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Research Paper

Proposed split-type vapor compression refrigerator for heat hazard control in deep mines

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HIGHLIGHTS

- SVCR system for heat hazard control in deep mine was proposed.
- Thermodynamic characteristic of the suction process was simulated and analyzed.
- Thermal performances of SVCR system are overall better than cooling water system.
- When the mine is not too deep and T_E is not too low, SVCR is the better choice.

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ABSTRACT

The thermodynamic performance of a proposed split-type vapor compression refrigerator (SVCR) for heat hazard control in a deep mine was numerically analyzed. The thermodynamic characteristics of the suction process of the proposed system were also simulated and analyzed. In the suction direction, the pressure, velocity, temperature, and specific enthalpy of R134a vapor dropped, whereas its specific volume and specific entropy rose. The variations in the superheat of the compressor inlet and the characteristics of the pressure drop of the suction process were also described in detail and analyzed. For comparison with the theoretical cycle, a variable, γ, defined as the COP ratio of the proposed system and the theoretical cycle, was presented, and the variations of γ were studied and discussed in detail. The proposed system was compared with a cooling water system and an ice slurry system, and results indicate that the thermal performance of the proposed system is better than that of the cooling water system. The thermal performance of the ice slurry system is better than that of the proposed system when a mine is sufficiently deep. However, when the mine is not too deep and the evaporation temperature, T_E, is not too low, the proposed SVCR system is the better choice.

1. Introduction

Heat hazard is a universal phenomenon in deep mines. The temperature of 1# well in Amandelbult, Africa [1] reaches 55 °C at a depth of 3300 m. The tunneling working face of the Fengyu lead–zinc mine [2] in Japan, which has a depth of 500 m, reaches 80 °C. Heat hazard is produced as a result of the following three primary factors: climate, geological, and mine factors. (1) In terms of the climate factor, a high ground temperature results in a high underground temperature [3]. (2) In terms of the geological factor, the temperature of a virgin rock increases with a gradient of (0.028–0.034) °C/m as the depth of the mine increases [4]. (3) The mine factor includes the heat sources of the digging machines and electrical equipment. Heat hazard presents significant problems to mining enterprises. A high air temperature increases the body temperatures of the miners [5], thereby considerably decreasing their labor efficiency [6]. In addition, mining accidents occur frequently as the temperature increases [7].

Circulating ventilation is the earliest method to be used for heat hazard control [8]. However, as the mine depth increases, the effectiveness of this approach also decreases because it has a low cooling ability [9]. As a result, circulating ventilation becomes an ineffective method in the face of serious heat hazards.

High-temperature exchange machinery system (HEMS) cooling technology has also been proposed to control heat hazards in mines that are subjected to mine water inrush [10]. In HEMS, the

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Nomenclature

c_p	specific heat capacity (kJ/(kg K))
C	procedural variable
COP	coefficient of performance
d	diameter (m)
G	mass flow of refrigerant (kg/s)
h	specific enthalpy (kJ/kg)
H	depth of mine (m)
m	mass flow (kg/s)
M	molar mass (kJ/mol)
N	number of suction tubes
p	pressure (MPa)
q	heat flow (kW)
Q_0	refrigeration capacity (kW)
Re	Reynolds number
s	specific entropy (kJ/(kg K))
T	temperature (K)
T_m	temperature in deep mine (K)
u	velocity (m/s)
v	specific volume (m^3/kg)
w_p	pump power (kw)

Greek symbols

δ	oil film thickness (m)
γ	*COP* ratio
η	efficiency
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
υ	kinematic viscosity (m^2/s)

Subscript

C	condenser
E	evaporator
ice	ice slurry
in	inlet
min	minimum
oil	lubricant
out	outlet
r	relative
ref	refrigerant
S	saturation
w	water

cold from the water inrush is extracted to cool the working faces of the tunnel. However, the application of HEMS is limited because not all mines experience sufficient water inrush.

The central air conditioning cooling system (CACS) has been used for heat hazard control for more than 90 years. CACS can be classified into the underground and ground types.

The underground-type CACS is installed in deep mines. The distinct advantage of this system is its low cold loss. However, its disadvantages consist of the difficulties in installation, maintenance, and discharge of the condensed heat. Moreover, it requires explosion-prevention equipment [11]. Thus, the ground-type CACS is more suitable than the underground-type CACS in engineering applications.

The ground-type CACS is installed on the ground. Depending on the cold medium, the ground-type system can be divided into three categories: the ice slurry [12], cooling ethanediol [13], and cooling water systems [14].

The solid–liquid phase change of H_2O endows the ice slurry system with the advantage of large cooling capacity [15], which decreases pipe diameters and water pump power and reduces the investment cost for the cold transport system. The ice slurry system reduces the temperatures of the Tangkou and Liangbei mines of China by 5 and 5.6 °C, respectively [16,17]. However, the ice slurry system has some obvious shortcomings. A large amount of cold loss occurs in the ice slurry maker of the cold transport system. Moreover, the ice slurry may block the vertical transport pipeline, thereby increasing the operating and maintenance costs.

The cold transport system of the cooling water [13] and the cooling ethanediol systems [18] is simple and avoids the risk of pipeline blockage. The cooling water system reduces the temperature of 12318$^{\#}$ well in Pansan Mine by (2.7–4) °C [19]. However, the low cooling capacities of the cooling water and ethanediol systems significantly increase the pipe diameters and water pump power. As a result, the operating costs increase considerably, particularly in significantly deep mines.

We propose a split-type vapor compression refrigerator (SVCR) for heat hazard control in deep mines to address the abovementioned problems. In the SVCR system, the refrigerant of the refrigerator is the only cooling medium. The liquid–vapor phase change provides the cooling medium with a high cooling capacity, and the system prevents the risk of pipeline blockage. The thermal properties of the SVCR system with R134a as refrigerant are studied in detail, and its thermodynamic performance is compared with those of the water cooling and ice slurry systems.

2. System description

Fig. 1 shows a schematic of the SVCR, cooling water, and ice slurry systems. R134a is selected as the refrigerant. For the SVCR system, the condenser and the compressor are installed on t he ground, and the evaporator and the valve are installed underground. The cooling water is cooled in the evaporator underground, and the cooling water is cycled between the fan coil system and the evaporator. For the cooling water system, all four refrigeration components are installed on the ground. The cooling water is cooled in the evaporator and then transported from the ground to the fan coil system installed in the working faces located underground. After passing through the fan coil system, the cooling water is transported back to the evaporator on the ground. For the ice slurry system, all four refrigeration components are installed on the ground. The recycled water becomes ice in the ice maker and becomes ice slurry in the ice slurry maker. The ice slurry is transported from the ground to the ice melter located underground, and the cold is transported to the working faces by the cooling water. The ice melt water is then transported back to the ice maker on the ground.

The pressure drop in the suction pipeline is very high. Therefore, the refrigeration capacity and the vapor superheating from the evaporator should be effectively controlled. In order to achieve the effectively control, a temperature sensor is installed in the outlet of the evaporator. The voltage difference signal of the temperature sensor is sent to the electromagnetic expansion valve, and then the voltage difference signal is translated to temperature signal. If the temperature is higher than the set values, the expansion valve will be adjusted to increase the mass flow of the refrigerant. If the temperature is lower than the set values, the expansion valve will be adjusted to decrease the mass flow of the refrigerant.

It is obvious that the suction pipeline of SVCR system is far longer than that of cooling water system and ice slurry system.