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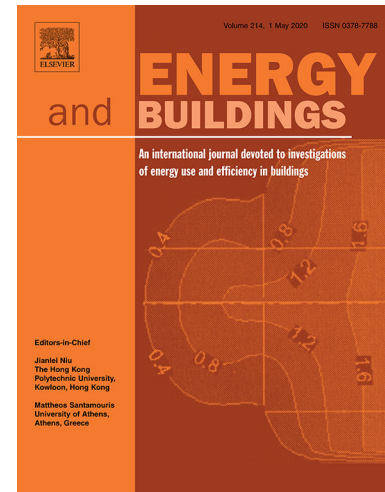
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Thermal and humid environment improvement of the protective clothing for medical use with a portable cooling device: analysis of air supply parameters

Xing Su^{a,b,*}, Shaochen Tian^{a,b}, He Li^{a,b}, Xu Zhang^{a,b}, Xiaolu Shao^{a,b}, Jun Gao^{a,b}, Hai Ye^c

^aSchool of Mechanical Engineering, Tongji University, Shanghai, China

^bKey Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, Shanghai, China

^cCollege of Architecture and Urban Planning, Tongji University, Shanghai, China

Abstract:

COVID-19 has caused a huge impact on people's daily life and has made great damage on national economy. All the epidemic situation not only require the improvement of medical science, but also the corresponding auxiliary research field, e.g. the improve of protective clothing for medical use (MUPC). Developing a new kind of MUPC with portable cooling devices to improve medical workers' thermal comfort and protection performance of MUPC is imminent. In this paper, an integrated MUPC with a portable vortex tube cooling device was studied with experimental method. In a phytotron, a manikin wearing the MUPC was experimentally studied in terms of the influence of environment temperature and cool air

*Corresponding Author: Tel: +86 21 65984243, Fax: +86 21 65983605

E-mail: suxing@tongji.edu.cn

supply conditions. On the basis of experiments, the MUPC inside air temperature and relative humidity, skin temperature of human body was studied with simulation method. Overall thermal sensation vote (TSV) and local TSV of human body were calculated, based on simulation results, to evaluate human thermal sensation. The results showed that, first, 50L/min cool air flowrate with 18~20°C supply temperature can create a good MUPC inside thermal sensation environment, for both head supply and body supply conditions. Both body supply condition and head supply condition cannot create a uniform MUPC inside thermal sensation environment. Second, MUPC inside air relative humidity is around or lower than 60% for most body parts, except for air supply position and body parts that air is difficult to reach. Thirdly, with cool air supplied into MUPC, a micro-positive pressure environment can be obtained, and the protection performance of MUPC can be improved.

Keywords: *protective clothing for medical use, portable cooling device, supply air parameter, thermal comfort, positive pressure*

1 Introduction

In December, 2019, COVID-19 exploded and soon spread all over the world within four months, and a total of 166 countries or regions appeared to be hit by the epidemic with more than 130,000 people have been diagnosed by the end of March, 2020 [1]. Not only COVID-19, in recent years, the explosion of infectious diseases, such as SARS and Ebola virus, have aroused people's high attention to health and safety issues. Frequently contacted with the patients, medical workers are easy to be infected in these public health emergencies. Till February 24, 2020, in China, more than 2055 medical workers from 476 medical institutions have been infected with COVID-19. The explosion of these epidemic not only requires the improvement of medical science, but also the auxiliary equipment and technologies. As one of the only isolation equipment between medical workers and the patients, the protective clothing for medical use (MUPC) is of great importance to reduce the

infection risks of medical workers. As high infectious are always accompanied with these diseases, the high protection level MUPC with extremely low air permeability is the most effective medical equipment. The air impermeability MUPC will also restricts the heat and water vapor transferred from human body to the MUPC outside environment. With the increasing of working time, thermal and humid environment in the MUPC gets worse. Working at this high temperature and humidity environment, the thermal sensation of medical workers is extremely uncomfortable, and this will also lead to a decline of working efficiency. To this end, improving medical workers' thermal comfort when wearing the air impermeability MUPC without reducing the MUPC protection performance is important and imminent.

One of the methods is to improving the heat and moisture transfer performance of the MUPC by adopting new materials. Water vapor permeability improvement mainly includes: unidirectional moisture conducting technology of fiber-reinforced polymer[2] and knitted polyester fabric [3], nano film technology of selective membrane [4] and biomimetic nanofiber [5], and polyester fiber Coolmax combined cotton [6]. Wu et al. [7] have developed a kind of 'water diode' fibrous film to make water penetrate from hydrophobic side and block moisture from the hydrophilic side. However, the changing of the film thickness is necessary to adjust the unidirectional water penetration ability, and whether the strength and lifetime of the film can meet the MUPC requirement still needs further research. Wang et al. [8] studied the moisture permeability performance of 6 kinds of non-woven, and found the lowest moisture permeability is only $37.78 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$ and the highest one is $1857.78 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$. Yang et al. [9] studied the moisture permeability of different MUPC materials under different environment temperature and humidity. The MUPC materials moisture permeability decreases with the decreasing of environmental temperature and the increasing of environmental relative humidity, and the lowest moisture permeability is $505.05 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$ under 32.2°C and 60% environmental condition. Obviously, in practical application, many

high level MUPC materials cannot meet the Chinese national standard [10] requirement of $2500 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$ moisture permeability, as the test condition is different from actual environment. Polyacrylonitrile fibers [11] has moisture permeability of $9200 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$, and after modification of the membrane, the moisture permeability reaches $11400 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$ [12] and $12500 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$ [13]. Nanofibrous membranes made of polyurethane [14], dimethylacetamide and acetone [15] and fluorinated polyurethane [16] [17] have moisture permeability higher than $9000 \text{ g}\cdot\text{m}^{-2}\cdot 24\text{h}^{-1}$. It should be noted that the improvement of MUPC moisture permeability performance by developing new types of materials may cause a reduction of MUPC protection performance, and the overall performance of new materials needs further study. To this end, the application of new types of high-water vapor permeability materials in the medical protection field still needs to be discussed for further study.

Compared with passive technologies, ventilation and air supply with portable cooling devices can be an effective way to maintain a more comfortable micro-climate. Installing fans on protective clothing and ventilation directly have been studied by many researchers [18-21]. With these mechanical ventilation garments, the heat and moisture dissipation of human can be exhausted to the external environment. However, the cooling effect is limited and the infectious risk is increased when adopting in the medical use. By adopting cooling devices, light weight and small size are the basic portable requirement. Semiconductor refrigeration devices, which utilize Peltier effect to achieve cooling, has the ability to minimize the volume of portable cooling devices [22]. Based on semiconductor refrigeration technology, Yin et al. [23] designed a water-cooled thermoregulation suit. With experimental test, a battery weighs 790g can help the cooling suit operate about 1h. Obviously, auxiliary devices, such as water pump and battery, are necessary to make the cooling suit operate. More important, an exhaust air fan should be attached to dissipate the heat from hot side to the outside environment. Compared with semiconductor cooling devices, the vortex tube has the potential to be an

alternative portable cooling device. Similar to semiconductor, vortex tube also has a cold end and a hot end. Cooling capacity of vortex tube is mainly influenced by compressed air pressure, air flowrate and cold mass fraction [24]. The major priority is that air supply fan or water pump can be removed as the compressed air is adopted as input energy, and the cool air can be supplied to most of the body parts easily. From this point of view, vortex tube is more suitable to be combined with MUPC to maintain a more comfortable thermal and humid MUPC inside environment.

Supplying cool air into the MUPC may have the ability of improving thermal comfort of medical workers as well as increasing the MUPC protection. Edwards et al. [25] established a model of the pressurized suit with 3D scanning technology and simulated the thermal environment of the pressurized suit. The most influential variable is the inlet air temperature, compared with air flow rate, the ambient temperature and heat transfer coefficient of the suit. Tian et al. [26] studied the micro-environment positive pressure powered air purifying MUPC, 99.99% of the simulating virus can be removed by the air filter. Wu et al. [27] also studied the protection factor of a positive-pressure bio-protective suit and found a protective factor of more than 100000 against $0.3\mu\text{m}$ aerosol particles with operating time of more than 4 h. The two types of positive pressure MUPC only concentrate on improving protection performance. Without cooling process, the air temperature in the micro-environment is higher than 32°C , which cannot meet the requirement of thermal comfort. The ventilation or air supplying position has great influence on the thermal comfort of human. Ueda et al. [18] studied the influence of clothing ventilation regions on the clothing humidity microclimates, by using a manikin with sweat function. Among the three ventilation regions, chest ventilation shows the highest ventilation index. In this study, the improvement of thermal comfort is limited due to the ventilation air is not chilled. Zhao et al. [19] studied ventilation garments with five different ventilation locations with a sweating thermal manikin, and found that the ventilation location should be placed at the spine area or lower back. With

fans and openings connected to external environment, this method is not suitable for the MUPC that requires low air permeability and high protection performance. Tesch et al. [28] established a heat and mass transfer model of an air fed pressurized suit to help define the optimum design and operation parameters. However, thermal sensation of human body and suit inside air relative humidity were not evaluated and studied with the simulation model. Lai et al. [29] investigated the cooling capacity of a personal cooling system with a thermal and sweating manikin. The cooling rate is 45W under sensible heat condition and 282W under sensible heat and sweating condition, which can maintain good thermal comfort while the wearer doing light work. Yang et al. [30] studied the cooling performance of air ventilation clothing with a thermal manikin. With 20 L/s ventilation rate, the total cooling capacity is about 230W/m², of which condition the mean skin temperature increased from 34°C to 34.5°C after 40min exercise, and decreases to 33.3°C after 20min reset. Kang et al. [31] studied a hybrid personal cooling system under different environment temperature and humidity. With ventilation fan flowrate of 20L/s and cooling capacity of 62W, the skin temperature can be controlled around 31.5°C.

In the previous research, portable cooling devices are seldom adopted with MUPC, and the splitting of MUPC, face mask and goggles makes the cool air difficult to be supplied into the breath zone. When combine vortex tube with compressed air cylinder carried by the medical workers, namely the portable cooling device, not only the thermal sensation of medical workers can be improved, but also the clean and fresh air is of benefit. Furthermore, the influence of air relative humidity on thermal comfort of the wearer with portable cooling devices still needs to be stressed and studied. In this article, firstly, an experimental setup was built with an integrated MUPC with low air permeability of the highest level, a manikin, a phytotron and a portable vortex tube cooling device. Secondly, the MUPC inside air temperature and skin temperature of the manikin were tested by varying the environment temperature, cool air flowrate and supply air temperature. Thirdly, with simulation method,

the thermal sensation of medical worker wearing the MUPC with the portable cooling device was evaluated in terms of MUPC inside air temperature, skin temperature and MUPC inside air relative humidity.

2 Methodology

2.1 Experimental setup and test sensors

A MUPC air supply performance experimental set up was built to evaluate the effect of supplied air conditions. The schematic figure of the experimental set up is shown in Fig. 1, and Fig. 2 gives the photograph of the experimental setup. The MUPC environment experiment applied a standing thermal manikin wearing a integrated MUPC. The manikin is hanged on a braket and put in a phytotron to maintain a stable temperature and humidity environment. The phytotron, namely artificial cliamate chamber, can controll the chaber inside air temperature, humidity and air velocity. The chamber is of 4.2m length, 3.6m width and 2.6m height. The temperature can be controlled from 10°C to 40°C, the reletive humidity can be controlled between 30% to 80%, and the air velocity is within 0.2m/s.

The thermal manikin dose not have the sweating function, therefore, the heating fuction is used to test the skin temperature and MUPC inside air temperature. The manikin has 22 body segments, including head, chest, arms, back, legs and et al. The average skin temperature of the 22 body segments is tested by the manikin, and transported to a computer through the data line. The manikin was set at fixed heat flux mode to simulate the heat dissipation rate of human. Medical workers need to do many kinds of work that are of different metabolic rate. In this study, moderate working intensity is chosen as the scenario condition to evaluated the supply air condition. The metabolism of adult with light labor is 80W/m², and propotion of sensible heat dissipation rate, except for breath and insensible perspiration, is about 75% of the total energy metabolism [32]. Thus, the sensible heat flux of manikin can be calculated as 60W/m². This sensible heat dissipation ratio is obtained from conventional environment without the impediment of perspiration by MUPC. Supply air condition will influence the sensible heat ratio value, due to the variation of MUPC inside air temperature and humdity environment. For simplication, the MUPC inside environment was assumed to be the same with conventional environment in this study. The clothing inside air temperature and average skin temperature were tested to evaluate the MUPC thermal environment and human thermal comfort. The sensors of the temperature recorder and the micro-manometer are both fixed at head, body and leg part, separatly. The MUPC is made of PP nonwoven cloth with 58g/m² combined TPU unidirectional permeable membrane.

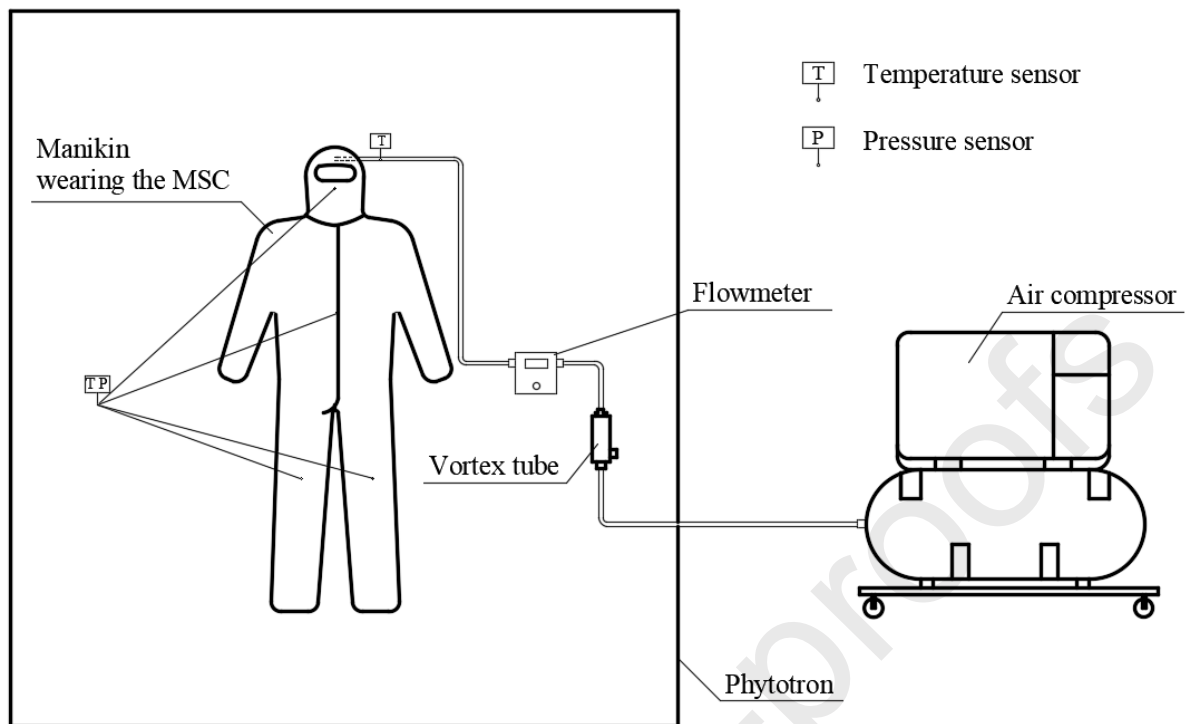


Fig. 1. Schematic figure of the MUPC experimental setup



Fig. 2. MUPC air supply performance experimental setup

The supply air conditions were controlled through a vortex tube cooling system. The compressed air inlet of the vortex tube is linked with an air compressor through a hose. It should be noted that the compressor used in this research is only to provide long endurance

time and stable compressed air. In practical application, the compressed air should be provided by an air cylinder for portability and prevention of pollution. Outlet air temperature and air flow rate at the cold side of the vortex tube, namely the supply air temperature and air flowrate of MUPC, were tested. All the experimental data were taken under steady-state conditions. The temperatures were measured by a series of high accuracy thermometer. An air flowmeter was adopted to measure the air flowrate of the cold side. The specifications of the measuring devices are listed in Table 1.

Table 1 Specifications of measuring devices

Measured parameter	Devices	Type	Accuracy	Range
Temperature	Temperature recorder	WZY-1	$\pm 0.3^{\circ}\text{C}$	$-50\sim 100^{\circ}\text{C}$
Air flow rate	Mass flow controller	Aera FC-772C	$\pm 0.005\%$	$0\sim 200\text{L}/\text{min}$
Relative pressure	Micro manometer	KIMO MP110	$\pm 0.5\%$ value $\pm 2\text{Pa}$	$-1000\sim +1000\text{Pa}$

2.2 Simulation model of the MUPC inside environment

The model of the human body and MUPC were sketched up with Pro ENGINEERING Wildfire 5.0. The simulation of the MUPC inside environment were conducted with FLUENT 2019, and the model is shown in Fig. 3. The air supply position is at the backside of head and upper limb in different cases, separately. The air outlet positions are at the two gaps between ankles and MUPC. In FLUENT, species transport was applied to simulate the MUPC inside humidity environment.

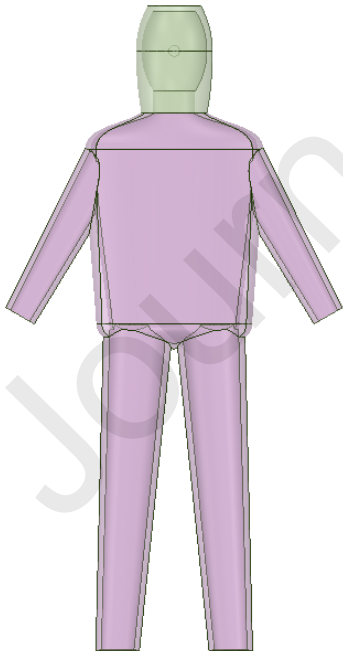


Fig. 3. Model of human body wearing the MUPC

During the air compression process, water vapor is removed from moist air when water vapor pressure exceeds the saturated water vapor pressure. The compressed air humidity ratio

is mainly decided by air humidity ratio before compression process and the compressed air pressure. In this study, moist air of 26 °C and 60% relative humidity is taken as the inlet condition of air compressor, and the inlet air pressure requirement of the vortex tube is 0.2Mpa. For simplicity, the compression process is taken as isothermal process, and the saturate water vapor can be calculated as following[33]:

$$\ln P_s = 23.196 - \frac{3816.44}{T + 273.15 - 46.13} \quad (1)$$

After compression, water vapor pressure is 4.036kPa, higher than the saturated water vapor pressure of 26 °C . As the proportion of dry air pressure and water vapor pressure is constant during the compression process, the humidity ratio of compressed air can be calculated as 10.64g/kg, and the relative humidity is 50.24%.

The main simulation parameters are shown in Table 2. The human body side is the first boundary condition, and the MUPC side is the third boundary condition. In consideration of studying the MUPC with relative low water vapor permeability [8, 9], the MUPC moisture permeability is set at 450 g·m⁻²·24h⁻¹.

Table 2. Parameters and supply air conditions of the simulation model

Parameters	Value
Air supply area	7.07cm ² for head supply 3.14 cm ² for body supply
Supply air temperature	18°C, 20°C, 22°C
Supply air flow rate	50 L/min, 100 L/min, 150 L/min
Supply air humidity ratio	10.64 g/kg
Heat dissipation rate	58W [34]
Moisture dissipation rate	184g/h [34]
Heat transfer coefficient of MUPC	4 W/ (m ² ·K)
Moisture permeability of MUPC	450 g·m ⁻² ·24h ⁻¹
MUPC outside temperature	26°C

2.3 Thermal sensation evaluation model

Skin temperature is a more accurate indicator to evaluate the thermal sensation of human body. Mean skin temperature of different body parts was calculated by FLUENT 2019 for the simulation model, and the overall mean skin temperature of the body was calculated as the area weighted skin temperature of all of the body parts, namely head, chest, arms, legs and et al. Overall thermal sensation vote (TSV) and local TSV are adopted as the indicators to evaluate overall thermal sensation and thermal sensation of different body part [35]. Overall TSV can be calculated as the following equation:

$$TSV_o = \begin{cases} +3 & \Delta T_{mean} > \ln 4/\omega \\ \frac{Exp(\omega \Delta T_{mean}) - 1}{1 - Exp(c \Delta T_{mean})} & 0 \leq \Delta T_{mean} \leq \ln 4/\omega \\ -3 & \ln 4/c \leq \Delta T_{mean} \leq 0 \\ & \Delta T_{mean} < \ln 4/c \end{cases} \quad (2)$$

where TSV_o is overall TSV, ΔT_{mean} is the difference of the actual average skin temperature and average skin temperature of moderate state, ω and c are parameters, equal to 0.62 and -0.47, separately.

Local TSV of different body part has the same expression with overall TSV. ω and c of different body part has different value. The moderate state temperature T_{mo} , ω and c values are shown in Table 3.

Table 3. Skin temperature of moderate state and calculation parameters[35]

Section	Overall	Head	Chest	Back	Arm	Leg	Hand	Foot
T_{mo}	33.51	33.6	34.2	34.5	32.9	33.5	33.6	32.0
ω	0.620	0.609	0.547	0.598	0.276	0.484	0.452	0.250
c	-0.470	-0.320	-0.342	-0.450	-0.226	-0.297	-0.155	-0.120

3 Results and discussion

3.1 Experimental results of the MUPC environment

With the MUPC experimental setup, the experimental results of skin temperature, MUPC inside temperature and manikin skin temperature under different conditions are shown in Table 4, and the MUPC inside air temperature and skin temperature of main body parts are shown in Fig. 4. Without cool air supplied into the MUPC, 24 °C and 26 °C environment temperature is tested to evaluate the effect of environment temperature. With cool air supplied into MUPC, the supply air flowrate varies from 60 L/min to 110 L/min, and supply air temperature varies from 16 °C to 22 °C. Symbol ‘F’, ‘B’, ‘L’ and ‘R’ means frontside, backside, left and right, respectively.

Table 4. Experimental results of MUPC inside air temperature and manikin skin temperature

Item		Results									
Case		1	2	3	4	5	6	7	8	9	10
Supply air temperature (°C)		No air supply	No air supply	16.1	17.1	18	18.1	18.5	19.5	20.5	21.9
Air flow rate (L/min)				80	95	80	110	70	70	60	100
Environment temperature (°C)		24	26	26	26	26	26	26	26	26	26
MUPC inside air temperature (°C)	Head-F	26.6	28	23.6	23.8	24.3	24.2	24.3	25	25.9	26.4
	Head-B	26.8	28.1	20.1	21	21.2	21	22.1	22.4	23.4	24.3
	Body-F	26	27	25	25.1	25.3	25.4	25.6	25.9	26.1	26.3
	Body-B	26.7	27.8	26.2	26	26.6	25.9	26.9	28.1	28.3	27.8
	Leg-F	26.1	28.6	29	28.9	28.9	28.7	29	29.1	29	28.9
	Leg-B	25.9	28.3	27.9	27.9	27.8	27.9	27.9	27.9	27.9	27.8
Skin temperature (°C)	Foot-L	31.4	33.2	33.1	32.9	33.3	33.1	32.9	33	33	33.1
	Foot-R	31.1	32.7	32.6	32.1	32.6	32.5	32.5	32.4	32.4	32.7
	Foreleg-L	31.4	33	33.1	32.8	33.2	32.5	32.9	33	33.1	33.2
	Foreleg-R	31.3	33.1	33.5	33.1	33.7	33.3	33.5	33.6	33.9	33.6

Thigh-FL	33.3	35	35.8	35	35.9	35	35	35.5	35.6	35.5
Thigh-FR	33.8	35.2	35.3	34.8	35.2	34.9	35.3	35.7	35.6	35.7
Thigh-BL	32.6	34.1	34.8	34	34.9	34	34.6	34.7	34.7	34.9
Thigh-BR	32.9	34.2	34.3	34.2	34.3	34	34.6	34.7	34.7	34.9
Pelvis	34.3	35.4	34.9	34	34.7	34.1	34.5	35	35	34.9
Back side	34.3	35.5	35	34.6	35	34.1	35	35.1	35.1	35.1
Head	33.1	34.7	27.8	28.1	28.5	29	29.5	29.5	30.3	31.4
Scull	33.7	35.3	30.9	31.6	31.8	32.3	32.4	34.6	34.9	33.3
Hand-L	31.6	33.5	33.7	33.5	33.5	33.2	33.3	33.6	33.5	33.8
Hand-R	31.5	33.5	33.5	33.4	33.7	33.3	33.4	33.3	33.1	33.8
Forearm-L	32.8	34.6	33.9	33.8	34.2	34.3	33.8	33.9	33.9	34.1
Forearm-R	33	34.8	34.2	33.9	34.4	34.1	34.1	33.9	34.2	34.3
Upper arm-L	33.3	34.9	33	32.7	33.5	33.6	33.7	33.9	34.1	33.6
Upper arm-R	32.8	35.3	33.1	32.8	33.7	33.1	33.6	33.9	34.1	34.7
Chest	34.5	35.7	34	33.9	34.6	33.8	34.3	34.6	35.1	35.4
Stomach	34.3	35.7	35.3	34.7	35.4	34.7	35.2	35.6	35.7	35.4
Upper Back	34	35.4	34.3	34.8	35.5	35	35.7	35.2	35.2	35.7
Low Back	33.8	35.1	34.9	34.4	35.1	34.1	35.2	35.3	35.4	35.2
Overall	32.9	34.5	33.6	33.4	33.9	33.5	33.8	34.1	34.3	34.3

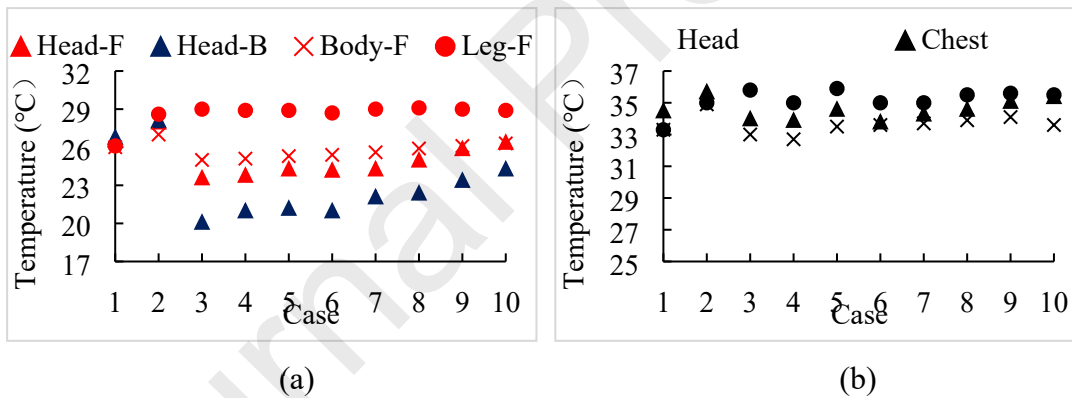


Fig. 4. MUPC inside air temperature (a) and skin temperature (b)

Without cool air supplied into the MUPC, the MUPC inside air temperature is higher than 27°C , when the environment temperature is 26°C . The decreasing of environment temperature causes a reduction of skin temperature and MUPC inside air temperature. With cool air supplied, skin temperature and MUPC inside air temperature at head position are at the lowest level, among all of the experimental conditions. Both supply air temperature and supply air flowrate have influence on skin temperature and MUPC inside air temperature. For head part, the most influential parameter is supply air temperature, and skin temperature of head vary slightly with the changing of air flowrate, for the experimented air flow range. For body and back part, the most influential factor is air flowrate, as cool air is much easier to be sent to these zones with higher air flow velocity. For arm part and leg part, both supply air

temperature and air flowrate have small impact on air temperature and skin temperature, the reason is that the supplied cool air is heated by head and chest, and the air flow velocity is low for arm and leg parts. The supplied cool air tends to flow to the body part than arm part, and the air temperature rises at leg part after heated by head and body.

The overall TSV of the 10 experimental cases were calculated, and the results are shown in Fig. 5. Without cool air supplied, the overall thermal sensation under 26 °C environment temperature is warm, and the overall TSV under 24 °C environment temperature is slightly lower than 0. For the 8 air supply cases, the variation range of TSV is from -0.1 to 0.6. For overall thermal sensation, the difference is not significant for the 8 air supply cases. The cool air is supplied to head part firstly, and this caused the relative high skin temperature difference of head. For chest and back part, the skin temperature difference among the 8 cases is much lower. The head part surface area is 9.6% of the whole body surface area, and the head skin temperature difference of the 8 cases is within 4 °C. Based on the low skin surface area ratio of head and the low temperature difference of other body parts, the difference of overall TSV is small among the 8 air supply cases.

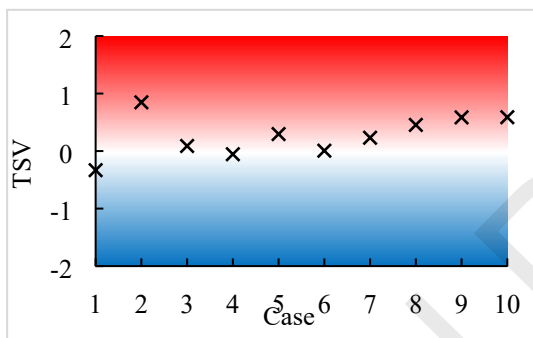


Fig. 5. Overall TSV of experimental results

With air supplied into the MUPC, positive pressure can be obtained, as Fig. 6 shows. It is obviously that the MUPC is inflated with the supplied air when the air-cooling device is operated, due to the low air permeability of the MUPC.

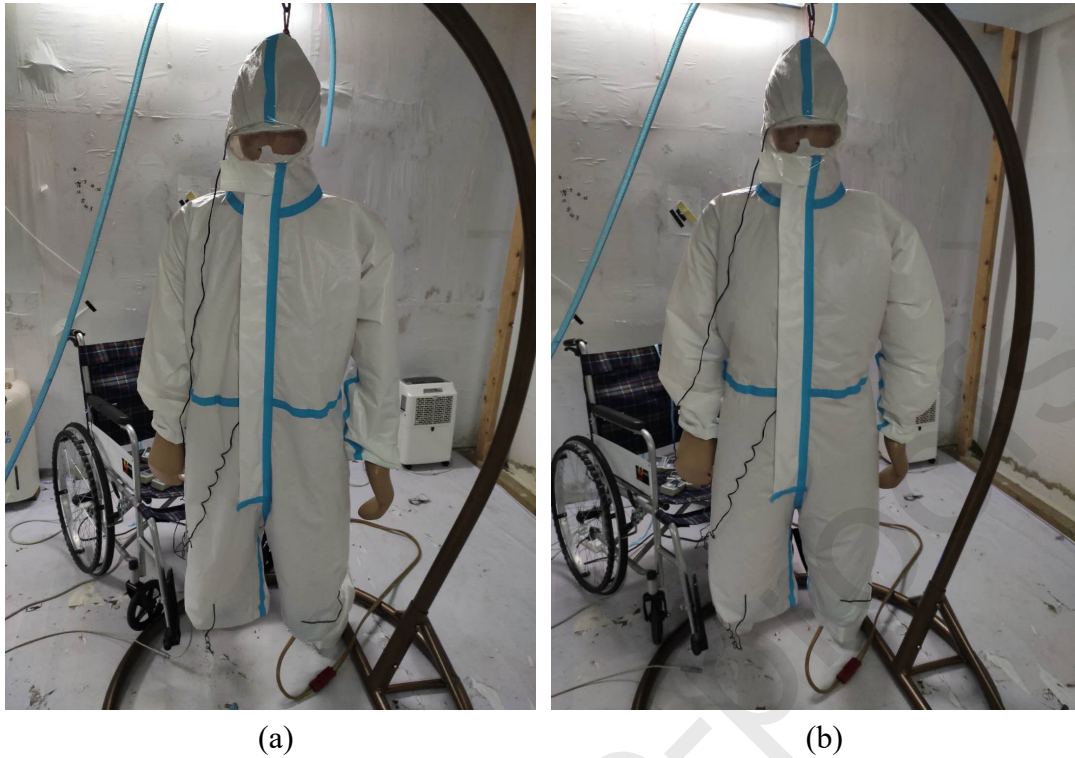
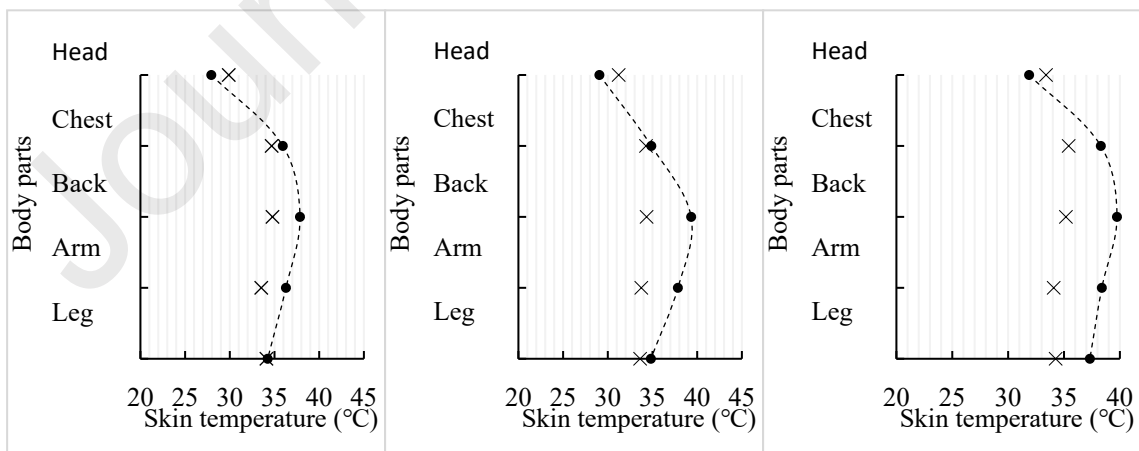


Fig. 6. MUPC without air supply (a) and MUPC with air supply (b)

The MUPC is inflated due to the fact that the MUPC inside pressure is higher than outside environment pressure. During the experimental process, the MUPC inside and outside pressure difference is 1~2 Pa. An MUPC inside micro-positive pressure environment can be achieved with air supplied into the MUPC.

The simulation model in FLUENT software was validated with the experimental results. The skin temperature of main body parts and MUPC inside air temperature of the simulation results and experimental data of three typical cases, namely case 3, case 6 and case 9, are shown in Fig. 7.



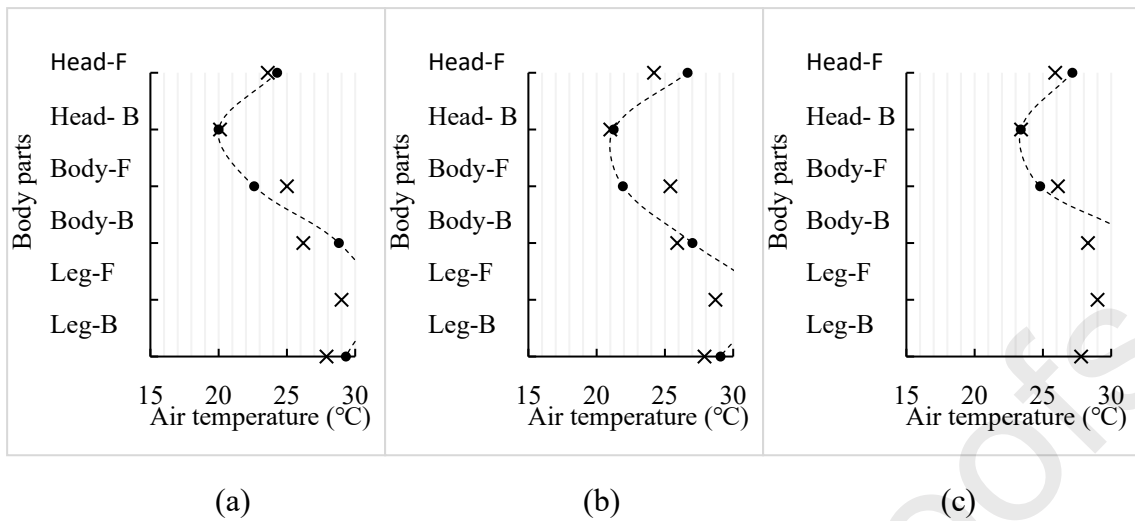


Fig. 7. Validation of skin temperature and MUPC inside air temperature of case 3 (a), case 6 (b) and case 9 (c). Experimental data: cross symbol, simulation results: circle dot with dashed line.

The deviation between the experimental data and the simulation results is mainly comes from the instruments accuracy, structure deviation between the manikin and the model, the air gap, as well. The validation results show that the maximum deviations between experimental data and simulation results are 14.75% for the arm skin temperature and 14.79% for the body back air temperature. The results of the simulation model can be used to predict the skin temperature and MUPC inside air temperature.

3.2 MUPC inside air temperature

When the cool air is supplied at head, the MUPC inside air temperature simulation results of different body part under different supply air temperature and air flowrate are shown in Table 5.

Table 5. Simulation results of head supply conditions

Flowrate (L/min)	Supply temperature (°C)	MUPC inside air temperature (°C)							
		Head-F	Head-B	Chest-F	Chest-B	Arm-F	Arm-B	Leg-F	Leg-B
50	18	25.97	19.39	23.93	24.35	31.67	31.6	31.49	30.91
	20	26.75	21.14	25.22	25.64	31.79	31.72	32.08	31.19
	22	27.61	22.98	26.38	27.37	31.89	31.83	31.31	31.75
100	18	25.67	20.32	21.66	24.09	31.68	31.59	29.72	28.12
	20	26.86	22.00	23.27	25.41	31.74	31.66	29.96	28.78
150	22	27.82	24.00	24.78	26.52	31.82	31.74	30.45	29.34
	18	24.53	20.99	21.00	23.14	31.55	31.47	29.63	26.94
	20	25.68	22.53	22.59	24.40	31.65	31.56	29.31	27.75

22 26.77 24.12 24.13 25.69 31.70 31.63 29.13 28.52

When the cool air is supplied at backside of head, the lowest MUPC inside air temperature is at the backside of head part, and the highest MUPC inside air temperature is at the arm part. MUPC inside air temperature decreases with the rise of air flowrate, due to the increasing of cooling capacity. Similar to the experimental results, air flowrate has little influence on the MUPC inside temperature at arm part. For body part and leg part, MUPC inside air temperature decreases with the increasing of supply air flowrate.

When the air supply position is at body, the MUPC inside air temperature simulation results of different body parts under different supply air temperature and air flowrate are shown in Table 6.

Table 6. Simulation results of body supply conditions

Flowrate (L/min)	Supply temperature (°C)	MUPC inside air temperature (°C)							
		Head-F	Head-B	Chest-F	Chest-B	Arm-F	Arm-B	Leg-F	Leg-B
50	18	32.28	32.41	29.50	28.73	30.67	29.77	26.48	30.51
	20	32.33	32.46	29.95	29.21	30.89	30.10	27.76	29.59
	22	32.40	32.52	30.41	29.70	31.13	30.40	27.87	29.23
100	18	28.01	28.69	27.13	26.16	26.01	26.33	25.37	25.90
	20	28.04	29.18	27.72	26.81	26.84	26.99	26.06	26.67
	22	28.33	29.70	28.37	27.48	27.43	27.67	26.90	27.45
150	18	24.86	27.00	24.57	25.24	24.80	24.37	24.20	24.48
	20	26.78	27.64	25.68	25.48	27.82	25.61	24.91	25.70
	22	26.70	28.51	27.61	26.68	25.66	26.76	26.19	26.54

When the cool air is supplied at body region, the temperature difference among all of the positions is not as high as head supply conditions. With 8 air outlet vents at both frontside and backside of belly and chest, the lowest temperature is at leg position, and then is body part and arm part. With the increasing of air flowrate, MUPC inside temperature of all parts decreases, especially for head part.

The rising of supply air temperature causes a rise in MUPC inside air temperature for all parts. When the air supply position is at head part, supply air temperature has the greatest effect on head part, and has the minimal impact on arm and leg parts. With small air flowrate of 50 L/min, cool air is difficult to reach the arm part and leg part, decreasing supply air temperature cannot cool down these positions very effectively. MUPC inside temperature of arm and leg part may not meet the requirement of thermal comfort due to the air temperature exceeding 30 °C . When cool air is supplied at body part, supply air temperature has small impact on the MUPC inside air temperature for all body parts.

3.3 Thermal comfort based on skin temperature

Thermal comfort is largely influenced by skin temperature of different body parts. Though the MUPC inside air temperature is less than 26 °C , whether medical worker is

comfortable still needs to be discussed according to skin temperature. When the supply air temperature is 20 °C and air flow rate is 50L/min, the skin temperature under different air supply positions are shown in Fig. 8.

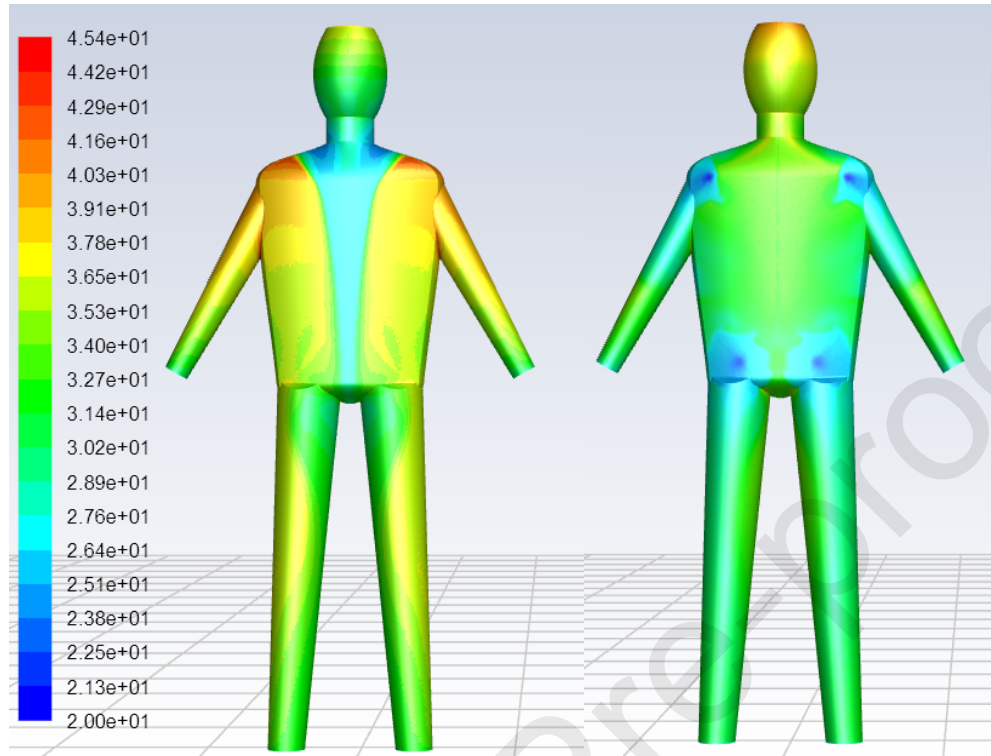


Fig. 8. Skin temperature with air supplied at head (left) and body (right)

Apparently, with same supply air temperature and same air flowrate, skin temperature of body supply condition is much lower than head supply condition. The highest skin temperature can be obtained at shoulder and scull for the two air supply positions, separately. In order to quantify the thermal comfort sensation, the calculation and analysis of different supply air conditions is necessary. Feet and hands are not in the MUPC, and supply air conditions has no impact on skin temperature of these body parts. Thus, experimental skin temperature results, with environment temperature of 26 °C, are adopted as the skin temperature in different simulation cases. The overall thermal sensation under different supply air position, supply air temperature and air flowrate calculation results are shown in Fig. 9.

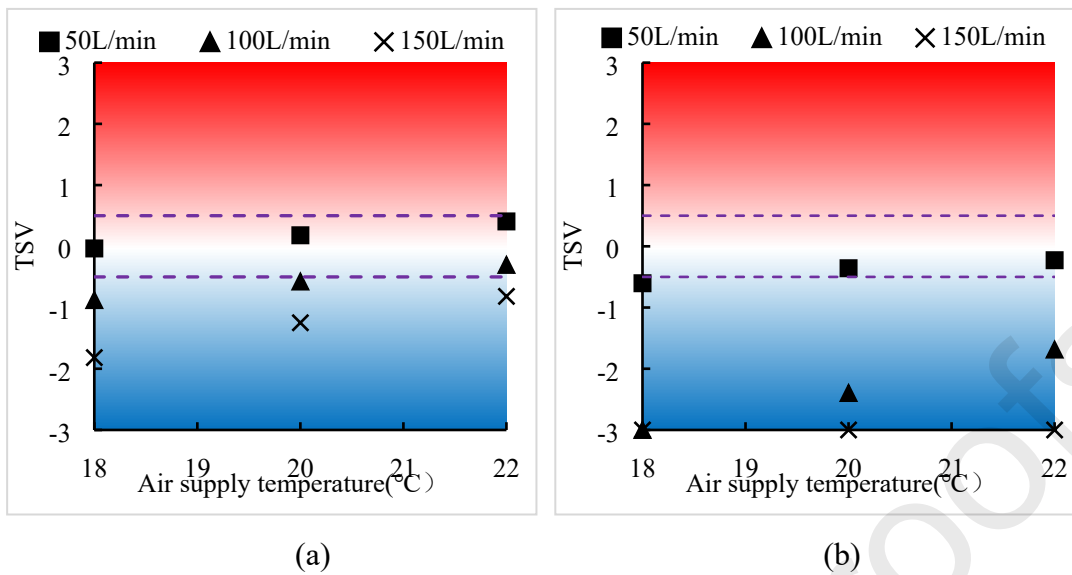


Fig. 9. Overall TSV with air supplied at head (a) and body (b)

Overall TSV increases with the increasing of supply air temperature and the decreasing of air flowrate, for the simulated two air supply positions. With cool air supplied at head, overall TSV is within the thermal comfort range when the supply air flowrate is 50L/min. When the supply air flowrate increases to 100L/min, TSV deviates from thermal comfort zone, and the medical worker may feel slightly cold. Air flowrate of 150L/min with supply air temperature from 18 °C to 22 °C is not suitable as TSV is below -1. For body supply conditions, overall TSV is lower than that of head supply conditions under the same supply temperature and flowrate, for all cases. 100 L/min and 150 L/min air flowrate conditions are not suitable for practical application due to the very cold thermal sensation. To achieve slightly cool thermal sensation, supply air conditions of 18 °C with 50 L/min and 22 °C with 150 L/min are better choices when cool air is supplied at head. Compared with head supply condition, 22 °C and 50L/min cool air supply condition can meet the requirement of thermal comfort, and the energy saving potential is much higher. Compared with experimental results in Fig. 5, the removing of moisture and sweat evaporation are benefit to decreasing the skin temperature and improving the thermal sensation.

As the MUPC inside air temperature of different body parts are different from each other, the study of local TSV of different body part is necessary. The results of local TSV of different cool air supply position and different supply air temperature cases, with 50 L/min air flowrate, are shown in Fig. 10.

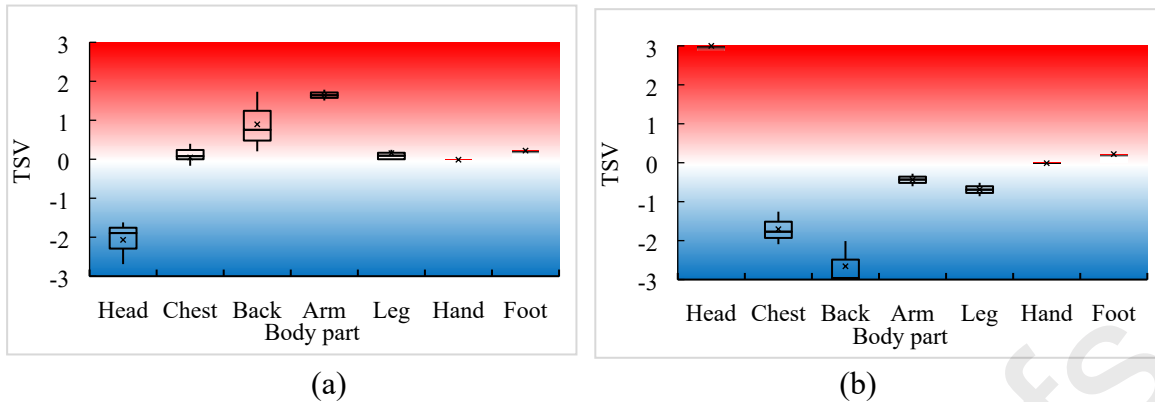


Fig. 10. TSV of local thermal sensation with air supplied at head (a) and body (b)

For head supply cases, the highest TSV can be obtained at arm part, and the lowest TSV is at head part. Chest, leg, hands and feet show the best local TSV, for the three simulated supply air temperature cases. Comfort thermal sensation of back part can be obtained with supply air temperature of 18°C . Head part has cold thermal sensation due to the local TSV lower than -1.5 . Supply air temperature has the greatest influence on local TSV of back part, and the second influential is head part. Compared with back and head, supply air temperature has little impact on local TSV of arm part and leg part. Obviously, when the cool air is supplied at body, head tends to feel hot and back and chest may feel cold. TSV of arm part can be improved, and slightly cool sensation can be obtained at leg compared with head supply conditions. With cool air supplied at body, supply air temperature has great influence on TSV of back and chest. TSV of head, arm and leg change slightly with the variation of supply air temperature. The local TSV results show great consistency with MUPC inside air temperature variation condition.

3.4 MUPC inside air relative humidity

Thermal comfort of human body is not only influenced by temperature, but also affected by air relative humidity. As the humidity source is human dissipation, the relative humidity of skin is nearly saturated. In this research, the middle face between human body and clothing is taken as the research object of the MUPC inside air relative humidity study. With 20°C and 50 L/min supply air condition, the air relative humidity calculation results of the middle face of human body and clothing are shown in Fig. 11.

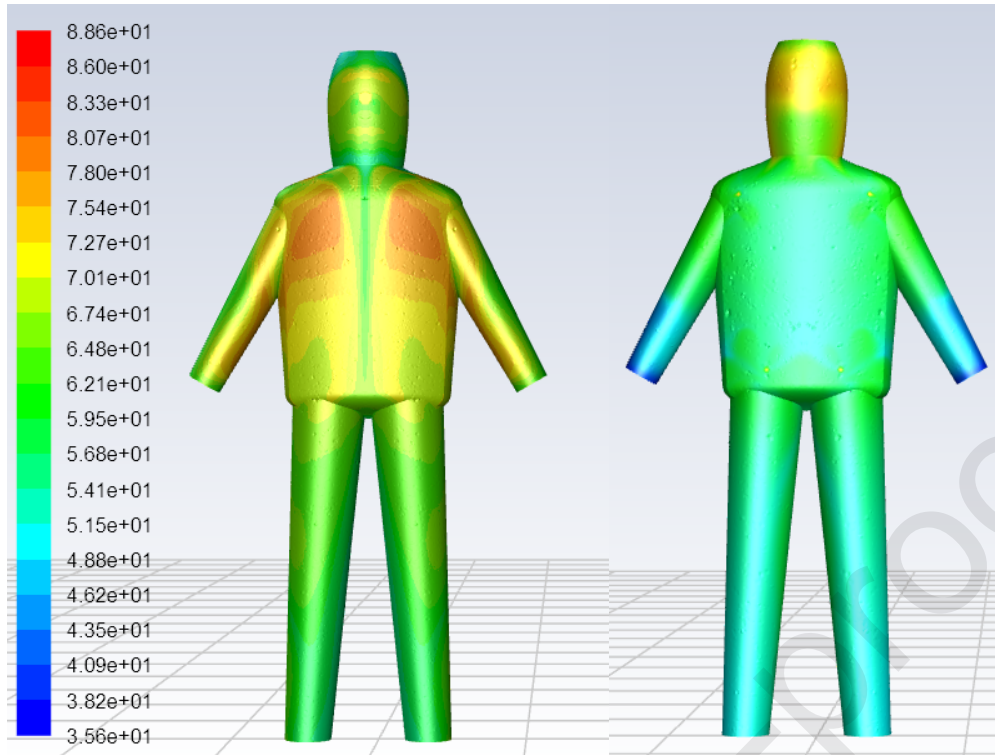


Fig. 11. MUPC inside air relative humidity with air supplied at head (a) and body (b)

With cool air supplied at head, relative humidity of majority body parts and arm part is higher than 70%, and head part and leg part have relatively low relative humidity around 60%. Cool and dry air reaches head part firstly, and then reaches body part and leg part. Dry air is difficult to reach arm part, causes the much higher air relative humidity. For body part, the supplied air mainly flows through the middle of chest, and left part and right part has poor relative humidity condition. When air is supplied at body part, body, leg and arm part have better relative humidity condition, which is between 50% and 65%, compared with head supply condition. In this condition, the supplied cool air is much more difficult to reach head part, and relative humidity of majority head part is higher than 70%.

To quantify the influence of air supply position, supply air temperature and air flowrate on the distribution of MUPC inside air relative humidity, the average MUPC inside air relative humidity of different body parts were calculated. When supply air temperature is 20°C, MUPC inside air relative humidity for different body parts vary with the air supply rate, and the results are shown in Fig. 12.

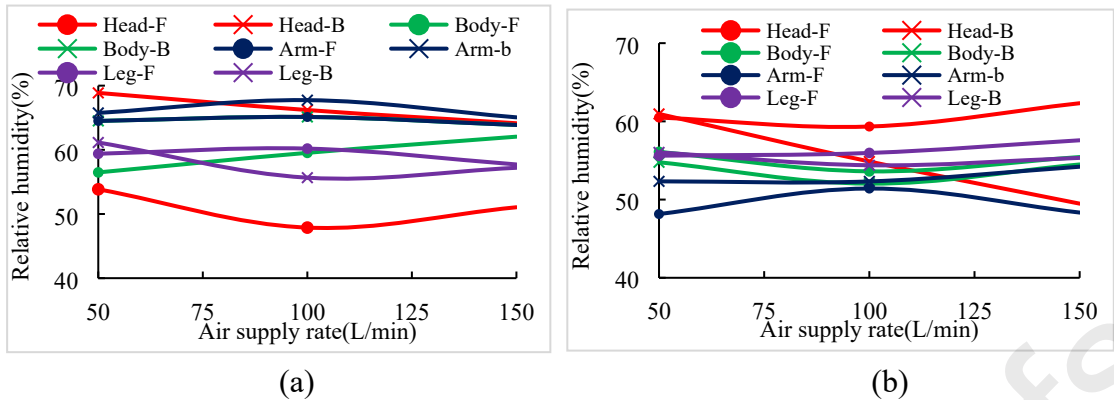


Fig. 12. MUPC inside air relative humidity of head supply (a) and body supply condition (b) with 20°C supply air temperature

Both MUPC inside air humidity ratio and air temperature have influence on air relative humidity. For head supply condition, the highest air relative humidity is at backside of head and arm part, but the reasons are not the same. For backside at head part, the cool air is supplied at this position, and the high relative humidity is caused by the low air temperature. The cool air is difficult to reach the arm part, and the high relative humidity of arm part is mainly due to the high air humidity ratio. MUPC inside air humidity ratio at front of head, leg part and body part are lower than 60%, and air relative humidity at leg part decreases with the rising of air flowrate. For body supply condition, the highest relative humidity appears at head, and the lowest relative humidity is at leg part. The highest relative humidity is around 60%, much lower than the highest relative humidity of head supply condition.

When supply air flowrate is 50 L/min, the MUPC inside air relative humidity for different body parts vary with the supply air temperature, and the results are shown in Fig. 13.

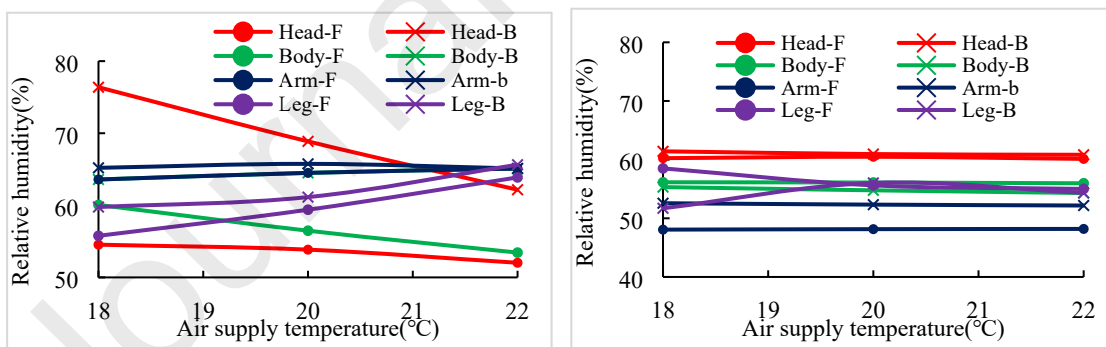


Fig. 13. MUPC inside air relative humidity of head supply (a) and body supply condition (b) with 50 L/min supply air flowrate

When cool air is supplied at head, the relative humidity of head backside and arm part is higher than 60%, with air supply temperature between 18°C and 22°C. Decided by the air flow characteristic, the supplied cool air flows from the backside of head to the frontside of body, causes the different variation trend of body backside and body frontside with the variation of supply air temperature. When the air supply position changes to body, relative humidity nearly maintains constant with the variation of supply air temperature. The lowest

relative humidity is at arm part, and the highest relative humidity is at head part. In this air supply condition, arm temperature is the second highest among the body parts, which causes the relative humidity tends to be lower than other body parts. With greater air density, cool and dry air is difficult to reach head part, under body supply condition.

4 Discussion

In practical application, the design of the vortex tube cooling device is important. Cool air supply positions and especially, supply air condition have great influence on wearer thermal sensation. The simulation results showed that the supply both air conditions and supply air position have influence on the system performance. Taking both temperature and relative humidity into consideration, with head supply condition, body part and leg part has the best thermal comfort due to the moderate temperature and relative humidity. Head part has much lower air temperature with moderate relative humidity, and a cold thermal sensation may cause uncomfortable feeling. With less cool and dry air flow to arm part, high air temperature and high relative humidity causes the worst thermal comfort for this region. When the air supply position changes from head to body, cool air is easier to reach arm and leg part, and the thermal sensation of these parts is improved. Body has low TSV with moderate air relative humidity, and head part has the worst thermal sensation due to much hot thermal sensation.

Both supply air temperature and air flowrate have effect on the energy saving potential and, more important, endurance time of the devices. Decided by the performance of vortex tube, decreasing the supply air flowrate and increasing the supply temperature have the ability to reduce the compressed air consumption. When taken overall TSV and energy consumption into consideration, the best cool air supply condition in this research is body supply with 50 L/min air flowrate and 22°C supply air temperature. While, as the compressed air is clean and fresh air, it is beneficial to medical workers health with the air supplied to breath zone directly. From this point of view, head supply condition is better than body supply condition.

Either head supplying or body supplying conditions does not have the ability to create a balance environment of all body parts, though the overall TSV is around zero in some cases. By supplying cool air at both head and body may have the ability to improve the thermal sensation difference among different body parts. On the other hand, the supply air temperature can be increased with two supply positions, to meet thermal comfort requirement. With high supply air temperature requirement, the endurance time of the devices can be further extended. In a word, the study of the portable cooling device, especially supply air conditions, needs for further study by experimenting the cooling devices with real men.

In this portable MUPC cooling device, cool air is supplied from the cold end of a vortex tube. The input air of the vortex tube is compressed air, and the compressed air is mainly stored in a gas storage tank in practical use. Compared with other kinds of personal cooling devices, such as clothing ventilation and phase change material cooling devices, vortex tube portable cooling devices can provide a more comfortable thermal environment and safety

medical working condition. As humidity ratio of the compressed air is low, dehumidification can be achieved during the cooling process, and the dehumidification capacity is decided by the air humidity ratio before compressed and the compressed air pressure. Clothing ventilation is bound to intake environment air to the MUPC air gap, and the MUPC will loss protection. Vortex tube can meet the requirement of medical workers' thermal comfort, without the installation of battery and fans. Except for the improvement of medical workers thermal sensation, the protection performance of the MUPC can also be improved with vortex tube and compressed air tank. With cool and clean air supplied into the MUPC, a micro positive MUPC inside environment can be created. Positive pressure has the ability to prevent the infiltration of outside air that contains viruses, bacteria and other micro-organisms, in the actual medical environment. Furthermore, the medical workers can adjust the cooling capacity by changing the cooling air ratio. Combined with compressed air tank, replacing the compressed air tank method can maintain a long endurance time. On the other hand, the volume of the compressed air tank should also be designed, which can be investigated for further study, in terms of endurance time and weight, though the air tank replacing method can be adopted.

5 Conclusions

The vortex tube combined compressed air cylinder can be formed as a portable cooling device, and can be used with MUPC to improve the medical workers thermal sensation. The cooling device is of small size and portable. With this kind of portable cooling devices, thermal comfort of the medical workers can be improved, and the protection performance is increased as micro-positive pressure is formed between MUPC inside and outside. Equipped with the portable cooling device, the thermal comfort of medical worker wearing MUPC was evaluated. The evaluation of the air supply parameters can be concluded as following:

- (1) The supplied air is difficult to flow to arm and leg part when supplied at head. Overall thermal sensation of 50L/min air flowrate can meet the thermal comfort requirement. Arm part has the warmest local thermal sensation, while head has the coldest thermal sensation.
- (2) TSV of Arm and leg part can be improved with cool air supplied at body, and hot and cold thermal sensation appears at head and back part, separately. To make the same overall TSV, the supply air temperature can be increased and the air flowrate can be reduced, compared with head supply condition.
- (3) Neither head supply condition nor body supply condition can create a uniform MUPC inside environment and a balanced thermal sensation of all body parts.
- (4) The protection performance of MUPC can be improved due to the fact that a micro-positive pressure environment in the MUPC is created with the supplied cool air.

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References

- [1] Z. Xie, Y. Qin, Y. Li, W. Shen, S. Liu, Spatial and temporal differentiation of COVID-19 epidemic spread in mainland China and its influencing factors, *Science of The Total Environment*, 744 (2020) 140929.
- [2] Y. Pan, G. Xian, H. Li, Numerical modeling of moisture diffusion in an unidirectional fiber-reinforced polymer composite, *Polymer Composites*, 40 (1) (2017) 401-413.
- [3] Y. Yang, L. Chen, T. Naveed, P. Zhang, A. Farooq, Influence of fabric structure and finishing pattern on the thermal and moisture management properties of unidirectional water transport knitted polyester fabrics, *Textile Research Journal*, 89 (10) (2018) 1983-1996.
- [4] A.M. Popa, L. Hu, D. Crespy, M. Henry, R.M. Rossi, Polyoxomolybdate-based selective membranes for chemical protection, *Journal of Membrane Science*, 373 (1-2) (2011) 196-201.
- [5] H. Wu, R. Zhang, Y. Sun, D. Lin, Z. Sun, W. Pan, P. Downs, Biomimetic nanofiber patterns with controlled wettability, *Soft Matter*, 4 (12) (2008) 2429-2433.
- [6] M. Li, J. Tu, Overall evaluation and prediction of heat-moisture comfort of Coolmax/cotton double-faced effect fabric, *Journal of Textile Research*, 31 (11) (2010) 39-43.
- [7] J. Wu, N. Wang, L. Wang, H. Dong, Y. Zhao, L. Jiang, Unidirectional water-penetration composite fibrous film via electrospinning, *Soft Matter*, 8 (22) (2012) 5996-5999.
- [8] Y. Wang, J. Li, G. Wang, L. Zhang, L. Shi, Study on thermal and moisture comfort of Nonwovens for medical protective clothing, *Journal of Donghua University (Natural Science Edition)*, 32 (6) (2006) 116-119 (in Chinese).
- [9] J. Yang, X. Wang, B. Li, Study on moisture permeability of medical protective clothing fabric under different temperature and humidity conditions, *Basic Sciences Journal of Textile Universities*, 18 (4) (2005) 389-394 (in Chinese).
- [10] Technica requirement for single-use protective clothing for medical use, in, Standards Press of China, Beijing, 2009 (in Chinese).
- [11] J. Wang, Y. Li, H. Tian, J. Sheng, J. Yu, B. Ding, Waterproof and breathable membranes of waterborne fluorinated polyurethane modified electrospun polyacrylonitrile fibers, *RSC Advances*, 4 (105) (2014) 61068-61076.
- [12] J. Sheng, Y. Xu, J. Yu, B. Ding, Robust Fluorine-Free Superhydrophobic Amino-Silicone Oil/SiO₂ Modification of Electrospun Polyacrylonitrile Membranes for Waterproof-Breathable Application, *ACS Appl. Mater. Interfaces*, 9 (17) (2017) 15139.
- [13] J. Sheng, M. Zhang, Y. Xu, J. Yu, B. Ding, Tailoring Water-Resistant and Breathable Performance of Polyacrylonitrile Nanofibrous Membranes Modified by Polydimethylsiloxane, *Acs Appl Mater Interfaces*, 8 (40) (2016) 27218-27226.
- [14] S. Jin, Y. Park, C.H. Park, Preparation of breathable and superhydrophobic polyurethane electrospun webs with silica nanoparticles, *Textile Research Journal*, 86 (17) (2015) DOI: 10.1177/0040517515617417.
- [15] F. Yang, Y. Li, X. Yu, G. Wu, J. Yu, B. Ding, Hydrophobic polyvinylidene fluoride fibrous membranes with simultaneously water/windproof and breathable performance, *Rsc Advances*, 6 (90) (2016) DOI: 10.1039/C1036RA17565A.
- [16] J. Ge, Y. Si, F. Fu, J. Wang, J. Yang, L. Cui, B. Ding, J. Yu, G. Sun, Amphiphobic fluorinated polyurethane composite microfibrillar membranes with robust waterproof and breathable performances, *Rsc Advances*, 3 (7) (2013) 2248-2255.
- [17] L. Zhang, Y. Li, J. Yu, B. Ding, Fluorinated polyurethane macroporous membranes with waterproof, breathable and mechanical performance improved by lithium chloride, *RSC Advances*, 5 (97) (2015) 79807-79814.
- [18] H. Ueda, Y. Inoue, M. Matsudaira, T. Araki, G. Havenith, Regional microclimate humidity of clothing during light work as a result of the interaction

- between local sweat production and ventilation, *International Journal of Clothing Science and Technology*, 18 (4) (2006) 225-234.
- [19] M. Zhao, C. Gao, F. Wang, K. Kuklane, I. Holmér, J. Li, A study on local cooling of garments with ventilation fans and openings placed at different torso sites, *International Journal of Industrial Ergonomics*, 43 (3) (2013) 232-237.
- [20] W. Yi, Y. Zhao, A.P.C. Chan, Evaluation of the ventilation unit for personal cooling system (PCS), *International Journal of Industrial Ergonomics*, 58 (2017) 62-68.
- [21] A. Hadid, R. Yanovich, T. Erlich, G. Khomenok, D.S. Moran, Effect of a personal ambient ventilation system on physiological strain during heat stress wearing a ballistic vest, *European Journal of Applied Physiology*, 104 (2) (2008) 311-319.
- [22] Y.J. He, C. Cao, J. Wu, G.M. Chen, Investigations on coupling between performance and external operational conditions for a semiconductor refrigeration system, *Int. J. Refrig.-Rev. Int. Froid*, 109 (2020) 172-179.
- [23] Y. Yin, Y. He, L. Wei, C. Song, Y. Zhang, X. Chen, W. Wang, H. Wu, Water cooled thermoregulation suit based on semiconductor refrigeration, *Energy Conservation*, 39 (08) (2020) 69-73.
- [24] P. Puangcharoenchai, P. Kachapongkun, P. Rattanadecho, R. Prommas, Experimental Investigation of Performance Enhancement of a Vapor Compression Refrigeration System by Vortex Tube Cooling, *Int. J. Air-Cond. Refrig.*, 28 (2) (2020) 10.
- [25] P. Edwards, K. Tesch, T.G. Karayiannis, M.W. Collins, M.A. Atherton, P. Young, M. Large, R. Brade, Design optimisation of air-fed full pressurised suits, *Fusion Engineering & Design*, 84 (2009) 716-721.
- [26] F. Tian, G. Cheng, Z. Wang, J. Yang, J. Yang, S. Liu, Mierolmvirlmm-t of posalve pressure powered air pll mescal protective equipmen, *Chinese Journal of Industrial Hygiene and Occupational Diseases*, 24 (3) (2006) 151-153.
- [27] J. Wu, L. Hao, R. Wang, Y. Yi, J. Qi, Research of positive-pressure bio-protective suit for Ebola disease, *Chinese Medical Equipment Journal*, 35 (12) (2014) 93-96 (in Chinese).
- [28] K. Tesch, M.W. Collins, T.G. Karayiannis, M.A. Atherton, P. Edwards, Heat and Mass Transfer in Air-Fed Pressurised Suits, *Applied Thermal Engineering*, 29 (7) (2009) 1375-1382.
- [29] D. Lai, F. Wei, Y. Lu, F. Wang, Evaluation of a hybrid personal cooling system using a manikin operated in constant temperature mode and thermoregulatory model control mode in warm conditions, *Textile Research Journal*, 87 (1) (2016) 46-56.
- [30] J. Yang, F. Wang, G. Song, R. Li, U. Raj, Effects of clothing size and air ventilation rate on cooling performance of air ventilation clothing in a warm condition, *International Journal of Occupational Safety and Ergonomics*, 4 (2020) 1-10.
- [31] Z. Kang, X. Wan, F. Wang, U. Raj, B. Yang, Numerical Analysis on the Cooling Performance of a Hybrid Personal Cooling System (HPCS) under Different Hot Environments, (2018) DOI: 10.20944/preprints201812.200034.v201811.
- [32] J. Zhan, Research on simulation heat dissipation equipment of human body in Train Environment Experiment, *Architecture and Civel Engineering*, Qingdao Technological University, 2018 (in Chinese).
- [33] T.S. Ge, F. Ziegler, R.Z. Wang, A mathematical model for predicting the performance of a compound desiccant wheel (A model of compound desiccant wheel), *Applied Thermal Engineering*, 30 (8) (2010) 1005-1015.
- [34] R. Zhao, C. Fan, D. Xue, Y. Qian, *Air Conditioning*, China Architecture and Building Press, Beijing, 2009 (in Chinese).
- [35] Y. Sun, Experiment study on human thermal sensation based on skin temperature, School of Civil Engineering, Dalian University of Technology, 2009 (in Chinese).

CRedit authorship contribution statement

Xing Su: Conceptualization, Writing - Review & Editing, Formal analysis, Supervision, Funding acquisition. Project administration. **Shaochen Tian:** Investigation, Data curation,

Writing - Original Draft, Visualization. **He Li:** Validation. **Xu Zhang:** Methodology. **Xiaolu Shao:** Formal analysis. **Jun Gao:** Software. **Hai Ye:** Resources.

- A medical use protective clothing was combined with a portable cooling device.
- The medical use protective clothing was tested with a manikin in a phytotron.
- Thermal sensation was evaluated in terms of skin temperature and air humidity.
- Overall thermal comfort is improved, and local thermal sensation is not uniform.
- A clothing inside micro-positive pressure environment can be obtained.