Design Engineering

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

Optimization Experiment of PCM on Thermal Environment inside Safety Helmet

Wentao Hu[1], Shuhan Liu[2], Kang Zhao[3], Yingjun Wang[1], Qianru Dai[1], Chaoping Hou[1,*]

[1]College of Architecture and Urban-Rural Planning, Sichuan Agricultural University, Chengdu 610065, P.R. China

[2]College of Architecture and Urban Planning, Qingdao University of Technology, Qingdao, 266033, PR China

[3]The eighth Project Technology Department of Infrastructure Business Division, China Railway Construction Group Co, LTD, BeiJing, 100855, China

*Corresponding Author: Chaoping Hou

Abstract:

In the process of physical state or molecular structure transformation, phase change materials can absorb the heat in the environment, and release the heat to the environment when necessary, so as to achieve the purpose of controlling the ambient temperature. Therefore, phase change materials are widely used in building energy saving, solar energy utilization, agricultural production and other fields. In this study, based on the thermal characteristics of phase change material (PCM) in high temperature and heat release in low temperature, four kinds of safety helmet models were established by using PCM patch. Through the air conditioning system, the working states of four kinds of helmet models in 30 ℃ and 16 ℃ thermal environments are simulated respectively. The temperature and humidity values of four kinds of safety cap models in different environments are measured by multi-channel temperature measuring instrument and temperature and humidity measuring instrument. Through comparative analysis: PCM Safety Helmet (c) has the effect of cooling and moisturizing at high temperature, and has the effect of thermal insulation at low temperature; in high temperature environment, the internal temperature of fan Safety Helmet (b) is higher, and the internal thermal environment is chaotic, so its cooling effect is poor; the cooling effect of Safety Helmet (d) in high temperature environment is not obvious.

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

***Keywords**: Safety helmet, Phase change material (PCM), Thermal environment.*

I. INTRODUCTION

For hot summer and cold winter areas, the working conditions of workers are hard, the labor security facilities are simple, and the probability of workers suffering from heatstroke or frostbite is high, which seriously affects the physical and mental health, personal safety and work efficiency of workers, so it is urgent to adopt efficient labor protection technology [1]. When the weather is hot, the thermal comfort balance of workers is disturbed, and the regulating factors of head skin react to exhaust excess heat and a lot of sweat. On the one hand, the excluded heat accumulates in the environment around the head, making the human body uncomfortable. On the other hand, a large amount of sweat will dehydrate the human body, and the above two factors are considered to be the most common causes of heatstroke in medicine [2,3]. In addition, when the outdoor temperature is low, the basic physiological functions of workers will decline, resulting in neurological dysfunction and complications, even appear temperature rise [4], coma [5], arrhythmia [6], brain damage such as ischemia [7] or internal organ failure [8]. Therefore, it is very important to improve the thermal comfort of workers by optimizing the thermal environment of safety helmet in preventing heatstroke and improving working conditions.

The improved design of safety helmet is used to cool the head. The most popular technology is the electric fan cooling technology. A small electric fan is installed in the front of the safety helmet, which speeds up the air flow inside the safety helmet by rotating the fan blades, improves the convective heat transfer rate between the air, and replaces the high-temperature air flow inside the safety helmet. In addition, it can also accelerate the evaporation rate of sweat from the head, making people feel cool and comfortable. JWO. C.S [9] designed a solar cooling system, which uses the electricity generated by solar cells to drive the cooling module and a small fan, so that cold air can enter the helmet and cool the head. Buist and streitwieser [10] designed an electric fan cooling device to dissipate heat from the inside of the helmet to the outside of the helmet. The cooling system has been proved to be a feasible method for headcooling. However, according to construction workers whowork outdoors, the fan safety helmet has a poor cooling effect in high-temperature open spaces, especially in the later period when it gets hotter and hotter.

ISSN: 0011-9342
Issue: 11 | Pages: 205 - 220

Recently,the technology of cooling and heating using phase change materials' high-temperature endothermic and low-temperature exothermic characteristics has been widely used. Phase change material is a material that changes its phase state with the change of temperature and can provide latent heat. At high temperature, phase change material changes from solid state to liquid state, which can absorb heat from surrounding environment and store it; at low temperature, phase change material changes from liquid to solid state, and releases the stored heat energy, so as to achieve the purpose of cooling [11]. Taking advantage of the characteristics of phase change materials, phase change materials have shown great development potential in the fields of aerospace, refrigeration and air conditioning, solar energy utilization, building energy conservation, heat recovery and other fields [12-16].

Phase change materials are widely used in the field of endothermic cooling. Fang Xuewang et al. [17] conducted an experimental study on the thermal comfort of phase change wall rooms in hot summer and cold winter areas, and compared them with ordinary rooms. The results show that setting phase change gypsum board on the room wall can reduce the indoor temperature, effectively reduce the room temperature fluctuation and improve the room comfort. Xian Shi [18] and others experimentallystudied the influence of the position of the phase change board made of micro-encapsulatedphase change material on the concrete wallon the indoor temperature and humidity. The experimental results show that: compared with the ordinary room without phase change board, the temperature of the room with phase change plate decreases by 4℃.

Phase change materials are widely used in the field of exothermic heating. Zhou Wei et al. [19] made composite phase change heat storage wall material by mixing phase change material and cement mortar, and applied the composite phase change heat storage wall material to the back wall of solar greenhouse, which improved the air temperature and solar energy utilization rate in the greenhouse. Wang Peng et al. [20] phase change materials with good performance are used in the greenhouse in winter, which improves the temperature of the greenhouse, which is not only conducive to the greenhouse energy saving, but also conducive to the growth of winter vegetables.

To sum up, in the high-temperature workplace and low-temperature working environment, ordinary safety helmet has been unable to meet the needs of the majority of workers. Even the cooling effect of fan cooling safety helmet in high temperature outdoor places is relatively poor, and can not meet the thermal comfort needs of users. The above researchers have done a lot of research on phase change materials, which show that phase change materials have the characteristics of cooling and heating, and are applied in various fields. Therefore, based on the thermal characteristics of high temperature phase change heat absorption and low temperature

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

phase change heat release of phase change material, the phase change material and safety helmet are organically combined to optimize the internal thermal environment of safety helmet, hoping to get the best safety helmet model.

II. METHODOLOGY

2.1 Materials and Components

The preparation of phase change materials is the most important step in order to obtain a kind of safety helmet model with the best internal thermal environment by building four kinds of safety helmet models on the basis of common safety helmet.The phase change material used in this experiment is CaCl2 • 6H2O, the weight of the phase change material is 60g, and the anti-phase separation agent is SiO2 of 2g, which was made by Fushun Petrochemical Research Institute.TA's Q200 differential scanning calorimeter (DSC) was used for the detection of phase change materials. This differential scanning calorimeter (DSC) characterized the phase change temperature and latent heat value of phase change material samples. The temperature measurement range was -70~70℃, and the scanning rate was 10℃/min. DSC curves of phase change materials are shown in Fig. 1. The melting range of phase change materials is 23~25℃, the melting temperature of phase change materials is 23.08℃, and the latent heat of phase change materials is 151.8 j/g.phase change materials ($CaCl_2 \cdot 6H_2O$).As the latent heat of phase change material ($CaCl_2 \cdot 6H_2O$) is better, and the melting range conforms to the comfortable temperature of human body, it is a good choice to optimize the thermal environment inside the helmet.

Design Engineering

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

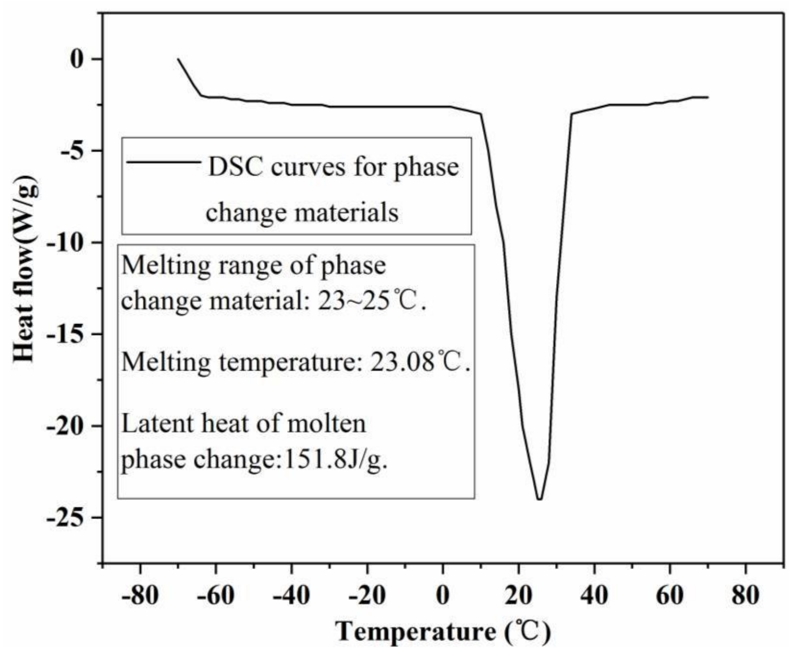

Fig 1: Schematic diagram of DSC curve of phase change material.

The packaging of phase change materials is an important part of improving the design of cooling helmet. As shown in Fig 2, the phase change material is packed in a flat aluminum foil envelope bag. The air in the aluminum foil bag is pumped by vacuum machine. The flat shape can increase the contact area between PCM and the inner space of helmet, increase the heat transfer area and heat transfer rate. The reason why aluminum foil sealing bag is selected is that the heat transfer coefficient of aluminum foil is high, which is beneficial to improve the heat transfer efficiency. The sealing bag is vacuumed to remove air and avoid the influence of air layer on heat transfer.

The working principle of safety helmet is shown in Fig 3. Phase change material is a kind of material that changes phase with temperature and provides latent heat. Phase change materials can absorb or release a lot of heat in the process of phase transformation, but the temperature remains basically unchanged. With this characteristic, phase change material can be used to adjust the temperature of safety helmet. In daily work, the common types of safety helmet are roughly divided into two types, one is ordinary safety helmet, the other is fan safety helmet. Among them, the fan safety helmet is widely used because of its low-cost advantagesandlow energy consumption helmet. The working principle of the fan is to speed up the air convection

Design Engineering

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

speed through the fan blade rotation, and accelerate the internal and external air convection helmet, so as to achieve the purpose of cooling.

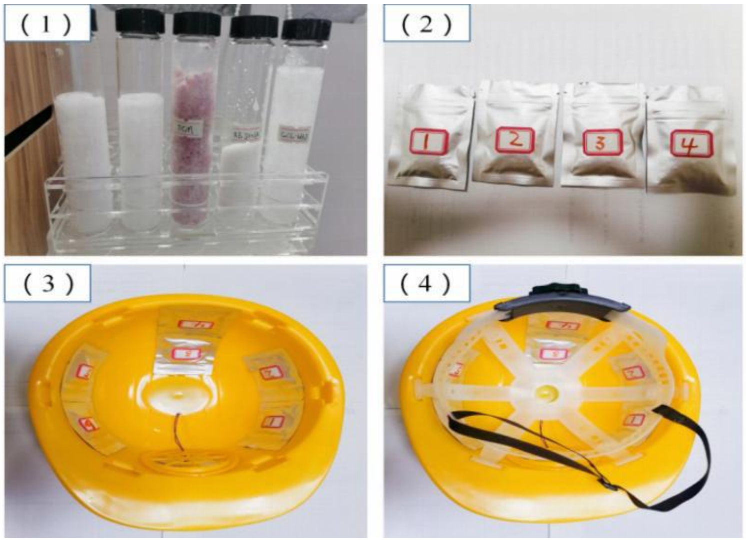

Fig 2: Schematic diagram of preparation and installation steps of phase change materialpatch, (1),(2),(3),(4).

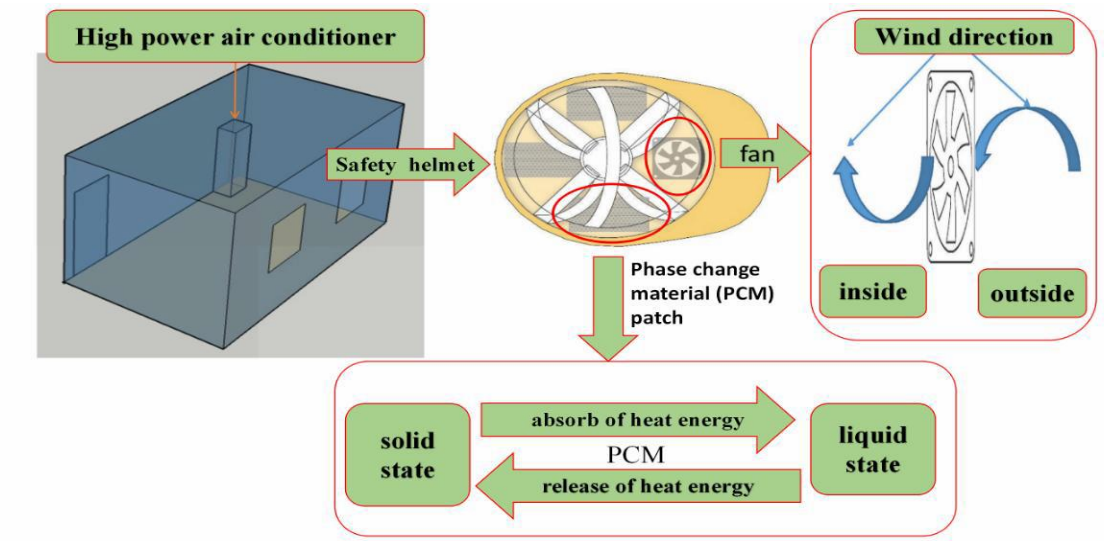

Fig 3: Schematic diagram of helmet cooling principle.

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

2.2 Design of Safety Helmet Model

As shown in Fig 4, four kinds of helmet models were constructed by placing phase change material patches in the interior of common helmet and fan helmet.Where the Safety Helmet (a) is the ordinary safety helmet;Safety Helmet (b) fan safety helmet;The Safety Helmet (c) is composed of a common safety helmet and a phase change material patch.The Safety Helmet (d) consists of a fan safety helmet and a phase change material patch.

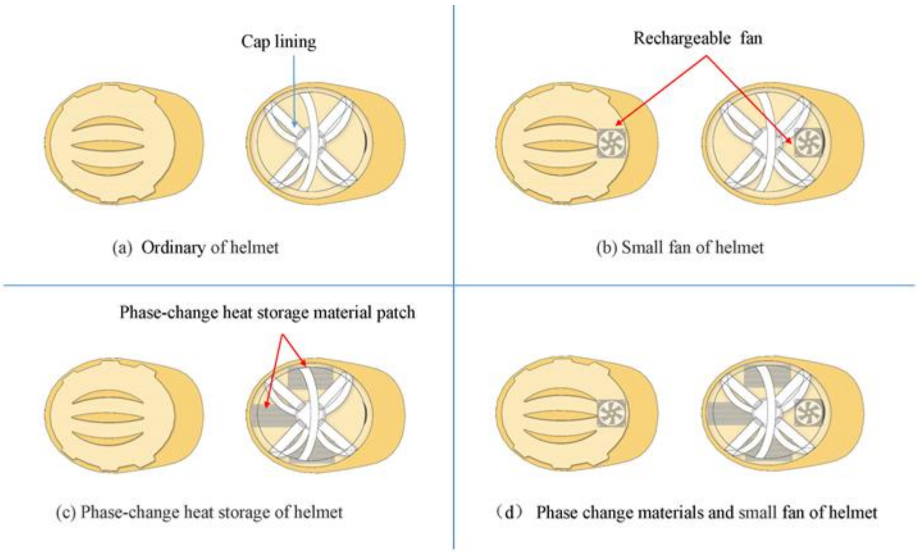

Fig 4: Schematic diagram of the design model of four safety helmets:(a), (b), (c), (d).

2.3 Spatial Model and Instrument Layout

An office with good sealing effect is selected as the spatial model. The geometric size of the office is 4m×7m×3.5m, and the wall thickness is 240mm. There are two external windows with geometric size of 1.5m×1.5m on the south wall. The office space model and dummy head model are shown in Fig 5. A self-supporting high-power air conditioner is set in the office to simulate high-temperature environment and low-temperature environment. In the office, four dummy head models are set up. The dummy head models are made of non heat dissipation materials. It is assumed that the difference of thermal performance can be ignored. The four kinds of safety helmet models were respectively installed on the dummy head and placed in the office.

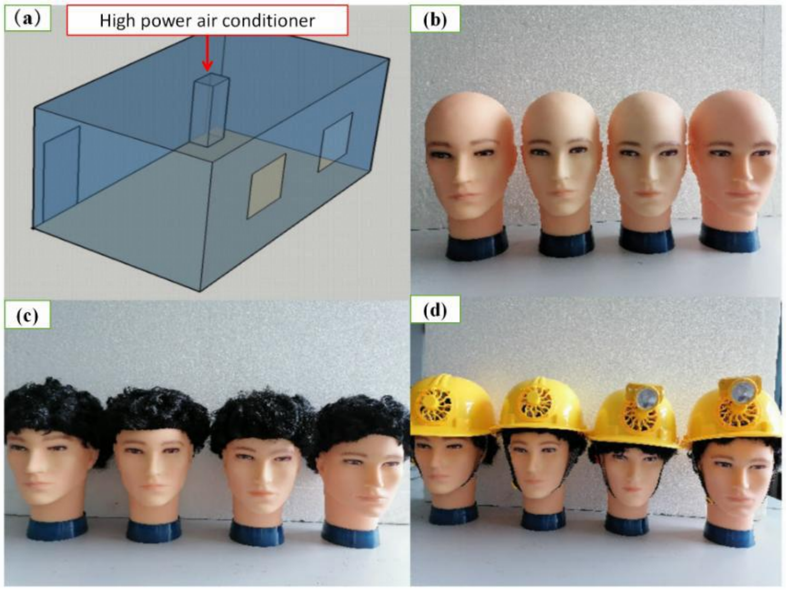

Fig 5: Office space model (a) and dummy head model (b), (c), (d)

As shown in Fig 6, multichannel temperature tester and temperature and humidity recorder are respectively set on the upper part of the inner side of the four kinds of helmet models to measure the temperature and humidity inside the helmet, which are T_1, T_2, T_3, T_4 and H_1, H_2, H_3 and H_4; multi channel temperature tester and temperature and humidity recorder are set in the office to measure the temperature and humidity of indoor air, which are T_5 and T_6, H_5 and H_6, respectively, The average temperature and humidity of two measuring points are taken, and the two measuring points are 1.5m away from the ground. Before the experiment, turn on the electric fans of Safety Helmet (b) and (d), and set anemometer to check the difference of wind speed. The performance parameters of the above experimental instruments are shown in Table 1.

ISSN: 0011-9342
Issue: 11 | Pages: 205 - 220

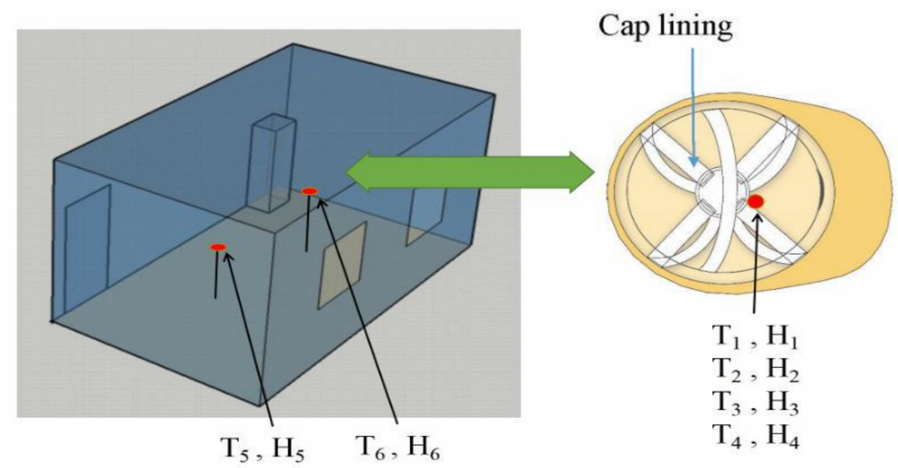

Fig6: Layout of instrument measuring points

TABLE I. Performance parameters of various experimental instruments

INSTRUMENTATION	TYPE	VARIABLE	ACCURACY
HYGROTHERMOGRAPH	JTR08ZI	AIR TEMPERATURE	-40 ℃-120 ℃ (±0.5 ℃)
		RELATIVE HUMIDITY	0-100% (±3%)
TEMPERATURE	JTR01Z	TEMPERATURE	-40 ℃-120 ℃ (±0.5 ℃)
ANEMOGRAPH	JTR07Z	WIND SPEED	0.05~2M/S (±0.03)
HIGH POWER AIR CONDITIONER	FREE-STANDING	COOLING AND HEATING	16 ℃-30 ℃ (±3%)

2.4 Description of Experimental Process

In order to optimize and analyze the internal thermal environment of different helmets, a helmet model with the best thermal environment was obtained. The experiment was carried out at 30℃ and 16℃ respectively:

(1) The experiment was carried out at 30℃.

Design Engineering

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

Close office doors and windows. Turn on the air conditioner and set the temperature to 30 ℃. In high temperature environment, turn on the electric fans of Safety Helmet (b) and Safety Helmet (d), measure the wind speed of two electric fans with anemometer, and check the difference of wind speed of safety helmet. As shown in Fig. 7, the difference of wind speed between Safety Helmet (b) and Safety Helmet (d) is small, so it is assumed that the thermal environment difference caused by wind speed is ignored. Start the experiment.

(2) The experiment was carried out at 16℃.

Close office doors and windows. Turn on the air conditioner and set the temperature to 16 ℃. Since the air temperature is low in the thermal environment of 16℃, it is not necessary to lower the temperature by fan, so turn off the electric fan of Safety Helmet (b) and (d). Therefore, in this experiment, Safety Helmet (a) and (b) are transformed into ordinary helmets, and Safety Helmet (c) and (d) are phase change material helmets. Start the experiment.

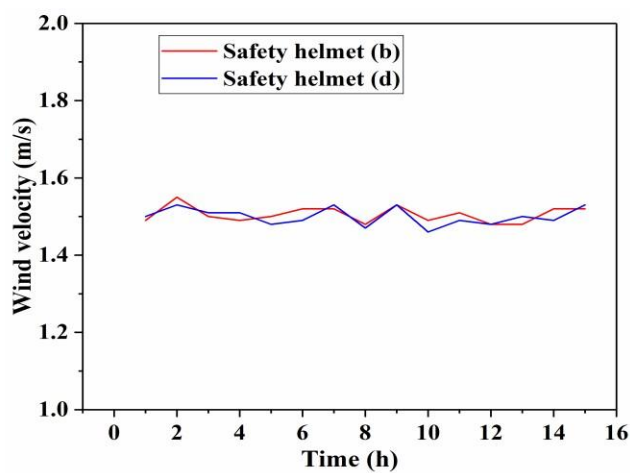

Fig 7: Wind speed diagram of Safety Helmet (b) and Safety Helmet (d)

III. RESULTS AND DISCUSSION

The experiment was conducted in Sichuan Agricultural University (China) in July 2020. In the first experiment, the high-power air conditioner was set at 30℃ to simulate the high temperature thermal environment. In the second experiment, the high-power air conditioner was set at 16℃ to simulate the low-temperature thermal environment. In addition, the time interval of the measuring instrument is set to record once every 10min. During the experiment, the changes of room air temperature and humidity with time are shown in Fig 8. In Fig. 8(a), the

Design Engineering
ISSN: 0011-9342
Issue: 11 | Pages: 205 - 220

indoor temperature rapidly rises to about 30 ℃ in the first two hours before the air conditioner is turned on, and then tends to be stable, indicating that the indoor temperature reaches the design value, and the air conditioner is not warming up and remains stable. The indoor relative humidity decreased gradually in the first 2 hours, and then stabilized at 55% RH. In Fig. 8(b), the indoor temperature rapidly drops to about 16 ℃ in the first two hours before the air conditioner is turned on, and then tends to be stable; the indoor relative humidity gradually rises in the first five hours, and then tends to be stable at about 63% RH.

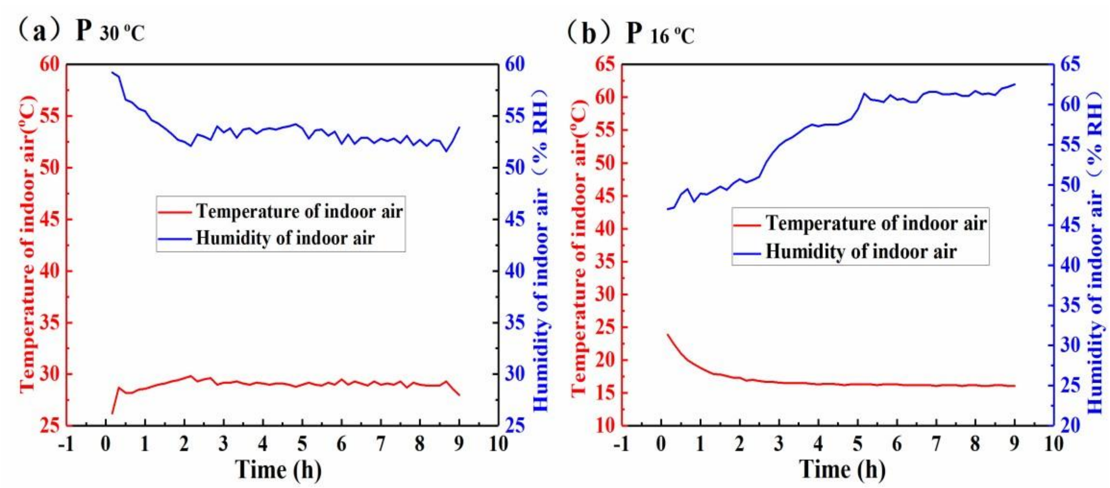

Fig 8: (a) is the schematic diagram of indoor air temperature and humidity under a thermal environment of 30 °C, and (b) is the schematic diagram of indoor air temperature and humidity under a thermal environment of 16 ℃.

3.1 Comparison of Temperature and Humidity inside the Safety Helmet Under 30℃ Thermal Environment

In Fig 9, the internal temperature of the four types of helmet is rising, and the humidity is falling in the first 2 hours. The reason is that the air conditioning starts to work, so that the indoor temperature reaches the degree of 30℃ thermal environment. After 2 hours, the temperature and humidity gradually tend to be stable, because the air conditioner no longer heats up after the indoor temperature reaches 30 ℃. As shown in Fig. 9, the temperature and humidity in Safety Helmet (a) is similar to that of the indoor air, because there is no cooling measure in the general Safety Helmet, its internal temperature fluctuation is greatly affected by

ISSN: 0011-9342
Issue: 11 | Pages: 205 - 220

the surrounding environment.

The temperature and humidity in Safety Helmet (b) and (d) fluctuate greatly, especially when the surrounding environment is stable. The reason is that both of them have installed electric fans to increase the convective heat transfer rate inside the Helmet and the surrounding environment, so the temperature and humidity inside the Helmet still fluctuate greatly in a stable environment.In addition, as shown in Fig 9(a), the internal temperature of Safety Helmet (b) and (d) is higher than that of Safety Helmet (a), and its cooling effect is poor. The reason is that in the high temperature environment, the fan accelerates the heat transfer inside and outside the helmet, resulting in a large amount of external hot air flowing into the safety helmet, which reduces the cooling effect of fan cooling technology and phase change material absorption cooling technology.Therefore, the cooling effect is not obvious in Safety (B) and (d) in a high temperature environment.As shown in Fig 9(b), the humidity of Safety Helmet (b) and (d) is lower, because the convection rate of air flow inside and outside the safety helmet is increased with the rotation of the fan blade, which leads faster evaporation of water, so the humidity is lower.

The internal temperature of Safety Helmet (c) is the lowest, which the overall temperature is lower than 28.5℃, and 1-4℃ lower than the indoor air temperature, indicating that it has good cooling effect; the temperature and humidity of Safety Helmet (c) fluctuates slightly, indicating that it has good temperature stability. In addition, the humidity of Safety Helmet (c) was significantly lower than that of the other three safety helmets at 30℃, which indicated that Safety Helmet (c) had good moisturizing effect. In conclusion, in a thermal environment of 30℃, Safety Helmet (c) not only has better temperature and humidity stability, but also has the effect of cooling and moisturizing.The reason is that phase change material patches are set inside Safety Helmet (c), and phase change material patches have the characteristics of high temperature heat absorption, so the temperature inside Safety Helmet (c) is reduced, so as to achieve the cooling effect; as we all know, when the temperature is relatively low, the humidity is relatively high due to the small evaporation of moisture.

Design Engineering

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

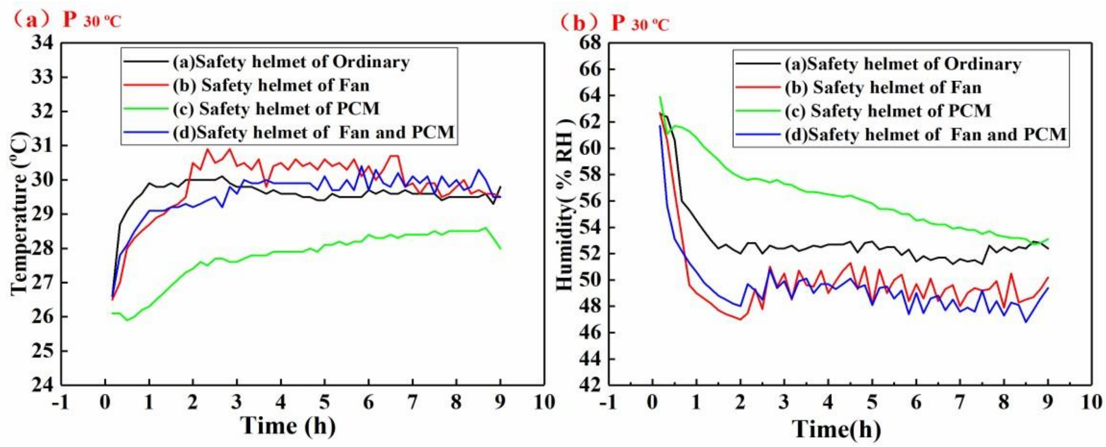

Fig 9: Schematic diagram of temperature and humidity changes over time in the safety helmet at 30℃.

3.2 Comparison of Temperature and Humidity inside the Safety Helmet Under 16 ℃ Thermal Environment

In the thermal environment of 16℃. Turn off the electric fan of the Safety Helmet (b) and (d), so that the Safety Helmet (a) and (b) become the ordinary safety helmet, and the Safety Helmet (c) and (d) are the phase change material safety helmet. In Fig 10, it is obvious that the internal temperature and humidity fluctuation trend of Safety Helmet (a) and (b) is basically consistent with the indoor air temperature and humidity fluctuation trend, indicating that the internal temperature and humidity fluctuation of ordinary safety helmet is greatly affected by the surrounding environment, and has no function of heat preservation and moisture preservation.

As shown in Fig. 10(a), compared with Safety Helmet (a) and (b), in the first 9 hours, the internal temperature of Safety Helmet (c) and (d) is 2-4℃ higher than the indoor air temperature, indicating The Safety Helmet (c) and (d) have a heat preservation effect and can last for 9 hours. The reason is that phase change material patches are set in Safety Helmet (c) and (d), and the phase change material not only has high heat storage capacity, but also has the characteristics of low temperature heat release. Therefore, the internal temperature of Safety Helmet (c) and (d) can be increased, so as to achieve the effect of heat preservation, and can last for 9 hours; In addition, compared with Safety Helmet (a) and (b), the humidity of Safety Helmet (c) and (d) is relatively low due to the higher internal temperature and larger water evaporation.

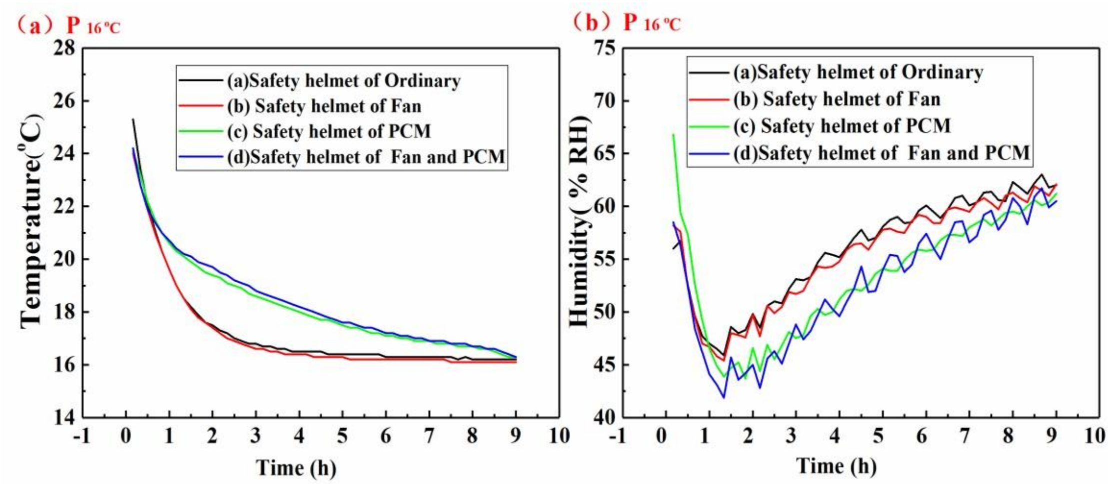

Fig 10: Schematic diagram of temperature and humidity inside the helmet with time under 16 ℃ thermal environment.

IV. CONCLUSION

The working states of four safety helmet models in 30 ℃ and 16 ℃ thermal environments were simulated by air conditioning system, through data comparison and analysis, the following results are obtained:

1). The phase change material is set inside the safety helmet, so that the Safety Helmet (c) has the effect of cooling and moisturizing at high temperature, and has the effect of heat preservation at low temperature. Therefore, the phase change material can optimize the thermal environment inside the safety helmet.

2). In high temperature environment, the internal temperature of fan Safety Helmet (b) is higher, and the internal thermal environment is chaotic, so its cooling effect is poor.

3). The Safety Helmet (d) is made by combining the phase change material absorption cooling technology with the fan cooling technology. However, in the high temperature environment, its internal temperature is high and the humidity fluctuates greatly, so the cooling effect of the Safety Helmet (d) is not obvious.

Design Engineering

ISSN: 0011-9342

Issue: 11 | Pages: 205 - 220

REFERENCES

[1] Chen X. et al. (2003) Thermal comfort, health and environment. HVAC. 33(4): 55-57.

[2] Hardy J. D., Dubois E.F., Basal metabolism, radiation, convection and vaporization at temperatures of 22 to 35 ℃, J. Nutr. 15 (1938): 477 – 497.

[3] Steven C. Sherwood, Matthew Huber (2010) An adaptability limit to climate change due to heat stress, Proc. Natl. Acad. Sci. USA 107 (21): 9552 – 9555.

[4] Li Jun, Zhang Xue-Yan, Zou Zhi-Meng, Wang Bin, Xia Ji-Kai (2015) Heat stroke: typical MRI and (1)H-MRS features, Clin. Imaging 39 (3): 504 – 505.

[5] Rajendra Singh Jain, Sunil Kumar (2015) Acute vertebrobasilar territory infarcts due to heat stroke, J. Stroke Cerebrovasc. Dis.:Off. J. Nat. Stroke Assoc. 24 (6): 135 – 138.

[6] Daniel Case, Richard Harrigan (2015) Heat stroke-induced sinoatrial node dysfunction, J. Emerg. Med. 49 (2): 143 – 146.

[7] Chang Chen-Kuei, Chang Ching-Ping, Liu Shyun-Yeu, Lin Mao-Tsun (2007) Oxidative stress and ischemic injuries in heat stroke, Prog. Brain Res. 162 (2): 525 – 546.

[8] Lee Ching-Wei, Perng Chin-Lin, Huang Yi-Shin, Luo Jiing-Chyuan, Hung Chi-Lai (2010) Multiple organ failure caused by non-exertional heat stroke after bathing in a hot spring, J. Chin. Med. Assoc. (JCMA) 73 (4): 212 – 215.

[9] Jwo C.S, Chien, C. C (2007) Solar Power-operated cooling helmet, U. S. Patent 200701376845A1.

[10] Buist R.J., Streitwieser G.D. (1988) The thermoelectrically cooled helmet, in: Proceeding of the Seventeenth International Thermoelectric Conference, Arlington, Texas, 16 – 18: 88 – 94.

[11] Wei X, et al. (2019) Photo-and electro-responsive phase change materials based on highly anisotropic microcrystalline cellulose/graphene nanoplatelet structure. Applied Energy, 236 (15): 70-80.

[12] Alam M, et al. (2019) Energy saving performance assessment and lessons learned from the operation of an active phase change materials system in a multi-storey building in Melbourne. Applied Energy, 238(15):1582-1595.

[13] Asgharian H, et al. (2019) A review on modeling and simulation of solar energy storage systems based on phase change materials. Journal of Energy Storage, 21: 186-201.

[14] Zhai X., et al. (2013) A review on phase change cold storage in air-conditioning system: Materials and applications. Renewable & Sustainable Energy Reviews, 22: 108-120.

[15] Ting H., et al. (2017) Application and experimental research of the phase change materials in building energy-saving. New Building Materials.

[16] Lopez-Sabiron A. M, et al. (2014) Carbon footprint of a thermal energy storage system using phase change materials for industrial energy recovery to reduce the fossil fuel consumption. Applied Energy, 135(15): 616-624.

[17] Fang X. et al. (2014) Study on the comfort of phase change exterior wall room in hot summer and cold winter. Science technology and Engineering, 14(11): 239-243.

[18] Shi. X. et al. (2014) Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels. Energy and Buildings, 71(3): 80-87.

[19] Zhou W., et al. (2010) Feasibility study on energy saving application of phase change energy storage wall material in Solar Greenhouse. BeiJing: Beijing University of Technology.

[20] Wang P. Research and development of wall materials for cool type phase change heat storage and thermal insulation greenhouse. YangLin: Northwest Agriculture and Forestry University.