The working principle analysis and numerical simulation of key equipment in HEMS

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Abstract. The rock temperature in deep coal mine is high, which seriously affects the mine safety production and restraints the exploration of coal resources. The cooling system HEMS (High temperature Exchange Machinery System) was developed using mine water inrush as a cold energy. The system was successfully applied in many coal mines in Xuzhou Mining Group, such as Jia he, San he jian and Zhang shuang lou coal mine. This technology makes good sense in energy conservation and pollution reduction. In this paper, the operation principle and numerical simulation of key equipment in HEMS were presented, which offer the theoretical basis for optimization design. The analysis of operational principle of key equipment was adopted by heat transfer theory and FLUENT was adopted for numerical simulation. After finishing the theoretical analysis, test result was used for proving the correctness of the theoretical analysis.

1. Introduction
Coal has been the major energy source in China for a long time and it accounted for more than 70% of China’s total primary energy consumption. Due to long periods of exploitation, coal resources have become increasingly exhausted with exploitation depth less than 1 km. Therefore, deep exploitation of coal mines becomes very important [1]. As mining depth increase, the rock temperature also increases and the temperature in coal mine and at the working faces can reach up to 30~40 °C [2]. Coal mine safety regulations in China stipulate that miners are not allowed to work when the air temperature at the mine working face exceeds 30 °C [3]. Consequently, it is urgent to reduce the temperature in order to improve the working conditions and to control the associated hazards.

There are in general two kinds of cooling technologies [4]; one is mine ventilation and the other is water or ice cooling systems [1]. Practice has shown that ventilation provides only a low cooling ability and cannot meet the needs of deep mine cooling with serious heat hazards. Water cooling is the technology usually applied in mine air-conditioning, which uses compression refrigeration equipment to cool the working face, with freon as refrigerant. The disadvantages of this system are high operation cost and high power consumption [5]. Ice cooling consists of sprinkling ice at the working face, where the ice is produced by an ice machine. Heat is exchanged during the process of ice melting into water...
Practice has shown that there are problems in designing pipelines for ice transportation; the key problem is ice blockage in pipe, and this method requires high standards of operational management and control [10].

A new type of cooling system is proposed where cold energy can be provided by mine water inrush. The cooling system High temperature Exchange Machinery System (HEMS) also permits a stepwise utilization of heat resources in deep mine. HEMS not only cools the working face and controls heat hazards in coal mine but also makes full use of deep mine water, which provide heat in winter for building and cooling for coal mine in summer. It improves environment and saves energy.

2. Key equipment and working principles

2.1. HEMS

The system is extracting cold energy from mine water inrush at all levels, then exchanging heat with high temperature air blowing to working face, then temperature on working face is decreased. The system comprises three stations: HEMS-I; HEMS-II; HEMS-PT. HEMS-I is cold energy extracting station. HEMS-II is cold and heat energy exchange system. Its characteristics are modular, assembled, movable and explosion prevention. HEMS-PT is pressure and heat exchange station [11]. A diagram of the HEMS cooling technology is shown in Fig.1 [12].

![Diagram of HEMS cooling system](image)

Figure 1. Diagram of the HEMS cooling system

HEMS-I is at level 500m and HEMS-II is at level 1000m underground, height difference between two stations produces pressure in pipes, so HEMS-PT is built to reduce water pressure [13].

The technology uses geothermal energy as cold energy, which is pollution-free and enormously decreases the discharge of gas and solid wastes, which achieve economic and social benefits. In the following paragraphs, I introduce the working principle and numerical simulation of key equipment.

2.2. HEMS-I

HEMS-I consist of four parts: compressor, condenser, expansion valve and evaporator. The principle of HEMS-I is reverse Carnot cycle, which is shown in Fig.2. The refrigerant used in HEMS-I is R134a. The refrigerant cycle in evaporator, compressor, expansion valve and condenser in HEMS-I, R134a in evaporator absorb heat exchanged with water and become gaseous refrigerant, in condenser, the gaseous refrigerant become liquid when meeting the cold water, thus more and more heat in deep coal mine is stored in water which can be used for building heating on the ground.

![Diagram of HEMS-I](image)

Figure 2. The diagram of HEMS-I

2.2.1 Model establishment of compressors

There are four parameters for compressors: air input coefficient, compressors’ input power, refrigerant flow rate and compressors’ motor speed.

(1) Air input coefficient

The air input coefficient (λ) is ratio of actual gas output and theoretical gas output, we can calculate it by formula:

\[ \lambda = \lambda_v \lambda_p \lambda_T \lambda_D \]

\(\lambda_v\)--volume coefficient; \(\lambda_p\)--pressure coefficient; \(\lambda_T\)--temperature coefficient; \(\lambda_D\)--release coefficient.

(2) Input power of compressors
The input power of compressors directly effects on the performance of HEMS-I, so it is important to calculate the input power of compressors. We can calculate it by formula:

\[ N_{in} = N_{ef} / \eta_{m0} \]

\( N_{in} \)—Input power; \( N_{ef} \)—effective power; \( \eta_{m0} \)—electrical efficiency;

(3) Flow calculation of refrigerant

The flow calculation of refrigerant can be calculated by formula:

\[ m_{com} = \lambda V_{th} / V_{ suc} \]

\( m_{com} \)—refrigerant flow; \( V_{th} \)—theoretical volumetric air delivery capacity; \( V_{ suc} \)—refrigerant’s specific heat on suction port;

(4) Motor speed of compressors

When the compressors are at work, Motor speed of compressors conforms to the following law:

\[ n = 120 f (1 - s') / p \]

\( n \)—compressors’ Motor speed; \( f \)—motor frequency; \( n \)—the rotating speed of compressors; \( s' \)—a difference in rate of motor rotating speed(constant); \( p \)—pole-pairs number of motor.

During model establishment of compressors, other parameters will be calculated, such as exhaust gas temperature and mass flow, I will not repeat the calculate method.

2.2.2 Model establishment of expansion valve

The expansion process is isolated for expansion valve. According to the first law of thermodynamics, the enthalpy is constant before and after the refrigerant through the expansion valve. Based on the hydraulic formula, the flow of expansion valve can be calculated by formula:

\[ m = C_d A \sqrt{\rho_{in} (P_{in} - P_{out})} \]

\( m \)—refrigerant’s mass flow; \( C_d \)—flow coefficient; \( A \)—flow zone of expansion valve; \( \rho_{in} \)—refrigerant density at the inlet of the valve. \( P_{in} \)—pressure at the inlet of the valve. \( P_{out} \)—pressure at the outlet of the valve.

2.2.3 Numerical simulation of condenser and evaporator

The condenser or evaporator is shown in Fig.2. As the working principle of condenser and evaporator is similar, the simulation of the two is same, so I just simulate the evaporator. From Fig.2, the curved pipe can be stretched as a straight pipe, so the model of evaporator can be simplified as Fig.3.

![Figure 3 the model of evaporator](image)

The dimension of model is shown in Fig.3. FLUENT is adopted to simulate the change of water temperature, the results is shown in Fig.4-5.

![Figure 4 Temperature at the end of pipe](image)  
![Figure 5 Water temperature changes in evaporator](image)

From Fig.4, we know water temperature change obvious, at inlet of the pipe is red, then it turns verdant green along the pipe, finally it turns blue. From Fig.5, we know water temperature is decrease by 1°C/18m. Water temperature is 12°C at pipe inlet, at pipe outlet, water temperature of numerical
results is 3°C, while the tested water temperature is 7°C, the different is 4°C, the phase transition of refrigerant is not considered, and problem should be solved in future.

2.3. HEMS-PT
The HEMS-PT, its structure and working principle is presented in Fig.6. It consists of many heat exchange plates, and these plates were fixed together.

In simulation, I chose a plate to build the model. The plate size is 1200mm×600mm, and thickness and depth of plate is 1mm and 4.5mm. Distance between two crinkle is 12.43mm, model after meshing is shown in Fig.7. Cold water flows above plate, and hot water flow down plate, the height of water flow is 2.25mm.

From Fig.8 (a), cold water temperature change is obvious, the colour become light blue from dark blue, from Fig.8 (a-b), we can see hot water temperature change is obvious, the colour become orange from red, the hot water temperature is decreased. There is temperature increase for cold water, but the change is not obvious, and heat exchange is obvious near the both side of the plate.

2.4. HEMS-II
2.4.1 Model establishment
In Jiahe coal mine, we adopt 9 HEMS-II for deep mine cooling. Every HEMS-II consists two surface air coolers. Every cooler has four pipes, and there are 32 pipes for 9 HEMS-II. Stack two coolers to form a HEMS-II. Based on this structure, we can choose a half of the HEMS-II as the calculated model. In order to simplify the model, distance between HEMS-II can be shortened. Finally, the size of the model is 1221mm×638mm, the layout and model is shown in Fig.9.
2.4.2 Simulation results of water temperature

From Fig.10-11, we know air temperature change is obvious, colour gradually turn green from red and air temperature is decreased to 19°C from 32°C. Air temperature is decreased by 1°C through one HEMS-II. The tested temperature is 20–21°C at the end of HEMS-II and the simulation results is 19°C, which shows that simulation result is correct. From Fig.12, we can see air temperature inside and at edge of HEMS-II is different. Cooling effect at edge of HEMS-II is not very good, so when we design HEMS-II, the edge size should be as small as possible.

3. Conclusions
The main conclusions are:

1) Reverse Carnot cycle working principle of HEMS-I is introduced. HEMS-I consists of four parts: compressors, condenser, evaporator and expansion valve. For compressors and expansion valve, formulas are given for model establishment; for condenser and evaporator, FLUENT is adopted to simulate heat exchange process, and phase transition of refrigerant should be considered in future.

2) The structure of HEMS-PT and its heat exchange process is analysed, FLUENT is adopted to simulate the heat exchange process, the tested results and simulation results are in agreement, which testifies the correctness of simulation.
(3) FLUENT is adopted to simulate heat exchange process for HEMS-II, simulation results compare with the tested data, the two are in agreement, which testifies the correctness of simulation. Cooling effect at the edge of HEMS-II was not very good and the edge size should be as small as possible.

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