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Research Paper

Experimental investigation and theoretical analysis of the human comfort prediction model in a confined living space

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HIGHLIGHTS

- Single and multiple factors human prediction comfort models were developed and verified.
- Oxygen, carbon dioxide, temperature and humidity tolerance limits were obtained.
- PMV method were modified and specialized in oxygen and carbon dioxide content comfort.
- The weight coefficients order between single and multiple factor comfort models were analyzed.
- A large number of human comfort experiments were implemented to obtain comfort data.

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ABSTRACT

We investigated the fitting point at which a reasonable level of comfort could be ensured for people in a refuge chamber as well as the longest amount of time they could comfortably be in the chamber before being rescued. Using theoretical analysis and experimental investigation, we developed human comfort prediction models, including a single environmental factor model and a multiple environmental factor model. The models considered four key factors: oxygen volume fraction, carbon dioxide volume fraction, environmental temperature, and humidity. We modified and applied the predicted mean vote grade method to analyze one group of data with 169 data points of human comfort with single and multiple environmental factors. A large number of human comfort experiments were implemented to obtain human comfort data and verify the results of our theoretical calculations. We analyzed and calculated the recommended tolerance limits of the four factors for the rescue subjects to survive to allocate the limited resources and reduce energy consumption to prolong the survival time of the subjects to wait for rescue. The living conditions in a refuge chamber should be controlled to the point at which the oxygen volume fraction is at 18–22.7%, the carbon dioxide volume fraction is less than 1%, the temperature is less than 35 °C, and the humidity is less than 80%. We obtained the relationship between the multiple-factor comfort model and single-factor comfort model. We found that the order of the weight coefficients is oxygen > temperature and humidity > carbon dioxide.

1. Introduction

Even with rapid economic and technological developments in the mining industry, there are still large numbers of casualties in coal mining accidents. The development of methods to avoid accidents and reduce casualties is a priority for coal-mining safety. The refuge chamber is a temporary shelter for trapped miners waiting to be rescued that provides a safe confined space [1–3]. Normally, an air quality control system, including an oxygen(O_2) supply system, air conditioning, and air purification system, can provide adequate O_2 supply, cooling, dehumidification, and the removal of harmful gases to protect the people inside the chamber [4,5]. A key problem with these environmental control systems is understanding how to allocate the limited resources to guarantee basic living conditions to allow trapped miners enough time to be rescued, because the space and energy storage inside a refuge chamber are limited.

A large number of studies [6–9] have shown that, in addition to physiological and psychological factors, environmental factors, such as air quality, temperature, humidity, pressure, air velocity, noise, vibration, and space size, affect human comfort in closed or relatively closed

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spaces, such as spacecraft, submarines, underground buildings, and high-speed trains. In these confined spaces, the O_2 supply is particularly important for the body's metabolism. Too high of an O_2 volume fraction will increase the risk of a fire and too low of an O_2 volume fraction will cause suffocation. Another important influencing factor is the existence of harmful gases, which mainly are produced through the metabolism of the human body; there are as many as 300 species, including carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), ammonia (NH_3), $F_{11}(CCl_3F)$, $F_{12}(CCl_2F_2)$, benzene(C_6H_6), and total hydrocarbons [10], and their main ingredient is CO_2. Temperature and humidity mainly affect the body's thermal comfort; if the temperature or humidity is too high, the human body's temperature regulation process is affected, which could endanger the health of those inside the confined space.

Thermal comfort studies are helpful for creating a favorable indoor environment to maintain an appropriate thermal environment and maintain a reasonable energy consumption [11–13]. Thermal comfort models have been widely applied to closed and semiclosed buildings [14–21], such as classrooms, underground constructions, and accommodation buildings, where people usually sit or engage in low-level activities as they normally would do in a refuge chamber. Zhai et al. [11] introduced an energy-efficient way to secure comfort in warm and humid environments, and they determined the threshold values for the temperature and humidity under which an acceptable level of comfort could be maintained. Yang et al. [12] introduced an adaptive thermal comfort model that used a thermal sensation empirical model to obtain a predicted mean vote (PMV) revised index for air-conditioned indoor environments in hot-humid regions. As a result of habituation, the upper limit of the effective thermal comfort temperature can be increased by 1.6 °C during the warm season based on the existing international standard that there is a great potential for saving energy from these air-conditioning systems in the summer. However, the environment in coal mine refuge chamber are always humid and muggy like the summer all the year round, so it will acquire a more great potential for energy saving from the air conditioning system in it.

Air-conditioning and air purification systems have been used widely in refuge chambers [4,5] and other closed and semiclosed buildings, [14–17] such as classrooms, underground construction, and accomendation buildings, where the human comfort model and energy-saving technology mainly concentrate on the temperature and humidity control systems. Most studies have focused on air-conditioning systems [18–23], but the control of the O_2 and CO_2 volume fractions are also important for confined refuge chambers and require the consideration of the space limitations and the lack of energy storage. People perform precision operations in these confined spaces (such as submarines, manned spacecraft, and aircraft [24]), so the O_2 volume fraction should be controlled at 19–21% (which is as close as possible to the normal atmospheric environment) to ensure work efficiency and operational safety. In a mine's refuge chamber, people need to reduce their amount of activity and wait for rescue; the lower limit of the O_2 tolerance range of the human body can be relaxed. If, however, the O_2 volume fraction is too high, it will increase the respiratory efficiency and add to the consumption of the CO_2 adsorbent, which will waste the O_2 supply and increase the risk of fire and explosion. Therefore, both the upper and lower limits of the O_2 volume fraction should be controlled. Researchers [25] have found that the lower limit of the O_2 volume fraction can be reduced, which could help to decrease the O_2 consumption. Meanwhile an acceptable comfort level can be maintained in the refuge chamber, which can be controlled within a certain range. Li et al. [25] have designed a new asymmetric five-point scale comfort degree evaluation system based on the ASHRAE seven-point scale method. Meanwhile, the comfort degree votes of oxygen content in the refuge chamber were obtained through analyzing questionnaires collected from the subjects. The lower and upper oxygen volume fractions are 18.5% and 22.5% respectively during long-time experiment. Finally, the relationship between the human body sensory comfort and oxygen volume fraction was obtained through the comfort curve fitting. Despite the contributions of this technique, published researches on this subject are quite few. According to these references, a more reasonable oxygen volume fraction tolerance range for the rescue subjects to survive could be explored to prolong the rescue time for refuge chambers with limited space and energy storage, which is the new research point to be solved in the environmental control system. And, there have been no relevant strictly basis and working standards settled before in refuge chamber, and miners usually set the temperature and humidity range too low only based on personnel feelings and experience, often causing a waste of energy. Moreover, the controlling of carbon dioxide volume fraction is of great significant and should also be taken into consideration. Therefore, the acceptable oxygen volume fraction, carbon dioxide volume fraction, temperature and humidity tolerance range for miners to survive in refuge chamber should be analyzed and obtained, which would be served as the technical parameters and basis for miners to control air conditioning system.

This paper aims to find the fitting point at which not only the longest rescue time could be reached, but also proper comfort could be ensured. In this research, we are committed to develop an empirical human comfort prediction model and the PMV (Predicted Mean Vote) grade method is modified and applied. A large number of human comfort experiments were implemented to obtain human comfort data and verify the results of theoretical calculations, and the oxygen volume fraction, carbon dioxide volume fraction, temperature and humidity tolerance range for rescue subjects to survive were analyzed and calculated.

2. Experimental

2.1. Experimental equipment and working principle

We conducted human comfort experiments in a mine simulation refuge chamber. The test principle is shown in Fig. 1. The chamber was monitored by a KJ70 coal mine safety production monitoring system, which had a good air tightness and internal effective volume of 8 m^3. The temperature and humidity were automatically monitored through GD7 mine multiparameter sensors (the sensors monitored the O_2, CO_2, CO, temperature, and humidity). Batteries provided the power for all the systems. We controlled temperature and humidity by ice-storage air conditioning, which achieved refrigeration using electric energy. We used a circulation fan for cooling and dehumidification. We removed CO_2 through the air purification system, which was adsorbed by soda lime in the fixed adsorption bed through the circulation fan. The O_2 supply was provided by a medical O_2 bottle with a decompression and flow control system.

2.2. Experimental methods

To avoid experimental errors and facilitate the analysis of the questionnaire feedback information, we modified the feedback for the feelings of comfort from the PMV and divided it into four indexes, "comfortable or no feeling" (0 points), "a bit uncomfortable" (−1 points), "uncomfortable" (−2 points), and "very uncomfortable" (−3 points), according to the seven levels of human thermal sensation and the humidity feeling evaluation scale method (PMV) from ASHRAE [26]. These levels were customized in the O_2 and CO_2 content comfort model in this research based on the characteristics of the refuge chamber. During this experiment, the rescue subjects needed to record numbers that described their feelings at fixed times. The data of the O_2 volume fraction, CO_2 volume fraction, temperature, and humidity were recorded by the monitoring system.

2.2.1. Single-factor effect analysis of the human comfort prediction

We selected eight healthy adult men as the first group. We tried to get close to the virtual rescue conditions of a coal mine. The test subjects were between 25 and 30 years old, between 60 and 80 kg, and