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Coupled cooling method and application of latent heat thermal energy storage combined with pre-cooling of envelope: Method and model development

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ABSTRACT

The traditional cooling methods cannot meet the requirements of safety, stability, reliability and no-power at the same time under some special circumstances. In this study, a new coupled cooling method of Latent Heat Thermal Energy Storage (LHTES) combined with Pre-cooling of Envelope (PE) is proposed and the numerical model of the coupled cooling method is developed. In the current study, a refuge chamber is selected as a case study. A semi-analytical method is used to analyze the cold storage performance of the Surrounding Rock (SR). Afterwards, a numerical model of the coupled cooling system, which takes the heat source, SR, Phase Change Material (PCM) and air heat transfer into consideration, is further established. The study identified that the simplified semi-analytical calculation formula with the diagram of the cold storage quantity of SR are very helpful for engineering calculation. The influence of the Fourier and Biot number on the cold storage capacity of SR can be easily analyzed. In addition, the whole-field model of the coupled cooling system is completely developed based on the PCM unit.

1. Introduction

Nowadays, there still exist some special spaces with high-temperature and in most situations the electric power supply breakdown in Aircraft, defense engineering, mine refuge and some other facilities [1,2]. Generally in such environment they have similar thermal environment and cooling demand [3].

As shown in Fig. 1, the underground mine refuge chamber is an important emergency rescue shelter, which provides sufficient time for the trapped miners to wait for the rescue. Such refuge chambers can prevent high-temperature, harmful gas and shock from outside. They should provide breathable air, food, water and a safe environment for up to 96 h. Thus, the refuge chamber is isolated from the mine environment without any power supply. In recent years, in the United States, South Africa and other major coal producing countries, the average annual fatalities of the coal mine is around 20 [4], while it is 1000 in China, as illustrated in Fig. 2 [5]. In order to save the lives of miners, Chinese government states that the refuge chambers or other emergency rescue shelters must be installed in all mines.

Refuge chambers will be hot and humid, depending on the internal as well as the environmental conditions. As a consequence, the cooling demand in mine refuge chamber is very crucial. Hao et al. [6] pointed out that when a person entered an airtight room, the indoor temperature would rise rapidly, leading to human body injury or even death if it is not cooled within a long time. Moreover, all power must be switched off when the gas (coal dust) explosion occurs in a coal mine, in this case the cooling system should keep working without external power supply. In China, the refuge chamber must meet the requirement that the temperature should not exceed 35 °C within 96 h without any external power supply.

The traditional cooling methods consist of CO_2 phase change cooling, the explosion proof electrical air conditioning, the ventilation cooling and the ice storage cooling [7].

CO_2 phase change cooling system [8], as illustrated in Fig. 3, is mainly used in the United State and Australia. But in China, it is not feasible due to the risk of leakage. In an accident, once the CO_2

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Nomenclature

a	thermal diffusivity, m^2/s
A	calculation accuracy
A_{mush}	fuzzy zone constant
B/C/D	constant number
c_P	specific heat, J/(kg·K)
e	the base of natural logarithms
E	simplified calculation coefficient
f	melt fraction
g	acceleration of gravity,m/s^2
h	convective heat transfer coefficient, $W/(m^2 \cdot K)$
h'	enthalpy, J/kg
H	high, m
J	Bessel function of the first kind
l	feature size, m
L	length, m
m	the times of sums
N	number
q	heat flux, W
Q	heat, J
r	radius, m
S	area, m^2; source term
t	temperature, K
u	velocity, m/s
v	velocity, m/s
V	volume, m^3
W	width, m
Y	Bessel function of the second kind

Greek symbols

α	expansion coefficient
β	compute number, m^{-1}
δ	thickness, m
Δ	difference
ε	constant number
η	correction factor
λ	thermal conductivity, W/(m·K)
ρ	density, kg/m^3
τ	time, s
υ	viscosity, m^2/s

Subscripts

a	air
b	Buoyancy term
c	cooled zone circle
exp	experimental result
f	flow air
i	inner/indoor
l	limited
m	melt
o	outer
s	solidification
w	wall
x	x direction
y	y direction
0	initial value

Abbreviation

CFD	Computational Fluid Dynamics
LHTES	Latent Heat Thermal Energy Storage
PE	Precooling of Envelope
PCM	Phase Change Material
SR	Surrounding Rock
UDF	User Define Function

Dimensionless numbers

Bi	Biot number
Fo	Fourier number
Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl Number
R_c	the dimensionless radius of cooled zone
Γ	the dimensionless radius of SR
Θ	the dimensionless temperature
Φ	the dimensionless radius of far boundary
Ψ_m	the dimensionless radius of inner wall

leakage occurred in the mine, it would cause a large number of casualties. In order to meet the national standards requirements, the CO_2 cylinders must be inspected, maintained or replaced every year. Meanwhile, the following deficiencies of CO_2 phase change cooling system should be noticed:

(i) If the ambient temperature is higher than 31 °C, the refrigeration capacity would rapidly decrease or even disappear because the critical temperature of CO_2 is 31 °C;
(ii) The CO_2 cylinders occupy space for the large usage of CO_2;
(iii) The CO_2 exhausted to the environment will affect the process of rescue.

The explosion proof air conditioning system [7], as illustrated in Fig. 4, is mainly used in South Africa and the United States for its excellent refrigerating effect and convenient adjustment. However, the air conditioning system would stop working when the gas explosion occurs. It is noted that Brick et al. [9] pointed out that the system must be equipped with a high capacity battery to run due to power outages caused by unexpected accidents. And currently the Chinese government states that the power supply under coal mine must be intrinsically safe.

Ventilation cooling is the way to carry fresh air to the chamber through the pre-embedded ventilation duct or the ground drilling hole [7]. This method can achieve the purposes of cooling and purification of indoor air in closed environments. Now it is widely used in South Africa and some other countries in numerous shallow coal mines, where the ground drilling can directly reach the refuge chamber. However, it is not suitable for China to use the ventilation cooling where the depth of mines is mainly distributed in 450–500 m. The reasons are analyzed as follows [7]:

(i) The damaged probability of the ventilation duct is very high in the deep mine when mine disaster occurs, and it is expensive to use ground drilling method;
(ii) The air will gradually heat up due to the effects of the air-wall convection, so it is difficult to cool the refuge chamber.

Ice storage cooling is normally used the latent heat of the ice to cool the refuge chamber [10]. The main components of the ice storage cooling system are the device space and the ice storage tank, as shown in Fig. 5.

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