A HEAT TRANSFER MODEL FOR A NOVEL THERMAL MANIKIN

by

Kai YANG [a], Ming-Li JIAO [b*], Hong-Yan LIU [a], and Wei-Yuan ZHANG [c]

[a] School of Fashion, Zhongyuan University of Technology, Zhengzhou, China
[b] Department of Materials and Chemistry, Zhongyuan University of Technology, Zhengzhou, China
[c] Department of Fashion, Donghua University, Shanghai, China

Original scientific paper
DOI: 10.2298/TSCI1504227Y

Thermal manikin is a functional instrument used to investigate the interaction between human body and its environment. A heat transfer model for a novel thermal manikin is established and verified experimentally, the results are of great importance to establish an international standard for manikins.

Key words: *heat transfer model, thermal manikin, verification experiment*

Introduction

Thermal manikin is an effective and functional instrument used to study the interaction of surface heat and moisture transfer from human body, and it embodies many human features (*i. e.* capable of generating heat and perspiration) [1]. Since the first thermal manikin was introduced in the early 1940s, more and more manikins have been made and used widely [2]. As thermal manikins have evolved from a one-segment model to various models with more than 30 individually heated segments, the measuring accuracy based on thermal manikin has been improved significantly [3]. However, research on heat exchange on thermal manikin itself is rare and preliminary, which affects the development of international standards related with manikins. Present thermal manikin is always covered with hard metal materials, whose heat transfer is so rapid that manikin's surface temperature always changes greatly with environmental temperature, which affects manikin's stability and garment's measuring accuracy. To overcome the shortcomings, Donghua University developed a novel thermal manikin, whose typical characteristic is its soft skin covering on the outer surface of copper layer, which is a kind of thermoplastic elastomer materials and has good physical properties similar to human skin. In this paper the heat transfer study on this novel thermal manikin is performed, and the heat transfer model is established. Verification experiments indicate that the model has a higher accuracy.

Heat transfer model

The sections of thermal manikin, such as arm, leg, trunk, and so on, could be considered as cylinder. So thermal manikin system's heat transfer is analyzed based on the theory of infinite long cylinder [4]. The heat circuit diagram of thermal manikin system is shown in fig. 1.

* Corresponding author; e-mail: johnml@163.com

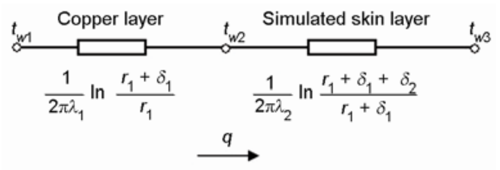

Figure 1. Heat circuit diagram of thermal manikin system

The thermal manikin system consists of three layers, which are copper layer, simulated skin layer, and air layer. The temperature field of this system is axisymmetric, so using cylindrical coordinates is more convenient. The heat transfer differential equation is:

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r\,\frac{\mathrm{d}t}{\mathrm{d}r}\right)=0 \tag{1}$$

The boundary conditions are:

$$r=r_1, \qquad t\big|_{r=r_1}=t_{w1} \tag{2}$$

$$r=r_1+\delta_1+\delta_2$$

$$-\lambda_2\,\frac{\mathrm{d}t}{\mathrm{d}r}\bigg|_{r=r_1+\delta_1+\delta_2}=2\pi(r_1+\delta_1+\delta_2)a(t_{w3}-t_f)+2\pi(r_1+\delta_1+\delta_2)\varepsilon\sigma_b(T_{w3}^4-T_f^4) \tag{3}$$

where r_1 [m] is the inner radius of long cylinder, δ_1 [m] – the thickness of copper layer, δ_2 [m] – the thickness of simulated skin layer, t_{w1} [°C] – the inner surface temperature of copper layer, t_{w2} [°C] – the interface temperature between copper layer and simulated skin layer (we suppose that the copper layer has a good contact with simulated skin layer, so the temperature of all points on the interface are the same), t_{w3} [°C] – the outer surface temperature of simulated skin layer, T_{w3} [K] – the Kelvin temperature of t_{w3}, t_f [°C] – the temperature of air layer, T_f [K] – the Kelvin temperature of t_f, λ_1 [Wm^{-1}°C^{-1}] – the thermal conductivity of copper layer, λ_2 [Wm^{-1}°C^{-1}] – the thermal conductivity of simulated skin layer, a [Wm^{-1}°C^{-1}] – the convective heat transfer coefficient between simulated skin layer and air layer, ε – the blackness of simulated skin layer, and σ_b – the radiation constant of blackbody, $\sigma_b = 5.67\cdot10^{-8}$ W/m^{2}K^4.

Integrating eq. (1), we obtain the general solution:

$$t=c_1\ \ln r+c_2 \tag{4}$$

where c_1 and c_2 are constants. We can see that the temperature distribution follows logarithmic curve.

Solving eqs. (1), (2), and (3), we can get the heat flux and temperature distribution of copper layer, simulated skin layer and air layer. The heat transfer of these three layers is analyzed as follows.

Copper layer

From copper layer's inner surface to outer surface, the heat exchange quantity per cylinder length is:

$$q_1=-2\pi r\lambda_1\,\frac{\mathrm{d}t}{\mathrm{d}r} \tag{5}$$

Separating the variables and making integral, we obtain:

$$q_1=\frac{t_{w1}-t_{w2}}{\dfrac{1}{2\pi\lambda_1}\ln\dfrac{r_1+\delta_1}{r_1}} \tag{6}$$

Simulated skin layer

From simulated skin layer's inner surface to outer surface, the heat exchange quantity per cylinder length is:

$$q_2 = -2\pi\lambda_2 \frac{\mathrm{d}t}{\mathrm{d}r} = -2\pi\lambda_0(1+bt)\frac{\mathrm{d}t}{\mathrm{d}r} \tag{7}$$

Separating the variables and making integral, we obtain:

$$q_2 = \frac{t_{w2} - t_{w3}}{\dfrac{1}{2\pi\lambda_m}\ln\dfrac{r_1+\delta_1+\delta_2}{r_1+\delta_1}} \tag{8}$$

where $\lambda_m = \lambda_0[1 + b/2(t_{w2} + t_{w3})]$.

Air layer

From simulated skin layer's outer surface to air layer, the heat exchange quantity per cylinder length is:

$$q_3 = 2\pi(r_1+\delta_1+\delta_2)a(t_{w3}-t_f) + 2\pi(r_1+\delta_1+\delta_2)\varepsilon\sigma_b(T_{w3}^4 - T_f^4) \tag{9}$$

According to the first law of thermodynamics, we obtain the heat balance equation:

$$q = \frac{t_{w1}-t_{w2}}{\dfrac{1}{2\pi\lambda_1}\ln\dfrac{r_1+\delta_1}{r_1}} = \frac{t_{w2}-t_{w3}}{\dfrac{1}{2\pi\lambda_m}\ln\dfrac{r_1+\delta_1+\delta_2}{r_1+\delta_1}} =$$

$$= 2\pi(r_1+\delta_1+\delta_2)a(t_{w3}-t_f) + 2\pi(r_1+\delta_1+\delta_2)\varepsilon\sigma_b(T_{w3}^4 - T_f^4) \tag{10}$$

where q [W] is the power consumed by thermal manikin's sections.

Experimental verification

To verify the accuracy of above heat transfer model, the verification experiments were performed in climate chamber by unclothed thermal manikin. The environmental temperature of climate chamber (t_f) was set at 18 °C, 21 °C, and 24 °C, respectively. Thermal manikin's inner surface temperature (t_{w1}) was set at 28 °C, 31 °C, 33 °C, 36 °C, 39 °C, and 42 °C, respectively. After thermal manikin came to a steady state, the power q consumed by each section was measured and this value was considered as experimental value. The experimental value was compared with modeling value. We just take the thigh section as an example, the comparative diagram is shown in fig. 2. We can see that the modeling value is fitting well with the experimental value. By calculating all the sections of thermal manikin, the maximum relative deviation be-

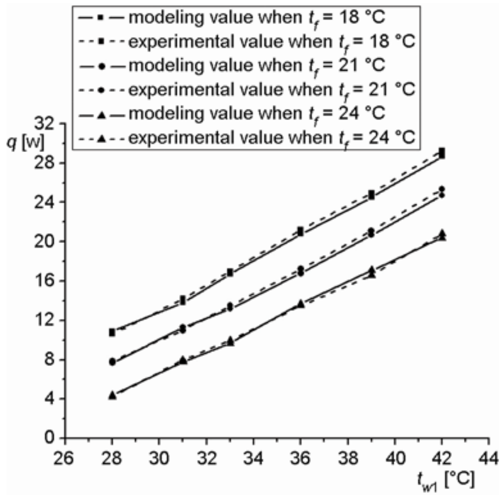

Figure 2. Comparative diagram of modeling value and experimental value (thigh section)

tween modeling value and experimental value is 3.11%, which approves above heat transfer model's higher accuracy.

Conclusions

This paper analyzes the heat transfer of a novel thermal manikin with soft simulated skin. According to heat transfer theory, the heat transfer of thermal manikin system's three layers was analyzed respectively. Then the heat transfer differential equation and heat balance equation were obtained. Finally the verification experiments were performed in climate chamber by unclothed thermal manikin. Results show that the modeling value is fitting well with the experimental value, and the maximum relative deviation is 3.11%, which approves heat transfer model's higher accuracy.

Acknowledgments

The work is supported by National Natural Science Foundation of China (Grant No. U1404507), and State Key Laboratory for Modification of Chemical Fibers and Polymer Materials, Donghua University, China (No. LK1213), and Research Project of China Textile Industry Institute (No. 2011076), and Research Project Cultivating Foundation in Zhongyuan University of Technology, and Science and Technology Key Project of Henan Province.

References

[1] Virgilio, A., *et al.*, Dynamic Clothing Insulation: Measurements with a Thermal Manikin Operating under the Thermal Comfort Regulation Mode, *Applied Ergonomics, 42* (2011), 6, pp. 890-899
[2] Yang, K., *et al.*, A Heat Dissipating Model for Water Cooling Garments, *Thermal Science, 17* (2013), 5, pp. 1431-1436
[3] Lee, J. Y., *et al.*, Validation of Clothing Insulation Estimated by Global and Serial Methods, *International Journal of Clothing Science and Technology, 23* (2011), 2, pp. 184-198
[4] Shang, X. M., *et al.*, Thermal Diffusion in Fabrics and a Graphics Algorithm for Apparel Pattern Reconstruction, *Thermal Science, 16* (2012), 5, pp. 1484-1487

Paper submitted: February 9, 2015
Paper revised: April 12, 2015
Paper accepted: April 30, 2015