Building and Environment 142 (2018) 180–187

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Analysis on body heat losses and its effect on thermal sensation of people under moderate activities

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ARTICLE INFO

Keywords:
Heat losses
Thermal sensation
Sweat heat loss
Moderate activity
PMV

ABSTRACT

The motivation of this study is to explore the changes of heat losses of people who undertake moderate activities and its effect on thermal sensation. Based on heat transfer equations and experimental data, heat losses have been calculated. The results have shown that in all conditions, the total ratio of latent heat loss (LHL) and sensible heat loss (SHL) is almost constant ranging from 0.9 to 0.95. With increase of LHL or decrease of SHL, people's mean thermal sensation vote (TSV) will increase regardless of whether they are in thermal balance. Skin wettedness is also related to TSV. Further study has discovered that ratios of LHL (R_{LHL}) and SHL (R_{SHL}) are correlated to TSV separately. By polynomial regression, two predicting equations have been fitted based on R_{SHL} and R_{LHL}, and they are essentially coincident with the sum of R_{SHL} and R_{LHL} being 0.93. The validity of predicting equations has been verified by using independent experimental data. Either of the equations can be used to predict TSV under moderate activities. Different from the current heat balance theory in thermal comfort, attention has been put on the change of ratios of heat losses in this paper, which provides a new perspective to understand thermal comfort under higher level of activities.

1. Introduction

One of the main functions of building is to provide suitable and comfortable indoor environment that people can work or live in. People are encountered with different thermal conditions on a daily basis in the built environment. The ability to predict human thermal responses and keep thermal comfort in different environmental conditions are the main incentive of thermal comfort studies [1,2]. Architects and engineers keep thinking of ways to improve the user's environmental comfort while improving the performance of buildings [3]. The thermal comfort research carried out in all kinds of building environment not only improves comfort, but also has positive effect on building energy saving [4–8]. The research on thermal comfort also reveals the related thermophysiological mechanism, and promotes the cognition of human body itself [9,10].

Researches related to thermal comfort can be divided into two directions, one is the research of models to predict thermal comfort, and the other is the study of thermophysiological models. The most applied models in thermal comfort studies is Fanger's PMV (Predicted Mean Votes) model based on equations for human body heat exchange, which has become a worldwide standard [11–13]. There are also other standards predicting thermal stress and provide protection for people in special environment (hot or cold exposure) based on heat balance of human body [14,15]. Thermophysiological models are mathematical descriptions of physiological responses and the complex heat transfer of the human body under different environmental conditions [16,17]. Thermophysiological models are part of the prediction method for evaluating thermal comfort and thermal state. The calculated output of the thermophysiological model (core and skin temperature) can be used as input for related models that predict thermal comfort, thermal sensation or thermal stress etc.

Both PMV and thermal physiological models are based on body heat production and heat transfer. And the heat transfer equations or models of human body have been studied widely [18–22]. These equations and models can be used to calculate various heat transfer quantities between human body and ambient environment. In application, the heat transfer equations are mainly used to calculate physiological parameters (core and skin temperature) and heat load of human body, for example, Gagge's two-node model and PMV model. However, there is little discussion on the effect of the proportion of different heat transfer quantities on thermal sensation in existing studies. This may because the doctrines, which states that human thermal comfort can be maintained if the heat generated by human metabolism is allowed to be dissipated and the thermal equilibrium is achieved between human body and surroundings. According to this theory, also the basis of PMV model, people can be thermally comfortable as long as they are in or

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https://doi.org/10.1016/j.buildenv.2018.06.019
Received 1 March 2018; Received in revised form 9 June 2018; Accepted 12 June 2018
0360-1323/

close to the state of thermal balance or thermal neutral, regardless of the ratio of different heat dissipations.

Due to human's thermoregulatory system effectiveness, heat balance by increasing sweat is achievable in higher activity levels. At higher level of activities, increased heat production stimulates the process of sweating, which will enhance evaporative heat obviously [23]. Therefore, the ratio of heat losses will become different. The proportion of latent heat loss (LHL) in total heat loss (THL) will be increased and sensible heat loss (SHL) will be decreased. Besides, sweating will not only increase LHL, but also enhance skin wettedness, which evokes uncomfortable sensation [24,25].

The following questions are raised up. Will this change in heat loss ratios affect people's thermal sensation? And if it does, what is the effect of change, and can it be used to establish correlations with thermal sensation? In order to get full understanding about these questions, this paper will focus on the changes of heat losses and its influence on thermal sensation in moderate activities.

2. Heat transfer equations

Metabolic activities of human body result almost completely in heat that must be continuously dissipated and regulated to maintain normal body temperatures. Insufficient heat loss leads to overheating, and excessive heat loss results in body cooling. Heat dissipates from the body to the immediate surroundings by several modes of heat exchange: sensible heat flow (including convection and radiation); latent heat flow from sweat evaporation and from evaporation of moisture diffused through the skin; sensible heat flow during respiration; and latent heat flow from evaporation of moisture during respiration. The equations used in this study to calculate different kind of heat losses will be listed and the meaning of symbols and parameters used in equations are shown in Table 1.

The following expression is the thermal balance equation that establishes the relation of heat production, heat loss and heat storage of human body.

$$M - W = C + R + E_{sk} + C_{res} + E_{res} + S \quad (1)$$

Fanger [26,27], Gagge and Hardy [28], Hardy [29], and Rapp and Gagge [30] give quantitative information on calculating heat exchange between people and the environment, which has been adopted in ASHRAE Handbook [31] and related standards [12,14,15]. The equations in steady-state energy balance are as the following, which are based mainly on reference [12] and [31].

Convective heat loss:

$$C = f_{cl} h_c (t_{cl} - t_a) \quad W/m^2 \quad (2)$$

Radiative heat loss:

$$R = f_{cl} h_r (t_{cl} - \overline{t_r}) \quad W/m^2 \quad (3)$$

Total evaporative heat loss from skin:

$$E_{sk} = E_{dif} + E_{sw} \quad W/m^2 \quad (4)$$

Evaporative heat loss of moisture diffused through the skin:

$$E_{dif} = 3.05[5.73 - 0.007(M - W) - p_a] \quad W/m^2 \quad (5)$$

Or by:

$$E_{dif} = (1 - w_{sw}) \times 0.06 \times E_{max} \quad (6)$$

Evaporative heat loss by sweat:

$$E_{sw} = 0.42[(M - W) - 58.15] \quad W/m^2 \quad (7)$$

The total heat and moisture losses due to respiration:

$$q_{res} = E_{res} + C_{res} \quad W/m^2 \quad (8)$$

Evaporative heat loss from respiration:

Table 1
Meaning of symbols and parameters used in equations.

Symbols/ Parameters	Meaning	Dimension
M	rate of metabolic heat production	W/m^2
W	rate of mechanical work accomplished	W/m^2
C	rate of convective heat	W/m^2
R	rate of radiant heat	W/m^2
E_{sk}	total evaporative heat loss from skin (including natural diffusion E_{dif} and regulative sweating E_{sw})	W/m^2
C_{res}	rate of convective heat loss from respiration	W/m^2
E_{res}	rate of evaporative heat loss from respiration	W/m^2
S	rate of heat storage in body	W/m^2
f_{cl}	clothing area factor	dimensionless
h_c	convective heat transfer coefficient	$W/(m^2{\cdot}K)$
h_r	linear radiative heat transfer coefficient	$W/(m^2{\cdot}K)$
t_{cl}	clothing surface temperature	°C
t_a	ambient air temperature	°C
$\overline{t_r}$	mean radiative temperature	°C
w_{sw}	skin wettedness caused by sweat	dimensionless
E_{max}	maximum evaporation rate from skin	W/m^2
p_a	water vapor pressure in ambient air	kPa
$\dot{m}_{sw}$	sweat rate	$g/(m^2.h)$
t_{sk}	mean skin temperature	°C
$t_{sk.n}$	mean skin temperature when people are in thermal neutral condition	°C
h_{fg}	latent heat of water vaporization	kJ/kg
r_{ev}	evaporation efficient of sweat	dimensionless
w_{sk}	skin wettedness of whole body	dimensionless
E_{req}	required evaporative cooling loss	W/m^2
M-W	body heat production	met (1 met = 58 W/m^2)
$p_{sk.s}$	water vapor pressure at skin, normally assumed to be that of saturated water vapor at t_{sk}	kPa
$R_{e,cl}$	evaporative heat transfer resistance of clothing layer	$(m^2{\cdot}kPa)/W$
h_e	evaporative heat transfer coefficient	$W/(m^2{\cdot}kPa)$
$h^{'}$	overall sensible heat transfer coefficient	$W/(m^2.K)$
LR	Lewis Ratio	K/kPa
i_m	total vapor permeation efficiency	dimensionless
I_{corr}	correction factor for conversion of static to dynamic insulation	dimensionless
v_a	wind speed relative to the person (equal to air velocity in this study)	m/s
v_w	walking speed of a person (maximum value is 0.7)	m/s
v_{ar}	relative air velocity due to body movement and air movement	m/s

$$E_{res} = 0.0173M(5.87 - p_a) \quad W/m^2 \quad (9)$$

Convective heat loss from respiration:

$$C_{res} = 0.0014M(34 - t_a) \quad W/m^2 \quad (10)$$

The detailed information about these equations will not be discussed here, as it has been fully stated in ASHRAE Handbook. The values of the relevant parameters are determined according to ASHRAE Handbook too [31].

Among these equations, the calculation of E_{sw} (equation (7)) should be used in nearly thermal neutral state [32]. In this study, experimental data of people taking moderate activities will be used. Most of the thermal conditions in experiments are warm or hot, which means this equation might not be suitable to calculate E_{sw}.

In a study of Kubota etc., an assumption has been proposed that the regulatory thermal sweating rate is a linear function of the deviation of mean skin temperature from that of thermal neutrality [33,34]. Based on Stolwijk's data, the following equation has been verified in their