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Research on the Effects of the High Temperature and Humidity Environment on Human Comfort in Coal Mine Emergency Refuge System

Jing Li *, Lei Yang, Tianbao Song and Ruikang Qi

School of Research and Safety Engineering, China University of Mining & Technology, 11 Xueyuan Road, Haidian District, Beijing 100083, China; zqt1700102110g@student.cumtb.edu.cn (L.Y.); tsz1600102078q@student.cumtb.edu.cn (T.S.); zqt1700102100g@student.cumtb.edu.cn (R.Q.)

* Correspondence: rainbow_lijing@163.com; Tel.: +86-1381-135-1654

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Abstract: A high temperature and humidity environment can be easily formed in a confined refuge system, which has a significant effect on the safety of refugees. Human survival experiments in a closed simulation chamber were carried out under high temperature and humidity conditions (the temperature was above 27 °C and the relative humidity was above 70%). The asymmetrical five-grade scale method was used first, and human comfort voting data were collected from 35 groups under different temperature and humidity conditions. A non-linear trend of the effects of different temperature and humidity conditions on human comfort was obtained through analysis, and the boundary curves for different human comfort conditions in a closed refuge chamber were determined. At the same time, a function prediction model of the apparent temperature was established, which had instructive meaning for the study and design of the environment controls and life support system in a closed rescue space for different fields.

Keywords: mine emergency refuge system; high temperature and humidity environment; human thermal comfort

1. Introduction

A coal mine emergency refuge system is a type of hermetic space that provides an airtight safe rescue station in which trapped miners may go into in case of a coal mine emergency for protection against explosion, fire, floods and other disasters. The outside of the hermetic space is made of stainless-steel corrugated board, which can withstand high temperature flue gas, explosion shock and other disasters. The inside of the space has an environmental control and life support system (ECLSS). The ECLSS includes five systems for oxygen supply, air purification, temperature and humidity regulation, environmental monitoring and power supply. It can provide oxygen, food, water, adjust the ambient temperature, remove toxic and harmful gases, and create basic conditions for survival, which can improve the chances of survivors receiving emergency rescue [1–5] (Figure 1).The relevant standards for the coal mine emergency refuge system require that the survivors have a life expectancy of more than 96 h [6] without power or fresh air after the disaster and that they have a reserve factor of no less than 1.1 (i.e., survivors have no less than 106 h of an appropriate living environment). It is especially important to define the temperature and humidity boundary parameters of the internal living environment for long-term survival in the emergency rescue space. If the space forms a high heat and humidity environment, it will cause serious physical and psychological impacts on the survivors, such as physical weakness, confusion and other symptoms. It may even lead to fainting and death.

Figure 1. Appearance and internal map of the coal mine emergency refuge system.

The definition of suitable temperature and humidity boundaries of a coal mine emergency refuge system is different from aerospace, submarine and other areas of confined space. The boundaries are mainly related to the conditions of the system's rescue function. First, the volume of a coal mine emergency refuge system is limited by the conditions of the downhole roadway and the transport cage. The diameter of the confined space is generally no higher than 2 m, and the length can be assembled based on the number of rescuers. The volume of this space is much smaller than aerospace refuges and refuges from other fields. Second, the coal mine emergency refuge system is designed for the occurrence of mine disasters, which lead to interruptions to the air supply system and power system as well as other systems. In addition, the ECLSS of the coal mine emergency refuge system must meet the rescue time for survivors independently. Due to the system space, energy consumption and other restrictions, it is necessary to require that all systems should reduce energy consumption as much as possible, while facilitating the maximum circumstances that lead to survival of personnel. The function of a coal mine emergency refuge system is to ensure the safety of survivors and increase their chances of surviving a disaster.

Therefore, the expectation of comfort in a coal mine emergency refuge system environment is pretty low. Survivors need to reduce their activity to reduce physical exertion and ensure that the system meets their minimum requirements for life while waiting for rescue. Therefore, the use of limited energy to ensure the basic living conditions of survivors and extend survival time as much as possible is a key issue for coal mine emergency refuge systems. The temperature and humidity boundary is key for energy consumption and life assurance. Therefore, defining the minimum temperature and humidity for life under rescue conditions is significant for evaluating survival in a high temperature and humidity environment, as well as researching safety and health under rescue conditions.

In recent years, researchers have conducted more thorough research on human body comfort in hot and humid environments, and those efforts have yielded many results. For example, Mors et al. [7] conducted a questionnaire survey on the thermal comfort of primary school students aged 9 to 11 in the classroom, in order to obtain a real thermal experience; Muhič et al. [8] studied the thermal environment in a mechanical ventilation management office and the impact of air quality on office workers; Jang et al. [9] evaluated the optimal temperature of a Korean maritime patrol boat room, found that the optimal temperature in the steering wheel room is 23 °C, the optimal temperature in the lounge is 29 °C; Pourshaghaghy et al. [10] studied the thermal comfort in the hospital ward; Abbritti et al. [11] evaluated the PMV value in the ward; Ampofo et al. [12] The thermal comfort of the British subway system was evaluated; Zhang et al. [13] evaluated the thermal comfort of rural residents in China and compared it with urban people under natural ventilation. These studies mainly focused on evaluating human body comfort in a low thermal humid environment (temperature below 30 °C and relative humidity below 70%) as well as the influence of a high temperature and humidity environment on a series of human body physiological parameters, such as tolerance time, body surface temperature, heart rate, and energy metabolism changes [14,15]. However, there is no exact numerical value for the lowest limit of the human comfort boundary in a high temperature and humidity environment under rescue conditions. This study simulates the living environment after a mine catastrophe, and includes a live 4-day survival test in a closed rescue space. The effects of a high temperature and humidity environment (the temperature is above 27 °C, and the relative humidity is above 70%) on human comfort are studied using human comfort questionnaires.

2. Research Methods

2.1. Experimental Conditions

This experiment is carried out in a simulated emergency refuge system (Figure 1) of a coal mine simulation tunnel. The structure of the cabin is shown in Figure 2, which consists of a transfer chamber, a life supporting compartment as well as an equipment bay. The transfer chamber includes high-pressure oxygen cylinders, an air curtain sprinkler system and toilets. The life supporting compartment is equipped with an air purifier, environmental monitoring system, oxygen supply system components, a temperature and humidity regulating system and box-type seats. The equipment bay primarily houses the temperature and humidity regulating system and the power supply system. There is a sealed door between the transfer chamber and life supporting compartment. The test simulation cabin size combined with the life support of the cabin and the setting of the circulatory system were calculated [16]. Combined with the standard requirement of 0.75 m^3 for the minimum required space for human survival [17], the internal volume was set to 9 m^3 and the capacity was set to accommodate 8 people. The oxygen volume is also referred to the emergency risk avoidance standard, and the oxygen volume fraction is controlled at 18.5% to 22.5% [5].

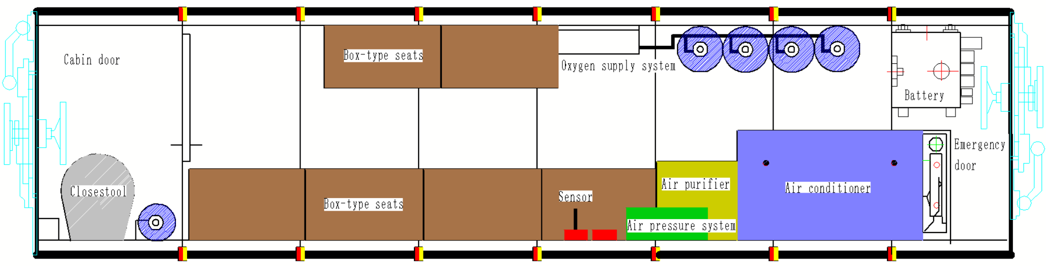


Figure 2. Internal structure of the coal mine emergency refuge system.

The cabin system is shown in Figure 3. To eliminate hazardous gases, such as carbon dioxide, that humans produce in this cabin, the air purification system selects a kind of JS pharmacy. The JS pharmacy is a carbon dioxide adsorbent made up of a mixture of various alkaline substances. It can not only dry gas, but also absorb acid gases such as carbon dioxide, sulfur dioxide, hydrogen sulfide. The air purifier will be switched on as soon as the carbon dioxide concentration in the cabin reaches 0.8%, and it can be turned off when the concentration is reduced to 0.3%. The environmental monitoring system adopts a CD-7 multi-parameter sensor that can monitor the cabin's internal and external environment parameters in real time, including oxygen, carbon dioxide, carbon monoxide, hydrogen sulfide, methane, temperature and humidity parameters. At the same time. the cabin is also equipped with a pulse sphygmomanometer and a thermometer to determine the physiological conditions of the people in this cabin.

(**a**) CD-7 multi-parameter sensor (**b**) Oxygen supply system (**c**) Air purification system (**d**) External monitoring system

Figure 3. Composition of the cabin system.

2.2. Methods

The life support experiments were conducted in a simulated chamber and all the subjects were healthy adult males. The subjects provided information on their thermal comfort during the test period in the chamber using questionnaires. When evaluating human body thermal and humidity comfort, the American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE) usually uses the classical 7-grade scale method, which classifies human comfort in a normal environment with seven grades [18]. To analyze the feedback easily, the research team referred to a similar valuation methodology. However, for a disaster environment, it makes little sense to study the chamber at a low temperature range (0 °C~25 °C). Therefore, the method we used focused on a higher temperature range (above 25 °C). In a disaster environment, the mine electrical power, compressed air and water supply may be cut off. The ECLSS of the chamber cannot devote too much focus on comfort only due to the primary goal of meeting the basic requirements for life support. For this study, comfort evaluation was configured as an asymmetric scale to focus on the range of discomfort. The thermal comfort of the subjects was divided into 5 grades as follows: slightly cool (1), comfortable (0), hot (−1), sweltering (−2) and intolerable (−3).

The relevant standard [6] of a coal mine emergency refuge system require that the personnel can survive in the system for no less than 96 h. Our research team conducted 3 tests in which the personnel all survive in the system for 96 h or longer. The test personnel are shown in Table 1.

Table 1. Datasheet for Field Experiments.

Number	Personnel	Age	Physical Conditions	Experiment Time	Comments
Experiment 1	Mine rescue team and students (four)	25–35	Fine	96 h	Clothes: uniforms; Activity: sit, replace the pharmacy and fill in the form occasionally
Experiment 2	Students and miners (eight)	20–35	Fine	106 h	
Experiment 3	Eight miners	20–35	Fine	106 h	

In this study, human comfort for temperatures of 25–37 °C and humidity levels of 70–95% RH is examined. The experiment is divided into 30 groups, and the temperature is divided into 25–27 °C, 27–29 °C, 29–31 °C, 31–33 °C, 33–35 °C, and 35–37 °C. The humidity is divided into 70–75%, 75–80%, 80–85%, 85–90%, and 90–95%.

In this study, three large-scale survival tests were carried out. The temperature and humidity range in the coal mine emergency refuge system covered most of the conditions required for the test. Some of the experimental temperature changes are shown in Figure 4. Some of the temperatures were not included in the test, and to ensure data integrity, additional tests were conducted. The experiment was divided into ten groups, each group included four subjects aged 20–35 years old. During the experiment, the temperature is adjusted by the air conditioner, and the humidity is adjusted by the humidity regulator. When the test temperature and humidity reached the test environment conditions, the door of the coal mine emergency refuge system was opened to let the test personnel enter, and then the survival test was conducted (no less than 2 h). The oxygen concentration in the cabin was 20–21%, and the concentration of carbon dioxide was <0.8% (which was adjusted by the air purifier) during all tests. During the test, the test personnel recorded their own comfort senses every 30 min through a pre-developed comfort table to obtain descriptive test results and quantitative data. The dress and activity status of the test personnel are shown in Table 2.

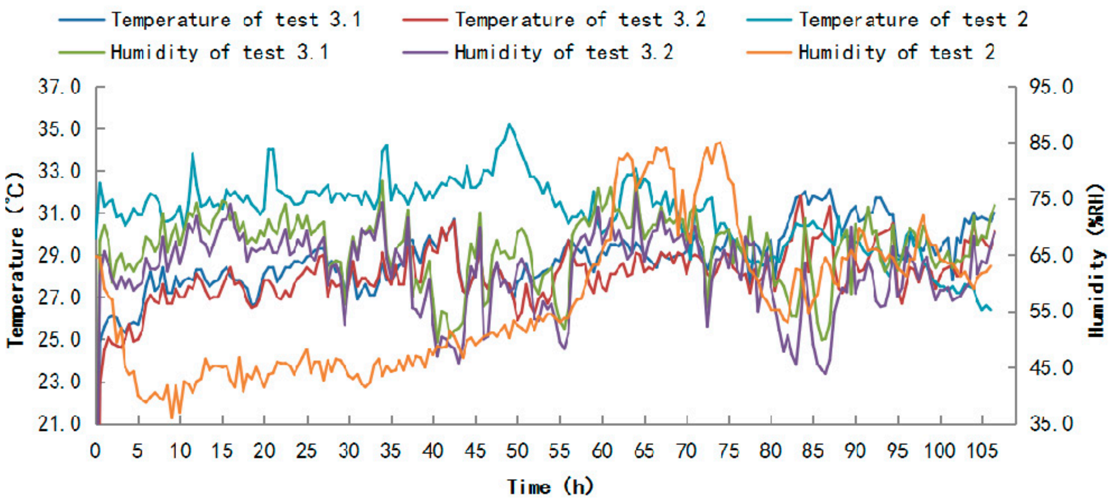


Figure 4. The temperature and humidity parameter curves of survival test (test 2 and test 3).

Table 2. Environmental parameters of the experiments.

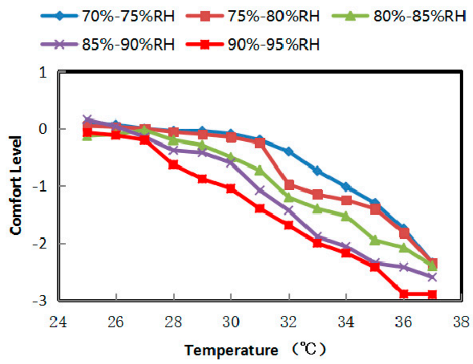
NO.	Temperature	Humidity
1 2	25–27 °C	85–90% 90–95%
3 4	27–29 °C	85–90% 90–95%
5 6 7	33–35 °C	70–75% 85–90% 90–95%
8 9 10	35–37 °C	80–85% 85–90% 90–95%

3. Results and Analysis

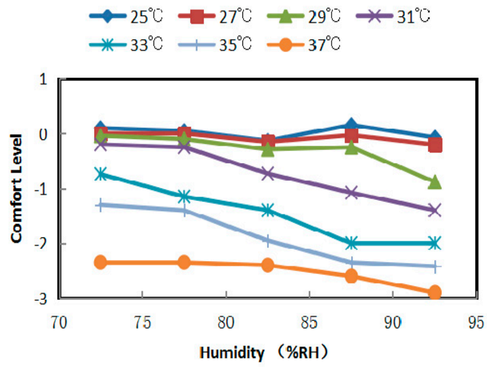
3.1. Effects of Temperature and Humidity on Comfort

As Figure 5a shows, when the temperature inside the chamber was below 27 °C, the curves for human comfort at different temperatures tended to be consistent, which indicated that the humidity inside the chamber had little effect on human thermal comfort. When the temperature was higher than 27 °C, the comfort tended to be reduced with the increase in temperature and the curves for different humidity levels started to diverge. It appears the influence of humidity on comfort increases gradually at this temperature point. Combined with the results shown in Figure 5b, it becomes apparent that the comfort level slightly oscillates in a range of ±0.1 and was hovering around zero points when the temperature was below 27 °C, which indicates that the changes in humidity has little effect on comfort level at low temperatures. When the temperature is between 28–31 °C and the humidity is higher than 75%, the comfort level decreases rapidly with the increase in humidity and the comfort level changes from slightly hot to sweltering. The comfort value decreases by approximately 0.5 per 10%

increment of the humidity. The results show that, in this temperature range, the changes in humidity have little effect on comfort when the humidity is in a range that is not very high (below 75%) and would result in a sharp drop in comfort when the humidity is at a higher range (above 75%). When the temperature is higher than 31 °C, the comfort level decreases rapidly with the increase in humidity. On average, the comfort level decreases by approximately 0.7 per 10% increment of the humidity. When the temperature reaches 37 °C, the normal temperature of the human body, the subjects reach the limit of the temperature range the human body could withstand. In this case, the limit on the temperature value depends entirely on personal physical condition, regional climate or other factors. The comfort level is in the unbearable range (−3), no matter how the humidity changes. It can be concluded that changes in humidity have a significant effect on thermal comfort at a high temperature range (31~37 °C).



(**a**) The vote scores under different temperature conditions



(**b**) The vote scores under different humidity conditions

Figure 5. Relationship between comfort level and temperature/humidity.

As Figure 5 shows, when the temperature reaches 35 °C and the relative humidity reaches 85%, the comfort level is sweltering (−2). Considering that the comfort level parameters can be reduced significantly in a situation in which the primary task in a refuge chamber is to survive, the power consumption of the temperature and humidity controlling system can be reduced at the cost of sacrificing comfort. According to the experimental results, the lower limit of the comfort level in the refuge chamber is −2, and the upper limits of temperature and humidity are 35 °C and 85% RH, respectively.

3.2. The Temperature and Humidity Boundary Curves for Different Comfort Levels

Comfort, in the current study, is a comprehensive reflection of environmental temperature and humidity rather than a single variable relationship. Therefore, it is impossible for us to determine the limit values of temperature and humidity in the refuge chamber simply by defining maximum temperature or humidity separately. Instead, we provide temperature and humidity boundary curves for the same comfort level. The combinations of temperature and humidity versus different comfort levels are shown in Figure 6.

Figure 6 shows that the area of human comfort between comfortable (0) and (−1) hot is wide, while the area between hot and sweltering (−2) is narrow because the expectation of refugees for comfort is quite low under emergency circumstances. When the environment temperature is much higher than the temperature of a normal working environment, people would feel quite hot and, with the temperature rising, their endurance reaches its limit and they would feel sweltering soon. When the comfort level is 0 and temperature is low (below 25 °C), the changes of humidity have no significant effect on comfort, which manifest as the low declining rate of humidity with the rising temperature. Additionally, the slope of the curves increased clearly when the temperature is higher than 25 °C, which indicates that the changes of high humidity have a significant impact on comfort at high temperatures.

To maintain the same comfort levels, the humidity declines rapidly with the increase of temperature when the comfort level is −1. When the comfort is −2, the demarcation of human thermal sensation in this specific interval becomes unclear because the conditions are sweltering. Therefore, the overall trend for the same comfort level is that the humidity declines with the increase of temperature, and in some small ranges, the humidity values remain unchanged.

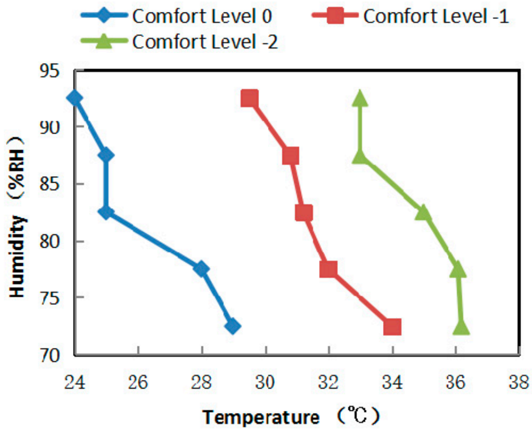


Figure 6. The temperature and humidity boundary curves under different comfort conditions.

Unlike the requirements for soldiers in submarines, the main objective of a refuge chamber is to ensure the safety of trapped miners in an emergency. Therefore, the lower limit of thermal comfort that can guarantee survival of people inside the refuge chamber is −2 (sweltering) and the temperature and humidity should be in a range of (33 °C, 90%RH) to (36 °C, 70%RH). Specifically, the temperature and humidity limit parameters should not be considered separately when both of them are very high, but every temperature value has a corresponding humidity range. Figure 6 shows the change interval of the comfort boundary that satisfies the safety requirements.

3.3. The Relationship of Temperature and Humidity at the Same Comfort Level

As shown in Figure 7, when the comfort level is 0, the temperature decreases by approximately 1–3 °C per 10% increment of the humidity; when the comfort level is −1, temperature decreases by approximately 1.5~2.5 °C per 10% increment of the humidity; and when the comfort level is −2, temperature decreases by approximately 1.5~2.5 °C per 10% increment of the humidity. This outcome occurs because, in this case, the sense of comfort is most sensitive when the comfort level is 0, and the changes in humidity are the largest compared to the extent of change for temperature. According to the statistics, if the temperature is higher than 25 °C and the humidity is higher than 70% RH, the temperature decreases by approximately 2 °C per 10% increment of the RH when human comfort is constant.

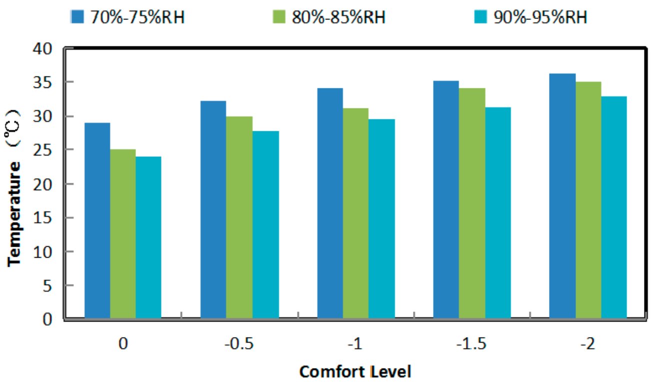


Figure 7. Temperature changes under the same conditions.

3.4. Prediction Model of Apparent Temperature

Under different circumstances, the classification standards of comfort are also different. Previous studies have shown that some humans have no intuitional feeling of comfort [19–21]. In this paper, the comfort levels 0, −1, −2, and −3 are matched with 26 °C, 30 °C, 34 °C, and 38 °C, which are true human thermal responses to the environmental temperature. Through processing of the previous data, a curve of the human apparent temperature and the temperature and humidity inside the chamber is obtained (Figure 8). Furthermore, through linear regression analysis of the data, a functional relationship between human apparent temperature and the environmental temperature and humidity can be described as Formula (1).

$$T_t = 18.65 + T^{(0.067T + 0.018H - 4.821)} \quad (1)$$

where R-Square = 0.9638; Tt is the apparent temperature; T is the environmental temperature inside the closed chamber, °C, $T \in (28\sim37\ °C)$; and H is the environment relative humidity inside the closed chamber, % $H \in (70\sim95\%)$.

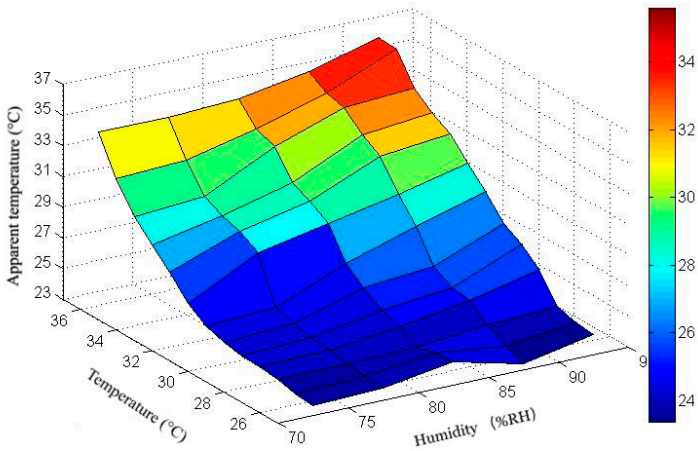


Figure 8. Surface diagram of apparent temperature.

4. Conclusions

In the high temperature and high humidity environment under rescue conditions, there is no exact value for the minimum comfort boundary of the human body, the comfort expectation of the person is quite low, and the miners are basically male. In this paper, we proposed an asymmetric five-level scale evaluation indicator for low comfort and carried out 35 real-life survival experiments with more than 1000 people. The thermal comfort index in the rescue capsule can be greatly reduced under the premise of ensuring human life safety, so as to obtain the lowest thermal comfort index under rescue conditions. The overall results indicate that comfort is the result of mutual coupling of temperature and humidity, and the influence of humidity on comfort is different depending on the temperature range. Finally, by matching the comfort and body temperature, the relationship between the body temperature and the temperature and humidity is obtained.

Based on the above results, analysis and discussion, the following conclusions were obtained:

1. Under rescue conditions studied here, 27 °C is the dividing line of significant change in human comfort. When the temperature is below 27 °C, humidity has little effect on comfort and the overall fluctuation range is ±0.1. When the temperature is between 28 and 31 °C and the humidity is higher than 75%, comfort is reduced by 0.5 for each 10% increase in humidity. When the temperature is between 31 and 37 °C, the comfort is reduced by 0.7 for each 10% increase in humidity. To ensure the comfort of humans is stable, for each 10% increase in humidity, the temperature needs to drop by approximately 2 °C.

2. This article identified the minimum conditions for life security for temperature and humidity in a confined space under rescue conditions in which the comfort score is sweltering (−2 points). The temperature range and humidity boundaries of (33 °C, 90% RH) to (36 °C, 70% RH) was obtained.
3. The prediction function of apparent temperature in a high hot-humidity environment was obtained by fitting the data, and the fitting degree was 0.9638.

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