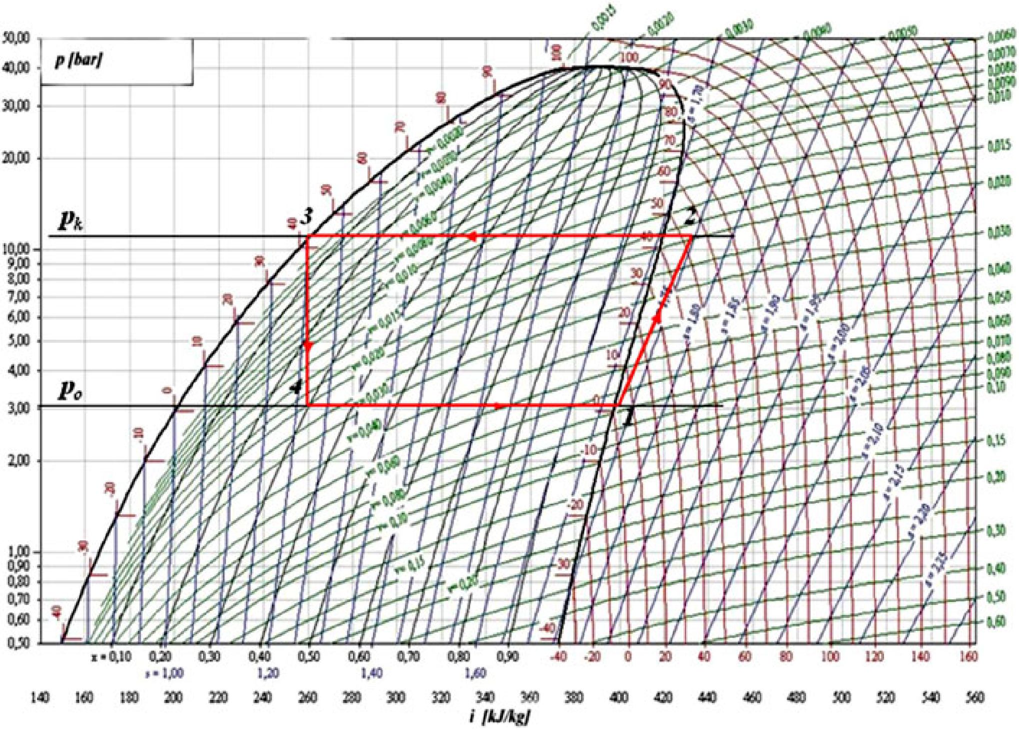

Fig. 5. Comparative Linde cycle for the mine cooling unit operated with the R134a refrigerant
p_o – evaporator pressure, p_k – condenser pressure

the ozone layer ODP = 0 (Ozone Depletion Potential), increases the greenhouse effect, the GWP ratio (Global Warming Potential) is 1300. Since it is a hygroscopic product, the system has to be tight. The presence of water in the system causes the refrigerant to break down. Oils used with the R134a refrigerant should be based on polyalkylene glycols (PAG) or ester oils (POE). Moisture in excess of 100-200 mg/kg may initiate hydrolysis of the ester oil producing acid. If copper components are present in the system, the "copper plating" effect may occur. Pure R134a refrigerant has no harmful effect on ferritic steel, copper and its alloys and aluminium. Neither is it aggressive to most plastics.

The R134a is a non-flammable and non-explosive substance under normal conditions. Explosive mixture is formed in high pressure with 60% share of air. The product is not toxic. Inhalation of a larger volume of R134a vapours causes narcotic effects, irritation of the mucous membranes and heart arrhythmias. It is heavier than air and its presence may lead to suffocation due to the displacement of air.

4. Mine cooling unit performance analysis

Under the targeted project no. 6 ZR8 2007C/06934, the Mine Cooling Unit, designed for central air conditioning systems of underground mines, was created. The unit was designed by EUROTECH Sp. z o.o. in cooperation with the staff from the AGH University of Science and Technology of Krakow Faculty of Mechanical Engineering and Robotics, Department of Mining, Dressing and Transport Machines and Department of Power Systems and Environmental Protection Facilities of Krakow. The prototype was tested at WUCH "PZL – Dębica" S.A., and the, underwent operational tests at O. ZG "Rudna". At present, several such units are operated in hard coal mines. The prototype of the GMC-1000 unit had cooling power 1000 kW. Also the GMC-2000 unit was built with cooling power 2000 kW. Tables 1-3 present the results of measurements of the GMC-100 units carried out on the prototype, and the results achieved in use in Rydułtowy-Anna Coal Mine, Table 4 shows the results achieved while operating the unit in Bielszowice Coal Mine. The unit in Rydułtowy-Anna Mine has been operated since 2009.

Workstation tests at PLZ Dębica SA Cooling Equipment Factory were aimed at determining the operating range, control system regulation properties, performance of the protective devices of the unit and to verify the achieved operating parameters for compliance with the design. Because of the equipment power rating and the resulting cost of the measurements, the scope of the experiments had to be minimised.

Table 1 shows the results of several chosen tests. Only the values measured during the experiment are given, and which were essential for the evaluation and determining the indices describing the performance of the equipment. Results achieved in the subsequent tests are given in the following columns. In the "Design value" column, the nominal values of individual parameters of the mine cooling unit are given.

During the tests, the output of the cooling compressor was changed with the capacity regulator. The capacity regulator provides for stepless adjustment of stream from 0 to 100%. The quantity of R134a refrigerant vapours compressed at a given moment and, at the same time, the compressor output, is changed with a hydraulically controlled capacity control slide.

The ice water temperature at the evaporator inlet (t_{w5}) was stable during individual tests, but the design of the workstation did not allow maintaining the temperature during the next tests. This resulted in the difference of the t_{w5} values from 11.1 to 17.4°C. Another value being adjusted was the vapour point t_o (vapour pressure), which was changed from –1.4 to +1.4°C during the measurements.

The following stage of the tests included the prototype testing in an underground mine, in operating conditions. The mine cooling unit was installed in O.ZG Rudna excavation. The results achieved during the experiment are given in Table 2.

The operational tests were aimed at checking the unit suitability for working in underground mine conditions. Individual tests were performed for different settings and input values of the system. Since the measurements were taken during the exploitation works at O.ZG Rudna, it was impossible to determine the values of the selected parameters. The values of the input parameters depended on the momentary load and ambient conditions.

The temperature of ice water flowing into the evaporator was stable during the individual tests (only such values were assumed as representative), but it changed because of the unit co-working with air coolers operating in the excavation. The t_{w5} temperature varied from 12.7°C to 19.1°C. Another value being adjusted was the vapour point t_o (vapour pressure), which was changed from –1.1 to +1.1°C during the measurements.

TABLE 1

Results of performance measurements of the GMC-1000 Mine Cooling Unit (WUCH “PZL Dębica” S.A.)

Measured or calculated value	**Sym-bol**	**Unit**	**Design value**	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Evaporation point	t_o	°C	0.5	-0.1	0	-0.3	0.8	-0.7	-1.4	-1.4	1.4	-1	-0.6
Condensation point	t_k	°C	42	43.1	41.3	43.1	43.8	41.1	41.9	39.8	40.6	37.2	39.5
Slide position	H	%	100	100	100	100	100	94	90	88	86	85	81
Current drawn	I	A		560	500	562	584	479	482	436	446	384	421
Vapour pressure	p_o	bar		1.9	1.9	1.9	2	1.9	1.9	1.8	2.1	1.8	1.9
Water temperature at the condenser inlet	t_{w3}	°C	28	15.6	16.2	16.1	28.2	16.2	17.9	15	16.6	10.4	15.3
Water temperature at the condenser outlet	t_{w4}	°C	38	38.5	35.2	37.9	39.3	36.9	37.9	31	35.4	28.4	33.2
Water temperature at evaporator 1 inlet	t_{w5}	°C	16.5	16.1	16.4	15.8	17.1	14.5	12.9	13.1	16.8	11.8	13
Water temperature at the evaporator 2 outlet	t_{w6}	°C	3	3.7	3.5	3.7	4.4	3.1	2.3	2.9	4.6	2.9	2.6
Evaporator water flow rate	V_p	m^3/h	65	70.26	67.68	70.8	69.6	70.08	70.5	70.44	67.86	93.6	69.9
Water temperature change in the condenser	Δt_{ws}	K	10	22.9	19	21.8	11.1	20.7	20	16	18.8	18	17.9
Water temperature change in the evaporator	Δt_{wo}	K	13.5	12.4	12.9	12.1	12.7	11.4	10.6	10.2	12.2	8.9	10.4
Condenser power output	Q_s	kW	1450.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cooling power	Q_o	kW	1110.0	1013.1	1015.2	996.1	1027.8	928.9	869.0	835.5	962.7	968.7	845.3
Power requirement	P_{el}	kW	350.0	388.0	346.4	389.4	404.6	331.9	333.9	302.1	309.0	266.0	291.7
Cooling power factor	ε		3.17	2.61	2.93	2.56	2.54	2.80	2.60	2.77	3.12	3.64	2.90
Logarithmic mean temperature difference	ΔT_m	K	7.27	8.55	8.35	8.69	8.41	8.22	7.84	8.39	7.76	7.49	7.19
Heat transfer coefficient	k	W/m^2K	638.61	495.66	508.58	479.67	511.39	472.64	463.71	416.57	518.75	541.21	492.07
Cooling efficiency Q_o/Q_n	E_{ch}		1.00	0.91	0.91	0.90	0.93	0.84	0.78	0.75	0.87	0.87	0.76
Evaporation and water temperature difference at the evaporator inlet	$t_{w5} - t_o$	K	16	16.2	16.4	16.1	16.3	15.2	14.3	14.5	15.4	12.8	13.6

TABLE 2

Results of performance measurements of the GMC-1000 Mine Cooling Unit (O.ZG Rudna)

Measured or calculated value	**Sym-bol**	**Unit**	**Design value**	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Evaporation point	t_o	°C	0.5	0.4	0.4	1.1	-0.8	-1.1	0	0	0.5	0.2	0.1
Condensation point	t_k	°C	42	39.3	41.7	45.7	39.4	39.4	47.3	44.5	42.6	30.2	44.4
Slide position	H	%	100	100	100	100	98	98	97	94	88	80	71
Vapour pressure	p_o	bar		1.9	2	2	1.8	1.8	1.9	1.9	1.9	1.9	1.9
Water temperature at condenser inlet	t_{w3}	°C	28	7.2	7.6	8	7.2	7.2	7.8	7.7	7.6	7.4	8.2
Water temperature at the condenser outlet	t_{w4}	°C	38	29.4	36.5	39.5	26.5	28.6	37.4	35.7	38.5	30.6	37.3
Condenser water flow rate	V_{sk}	m^3/h	125	58	32	39	59.6	59	40	42	36	50	28.5
Water temperature at evaporator 1 inlet	t_{w5}	°C	16.5	19.1	12.7	19.5	18.9	17.7	18.4	17.4	15.1	14.9	13.4
Water temperature at the evaporator 2 outlet	t_{w6}	°C	3	2.1	3.3	4.4	1.7	1.5	3.2	2.8	2.4	1.9	2.5
Evaporator water flow rate	V_p	m^3/h	65	54.4	57.37	58	56.4	56.2	52	51.8	57.5	51.2	49.7
Water temperature change in the condenser	Δt_{ws}	K	10	22.2	28.9	31.5	19.3	21.4	29.6	28	30.9	23.2	29.1
Water temperature change in the evaporator	Δt_{wo}	K	13.5	17	9.4	15.1	17.2	16.2	15.2	14.6	12.7	13	10.9
Condenser power output	Q_s	kW	1450.9	1494.5	1073.4	1425.9	1335.1	1465.5	1374.3	1365.0	1291.2	1346.4	962.6
Cooling power	Q_o	kW	1110.0	1076.2	627.6	1019.2	1128.9	1059.5	919.8	880.1	849.8	774.6	630.4
Power requirement	P_{el}	kW	350.0	418.3	445.9	406.7	206.2	406.0	454.5	484.9	441.4	571.8	332.2
Cooling power factor	ε	-	3.17	2.57	1.41	2.51	5.47	2.61	2.02	1.81	1.93	1.35	1.90
Logarithmic mean temperature difference	ΔT_m	K	7.27	7.09	6.51	8.79	8.33	8.19	8.69	7.99	6.23	6.03	6.37
Heat transfer coefficient	k	W/m^2K	638.61	635.14	403.61	485.29	566.89	541.35	442.88	460.76	570.90	537.78	414.36
Cooling efficiency Q_o/Q_n	E_{ch}	-	1.00	0.97	0.57	0.92	1.02	0.95	0.83	0.79	0.77	0.70	0.57
Evaporation and water temperature difference at the evaporator 1 inlet	$t_{w5} - t_o$	K	16	18.7	12.3	18.4	19.7	18.8	18.4	17.4	14.6	14.7	13.3

Tables 3 and 4 summarise the measurement results from constant performance monitoring of the GMC-1000 and GMC-2000 units, carried out remotely in the mines where the units are installed. The values of the parameters depend on the conditions underground and the load resulting from the ice water required for the gallery air coolers.

Some values of the parameters of the cooling unit performance were derived from direct measurements and some were calculated. The temperature increments, condenser heat power, heat transfer coefficient, cooling power ratio, cooling efficiency and power requirement of the compressor drive values are calculated. The power requirement of the compressor drive in mine conditions was determined based on the evaporator and condenser energy balance (Table 3).

TABLE 3

Results of performance measurements of the GMC-1000 Mine Cooling Unit (Rydułtowy-Anna Coal Mine)

Measured or calculated value	**Symbol**	**Unit**	**Design value**	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Evaporation point	t_o	°C	0.5	0	3.9	2.8	6	3	5.2
Condensation point	t_k	°C	42	53	53	53	53	53	53
Slide position	H	%	100	81	77	77	70	67	64
Vapour pressure	p_o	bar		1.9	2.3	2.2	2.6	2.2	2.5
Water temperature at condenser inlet	t_{w3}	°C	28	29	34	33	34	34	37
Water temperature at the condenser outlet	t_{w4}	°C	38	35	39	39	39	38	41
Condenser water flow rate	V_{sk}	m^3/h	125	135	145	145	145	135	145
Water temperature at evaporator 1 inlet	t_{w5}	°C	16.5	17	19	17	21	13	16
Water temperature at the evaporator 2 outlet	t_{w6}	°C	3	8	7	6	10	6	7
Evaporator water flow rate	V_p	m^3/h	65	56	52	52	52	57	52
Water temperature change in the condenser	Δt_{ws}	K	10	6	5	6	5	4	4
Water temperature change in the evaporator	Δt_{wo}	K	13.5	9	12	11	11	7	9
Condenser power output	Q_s	kW	1450.9	940.2	841.5	1009.8	841.5	626.8	673.2
Cooling efficiency (calculated)	Q_o	kW	1110.0	586.5	726.1	665.6	665.6	464.3	544.6
Power requirement	P_{el}	kW	350.0	353.7	115.4	344.2	175.9	162.5	128.6
Cooling power factor	ε	–	3.17	1.66	6.29	1.93	3.78	2.86	4.24
Logarithmic mean temperature difference	ΔT_m	K	7.27	11.94	7.58	7.38	8.32	5.81	5.02
Heat transfer coefficient	k	W/m^2K	638.61	205.53	400.87	377.27	334.65	334.14	453.65
Cooling efficiency Q_o/Q_n	E_{ch}	–	1.00	0.53	0.65	0.60	0.60	0.42	0.49
Evaporation and water temperature difference at the evaporator 1 inlet	$t_{w5} - t_o$	K	16	17	15.1	14.2	15	10	10.8
Cooling efficiency – measured	Q_{op}	kW	1110.0	593.0	696.0	677.0	690.0	484.0	532.0

TABLE 4

Results of performance measurements of the GMC-2000 Mine Cooling Unit
(Bielszowice Coal Mine of Ruda Śląska)

Measured or calculated value	**Sym bol**	**Unit**	**Design value**	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Evaporation point	t_o	°C	0.5	5.8	7.8	9.9	4.7	3.9
Condensation point	t_k	°C	42	56.5	56.4	56.4	56.5	56.4
Slide position	H	%	100	74	68	60	57	57
Vapour pressure	p_o	bar		2.5	2.8	3.4	2.4	2.3
Water temperature at condenser inlet	t_{w3}	°C	28	45.2	44.8	46.4	48.7	48.4
Water temperature at the condenser outlet	t_{w4}	°C	38	52.1	52	52.6	54.6	54.7
Condenser water flow rate	V_{sk}	m^3/h	250	200	195	201	165	165
Water temperature at evaporator 1 inlet	t_{w5}	°C	16.5	23.4	25.1	26.8	17.1	16.6
Water temperature at the evaporator 2 outlet	t_{w6}	°C	3	6.8	7.9	11.2	5.3	5.3
Evaporator water flow rate	V_p	m^3/h	127	91	90	92	91	91
Water temperature change in the condenser	Δt_{ws}	K	10	6.9	7.2	6.2	5.9	6.3
Water temperature change in the evaporator	Δt_{wo}	K	13.5	16.6	17.2	15.6	11.8	11.3
Cooling efficiency (calculated)	Q_o	kW	2000.0	1745.6	1788.8	1658.5	1240.8	1188.3
Logarithmic mean temperature difference	ΔT_m	K	7.27	5.79	3.34	6.08	3.90	5.12
Heat transfer coefficient	k	W/m^2K	575.33	630.91	1121.22	570.47	666.25	485.11
Cooling efficiency Q_o/Q_n	E_{ch}		1.00	0.87	0.89	0.83	0.62	0.59
Evaporation and water temperature difference at the evaporator 1 inlet	$t_{w5} - t_o$	K	16	17.6	17.3	16.9	12.4	12.7
Cooling efficiency – measured	Q_{op}	kW	2000	1758	1801	1670	1249	1196

Figures 6 and 7 present the scatter plots of the relationship between the unit cooling power Q_o and the position of the H slide adjusting the compressor output.

Figure 6 shows the results for the GMC-1000 unit obtained during the prototype tests (in Dębica and Rudna) and in Rydułtowy - Anna Coal Mine. Due to a higher power rating, the results obtained for the GMC-2000 unit are shown in figure 7.

The cooling power of a unit increases with the increase of the stream of refrigerant compressed in the compressor (fig. 6). For the control slide position corresponding to $H = 100\%$, the cooling power was found both lower and higher than the nominal value. This depends on the stream of ice water flowing through the evaporator and its temperature. Changes of the cooling power depending on the position of the slide determine the adjustment and control potential of the system parameters. With the cooling unit operating at normal conditions in a mine, the control slide position is always below the maximum value. The highest settings of the control slide are little above 80% (for the GM-1000). This means that there is a considerable reserve of cooling efficiency of those units.

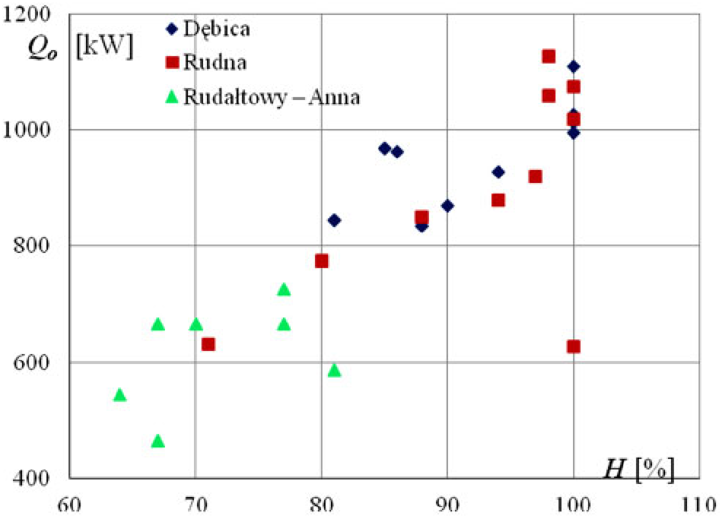

Fig. 6. Cooling power depending on the slide position for the GMC-1000 unit

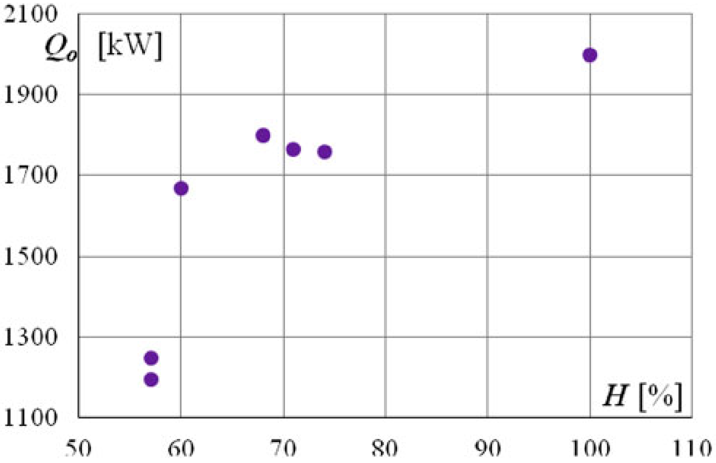

Fig. 7. Cooling power depending on the slide position for the GMC-2000 unit

The following figures (fig. 8 and 9) show the relationship between lowering the ice water temperature in the evaporator depending on the unit cooling power. Due to the differences in the power rating of the cooling units, figure 8 shows the temperature decrements for the GMC-1000 unit, and for the GMC-2000 in figure 9.

The calculated decrease of ice water temperature in the cooling unit is identical for both cases – Δt_{wo} = 13.5 K. The actual decrease of the ice water temperature in the evaporator can considerably exceed the values assumed. The highest temperature difference values achieved are

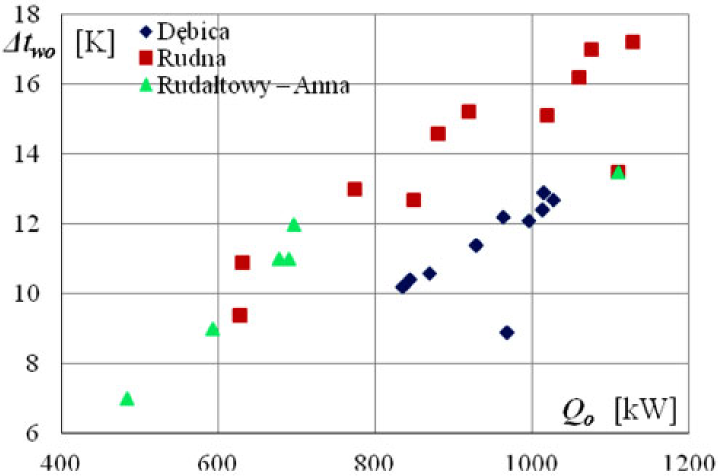

Fig. 8. Ice water temperature decrease Δt_{wo} w in the evaporator depending on the cooling power in the GMC-1000 unit

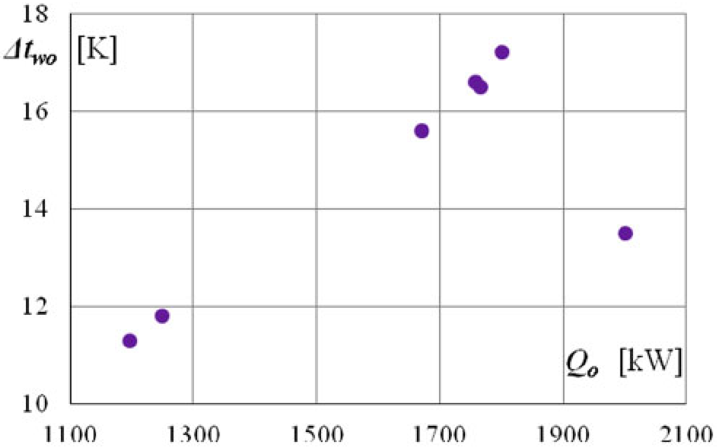

Fig. 9. Ice water temperature decrease Δt_{wo} w in the evaporator depending on the cooling power in the GMC-2000 unit

17 K for both cooling units. Lower power rating of a unit correspond to smaller values of the ice water temperature decrease. Markedly smaller temperature differences are the case when lowering the cooling power by about 25%. With cooling capacities differing little from the nominal capacity, it is possible to achieve higher temperature difference than assumed. Note, however, that, if this is the case, the stream of cooling water for the gallery air coolers is smaller. Figures 8 and 9 prove the linear relationship between the ice water temperature decrease and cooling power of the mine cooling unit.

The cooling efficiency ratio was defined as the relationship between the actual cooling power and the nominal cooling power. It is a dimensionless ratio with the values ranging from 0 to 1 (values slightly above 1 are possible for the cooling power above the nominal), therefore its values for both power ratings are shown in one plot (figure 10). The wide range of cooling efficiency values obtained from the measurements proves very good regulating properties of the unit. A rule can be formulated that decreasing the capacity slide setting corresponds to a higher decrease of the cooling efficiency ratio.

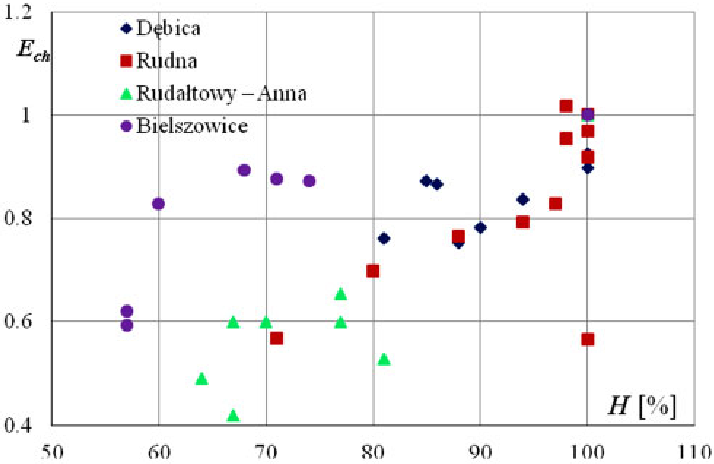

Fig. 10. Relationship of the cooling efficiency E_{ch} of the mine cooling unit and the position of the control slide H

The results achieved for the selected parameters are shown in a form of scatter plots, as for the conditions of the prototype tests and the operation of mine cooling equipment did not allow determining the values of the selected parameters and studying their effects on the performance of the cooling unit. In this situation, the number of variables is too high to determine the functional relationships for individual values. The results obtained make it possible to evaluate the mine cooling unit against its designed specifications.

5. Summary

The values of operating parameters achieved by the GMC-1000 and GMC-2000 mine cooling units on the testing workstation and in the operating tests have confirmed the design specifications. The values assumed at the design stage were achieved in the workstation tests. The cooling power assumed was 1000 kW, and during the measurements 1250 kW was achieved. Such power was achieved at 100% setting of the slide controlling the flow of the refrigerant through the compressor and the decrease of ice water temperature in the evaporator 11.4 K. This results in 25% cooling power reserve in relation to the nominal cooling power, the ice water temperature decrease in this case is 15.5% lower in relation to the assumed value. The power reserve is higher in relation to the shortage of temperature decrease, which means that it is possible to achieve the required temperature drop even with lower cooling power values. This makes is possible to regulate the cooling unit parameters in a wide range.

In several measurements, the water cooling temperatures were more favourable than assumed at the GMC design stage. Broad variability ranges of the parameter values create great control possibilities for the operation of the GMC-1000 and GMC-2000 mine cooling units. Achieving the designed cooling degree of ice water will allow the required cooling of air by the longwall air cooler.

The results achieved in the workstation tests, during the test run and operation in mines allow the conclusion that the mine cooling unit is suitable for use in central air conditioning systems of underground mines.

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