A HEAT DISSIPATING MODEL FOR WATER COOLING GARMENTS

by

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A water cooling garment is a functional clothing used to dissipate human body's redundant energy in extravehicular environment or other hot environment. Its heat dissipating property greatly affects body's heat balance. In this paper, a heat dissipating model for the water cooling garment is established and verified experimentally using the experimental thermal-manikin.

Key words: *heat dissipating model, water cooling garment, verification experiment*

Introduction

Lots of occupations expose workers to hot environmental settings, such as extravehicular activities, steelmaking workshop and so on, which greatly affects worker's performance and productivity, and even threatens the life of worker [1]. So many cooling technologies have been employed to manage heat stress in daily activities. A water cooling garment is a kind of personal cooling technologies, which is designed to cool the immediate surroundings of the wearer. In scenarios where impermeable protective clothing is required, the water cooling garment also serves as the most effectively means of heat stress management [2, 3]. The water cooling garment is usually combined with cooling source to compose a complete refrigeration system, and to dissipate human body's metabolic heat and maintain dynamic heat balance [4]. So the heat dissipating property of water cooling garment is the key index in designing and evaluating it. There have been many researches focusing on water cooling garment's study, including creating innovative materials, developing a more powerful cooling source. But there has been less study about water cooling garment's heat dissipating model, which always regards water cooling garment as a part of spacesuit and studies spacesuit's heat transfer [5]. So in this paper, water cooling garment is considered as the research object, and the heat transfer of water cooling garment is studied.

Water cooling garment used in this study is composed of basic clothing, heat dissipating tube and water exchange connecting pipe. Considering that thermal property of fabric is of major concern for comfort of cloth [6], basic clothing is made of flame retardant cotton/elastic fiber blended fabric, which has better thermal comfort property and flame retardancy [7]. Based on apparel pattern-making theory [8], basic clothing adopts tights structure to ensure better heat exchange between water cooling garment and human body. Heat dissipating tube is the core part of water cooling garment, cooling water exchanges heat with human body

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during flowing in heat dissipating tube. Heat dissipating tube is seamed in basic clothing and covers all parts of human body except hand, foot and lower leg. Water exchange connecting pipe has intake pipe and outlet pipe, which connect with heat dissipating pipe to compose a complete circulating pipeline.

The research of water cooling garment always applies thermal manikin to replace real body, which can evaluate garment's heat dissipating performance objectively [9]. This paper investigates the heat dissipating property of water cooling garment based on a copper thermal manikin. Water cooling garment's heat dissipating model is established based on heat transfer theory, and then verification experiments are performed, which indicates that the model has a high accuracy.

Heat dissipating model of water cooling garment

Hypothesis of model

Heat transfer of water cooling garment with human (or thermal manikin) is very complicated, which includes the following heat flow: heat conduction flow from human body to underwear, heat conduction flow from underwear to garment's tube wall, mass transfer flow from human to garment, human's radiant heat flow, convective heat flow between outer surface of tube wall and environment, and so on. So, to satisfy practical engineering application and simplify analysis, the following hypotheses were proposed in establishment of water cooling garment's heat dissipating model based on thermal manikin.

– Water cooling garment's heat transfer is analyzed only on steady state, which simplifies the analyzing and decreases the actual calculation greatly.
– Heat transfer of basic clothing in water cooling garment and the heat transfer of thermal manikin are along their normal direction.
– The radius of tube in water cooling garment is much smaller than curvature radius of all sections in thermal manikin, so water cooling garment's basic clothing and thermal manikin are all treated as homogeneous plate compared with water cooling garment's tube.
– Underwear is cotton or cotton/flax blended knitting-fabrics, which has little influence on heat transfer between water cooling garment and thermal manikin. So the underwear is neglected in analysis.
– To simplify heat transfer analysis, water cooling garment is just in outside environment. In addition, the manikin used in this study is a dry copper manikin, so sensible heat transfer is considered only.

Heat dissipating model based on thermal manikin

Taking water cooling garment as research object, its heat transfer is cooling water's heat exchange with thermal manikin and with air layer by convection and conduction. The heat circuit diagram is shown in fig. 1.

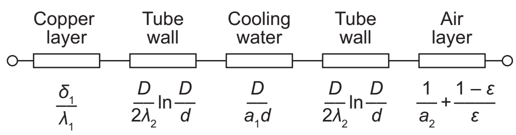

Figure 1. Water cooling garment's heat circuit diagram

Take micro-unit d*l* in water cooling garment's tube, and its temperature variable quantity is d*t*. According to heat transfer theory, the heat d*q* taken away by cooling water in micro-unit d*l* is:

$$\mathrm{d}q = \frac{\pi}{4} d^2 u \rho C_\mathrm{p} \mathrm{d}t \tag{1}$$

where d [m] is the inner radius of tube, u [ms^{-1}] – the water velocity, ρ [kgm^{-3}] – the water density, and C_p [Jkg^{-1}°C^{-1}] – the water specific heat at constant pressure.

According to fig. 1, the heat exchange resistance between water cooling garment and thermal manikin includes copper layer's heat conductive resistance, tube wall's heat conductive resistance, convective resistance between cooling water and tube wall. So the heat dissipating quantity (dq_1) between micro-unit dl in water cooling garment and thermal manikin is:

$$\mathrm{d}q_1 = \pi D\mu \mathrm{d}l \frac{1}{\dfrac{\delta_1}{\lambda_1} + \dfrac{D}{2\lambda_2}\ln\dfrac{D}{d} + \dfrac{D}{a_1 d}}(t_\mathrm{w} - t) \tag{2}$$

where D [m] is the external diameter of tube, μ – the effective area ratio of water cooling garment covering thermal manikin, δ_1 [m] – the thickness of copper layer, λ_1 [Wm^{-1}°C^{-1}] – the thermal conductivity of copper layer, λ_2 [Wm^{-1}°C^{-1}] – the thermal conductivity of tube wall, a_1 [Wm^{-1}°C^{-1}] – the convective heat transfer coefficient between cooling water and tube wall, t_w [°C] – the interface temperature of copper layer and tube wall, and t [°C] – the temperature of cooling water. Let:

$$\frac{1}{\dfrac{\delta_1}{\lambda_1} + \dfrac{D}{2\lambda_2}\ln\dfrac{D}{d} + \dfrac{D}{a_1 d}} = K_1$$

then the eq. (2) can be simplified to the equation:

$$\mathrm{d}q_1 = \pi D\mu K_1(t_\mathrm{w} - t)\mathrm{d}l \tag{3}$$

The heat exchange resistance between water cooling garment and air layer includes convective resistance between cooling water and tube wall, tube wall's heat conductive resistance, convective and radiative resistance between tube wall and air layer. So the heat dissipating quantity (dq_2) between micro-unit dl in water cooling garment and air layer is:

$$\mathrm{d}q_2 = \pi D(1-\mu)\frac{1}{\dfrac{D}{a_1 d} + \dfrac{D}{2\lambda_2}\ln\dfrac{D}{d} + \dfrac{1}{a_2} + \dfrac{1-\varepsilon}{\varepsilon}}(t_\mathrm{f} - t)\mathrm{d}l \tag{4}$$

where a_2 [Wm^{-1}°C^{-1}] is the convective heat transfer coefficient between tube wall and air layer, ε – the blackness of tube wall, and t_f [°C] – the temperature of air layer. Let:

$$\frac{1}{\dfrac{D}{a_1 d} + \dfrac{D}{2\lambda_2}\ln\dfrac{D}{d} + \dfrac{1}{a_2} + \dfrac{1-\varepsilon}{\varepsilon}} = K_2$$

then the eq. (4) can be simplified to the equation:

$$\mathrm{d}q_2 = \pi D(1-\mu)K_2(t_\mathrm{f} - t)\mathrm{d}l \tag{5}$$

According to the first law of thermodynamics, we get:

$$\mathrm{d}q = \mathrm{d}q_1 + \mathrm{d}q_2 \tag{6}$$

Put eq. (1), (3), and (5) into eq. (6), and we get:

$$\frac{\pi}{4}d^2 u\rho C_\mathrm{p}\mathrm{d}t = \pi D\mu K_1(t_\mathrm{w} - t)\mathrm{d}l + \pi D(1-\mu)K_2(t_\mathrm{f} - t)\mathrm{d}l \tag{7}$$

Separate the variables, and make integral, we get:

$$\int_0^l \mathrm{d}l = \int_{t_{\text{in}}}^{t} \frac{d^2 u\rho C_\text{p}}{4D} \frac{1}{(\mu K_1 t_\text{w} + K_2 t_\text{f} - \mu K_2 t_\text{f}) + (\mu K_2 - \mu K_1 - K_2)t} \mathrm{d}t \tag{8}$$

where t_{in} [°C] is inlet temperature of cooling water.

So the relationship of cooling water's temperature t varied with tube length l is:

$$t = \frac{1}{\mu K_1 + (1-\mu)K_2} \cdot \left\{ \mu K_1 t_\text{w} + (1-\mu)K_2 t_\text{f} - [\mu K_1 (t_\text{w} - t_{\text{in}}) + (1-\mu)K_2(t_\text{f} - t_{\text{in}})] \mathrm{e}^{\frac{-4Dl}{d^2 u\rho C_\text{p}}[\mu K_1 + (1-\mu)K_2]} \right\} \tag{9}$$

Put eq. (9) into eq. (3) and make integral, we get the heat dissipating capacity between water cooling garment and thermal manikin:

$$q_1 = \int_0^L \pi D\mu K_1 \left\{ t_\text{w} - \frac{1}{\mu K_1 + (1-\mu)K_2} \cdot \left[\mu K_1 t_\text{w} + (1-\mu)K_2 t_\text{f} - [\mu K_1 (t_\text{w} - t_{\text{in}}) + (1-\mu)K_2(t_\text{f} - t_{\text{in}})] \mathrm{e}^{\frac{-4Dl}{d^2 u\rho C_\text{p}}[\mu K_1 + (1-\mu)K_2]} \right] \right\} \mathrm{d}l =$$

$$= \frac{\pi D\mu K_1 L(1-\mu)K_2(t_\text{w} - t_\text{f})}{\mu K_1 + (1-\mu)K_2} + \frac{\pi d^2 u\rho C_\text{p} \mu K_1 [\mu K_1(t_\text{w} - t_{\text{in}}) + (1-\mu)K_2(t_\text{f} - t_{\text{in}})]}{4[\mu K_1 + (1-\mu)K_2]^2} \left[1 - \mathrm{e}^{\frac{-4DL}{d^2 u\rho C_\text{p}}[\mu K_1 + (1-\mu)K_2]} \right] \tag{10}$$

where L [m] is tube's total length.

Put eq. (9) into eq. (5) and make integral, we get the heat dissipating capacity between water cooling garment and air layer:

$$q_2 = \int_0^L \pi D(1-\mu)K_2 \left\{ t_\text{f} - \frac{1}{\mu K_1 + (1-\mu)K_2} \cdot \left[\mu K_1 t_\text{w} + (1-\mu)K_2 t_\text{f} - [\mu K_1 (t_\text{w} - t_{\text{in}}) + (1-\mu)K_2(t_\text{f} - t_{\text{in}})] \mathrm{e}^{\frac{-4Dl}{d^2 u\rho C_\text{p}}[\mu K_1 + (1-\mu)K_2]} \right] \right\} \mathrm{d}l =$$

$$= \frac{\pi D\mu K_1 L(1-\mu)K_2(t_\text{f} - t_\text{w})}{\mu K_1 + (1-\mu)K_2} + \frac{\pi d^2 u\rho C_\text{p} (1-\mu)K_2 [\mu K_1(t_\text{w} - t_{\text{in}}) + (1-\mu)K_2(t_\text{f} - t_{\text{in}})]}{4[\mu K_1 + (1-\mu)K_2]^2} \left[1 - \mathrm{e}^{\frac{-4DL}{d^2 u\rho C_\text{p}}[\mu K_1 + (1-\mu)K_2]} \right] \tag{11}$$

So, water cooling garment's total heat dissipating capacity q is:

$$q = q_1 + q_2 = \frac{\pi d^2 u\rho C_p[\mu K_1(t_w - t_{in}) + (1-\mu)K_2(t_f - t_{in})]}{4[\mu K_1 + (1-\mu)K_2]}\left[1 - e^{\frac{-4DL}{d^2 u\rho C_p}[\mu K_1 + (1-\mu)K_2]}\right] \tag{12}$$

Water cooling garment's total heat dissipating efficiency η is:

$$\eta = \frac{q_1}{q}\cdot 100\% \tag{13}$$

Experimental verification

To verify the accuracy of above heat dissipating model, the verification experiments were performed in climate chamber by thermal manikin wearing water cooling garment. The environmental condition of climate chamber was 21 °C, 60% RH, and the wind speed was less than 0.1 m/s. Set thermal manikin's surface temperature was 33, 35, and 37 °C, respectively, which were close to the surface temperature of human body, and then adjust water cooling garment's different inlet temperature (t_{in}), and finally record water cooling garment's outlet temperature (t_{out}) when the experiments reached stable state. Water cooling garment's heat dissipating capacity q can be calculated by the formula:

$$q = \frac{\pi}{4} d^2 u\rho C_p (t_{out} - t_{in}) \tag{14}$$

Heat dissipating capacity's experimental value was compared with modeling value, and the comparative diagram was shown in fig. 2. We can see that the modeling value is fitting well with the experimental value. By calculation, the maximum relative deviation is 2.034%, which approved heat dissipating model's higher accuracy.

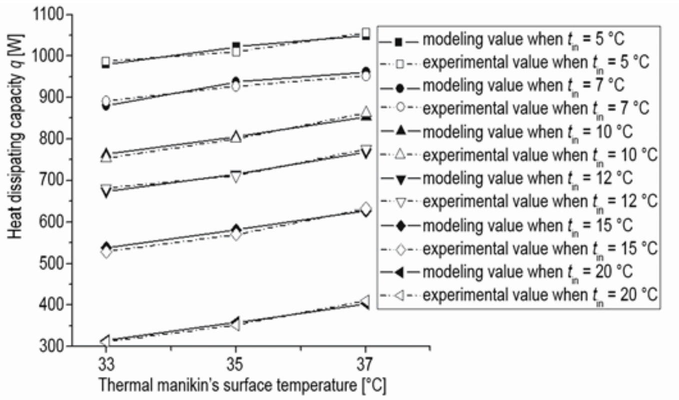

Figure 2. Comparative diagram of modeling value and experimental value

Conclusions

In this paper, the research of water cooling garment's heat dissipating property was performed, and the heat dissipating model was established based on experimental thermal manikin. According to the heat transfer analysis of water cooling garment, the heat dissipating capacity of water cooling garment with thermal manikin and with air layer were derived, and then water cooling garment's total heat dissipating capacity and efficiency were obtained. To verify the accuracy of above heat dissipating model, the verification experiments were performed in climate chamber by thermal manikin wearing water cooling garment. Results show that the modeling value is fitting well with the experimental value, and the maximum relative deviation is 2.034%, which approved model's higher accuracy.

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