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Application of Ice Slurry as a Phase Change Material in Mine Air Cooling System—A Case Study

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Abstract

Fossil fuels, including coal, are a basis of energy systems in many countries worldwide. However, coal mining is associated with several difficulties, which include high temperatures within the coal mining area. It causes a need for cooling for safety reasons and also for the comfort of miners' work. Typical cooling systems in mines are based on central systems, in which chilled water is generated in the compressor or absorption coolers on the ground and transported via pipelines to the air coolers in the areas of mining. The progressive mining operation causes a gradual increase in the distance between chilled water generators and air coolers, causing a decrease in the efficiency of the entire system and insufficient cooling capacity. As a result, it is necessary to increase the diameter of the chilled water pipelines and increase the cooling capacity of the chillers, which is associated with additional investment and technical problems. One solution to this problem may be the use of so-called ice slurry instead of chilled water in the existing mine cooling system. This article presents the cooling system, located in the mine LW Bogdanka S.A., based on ice slurry. The structure of the system and its key parameters are presented. The results show that switching from cooling water to ice slurry allowed the cooling capacity of the entire system to increase by 50% while maintaining the existing piping. This demonstrates the very high potential for the use of ice slurry, not only in mines, but wherever further increases in piping diameters to maintain the required cooling capacity are not possible or cost-effective.

Keywords: ice slurry; phase change material; mine; cooling system

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1. Introduction

Mines play a vital role in the modern industrialized world by enabling the extraction of fuels and various raw materials essential for every industry. One of the most critical challenges in the mining sector is the high temperature in underground extraction areas, which adversely affects both the health and comfort of miners [1] as well as the performance and longevity of underground equipment [2]. Therefore, effective cooling of these areas is necessary to ensure safe and comfortable working conditions.

Mine cooling technologies can generally be categorized into artificial methods (e.g., mechanical refrigeration systems, ice slurry cooling systems) and non-artificial methods (e.g., ventilation, heat source insulation). However, in deep, high-temperature mines, non-artificial methods alone are insufficient [3]. Consequently, mechanical refrigeration technology has become the predominant solution. This approach involves generating chilled water using refrigeration units and distributing it through insulated pipelines to air

coolers installed at the extraction areas [3]. However, in mines, the distance between the mine face and the mine shafts tends to become increasingly longer over time. Then, the pipelines transporting chilled water to the air coolers also become increasingly longer [4]. Despite thermal insulation, the increasing length of the chilled water transport pipelines translates into increasing heat loss, which results in an increase in the temperature of the chilled water supplied to the coolers in the mining work areas. If the temperature of the chilled water at the inlet to the coolers increases, the performance of the air coolers decreases, and it becomes increasingly difficult to achieve the required air temperature at the extraction area. In order to be able to increase the performance of the existing cooling system using chilled water and also to reduce the chilled water temperature at the inlet of the air coolers, the flow rate of chilled water in the pipelines usually has to be increased significantly [5]. Until now, this has been the only way used to increase the cooling capacity of a centralised system. Unfortunately, in order to be able to do this, not only the surface infrastructure has to be expanded, but also the vertical and horizontal pipelines have to be replaced with larger ones. Due to the fact that the centralised cooling system covers the entire mine, such a solution would require a temporary reduction or even suspension of the mining work, and therefore it is very costly. An alternative solution to date could be the construction of a completely new shaft with associated infrastructure, a new machine hall on the surface, and the installation of new vertical and horizontal pipelines. Such a solution does not require any mining downtime, but it is time-consuming and also very costly. Therefore, solutions that enable an increase in the cooling capacity of mine refrigeration systems are in high demand. One such technology is the use of ice slurry as a replacement for chilled water [6]. Ice slurry is a mixture of water, fine ice particles, and typically a freezing point depressant [7]. Its primary advantage over chilled water lies in its significantly higher energy storage density, owing to the latent heat absorbed during the solid–liquid phase transition of ice (approximately 334 kJ/kg).

This paper shows another solution to the problem of increasing the capability of transporting cooling with the use of existing infrastructure. The solution in question is based on the use of ice slurry, as a phase change material (PCM), instead of chilled water in the existing mine cooling system. The case described in the paper relates to the world's first central air-cooling system, launched in recent years in the LW Bogdanka S.A. mine, in which ice slurry circulates in a closed-loop system from the production site on the surface to underground air coolers in the mining areas.

The paper is divided into four sections. The first section provides a brief background on the issue of mine cooling. The second section offers a literature review on air cooling in underground mines, addressing key challenges such as heat losses in pipelines and examining the characteristics of ice slurry. The third section details the implementation of a central air-cooling system utilizing ice slurry, introduced at the LW Bogdanka S.A. mine in 2021. The final section presents the conclusions derived from the study.

2. Air Cooling in Mines

Where there is a significant demand for cooling power, chillers are used which are located on the surface or underground in the immediate vicinity of the extraction areas. Where the demand for cooling is increased, one solution that is always considered involves provision of additional cooling by means of compressor units of lower capacity. This solution is called group or local air-conditioning. Unfortunately, a side-effect of the production of cooling underground is always the production of heat (a larger quantity at that) which has to be extracted from these devices. Heat from underground cooling equipment can be transferred to the airflow ventilating the mine (if its temperature and the air humidity are not too high) or to the drainage system of the mine, or to the return water from the central

cooling system (if the mine has one). Transferring this excess heat to the return water from the central air-conditioning system involves raising the temperature of the water, which in turn is further associated with the need to lower it further at the Surface-Based Air Conditioning Station (SBACS) (the need to increase the cooling capacity at the surface). Unfortunately, such a solution entails the need to cover the cost of producing cooling twice. The first time the costs occur with the local additional cooling of the feed chilled water in the underground pipeline, and the second time with the cooling of the return water (to which the excess heat has been transferred) at the SBACS. Therefore, local additional cooling of the water in the central air-conditioning pipeline is not economically feasible for large systems and can only be used locally with small-scale cooling capacity [8].

Group air-conditioning usually consists of two water chillers installed in parallel. It should be borne in mind that if evaporators containing a refrigerant are used in a group air-conditioning solution, toxic refrigerants such as ammonia must not be used underground for safety reasons. In group air-conditioning, water pipelines are usually very short and there is no need for shaft pipelines or water hydrostatic pressure reduction devices when discharging condensation heat into the ventilation air.

Mines with high cooling power requirements use central air conditioning by installing chillers (with large capacities) to cool the water at the surface. From the surface, the water is transported underground via shaft pipelines, and from there the cooling is fed via chilled water pipelines to the mining work areas and underground air coolers. A typical central mine cooling system (central mine air conditioning) consists of three main parts, i.e., above-ground, shaft, and underground [9]. Figure 1 shows a block diagram of a central mine cooling system.

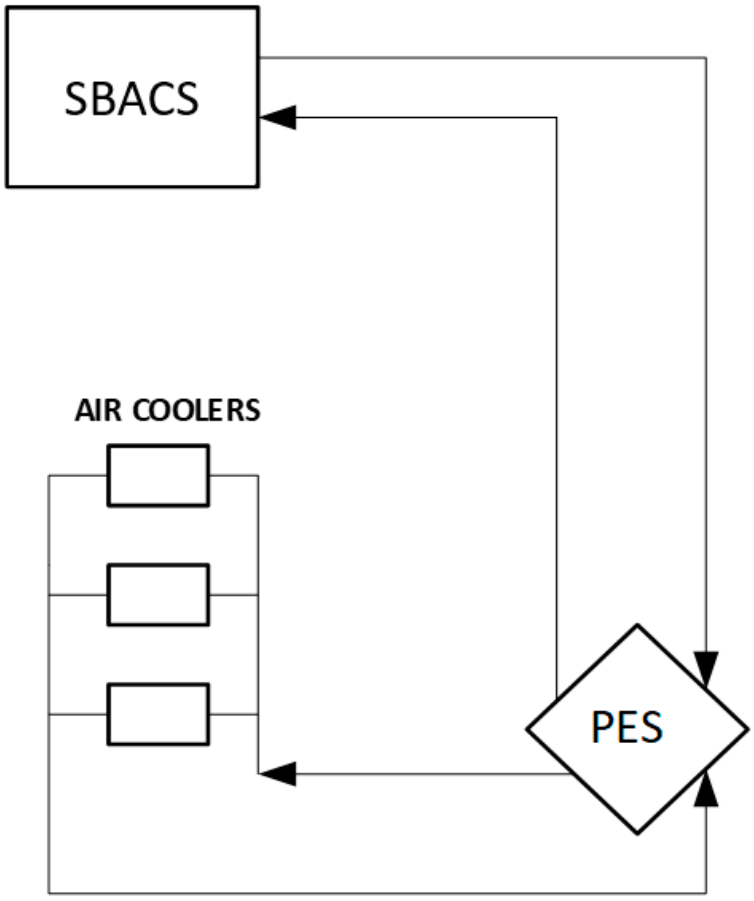


Figure 1. Block diagram of a central mine cooling system.

In the above-ground part, there is always a main machine hall called SBACS. In this hall, there are usually refrigeration compressors and/or absorption chillers (usually with cooling towers to extract waste heat from the system) together with power, protection, control, and adjustment systems. In addition, the SBACS usually contains a device for replenishing and filtrating water circulating in the system. At the water outlet from the SBACS, there are pumps installed to force the flow of chilled water in the pipeline between the above-ground part of the system and the shaft and underground parts. In the shaft part of the central cooling system, there are usually two high-pressure pipelines (at least the feed pipeline is thermally insulated). These are routed vertically in the shaft and are used to deliver chilled water down the mine and to return the heated water to the surface for re-cooling at the SBACS. The underground part of the central mine cooling system usually consists of a Pressure Exchanger System (PES), circulating pumps, which force the flow of cold water, and a system of insulated (feed) and uninsulated (return) low-pressure pipelines that bring the chilled water to the air coolers in the extraction areas of the mine.

Figure 2 shows a diagram of the operation of one Pressure Exchanger System (PES) module. Chilled water is supplied to the PES chamber from the SBACS. While the chamber is being filled with chilled water from the SBACS, the warm water present in the chamber is pushed into the SBACS (using the potential energy of the water from the vertical shaft pipeline). After the PES chamber has been filled with chilled water, it is sent through the horizontal pipelines towards the air coolers and is replaced by warm water that is pumped from the air coolers. The entire PES consists of three such chambers operating in a certain sequence of filling and emptying, which enables the continuous supply of chilled water to the air coolers.

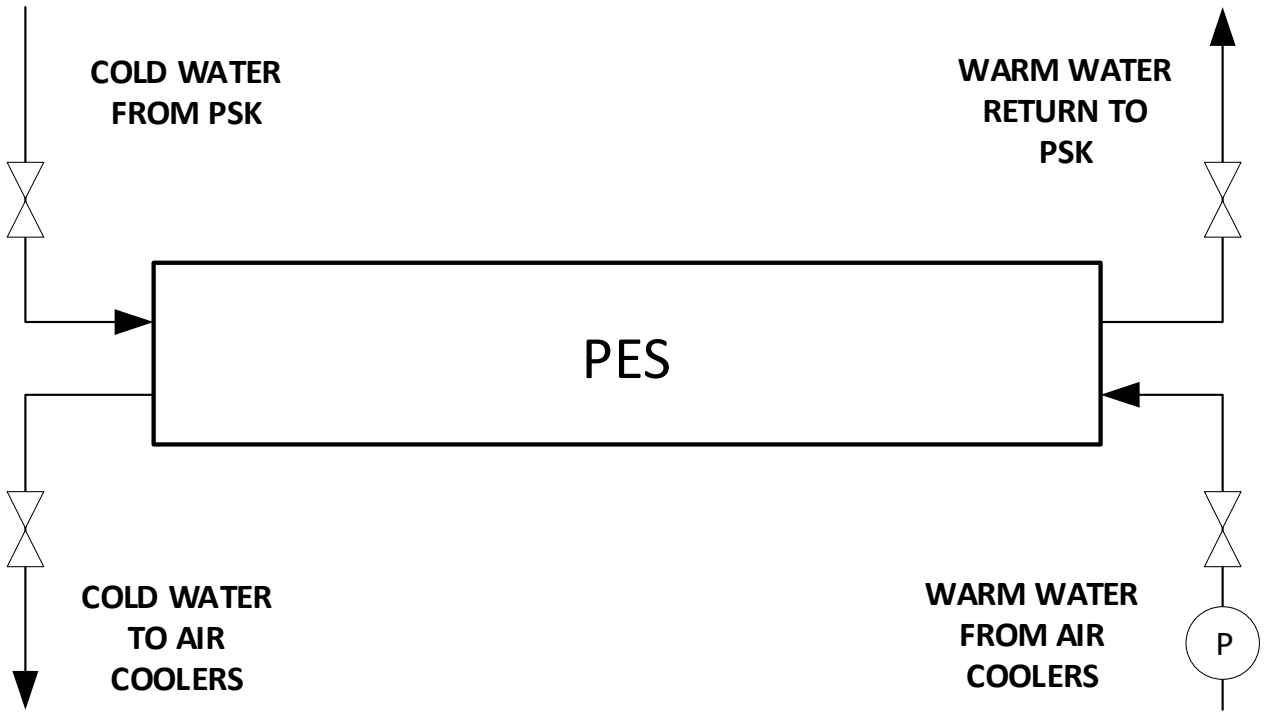


Figure 2. Operation of the Pressure Exchanger System (PES).

The main advantage of the central mine cooling system is that the chilled water is prepared at the surface, which allows the waste heat generated in the process to be easily dissipated or used for energy purposes, or to use so-called free cooling for pre-cooling of the warm water. It is also possible to recover the thermal energy contained in the warm water pumped out. Thanks to the presence of machines on the surface, it is also possible

to use thermal waste energy, e.g., from cogeneration engines, to power the absorption chillers at the SBACS. The location of the chillers on the surface also makes it possible to use working fluids that are efficient but dangerous to humans in the chillers. An example of such a working fluid would be ammonia the toxicity of which is an obstacle to using it underground. Another advantage of such a central cooling system is the low cost of pumping chilled water due to the use of the U-tube effect in the shaft piping and the PES. The installation of the chillers in the SBACS and the production of cooling on the surface mean that there is no need to supply high-power electricity to the chillers in the extraction areas (as in the case of local and group systems).

The disadvantages of a central mine cooling system include the relatively high capital costs of the system, mainly because of the need to build a surface hall with water cooling equipment, to build two high-pressure pipelines in the shaft, and to build a PES at virtually every level of the mine. The high costs are to a large extent due to the necessity to build a network of underground chilled water pipelines.

A certain variation of the central mine cooling system with chilled water is a system using ice particles. An example of the use of such a system with ice particles is the 3.5 km deep Mponeng mine in South Africa [10]. In this mine, ice particles are produced in the above-ground part of the system, which are then delivered gravitationally to underground reservoirs where they stabilise the water temperature at 2 °C. From the underground reservoirs the chilled water is pumped to air coolers in the extraction areas, and from there it is pumped back to the surface [10]. Figure 3 shows a block diagram of the air cooling system at the Mponeng mine in South Africa.

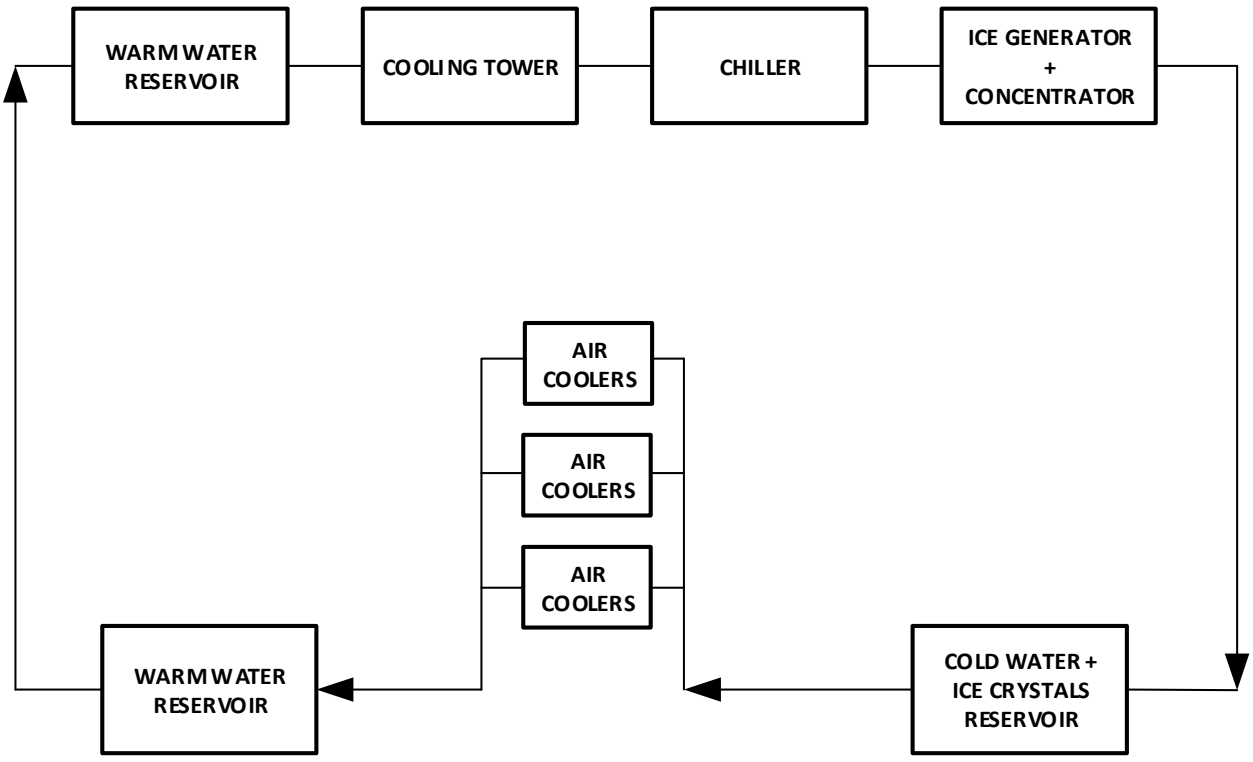


Figure 3. Block diagram of the air cooling system at the Mponeng mine.

The warm water returning from the mine is collected in a surface warm water reservoir and is then pre-cooled (in the cooling tower and chiller). After having been cooled down to a temperature in the range of 3 °C to 6 °C, the water flows into the Vacuum Ice Maker (VIM). In the VIM, operating at the triple point of water (at a temperature of about 0 °C and a pressure of 600 Pa at which solid, liquid, and gas phases coexist), ice particles are

formed. Figure 4 shows a block diagram of the system for producing ice particles (slurry) at the Mponeng mine.

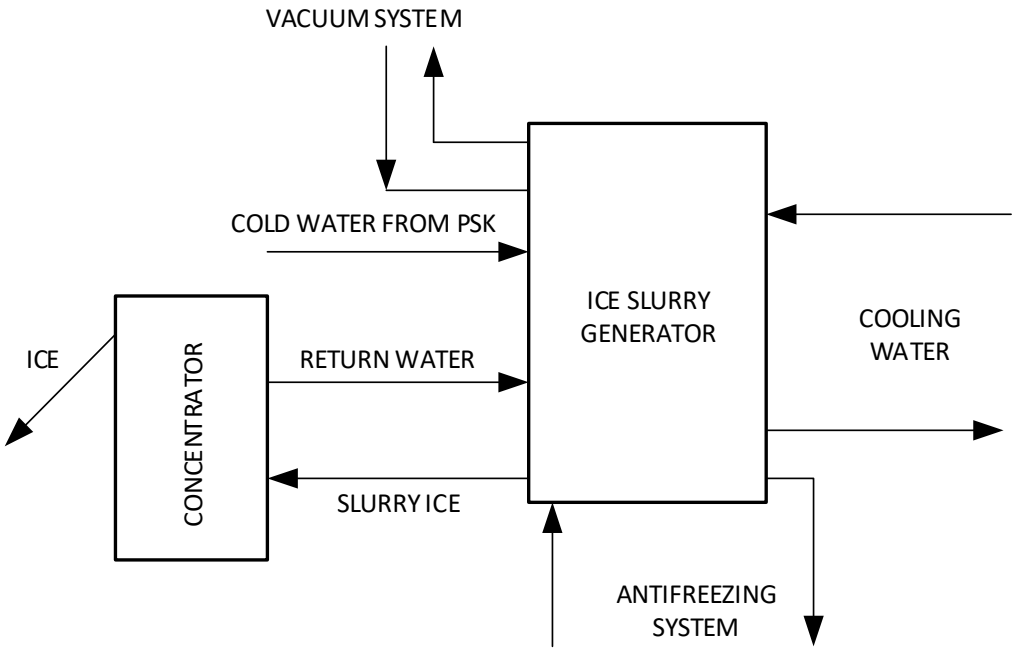


Figure 4. Schematic of the system for producing ice particles (slurry) at the Mponeng mine.

In the VIM the water is under very low pressure, which causes some of the water to evaporate. Due to the process of evaporation, heat is extracted from the remaining water in the generator, resulting in a mixture of water and ice particles. The ice slurry thus formed is pumped into the concentrator where the two phases are separated due to the difference in density of ice and water. The water without ice particles is pumped back to the VIM and the ice is collected and sent via a conveyor belt system to the mine shaft and further underground to the various levels where the mining is carried out. The ice produced on the surface accumulates in underground cold water reservoirs where it stabilises water temperature as it melts. The disadvantage of this solution is an increase in air humidity in the mine due to the operation of underground cold and warm water reservoirs. The water stored in these reservoirs becomes contaminated (mainly from the air in the mine) and must be cleaned before it can be used again. The ice particles only have the function of stabilising the temperature of the cold water in the reservoir. Due to the large capacity of the cold water reservoirs, it is not possible to mix the particles thoroughly with the water, so they accumulate on the surface of the reservoir. Therefore, the water that is piped to the distant air coolers is heated as a result of heat losses (the temperature of the feed water to the air coolers therefore rises). Another disadvantage of this solution is the significantly higher cost of pumping the warm water to the surface compared with the PES systems (no possibility of using the U-tube effect).

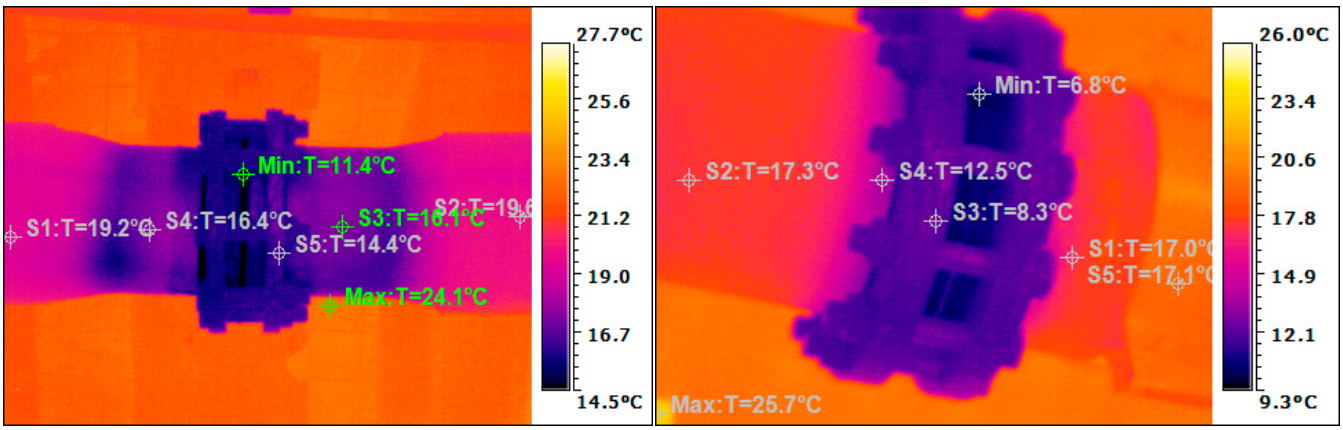
2.1. Heat Losses in the Pipelines

It is estimated that, depending on the length and condition of the pipelines in the mine, as much as half to two-thirds of the available capacity of the surface cooling system (at the SBACS) is lost due to heat losses through the walls of the underground pipelines (because of excessively high water temperature at the inlet to the air coolers) [8]. Taking only this aspect into account, producing cooling locally (where there is the demand) would be most advantageous. Unfortunately, as is well known, where cooling is produced, waste heat is always generated, which is very difficult to remove in underground conditions.

Air coolers used in extraction areas do not achieve their rated cooling capacities. Their nominal capacities are quoted by the manufacturers with reference to a feed water temperature of typically 2 °C while under actual conditions in the mine, the feed water flowing into the remote air coolers can often even exceed 8 °C. Thus, it is still cool water, yet too warm to achieve the required air temperature at the miners' work area with the assumed number of coolers.

The situation becomes even worse when the velocity of the water is low and the volume flow rate in the supply pipes is low. Unfortunately, an increase in the velocity of the water will result in an increase in the flow resistance in the pipeline network (and an increase in the pressure), which in turn entails an increase in the costs of transport and the necessity to use pipelines of higher strength. It should also be remembered that the air coolers reduce the temperature of the air, but also dehumidify the air as a result of its contact with the surface of the exchanger at a temperature below the dew point. The air in mine workings usually has a high humidity (70–85%) [8], which means that the cooler does not cool the air to the expected temperature (according to the manufacturer's specifications) because water vapour condenses on the surface of the cooler during air cooling (the latent heat of condensation depends on the amount of condensed water, and the amount of this water depends on the humidity of the air at the inlet to the cooler).

The majority of underground mines experience an increase in their underground infrastructure during the course of their operation due to the need to move the mining areas horizontally and vertically (seams at different depths). As the underground infrastructure of a mine is extensive and constantly growing, the underground network of chilled water pipelines is also extensive. Despite the use of thermally insulated pipelines, significant heat losses occur in such a central mine cooling system. Most commonly, two types of pipes are used to transport chilled water, i.e., insulated steel pipes or pre-insulated plastic pipes. Figure 5 shows examples of infrared images of two sections of chilled water piping in a mine including flanged connections. Figure 5a shows a photo of a pre-insulated plastic pipe and Figure 5b a photo of an insulated steel pipe.



(**a**) (**b**)

Figure 5. A section of a diameter nominal DN150 chilled water pipeline in a mine with flanged connection (infrared photo): (**a**) pre-insulated plastic pipeline; (**b**) insulated steel pipeline.

Both photographs were taken on the same day and at the same location in the mine. It should also be added that the temperature of the chilled water (about 5.5 °C) as well as the mass flow rate of the water were also the same. Although the temperature and humidity were similar in both cases (26.5 °C, 72%), differences can be seen in the surface temperatures of the two pipelines (outer diameter). The external surface temperature of the pre-insulated pipeline is approximately 2 °C higher than that of the insulated steel pipeline.

This is due to the fact that in this case, the pre-insulated pipeline has an almost one-third thicker insulation than the insulated steel pipeline, i.e., it is also characterised by lower heat losses. Given the small dimensions of the connections, their surface temperatures, and the fact that flanged connections are usually found every 6 m in the pipeline, the expected heat losses at the connection flanges will be negligible compared with those at the pipes. Due to the flange design, lower heat losses occur at the flanges in the pre-insulated plastic pipeline. Depending on the temperature and humidity of the air in the mine, the temperature of the chilled water in the pipeline and the thickness of the pipeline insulation, heat losses of 22–58 kW/km of pipeline can be expected in the case under consideration (taking into account heat losses at the flanges).

2.2. Ice Slurry

Ice slurry is a mixture of a liquid, usually water-based, and ice particles. The ice particles are usually no larger than 0.5 mm in size [11]. Some properties of ice slurry depend on the type of base liquid from which the slurry is produced. For instance, if ice slurry is produced from water, its temperature will not be below 0 °C. Such ice slurry can be used in air cooling systems in mines. Adding a substance such as, e.g., ethyl alcohol to water lowers its freezing point so that the slurry can reach a temperature below 0 °C [11].

Ice slurry has found in numerous applications, including food preserving, air conditioning, and pipeline pigging [7]. However, due to the high enthalpy of fusion and low melting point of ice, ice slurries are ideal for transporting and storing cooling. The main advantage of ice slurry over traditionally used coolants, such as water, is a high specific heat capacity, the fact that it is neutral to the environment, and the possibility of using ice slurries not only as a heat carrier, but also as a heat storage medium. The disadvantages of ice slurry compared with other coolants are its higher viscosity, its tendency to clump, and the variability in rheological properties over time due to the melting of ice crystals [12]. Unlike water, the practically constant temperature of ice slurry allows for a greater temperature difference of the media in heat exchangers, making it possible to use exchangers with smaller heat transfer surfaces. Due to the almost constant melting point of ice, higher heat exchanger efficiencies are achieved and a lower temperature of the cooling medium can be achieved. Figure 6 shows a comparison of the relative cooling capacity [kW/(kg/s)] for an ice slurry stream with a temperature of 0 °C and an ice content of 5–20% at the feed and 15 °C at the return with water with a temperature of 2–10 °C at the feed and 15 °C at the return.

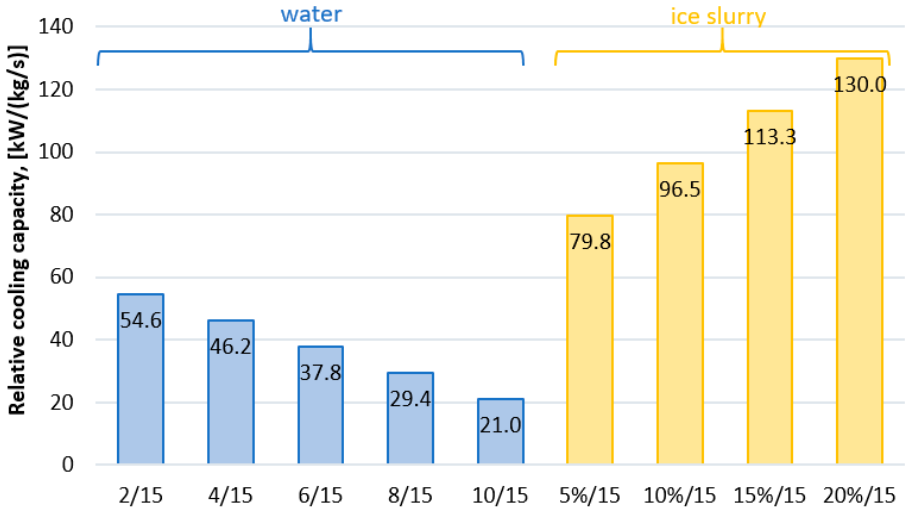


Figure 6. Comparison of relative cooling capacity [kW/(kg/s)] for ice slurry at 0 °C and an ice content of 5–20% (15 °C return) with water at 2–10 °C (15 °C return).

When analysing Figure 6, it should be taken into account that it is quite difficult to obtain a low feed water temperature (e.g., 2–4 °C) at the feed of a remotely located exchanger. The water will heat up as it flows through the pipeline due to heat loss, and achieving a low temperature (around 0 °C) at the outlet of the chiller is also rarely possible for fear of damaging the unit. When using chilled water in an extensive cooling system, therefore, it is actually temperatures of 5–6 °C or even higher that can be expected at the feed of remotely located heat exchangers. For systems using ice slurry, its temperature is 0 °C if there are still ice particles in it. The higher proportion of ice particles in the slurry at the feed of heat exchangers results in a higher relative cooling capacity than that of water.

Ice slurry can have different contents of ice particles, and the rheological properties of such slurry depend on the content of these particles in the mixture. Most researchers believe that there is a certain threshold value for the mass content of ice particles (approx. 15% of ice particles in the slurry) above which the ice slurry begins to exhibit increasingly pronounced non-Newtonian fluid characteristics [13–15].

Figure 7 shows the main operational problems associated with ice slurry. If the flow of the ice slurry in the pipeline is stopped, or its velocity decreases significantly, there will be a loss of homogeneity due to the difference in density between ice and water. The ice particles will start to accumulate in the upper part of the pipeline and the water in the lower part [16]. This is particularly disadvantageous if there are pipe tees or manifolds with vertical branches in the pipeline. If this is the case, there will be an uneven separation of the solid and warm fractions, which may even result in blockage of the slurry flow. Another problem that can occur when the flow is stopped is the separation of the solid and liquid fractions in the riser pipe. In this situation, the accumulated particles may in some cases be pushed out of the riser pipe.

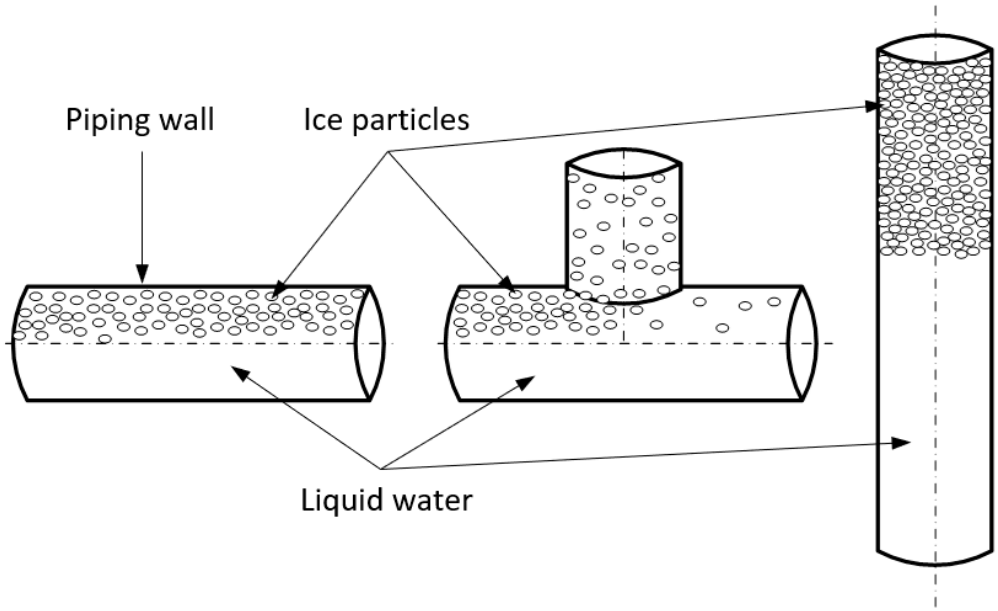


Figure 7. Main operational problems associated with ice slurry.

According to the literature, the models that are most commonly used to describe the rheological properties of the slurry are those by Bingham, Ostwald, Casson, and Herschel–Bulkley [17]. The production and transport of ice slurry involve quite complex processes because depending on the method of ice production (e.g., ice generators using scrapers or vacuum), the size of the ice particles, the flow velocity, as well as the diameter and shape of the conduit through which the slurry flows, there may be, e.g., sedimentation

of ice particles in the slurry, inhomogeneity in its composition, or even differences in the velocity of the solid and liquid phases of the slurry [13,18].

The literature on the subject presents the results of experimental studies of frictional resistance of ice slurry flowing in straight sections [14,17,19,20] and local resistance in most basic pipeline components, such as constrictions, expansions, elbows, and tees [15,21], and in heat exchangers [22–24]. The results and method of flow calculations of ice slurry in very long vertical pipeline sections are also shown [5].

The results of the investigations show that in the laminar range, the local loss coefficients increase with increasing ice particle content in the slurry. In the turbulent range, the local loss coefficients of the ice slurry flowing through the pipeline components are the same as for Newtonian fluids regardless of the content of ice particles in the slurry.

Only a few publications describe flow resistance of ice slurry in valves. Some similarities between the flow of ice slurry in valves and the flow of other non-Newtonian fluids can be seen in papers [25–27]. The results of these studies show that in the turbulent range, irrespective of the content of ice particles in the slurry, the local loss coefficients of the ice slurry flowing through valves are the same as the literature data for Newtonian fluids. The paper [28] presents experimental values of local loss coefficients for gate valves through which ice slurry formed with an ethanol solution flows. The results presented in the paper show that the values of the local loss coefficients in the laminar range for gate valves through which ice slurry flows also depend on the ice content of the mixture. In most cases, the more ice particles in the slurry, the higher the local loss coefficients in the gate valves in the laminar range. In the turbulent range, the values of the local loss coefficients in the gate valves were found to be in agreement with the theoretical values for Newtonian fluids from the literature. The papers [15,29] present the results of studies of flow resistance of ice slurry formed with an ethanol solution in globe and ball valves. Previously published research papers on heat and mass transfer of ice slurry and its flow resistance in various pipeline fittings allowed numerous applications of this slurry in cooling and air-conditioning systems of buildings, in cooling storage systems, fishing, dairies, fire-fighting, and even in medicine and for artificial snowmaking on ski slopes [30]. Ice slurry can also be used for cleaning drinking water pipelines [31]. Ice slurry is also suitable for use as a coolant in air cooling systems in mines [10,13,32,33]. A certain danger associated with the use of ice slurry is the possibility of clogging of the system and uneven distribution of the medium in the branches (care should always be taken to ensure adequate flow velocities in the system that homogenise the composition of the mixture and avoid tees and manifolds installed vertically). It is also necessary to eliminate the segregation of ice in the accumulation reservoir by means of stirrers, which slightly increases electricity consumption compared with single-phase coolant systems.

3. Mine Cooling System Using Liquid Ice Slurry—LW Bogdanka S.A. Case Study

Prior to the extension, the central cooling system of the LW Bogdanka S.A. mine was based on the production of chilled water with a temperature of approx. 1.5 °C on the surface and transferring it via a network of pipelines underground to air coolers in the extraction areas. The water cooled at the Surface-Based Air Conditioning Station (SBACS), in an amount of approx. 264 m^3/h, flowed through insulated shaft pipelines and further through the PES towards the face and longwall coolers. The return pipeline sent water at a temperature of approx. 20 °C through the PES and return shaft piping back to the SBACS. At the SBACS, the return water was again cooled to a temperature of about 1.5 °C by means of cooling equipment and sent again (in a closed circuit) via the PES to the underground cooling receivers at a depth of 990 m. The cooling capacity of this air-conditioning system

was approx. 6 MW. The design of the new cooling system took advantage of the possibility of using water ice, which, combined with chilled water with reduced temperature from the existing cooling system, is now the transport medium for the cooling in the mine.

Figure 8 shows a block diagram of the upgraded mine cooling system using ice slurry at LW Bogdanka S.A. During the modernisation of the central cooling system of the LW Bogdanka S.A. mine, the entire existing infrastructure was used, i.e., the SBACS hall, surface pipelines, vertical (shaft) pipelines, PES, and horizontal underground pipelines, as well as the built-in air coolers. As part of the upgrade, a system for the production of ice slurry was added to that old cooling system with a capacity of about 6 MW. To this end, a second machine hall was added on the surface, in which a vacuum ice particle generator, an ice concentrator with a belt feeder, a mixer, and a pump system were installed. An ammonia chiller was used to cool the ice particle generator while cooling towers on the roof of the new hall were used to discharge waste heat. The entire system is complete with an automatic purification system for the water feeding the generator and a control system with valves. It is worth noting that all the components of the new ice slurry production system are located in the new machine hall, which is situated right next to the old SBACS. The new system (after conversion) allows automatic or manual switching to the old mode of operation (operation using only chilled water). The main part of the extension of the air-conditioning system in the mine is the system for the production of ice particles, which has been entirely located on the surface. The ice particle generating system itself consists of a VIM850 vacuum ice particle generator (Figure 9) and an ice particle concentrator (Figure 10), a mixer (Figure 11), a belt feeder and a pump system, as well as a filtration system for the water feeding the generator.

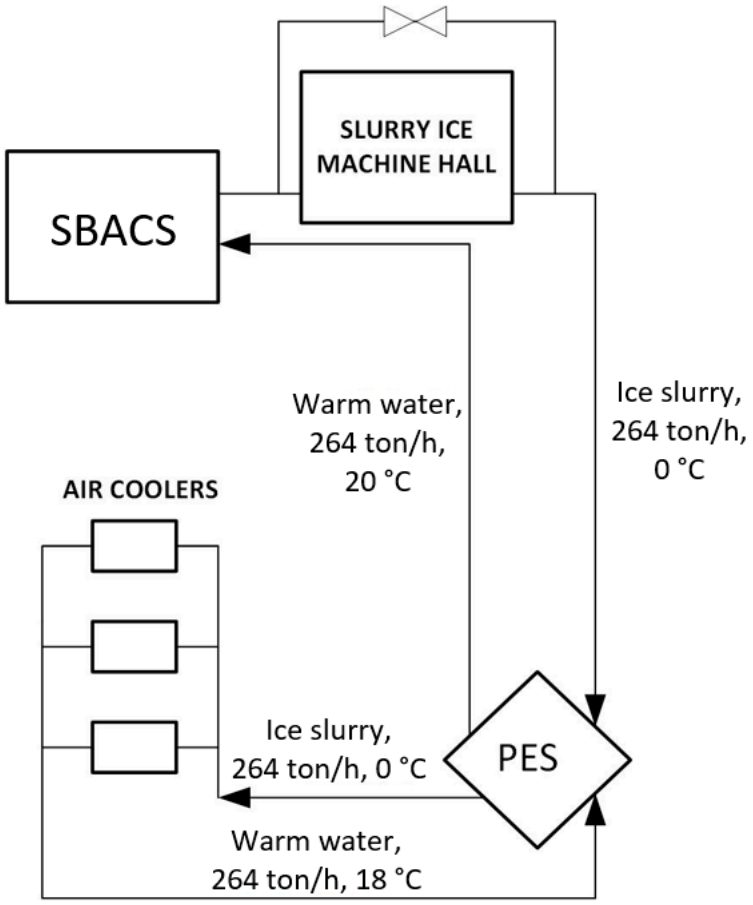


Figure 8. Block diagram of the upgraded mine cooling system using ice slurry.



Figure 9. VIM850 vacuum generator.



Figure 10. Photo of the ice particle concentrator.



Figure 11. Photo of the mixer with belt feeder.

The VIM850 generator has a maximum cooling capacity of 3.1 MW and is rated to produce 1120 tonnes of ice per day with 75% ice particle content. The particles range in size from 0.5 to 1 mm. The unit utilises the triple point properties of water and produces a mixture of water and snow. The mixture is pumped out of the generator into a concentrator which separates the water from the snow crystals and washes the particles so that high quality is obtained. In the VIM generator, water vapour is continuously sucked up, compressed, and fed into the condenser by a special compressor. The VIM generator is cooled using cooling water at 5 °C, supplied from a standard ammonia chiller (separated closed circuit) equipped with cooling towers. Cooling towers were used to receive heat from the ammonia chiller cooling the VIM generator. In the proposed solution, the ice particles generated are delivered from the concentrator to a specially designed mixer by means of a belt feeder. In the concentrator, the ice particles and liquid are separated. The ice particles, due to their lower density, flow upwards in the concentrator, from where they are mechanically scraped onto the belt feeder (Figure 12).

The water separated in the concentrator is pumped back to the VIM generator. The ice particles delivered to the mixer by means of the belt feeder are mixed with chilled water with a temperature of 1.5 °C, supplied from the SBACS. The mixer is cylindrical in shape and contains a mechanical stirrer. This solution does not interfere with the operation of the existing chilled water system or the SBACS itself, and furthermore, it allows the new system for the production of ice particles to be automatically disconnected and the air-conditioning system to operate with chilled water alone where the demand for cooling is low in the mine, or, e.g., when maintenance work is carried out on the ice slurry production system.



Figure 12. Ice particles mechanically scraped in the concentrator.

The proposed solution utilising ice slurry makes it possible to significantly increase the capacity to transport cooling in the central air-conditioning system in the mine without expanding the existing infrastructure, i.e., without increasing the diameter of the pipelines of the primary and secondary circuits. The upgrade of the air-conditioning system at the LW Bogdanka S.A. mine resulted in an increase in the cooling capacity of the system to 9.1 MW. Moreover, the temperature of the medium at the inlet to the shaft pipelines was reduced from 1.5 °C (in the case of chilled water) to 0 °C (ice slurry). In the region of the coolers, a reduction in the temperature of the medium from 8–12 °C to 0–2 °C was achieved. Very importantly, the construction of the air-conditioning system did not affect the operation of the existing air-conditioning system during the upgrade. The construction of the new system was carried out in parallel with the operation of the existing cooling system without any necessary shutdowns or reconstruction of the piping in the system (in contrast to conventional expansion of chilled water cooling systems). Interesting features of this system include the fact that it is equipped with various monitoring and security systems, e.g., a system for automatic emergency melting of ice particles from the pipelines, a system for automatic disconnection of ice particle production and return to chilled water operation even in the event of a power failure in the new hall, full monitoring of the current electricity consumption of the extended system, including lighting and ventilation, and remote supervision of ice slurry production (no need for the presence of employees to monitor the system in the new hall).

Operation of the System

A water flow of approx. 264 m^3/h with a temperature of 1.5 °C at the outlet of the SBACS is routed to the new hall and then split into two parts. The smaller part of it, 40–47 m^3/h, depending on the current operating parameters of the system, is diverted to feed the VIM ice particle generator. At the output of the VIM generator and of the ice concentrator, a stream of 40–47 tonnes/h of ice with 75% content of particles is obtained. The ice particles are transported on a belt conveyor to the mixer. In the mixer, the ice particles produced in the VIM generator are mixed with water at a temperature of 1.5 °C (approx. 214 m^3/h). As a result of the mixing, all the water in the mixer is cooled and its temperature evens out at about 0 °C. After the mixing, the ice slurry is pumped into the

shaft pipelines. Assuming that the total mass flow rate of the mixture (chilled water and ice particles) is 264 tonnes/h and taking into account the estimated heat and mixing losses, the mass content of the ice particles in the mixture is approx. 10% at the inlet to the shaft piping. During the summer, due to heat losses in the shaft pipeline downstream of the PES feeder, i.e., at the inlet to the horizontal shaft pipeline towards the extraction areas at a depth of about 990 m, the proportion of ice particles in the mixture is about 8%. As there are ice particles in the water, which stabilise its temperature in the pipeline at 0 °C, the same temperature level can be achieved at the feed of most of the air coolers in the extraction areas of the mine. The pipeline network in the mine has branches through which the ice slurry is supplied to the different extraction areas of the mine. Depending on the distribution of the slurry flow in the pipeline branches in the mine, more or less cooling can be delivered to the individual areas. Thus, ice slurry with a certain amount of ice particles or chilled water alone without ice particles (after melting in the pipeline) can flow into the individual extraction areas of the mine. Not without significance here are also the thermal losses of the pipeline which depend primarily on the length and diameter of the pipeline and the quality of the thermal insulation of the pipeline. When ice particles were added to the chilled water in the cooling system of the mine, the temperature of the medium in the underground pipelines dropped even several kilometres away from the PES feeder. In some cases, the temperature of the ice slurry at the inlet to the coolers was about 0 °C and 1–2 °C in the remote coolers. When the system was previously operated with chilled water, the temperature of the outermost parts of the pipeline was above 8 °C.

Following the extension of the air-conditioning system of the LW Bogdanka S.A. mine to include a system for the production of ice slurry, the efficiency of cooling in all extraction areas of the mine was significantly improved. Prior to the modernisation of the cooling system, it was not possible to achieve a chilled water temperature of 0 °C not only at the feed of the coolers at the face of the mine, but even at the outlet from the SBACS (due to possible damage). The results of the measurements show that the effect of using ice slurry is that a significant reduction was achieved in the temperature of the air in the mine, in the workings, even to a temperature of about 20 °C. In some areas of the mine, it was possible to increase the amount of cooling received and increase the amount of the ventilation air by about 30% while using the same number of coolers as with chilled water. This resulted in a decrease in air temperature in this area of the mine by almost 6 °C relative to the operation of the system with chilled water (even when the additional cooling by local compressor units is switched off).

The ice slurry generator alone consumes 6.8 kWh of electricity per ton of ice produced. Naturally, the generator operates in conjunction with additional equipment, such as a concentrator, mixer, feeder, and slurry pumps, which are not present in systems operating solely with chilled water. This additional equipment consumes 2.7 kWh per ton of ice produced. Thus, 9.5 kWh is an extra amount of electricity that would be used compared to a system working only with chilled water. The remaining components of the ice slurry system are analogous to those in systems using chilled water, with energy consumption in this part estimated at 23.2 kWh per ton of ice produced. It follows that the total energy consumption in the ice slurry system with a cooling capacity of 3.1 MW is approximately 41% higher than that of a chilled water system with the same capacity. The investment costs for equipment, in the case of expanding an existing 6 MW chilled water cooling system with a 3.1 MW ice slurry system, are about 70% higher than the investment costs of expanding with a 3.1 MW chilled water system.

However, a direct comparison of mine cooling systems using chilled water and those using ice slurry based solely on energy consumption and investment costs is not fully representative. It is necessary to consider not only energy intensity or capital expenditures

but, above all, the effectiveness of air cooling provided by these systems. Given the large scale of such mine cooling systems (usually covering several dozen square kilometres), determining the overall cooling effectiveness is quite complex. Nevertheless, by estimating heat losses in pipeline sections transporting the cooling medium, it is possible to infer under what conditions (medium temperature and flow rate) the cooling effectiveness of ice slurry and chilled water systems can be compared. Precisely determining heat losses in real, branched systems would require measuring losses along the entire pipeline, including all branches. For simplification, however, a simpler method can be used by selecting a single pipeline section (preferably of medium length) that ends with air coolers.

For technological reasons, the temperature of the chilled water at the mine surface is 1.5 °C (at the shaft inlet). For further analysis, a medium-length pipeline section was selected in which the temperature of the chilled water at the air cooler inlet was 8.0 °C, which gives the temperature difference of $\Delta T = 6.5$ °C. At the same time, in the system based on ice slurry, the medium temperature at the same point was 2.7 °C, which gives the temperature difference of $\Delta T = 1.2$ °C. To estimate the difference in cooling effectiveness, the supply temperature of 2.7 °C (as achieved when using ice slurry) can be taken as the reference temperature.

Now, the key question is: what flow rate of chilled water would be needed in this pipeline section to achieve a supply temperature of 2.7 °C at the inlet to the air coolers? To reach the desired chilled water temperature at the air cooler inlet, the flow rate of chilled water in this section would need to be 5.4 times higher. This also means that the cooling capacity transported through this pipeline section would need to be 5.4 times greater. If this were to be scaled to the entire system, it would be necessary to install chilled water cooling equipment at the mine surface with approximately five times the cooling capacity (which would also imply around a fivefold increase in the cost of producing chilled water). Of course, this estimate is based on one specific section of the mine's cooling pipeline. In shorter pipeline sections, the difference would be smaller; conversely, in longer sections, the advantages of using ice slurry instead of chilled water would be even more significant.

The expansion of the cooling system at the LW Bogdanka S.A. mine involved the addition of an ice particle production and mixing system to the existing chilled water installation. Following this expansion, the surface cooling capacity increased by only about 50% (from about 6 MW to 9.1 MW), but with an approximately 68% increase in operating costs. Nevertheless, this upgrade allowed the supply temperature of the medium feeding all underground air coolers to be reduced to the required specification level—and in some cases, even lower. Following the reconstruction of the cooling system in 2021, LW Bogdanka S.A. is the first and so far only mine in the world that uses liquid ice slurry in a closed pipeline system for air cooling.

The example of a large-scale cooling system based on ice slurry demonstrates that this technology can be effectively implemented in practical, real-world conditions. The primary constraint that may limit the broader adoption of ice slurry systems is the requirement for space to accommodate the ice slurry generator, along with the associated capital investment. However, it is important to note that the equipment used in ice slurry installations—such as pumps and pipelines—is standard and identical to that employed in conventional water-based systems. To date, no adverse effects of ice slurry on the equipment have been observed at the LW Bogdanka S.A. mine. Although it has been suggested that ice slurry may disturb existing mature corrosion scales and tubercles within piping systems [34], such effects have not been reported in the current installation at LW Bogdanka S.A. Nevertheless, given the continuous 24/7 operation of the system, it presents a valuable opportunity to monitor and assess any long-term impacts of ice slurry on the piping infrastructure over the coming years.

4. Conclusions

During mine operation, the pipelines transporting cold water to air coolers in mining areas are significantly extended. Despite thermal insulation, the extension of pipelines transporting cold water causes greater thermal losses, which results in an increase in the temperature of the water supplied to the air coolers. If the temperature of the water at the entrance to the coolers increases, the efficiency of the air coolers decreases, and it becomes more difficult to achieve the required air temperature at the extraction site. The article describes one of the solutions to the above problem, which involves the use of ice slurry (as PCM) instead of chilled water as a medium transporting cooling in the air cooling system of one of Polish mines.

The solution used in 2021 in the Polish mine allows the use of existing infrastructure (chilled water equipment and pipelines). Thanks to the use of ice slurry in the cooling system pipelines, the cooling capacity of the entire system was increased by 50%, with similar costs of pumping water. The power of air coolers in mining areas has also increased due to the supply of a medium with a lower temperature. This use of ice slurry in the central cooling system allowed for a more effective reduction in air temperature in miners' working areas. The use of ice slurry in systems previously operated with chilled water can therefore bring tangible benefits. Where it is no longer possible to increase the capacity to transport cooling using chilled water without extending the pipelines, ice slurry can be successfully used instead. As shown in the article, such a change does not require the reconstruction of the pipelines, but only the addition of a new part of the system responsible for the production of ice particles and the preparation of the ice slurry. The ice slurry solution appears to be particularly beneficial for air cooling systems in underground mines, but can also be applied to other cooling systems not located underground.

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Abbreviations

The following abbreviations are used in this manuscript:

PCM	Phase Change Material
PES	Pressure Exchanger System
SBACS	Surface-Based Air Conditioning Station

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