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A Smart Temperature-Regulating Garment for Portable, High-Efficiency and Comfortable Cooling

In a conventional liquid cooling garment (LCG), overcooling of the water inlet temperature shortens the working time and worsens thermal comfort. Such problems have not been well solved so far. In this study, we propose a smart cooling garment with a developed temperature regulation system, effectively reducing un-necessary loss of power consumption and hence extending the work duration. Testing on a thermal manikin was conducted to evaluate the performance of temperature-regulating LCG. The results showed that, compared to the conventional LCG, the proposed system achieved the rapid and accurate adjustment of water temperature, improved the working time by more than 37% with the total weight barely increased, and ensured the thermal comfort of the wearers. The developed LCG opens the possibility for the smart control of the temperature, fitting for the user's preferences regarding the working time and thermal comfort sensations. [DOI: 10.1115/1.4051754]

Keywords: liquid cooling garments, temperature regulation system, duration time, thermal comfort

1 Introduction

Professionals, such as firefighters, traffic police, miners, routinely work in the hostile hot open areas for hours without cooling. They suffer from excessive heat stress, which may lead to physiological hazards such as heat cramps, heat syncope, and heat exhaustion [1,2], affecting their working performances. Traditional cooling methods, like air-conditioning and fans, are unlikely to be applied for those professionals, because they are not portable and not feasible for large open areas. In recent years, the personal cooling garment has been specially developed for those professionals [1,3,4]. Light and portable garments that can cool the micro-environment around the individual while working are regarded as one of the most practical and cost-effective cooling methods [5–10].

Liquid cooling garment (LCG) [1,11–14] is one of the common types. As shown in Fig. 1, the traditional LCG uses liquid coolant (water or ethylene glycol) as circulating fluid. The liquid coolant, initially stored in a reservoir, is driven by external power (such as a battery-powered micropump) to circulate inside the tubing network embedded inside the basic garment. For each cycle, the liquid coolant brings the heat from the physical body and then exchanges it with the heat sink (i.e., ice packs) inside the reservoir. In the early stage of working, the liquid coolant gets chilled with a dramatic temperature drop, excessively consuming the cold energy. Thus, conventional LCGs suffer from low cooling efficiency (1∼2 h/kg ice [6,11,15]), resulting in a short working time. One possible solution to extend the working time is to pack a larger cooling source, which however leads to weight issue. Therefore, it is important to develop an LCG with better cooling efficiency. Additionally, overcooling in the early use stage may introduce physical discomfort issues related to body thermoregulation [16,17]. Some efforts [14,18] have been made to tackle these discomfort issues. However, the issue of low cooling efficiency has not yet been considered.

In this study, a smart cooling garment with a temperature regulation system was developed. The liquid coolant inlet temperature of the garment was modulated to be a stable value according to the wearer's needs by a chip-controlled temperature regulation system. It saved the cold energy within the whole working period, extending the working time. Experiments showed that in contrast to conventional LCG, the smart system enhanced the cooling efficiency by more than 37% with the total weight barely increased, and ensured physical comfort as well.

2 Designs and Experiments

The smart cooling garment, which is illustrated in Fig. 2, consisted of a vest, micropump, portable power supply, and temperature regulation system. The details of the vest are described in the Supplemental Material on the ASME Digital Collection. The micropump was self-designed with only 150 g, especially suitable for various portable applications. Its design and manufacturing have been described in detail elsewhere [19,20]. The portable power supply is a lithium battery (24 V, 3500 mAh).

The temperature regulation system is the key element of the designed smart cooling garment. It has the function of automatically temperature-regulating with the aid of on-line monitoring. As shown in the right side of Fig. 2, it consists of a reservoir, a sturdy plastic container, a check valve, a three-way valve, a

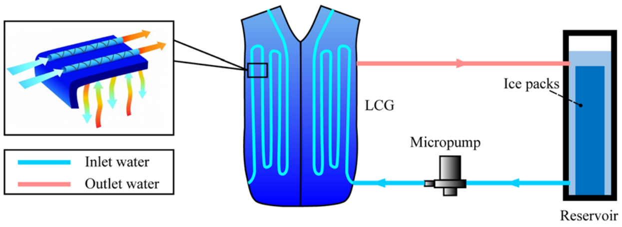

Fig. 1 Schematic diagram of typic LCG system

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Contributed by the Electronic and Photonic Packaging Division of ASME for publication in the JOURNAL OF ELECTRONIC PACKAGING. Manuscript received April 16, 2021; final manuscript received July 8, 2021; published online September 15, 2021. Assoc. Editor: Ercan Dede.

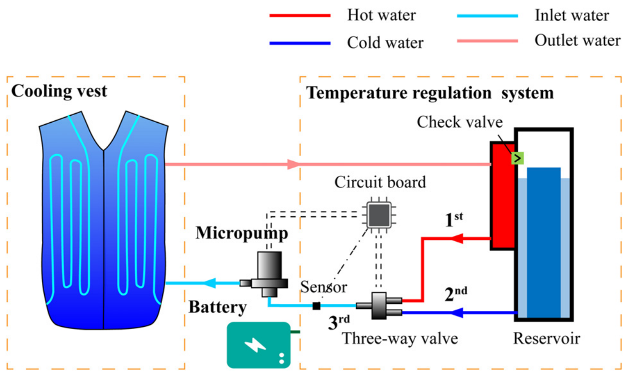

Fig. 2 Schematic diagram of the smart cooling garment

sensor, and a circuit board. The reservoir initially holds 400 g weight, 0 °C ice, and the plastic container attached to the reservoir holds 400 g, 25 °C water. They are connected by a check valve allowing water to flow unidirectionally from the plastic container to the reservoir. Heat exchange between the surfaces of the reservoir and the plastic container is suppressed by the thermal insulation treatment at the surfaces. When water circulates, the outlet hot water flows back to the plastic container and then directs to the first (indicated in Fig. 2) way of the three-way valve, while another branch of water from the reservoir directs to the second way of the valve. Then, the two branches of water allow the modulation of inlet water temperature by a circuit to control the flow rate of each branch (see details in the next paragraph). This is different from the conventional LCG, in which only one branch of water was used, as shown in Fig. 1. Note that, during work, the water in the plastic container gets gradually warmer due to the continuous heat accumulation. So, it will push into the reservoir through the check valve due to the increased fluid pressure. This avoids over-heat in the plastic container. Setting the goal temperature of inlet water with a fixed value (generally speaking, the suitable temperature range is between 15 and 25 °C [21]), the excessive cooling capacity is avoided to extend the working time, and excessively low temperatures are avoided as well, thereby improving thermal comfort.

Automatic control of the inlet temperature is achieved by the circuit board (chip ATmega328P), the three-way valve, and the digital temperature sensor (DS18B20) placed after the third way of the three-way valve. The on-line temperature was constantly adjusted based on the feedback signal from the sensor until the temperature error is within ±0.5 °C. The closed-loop control system is illustrated in Fig. 3. When measuring on-line temperature, Tw was higher than the setting temperature T_{set}, the cold water valve (first) was enlarged, and the hot water valve (second) was narrowed by the electronically controlled three-way valve. The process will be reversed when $T_{\text{w}} < T_{\text{set}}$. The above control process was based on proportional-integral-derivative (PID) control, with the details seen in the Supplemental Material on the ASME Digital Collection. The digital thermometer DS18B20 and PID control ensure the system high stability and sensitivity. Note that the miniaturized electronically controlled three-way valve was self-designed and manufactured with a compact size and light weight (only 120.6 g), which is beneficial for a portable smart system. An alternative way is to use two commercial two-way valves (one weight more than 300 g), which however, will result in complications and excessive weight for the garment system. Moreover, the system is able to connect smartphones via Bluetooth wireless links, enabling a smart control by the wearer.

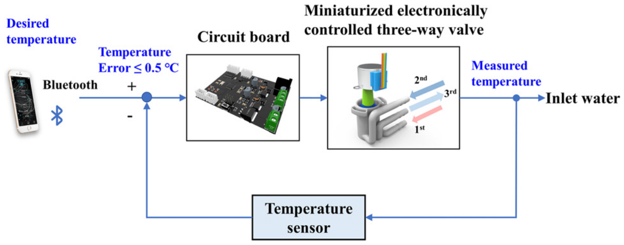

Fig. 3 The closed-loop control system diagram

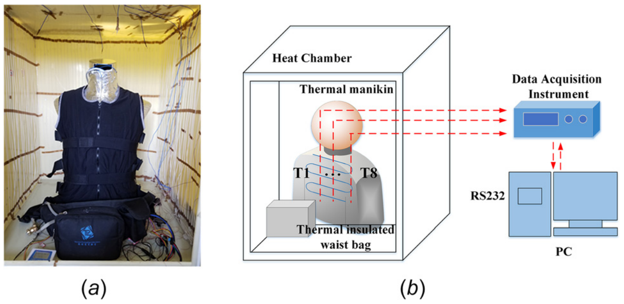

Fig. 4 (*a*) A photo of the overall performance experimental setup and (*b*) the schematic of the test system

The prototype garment was manufactured to verify the cooling effect. In previous reports, the prototype garments were usually bulky and thereby difficult to use in practical applications (for example, 5.31 kg [7], 3.4 kg [8]). In this work, the prototype was only ∼2.5 kg due to the miniaturized cooling unit. Therefore, it was more portable and beneficial for a variety of occupations. For comparison, a garment without temperature regulation system was manufactured. It weighed 2.3 kg (equipping with an equal amount of ice 400 g). An experimental setup, shown in Fig. 4, was developed to verify the garment's performance. Testing was performed on a modified thermal manikin [11] wearing the prototype garment at an ambient temperature of 40 °C provided by a controlled environment chamber. The thermal manikin was electrically uniformly heated. The surface temperature of the manikin was set to be 33 °C as suggested by [11]. Eight thermocouples from T1 to T8 were deployed in pairs on the surface of the thermal manikin. The dotted red lines in Fig. 4(*b*) represent the different data acquisition paths. The inlet and outlet temperature of the cooling vest were recorded with another two thermocouples. Four thermocouples were located inside the heating chamber (1/2 the height of the space) to record the ambient temperature. All thermocouples were Type K (TT-K-30, accuracy 0.4%, Omega, Norwalk, CT).

When the whole experimental system reached steady-state after 30 min, the cooling vest was activated to cool the manikin. Two sets of experiments were conducted. One was to verify the capability of temperature-regulating by monitoring the inlet

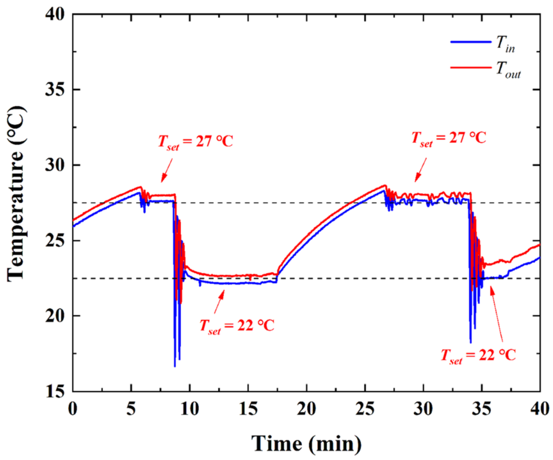

Fig. 5 The regulating effect of water inlet temperature in this system

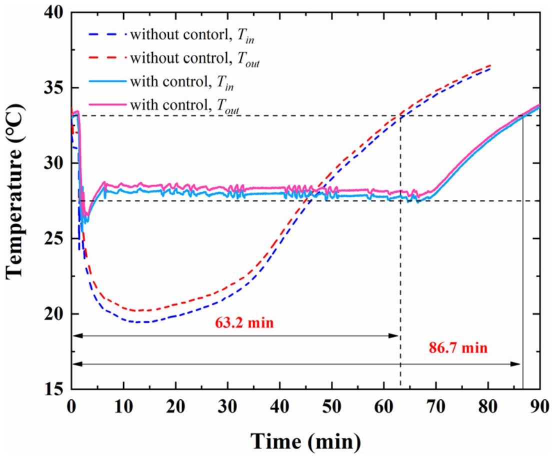

Fig. 6 Comparison of work duration tests with/without control

temperature response while shifting the inlet target temperature. The second was to examine the working time by recording the inlet temperature increase until it reached the set point value for the manikin (33 °C). A second set of experiment was also conducted for the conventional LCG for comparison.

3 Results and Discussion

Initially, the capability of the temperature regulating system was verified. Figure 5 shows the measured water inlet temperature (T_{in}) and outlet temperature (T_{out}). Some oscillations of water temperature were due to the impact of water flow during the regulation process. Initially, the flow rate of room temperature water was 1120 mL/min, while the flow rate of cold water was 0 mL/min. The water inlet temperature (T_{in}) got gradually warmer, as it absorbed heat from the manikin and hot environment. After 5 min, we set 27 °C as the target water inlet temperature. It can be seen that the water inlet temperature remained constant once the desired temperature was set. After the 5-minutes stable period, we set a lower water temperature (22 °C) as the target. The adjustment of temperature is also very accurate and rapid within 1 min due to the PID control. The procedures were repeated in subsequent experiments. The results showed that the precision of temperature control is ±0.5 °C. It proved that the system has a high stability and sensitivity.

Figure 6 shows testing results for the temperature regulating LCG, as well as results from the conventional LCG for comparison. For the conventional LCG system, the temperature dropped dramatically by ∼15 °C within 10 min in the early stage. And then, the temperature rose gradually for about 20 min in the middle stage to be thermal equilibrated. After 35 min of work, the temperature increased much faster due to the consumption of the cold source. Finally, the inlet temperature reached the set point temperature of the manikin (33 °C). While for the temperature-regulating LCG, in the early stage, the inlet temperature approached the target temperature shortly (within 7 min). So, at the early stage of working, the water inlet temperature of the LCG remained higher to avoid excessively consuming cooling capacity, better than the conventional LCG. After that, it stayed constant for almost 65 min. Afterward, the inlet temperature gradually

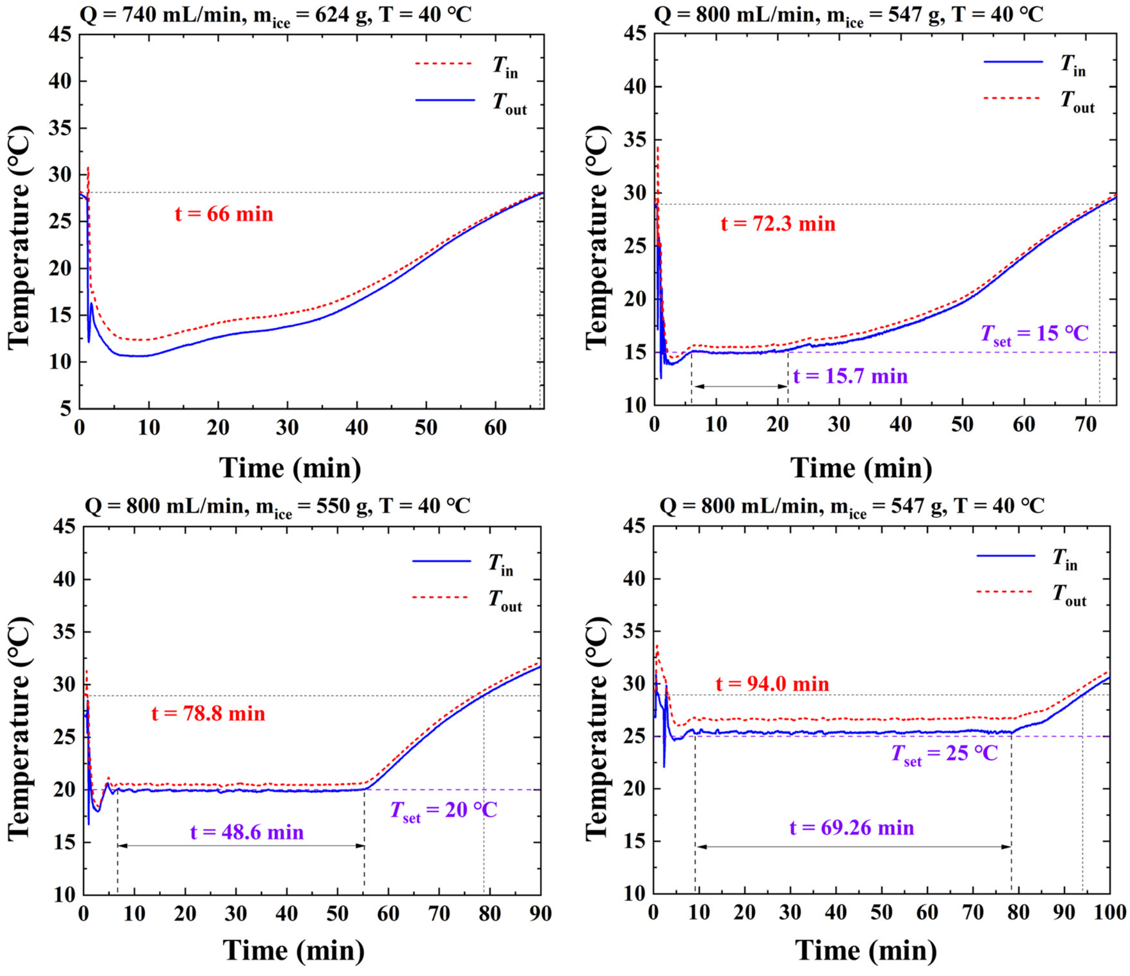

Fig. 7 Work duration tests with different water inlet temperature

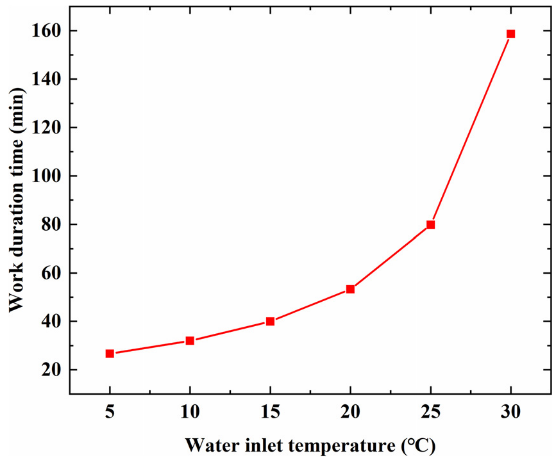

Fig. 8 The work duration time of LCG varies with water inlet temperature

increased to the manikin temperature and finally to the environment temperature due to the depletion of the cold source. The working duration time is set as the time between the starting time, and the time when water inlet temperature Tin reaches 33 °C, the surface temperature of the manikin. A maximum work duration time of 63.2 min was obtained for the conventional LCG, while a 37.2% (86.7 min) increase in work duration time was achieved for the temperature-regulating LCG. In addition, from the testing results, it can be speculated that a person wearing a conventional LCG may suffer from extreme coldness ($<$20 °C) for about 20 min. It has been reported that the low temperature of coolant (below 15 °C) can be harmful for the user: overcooling of cold water at the work onset may produce vasoconstriction and decreased heat extraction with the chilly sensation which persists long after a more reasonable cooling level is resumed [1]. This discomfort was not seen in the temperature regulating LCG, due to its water temperature control [21].

Figure 7 shows the influences of different water inlet temperatures on the work duration tests under the high-temperature environment of 40 °C. It can be seen that the working time of the system without water temperature control was only 66 min. When the water temperature control target was set at 15 °C, 20 °C, and 25 °C, the working time of the system was extended to 72.3 min, 78.8 min, 94 min, respectively. Meanwhile, the target temperature was maintained for 15.7 min, 48.6 min, and 69.26 min, respectively. By increasing the set point temperature of the LCG, the overall duration time was obviously enhanced. The prolongation of working time was due to the full utilization of the cooling capacity of the cooling source under the control of water temperature, which effectively reducing un-necessary consumption of the phase change energy storage.

In addition, we created a rudimentary model to predict the theoretical duration of the LCG working time and investigate the effect of the target water temperature on working time. The removal rate of the LCG stays constant under the same working conditions due to a constant water inlet temperature, and the cooling energy provided by ice packs is fixed. So, we can calculate the theoretical working time using the following equation:

$$t = \frac{m\Delta H}{Q_w} \tag{1}$$

where m is the mass of ice and ΔH is the latent heat of ice, 335 kJ/kg.

Through the analysis of heat transfer in the LCG system, the heat flux Q_w, which indicates the heat dissipating capacity of LCG, is calculated by the following equation [11]:

$$Q_w = q_m c_p (T_\text{out} - T_\text{in}) \tag{2}$$

Where q_m is the mass flow rate of the circulating system, c_p is the specific heat capacity of water (4200 J/(kg·K)), Tin and Tout are the inlet and outlet temperature of the tubing network, respectively. The detail derivation of heat dissipating model is given in the Supplemental Material on the ASME Digital Collection. In Fig. 8, the work duration time is plotted as a function of water inlet temperature. The working time shows a nonlinear increase with T_in. Especially when $T_\text{in} > 20$ °C, the working time is dramatically improved. This result provides guidance for users to choose the target temperature to fitting individual preferences regarding the working time and thermal comfort sensations.

4 Conclusion

A smart cooling garment with temperature regulation system was developed. The water inlet temperature was modulated to avoid overcooling and excessive cold energy consumption, effectively enabling the longer cooling periods, better thermoregulation capability and excellent thermal comfort for the cooling garment. Testing using a thermal manikin was conducted to evaluate the performance of temperature-regulating LCG. In contrast to a conventional LCG, the smart system improved the working time by more than 37% with the total weight barely increased and ensured the thermal comfort of the wearers. The promoted temperature regulation system opens the possibility for the smart control of temperature in the cooling garment, fitting individual preferences regarding the working time and thermal comfort sensations.

Acknowledgment

Special thank also goes to Dr. Chao Yuan for valuable discussion.

Funding Data

- National Natural Science Foundation of China (Grant Nos. 51706079 and 51625601; Funder ID: 10.13039/501100001809).

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