Investigation of the Convective Heat Transfer Coefficient of the Hand and Fingers in Firefighter Gloves Using a Thermal Hand

Jie Yang[1], Li Wang[2], Weiwei Chen[1,3], Rui Li[1], Liwen Wang[1], Huanjiao Dong[1], Chunhui Xiang[1], AKM Mashud Alam[1], and Guowen Song[1]
[1] Iowa State University, USA
[2] Tianjin University of Technology, China
[3] Jiangsu College of Engineering and Technology, China

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Introduction The NFPA (National Fire Protection Association) reported that 62,085 firefighters were injured in the U.S. in 2016, and the hand is one of the most vulnerable areas suffering burn injuries, which accounts for 23% to 39% of the total burn injuries (Haynes, 2017; Kahn et al., 2012). The heat transfer coefficients of the hands are critical inputs of the thermoregulation model that can simulate thermal responses of the hand and fingers. Besides, the hand has a greater surface area to mass ratio and complex anthropometric parameters, thus is extremely important in heat transfer and thermoregulation. However, the convective heat transfer coefficients of the fingers, palm, and dorsal of the hand are not fully investigated and understood. Accordingly, there is an urgent need for full understanding of the convective heat transfer coefficients in both the whole-hand and regional segments. The results of this study will provide guidance for the thermal model development, cold and burn injuries assessment, and design of high-performance protective gloves.

Methods A 7-zone thermal hand manikin 'Newton' (Thermetrics, Seattle, USA) was used to investigate the convective heat transfer coefficients of the hand and fingers. It has a total surface area of 0.0462 m^2 and is comprised of thumb, index finger, middle finger, ring finger, little finger, palm, and dorsal. The skin temperature, heating power, and sweating rate of each zone were independently controlled and recorded by the software ThermDAC. A type of firefighter glove (P8-FUSION, Pro Tech 8™, USA) was selected in this study. The skin temperature of each zone of the hand manikin was set at 35.0 °C. The tests were carried out in a climate chamber in which the air temperature and relative humidity were controlled at 20 ± 0.5 °C and 65 ± 5 %, respectively. The air velocity of the chamber climate was less than 0.1 m/s. All the tests were repeated at least three times.

The thermal hand manikin exchanged heat with the environment through the convection and radiation in the tests. The heat transfer coefficients can be simplified as the follows:

$$h = \frac{Q_{dry}}{T_{sk} - T_a} \quad (1)$$

$$h_r = \frac{\varepsilon \cdot \sigma \left(T_{sk}^4 - T_a^4 \right)}{T_{sk} - T_w} \quad (2)$$

$$h_c = \frac{Q_{dry}}{T_{sk} - T_a} - \frac{\varepsilon \cdot \sigma \left(T_{sk}^4 - T_a^4 \right)}{T_{sk} - T_w} \quad (3)$$

where h is the *combined heat transfer coefficient,* W/(m^2·°C); Q_{dry} is the dry heat loss (convection and radiation) between the thermal hand manikin and the environment, W/m^2; T_{sk} is the surface temperature of the hand manikin, °C; T_a is the ambient temperature, °C; h_r is the radiative heat transfer coefficient, W/(m^2·°C); ε is the blackness of the manikin surface, dimensionless; σ is the Stephan-Boltzman constant, 5.67×10^{-8} W/(m^2·K). T_w is the temperature of the wall, °C; h_c is the convective heat transfer coefficient, W/(m^2·°C).

Results and Discussion The measured dry heat flux (Figure 1) of the hand was 117.80 W/m^2, and the regional heat flux varied between 96.99 W/m^2 and 139.13 W/m^2 for the middle finger and the thumb, respectively. The combined heat transfer coefficient of each zone was 9.28, 8.77, 7.16, 7.78, 8.95, 6.46, and 8.06 W/(m^2·°C), respectively. The combined heat transfer coefficient and radiative heat transfer coefficient of the hand was 7.85 and 5.06 W/(m^2·°C), respectively. The convective heat transfer coefficient (Figure 2) of the whole-hand was 2.79 W/(m^2·°C). Furthermore, the h_c of the thumb, index finger, little finger, and the dorsal varied from 3.0 to 5.0 W/(m^2·°C), followed by the middle finger and ring finger in the range of 2.0 and 3.0 W/(m^2·°C). The palm had the lowest h_c of 1.41 W/(m^2·°C). The difference in the convective heat transfer coefficient between each zone may be caused by the curvature and the heat transfer from the adjacent fingers (Chen et al., 1999). A significant difference (p<0.05) was observed in the h_c among the five fingers, palm, dorsal, and the whole-hand. However, no significant difference (p>0.05) was found between the thumb, index, little finger, and dorsal, as well as that between the middle, ring, palm, and the dorsal.

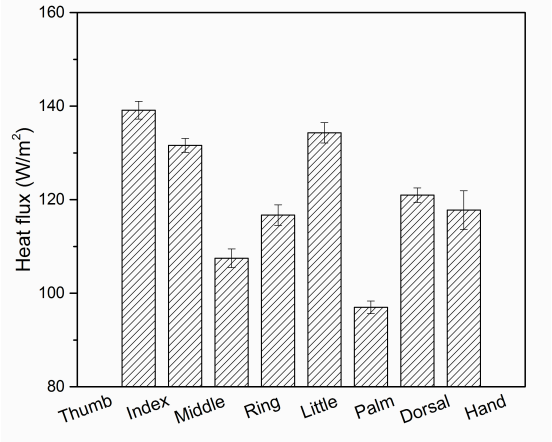

Figure 1. Measured heat flux from hand manikin

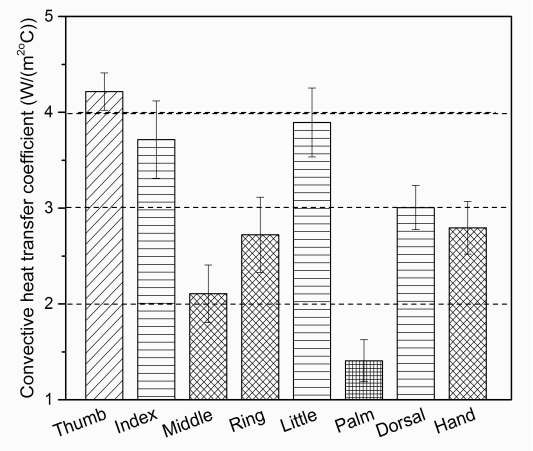

Figure 2. Convective heat transfer coefficient

Conclusion The ANOVA test showed a significant difference in the convective heat transfer coefficient among the zones of the hand (p<0.05). The thumb, index, and little finger had larger convective heat transfer coefficient, and palm had the lowest heat transfer coefficient.

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