EFFECTS OF TRANSIENT TEMPERATURE ON HUMAN'S HEAT LOSSES

by

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The objectives of the paper are to analyze human convection, radiation, evaporation, respiration, conduction, and diffusion heat losses when the operative temperature increases from 26-34.4 °C and then decreases from 34.4-26 °C with a ratio of 1.4 °C per 5 minutes. A energy balance model is used for sedentary subject. The results show that during temperature rising, all the heat losses are linear functions of temperature, while during temperature dropping, the convection, diffusion, and respiration heat losses are quadratic functions of temperature. The results are useful for thermal comfort evaluation and heating, ventilation, and air conditioning design.

Key words: *heat loss, transient temperature, human body*

Introduction

Human heat loss is a very important index. It can be used to calculate thermal resistance and evaluate thermal comfort. Osczevski [1] measured the heat loss of cheek to calculate thermal resistance in resting subjects. Dixit and Gade [2] tested the heat loss of the same part in active and inactive individuals. Oliveira *et al*. [3] analyzed the natural and forced convection heat losses from a thermal manikin to obtain the convective heat transfer coefficients. Wang *et al.* [4] provided a correction of heat loss method to calculate clothing real evaporative resistance from a thermal manikin. Yang *et al.* [5] established a heat transfer model for a novel thermal manikin. Bilgili *et al*. [6] investigated the effects of seasonal weather differences on the human body's heat losses in the Mediterranean region of Turkey. In most researches, the heat losses were analyzed in the steady-state condition. While in this research, the heat losses in the transient environment will be presented.

Mathematical model

Steady-state energy balance model developed by Fanger [7] is commonly used for thermal interaction between the human body and the environment. However, in transient condition, this method should be revised. For a sedentary subject, the energy balance model can be written:

$$M \quad R \quad C \quad E_{\mathrm{sw}} \quad E_{\mathrm{dif}} \quad B \quad D \quad mc\frac{\mathrm{d}t}{\mathrm{d}\tau} \tag{1}$$

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where M [W] is the internal heat production in human body, R [W] – the heat loss by radiation from the outer surface of the clothed body, C [W] – the heat loss by convection from the outer surface of the clothed body, E_{dif} [W] – the heat loss by water vapor diffusion through the skin, B [W] – the heat loss of respiration, D [W] – the heat loss by conduction, E_{sw} [W] – the heat loss by evaporation of sweat from the surface of the skin, m [kg] – the body mass, c [Jkg^{-1}°C^{-1}] – the specific heat of body, t [°C] – the body temperature, and τ [s] – the time.

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

$$R \quad A_1 f_{eff} f_{cl} \varepsilon\sigma[(t_{cl} \quad 273)^4 \quad (t_{mrt} 273)^4] \tag{2}$$

where A_1 [m^2] is the area of human body that participates in radiation heat transfer, f_{eff} – the effective radiation area factor, f_{cl} – the ratio of the surface area of the clothed body to the surface area of the nude body, ε – the emittance of the outer surface of the clothed body, σ – the Stefan-Boltzmann constant, t_{cl} [°C] – the outer surface temperature of the clothed body, and t_{mrt} [°C] – the mean radiant temperature.

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

$$C \quad A_2 f_{cl} h_c (t_{cl} \quad t_a) \tag{3}$$

where A_2 [m^2] is the area of human body that participates in convection heat transfer, h_c [Wm^{-2}°C^{-1}] – the convective heat transfer coefficient, and t_a [°C] – the air temperature close to a human being.

The equation for the heat loss by water vapor diffusion through the skin is:

$$E_{dif} \quad \gamma\chi A_3 (P_{skin,s} \quad P_a) \tag{4}$$

where γ is the heat vaporization of the water, χ [kgs^{-1}m^{-2}kPa^{-1}] – the permeance coefficient of the skin [7], A_3 [m^2] – the area of the whole human body, $P_{skin,s}$ [Pa] – the saturated vapor pressure at skin temperature, and P_a [Pa] – the vapor pressure in ambient air.

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

$$E_{rsw} \quad \omega 16.7 h_c (0.256 t_{skin} \quad 3.37 \quad P_a) \tag{5}$$

where ω [%] is the skin wetness, and t_{skin} [°C] – the surface temperature of skin.

Respiration contains latent and dry heat loss. It is:

$$B \quad 0.0014 M (34 \quad t_a) \quad 0.0173 M (5.867 \quad P_a) \tag{6}$$

The heat loss by conduction is:

$$D \quad A_4 K (t_{cl} \quad t_a) \tag{7}$$

where A_4 [m^2] is the contact area between human body and chair and K [Wm^{-2}°C^{-1}] is the transfer coefficient of chair.

Experiment

The radiant temperature was controlled by the electro-thermal films, and the air temperature was controlled by the air-conditioning. The two temperatures increased in 26-34.4 °C, and then decreased in 34.4-26 °C. Operative temperature is the average of the air temperature and the mean radiant temperature weighted, respectively, by the convective heat transfer coefficient and the radiant heat transfer coefficient for the occupant [8]. It was calculated by:

$$t_o = \frac{h_a t_a + h_r t_{mrt}}{h_a + h_r} \tag{8}$$

where t_o [°C] is the operative temperature and h_a and h_r [Wm^{-2}°C^{-1}] are the convective heat transfer coefficient and radiant heat transfer coefficient for the entire body, respectively.

During the experiment, the radiant temperature was close to air temperature, the relative humidity was about 50%, and the air speed was 0.06 m/s. Based on the radiant temperature and air temperature, the operative temperature was obtained according eq. (8). The subjects included six males and six females. They simulated light activity (sedentary), and the clothing thermal resistance was 0.52 clo.

Results

Figures 1(a) and 1(b) present the radiation, convection, evaporation, conduction, respiration, and diffusion heat losses when the operative temperature changes at the rate of 1.4 °C per 5 minutes. The radiation, convection, and evaporation heat losses change greater with operative temperature than the other three heat losses. The evaporation heat loss increases as the operative temperature increases, while the other heat losses are opposite. In high temperature, evaporation is the main heat loss, while in low temperature, radiation, and convection heat losses are the main heat losses.

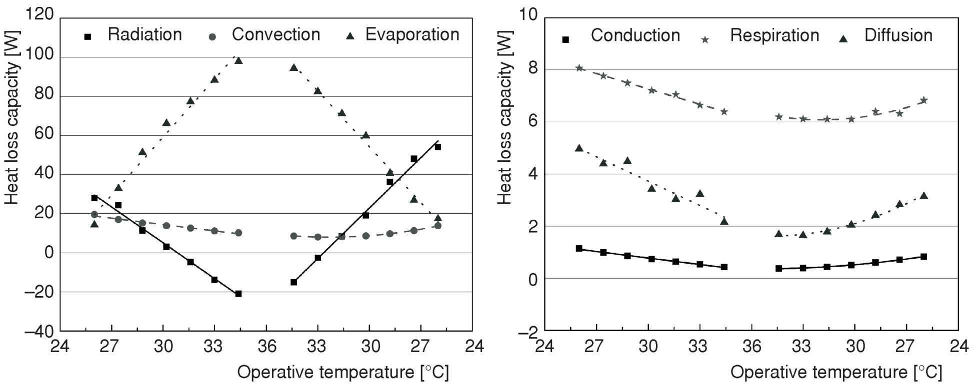

Figure 1. Human heat losses affected by different operative temperatures

Compare the operative temperature rising and dropping, the heat losses are different. During rising, all the heat losses are linear functions of temperature. While during dropping, the radiation, evaporation, and conduction heat losses are linear functions of temperature, but the convection, diffusion, and respiration heat losses are quadratic functions of temperature. The heat losses during dropping change more slowly with temperature than those during rising, because human body experienced temperature rising, and stored some heat.

Conclusions

In transient environment, heat losses of human body are obtained, among which the radiation, convection, and sweat evaporation are the main heat loss, and vary greatly with operative temperature, while the conduction, respiration and water vapor diffusion change little with it.

The heat losses during rising are different with those during dropping. During rising, all the heat losses are linear functions of temperature. While during dropping, the radiation, evaporation and conduction heat losses are linear functions of temperature, but the convection, diffusion, and respiration heat losses are quadratic functions of temperature. Due to the heat storage of human body, the heat losses during dropping change more slowly with temperature than those during rising.

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