Influence of ambient temperature on the efficiency of underground spot cooling system

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Abstract. In mine air conditioning systems, the vapour compression refrigeration cycle seems to be currently the most widespread method of artificial cooling. In literature some other methods for cooling a mine are also presented, like using free-cooling in refrigeration systems. Mine workings in Jiu Valley are using the primary and secondary ventilation system for cooling the underground. Today the activities are focused mainly on mine closure as a part of transition to the low carbon economy, and this situation brings new challenges regarding the mine ventilation system, which was designed to meet the needs of a full-scale operation. As a result, locally ambient temperatures can rise, and spot cooling systems can be used, in order to cool the air. Such a system has been considered and calculations have been made to evaluate its thermal efficiency at different ambient temperatures.

1 Introduction

In underground mines there are multiple heat sources. A brief list of them shows the complexity of the problem. Some of the sources are of natural origin like, virgin rock temperature that can reach 60 ℃ for deep mines, auto-compression of air that can add 10 ℃ for every 1000 m relative to the surface [1]. Other sources of heat are related to human activity: machinery, mine water influx, explosive detonations, friction between falling rock, human metabolism, pipelines and oxidation [2].

As the demand for mineral resources is growing mines became deeper and more mechanized. Consequently, mine environment has become more extreme as temperature and humidity levels continue to intensify due to sources listed above. In most countries, mine legislation requires a certain underground working temperature. Poor microclimatic conditions affect miners, causing a reduction of perception, concentration, attention, and perceptiveness [3]. Mine cooling systems therefore forms an integral part of ensuring safe underground working conditions. To comply with legislation, mines employ complex ventilation and cooling systems which can account for up to 25% of a mine's electricity usage [1] which highlights the extent of the economic aspect of the problem.

As mines evolved, so did the systems designated primarily to assure safe working conditions and as a component of safety measures, to evacuate the heat from underground.

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Historically first system used to evacuate heat is the primary and secondary ventilation system which usually consists of the main ventilation fans and smaller fans assuring local ventilation of working areas.

As mines became deeper the result is a decrease in the effectivity of primary and secondary ventilation and cooling, which led to the need for additional cooling.

2 A short review of underground cooling systems

Underground cooling systems can be broken down into different categories based on their scale. Three wide ranging categories can be identified: central cooling, spot cooling and micro-climate cooling [2].

Centralized cooling is often referred to as bulk air cooling or primary cooling and they are used in mines where heat load is high, providing cooling throughout the mine workings. This cooling system usually consists of two non-mobile heat exchange systems: the bulk air cooler (BAC), which acts as an evaporator that cools the surrounding air. The BAC system includes a cooling tower or evaporative coolers of water [2]. The other system includes the refrigeration plant [2], which acts as a condenser where heat is rejected to the surrounding area. In some cases, free-cooling is employed in central air-conditioning systems of underground mines [4]. In paper [5] shows that "Ice from surface" approach which includes the main hoisting shaft downcasting ultra-cold ventilation, is providing sufficient cooling down to the 1400 m depth scenario, but not beyond. In the same paper is presented another approach, the fridge shaft. This method can provide cooling down to 1400 m, and by increasing the fridge shaft size (7-8 m diameter) up to 2000 m. As operation gets deeper these requirements become unreasonably high and clearly this approach is not viable. This highlights the limits of centralized cooling. Also chilled water from surface to underground air coolers can be taken into account. As shown in [2] when water is pumped underground the potential energy is converted directly to heat, warming the water. For example, this temperature rise can reach 2.34 ºC per 1000 meters of elevation change [2].

In paper [6] the proposed cooling system is a downhole centralized cooling system using mine water as the cooling source with a focus on underground mines with inflow water or water seepage.

Large surface cooling systems are common on medium- and deep-level mines with varying layouts and operations, according to mine-specific cooling needs, but the main components and cooling methods essentially remain the same. Their designs have not changed significantly since their inception in the 1970s [7] [8].

Spot cooling systems are referred to as decentralized, tertiary, face, or in-stope air cooling systems [7]. Spot cooling systems are used in areas with localized heat problems, areas that are often away from the main airways. Spot cooling or underground air cooling can be done by any or all of the following, depending on site-specific circumstances: chilled service water; secondary air cooling of intake air; controlled recirculation in ventilation districts and related bulk air cooling; tertiary or in-stope air cooling [5] [7].

Micro-climate cooling is used to cool directly the area surrounding the worker, and, these are the most efficient ways to cool the site where the work is done [2]. In case of mechanized mines air-conditioned cabins can be used on mining equipment which allows mine workers to stay out of the heat, but they didn't cool the mine environment. As a result, heat stress is not completely eliminated, as not all tasks can be completed from inside of an air-conditioned cabin.

Usage of MCUs (Mobile Cooling Units) is analysed in paper [5], highlighting that MCUs are exposed to ambient stress in harsh underground conditions, and the lack of maintenance can make them inefficient. As a result, they can negatively impact the very ambient conditions to which they should be positively contributing.

3 Design of an appropriate cooling system for mines located in the Jiu Valley

Exploitation of coal has a long tradition in the Jiu Valley, but today the activities are focused mainly on mine closure as a part of transition to the low carbon economy [9] according to EU directives.

This situation brings new challenges regarding the mine ventilation system, which was designed to meet the needs of a full-scale operation.
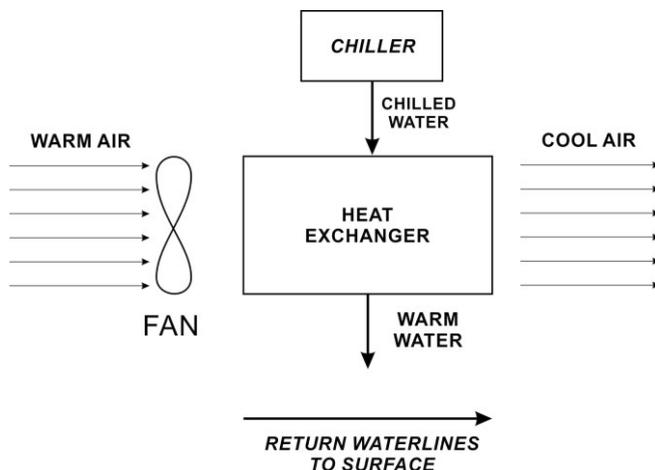
An important source of heat that can rise temperatures underground is the geothermic gradient, which in case of Jiu Valley is low as geothermal flow is 75-85 mW/m^2 [10].

Regarding the auto compression of air, mines in Jiu Valley are not very deep, as a result this component has a small influence on underground temperatures. Deepest mine was Petrila mine having a depth of approx. 1000 m, which have been closed since 2015.

Regarding the degree of mechanization in paper [11] emphasized that working room and fall of coal and rock methods (SCRI) and in the present longwalls, in all variants are not used anymore and there is a continuous decrease of the front face production capacity as mining activities will come to an end. Consequently, heat related to machinery and explosive detonations are decreasing constantly.

According to conditions listed above the main method used in Jiu Valley for cooling the underground was, and it is at the present day, the primary and secondary ventilation system, consisting of the main ventilation fans and smaller fans for local ventilation of working areas. As the configuration of underground mine workings are constantly changing the need to evacuate heat can occur locally, as a result, possibility of using spot cooling systems in order to evacuate heat are analysed further.

A great variety of cooling systems are presented above [2-7] but the schematics of all can be resumed as in Fig. 1.
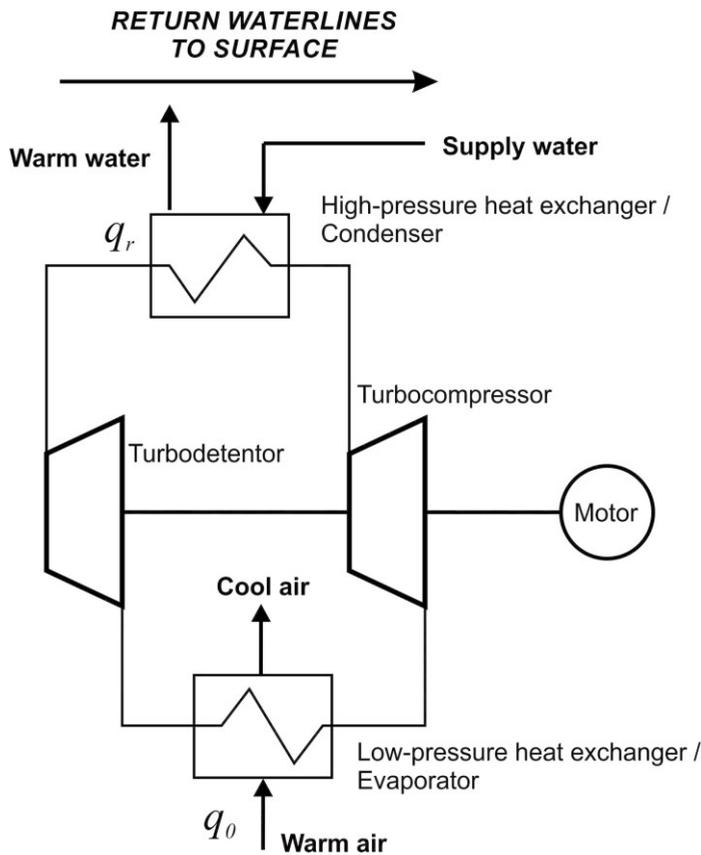

Fig. 1. Schematics of an underground air-cooling system

As presented in Fig. 1, the chiller can be placed underground or above ground, in both cases there may be advantages and disadvantages. For example, in order to deliver chilled water from surface, ducts must be insulated, and even so, water can warm up by compression [2]. If considering placing chiller units underground, they have to be set up in an area where it

can directly reject heat into a return airway, but this situation is not always ideal as new airways are not always close to return airways.

Studying the schematics of the air-cooling system, can be seen that in the process of cooling air two heat exchanger are used: the evaporator located in the chiller unit which will cool the water and the air-water heat exchanger that will cool the underground air. This suggest that the configuration can be simplified, using a chiller to cool the air. In order to evacuate the heat, supply water can be used to cool the high-pressure heat exchanger. That way no heat will be rejected in the surroundings, and as a result, the chiller can be placed anywhere in the mining works, no need to be close to the return airways. Airflow on the low-pressure heat exchanger (evaporator) can be provided using local ventilation fans, which usually are located in these mine workings.

The projected configuration is shown in Fig. 2.

Fig. 2. Schematics of heat rejection using chiller

The most common types of chillers are vapour compression chillers which are using a great variety of refrigerants e.g. ammonia (R717), as a result any leakage can be hazardous in the underground environment.

In order to avoid that, a gas compression chiller can be used with air as refrigerant, this way the risk of using dangerous refrigerants can be avoided.

The setup above keeps the advantages of spot cooling systems, like mobility, eliminating some disadvantages like using ducts for providing chilled water. A mobile spot cooler is ideal as it can be designed to be portable and thus used in other active production workings [2].

4 Efficiency of the gas compression chiller in underground working conditions

Characteristic parameter of the gas compression chiller is the COP (Coefficient Of Performance) ε_f, calculated using [12]:

$$\varepsilon_f = \frac{q_0}{|l|} = \varepsilon_C \cdot \eta_E \tag{1}$$

where: q_0 – specific cooling power kJ·kg^{-1}; l - the specific work done in kJ·kg^{-1}; η_E - the exergy efficiency of the chiller; ε_C - COP of the ideal Carnot cycle.

Both energy and exergy methods can be used for assessing the performance of a system. However, deviations from the ideal (reversible) condition are not identified with energy analysis. For this reason, exergy analysis is used. Exergy analysis can provide a powerful tool for analysing, assessing, designing, improving, and optimizing systems and processes.

This is the reason why the actual cycle of the gas compression chiller is analysed using exergy analysis [13].

Based on algorithm presented in paper [12], the exergy efficiency of the actual cycle can be computed using:

$$\eta_E = \frac{|l_{minC}|}{|l|} \tag{3}$$

where: l_{minC} is the minimum specific work of the reverse Carnot cycle kJ·kg^{-1}; l is the specific work of the actual cycle kJ·kg^{-1}.

Data required for the calculation were chosen taking into account that the desired temperature of the air is T_0=25 °C, and the temperature drop required for heat transfer is set to Δt_0=4 °C. The temperature drop required for heat transfer in the high-pressure heat exchanger (condenser) is set to Δt_r=6 °C, and in order to evaluate the influence of ambient temperature on the efficiency of chiller calculation are going to be performed for T_a=35 °C, 45 °C and 55 °C.

Coefficient of relative pressure drop in the low-pressure and high-pressure heat exchangers will be $\psi_r=\psi_0$=3 %, while the efficiency of the compression is η_c=0.85, the expansion efficiency η_d=0.87 and the compression ratio β_c=5.
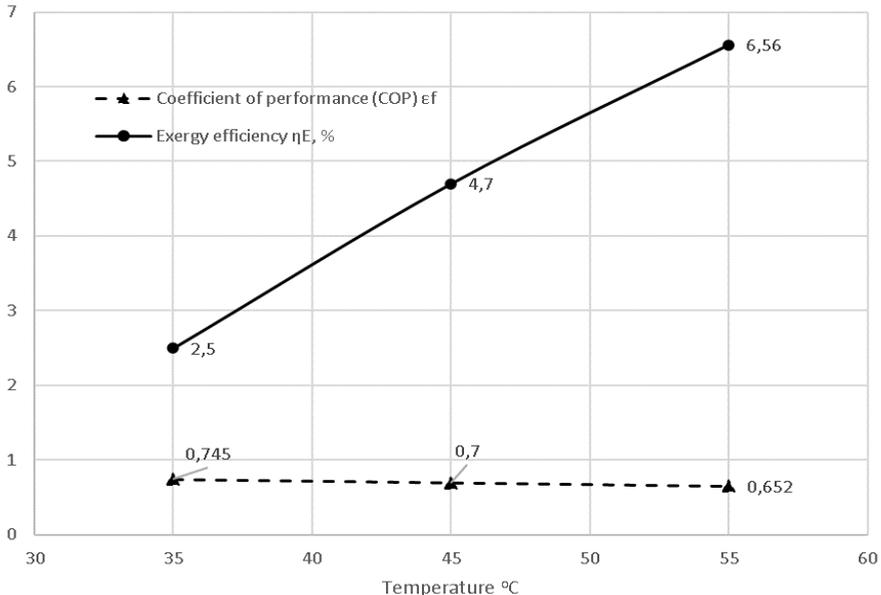
Results are presented in Table 1 and Fig. 3.

Table 1. Chiller characteristics for different ambient temperatures.

Nom.	T_a=35 °C	T_a=45 °C	T_a=55 °C
Specific cooling power q_0, kJ·kg^{-1}	78.019	71.099	64.178
Specific work done l, kJ·kg^{-1}	104.732	101.608	98.483
Coefficient of performance (COP) ε_f	0.745	0.7	0.652
COP of the ideal Carnot cycle ε_C	29.8	14.9	9.93
Work of ideal Carnot cycle l_{minC}, kJ·kg^{-1}	2.618	4.772	6.461
Exergy efficiency η_E, %	2.5	4.7	6.56
Losses due to irreversibility of:			

Compression π_{irc}, %	18.617	19.812	21.084
Expansion π_{ird}, %	20.633	21.958	23.367
Pressure drops in heat exchangers π_{l0+} π_{lr}, %	5.142	5.472	5.822
Heat transfer in evaporator $\pi_{\Delta T0}$, %	13.629	11.917	10.246
Heat transfer in condenser π_{qr}, %	39.479	36.145	32.919

Analysing data in Table 1, first of all attention is drawn by the value of exergy efficiency ranging from 2.5 to 6.56 %. The value is very small, but expected for this type of chiller [12]. Compared with data in literature [14], with vapour compression chillers having COP 7.0, it is obvious why this type of chiller is not commonly found in operation.

Influence of ambient temperature on the COP (ε_f) and exergy efficiency (η_E) of the chiller is presented in Fig. 3.

Fig. 3. Influence of ambient temperature on chiller characteristics

Data represented in Fig. 3., illustrates the how ambient temperature is influencing COP (ε_f) and exergy efficiency (η_E) of the chiller. While exergy efficiency of the chiller is increasing with the ambient temperature, COP of the chiller decreases with a small rate. This is due to the fact that the two are linked by equation (1). While exergy efficiency is increasing, COP of Carnot cycle ε_C is decreasing steeper (see Table 1), resulting a slight decrease of the chiller COP (ε_f).

As temperature is increasing, internal losses - losses due to irreversibility of compression π_{irc} and expansion π_{ird} – are increasing too. Losses due to irreversibility of compression π_{irc} are increasing from 18.617 to 21.084 kJ·kg^{-1}, while those due to expansion π_{ird} from 20.633 to 23.367 kJ·kg^{-1}.

Losses due to heat transfer in evaporator $\pi_{\Delta T0}$ are decreasing as ambient temperatures are rising, from 13.629 to 10.246 kJ·kg^{-1}.

Losses due to heat transfer in condenser π_{qr}, which have the largest share among losses, are decreasing as ambient temperatures are rising, from 39.479 to 32.919 kJ·kg^{-1}.

The specific work of the cycle l is also decreasing from 104.732 to 98.483 kJ·kg^{-1} while ambient temperature is rising from 35 to 55 °C.

5 Conclusion

Transition to the low carbon economy according to EU directives, brings with it new challenges to the mining industry. As mines are in a closure process, mining workings are constantly changing. Even in this situation safety must be a major concern. An important part of assuring a safe working environment is to ensure an adequate temperature.

A review of current cooling practices combined with the actual needs of Romanian mining industry located in Jiu Valley, led to a solution proposal for cooling the ambient in mining workings.

The usage of the proposed spot cooling systems was analysed, and some major conclusions can be synthetized as follows:

- important advantages when using a gas compression chiller with air as refrigerant is that no hazardous gases can reach mining works in case of faulty operation;
- another advantage is that placing the chiller in underground there is no need for installing an extensive network of ducts (usually insulated) in order to carry chilled water from surface;
- existing local ventilation fans can assure airflow on the low-pressure heat exchanger (condenser);
- although the COP of the chiller is low, the fact that it can be used safely underground compensates for this shortcoming;
- even if the COP of the chiller increases as ambient temperatures rise, there is a limitation for it, as ambient temperatures can't rise indefinitely in the mining workings.

This exergy analysis showed that from a thermal point of view the chosen solution is a feasible one, but the final project will have to take into account other restrictions imposed by working underground, such as lack of space.

Also, economical aspects like operating cost and capital investment cannot be neglected.

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