Journal of Thermal Biology 49-50 (2015) 47–54

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Design and testing of a liquid cooled garment for hot environments

Tinghui Guo, Bofeng Shang, Bin Duan, Xiaobing Luo*

School of Energy and Power Engineering, Huazhong University of Science and Technology, 430074 Wuhan, China

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form
16 January 2015
Accepted 16 January 2015
Available online 30 January 2015

Keywords:
Liquid cooled garment
Heat transfer model
Performance test
Heat stress

ABSTRACT

Liquid cooled garments (LCGs) are considered a viable method to protect individuals from hyperthermia and heat-related illness when working in thermally stressful environments. While the concept of LCGs was proposed over 50 years ago, the design and testing of these systems is undeveloped and stands in need of further study. In this study, a detailed heat transfer model of LCG in a hot environment was built to analyze the effects of different factors on the LCG performance, and to identify the main limitations to achieve maximum performance. An LCG prototype was designed and fabricated. Series of tests were done by a modified thermal manikin method to validate the heat transfer model and to evaluate the thermal properties. Both experimental and predicted results show that the heat flux components match the heat balance equation with an error of less than 10% at different flowrate. Thermal resistance analysis also manifests that the thermal resistance between the cooling water and the ambient (R_2) is more sensitive to the flowrate than to the one between the skin surface and the cooling water (R_1). When the flowrate increased from 225 to 544 mL/min, R_2 decreased from 0.5 to 0.3 °C m^2/W while R_1 almost remained constant. A specific duration time was proposed to assess the durability and an optimized value of 1.68 h/kg was found according to the heat transfer model. The present heat transfer model and specific duration time concept could be used to optimize and evaluate this kind of LCG respectively.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

A stable core body temperature is essential for maintaining optimal functions of the human body. However, when working in extreme hot and stressful environments, it is often arduous to achieve this without extra cooling (Angelo, 2009). Examples of such extreme situations can be found in many working places, such as mines, foundries, construction sites, boiler factories and inside military vehicles. In these environments, excessive heat can lead to failure of the human thermoregulatory system, resulting in heat-related illness such as heat cramps, heat syncope, heat exhaustion and heat stroke (Koppe et al., 2004; Altman et al., 2012).

To reduce the health risk caused by these hazard heat environments, microclimate cooling technologies have been developed to enhance heat exchange between the human body and the environment. Cooling garments have been proved to be one of the most promising technologies. Since the first prototype proposed for crewman by Burton and Collier at the Royal Aircraft Establishment in 1960s (Burton and Collier, 1964), liquid cooled garments (LCG) have been widely adopted as an effective cooling technology with advantages of higher cooling efficiency, reliability and adjustable capacity, compared to other microclimate cooling techniques, such as air cooling and phase change cooling (Nunneley, 1970).

Prototypes of LCG have been built for a variety of applications. McLellan and Selkirk (2006) gave detailed description of an LCG used for firefighters to manage the heat stress. 70% of the cooling was achieved within the first 10 min, even though the prototype could not last for more than 20 min in practical usage. Beenakker et al. (2001) used LCGs to treat multiple sclerosis patients. Experimental results showed that the active cooling garment did relieve fatigue and improve muscle strength and postural stability. LCG technology is crucial in the field of aerospace medicine (Webbon et al., 1981; White and Roth, 1979; Chambers, 1970; Nunneley et al., 1971; Light and Norman, 1980). LCGs are still the main cooling technology to remove heat stress for astronauts (Miller et al., 2011; Nyberg et al., 2001; Perez et al., 2003; Qiu et al., 2001; Campbell et al., 1998). However, it is notable that the specific design of LCG for spacesuit is often not practical in other fields.

Based on the review of the abovementioned researches, we conclude that the design of LCG is still immature and most prototypes are made based on experimental experience, even though the concept of LCG was proposed half a century ago. The design of an LCG involves principles of physiology, bio-medical, engineering and ergonomics. It is a challenge to design a compact and portable LCG which has high cooling efficiency to maintain the thermal

---

* Corresponding author. Fax: +86 2787540724.
E-mail address: Luoxb@hust.edu.cn (X. Luo).

http://dx.doi.org/10.1016/j.jtherbio.2015.01.003
0306-4565/© 2015 Elsevier Ltd. All rights reserved.

comfort while minimizing the cost of coolant and power requirements. Since many factors need to be considered in the design, a theoretical model that takes all of the factors into account to analyze the performance of LCG is desirable.

In this paper, a detailed theoretical model of heat transfer from the human skin to the environment through the LCG was built. A prototype of a water cooled garment that was optimized based on the model was fabricated. A series of performance tests were conducted using a modified thermal manikin method to validate the heat transfer model. It was found that the errors between the experimental results and the calculated results were less than 10%. A maximum work duration time of 3.36 h for the LCG was obtained at 45 °C ambient temperature when the flowrate was 224.5 mL/min and the max cooling rate was 243.2 W/m^2.

2. Principles of LCG

Fig. 1 shows the schematic of a liquid cooled garment system. The basic working mechanism of this LCG is that the cold liquid, driven by the micropump, flows through the tubing network embedded in basic garment and takes away the heat. After dissipating the extra heat produced by the human body or from the hazard heat environment, the cold liquid turns warm and is then circulated to the liquid reservoir and re-cooled by the ice pack. The process repeats until the ice pack melts and the whole liquid system becomes warm. The basic garment is usually made of cotton fabrics with high elasticity, thus the tubes can firmly contact with the human body.

3. Thermal analysis and system design

To maintain a stable body temperature, the heat loss needs to balance the heat production and the heat gain. Otherwise, the heat content of the body will change, which will cause core body temperature fluctuating. Metabolic heat produced inside the body either provides the energy for working or ends as heat. The heat storage can be written as (Havenith, 2002)

$$Q_s = (Q_m - W) - (Q_{conv} + Q_{cond} + Q_r + Q_{eva} + Q_{res}) \quad (1)$$

where Q_s is the heat storage of the body, Q_m is the metabolic heat production, W is the mechanical work power, Q_{conv} is the heat loss due to convection, Q_{cond} is the heat loss due to conduction, Q_r is the heat loss due to radiation, Q_{eva} is the heat loss due to sweat evaporation, and Q_{res} is the heat loss due to respiration.

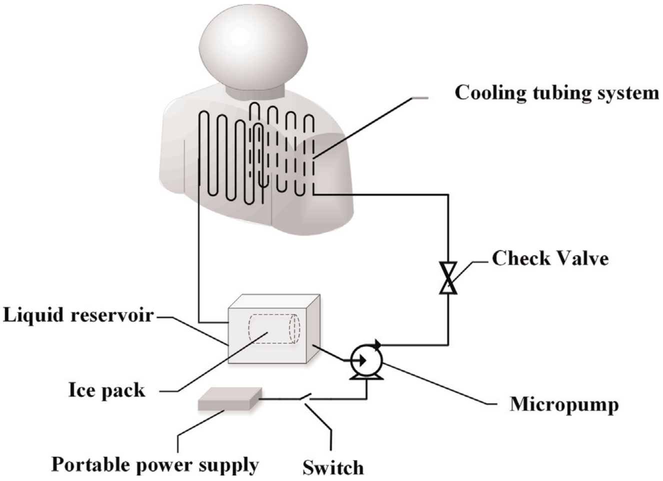

Fig. 1. The schematic of a liquid cooling garment system. The micropump drives the cold water flowing through the tubing system to exchange heat with human body. The water then goes back to the liquid reservoir and gets chilled by the icepack, and that cycle repeats. Switch and valve are used to control the system.

It should be noted that the heat loss components in Eq. (1) can be neglected, which means that human body actually gains heat. For instance, when the ambient temperature is higher than the skin, the radiation heat flux Q_r from the environment actually enters the human body. This formula can be modified to apply to the situation where the LCG is used. The effective mechanical work power is small and can be neglected in most cases. When wearing an LCG, the clothes is tightly close to the skin, acting as a barrier for the sweat evaporation. Moreover, the sweat production can be decreased or even stopped due to the cooling effect of LCG on the body. In most of the cases, the heat loss by respiration and conduction would be less than 5% and 1%, respectively. Therefore, this part of heat loss is also negligible for engineering analysis (Koppe et al., 2004). Based on the analysis above, following hypotheses were proposed to simplify the heat transfer model:

1. The heat transfer is steady-state.
2. Heat transfer occurring in the cooling garment and on the skin are only along the normal direction.
3. The cooling garment and the human skin are treated as homogeneous plate.
4. The effect of the air layer trapped between the LCG and the human skin is neglected, and the temperature of skin is regarded as the same with the temperature of the inner side of the basic garment.
5. The effects of sweat evaporation and respiration are ignored.
6. The velocity of the ambient air is zero, meaning that the type of convection is natural convection.

Thus the heat balance equation can be written as

$$Q_w = Q_{conv} + Q_r + Q_m \quad (2)$$

where Q_w is the total heat taken away by the cooling water of the LCG. Based on the assumptions that the whole human skin and the cooling garment are homogeneous and the heat transfer is steady-state, the heat flux form of Eq. (2) can be given as

$$q_w = q_{conv} + q_r + q_m \quad (3)$$

Fig. 2 shows the heat transfer processes that occurring among the human skin, LCG and the ambient environment in hot environments. The heat flux q_w, which indicates the heat removal rate of LCG, is calculated from the measurement of inlet and outlet temperature as well as the flow rate:

$$q_w = \dot{m}c_p(T_{out} - T_{in})/A_{cl} \quad (4)$$

where $\dot{m}$ is the mass flow rate of the circulating system in kg/s, c_p is the specific heat capacity of water (4.2 kJ/(kg K)), T_{out} and T_{in} are the outlet and inlet temperature of the tubing network, respectively, A_{cl} is the effective cooling area of the LCG. R_{conv} and R_r are the convective and radiative thermal resistance between the LCG and the ambient environment. The thermal resistance between the human skin and the cooling garment R_s can be calculated as follow:

$$R_s = \frac{T_s - T_{cl}}{q_m} \quad (5)$$

where T_s and T_{cl} are the temperature of the human skin and the clothes, respectively.

The heat flux of the heat loss by the convection q_{conv} is given by

$$q_{conv} = h_c f_{cl}(T_{cl} - T_a) \quad (6)$$

where T_a is the ambient temperature; f_{cl} is the clothing area factor,

Download English Version:

https://daneshyari.com/en/article/2842757

Download Persian Version:

https://daneshyari.com/article/2842757

Daneshyari.com