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Human local and total heat losses in different temperature

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HIGHLIGHTS

- In low temperature, the thigh, leg and chest have great heat losses.
- In high temperature, the chest, abdomen, thigh and head have great heat losses.
- 6 kinds of heat losses change obviously different with operative temperature.
- Radiation and convection heat losses are mainly affected by the area of local body.
- Evaporation heat loss is mainly affected by the sweat proportion of the local part.

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ABSTRACT

This study investigates the effects of operative temperature on the local and total heat losses, and the relationship between the heat loss and thermal sensation. 10 local parts of head, neck, chest, abdomen, upper arm, forearm, hand, thigh, leg and foot are selected. In all these parts, convection, radiation, evaporation, respiration, conduction and diffusion heat losses are analyzed when operative temperature is 23, 28, 33 and 37 °C. The local heat losses show that the radiation and convection heat losses are mainly affected by the area of local body, and the heat loss of the thigh is the most in the ten parts. The evaporation heat loss is mainly affected by the distribution of sweat gland, and the heat loss of the chest is the most. The total heat loss of the local body shows that in low temperature, the thigh, leg and chest have much heat loss, while in high temperature, the chest, abdomen, thigh and head have great heat loss, which are useful for clothing design. The heat losses of the whole body show that as the operative temperature increases, the radiation and convection heat losses decrease, the heat losses of conduction, respiration, and diffusion are almost constant, and the evaporation heat loss increases. By comparison, the heat loss ratios of the radiation, convection and sweat evaporation, are in agreement with the previous researches. At last, the formula about the heat loss ratio of convection and radiation is derived. It's useful for thermal comfort evaluation and HVAC (heating, ventilation and air conditioning) design.

1. Introduction

Human local skin temperature (LST) is widely tested to calculate mean skin temperature (MST). The common methods are 3-site method [1], 4-site method [2], 6-site method [3], 7-site method [4,5], and 10-site method [6]. Liu et al. [7] evaluated 26 types of MST calculation method based on the experimental dare, and found that the method with 10 sites is the most appropriate one. Liu et al. [8] tested the LST of 10 parts to study the human behavior in 4 temperature differences between radiant and air temperature. In the same year, they tested the LST of 32 sites to reveal the effects of clothing thermal resistance and operative temperature on skin temperature [9], and the effects of radiant temperature on human skin temperature and surface temperature [10].

However, human local heat loss is little researched. Osczevski [11] measured the heat loss of cheek to calculate thermal resistance in resting subjects. Brajkovic and Ducharme [12] tested the heat loss of the same part in active and inactive individuals. In these researches, only one local part is tested, the heat losses in other local parts are unclear. Oliveira et al. [13] analyzed the natural and forced convection heat losses from a thermal manikin to obtain the convective heat transfer coefficients. Wang et al. [14] provided a correction of heat loss method to calculate clothing real evaporative resistance from a thermal manikin. Bilgili et al. [15] investigated the effects of seasonal weather differences on the human body's heat losses in the Mediterranean region of Turkey.

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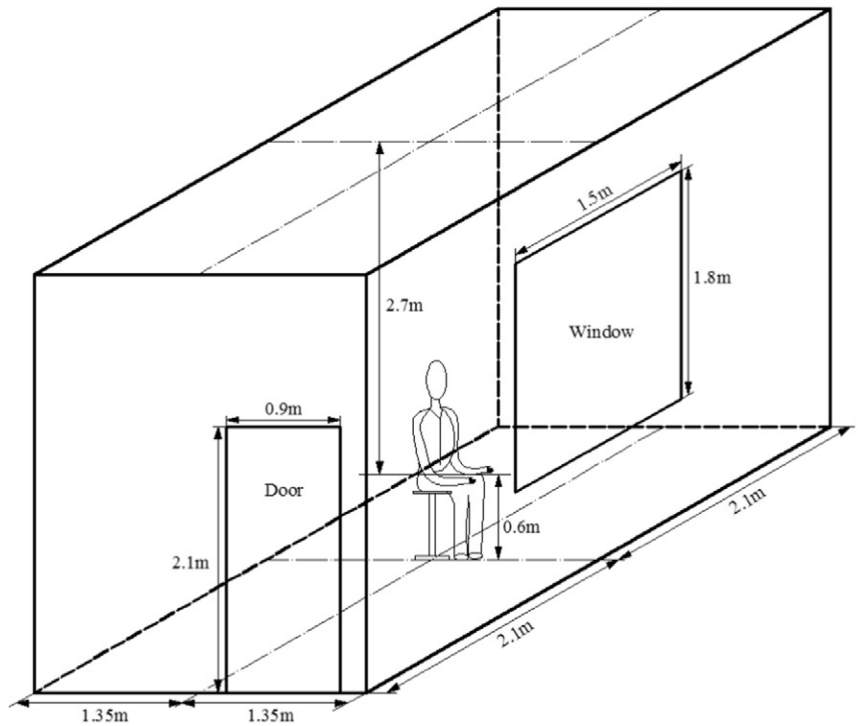

Fig. 1. The location of the subject in the climatic chamber.

In their research, the radiation, convection, evaporation and respiration heat loss were analyzed by using the heat balance equation. This research provides useful methods for present paper.

In this research, human body is divided into ten parts, namely head, neck, chest, abdomen, upper arm, forearm, hand, thigh, leg and foot. The convection, radiation, evaporation and diffusion heat losses for each part are provided, and the respiration and conduction heat losses for special part are also provided. The different heat losses and different local parts are analyzed deeply, and the relationship between heat loses and thermal sensation vote (TSV) are investigated.

2. Mathematical model

Steady-State Energy Balance model developed by Fanger [16] is commonly used for thermal interaction between the human body and the environment. Steady-state model assumes that the body is in a thermal equilibrium and its energy storage is negligible. For a sedentary human in an office, the conduction heat loss between clothed body and chair should be considered, but the external mechanical power also is zero. So the energy balance of body is expressed as:

$$M = R + C + E_{sw} + E_{dif} + B + D \quad (1)$$

where R is the radiation heat loss from the outer surface of the clothed body (W), C is the convection heat loss from the outer surface of the clothed body (W), E_{dif} is the diffusion heat loss from the skin (W), B is the respiration heat loss (W), D is the conduction heat loss (W), E_{sw} is the evaporation heat loss of sweat from the surface of the skin (W), and M is the internal heat production in the human body (W), cited in ASHRAE [17].

The radiation heat loss from the outer surface of the human body can be expressed by:

$$R = A_{Du} f_{eff} f_{cl} \varepsilon \sigma \left[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4 \right] \quad (2)$$

where A_{Du} is DuBois area (m^2), f_{eff} is the effective radiation area factor, f_{cl} is the ratio of the surface area of the clothed body to the surface area of the nude body, ε is the emittance of the outer surface of the clothed body, σ is the Stefan-Boltzmann constant, t_{cl} is the outer surface temperature of the clothed body (°C), and t_{mrt} is the mean radiant temperature (°C).

The convection heat loss from the outer surface of the clothed body can be expressed by the following equation.

$$C = A_{Du} f_{cl} h_c (t_{cl} - t_a) \quad (3)$$

where h_c is the convective heat transfer coefficient (W/(m^2·°C)), and t_a is the air temperature close to a human being (°C).

For still air, the heat transfer happens by free convection. So h_c is a function of the temperature difference of $(t_{cl} - t_a)$. Kurazumi et al. [18] investigated the convective and radiative heat transfer coefficients of the human body in seven postures. The empirical formulas were proposed for the convective heat transfer coefficient of the entire human body under natural convection. The convective heat transfer coefficients for chair sitting were cited in that paper.

The equation for the diffusion heat loss from skin is:

$$E_{dif} = \gamma \chi A_{Du} (P_{skin,s} - P_a) \quad (4)$$

where γ is heat vaporization of the water (J/kg). It is found in the literature [19] according to temperature. χ is permeance coefficient of the skin (kg/(s·m^2·kPa)). It is 1.271×10^{-6} kg/(s·m^2·kPa) cited in literature [16,20]. $P_{skin,s}$ is the saturated vapour pressure at skin temperature (kPa). P_a is the vapour pressure in ambient air (kPa).

The evaporation heat loss of sweat secretion can be written as:

$$E_{rsw} = \omega 16.7 h_c (0.256 t_{skin} - 3.37 - p_a) \quad (5)$$

where t_{skin} is the surface temperature of skin (°C), and ω is the skin wetness (%).

Li and Zheng [20–23] did a lot of research on sweating. They found that the sweating was closely related to body surface impedance, and presented the empirical equations of skin wetness for the forehead, neck, chest, back, axilla, upper arm, forearm, palm of hand, back of