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Evaluation model of individual thermal comfort based on mean skin temperature

Liu Weiwei[1] Lian Zhiwei[2] Deng Qihong[1]

([1] School of Energy Science and Engineering, Central South University, Changsha 410083, China)
([2] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China)

Abstract: The local skin temperatures of 22 subjects at air temperatures of 21, 24, 26, 29 ℃ are measured, and the mean skin temperatures are calculated by ten skin temperature measuring points. The thermal comfort levels and the thermal sensations of these subjects are also investigated by a questionnaire. The Mahalanobis distance discrimination method is applied to establish the evaluation model for the thermal comfort based on the mean skin temperature. The experimental results indicate that the difference of the mean skin temperatures between the comfort level and the discomfort level is significant. Using the evaluation model, the mean skin temperature at the thermal comfort level is 32.6 to 33.7 ℃, and the thermal comfort levels of 72% of the subjects are correctly evaluated. The accuracy of the evaluation model can be improved when the effects of sex of the subject on the mean skin temperature and the thermal comfort are considered. It can be concluded that the mean skin temperature can be used as an effective physiological indicator to evaluate human thermal comfort in a steady thermal environment.

Key words: thermal comfort; mean skin temperature; Mahalanobis distance discrimination method; thermoregulation

Human thermal comfort is defined in the international standards ISO 7730 as "that condition of mind in which satisfaction is expressed with the thermal environment"[1]. Till now, thermal comfort is evaluated by using subjective evaluation methods, such as a thermal comfort questionnaire. Therefore, the evaluation results depend on the subjective expressions of the subjects, which is easily influenced by some psychological factors. For example, in a comfortable thermal environment, one may express a feeling of discomfort when he or she is in a very bad mood. Obviously, this kind of discomfort is not induced by the thermal environment but by the mood. As a result, his or her true feeling of thermal comfort cannot be reflected by a questionnaire. In fact, though thermal comfort is a condition of mind, when people have a feeling of thermal comfort or discomfort, their physiological states are different[2–3]. Using the physiological parameters, the evaluation results should be more objective and reliable than the results of the subjective evaluation methods.

Skin, scattered with a great number of cold/warm receptors connected to the cold/warm neurons in the anterior hypothalamusy, is one of the most important organs in the thermoregulatory system. Mean skin temperature is an important physiological parameter of human skin. Due to the important physiological process of vasoconstriction or vasodilatation, the mean skin temperature changes with the thermal environment and contributes much to thermal comfort[2, 4–5]. Fanger[6] indicated that the mean skin temperature was on a certain scale when people felt thermally comfortable. Some studies also indicated that the mean skin temperature was related to the thermal sensation and the thermal comfort[7–12]. Therefore, it is possible to use the mean skin temperature as an important objective index to evaluate thermal comfort. This study establishes a method to evaluate individual thermal comfort in a steady thermal environment based on the mean skin temperature.

1 Materials and Methods

1.1 Subjects

Twelve male and ten female college students (age: 23.9 ± 0.4 years, height: 170.6 ± 1.1 cm, weight: 61.2 ± 1.6 kg) are recruited for the experiments. All the subjects are healthy non-smokers. They do not take prescription medication and have no history of cardiovascular diseases. All the protocols are approved by the university's ethics committee and conform to the guidelines contained within the Declaration of Helsinki. Verbal and written informed consent is obtained from each subject prior to the participation in the protocol. The subjects are asked to avoid caffeine, alcohol, and intense physical activity at least 12 h before each experimental session.

1.2 Instruments

The local skin temperatures are measured by ten copper-constantan thermocouples attached to the skin-measuring sites by the medical plaster, as shown in Fig. 1. During the measurements, the thermocouples are linked to a multi-channel data collector (Keithley 2700, Keithley Instruments, USA), and the skin temperatures are automatically recorded to a computer via the data collector. Before the measurements, all the thermocouples are calibrated against a standard mercury thermometer with a precision of 0.1 ℃. The accuracies of the thermocouples are 0.2 ℃.

Four main environmental factors, air temperature, air humidity, air velocity, and mean radiant temperature, are measured during the experiments. The ambient temperature is measured using a standard mercury thermometer (Shanghai Huo Er Co., Ltd., China). The indoor air velocity is tested using an anemoscope (TSI Compuflow 8585, E&E Process Instrumentation, Canada), and the relative humidity of indoor air is measured with a dry-wet bulb thermometer (Shanghai Huachen Medical Instruments Co., Ltd., Chi-

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Biography: Weiwei Liu (1980—), male, doctor, associate professor, wliu@mail.csu.deu.cn.
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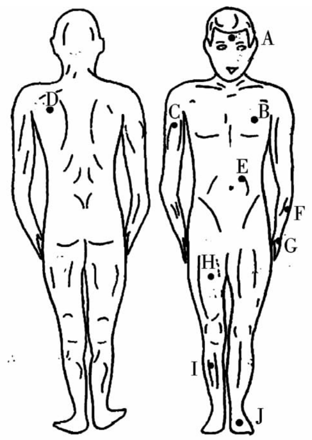

Fig. 1 Skin temperature measuring points

na). The black-bulb temperature is measured by a standard thermometer (diameter of 150 mm, Shanghai Huo Er Co., Ltd., China). The mean radiant temperature can be calculated by

$$T_r = [(t_g + 273)^4 + 0.4 \times 10^8 (t_g - t_a)^{5/4}]^{1/4} - 273 \quad (1)$$

where T_r is the mean radiant temperature; t_g is the black-bulb temperature; t_a is the air temperature.

1.3 Experimental protocol

The vests and shorts with about 0.3 clo are compulsory for the subjects. Considering that the air temperature is a main environmental factor affecting human thermal comfort[6], the skin temperatures of the subjects are measured at four air temperatures of 21, 24, 26, 29 ℃. Other thermal conditions such as the air velocity and the air humidity are kept invariable throughout the experiments. The experiments at the four indoor temperatures are carried out for only one subject in a single day. During the experiment, the subject does not know the next exposure temperature.

The measurements are made after the subject has stayed at a given ambient temperature for 40 min. During this period, the subject is asked to quietly lie on a bed. Afterwards, the local skin temperatures are measured. After the measurements, he or she is asked to complete a questionnaire about thermal comfort.

The experiments are performed in a climate chamber. All the measurements are carried out between 13: 00 (after lunch) and 17: 30. There is only one window in the climate chamber and no direct solar radiation is allowed to enter. The air temperature is controlled by using a wall-mounted air conditioner. Other thermal conditions such as the air velocity and the air humidity are kept almost invariable throughout the experiments.

1.4 Thermal sensation and thermal comfort

Thermal sensation greatly affects thermal comfort. The ASHRAE 7-point scale is used to assess the thermal sensations of the subjects. During the experiments, a thermal sensation scale is obtained by a questionnaire, in which the subject is required to choose a point (from −3 to +3) according to the thermal sensation that he or she experiences.

In the experiments, the thermal comfort of the subjects (comfortable or uncomfortable) with a particular thermal sensation is asked in the questionnaire. And the subjects are asked to describe whether they sweat when they feel warm or hot.

1.5 Calculation of mean skin temperature

A ten-point formula is used to calculate the mean skin temperature, which can be expressed as[13]

$$t_{sk} = 0.06t_A + 0.08t_C + 0.06t_F + 0.05t_G + 0.12t_D + 0.12t_B + 0.12t_E + 0.19t_H + 0.13t_I + 0.07t_J \quad (2)$$

where t_{sk} is the mean skin temperature; t_A to t_J are the skin temperatures of the ten measuring points shown in Fig. 1, respectively.

1.6 Mahalanobis distance discrimination method

The evaluation of the thermal comfort by mean skin temperature can be solved based on the theory of multivariate analysis[14]. Therefore, the Mahalanobis distance discrimination method is applied to establish the evaluation model.

The Mahalanobis distance between a sample and a population is defined as

$$d^2(y, \boldsymbol{G}) = (y - \mu)' \boldsymbol{V}^{-1} (y - \mu) \quad (3)$$

where $d^2(y, \boldsymbol{G})$ is the Mahalanobis distance between the sample y and the population $\boldsymbol{G}$; μ is the mean of the population; $\boldsymbol{V}$ is the covariate matrix of the population and $\boldsymbol{V} > \boldsymbol{0}$.

The Mahalanobis distance discrimination method is used to judge which population a sample belongs to according to the minimum of the Mahalanobis distance. The principle is described as follows.

Suppose that D_i is a set of samples in which the Mahalanobis distance from any sample to the population G_i is minimal, Then,

$$D_i = \{y: d^2(y, G_i) \leqslant \min_{j \neq i} d^2(y, G_j)\} \quad i = 1, 2, \ldots, k; j = 1, 2, \ldots, k \quad (4)$$

where $d(y, G_i)$ is the Mahalanobis distance between the sample y and the population G_i; k is the total number of the populations. Thus, if y falls within the set D_i, then $y \in G_i$.

The Mahalanobis distance discrimination method is available when the difference among several populations is significant. When evaluating the thermal comfort by mean skin temperature, a set of the skin temperatures at a thermal comfort level is a population, and one person's skin temperature in the thermal environment is a sample.

1.7 Statistical analysis

Data are expressed as means ± SEM. An ANOVA (Student-Newman-Keuls test) is used to perform a test of significance on mean skin temperatures at different thermal comfort levels. The level of significance is set to $p < 0.05$.

2 Results and Discussion

2.1 Thermal comfort and thermal sensation

Tab. 1 shows that an indoor air temperature of 21 ℃ make most subjects feel uncomfortable with a sensation of coolness or cold. 29 ℃ is a temperature likely to provoke a sensation of warmth, with 15 subjects feeling uncomfortable. At the temperatures of 24 and 26 ℃, all the subjects feel comfortable.

Tab. 1 Number of subjects for thermal comfort and thermal sensation

Temperature/℃	Hot		Warm		Slightly warm		Neutral		Slightly cool		Cool		Cold	
	C	U	C	U	C	U	C	U	C	U	C	U	C	U
21	0	0	0	0	0	0	0	0	0	0	2	9	0	11
24	0	0	0	0	0	0	2	0	5	0	15	0	0	0
26	0	0	1	0	2	0	18	0	1	0	0	0	0	0
29	0	0	7	15	0	0	0	0	0	0	0	0	0	0

Note: C means comfortable and U means uncomfortable.

2.2 Mean skin temperatures at different thermal comfort levels

Considering the thermal sensations of the subjects, the thermal comfort can be divided into three levels, cool discomfort, comfort and warm discomfort. The statistical results of the mean skin temperatures of the subjects at the three thermal comfort levels are listed in Tab. 2.

Tab. 2 Mean skin temperatures at three thermal comfort levels

Item	Cool discomfort	Comfort	Warm discomfort
Number of samples	22	51	15
Mean ± SEM/℃	31.94 ± 0.17	33.10 ± 0.09	34.23 ± 0.14
Std. deviation/℃	0.79	0.63	0.54
Minimum/℃	30.13	31.85	32.52
Maximum/℃	33.38	34.66	35.20

In the experiments, two characteristics on the mean skin temperatures at different thermal comfort levels are observed. First, the difference in the mean skin temperatures at the comfort and discomfort levels is statistically significant (Student-Newman-Keuls test, $P < 0.05$), due to the significant effect of the thermoregulation on the mean skin temperatures. Secondly, the trend in the mean skin temperature is nearly linear when the thermal sensation changes from cold to warm, which reflects the sensitivity of the mean skin temperature to the thermal sensation. Similar results can also be found in previous studies[15-16]. Both the characteristics indicate that the mean skin temperature is a proper index to reflect human thermal comfort with a detailed division by thermal sensation.

2.3 Evaluation model

An evaluation model of thermal comfort based on the mean skin temperature can be established by the Mahalanobis distance discrimination method. The evaluation model can be expressed as

$$y \in G_1 \qquad t_{sk} < 32.6\ ℃$$

$$y \in G_2 \qquad 32.6\ ℃ \leqslant t_{sk} \leqslant 33.7\ ℃$$

$$y \in G_3 \qquad t_{sk} > 33.7\ ℃$$

where G_1, G_2, G_3 are the populations of cool discomfort, comfort and warm discomfort, respectively.

Clearly, the mean skin temperature 32.6 ℃ is the limit between cool discomfort and comfort, and 33.7 ℃ is the limit between comfort and warm discomfort. The mean skin temperature range for the thermal comfort level is illustrated in Fig. 2.

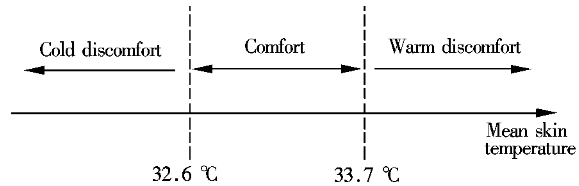

Fig. 2 Scale of mean skin temperature at different thermal comfort levels

2.4 Reliability of evaluation model

This evaluation model indicates that when a person's mean skin temperature is within the range of 32.6 to 33.7 ℃, his or her thermal comfort level is evaluated as comfort. However, due to the physiological differences in the mean skin temperature, the model is not appropriate for everyone.

An index of the accuracy is used to reflect the reliability of the evaluation method, which can be calculated by

$$A = \frac{N_T}{N_T + N_F} \times 100\% \tag{5}$$

where A is the accuracy; N_T is the number of the correctly evaluated samples; N_F is the number of the wrongly evaluated samples.

The evaluation results based on the evaluation rule is listed in Tab. 3. The mean skin temperatures and the thermal comfort levels are obtained from the 22 subjects in the experiments.

Tab. 3 Evaluation results of thermal comfort levels

Item		Cool discomfort	Comfort	Warm discomfort	Total
Number of samples	True	18	32	13	63
	False	13	4	8	25
Accuracy/%		58	89	62	72

Note: "True" means correctly evaluated; "false" means wrongly evaluated.

The total number of the samples is 88. As depicted in Tab. 3, the number of the correctly evaluated samples is 63, and the accuracy is 72%. That is, most subjects' thermal comfort levels are exactly evaluated according to their mean skin temperatures. The results indicate that the mean skin temperature can be used as a reliable objective index to evaluate thermal comfort. For the comfort level, the accuracy reaches a high value of 89%.

However, it can also be seen that 28% of the total number are wrongly evaluated. A main reason for this is that the difference in the mean skin temperatures exists for different persons though they are at the same comfort level. The data in this study indicate that several subjects' mean skin temperatures do not fall within the statistical scale of the mean skin temperature at the thermal comfort level. As a result, their thermal comfort levels are not correctly evaluated. Therefore, if the effect of the individual difference in the mean skin temperature and the thermal comfort can be reduced, a high reliability can be achieved.

2.5 Limitation of evaluation method

When heavy sweat occurs, the strong evaporative cooling effect is a predominant factor that determines the thermal comfort[11]. In this state, the mean skin temperature cannot reflect the true feeling of the thermal comfort.

The model in this study is established based on the mean skin temperatures and the feelings of the thermal comfort in a steady and uniform thermal environment. It needs to be further studied that whether or not the mean skin temperature is an effective index in evaluating the thermal comfort in a transient and non-uniform thermal environment.

3 Conclusion

The difference in the mean skin temperatures at the comfort and discomfort levels is significant. Using the evaluation method established in this study, most(72%) subjects' thermal comfort levels are correctly evaluated by their mean skin temperatures. Therefore, considering the physiological relationship between the skin temperature and the thermal comfort, the mean skin temperature can be used as an effective physiological indicator to evaluate human thermal comfort.

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基于平均皮肤温度的个体热舒适评价模型

刘蔚巍[1]　连之伟[2]　邓启红[1]

([1] 中南大学能源科学与工程学院, 长沙 410083)

([2] 上海交通大学机械与动力工程学院, 上海 200240)

摘要: 在环境温度为21,24,26,29 ℃的条件下测量了22个受试者的局部皮肤温度,并基于10个皮肤温度测试点对受试者的平均皮肤温度进行了计算. 然后,对受试者的热舒适程度和热感觉进行了问卷调查. 采用马氏距离判别法建立了基于平均皮肤温度的个体热舒适评价模型. 实验结果表明,受试者在热舒适与热不舒适时的平均皮肤温度有显著差异. 根据评价模型可知:人体感到热舒适时的平均皮肤温度范围为32.6~33.7 ℃;该模型对72%的受试者的热舒适程度进行了正确判断;考虑性别差异对平均皮肤温度和热舒适程度的影响有助于提高模型的精确度. 因此,平均皮肤温度可作为一个有效评价稳态热环境下个体热舒适的生理指标.

关键词: 热舒适;平均皮肤温度;马氏距离判别法;体温调节

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