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Effect on human metabolic rate of skin temperature in an office occupant

Rosli Abu Bakar[1,*], *Norfadzilah* Jusoh[1], *Ahmad* Rasdan Ismail[2], and *Tanti* Zanariah Shamshir Ali[1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang (UMP), 26600 Pekan Pahang, Malaysia
[2]Faculty of Creative Technology and Heritage, Universiti Malaysia Kelantan (UMK), Beg Berkunci No. 01, 16300 Bachok, Kelantan, Malaysia

Abstract. The motivation of this study is to get a better understanding about the real thermal sensation of people in an office environment who undertakes moderate activities. The purpose of this study was to investigate occupant real thermal sensation at three tasks of activities and skin temperature to figure out its impact on thermal sensation in an office environment. All measurements were conducted in a climate chamber. In total, fifteen subjects were participated in three kinds of activities and skin temperatures, which is eleven locations were measured using thermocouple sensors. The results showed that the temperature is the one of the factors which affect metabolic rate. There is a strong linear relationship between these three tasks of activities and metabolic rate with the skin temperature. Furthermore, the results indicate that there was a greater increase thermal sensation when the metabolic rate 1.6. The conclusions of this study can provide some references to set a standard for air conditioning design and to set operating parameters of different functional architectures.

1 Introduction

Building environment has a great impact on people's health, comfort and productivity [1-3]. Thermal comfort studies are helpful to create a favorable indoor climate, maintain a productive thermal environment and keep reasonable energy consumption [4-6]. Most thermal comfort studies have focused on office building, classrooms or homes in which people usually sit or take low level activities. Actually, people may undertake various activities indoors such as those who work on assembling lines or those who exercise in building. With the increase of activity, the body heat production and thermal regulation process involved would be different from low activities [7]. Also, the thermal environment that makes people feel satisfied could not be similar.

Malaysia is a hot and humid tropical country that lies between 1^{o} and 7^{o} north and 100^{o} and 120^{o} east. Most locations have a relative humidity of 80-88% rising to nearly 90% in the highland areas and never fall below 60%. The mean maximum daytime temperature

[*] Corresponding author: rosli@ump.edu.my

recorded is 29-32 °C while the minimum temperature is 22-24 °C with a rainfall of 1000 mm per year [8,9].

Based on the literature review, few thermal comfort studies have been conducted in Malaysia before the 1990s. According to the Energy Efficiency Guideline by the Ministry of Energy, Telecommunications and Posts (1989) and the Malaysia Standard MS 1525 [10], the proposed temperature for the air-conditioned nonresidential buildings is 23-26 °C. These Figures are similar to the ASHRAE 55 [11] and ISO 7730 [12] standards. However, since 1990's with an increase of energy usage in the commercial sector, more research has been conducted in the area of thermal comfort to find appropriate means to provide comfortable indoor environments and to reduce energy consumption and costs. Studies have shown that an increase of 1.5 °C in indoor setting temperature give 15.8% energy saving [13,14].

The purpose of this study was to investigate occupant real thermal sensation at three tasks of activities and skin temperature to figure out its impact on thermal sensation in an office environment.

2 Experimental setup

The experiment was carried out in a climate chamber (L × W × H = 3.6 m × 2.4 m × 3.6 m), which was placed inside an air conditioned room. Other than that, the air temperature inside the chamber could be controlled within ±0.5 °C. Fig. 1 showed the arrangement of the study. This diagram illustrated the environment of equipment was placed behind the subject.

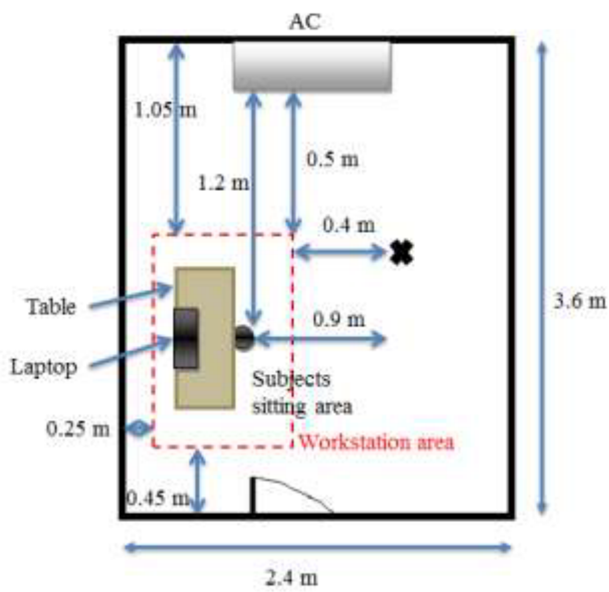

Fig. 1. The arrangement in environmental chamber.

2.1 Design of experiment

Thermal comfort tests with human subjects were conducted to test the thermal sensation of human for various thermal conditions. 15 volunteers (eight male and seven female) students were recruited in this study. The number of subjects in the study was agreed by Goldman [15]. He has 50 years' experience in the field of human thermal comfort and state that minimum subject for the study of human comfort is as many as six people.

All 15 subjects were using in this study to measure skin temperature while doing multitask in the chamber (represent an office room). There are three tasks the subjects must follow such as relaxing while sitting, typing or writing and printing paperwork as shown as in Table 1.

Table 1. Types of the task with the metabolic rate.

No. of Task	Types of the task	Metabolic rate (Met)
1	Thinking	1.0
2	Sitting while typing	1.2
3	Printing	1.6

Existing thermoregulation models have selected three to fifteen body segments for skin temperature measurement to estimate mean skin temperature [16]. The most frequently used body locations for assessing skin temperature in the 16 existing thermoregulation models are the chest, thigh, anterior-calf, wrist, posterior upper arm, forehead, abdomen, hand, foot and scapula. The body areas are ordered by the selection frequency in the existing models alongside the sum of the weight factors assigned in each model's formula.

These body locations for skin temperature sensors are important for both control effectiveness and for practical system application of wearable sensors. In this study, 11 body locations were selected from those most frequently used in the existing models to measure skin temperatures, which are forehead, posterior upper arm, wrist, back of the hand, chest, belly, thigh, anterior calf, posterior calf, and instep of a foot. The sensing interval was 10 min for all the measurements. As the posterior-calf has a larger weight factor than the scapula, and is a more convenient sensor location, the researchers selected the posterior-calf as the 10 skin area for the experiment.

Thermocouple sensors used to measure skin temperature during the experimental chamber is running. Usually, the thermocouple sensors were held to the skin of different sites on the subjects (see Fig. 2) with porous medical tape to measure the local skin temperatures.

2.2 Experimental procedure

The steps and duration of experiment were shown in Table 2. The subjects entered the chamber and spent 10 min at the chamber prior to the test acclimatize with the room temperature [17-19]. All the three tasks of activities during which the subjects were exposed to multiple thermal conditions.

Table 2. Steps and duration of experiment.

Step	Activity	Duration (min)
1	Measured demographic of subjects	30
2	Standby in a waiting room	10
3	Start the measurement with Task 1	10 x 5 = 50
4	Break	5
5	Task 2	10 x 5 = 50
6	Break	5
7	Task 3	10 x 5 = 50
	Total	**200**

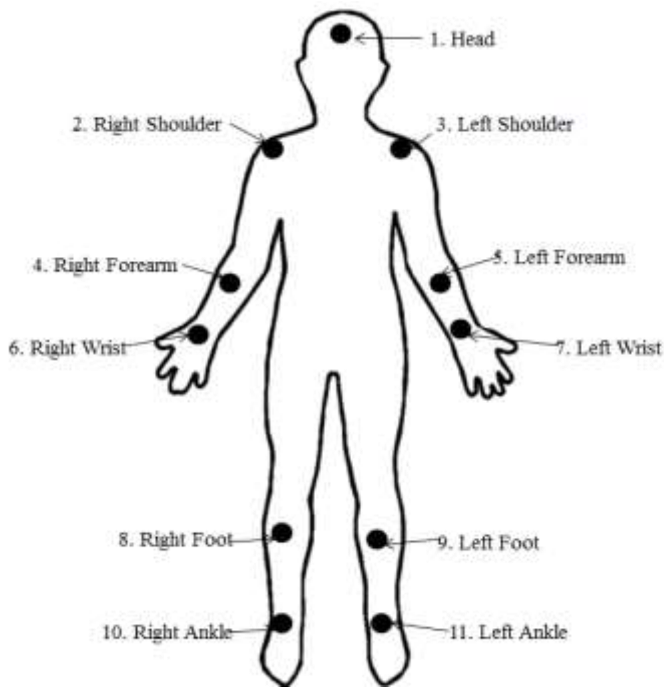

Fig. 2. Measurement points of skin temperature.

3 Theoretical models

This study is based on the thermal comfort of the human body. Therefore, it is necessary to understand what thermal comfort meaning and how to assess thermal comfort. Through many years' study on thermal comfort, Fanger [20] proposes conditions which is can satisfy thermal comfort; a) heat production and heat loss should satisfy the heat balance equation under the condition of steady state, b) skin temperature should be adapted to the thermal comfort level. Only satisfying these conditions at the same time can thermal comfort be realized. Thus, this paper based on these thermal comfort conditions to carry on this research.

3.1. The body heat balance equation

The suitable temperature is necessary to maintain the body's normal life people' activities. Thus, the body's heat production and heat dissipation should be in balanced. The body heat balance equation can be obtained [11] as Eq. (1):

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

where, M [W/m^2] is metabolic rate, W [W/m^2] is mechanical work, C [W/m^2] is the convection heat loss of skin, R [W/m^2] is the radiation heat loss of skin, E_{sk} [W/m^2] the is skin evaporation heat loss, C_{res} and E_{res} [W/m^2] are sensible and latent respiratory heat loss, respectively, S [W/m^2] is heat storage of human body.

In general, W is very low, for most kinds of activities, $W \approx 0$ [21]. S is an important factor which affects the thermal comfort of dynamic environment [22]. However, the mainly consideration of this paper is steady state, so S=0. The detailed computational methods of variables in Eq. (1) can be expressed [11]:

a) Convection heat loss, C is the convection heat transfer between the body surface and the surrounding environment. When air temperature is higher than the surface skin temperature, the value of C is positive, otherwise, the value of C is negative. Convection heat loss can be obtained as follows:

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

$$f_{cl} = 1/(1 + 0.155 \times (h_c + h_r) \times I_{cl}) \quad (3)$$

$$t_{cl} = t_{sk} - 0.155 \times I_{cl} (M - W - (C_{res} + E_{res}) - E_{sk} - S) \quad (4)$$

where f_{cl} is the clothing area coefficient; h_c [W/(m^{2o}C)] is a convective heat transfer coefficient, h_c=8.3$V^{0.5}$; h_r [W/(m^{2o}C)] is radiation heat transfer coefficient; t_{cl} [^{o}C] is the clothing surface temperature; t_a [^{o}C] is air temperature; t_{sk}[^{o}C] is skin temperature; I_{cl} [(m^{2}kPa)/W] is clothing insulation.

b) Radiation heat loss, R is the radiation heat transfer between the body surface and the surrounding environment. When the surface skin temperature is higher than the mean radiant temperature, the value of R is positive, otherwise, the value of R is negative, which can be seen in Eq. (5):

$$R = f_{cl} h_r (t_{cl} - t_r) \quad (5)$$

$$h_r = f_{rad} \varepsilon [(t_{cl} + 273.15)^2 + (t_r + 273.15)^2] \times$$
$$[(t_{cl} + 273.15) + (t_r + 273.15)] \times 5.67 \times 10^{-8}$$

where f_{rad} is the effective correction factor of human body surface, f_{rad} = 0.72; ε is the surface emissivity of the human body, ε = 0.97.

c) Skin evaporation heat loss, E_{sk} includes sweat evaporation heat loss and diffusion heat loss of moisture:

$$E_{sk} = \omega (p_{sk} - p_a) R_{ecl} h_e \quad (6)$$

$$R_{ecl} = 1/(1 + 0.143 \times h_c \times I_{cl} \quad (7)$$

$$LR = h_e / h_c \quad (8)$$

where ω is skin moisture index; p_{sk} [kPa] is a skin surface vapor pressure; p_a [kPa] is water vapor partial pressure of the surrounding air; R_{ecl} is clothing moisture permeability coefficient; LR = 16.5.

d) Respiratory heat loss includes sensible and latent respiratory heat loss, it can be obtained:

$$C_{res} + E_{res} = 0.0014 M (34 - t_a) + 0.0173 M (5.87 - p_a) \quad (9)$$

where f_{cl} and R_{cl} are determined by I_cl and h_c; h_c and p_{sk} are related to air velocity (v) and t_{sk}, respectively; t_{cl} is determined by t_{sk} and t_a; p_a is determined by t_a and RH; t_{sk} is related to M and W. Thus, if t_a, t_r, RH, v and I_{cl} are known and the upper limit of ω determined, the biggest metabolic rate can be obtained under the condition of thermal comfort [23].

4 Results and discussion

4.1 Skin temperature

This section presents the relationship between the mean skin temperature and the thermal sensation which will also allow the prediction of thermal comfort. An analysis regarding the relationship between the mean skin temperature and the thermal sensation was conducted in order to determine the effect of metabolic rate on that relationship. The data were grouped based on the metabolic rate of the subjects.

Fig. 3 show effect of skin temperature on room temperature at different body segments. There are 11 body segments consists Head (1), Right Shoulder (2), Left Shoulder (3), Right Forearm (4), Left Forearm (5), Right Wrist (6), Left Wrist (7), Right Foot (8), Left Foot (9), Right Ankle (10) and Left Ankle (11) as illustrated in Fig. 2. Fig. 3 presented the highest body segment effect is left shoulder. This is because the left shoulder position is opposite with the door of the environmental chamber. All the body segment in left position is higher than right position. This also because, the right position faces the hanging wall of air conditioning. It also happens on the right forearm and right foot, both this body segments are placed on the table and on the floor. Furthermore, no barriers for temperature go through to these body segments.

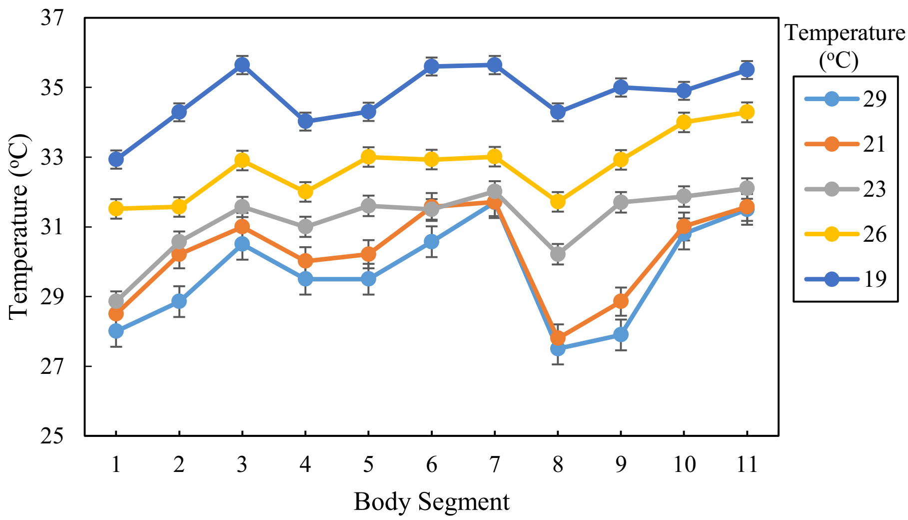

Fig. 3. Effect of skin temperature on room temperature at different body segments.

Fig. 4 shows that thermal sensation increased with the mean skin temperature in all three metabolic rate. For a given mean skin temperature, higher metabolic rate yielded a higher thermal sensation except around 34.89 °C mean skin temperature (p-value < 0.001). The results of the regression analysis for thermal sensation (see Figure 3) show a strong linear dependency for skin temperature of human. The change in mean skin temperature yielded similar changes in thermal sensation for low and medium metabolic rate conditions. However, the change in thermal sensation during the high metabolic conditions was less than the other two conditions. It can be seen that a straight line fits the data well for 1.0, 1.2 and 1.6 Met (R^2=0.7541, R^2=0.8679 and R^2=0.8467) respectively.

Under all conditions of activities, overall thermal sensation and skin temperature are correlated with each other closely. Skin temperature of 34.89 °C corresponds to thermal sensation of 0.79, that is to say, the subjects felt uncomfortable when their whole body is 34.89 °C which are more rigid than the definition proposed by Gagge et al. [24] and Fanger [25].

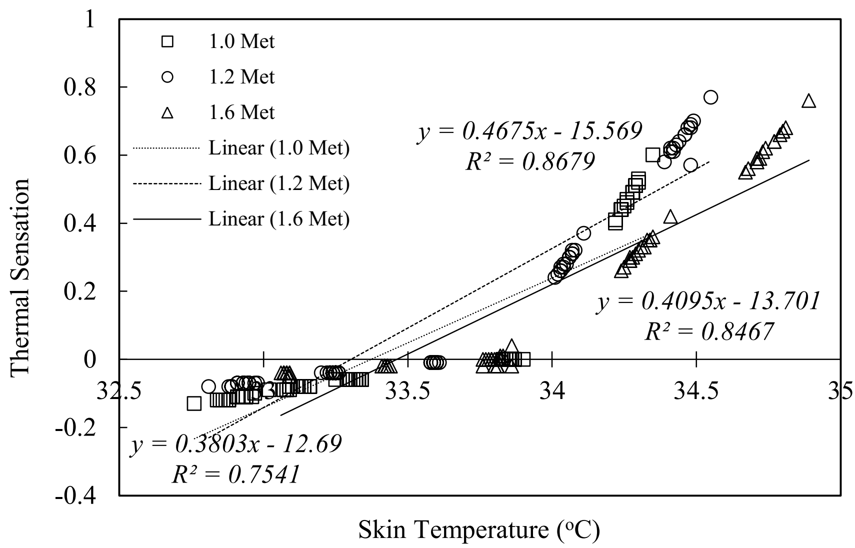

Fig. 4. The relationship between skin temperature and thermal sensation under three metabolic rate conditions.

4.2 Heat balance and heat loss of the human body

In this section, a heat balance analysis of the human body based on the specific test conditions was presented. The amount of heat stored inside the body was calculated through the increase in body temperature. The tympanic temperature measurements showed that the core body temperature is relatively stable throughout the experiment (see Table 3) and the difference between the measurements was statistically insignificant. Therefore, there was no heat storage in the body between the body temperature measurements and all the generated heat was dissipated to the environment through conduction, convection, radiation and evaporation.

Table 3. Body core temperature.

Mean body core temperature (°C)	Body core temperature Std. Dev.
36.85	0.029

The evaporative heat losses for males and females are similar were calculated as 5.01 W/m^2 respectively as illustrated in Table 4.

Table 4. Evaporative heat loss in males and females.

Gender	Average Met	Average surface area (m^2)	Duration of test (hour)	Evaporative heat loss (W/m^2)
Male	1.27	1.79	3.20	5.01
Female	1.27	1.60	3.20	5.01

An analysis was conducted to determine the relationship between the heat conduction through the body and the thermal comfort. The difference between the core temperature and skin temperature (ΔT_{cr}-T_{sk}) was normalized for body mass index (*BMI*) to take into account the insulation properties of the body. A significant correlation was detected between the ΔT_{cr}-T_{sk} and the thermal comfort at $\alpha = 0.05$ (Pearson correlation: 0.58). Fig. 5 showed the relationship between these two variables. The correlation was also significant without *BMI* normalization, however, with a lower correlation coefficient (Pearson correlation: 0.21). This shows that thermal discomfort increases with the increased thermal strain on the body, which is the difference between the core body and the skin temperature. It can be seen that core body temperature a straight line fit data well (R^2=0.58).

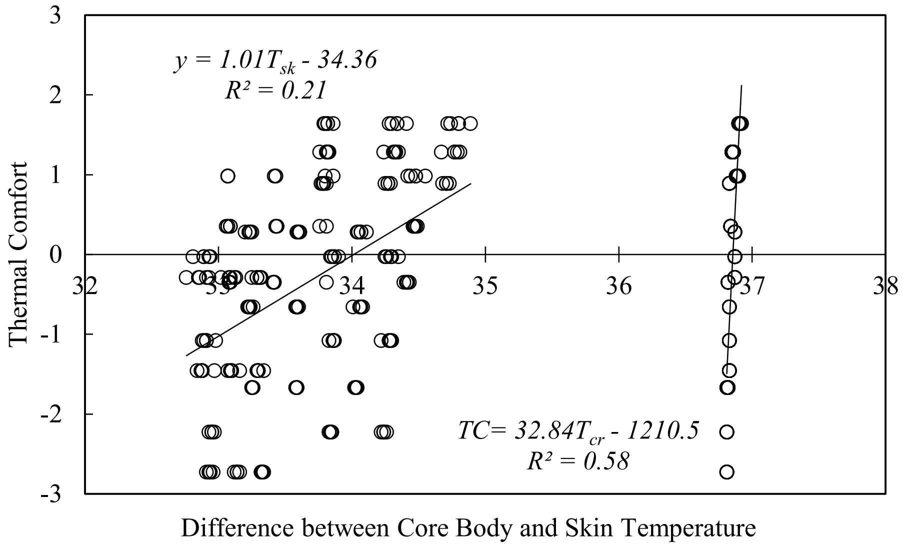

Fig. 5. Correlation between thermal comfort and the difference between core body and skin temperature.

5 Conclusions

In this paper, the effect of the increased activity level of thermal sensation was investigated. Moreover, theoretical analysis and experiment were combined to study the metabolic rate on skin temperature in different thermal conditions. The conclusions of this paper can be drawn as follows:

a) Air temperature is the one factor which affects the metabolic rate in different thermal conditions.
b) The mathematical model was established according to experiment and the thermal sensation range of skin temperature to the metabolic rate.

The conclusions of this study can provide some references to set a standard for air conditioning design and to set operating parameters of different functional architectures. Besides that, this study can achieve the goals of thermal comfort and energy conservation to some extent.

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