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# Coupled cooling method and application of latent heat thermal energy storage combined with pre-cooling of envelope: Sensitivity analysis and optimization

Gao Xiangkui[a], Yuan Yanping[a,*], Cao Xiaoling[a], Wu Hongwei[b], Zhao Xudong[c]

[a] School of Mechanical Engineering, Southwest Jiaotong University, 610031, Chengdu, China
[b] School of Engineering and Technology, University of Hertfordshire, Hatfield, AL10 9AB, United Kingdom
[c] School of Engineering, Faculty of Science, University of Hull, Hull, HU6 7RX, United Kingdom

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ABSTRACT

Cooling system for mine refuge chamber provides comfortable environment for miners to avoid heat damage. The existing cooling systems have their own application scopes and limitations. The coupled cooling method of Latent Heat Thermal Energy Storage (LHTES) combined with pre-cooling of envelope (PE) is a new free cooling method which is suitable for high-temperature, passive, impact and other harsh environment. Then, to improve the thermal comfort and reduce energy consumption, the effect of the pre-cooling temperature, melting temperature of PCM, aspect ratio and amounts of PCM unit on the indoor temperature are investigated in a systematic manner. Furthermore, the system is optimized and the generalized results for the evaluation parameter are given. Analysis of the results may lead to following main conclusions: (i) the method really controls the indoor temperature and the saving amount of PCM is more than 50% compared to the traditional LHTES systems; (ii) the temperature control (TC) performance of PCM would drop significantly if it melts more than 80%; (iii) under current operating conditions, the optimal melting temperature is about 29 °C and the aspect ratio of PCM unit is 60:500; (iv) per 1 °C the pre-cooling temperature dropped, 19% the actual amount of PCM decreased for the case studied.


## 1. Introduction

In Aircraft, defense engineering, mine refuge and some other facilities (Zhang et al., 2016, 2017), there still exists some special spaces with high-temperature and no-power in certain circumstances. Taking the underground mine refuge chamber (Zhang et al., 2016, 2017) as an example, it is an important emergency rescue shelter, which provides sufficient time for the trapped miners to wait for the rescue. When the mine accident happens, the refuge chamber will become an isolated, hot and humid space, depending on the internal as well as the environmental condition and there is no power supply. As shown in Table 1, the existing cooling methods, which consist of $CO_2$ phase change cooling, the explosion proof electrical air conditioning, the ventilation cooling and the ice storage cooling, have their own application scopes and limitations (Piao et al., 2013). LHTES system also cannot control the temperature independently due to the large cold loads (Kielblock et al., 1988) or the small operating temperature range.

To solve this problem, a new coupled cooling method of LHTES combined with pre-cooling of envelope is proposed by Yuan et al. (2017). As shown in Fig. 1(a), the envelope is pre-cooled by forced-air in peacetime

*Abbreviations:* ETCP, Effective Temperature Control Period; LHTES, Latent Heat Thermal Energy Storage; PE, pre-cooling of envelope; PCM, Phase Change Material; SR, surrounding rock; TC, temperature control; UDF, User Define Function.

* Corresponding author.
E-mail address: ypyuan@home.swjtu.edu.cn (Y. Yuan).
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## Nomenclature

| | |
|---|---|
| $a$ | Thermal diffusivity, $m^2/s$ |
| $A$ | Area, $m^2$ |
| $c_p$ | Specific heat, J/(kg K) |
| $g$ | Acceleration of gravity, $m/s^2$ |
| $h$ | Convective heat transfer coefficient, $W/(m^2 K)$ |
| $H$ | High, m |
| $l$ | Feature size, m |
| $L$ | Length, m |
| $N$ | Number |
| $q$ | Heat flux, W |
| $Q$ | Heat, J |
| $r$ | Radius, m |
| $t$ | Temperature, °C |
| $V$ | Voltage, $m^3$ |
| $W$ | Width, m |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | Expansion coefficient |
| $\gamma$ | The evaluation parameter of heat tolerance time |
| $\delta$ | Thickness, m |
| $\Delta$ | Difference |
| $\lambda$ | Thermal conductivity, W/(m K) |
| $\rho$ | Density, $kg/m^3$ |
| $\tau$ | Time, s |
| $\upsilon$ | Viscosity, $m^2/s$ |

*Subscripts*

| | |
|---|---|
| $a$ | Air |
| $e$ | Extreme endurance |
| $f$ | Flow air |
| $i$ | Inner/indoor |
| $m$ | Melt |
| $o$ | Outer |
| $pc$ | Pre-cooling |
| P | Person |
| R | Refuge chamber |
| R1 | Side wall of refuge chamber |
| R2 | Vault of refuge chamber |
| $w$ | Wall |
| 0 | Initial value |

*Dimensionless numbers*

| | |
|---|---|
| $Gr$ | Grashof number |
| $Nu$ | Nusselt number |
| $Pr$ | Prandtl number |

and the PCM of suitable temperature are encapsulated into units to store cold. As shown in Fig. 1(b), fully using sensible heat storage capacity of envelope and latent heat storage capacity of PCM can control the temperature in working time.

The coupled cooling method can not only expand the operating temperature difference of PCM, but also bear numerous cold loads to reduce the amount of PCM by pre-cooling the envelop. This method meets the requirements of safety, no power, stability and reliability under special environment and widens the application range of LHTES system for temperature control (Yuan et al., 2017).

In order to save energy, the natural cold source, such as low-temperature water (the water temperature is less than 15 °C), cold air (winter), snow or ice, should be fully utilized. When the natural cold source cannot meet the pre-cooling demand, the cold air from the mining working face should be partly shunted into the refuge chamber. And intermittent cold storage technology can be used since the thermal diffusivity of the rock is small and there is no heat source in the room. As a consequence, the indoor temperature could not have a remarkable rise during a rest period.

In theory, LHTES can not only reduce the mismatch between supply and demand but also improve the performance and reliability of energy systems (Barzin et al., 2015). In fact, many places of LHTES should be optimized and improved in the application process. Over the past decades, extensive research efforts have been made on the sensitivity analysis and optimization for different LHTESs (Gowreesunker and Tassou, 2013; Gracia et al., 2013; Ramakrishnan et al., 2016; Fernandes et al., 2016; Iten et al., 2016; Peng et al., 2014).

Sensitivity analysis and optimization of the PCM unit can enhance the effectiveness of heat transfer. The operation characteristics and influencing factors of the PCM unit mainly involve the natural convection, the arrangement of fins and the change of unit structure. To improve the thermal storage performance of the circular finned tube, the influence factors such as the fin pitch, the fin height, the fin thickness and the inner radius of the tube, were numerically investigated by Wang et al. (2016). A recent study of Yuan et al. (2016) mainly focused on the fin angle's influence on the heat storage rate of annular PCM unit. Their results showed that there existed maximum melting heating rate when the fins are vertical. Borderon et al. (2015) designed a new PCM-air heat transfer ventilation system based on the night ventilation unit. To ensure the air heat exchanger can adapt to different climatic conditions, running different ventilation conditions should correspond to the external environments to achieve the optimum utilization of cold. Solgi et al. (2016) also studied the PCM-air heat exchanger and tried to find the suitable condition to start the night ventilation. It was found that the composite PCM for heat storage will greatly reduce the indoor load.

The operation characteristics and influencing factors of the PCM envelope mainly focused on the selection of PCM and the layout mode. Kheradmanda et al. (2014) applied the mixed phase change mortar to building facades, and tested the performance and energy conservation by a combined numerical and experimental method. Results showed that joining the phase change mortar would be helpful in reducing indoor load and maintaining the stability of the indoor temperature. Thiele et al. (2015) and Chaiyat and Kiatsiriroat (2014) studied the concrete wall with phase change micro capsule in different areas. It was concluded that there was more load reduction in summer than that in winter, and different energy savings are demonstrated in different areas. Kong et al. (2014) investigated the influence of two different installation forms of shape-stabilized PCM on the indoor thermal comfort. One is the panels installed on the outside surface of walls and roofs (PCMOW) with acid capric contained, the other is the panels installed on the inside surface of walls and roofs (PCMIW) with capric acid (95 wt%) and 1-dodecanol (5 wt%) contained. Their experimental and numerical results showed that the PCMIW system has a better control effect than that of the PCMOW system. Zhou et al. (2008) used the enthalpy model to calculate a solar room with the shape-stabilized PCM plates and then analyzed the effect of melting temperature of PCM, heat transfer coefficient, the position and thickness of PCM plates etc. on indoor temperature. They found that the PCM plate can be fully stored in the daytime and released at night to improve the indoor comfort.

Unlike common LHTESs, there are unique application environment and control target for the coupled cooling method. The coupled cooling method consists of two processes: the pre-cooling process and the coupled cooling process. And the coupled cooling process includes the heat transfer among PCM units, envelop, air and heat sources in a closed space. Therefore, to improve the operation efficiency and reduce energy consumption, the sensitivity analysis and optimization of the coupled cooling system, new tasks, should be done.

To solve the cooling problem in high-temperature, passive, impact and other harsh environments, based on the new coupled cooling method of LHTES combined with pre-cooling envelop and the numerical simulation model which considering the heat source, surrounding rock (SR), PCM and air heat transfer, the thermal performance of the coupled cooling method is analyzed and an evaluation parameter of heat tolerance is proposed to evaluate the temperature control effect