Experimental Study on the Effect of Air Cooling Garment on Skin Temperature and Microclimate

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Abstract. The Air Cooling Garment (ACG) was employed to study skin temperature and Clothing Inner Microclimate (CIMC) Regulation, which provides theoretical basis for further optimization of aerodynamic layout of AGG towards human thermal comfort improving. 15 male postgraduates served as subjects in the experiment, each runs at 5 km/h (to simulate Moderate Work, MW) or 7.5 km/h (Heavy Work, HW) on the treadmill in an artificial climate chamber with or without the Air Cooling Garment (ACG) for 40 min respectively. The temperature of the artificial climate chamber changed from 24 to 34 °C. The skin temperature of upper body, clothing inner Wind Velocity (WV), Relative Humidity (RH) and temperature were measured. Results showed that the skin temperature decreased much more significantly with the ACG than without when the ambient temperature is over 26 °C, especially when engaged in HW. The WV and RH in clothes changed with the labor intensity, rather than the ambient temperature. The variation of clothing inner temperature field was different, with the front and back sides decreased with labor intensity, while the left and right sides were not affected. It proved that the ACG can improve CIMC and enhance human thermal comfort effectively.

Keywords: Air cooling garment · Skin temperature · Clothing inner microclimate · Labor intensity

1 Introduction

Miners working in the high-temperature environment, in deep buried mine will possibly develop a series of symptoms such as thermal fatigue, heat cramp sand heat exhaustion. These symptoms may pose serious health risk and reduced production efficiency [1]. High temperature personal protective equipment, with the advantage of a very good cooling effect low cost and high security, is widely used in fire, mining, and metallurgical industries [2–4].

High-temperature personal protective equipment mainly refers to the cooling clothes used by personal. According to the cooling principle and characteristics of cooling medium, it can be divided into liquid cooling clothes, phase-change cooling clothes and ACG [5]. By heat conduction, the liquid cooling clothes mainly use cool liquid to reduce the body temperature [6–8]. Solid liquefaction is an endothermic

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process, in which phase-change cooling clothes play a better role on local cooling [9–11]. Furthermore, ACG is more applicable in mine environment, which is characterized by economy, lightweight, comfort, and so on [12]. Both the fan-type and ventilated ACG can reduce skin temperature, sweat, heat stress, increase heat dissipation, maintain heat balance and improve human comfort effectively [13–16]. In comfortable condition, local heating or cooling on the subject may enhance human thermal comfort. A strong local thermal sensation determines the overall thermal sensation [17, 18]. The human physiological indexes change remarkably with environmental temperature and humidity. Skin temperature is a good index of local thermal sensation, and CIMC determines the degree of thermal comfort [19, 20]. Therefore, reducing the clothing inner temperature can improve thermal comfort effectively.

Deep underground mines, characterized by high temperature and humidity, have great harm to miners' mental and physical health. Reducing the ambient temperature or improving the CIMC is a good way to enhance the thermal comfort of workers, which can create a safe and comfortable working environment for miner. The research used a self-developed ACG to study its cooling effects on skin temperature of upper body and clothing inner microclimate at different labor intensity and ambient temperature. The study provided theoretical basis for further optimization of ACG aerodynamic layout and thermal comfort improving.

2 Methods

2.1 Equipment

The experimental simulation environment was in the artificial climate chamber with an internal dimension 3 m × 2.5 m × 2.2 m, which could simulate the required stable experimental environment. The grade 1 standard thermometer (minimum scale value: 0.05 °C) and JT-IAQ indoor thermal environment comfort tester (accuracy: ±1.5%) were used to calibrate ambient temperature and RH respectively in the experiment. Skin temperature was measured by the thermocouple temperature sensor DS1922L (MAXIM, US, resolution 0.0625 °C), breathable medical tapes were used to stick on the skin surface. CIMC was measured by HD29 sensor (Delta, Italy), in addition, the date stored and read by Agilent Workstation.

The ACG adopted supporting structure, with air compressed through main and branch pipeline, the airflow channels were formed between the body surface and clothing. The air supply branch pipe was evenly symmetrically distributed over the inner surface of ACG. The compressed air blew to the human body surface though the holes in the gas branch pipe at a controlled speed. The ACG makes full use of the endothermic process of compressed air expansion, the enhanced human skin sweat decalescence and thermal convection, reinforces the cooling effect, and thereby is effective and efficient in microclimate control.

2.2 Experimental

15 male postgraduates whose age averages 24, height 171 ± 3.6 cm, weight 62.4 ± 6.4 kg were employed for the study. They were all healthy and with no bad habits. During the experiment, the subjects' upper body were either naked or wore ACG, and wearing long trousers. The wind speed in climate chamber was less than 0.05 m/s. According to the symmetry of temperature distribution on human body from literature [21], we selected ten points of human upper body to stick the temperature sensors. The five measuring points in front of the body were at left chest, right chest, middle, left abdomen and right abdomen respectively, the other five points in the back were left scapula, right scapula, middle, left waist, right waist respectively, as shown in Fig. 1. Each one was tested for 45 min, including 5 min for pre-adaptation in the chamber and 40 min running on treadmill.

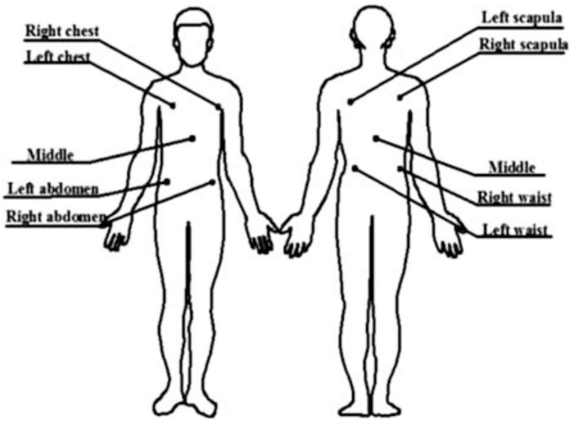

Fig. 1. Distribution of the ten measuring points

Microclimate measuring instruments were at four positions (front, back, left, right) of inner clothing. As shown in Fig. 2, subjects wearing ACG in the experiment.

According to West Germany labor intensity classification, MW was 232 W and HW was 348 W. Metabolic was calculated as follows [22]:

$$M_w = 1.5W + 2(W + L)(L/W)^2 + \eta(W + L)(1.5V^2 + 0.35VG) \quad (1)$$

Where M_w = metabolic rate, W; W = naked weight, kg; L = load carried, kg; V = speed of walking, m/s; G = grade, %; η = terrain factor (η = 1.0 for treadmill). Due to the required labor intensity, we chose running speed as 5, 7.5 km/h, the value of other parameters were: W = 62.4 kg, L = 0.8 kg, η = 1, G = 0, so metabolic rate were 276.5, 505.1 W.

According to "Coal Mine Safety Regulations" (China), the air temperature should not exceed 26 °C in the working place, the workers must stop working when temperature over 30 °C. So the experimental conditions were set as follows (Table 1).

Fig. 2. Subjects in experiment wearing ACG

Table 1. Experimental conditions

	Air supply rate (m^3/h)	Temperature (°C)	Humidity (%)	Labor intensity
No ACG	0	24, 26, 28, 30, 32, 34	90	MW, HW
Wearing ACG	10			

The ACG air temperature was 29–31 °C, pressure was 0.8 MPa

2.3 Statistical Analysis

The data of skin temperature, clothing inner WV, RH and temperature were expressed by mean and standard deviation (SD). The mean skin temperature was the average of ten parts of skin temperature. The graphs were drawn with Origin, the Person correlation test and *t*-test for significant analyses were calculated by SPSS.

3 Results

3.1 Skin Temperature

The skin temperature with or without wearing ACG in MW and HW were measured by the temperature sensor as shown in Fig. 3. Two groups of data before and after dressing were analyzed by T paired test.

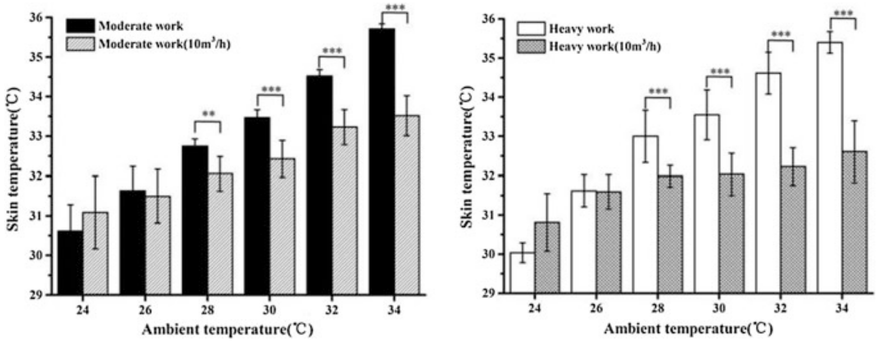

Fig. 3. The skin temperature of ten parts of 12 subjects during 40 min running at 5 or 7 km/h with wearing ACG or not

As shown in Fig. 3, in MW and HW, the skin temperature of upper torso was significantly affected by ambient temperature ($P < 0.05$). Skin temperature increased obviously, which was not related to the clothes. After wearing ACG, the correlation between the ambient temperature and skin temperature decreased ($n = 15$, $r^2 = 0.998$, 0.988; $r^2_{wear} = 0.994, 0.946$).

When the ambient temperature was higher than 26 °C, the skin temperature decreased ($P < 0.01$) significantly, and the maximum decrease of skin temperature is 2.789 °C. When the ambient temperature arrived at 28 °C, the skin temperature with wearing ACG in HW was lower than that in MW condition. However, there was no significant difference of skin temperature in different working conditions without wearing cold clothing. It showed that the ACG would be better used in HW.

The SD decreased with the increasing of ambient temperature with no ACG, but there was no significant difference with wearing ACG.

3.2 Microclimate

Through the microclimate measuring instrument, the changes of wind speed and relative humidity in each part of the garment under moderate and severe working conditions are shown in Tables 2 and 3.

According to Tables 2 and 3, it is found that the change of wind speed and relative humidity in different parts of the garment is independent of the ambient temperature. But the state of labor has great influence on the microclimate inside the clothing.

Table 2. The values of WV and RH were measured in MW when subjects were wearing ACG, each part has different WV and RH in different temperature

Part	Microclimate	Ambient temperature (°C)					
		24	26	28	30	32	34
Front	Velocity (m/s)	0.31 ± 0.01	0.34 ± 0.03	0.32 ± 0.00	0.34 ± 0.02	0.37 ± 0.02	0.32 ± 0.01
	Humidity (%)	58.64 ± 1.22	54.74 ± 1.65	57.61 ± 0.94	57.72 ± 0.80	51.74 ± 1.75	62.78 ± 1.93
Back	Velocity (m/s)	0.16 ± 0.00	0.15 ± 0.01	0.12 ± 0.00	0.16 ± 0.03	0.14 ± 0.03	0.17 ± 0.02
	Humidity (%)	65.54 ± 1.32	65.43 ± 1.75	67.04 ± 1.68	65.20 ± 1.39	64.16 ± 0.56	75.78 ± 2.37
Left	Velocity (m/s)	0.45 ± 0.06	0.37 ± 0.02	0.35 ± 0.03	0.36 ± 0.00	0.39 ± 0.04	0.38 ± 0.03
	Humidity (%)	54.50 ± 0.90	54.12 ± 0.46	54.39 ± 1.02	63.24 ± 1.73	58.64 ± 1.27	53.53 ± 1.35
Right	Velocity (m/s)	0.35 ± 0.00	0.37 ± 0.02	0.41 ± 0.04	0.46 ± 0.07	0.39 ± 0.01	0.45 ± 0.03
	Humidity (%)	52.32 ± 1.48	49.79 ± 2.83	55.96 ± 1.23	50.36 ± 1.48	53.12 ± 0.67	48.06 ± 1.04

Table 3. The values of WV and RH were measured in HW when subjects were wearing ACG, each part has different WV and RH in different temperature

Part	Microclimate	Ambient temperature (°C)					
		24	26	28	30	32	34
Front	Velocity (m/s)	0.38 ± 0.02	0.36 ± 0.01	0.38 ± 0.00	0.34 ± 0.02	0.39 ± 0.01	0.41 ± 0.02
	Humidity (%)	68.32 ± 1.56	66.69 ± 1.92	72.09 ± 2.45	76.12 ± 2.75	80.26 ± 2.90	79.07 ± 3.58
Back	Velocity (m/s)	0.20 ± 0.00	0.22 ± 0.01	0.26 ± 0.02	0.23 ± 0.00	0.19 ± 0.01	0.18 ± 0.01
	Humidity (%)	100	100	100	100	100	100
Left	Velocity (m/s)	0.37 ± 0.02	0.37 ± 0.01	0.36 ± 0.00	0.40 ± 0.04	0.41 ± 0.02	0.42 ± 0.03
	Humidity (%)	70.14 ± 0.98	62.21 ± 1.67	70.03 ± 1.26	71.13 ± 2.37	63.24 ± 2.48	76.65 ± 3.35
Right	Velocity (m/s)	0.45 ± 0.02	0.38 ± 0.00	0.35 ± 0.01	0.49 ± 0.03	0.46 ± 0.02	0.39 ± 0.01
	Humidity (%)	73.59 ± 1.05	73.48 ± 1.96	69.22 ± 2.05	67.15 ± 1.90	68.78 ± 3.27	73.01 ± 2.39

During the experiment, the clothing inner RH maintained at a steady state, indicating that the ACG could be discharge of sweat to the outside timely. So we could get the Fig. 4.

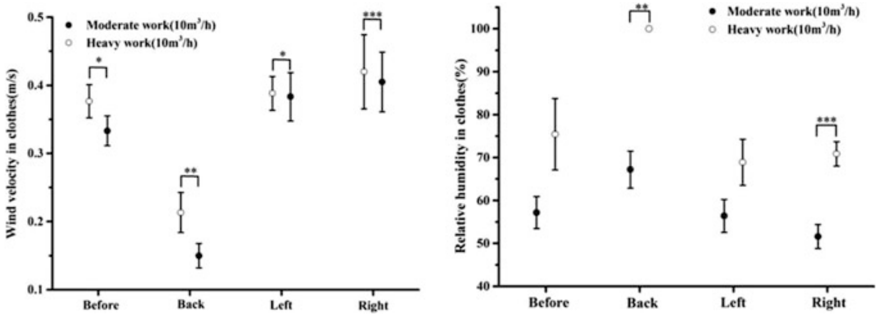

Fig. 4. Mean ± SD WV and Mean ± SD RH in different parts of the garment, in MW or HW condition, the significance was also shown

As shown in Fig. 4, the WV and RH were higher in HW than those in MW. The WV in back was the lowest, but the RH was the highest. The effect of WV on the body was stronger in HW than that in MW ($P < 0.05$), the evaporation and convection was the main heat dissipation mode. The intensity of labor only had a significant effect on the relative humidity of the back and right side ($P < 0.01$), and had no significant effect on the front and left side ($P > 0.05$).

Clothing Inner Temperature. The temperature in the clothing has a great influence on the thermal comfort of the human body. By discussing the changes in the temperature of the clothes under different labor intensity and ambient temperature, the effectiveness of the air cooling clothes is judged. Through experiments, it is found that the temperature inside the four parts of the front, rear, left and right can reach a stable state at a certain ambient temperature. The temperature of each part of the garment varies with the ambient temperature under different working conditions as shown in Fig. 5.

As shown in Fig. 5, the increase of labor intensity could significantly reduce the temperature in front and back sides thus improved comfort. The temperature inside and outside the clothing is not affected by the labor intensity, and the temperature inside the two sides of the subject is almost symmetrical. In MW, when the ambient temperature reached 34 °C, the temperatures in both back and front sides were lower than ambient temperature. When the ambient temperature reached 32 °C, temperatures in the both front and back sides were lower than ambient temperature in HW. That is to say that WV and RH played a leading role on the improvement of human thermal comfort. It can be seen that the temperature in front and back sides had greater impact on thermal comfort and skin temperature than the left and right sides.

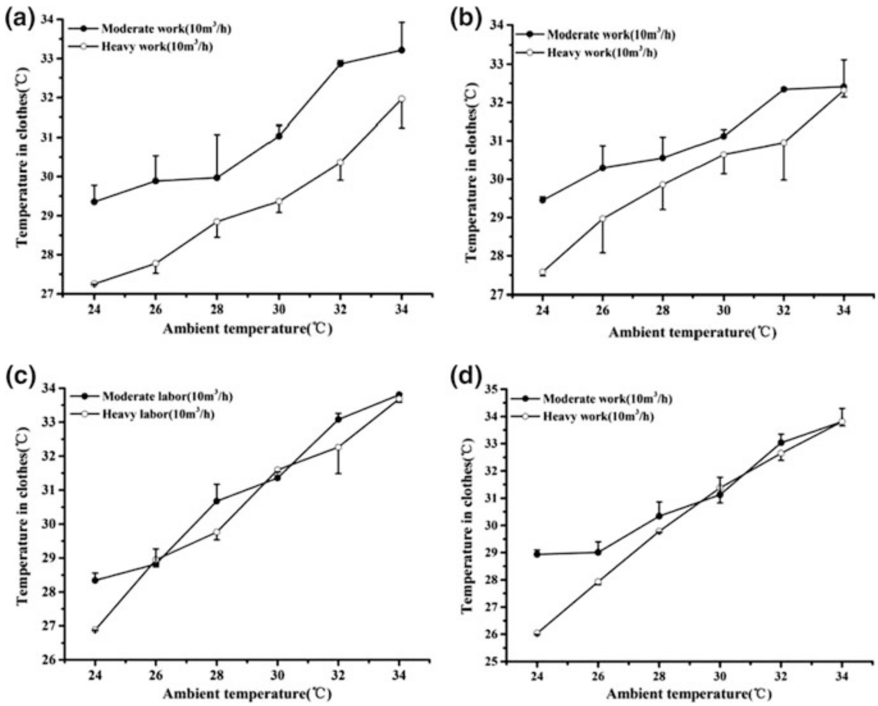

Fig. 5. Temperature of front (**a**), back (**b**), left (**c**), right (**d**) changing with ambient

4 Conclusions

(1) The ACG could effectively reduce skin temperature, enhance microclimate, and improve human thermal comfort under different working conditions, in particular, to meet the requirement of heavy physical work.
(2) The temperature distribution in the ACG clothing is very uneven. The temperatures in front and back sides are relatively low, which has great influence on the human body. The temperatures on both sides are high, but it has little influence on the human body.
(3) When ambient temperature reaches 28 °C and above, the ACG has a good cooling effect on skin temperature and the greater the labor intensity, the better the cooling effect.
(4) The wind speed and relative humidity have more influence on human comfort than in condition of heavy working than moderate labor.

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