COMPOSITE DESIGN AND THERMAL COMFORT EVALUATION OF SAFETY HELMET WITH PHASE CHANGE MATERIALS COOLING

by

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Higher temperature and humidity will adversely affect the thermal comfort of helmet users. In order to improve the comfort level of the helmet and obtain an optimal cooling helmet model, four kinds of helmet models were established by using phase change material, heat-absorbing cooling technology, and fan cooling technology. Through the air conditioning system, the working states of four kinds of helmet models in the thermal environment of 30 °C were simulated, and the thermal comfort of four kinds of helmet models was evaluated. The results show that: high temperature environment is an important factor affecting the cooling effect of fan helmet fan, Under high temperature environment, the helmet with fan cooling technology has a certain cooling effect in the early stage, but after 30 minutes, the cooling effect becomes worse and worse. Under high temperature environment, phase change materials safety helmet has a good cooling effect, but poor ventilation results in the excreted sweat clinging to the scalp and hair, resulting in a poor user experience. There are defects in using phase change material heat absorption cooling technology or fan cooling technology alone. The helmet combines phase change material heat absorption cooling technology with fan cooling technology, so that the cooling effect and internal thermal environment stability of the helmet are the best, and the thermal sensation of human body is the best. Therefore, the helmet is an optimal design model.

Key words: *safety helmet, phase change material, fan cooling technology, thermal comfort*

Introduction

Safety helmet are an essential piece of personal protective equipment for all industries and construction sites. When the temperature and humidity levels are high, the thermal comfort of users will be adversely affected. The uncomfortable feeling seriously affects users' mental health, personal safety and work efficiency, so it is urgent to adopt efficient labor protection technology. Since the head is an important organ for physiological regulation of the human body, as well as a part of the body with high heat, the control of the human body temperature regulator is crucial to maintain the thermal comfort of helmet users [1-4]. In addition, when the outdoor temperature exceeds 35 °C, the basic physiological functions of workers will decline

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[5], leading to neurological dysfunction and complications, temperature rise [6], coma [7], arrhythmia [8], brain injury such as ischemia [9] or internal organ failure [10]. The human body's heat stress response can also lead to fatigue and affect individual work performance, alertness and ability [11]. Therefore, it is extremely important to improve the thermal comfort of workers by cooling their heads to prevent heat stroke, improve their personal health and improve their working conditions.

The improved design of the helmet is used for cooling the head. The popular technology is the electric fan cooling technology. A small electric fan is installed at the front of the helmet to speed up the air-flow inside the helmet by rotating the fan blade, so as to improve the convective heat transfer rate between the air and replace the high temperature air-flow inside the helmet. Additional, still can quicken the evaporation rate of head sweat, make the person feels cool and comfortable. A solar cooling system is designed by Jwo *et al*. [12], the solar cooling system USES the electricity generated by the solar cells to drive the cooling module and a small fan so cold air can enter the helmet and cool the head. Buist and Streitwieser [13] designed an electric fan cooling device that diffuses heat from the inside to the outside of the helmet, the cooling system proved to be a feasible method for cooling the head. However, according to the construction workers working outside, the fan safety helmet has a poor cooling effect in hot open places, especially when it gets hotter and hotter in the later period [14].

Recently, the cooling technology based on high temperature heat absorption of phase change materials (PCM) has been widely used, especially in the field of helmet cooling. Saud Ghani studied the application of PCM in thermal comfort control of safety helmets under forced convection [15], a 3-D CFD model of an industrial helmet and a human head was established to evaluate the thermal performance of the helmet under different harsh working conditions. The results showed that the forced convection reduced the maximum temperature on the outer surface of the helmet by about 10 °C, and the PCM embedded in the helmet could prolong the thermal comfort period. Tan *et al*. [16], designed a PCM cooled helmet with a PCM that encapsulated the PCM in a bag and placed it between the helmet and the wearer's head. A PCM is used to absorb and store heat inside the helmet, thus cooling it down.

Fok *et al*. [17] studied the application of PCM in motorcycle helmet cooling, and the effects of simulated solar radiation, wind speed and heat generation on cooling system were experimentally studied. The results show that the thermal comfort period of helmets can be prolonged by using PCM compared with that of ordinary helmets. Chelliah *et al.* [18], suitable PCM was encapsulated in an aluminum foil bag and applied in the cooling system of motorcycle helmet. The SKTCHER software was used for modelling and flow simulation, and the results showed that PCM could be used to remove heat from inside the helmet. However, the PCM helmet has a defect of poor ventilation during use, and sweat discharged due to high temperature attaches to the hair, resulting in poor user experience.

To sum up, the cooling design improvement of hard hat by domestic and foreign scholars mainly focuses on two aspects. On the one hand, a small electric fan is used to cool the inside of the helmet. On the other hand, the heat absorption property of PCM is used to cool down the inside of the helmet. The results show that fan technology and PCM have some effect on cooling the helmet head, but they are accompanied by defects such as poor high temperature experience and poor ventilation. At the same time, scholars at home and abroad have only designed and applied the fan technology and PCM individually, but have not organically combined the fan technology and PCM to apply the cooling technology to the safety helmet. In order to improve the comfort of workers, an optimal cooling helmet model is obtained. In this study, based on the cooling technology of fans and the heat-absorbing characteristics of PCM, four kinds of safety helmet models were established by using electric fans and encapsulated PCM patches, in the hope of obtaining an optimal cooling safety helmet model.

Methodology

Materials

The preparation of PCM 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 PCM used in this experiment is $CaCl_26H_2O$, the weight of the PCM is 60 g, and the anti-phase separation agent is SiO_2 of 2 g, which was made by *fushun petrochemical research* institute. The *TA*'s Q200 differential scanning calorimeter (DSC) was used for the detection of PCM. This DSC characterized the phase change temperature and latent heat value of PCM samples. The temperature measurement range was –70-70 °C, and the scanning rate was 10 °C per minute. The DSC curves of PCM are shown in fig. 1. The melting range of PCM is 23-25 °C, the melting temperature of PCM is 23.08 °C, and the latent heat of PCM is 151.8 j/g. As the latent heat of PCM ($CaCl_26H_2O$) is better, and the melting range conforms to the comfortable temperature of human body, it is a good choice for PCM and safety helmet.

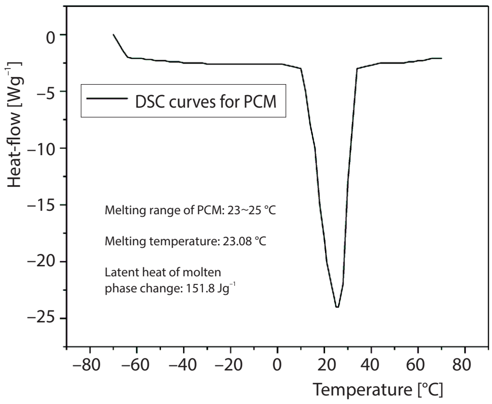

Figure 1. Schematic diagram of DSC curve of PCM

The encapsulation of PCM is an important step in the design of improved cooling helmet. As shown in fig. 2, PCM are packaged in a flat aluminum foil envelopment bag. The air in the aluminum foil envelopment bag is extracted by a vacuum machine. The flat shape can increase the contact area between the PCM and the inner space of the helmet, increase the heat transfer area and increase the heat exchange rate. The reason for choosing aluminum foil sealing bag is that the heat transfer coefficient of aluminum is high, which is conducive to improving the heat transfer efficiency. The sealing bag is vacuumed to remove the air and avoid the influence of air layer on heat transfer.

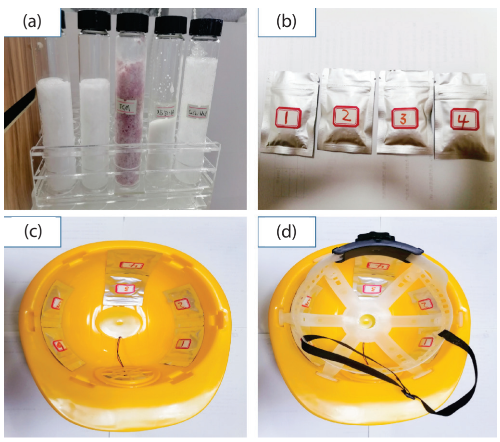

Figure 2. Schematic diagram of preparation and installation steps of PCM patch; (1), (2), (3), and (4)

As shown in fig. 3 is operating principle of hard hat. The PCM is a substance that changes phase with temperature and provides latent heat. The PCM can absorb or release a lot of heat during the phase change process, but the temperature remains basically unchanged. Using this characteristic, the PCM can be used to adjust the temperature of the safety helmet. In daily work, common types of safety helmets are roughly divided into two types, one is ordinary safety helmet, and the other is fan safety helmet. Among them, fan safety helmet is widely used because of its advantages of low cost, low energy consumption and heat protection [19]. The working princi-

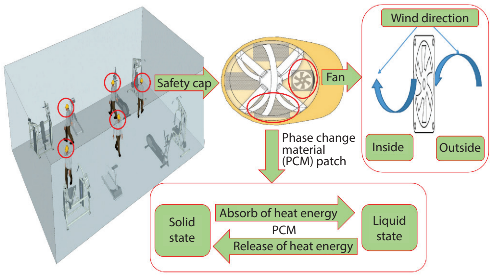

Figure 3. Schematic diagram of helmet cooling principle

ple of the fan helmet is to speed up the air convection rate through the rotation of the fan blade, and speed up the air convection inside and outside the helmet, so as to achieve the purpose of cooling.

Design of safety helmet model

As shown in fig. 4, four kinds of helmet models were constructed by placing PCM 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 PCM patch, and the safety helmet (d) consists of a fan safety helmet and a PCM patch.

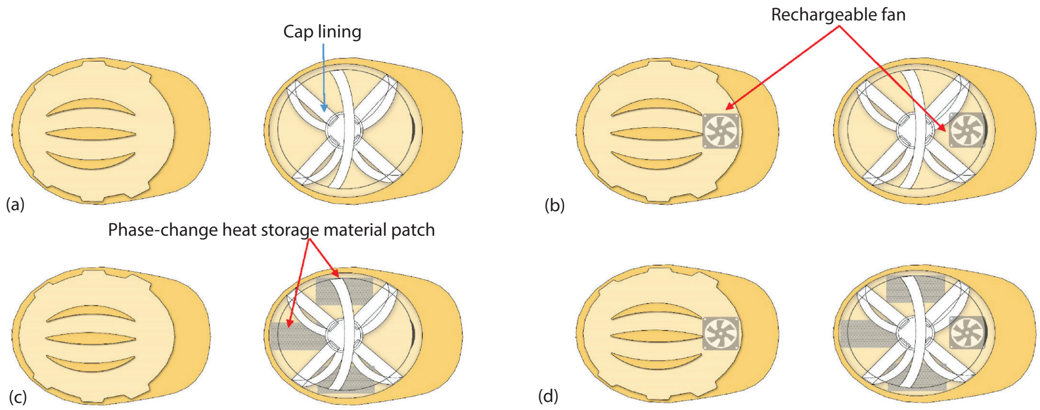

Figure 4. Schematic diagram of the design model of four safety helmets; (a), (b), (c), and (d)

Figure 5. Schematic diagram of volunteer simulated labor

Lay-out of test site ang equipment lay-out

A simulation laboratory with good air-tight effect was selected for the test site. A high power air conditioner with a constant temperature of 30 °C is set in the simulation laboratory to simulate the working environment of workers. As shown in fig. 5, four healthy adult male volunteers wear four models of hard hats and light clothes in summer to simulate the labor intensity of workers through fitness equipment. At the same time, the continuous working time of workers can reach two hours in one cycle. After completing one cycle, the four volunteers took a break and exchanged four kinds of safety helmets in turn before entering the next cycle. A total of four experiment cycles were performed. In the four experiment cycles, randomly select two sets of experimental data type 1 and type 2 as experimental results.

The arrangement of measurement points is shown in fig. 6. Temperature and humidity recorders are, respectively installed in the four helmet models. The temperature and relative humidity (RH) inside the helmet are measured as T_1, T_2, T_3, T_4 and H_1, H_2, H_3, H_4, respectively; Multi-channel temperature tester and temperature and humidity recorder are set up in the laboratory to measure the indoor air temperature and RH, the measuring point is 1.5 m from the ground, which is T_5, T_6, T_7 and H_5, H_6, and H_7. The thermocouple temperature probe of the multi-channel temperature tester was set on the surface of the inner wall of the laboratory. The measuring point was 1.5 m away from the ground, and the inner wall surface was T_8, T_9, and T_{10}, respectively, to measure the average temperature of the inner wall surface. The performance parameters of the experimental instrument are shown in tab 1.

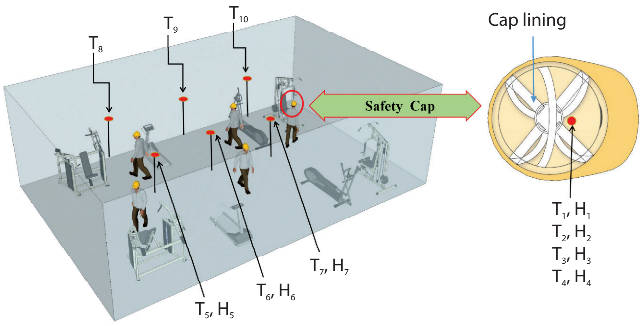

Figure 6. Arrangement of measuring points

Table 1. Table of performance parameters of experimental instruments

Instrumentation	Type	Variable	Accuracy
Temperature	JTR01Z	Temperature	–40-120 °C (±0. 5°C)
Anemograph	JTR07Z	Wind speed	0. 05~2 m/s (±0. 03)
High power air conditioner	Free-standing	Cooling and heating	16-35°C (±0. 5°C)
Hygrothermograph	JTR08ZI	RH	0-100% (±3%)

Thermal comfort evaluation

In order to comprehensively analyze the influence of six parameters of indoor thermal environment on human thermal comfort, after extensive experimental research and statistical investigation, Danish scholar P. O. Fanger has compiled a Fanger thermal comfort equation eq. (1) on the basis of the human body heat balance equation and the matched PMV thermal sensation scale. Among them PMV numerical value –3, –2, –1, 0, 1, 2, 3 corresponding *quite cold*, *cold, slightly cold, comfortable, a little hot, hot, quite hot*. This equation comprehensively and reasonably describes the quantitative relationships between human thermal comfort and six thermal environmental physical quantities [20, 21]:

$$\begin{aligned} PMV &= f\,(t_a,\ \varphi_a,\ t_s,\upsilon_a,\ M,I_{cl}) = \{-3,-2,-1,0,1,2,3\} = \\ &= [0.303\mathrm{e}^{-0.036\mathrm{M}}+0.028]\{M-W-3.05\cdot 10^{5-}[5733-6.99(M-W)- \\ &-\varphi_a 610.6\mathrm{e}^{\frac{17.260t_a}{273.3+t_a}}]-0.42[(M-W)-58.15]-1.7\cdot 10^{-5}M(5867- \\ &-\varphi_a 610.6\mathrm{e}^{\frac{17.260t_a}{273.3+t_a}})-0.0014M(34-t_a)-3.69\cdot 10^{-8}(1.00+1.29I_{cl})\cdot \\ &\cdot[(t_{cl}+273)^4-(t_s+273)^4]-(1.00+1.29I_{cl})h_c(t_{cl}-t_a)\} \end{aligned} \tag{1}$$

In the thermal comfort equation, the quantitative relationship between human thermal comfort and six physical quantities of thermal environment is described comprehensively and reasonably. The six physical quantities of thermal environment are: t_a is the indoor air temperature, φ_a – the relative humidity, t_s – the average radiation temperature, υ_a – the air-flow velocity, M – the human physical activity, and I_{cl} – the clothing thermal resistance. In the simulation lab, the assumption is that thermal comfort evaluation of four kinds of helmet model, the temperature and RH is one of the important indices for specific evaluation analysis, so this study on the thermal comfort equation six thermal environment parameters of RH, and the average radiation temperature, air velocity, the body exercise, clothing thermal resistance are configured, you can find out with the thermal comfort PMV value corresponding to the temperature and temperature range.

In the simulation laboratory, temperature and humidity measuring instrument and wind speed measuring instrument are firstly used to set and measure the internal parameters of the simulation laboratory. The indoor temperature, RH, average radiation temperature and wind speed of the simulation laboratory can be obtained. According to the size of the indoor wall and the temperature of the wall surface area, the average radiation temperature can be obtained [21]. According to the light and light working clothes of four volunteers in summer, the thermal resistance of clothing was obtained [22]. By summing up the parameters of the aforementioned simulation laboratory thermal environment, tab, 2 can be obtained. Then, the relevant parameters of the thermal environment in the simulation laboratory were substituted into the Fanger thermal comfort equation, eq. (1), and the corresponding temperature value and temperature range of PMV value of the volunteers wearing safety helmets in the simulation laboratory could be calculated, as shown in fig. 7(a).

In this study, Edward *et al.* [23] and Toftum *et al.* [24] were used as the standard to evaluate the humidity of the helmet. As is shown in fig. 7(b), when the humidity is below 30% RH, it is very dry. When the humidity is greater than 70% RH, it is extremely wet, in which 30~40% RH and 60~70% RH are slightly comfortable. According to the temperature and humidity value and temperature and humidity range corresponding to the thermal comfort PMV value, the thermal comfort of four kinds of safety helmets was evaluated.

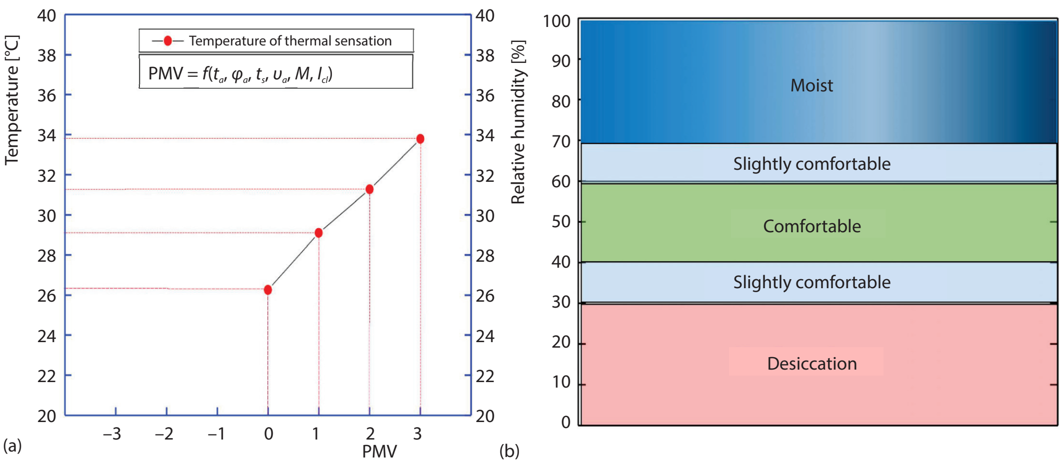

Figure 7. (a) Relation between thermal sensation and temperature, (b) relationship between thermal sensation and RH

Table 2. Simulation laboratory thermal environment parameters

Names of parameters	Unit	Reference value
Indoor temperature	[°C]	30
RH	[%]	40
Average radiant temperature	[°C]	29
Air-flow velocity	[ms^{-1}]	0. 1
Human physical activity	[Wm^2]	116
Light and thin clothing thermal resistance in summer	[Wkm^{-2}]	0. 3
Room size	[m^3]	10×7×3. 5

Results and discussions

Four volunteers wear four models of hard hats to simulate the labor intensity of workers. The temperature and humidity inside the hard hats are shown in figs. 8 and 9. The internal temperature and humidity curve of the fan helmet (b) fluctuated the most. The average temperature inside the helmet (b) was generally higher than that of the other three kinds of helmets, and its RH was lower than that of the other three kinds of helmets. As shown in fig. 8 Type 1 and Type 2, in the first 30 minutes, the internal temperature of the helmet (b) was relatively low and the rising speed was slow. The overall thermal sensation was between a little hot and hot. After 30 minutes, the internal temperature of the helmet (b) continues to rise, and the overall thermal sensation is in the extremely hot range. As shown in fig. 9 Type 1 and Type 2, in the first 15 minutes, although the interior of the helmet (b) is within a slightly comfortable range, its RH curve drops rapidly. After 15 minutes, the helmet (b) remained dry and continued to descend. The reason is that the cooling principle of the electric fan is to speed

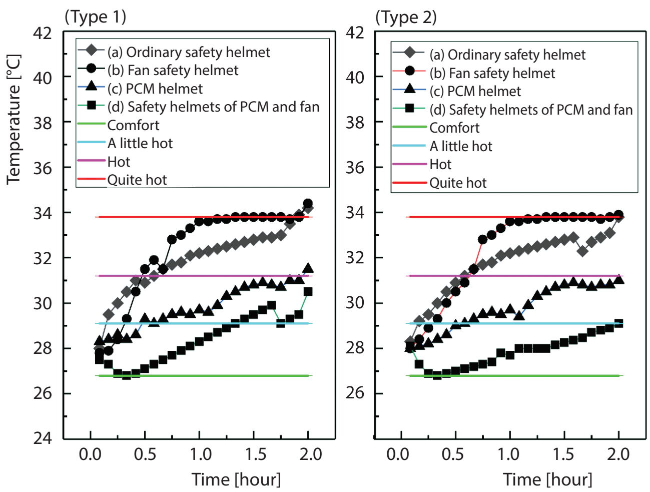

Figure 8. Safety helmet (a), (b), (c), and (d) internal temperature changes with time in Type 1 and Type 2 experiments

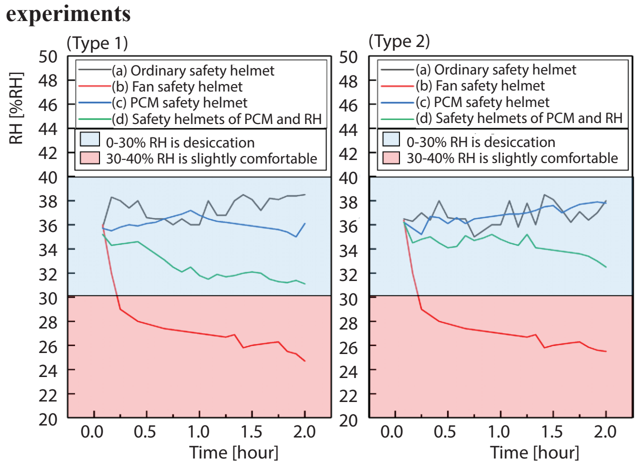

Figure 9. Safety helmet (a), (b), (c), and (d) internal humidity changes with time in Type 1 and Type 2 experiments

up the air circulation inside and outside the helmet through high speed rotation of the fan blade, improve the convective heat transfer rate between the air, so as to speed up the heat dissipation and sweat evaporation, and achieve the cooling effect. However, in the high temperature workplace, the inner part of the helmet dissipates heat due to human movement and accumulates in the space to form a high temperature space. Therefore, the air circulating inside and outside the helmet is high temperature, which causes the fan to fail to achieve the purpose of heat dissipation, so the cooling effect of the fan is greatly reduced. From the internal temperature and humidity curves of the fan helmet (b), it can be concluded that the high temperature environment is an important factor affecting the cooling effect of the fan helmet (b). When in the high temperature environment, the common helmet using a single fan cooling technology has a poor cooling effect.

The average temperature inside the PCM helmet (c) is generally lower than that of the fan helmet (b), and its RH fluctuates less. As shown in fig. 8, in the first 30 minutes, the internal temperature of the helmet (c) was below 29 °C, with a slow rising speed. The overall thermal sensation was between comfortable and a little hot. After 30 minutes, the internal temperature of the helmet (c) was below 31 °C, and the rising speed was still slow. The overall thermal sensation was between a little bit hot and hot. As shown in fig. 9 Type 1 and Type 2, the humidity inside the helmet (c) is always in a slightly comfortable range, and its humidity curve fluctuates relatively low. The reason is that the PCM safety helmet (c) has a PCM patch installed inside it, which can be used for cooling. At the same time, the PCM high temperature heat absorption mode has little disturbance to the thermal environment inside the safety helmet, which makes the temperature and humidity inside the safety helmet fluctuate little and the internal thermal environment stable. Therefore, in the high temperature environment, the cooling effect and temperature and humidity stability of PCM helmet (c) are better than that of fan helmet (b). However, according to the records of the on-site volunteer users, the PCM safety helmet (c) has poor ventilation, and the sweat from the volunteer users is concentrated on the scalp and hair, which makes the human body feel uncomfortable. Therefore, in the high temperature climate, although the safety helmet (c) has a good cooling effect, its poor ventilation results in poor user experience.

A new kind of cooling hard hat is designed by combining the PCM heat absorption technology with the fan cooling technology. As shown in figs. 8 and 9, the internal temperature of the safety helmet (d) is between 27 and 30 °C within 2 hours, and the temperature curve is relatively gentle. The overall thermal sensation is between comfort and a little heat, and the cooling effect is relatively best. The RH of the safety helmet (d) is always in a slightly comfortable range, and its humidity curve fluctuates relatively low. Reason is in the PCM heat absorption cooling technology on the basis of setting the fan for cooling, one aspect, the fan cooling technology can make up for the defect of endothermic cooling PCM, such as using PCM when the environment of high temperature heat absorption cooling, has good cooling effect, but cannot solve due to the attachment of the human body movement rule out a large number of sweat on the scalp and hair. But fans can improve ventilation, evaporate sweat and cool the head. Therefore, in high temperature environment, setting a fan can solve the problems of poor ventilation effect of PCM safety helmet (c) and poor thermal sensation of users. On the other hand, PCM cooling technology can compensate for fan cooling. For example, when the fan works in a high temperature environment, the air circulating inside and outside the helmet is at high temperature, resulting in greatly reduced cooling effect of the fan. However, PCM have powerful functions of heat absorption and heat storage, which can absorb heat from the air to achieve the cooling effect. Therefore, the problem of poor cooling effect of fan safety helmet (b) in high temperature environment can be solved. Among the four helmet models, the helmet (d) combines the PCM with the fan cooling technology, which is complementary to each other. The cooling effect and internal thermal environment stability of the helmet are the best, and the thermal sensation of human body is the best. Therefore, the helmet (d) is an optimal design model.

Conclusions

The working conditions of construction workers wearing four kinds of improved safety helmets under 30 °C thermal environment were simulated in the laboratory, and the thermal comfort of four kinds of safety helmets was evaluated. According to the law of internal temperature and humidity of the helmet, the following conclusions are drawn qualitatively to a certain extent.

- High temperature environment is an important factor affecting the cooling effect of the fan helmet (b). Under high temperature environment, the helmet with fan cooling technology has a certain cooling effect in the early stage, but after 30 minutes, the cooling effect becomes worse and worse.
- Under high temperature environment, PCM hard hat (c) has a good cooling effect, but poor ventilation results in the excreted sweat clinging to the scalp and hair, resulting in a poor user experience.
- The use of a single PCM heat-absorbing cooling technology or fan cooling technology is defective. The helmet (d) combines the PCM heat-absorbing cooling technology with the fan cooling technology, so that the cooling effect and internal thermal environment stability of the helmet are the best, and the thermal sensation of human body is the best. Therefore, the helmet (d) is an optimal design model.

In the construction of the whole idea of the experiment, there are still some deficiencies. The heat loss of human body is different in different stages, which will affect the measurement value to a certain extent. Therefore, the conclusion of this experiment is only qualitative treatment, not quantitative research. If doing quantitative research, it is recommended to use the human body simulation model, which can control the heat loss of the human body simulation model and make the measurement data more accurate.

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Nomenclature

I_{cl} – clothing thermal resistance, [Wkm^{-2}]
h_c – convective heat exchange coefficient, [sm^{2}W^{-1}]
M – human physical activity, [Ws^{-1}]
t_a – indoor air temperature, [°C]
t_s – average radiation temperature, [°C]
t_{cl} – average outer surface temperature of dressed persons, [°C]
W – power of human, [Ws^{-1}]

Greek symbols

φ_a – Relative humidity, [% RH]
υ_a – Air-flow velocity, [sm^{-1}]

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