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Experimental study of phase change material's application in refuge chamber of coal mine

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Abstract

We identified the main heat source of the refuge chamber was hedge staff by analyzing the heat source of the refuge chamber. We identified the calculation method of the heat released by the hedge staff and calcium hydroxide when absorbed CO_2. We designed the experimental program of temperature control of phase change material according to the estimate of heat dissipating capacity in 96 hours. Ultimately, we conducted simulation experiments and verified the effect of temperature control of the phase change material.

Keywords: refuge chamber; heat load; phase change material.

Nomenclature

Q	quantity of heat (W)
ΔH	enthalpy change (kJ/mol)

1. Introduction

After the gas explosion, fire or other accidents happened in coal mine, a considerable part of casualties were due to high temperature and toxic and harmful gas [1] when personnel were trapped in the underground. Therefore, when the disaster incident happened in the Underground Coal Mine and the escape routes were blocked or self-help couldn't guarantee their effective escape, retreating to the underground of emergency facilities (the refuge chamber or rescue cabin) and waiting to be rescued was the primary choice to ensure the safety for personnel [2]. The urgent danger prevention facilities were confined space in which the fluidity of air was relatively bad. During the urgent act of rescue, personnel all went to the urgent danger prevention facilities in which the heat released by personnel and equipment used to ensure the existence of hedge stuff was very high. And if we didn't take measures to control it timely, the heat would endanger the hedge stuffs' health and life safety when it accumulated to a certain extent [3–4].

At present, the way to control the temperature of coal mine refuge chamber includes ice thermal storage and carbon dioxide phase-change cooling. Ice cooling ensures the ice within the ice container of hedging facilities always in a frozen state by the mean of daily refrigeration and ice-storage. After coal mine disaster, it can provide appropriate temperature and humidity environment for hedge staff by using the latent heat of fusion and cooling capacity of water. Ice cooling system design is simple, and the ice also has a safe and non-toxic characteristics. In emergency circumstances, the water melted from ice is also available for hedge staff. However, the refrigeration compressor runs all the year round with high failure

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rate and maintenance costs. Carbon dioxide phase change cooling uses liquid CO_2 as refrigerant. After throttling or expansion, it is imported heat exchanger to absorb the heat of the gas within the refuge chamber. Finally, CO_2 is imported motor and drives the air purifier to clean up the air. The advantages of this kind of cooling are running without power, less maintenance and low costs, etc. However, CO_2 can't be used in high temperature mine because of the lower critical temperature (31.1 ℃). Also the system operating need a larger space, running pressure is very high, but filling density is low. Once the CO_2 leaks, the leakage will cause fatal damage to hedge staff [5–7].

2. Analysis on heat resource of refuge chamber

The indoor heat of the refuge chamber includes the human body heat, air purifier cooling and electricity equipment cooling.

2.1. Human emissions of heat load

Energy generated by the human energy metabolism equals to the sum of energy both consumed by doing work and directly or indirectly transited into heat in vitro. The body's heat balance can be expressed as the following formula [8]:

$$M-W-C-R-E-S=0 \tag{1}$$

where M is human energy metabolism rate, and it was determined by the size of the body's activity. W/m^2; W is human mechanical work, W/m^2; C is heat that human appearance into the surrounding environment through the form of convection, W/m^2; R is heat that human appearance into the surrounding environment through the form of radiation, W/m^2; E is the heat taken away by the sweat evaporation and the water vapor exhaled by the body, W/m^2; S is the heat storage, W/m^2.

Under the normal circumstances of emergency refuge, W=0, S=0. Therefore we could approximately get heat dissipation of body by measuring the human energy metabolism.

There are two methods of measurement of human energy metabolism, one is the direct method and the other is the indirect method. The direct one let the person to be tested into a special testing environment and collected the total heat emanating within a certain time, then converted into energy metabolism per unit time [9]. The device and process of direct measurement is more complex. Direct method is subject to a number of factors, they are convective heat transfer coefficient of the test room, coefficient of convection mass transfer, clothing thermal resistance and moisture permeability, the age, physical condition and the degree of neurological tension of the hedging personnel. In order to obtain a universal measurement results requires a lot of sample size [10].

Therefore, we commonly used indirect calorimetry. The measuring principle is based on the law of definite proportion, meaning that there is proportional relationship between the amounts of reactants and the amounts products. According to the definite proportion, we determined the amount of CO_2 produced and O_2 consumed during the mixed oxidation of sugar and fat in different proportions (As the energy in the body mainly from sugar and fat oxidation, protein metabolism is less and can be negligible [11]), then calculated the respiratory quotient of non-protein. We can indirectly calculate the heat production by body refer to Table 1 [9], which provides the heat price of oxygen and respiratory quotient of non-protein.

Table 1. Heat price of oxygen and respiratory quotient of non-protein

Respiratory quotient of non-protein	Percentage of oxidized/%		Heat price of oxygen/(kJ·L^{-1})
	Sugar	Fat	
0.85	50.7	49.3	20.36
0.86	54.1	45.9	20.41
0.87	57.5	42.5	20.46
0.88	60.8	39.2	20.51
0.89	64.2	35.8	20.56
0.90	67.5	32.5	20.61

Under the normal circumstances of emergency refuge, the hedge staffs were considered in mild active. Beijing Science and Technology University had conducted 7 groups of human survival experiment in the mine closed simulated cabin, and got the body's oxygen consumption and carbon dioxide exhaled amount under different activity intensity state. The results are shown in Table 2 [12]. Therefore, we can calculate body heat dissipation under mild activity by indirect calorimetry:

$$Q_1=0.37\ \text{L/(min·person)}\times 20.41\ \text{kJ/L}=7.552\ \text{kJ/(min·person)}=125.87\ \text{W/person} \quad (2)$$

Table 2. Respiratory quotient of human under different active state within a confined space

Active state	Amount of Oxygen consumption/(L·min^{-1})				Volume of carbon dioxide output/(L·min^{-1})				Respiratory quotient
	Test value			Mean value	Test value			Mean value	
Sleep	0.24	0.24	0.25	0.24	0.22	0.21	0.22	0.21	0.875
Mild activity	0.36	0.38	0.37	0.37	0.32	0.33	0.31	0.32	0.86
Moderate activity	0.84			0.84	0.76			0.76	0.90

2.2. Heat load produced by air purification device

In confined space, the CO_2 concentration rapidly increased because of the person's activity, and it is the most important factor that threatened the person's safety and it should be solved firstly [13]. At present, we generally use soda lime (the main component is $Ca(OH)_2$) to absorb CO_2 in the urgent danger prevention facilities by comprehensively considered cost, absorption efficiency and stability and so on. The absorption process is exothermic. A part of heat generated in reaction is used to improve airflow temperature that dissipated to the hedge facility, another part accumulate in the purification device. As purification device is located in hedging facilities, heat eventually distributed to the urgent danger prevention facilities. Therefore, the chemical reaction heat calculated can be considered as the heat load generated by the air cleaning device.

The chemical reaction heat equals to the sum of the enthalpy formation of product minus the sum of the enthalpy formation of the reactants. According to Hess Law, when the whole process in a constant volume or constant voltage state, the chemical reaction heat is unrelated to the specific ways, but only depends on the start and final state of the reaction. Therefore, we can determine the standard enthalpy of formation of reactants and resultant by checking the "material standard molar enthalpy of formulation" (Table 3 [14]). Chemical reaction heat can be calculated according to the law of conservation of energy.

Table 3. Standard molar enthalpy of formulation of inorganic compounds

Inorganic compounds	CO_2 (g)	H_2O (l)	$Ca(OH)_2$ (s)	$CaCO_3$ (s)
ΔH/（kJ·mol^{-1}）	−393.51	−285.84	−986.58	−1 206.88

$$Ca(OH)_2\ (s)+CO_2\ (g)=CaCO_3\ (s)+H_2O\ (l)$$

$$\Delta H=(-1\,206.88\ \text{kJ/mol})+(-285.84\ \text{kJ/mol})-(-986.58\ \text{kJ/mol})-(-393.51\ \text{kJ/mol})=-112.63\ \text{kJ/mol} \quad (3)$$

As can be seen from Table 3, 112.63 kJ of heat is emitted when calcium hydroxide absorb 1 mol of CO_2. In mild activity, a person generated 82.3 mol CO_2 within 96 hours, and total amount of heat liberation is 9 268.4 kJ [12]. On average, heat load generated by a personal discharge of CO_2 as the follow formula:

$$Q_2=1.61\ \text{kJ/(min· person)}=26.8\ \text{W/person} \quad (4)$$

2.3. Heat load of electrical equipment

The consumer equipment mainly included lighting monitoring equipment when the indoor cooling system and air purification systems without the power in refuge chamber. The total power of the equipment was about 500 W. Assume that electricity consumed by the consumer equipment completely converted to heat. It's only 500 W heat load. As a result, it can be seen that the heat dissipation of equipment had small ratios of the total load.

Therefore, hedge person is the most important heat source when analysing the refuge chamber heat source. In the calculation of the total indoor heat of the refuge chamber, we can roughly estimate the heat dissipation from the equipment. It wouldn't produce big error.

3. Study on temperature control of phase material

Latent heat refers to the heat absorbed or released during substances change from one phase to another phase. As the latent heat of material phase change is much greater than the sensible heat. Therefore, we generally use the latent heat in the phase change process of material for the temperature control in refuge chamber. For example, ice thermal storage and carbon dioxide refrigeration all follow the principle of latent heat cooling.

Research found that the annual mean temperature of low-temperature coal mine at about 20 ℃. Crystalline salt hydrate of inorganic phase change materials is widely used in society. It has a larger heat of fusion and fixed melting pint and able to provide a variety of phase change material whose melting point range from 1 ℃ to 100 ℃. Therefore we can choose the crystalline salt hydrate of inorganic phase change material whose melting point range from 20 ℃ to 30 ℃ to conduct the temperature control in the refuge chamber.

3.1. Principle and performance parameters of crystalline salt hydrate of inorganic phase change materials

The formula of hydrated salty molecular is $AB{\cdot}nH_2O$, "AB" denotes an inorganic salt, "n" is the number of crystal water. Hydrated salt melted into water and salt at a certain temperature after absorbed heat and store heat in it. It is a reversible reaction, water and salt will change back to the hydrated salt if the heat is released at low temperature. The reaction formal were [15]

$$AB \cdot nH_2O \xrightarrow{\text{heated } T>T_m} AB + nH_2O - Q \tag{5}$$

$$AB \cdot nH_2O \xleftarrow{\text{cooled } T<T_m} AB + nH_2O - Q \tag{6}$$

There is a non-toxic, non-corrosive, non-polluting crystalline salt hydrate of inorganic phase change materials, and the melting temperature is 28 ℃, the latent heat is 360 kJ/L, the specific heat capacity is 1.6 kJ/(kg·K), the thermal conductivity is 0.6 W/(m·K), the undercooling is 1 ℃. In short, its performance parameters meet the design requirements of low-temperature mine refuge chamber temperature control system.

3.2. Stimulate experiment on performance of phase change materials

The refuge chamber in the south No.2 mining area of Shanxi coal mine just use phase materials for cooling. To ensure that the cooling scheme if phase change materials meet the requirements of the temperature indicators(the ambient temperature for maintaining survival is less than 35 ℃ in 96 hours hedge case), we conduct a simulation experiment first.

▪*3.2.1. Experiment scheme*

The establishment of the experimental model is the main part of the experiment. The model includes two parts: one is simulation of the structure, another is equal proportion sampling of the heat. In this experiment, we checked the effect of the test based on an example of a specific coal mine. As the heat exchanger means of the person in the refuge chamber are radiation heat transfer and convection heat transfer (except for high-temperature environments), but this experiment is to verify the material absorption rate. When the heat source and the external environment is determined, the absorbed rate of units of heat in unit time is proportional to the radiating area, so the most important influencing factor is radiating area [16]. Therefore, we conduct effect experiment through equal proportion sampling of the radiation area of the material and the heat in the refuge chamber.

The survival ventricular of refuge chamber in the south No.2 mining area of Shanxi coal mine adopt rectangular section with size of 32 m×3.8 m×3.2 m , the heat transfer surface area of 472.32 m^2 (of about 480 m^2) and rated hedge staff of 100. According to the similarity principle, we reduced the heat load and heat transfer area proportionally and made an experimental box with internal radiating area of 4.8 m^2, then placed heat load of one person in the experimental box tested the cooling effect of phase change material. We can see from above, a person's heat output is

$$Q=Q_1+Q_2+500/100 \text{ W}=157.67 \text{ W} \tag{7}$$

All heat release of 4 days: 157.67 W×96 days×60 hours×60 min=54 491 kJ. Each person need change material about 182 L if leave the stand-by factor of 1.2 times.

3.2.2. Experimental device and experimental procedures

Make a rectangle ferruginous experimental box with size of 1 m×0.9 m×1.2 m. Affixed insulation cotton to the exterior-surface and prevented the heat exchange between the external environment and experimental box. Directly encapsulated the phase change material of 176 L in the color steel plate. Then affixed the color steel plate to the experimental box and kept internal surface area of approximately 4.8 m^2. Placed a 150 W incandescent lamp at the bottom of the experimental box as the experimental heat source, and installed a 20 W small-size fan to the top of the box for air convection. The aim is to distribute the heat evenly. The motor and fan were all in the box which was a confined space. Therefore, the energy consumption of fan will eventually become heat scattered into the experimental box [17], so the final heat load of it is 170 W.

Choose a K-type thermocouple as temperature sensor and the Agilent 34970 as a data acquisition. We had arranged three temperature sensors. Two of them were used to measure the temperature of inside and the cooling plate. The other one was used to measure the temperature of the external environment of experimental box. Then do the real-time collection of the temperature changes during the experiment from the data collection instrument.

In the experiment, we opened the door of the experimental box and put it into an air-conditioned room with the temperature of 13 ℃ firstly, then ensure all the phase change material in the solid state. After all material coagulated completely, we opened the door of the experimental box, then opened the lamp and fan, and began the experiment and collected the data. The result was shown in Fig.1.

3.2.3. Experimental results and analysis

(1) It can be seen from Fig.1, during the experiment, the temperature of the external environment changed greatly, but the temperature changes of the internal and the inside-wall remained steady. This showed that the insulation between the experimental box and the external environment was good, and the external environment did not cause a large interference on experiment. The experimental tank insulation treatment was essentially to meet the experimental requirements.

(2) Because the material was not reached transition temperature, so temperature inside the box early rose faster and increased from 15 ℃ to 28 ℃ within 17 hours. It can be seen that when using phase change material to control temperature, it's pre-temperature control was weak, the ambient temperature quickly rose.

(3) The temperature of the internal environment of box rose to 29.6 ℃ in 30 hours, the temperature of the inside of the box remained stable and maintained at about 30 ℃ when 76 hours after the beginning. It indicated that the material began to absorb heat when melting and the effect of control temperature was nicer. Between 76 hours to 96 hours, the temperature of inside rose slowly and eventually closed to 33 ℃. It can be seen from the curve, the heat absorption efficiency of the material decreased and the ability of control temperature was gradually failure. Therefore, in practical applications, we can consider temporary measures to help cool the heat in the chamber to prevent increasing heat caused from accidents.

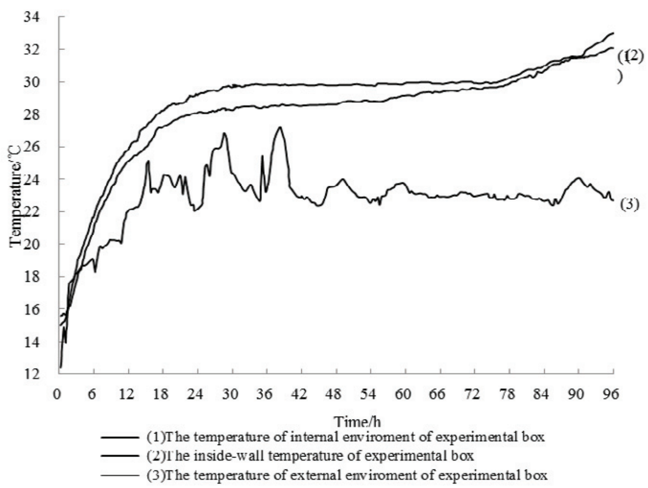

Fig. 1. Inside and outside temperature changes at different time.

4. Conclusions

The results showed that using phase change materials at refuge chamber of low-temperature mine was feasible. It can meet the national requirements of temperature control for the urgent danger prevention facilities in mine. Compared with ice thermal storage and carbon dioxide refrigeration, the use of the phase change materials can make the cooling system in refuge chamber maintenance-free and with zero operating cost, also we needn't to worry about refrigerant leakage and other hidden dangers. At the same time, the processing of the package of the phase change material also can be used as the internal decoration of chamber. It also can relieve the pressure of hedge staff.

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