A Statistical Study to Evaluate the Performance of Liquid Cooling Garments Considering Thermal Comfort

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Liquid cooling garments (LCGs) are considered feasible cooling equipment to protect individuals from hyperthermia and heat-related illness when working in extremely hot and stressful environments. So far, the goals for the optimization design of LCGs are mostly from the perspective of enhancing its efficiency and working time. However, thermal comfort is the key factor that is often not considered. In fact, many situations may cause discomfort. For example, the inlet temperature of the liquid-cooling vest changes constantly resulting in the change of thermal states of the human body. So, it is very significative to develop a method to evaluate the performance of LCGs considering thermal comfort. In this paper, an uncomfortable time ratio was proposed to evaluate the performance of LCGs considering thermal comfort. A series of tests were conducted by a modified thermal manikin method to evaluate the thermal properties. According to the analyses, the duration working time was 82.77 min, while the uncomfortable time ratio was too large, up to 57.6%. It showed that the thermal comfort should be considered when optimizing the performance of LCGs. The influences of different parameters such as volume of ice, flowrate, inlet temperature on the performance of LCGs were investigated through orthogonal experimental design. The statistical analysis illustrated that the influence of the volume of ice on the uncomfortable time ratio is greater than that of flowrate and ambient temperature. It is concluded that this method is useful for the control and design of LCGs considering thermal comfort. [DOI: 10.1115/1.4047470]

Keywords: liquid cooling garments, thermal comfort, orthogonal experiment design, analysis of variance

1 Introduction

A stable core body temperature is essential to maintain the optimal functions of the human body [1–4]. However, it is arduous to achieve this in extremely hot environments as a result of excessive heat. Under conditions where air-condition is not feasible, such as firefighting, industrial activities, and outdoor sports, individual cooling is proposed as a practical solution to alleviate heat stress [5–7]. Personal cooling garments (PCGs) have been designed as an effective and economical means of reducing heat stress and improve the associated work performance in thermally stressful environments [8–11]. Three types of PCGs are developed according to the cooling technique used, i.e., liquid cooling garments (LCGs) [12–16], air cooling garments [17,18], and phase-change garments [19,20]. The high heat capacity of water shows the superiority in decreased pumping power and lower system weight. Therefore, LCGs are widely used in civilian and military fields. On the other hand, LCGs which utilize ice as the cooling source, are found to be very efficient and economical. As a result, this kind of cooling vest is the most commonly used active cooling garments in today's applications.

Ever since the first prototype was proposed by Burton and Collier in the 1960s [8], many researches have been carried out to study and improve its performance. Burton et al. [21] studied experimentally the effects of flowrate and inlet temperature on the cooling efficiency of LCGs. It was found that the heat removal rate is related nonlinearly to flowrate. In more detail, flowrate showed little improvement in cooling when flow rates exceeded 1 L/min. The water inlet temperature is also one of the key parameters to determine the thermal properties of LCGs. The practical limits of inlet temperature depend on the cooling system. Guo et al. [12] built a detailed heat transfer model of LCG in a hot environment to analyze the effects of different factors on the LCG performance. The experiments were conducted by a modified thermal manikin method at different ambient temperature (35–50 °C) with the flowrate varying from 224.5 to 544.2 ml/min, when the water was cooled by an icepack with a volume of 600 ml. The thermal manikin is used to simulate the sensible heat produced by the human body. It can simulate the high metabolic heat of a human body for a long time, which is difficult for a real person to perform, so it is reasonable and economical to evaluate the performance of the LCG by using a thermal manikin rather than a person [8,9,12,19]. It proved that the ambient temperature and flowrate have a great effect on the work duration time of the LCG. The maximum cooling power of LCG achieve 243.2 W/cm^2 at ambient temperature of 45 °C with flowrate of 544.2 ml/min, which showed significance on cooling performance of the vest. Wang et al. [19] investigated the performance of a liquid-cooling garment with the application of micro-encapsulated phase-change material suspension (MEPCMS). The experimental results showed that the inlet temperature, flowrate, and volume concentration of the MEPCMS are three key parameters affecting the performance of the LCG, which can be enhanced significantly by a proper

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combination of these parameters. For example, when the inlet temperature, mass flowrate, and volume concentration of the MEPCMS were selected as 11 °C, 200 g/min, and 20%, respectively, the heat dissipation of the LCG was enhanced by up to 26% with no obvious increase of the pump power compared with that using water as the working fluid, the temperature distribution in the human body became more uniform, and the capability of the LCG to adapt large heat load change became stronger.

However, these studies did not evaluate the performance of thermal comfort and only focused on how to enhance the system's cooling efficiency and work duration time. In fact, thermal comfort is another aspect that should be paid more attention to Refs. [15] and [22], because many situations may cause discomfort. For example, as the ice melts, the inlet temperature of the liquid-cooling vest changes constantly resulting in the change of thermal states of the human body, which lead to discomfort of human. So, it is very significative to develop a method to evaluate the performance of LCGs considering thermal comfort.

2 Methods

In this paper, an uncomfortable time ratio was proposed to evaluate the performance of LCGs considering thermal comfort. It defined the proportion of uncomfortable time including overcooling and overheating in the entire working time. A series of tests were conducted by a modified thermal manikin method to evaluate the thermal properties. Then, we proposed a statistical method to investigate the significance of various factors on the duration working time and uncomfortable time ratio. The quantitative evaluation and analysis were investigated through orthogonal experiment design. By this means, the most influential factor on the performance of LCGs was finally determined.

2.1 Principles of Liquid-Cooling Garment. Figure 1 shows the schematic of a typical LCG system. Cooling liquid is circulated inside the tubing network embedded in a basic garment using a battery-powered micropump and take away the heat produced by the human body. As the cooled liquid turns warm, it is then circulated to the cooling source (i.e., ice packs) for recooling purposes. The process repeats until the ice pack melts and the circulating liquid becomes warm [6,8,9,12]. To enhance the conductive heat between the skin and fabrics, the basic garment is usually made of fabrics with high elasticity; thus, the tubes can firmly contact with the human body [6]. Unfortunately, cooling vests that using ice as the cooling source also have some drawbacks: (1) the work duration time of the system is limited to the volume of ice; (2) it may decrease local skin temperature too much and causes discomfort; and (3) it causes condensation when the cooling liquid is too cold in LCGs, which also affects the wearing comfort [9].

2.2 Performance of Test. A modified thermal manikin method was verified to effectively evaluate the thermal properties of LCGs [12]. Figure 2 shows the schematic of the test system by this method. A half thermal manikin was put in the heat chamber to get a steady and conditioned hot environment. The thermal manikin was electrically heated uniformly to simulate the heating human body. The micropump was powered by a portable power supply. The volume flowrate was measured by a turbine flowmeter (YF-S401) with ±2% accuracy. The solid blue loop represented the water circulation system, while the dotted red lines represented the different data acquisition paths. All temperatures were measured by the k-type thermocouple (TT-K-30, accuracy 0.4%, Omega, Norwalk, CT). Eight thermocouples from T1 to T8 were

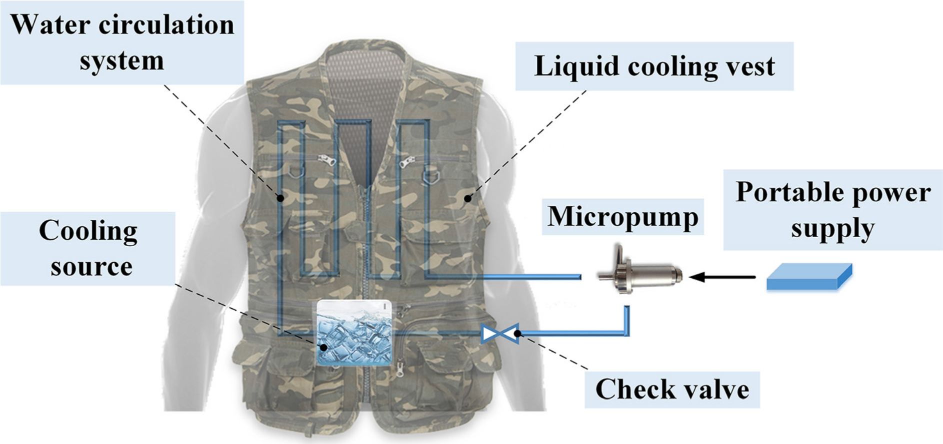

Fig. 1 Schematic of a typical LCG system

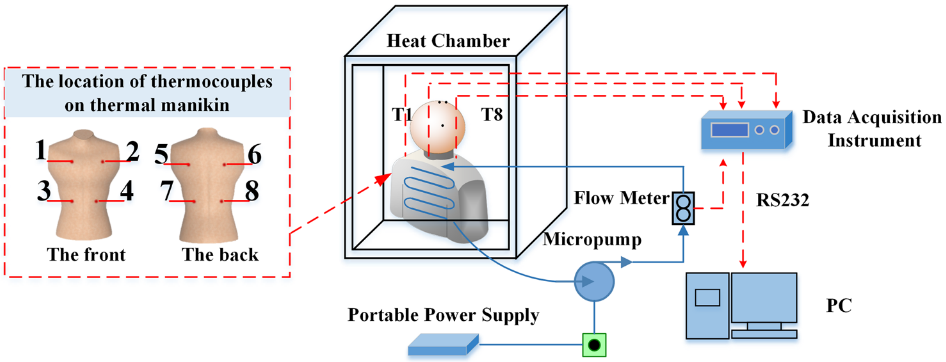

Fig. 2 Schematic of the performance test setup for LCGs

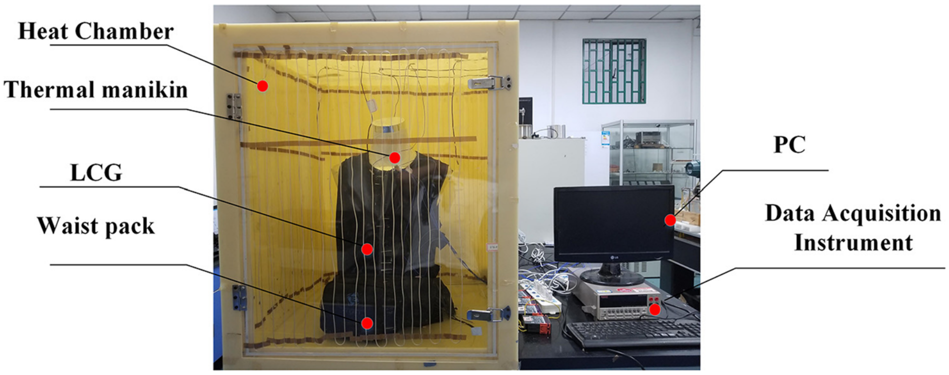

Fig. 3 A photo of the overall performance experimental setup for LCGs

deployed in pairs on the surface of the thermal manikin. The inlet and outlet temperatures of the cooling vest were also recorded with another two thermocouples. Four thermocouples were located inside the heat chamber to record the ambient temperature. Figure 3 displayed the photo of the overall experimental setup for LCGs. The prototype had a total of four tubings sewn into the lining which each begins and ends in manifolds located at the waist. The individual tubes were 2.5 m in length with 3/5 mm of internal and external diameters, respectively, for a total length of tubing in the cooling vest of 10 m. The basic garment was made of flexible spandex and cotton mixture mesh fabric. Four velcro sets were set to ensure the tubes tightly close to the skin, to improve the efficiency of heat transfer. A zipper was used to make the LCG easy to take on and off. For thermal insulation, cooling units included icepack, micropump, battery were put into the waist pack.

The experiment procedures were as follows:

(1) Dressed the half manikin in the cooling vest, and placed it in the center of the heat chamber.
(2) The ambient temperature in the heat chamber was set to the target temperature to simulate the hot environment. The surface temperature of the manikin was set to 33 °C, as suggested by ISO [23].
(3) When the heat exchange reaching the steady-state, the cooling vest is activated to cool the manikin. All data are continuously recorded until the temperature of cooling water reaches the set temperature of the manikin, which indicates that there is no cooling effect.

3 Results and Discussion

Based on the abovementioned introduction, there are three key factors in this system: volume of ice and flowrate, and ambient temperature. To be portable, the cooling vests that use ice as the cooling source usually do not equip with a lot of ice in actual use. So, we keep it consistent with the actual work and change the volume of ice from 250 ml to 650 ml in the experiments. Flowrate shows little improvement in cooling when flowrate exceeds a certain value which depends on the cooling system [21]. As a result, we change the flowrate from 500 ml/min to 1200 ml/min based on practical considerations. The range of ambient temperature from 35 to 45 °C is often used in the literatures [8,9,12].

3.1 Experiments Results. Through the above experiments, the work curves of LCGs in different conditions were obtained. Figure 4 shows a typical work duration test at 40 °C ambient temperature with a flowrate of about 1200 mL/min and 600 ml ice. The minor fluctuations of ambient temperature and the surface temperature of manikin were caused by the flaw of the imperfect temperature control. T_{air} represents the ambient temperature inside the heat chamber. T_{skin} represents the surface temperature of the manikin, which simulates the skin temperature of human body. T_{in} represents the inlet temperature of liquid-cooling circulation, while T_{out} represents the outlet temperature of liquid-cooling circulation. The ambient temperature and skin temperature were controlled by a separate proportional integral-derivative controller, respectively. Their sinusoidal fluctuations were caused by the imperfect proportional integral-derivative control. And the controller of ambient temperature response and adjust lowly, so ambient temperature showed a smaller frequency fluctuation. The inlet and outlet temperatures were directly measured by the k-type thermocouple, so they did not show any fluctuations. The work duration is defined as the time range from the startup of the cooling system to the moment when the temperature of the cooling water reaches the target manikin surface temperature [4]. In this case, the work duration time is calculated to be 82.77 min. As shown in Fig. 4, the inlet temperature will drop rapidly when the LCG is activated, which results in an excessive heat removal rate. Therefore, we define the inlet water temperature below 20 °C as an overcooling state, meaning that people will feel cold in actual work. As the ice melt, the circulating liquid turns too warm to take away the heat of the body. Similarly, we define the inlet water temperature beyond 30 °C as an overheating state, meaning that people will feel hot in actual work. According to the system, the appropriate temperature range we chose was 20–30 °C, which was calculated according to the heat balance of the human body. The calculation method was introduced in Ref. 7. To quantitatively analyze the influence of these uncomfortable states, an uncomfortable time ratio was proposed to evaluate the performance of LCGs considering thermal comfort. It is defined the proportion of uncomfortable time including overcooling and overheating in the entire working time. In the case of Fig. 4, the uncomfortable time ratio is calculated to be 57.6%. It demonstrated that thermal comfort needs to be considered in actual use,

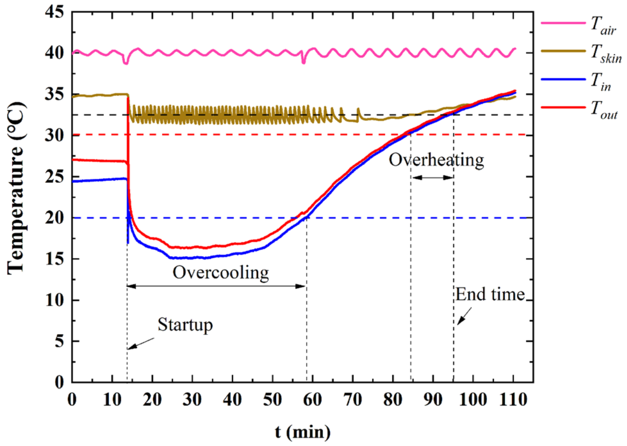

Fig. 4 A typical work duration test at 40 °C ambient temperature with a flowrate about 1200 mL/min and 600 ml ice

Table 1 The effects of flowrate and volume of ice on the work duration time and uncomfortable time ratio

Exp. no.	Ambient temperature (°C)	Flowrate (mL/min)	Volume of ice (mL)	Work duration time (min)	Uncomfortable time ratio (%)
1	40	500	250	54.58	26.3
2	40	500	450	77.73	64.4
3	40	500	650	99.67	61.9
4	40	850	250	51.95	19.5
5	40	850	450	69.87	66.2
6	40	850	650	92.47	70.1
7	40	1200	250	50.38	18.3
8	40	1200	450	63.88	65.7
9	40	1200	650	82.77	69.6

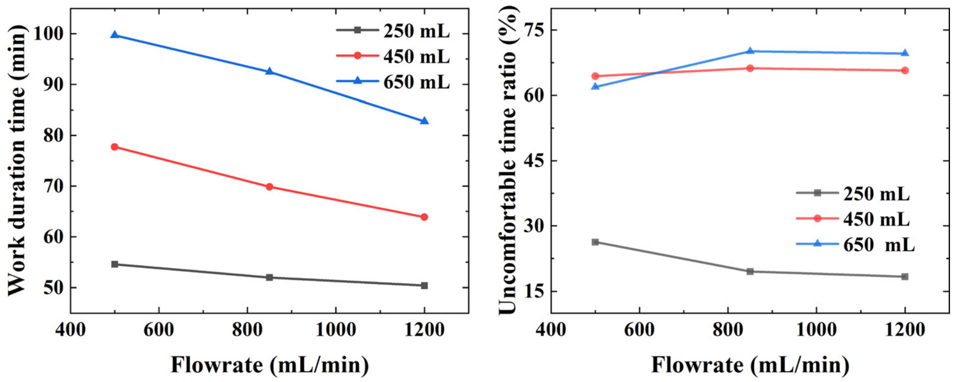

Fig. 5 the effects of flowrate and volume of ice on: (*a*) the work duration time and (*b*) uncomfortable time ratio

only concerning about maximum work duration time may not be perfect.

Next, we studied the effects of flowrate and volume of ice on the work duration time and uncomfortable time ratio at the same ambient temperature as 40 °C. The experimental data are recorded in Table 1. As shown in Fig. 5, the work duration time of liquid cooling vest is gradually shortened with the increase of the flowrate. From the trend of the three curves that represent the different volume of ice, the variation gradually increases as the volume ice increase, indicating that the volume of ice plays the most essential role in work duration time. Therefore, in order to increase the work duration time of the system, the volume of ice can be increased as much as possible with a low flowrate. However, there are different trends of uncomfortable time ratio. The uncomfortable time ratio shows light dip with increasing flowrate in a low volume of the ice, while opposite trends in a larger volume of ice. Detailed statistical analyses were carried out in the following sessions.

3.2 Orthogonal Experimental Design. Orthogonal experimental design is a popular method to deal with the test. It has been successfully applied to many fields and saving a large amount of time for acquiring the optimum level group [24,25]. The quantitative evaluation and analysis were investigated through orthogonal experiment design. In this way, the most influential factor on the performance of LCGs was finally disclosed. Here, we cared more about the effects of flowrate, inlet temperature, and ambient temperature on the performance of LCGs, based on the review of previous researches. Thus, there were three key factors in the orthogonal experimental design: the ambient temperature (factor A), flowrate (factor B), and the volume of ice (factor C). And then, the orthogonal table $L_9(3)^4$ was designed, in which a blank column was set for the error evaluation. The parametric range were chosen according to the practical operating condition. Three levels were chosen for each factor according to the preliminary experimental results. More specifically, three levels of 35, 40, and 45 °C were set for the ambient temperature. Three levels of 500, 850, and 1200 mL/min were used for the flowrate. Three levels of 250, 450, 650 mL were used for the volume of ice. By the combinations of different parameters, the performance of LCGs such as work duration time, uncomfortable time ratio can be obtained by the experiment results. Based on the investigation factors and the corresponding levels, the designed orthogonal experimental table is shown in Table 2.

3.3 Range Analysis. The aim of range analysis is to clarify the significance levels of different factors on the working performance of LCGs. The statistics of the range analysis of the effect of different factors on the uncomfortable time ratio were calculated and summarized in Table 3. The *K* value for each level of a parameter was the average of three values shown in Table 3, and the range value (*R*) for each factor was the difference between the maximal and minimal value of the three levels. Based on the results of range analysis, the significance sequence of all the investigated influencing factors was ranked as follows: factors C, A, and B. Therefore, it was concluded that the volume of ice (factor C) had the most significant influence on the uncomfortable time ratio.

3.4 Analysis of Variance. From the range analysis, it was concluded that the volume of ice had the most significant influence on the uncomfortable time ratio compared with other factors, and then, analysis of variance was also carried out. In the experimental scheme, a blank column was set in the orthogonal table for error estimation. The sum of squares of deviation (SS), degree-of-freedom (DF), and mean-squared deviation (MS) of performance of LCGs were summarized in Table 4. The *F* value of a factor is the ratio of the MS value of the factor to that of the error line. By comparing the obtained *F* value with the theoretical one of specific level and DF, the significance level can be determined for

Table 2 Design of orthogonal table $L_9(3)4$ and performance of LCGs

	Ambient temperature (°C)	Flowrate (mL/min)	Volume of ice (mL)		
Exp. no.	Factor A	Factor B	Factor C	Work duration time (min)	Uncomfortable time ratio (%)
1	35	500	250	94.78	36.3
2	35	850	450	92.18	68.3
3	35	1200	650	82.42	67.2
4	40	500	450	77.73	64.4
5	40	850	650	92.47	70.1
6	40	1200	250	50.38	18.3
7	45	500	650	84.62	68.9
8	45	850	250	45.3	15.7
9	45	1200	450	54.73	69

Table 3 Range analyses for uncomfortable time ratio

Statistics	Factor A	Factor B	Factor C
K1	57.267	56.533	23.433
K2	50.933	51.367	67.233
K3	51.2	51.5	68.733
R	6.334	5.166	45.3

Table 4 Analyses of variance for the work duration time

Statistics	SS	DF	MS	F^a
Factor A	76.987	2	38.49	0.553
Factor B	52.047	2	26.02	0.374
Factor C	3972.78	2	1986.39	28.539^b
Error	139.21	2	69.61	

[a] $F_{0.05}(3,3) = 9.28$, $F_{0.01}(3,3) = 29.5$.

[b] $P < 0.05$.

each factor [24]. As shown in Table 4, factor C showed significance (${}^bP < 0.05$) in affecting the performance of LCGs. The influence of factors A and B were not significant.

Based on the statistical analysis above, the volume of ice was found to have the most significance in affecting the performance of LCGs during the process. This case gives an example that the proposed statistical method can be successfully used in detecting the most influential factor on the performance of LCGs. Through the analysis of variance, the significance of each factor can be determined. During the process of designing the LCGs, more efforts need to be dedicated to improving the performance of LCGs considering thermal comfort.

4 Conclusion

In this paper, an uncomfortable time ratio was proposed to assess the performance of LCGs considering thermal comfort. It defined the proportion of uncomfortable time including overcooling and overheating in the entire working time. A series of tests were conducted by a modified thermal manikin method to evaluate the thermal properties. According to the analyses, the duration working time was 82.77 min, while the uncomfortable time ratio was too large, up to 57.6%. It showed that the requirement of comfort should be considered in optimizing the performance of LCGs. The influence of different parameters such as the volume of ice, flowrate, ambient temperatures on the performance of LCGs were investigated through orthogonal experimental design. The statistical analysis illustrated that the influence of the volume of ice on the uncomfortable time ratio is greater than that of flowrate and ambient temperature. In general, thermal comfort have to be judged by physiological experiment, which is complicated and troublesome. This work is aimed to provide an objective metric and simple method to evaluate the performance of LCG consider thermal comfort. It is useful for the control and design of LCGs.

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