RESEARCH ON THE CALCULATION METHOD OF DRESSING THERMAL RESISTANCE BASED ON INFRARED THERMAL IMAGING TECHNOLOGY

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Abstract. With the popularity of intelligent technology, it has become an important trend to control the air conditioning terminal equipment intelligently to build the comfortable indoor environment. Therefore, it is necessary to automatically collect environmental and individual parameters (metabolic rate and clothing thermal resistance) and calculate PMV to predict human thermal sensation in real time. In this process,environmental parameters can be automatically measured and uploaded by the device. The metabolic rate is related to human level of activity . However,clothing thermal resistance is affected by many factors such as environment and level of activity.Taking the clothing thermal resistance as a fixed value according to thermal comfort standards will lead to deviations in thermal sensation prediction. In addition, many Chinese dresses cannot be found corresponding thermal resistance value in the thermal standard. In view of this,this paper studies two algorithms to obtain clothing surface temperature and calculate clothing thermal resistance by taking thermal image of the dressed human body with the infrared thermal imager,and compare them with the method of finding the clothing thermal resistance database in thermal comfort standard.And then,we calculate the PMV(predicted mean vote) using clothing thermal resistance obtained by three methods.The results of PMV and the questionnaire(ASV) are compared to analyze the feasibility of these methods. The results show that the mean deviation between the PMV calculated by one algorithm and the ASV is 0.33 scale when sitting in single-layered dress in summer,and that is 0.45 scale when sitting in multi-layered dress in winter.The results of PMV is significantly correlated with ASV. All of these prove that clothing thermal resistance can be calculated by this non-contact method, and it can be benefit to obtain indoor human thermal sensation and adjust and control thermal environment intelligently.

1 Introduction

With the trend of intelligent control of environmental control equipment, it becomes necessary to collect and analyze personnal and environmental parameters in real time.When testing and evaluating the indoor thermal environment,environmental parameters can be measured and adjusted in real time by various devices.The metabolic rate of the human body can be set with reference to thermal comfort standards according to the level of activity. Different from the above parameters, due to individual differences, the dressing situation of each person in the same environment is different.

At present, clothing thermal resistance is often determined by questionnaire survey of actual dress combined with the clothing thermal resistance database in thermal comfort standard ISO 9920.However, due to our multi-layered dressing habits and increasing diversity of modern clothing types and combinations, the database can no longer meets the demand.Moreover, the actual dressing thermal resistance in wearing state will also change. Konarska [1] et al. arranged thermocouples on the surface of human body to measure the skin temperature and calculated clothing thermal resistance through human body heat balance analysis. Olesen and Nielsen [2] and McCullough [3] et al. obtained the relationship between clothing weight and thermal resistance by regression analysis.Although these methods are low cost, they cannot achieve real-time intelligent evaluation of human thermal comfort because they all interfere with the subject and cannot be used to obtain the clothing thermal resistance by non-contact methods.

Therefore, with the advent of non-contact testing methods for infrared thermography, Matsumoto [4] et al. established a database of the relationship between clothing weight and clothing thermal resistance.The infrared thermal imager recognized the image of the garment and predicted the mass of the garment, and estimated the thermal resistance range. However, it is difficult to predict clothing thermal resistance without the actual weight of garment accurately.

Miura [5] et al. used infrared thermal imager to photograph the surface temperature of the dressed human body and extract the skin temperature of exposed area and clothing temperature to estimate clothing thermal resistance. However, the experiments were

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conducted on a small number of subjects and only on upper body attire. Jeong-Hoon Lee [6] proposed an algorithm to calculate clothing thermal resistance by using infrared thermal imager to capture the temperature of the face, neck and clothing surface.The algorithm also considered the influence of wind speed and step speed, and was verified by simulation. These two methods are based on infrared thermography,and the difference lies in calculation formula and the method of obtaining skin temperature. Considering that the mean skin temperature is closely related to human thermal sensation, the author substitutes mean skin temperature in the algorithm proposed by Miura et al. to calculate clothing thermal resistance (called Method 2).At the same time,considering that the face and neck are sensitive to human thermal sensation, clothing thermal resistance is calculated by substituting the face and neck temperature in Jeong-Hoon Lee's algorithm (called Method 3).

In this paper,in the conditions of light summer clothes and heavy winter clothes, the clothing thermal resistance is calculated respectively by taking the value of clothing thermal resistance database in thermal comfort standard (called Method 1), Method 2 and Method 3 .We calculated the PMV values obtained by the three methods respectively, and then compared the actual thermal sensation vote. The feasibility of different methods in calculating indoor actual dressing thermal resistance is analyzed, which provides basic data for automatic evaluation and regulation of thermal environment.

2 Three kinds of clothing thermal resis -tance algorithm

Method 1 is to find clothing thermal resistance database according to clothing matching, and then calculate thermal resistance of the whole set of clothing with formula (1). The clothing thermal resistance database is taken from ISO 9920 [7] .

$$I_{cl} = 0.161 + 0.835\sum I_{clu,i} \quad (1)$$

Where $I_{clu,i}$ is thermal resistance of a single garment, clo;$I_{clu,i}$ is thermal resistance value of the whole set of garment, clo.

Method 2 is to take the whole-body temperature distribution image of the subject with the infrared thermal imager, and obtain the clothing surface temperature after being processed by the software AnalyzIR (the emissivity of dark clothing is 0.95 and that of light color is 0.9 in this experiment).Miniature skin temperature sensors are pasted on the subject's forehead, chest, back, left and right hand backs, left and right upper arms and left and right thighs to calculate the mean skin temperature [8].The air temperature and air velocity are measured by portable anemometer, and the black-bulb temperature is measured by black-bulb thermometer.

Miura's method is adopted for the calculation formula of clothing thermal resistance, but skin temperature is substituted for the mean skin temperature. The calculation formulas are shown in (2) - (5) [5].

$$I_{cl} = \frac{1}{0.155h}\frac{t_{sk}-t_{cl}}{t_{cl}-t_o} \quad (2)$$

$$t_{sk} = 0.07t_{head} + 0.175t_{chest} + 0.175t_{back} + 0.025t_{L\ hand\ back} + 0.025t_{R\ hand\ back} + 0.07t_{L\ upper\ arm} + 0.07t_{R\ upper\ arm} + 0.195t_{L\ thigh} + 0.195t_{R\ thigh} \quad (3)$$

$$t_0 = At_a + (1-A)t_r \quad (4)$$

Table 1. Table of A values

v_r	0~0.2m/s	0.2~0.6m/s	0.6~1.0m/s
A	0.5	0.6	0.7

where h is the heat transfer coeffiffifficient of the human body (set to 8.6 assuming a calm indoor environment [9]) ; I_{cl} is clothing thermal resistance,clo; t_{sk} is the mean skin temperature,℃； t_{cl} is the clothing surface temperature,℃; $t_0$is the operating temperature,℃;t_a is the air temperature, ℃ ; t_r is the mean radiation temperature,℃.

$$t_r = [(t_g+273)^4 + \frac{0.25*10^8}{\varepsilon_g}(\frac{|t_g-t_a|}{D})^{1/4}(t_g-t_a)]^{1/4} - 273 \quad (5)$$

Where t_g is the black-bulb temperature,℃; ε_g is the emissivity,taken as 0.95; D is diameter of black-bulb thermometer,m.

Method 3 is to collect temperature distribution image of human body surface with infrared thermal imager, and calculate the clothing surface temperature and skin surface temperature with AnalyzIR.The air temperature and air velocity are measured by portable anemometer.

The calculation formula of clothing thermal resistance adopts the method proposed by Jeong Hoon Lee, but skin temperature is replaced by the skin temperature of face and neck. The calculation formulas are shown in (6) - (11) [6].

$$0.305I_{cl}^2 + I_{cl} - \frac{1}{0.155C_{orr,tot}}\{\alpha + I_{a-st}(C_{orr,ia} - C_{orr,tot})\} = 0 \quad (6)$$

$$\alpha = \frac{t_s - t_{cl}}{h_c(t_{cl}-t_a) + 3.85*10^{-8}(t_{cl}^4 - t_r^4)} \quad (7)$$

$$h_c = \begin{cases} 2.38|t_{cl}-t_a|^{0.25} & 2.38|t_{cl}-t_a|^{0.25} \geq 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & 2.38|t_{cl}-t_a|^{0.25} \geq 12.1\sqrt{v_{ar}} \end{cases} \quad (8)$$

$$C_{orr,tot} = \begin{cases} C_{orr,tot} & I_{cl} \geq 0.6 \\ \frac{I_{cl}(C_{orr,cl} - C_{orr,ia})}{0.6} & I_{cl} < 0.6 \end{cases} \quad (9)$$

$$C_{orr,ia} = e^{\{-0.559(v_{ar}-0.15)+0.057(v_{ar}-0.15)^2+0.271v_w-0.027v_w^2\}} \leq 1.0 \quad (10)$$

$$C_{orr,cl} = e^{\{-0.263(v_{ar}-0.15)+0.0272(v_{ar}-0.15)^2-0.193v_w+0.101v_w^2\}} \leq 1.0 \quad (11)$$

$C_{orr,ia}$ and $C_{orr,cl}$ represent the correction factors for wind speed and human walking speed respectively. αrepresents the temperature gradient between the skin and the clothing surface divided by the dry heat loss per unit of human surface area (convection and radiation).The formula deduces the dynamic field with a correction factor reflecting the air velocity effect from the static definition, so it is a general algorithm of clothing thermal resistance under static and dynamic conditions.

3 Experimental survey

3.1 Subjects and dress

The experiments are carried out in the laboratory of Qingdao University of Technology. It is divided into two conditions: single-layered dress in summer and multi-layered dress in winter. There is no air conditioning in the room. The windows are opened in summer for natural ventilation, and the windows are closed in winter. Environmental parameters such as air temperature, black-bulb temperature, relative humidity and air velocity around the subject are measured during the experiment. The subjects sit still and the infrared thermal imager collects the temperature of the human body and clothing surface.

The subjects are 35 healthy college students, including 18 males and 17 females. And individual information is shown in Table 2:

Table 2. Information regarding subjects

Sex	Age	Height (m)	Weight (kg)
Male	23.7±0.8	177.3±2.7	70.4±8
Female	24±0.8	164.6±4.2	53.9±5.3
Average	23.8±0.8	171.3±7.1	62.4±10.8

The experiment is divided into two conditions, summer and winter, and there are 70 experiments in total.Subjects can wear their own dress according to their needs. There are four kinds in summer and five kinds in winter. See Table 3 for details:

Table 3. Subject's clothing combination

Season	clothing combination	Num
Summer	Short -sleeved top + shorts + sandals	12
	Short -sleeved top +short skirts + sandals	4
	Short -sleeved top+thin pants+sneakers	14
	Thin long -sleeved top +thin pants + sneakers	5
Winter	Long-sleeved top+long pants + sneakers	3
	Thermal underwear +long -sleeved top + long pants +sneakers	12
	Thermal underwear + thick long -sleeved top +jacket +long pants +sneakers	13
	Thermal underwear +long -sleeved top + coat +long pants +boots	4
	Thermal underwear +long -sleeved top + down jacket +long pants +sneakers	3

3.2 Experiment process

(1)The subjects sit in the laboratory for 20 minutes to adapt to the environment.

(2)Miniature skin temperature sensors are pasted on the subjects' forehead, chest, back, left and right back of hands, left and right upper arms and left and right thighs. The subjects sit for 15 minutes. The infrared thermal imager is used to take images of the subject's temperature distribution, and the subjects need to fill out their clothing matching and thermal comfort questionnaire. (as shown in Figure 1-2)

(3)During this period, the air temperature, air velocity, relative humidity and dew point temperature are measured by portable anemometer, and the black-bulb temperature are measured by black-bulb thermometer. They are placed on the table in front of the subjects for data collection. The information of equipment used in the experiments is shown in Table 4.

(4)After the test, the subjects take down sensors. The same steps are followed for single-layered dress in summer and multi-layered dress in winter respectively.

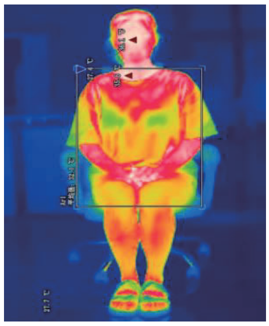

Fig. 1. Subject sit in experiment. **Figure 2.** Thermal image taken by infrared thermal imager

Table 4. Equipment used in the experiments

Equipment	Specifications	pic
Portable anemometer	NK 5500, (v): ±3%, 0.1m/s; (t): 1℃, 0.1℃; (φ):3%, 0.1	
Black-bulb temperature	HI-2000SD, 0.1℃, ±0.6℃	
Infrared thermal imager	Fortric326c, 0.1℃, ±2%	
Miniature skin temperature sensors	iButton DS1923, 0.1℃, ±0.5℃	

4 Results and analysis

4.1 Single-layered light dress in summer

Three algorithms [Eqs. (1)- (11)] are used to calculate clothing thermal resistance in winter and summer conditions,and they are marked as I_{cl1} I_{cl2} and I_{cl3}.And then we calculate the PMV values, marked as PMV_1、PMV_2 and PMV_3 respectively. The results are as follows:

The results of clothing thermal resistance calculated by the three methods are processed by ORIGIN for outliers (as shown in Figure 3).

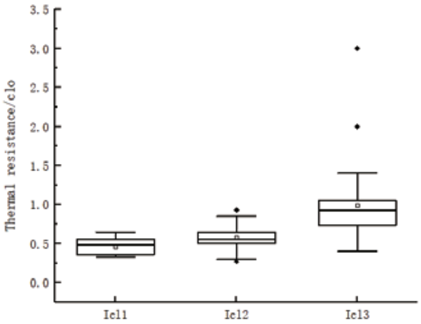

Fig.3. Box diagram of clothing thermal resistance in summer

It can be seen that I_{cl1} is minimum and stable when subjects sit in single-layered dress in summer. I_{cl3} is generally larger than I_{cl2}, and both are larger than I_{cl1}. The mean value of I_{cl1} is 0.46clo. That of I_{cl2} is 0.58clo, and that of I_{cl3} is 0.89clo. Method 1 calculates clothing thermal resistance without being worn on the human body according to the thermal comfort standard ISO7730. Method 2 and Method 3 calculate the thermal resistance of dress human body taking into account the overall thermal resistance of the interaction between human body and clothing, and between clothing and environment. Therefore, clothing thermal resistance calculated by Method 2 and Method 3 is larger than that calculated by Method 1.

In order to analyze the difference of three calculation methods of clothing thermal resistance in the prediction of human thermal sensation, the thermal resistance calculated by three methods is brought into the PMV calculation formula. The obtained PMV_1、PMV_2 and PMV_3 are compared with the actual thermal sensation(ASV) obtained from the questionnaire.The results of the mean deviation of PMV_1、PMV_2、PMV_3 and ASV are shown in Table 5.

Table 5. Mean deviation between PMV and ASV in summer

MD between PMV_1 and ASV(scale)	MD between PMV_2 and ASV(scale)	MD between PMV_3 and ASV(scale)
0.68	0.48	0.33

The correlation analysis between PMV and ASV was performed using SPSS ,and the results obtained are shown in Table 6.

Table 6. Correlation between PMV and ASV in summer

	PMV_1 and ASV	PMV_2 and ASV	PMV_3 and ASV
case	35	33	33
Significance coefficient α	0.356	0.078	0.000
Correlation coefficient r	0.161	0.311	0.593**

The results show that PMV_3 is significantly correlated with ASV.($\alpha < 0.01, 0.5 \leqslant r < 0.8$, α represents the level of significance,r is the correlation coefficient) PMV_2 is low correlated with ASV.($\alpha < 0.1, 0.3 \leqslant r < 0.5$) There is no correlation between PMV_1 and ASV.($\alpha < 0.5, r < 0.3$) The deviation between PMV and ASV is the smallest calculated by Method 3 and the largest calculated by Method 1.The thermal sensation calculated by Method 3 is the closest to subjects' actual thermal sensation. Therefore, Method 3 can predict the thermal comfort of indoor people more accurately in summer when sitting in a single-layered dress than Method 1 and Method 2.

4.2 multi-layered heavy dress in winter

Similarly,the results of clothing thermal resistance calculated by the three methods are processed by ORIGIN for outliers (as shown in Figure 4).

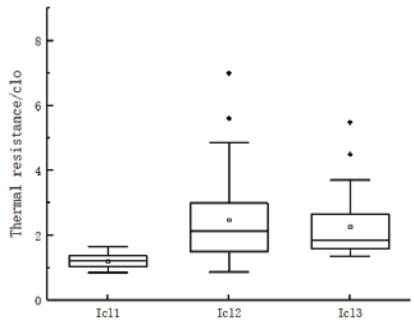

Fig.4. Box diagram of clothing thermal resistance in winter

It can be seen that compared to the result in summer, I_{cl2} and I_{cl3} are larger than I_{cl1}. Overall, I_{cl2} is slightly larger than I_{cl3}. The mean value of I_{cl1} is 1.21clo. That of I_{cl2} is 2.16clo, and that of I_{cl3} is 2clo.

The PMV calculated by three methods were compared with the ASV ,and the results of the mean deviation of PMV_1、PMV_2、PMV_3 and ASV are shown in Table 7.

Table 7. Mean deviation between PMV and ASV in winter

MD between PMV_1 and ASV(scale)	MD between PMV_2 and ASV(scale)	MD between PMV_3 and ASV(scale)
0.68	0.57	0.45

The correlation analysis between PMV and ASV was performed using SPSS ,and the results obtained are shown in Table 8.

Table 8. Correlation between PMV and ASV in winter

	PMV_1 and ASV	PMV_2 and ASV	PMV_3 and ASV
case	35	33	33
Significance coefficient α	0.075	0.078	0.081
Correlation coefficient r	0.305	0.311	0.308

The results show that PMV_3 is low correlated with ASV.(α < 0.1,0.3 ≤ r < 0.5) PMV_2 is low correlated with ASV(α < 0.1,0.3 ≤ r < 0.5) and PMV_1 is low correlated with ASV.(α < 0.1,0.3 ≤ r < 0.5) The deviation between PMV and ASV is the smallest calculated by Method 3 and the largest calculated by Method 1.The correlations between PMV values and ASV were both low. The thermal sensation calculated by Method 3 is the closest to subjects' actual thermal sensation. Therefore, Method 3 can better predict the thermal comfort of indoor people in winter when sitting in multi-layered dress.

5 Conclusion

This paper studies two non-contact algorithms for measuring dressing thermal resistance and analyzes the feasibility of the algorithm in different conditions to evaluate human thermal sensation, and compares it with the traditional method of finding clothing thermal resistance database. The results show that when the indoor people sit with a single-layered dress in summer, the actual dress thermal resistance measured by Method 2 and Method 3 is slightly larger than the static dress thermal resistance measured by Method 1. The mean deviation between PMV_3 and ASV is the smallest, which is 0.33 scale, and the correlation coefficient r of the two is 0.593**,which is highly significant.Therefore, the non-contact Method 3 can evaluate the thermal sensation of indoor sitting people with light single-layered summer dress effectively. When the indoor sitting people with heavy multi-layered dress, the difference between actual thermal resistance measured by Method 2、Method 3 and Method 1 is larger than that in summer. The mean deviation between PMV_3 and ASV is the smallest, which is 0.45 scale, and the correlation coefficient r of the two is 0.308, which belongs to low correlation. These show that the predicted accuracy of Method 3 in the case of multi-layered dressing in winter is slightly worse than that in the case of single-layered dressing in summer, but it is also a good way to evaluate the thermal comfort of indoor personnel in winter. The predicted results of Method 3 in both summer and winter conditions are better than those of Method 2, and the data collected by Method 3 has no interference to personnel.

Through Method 3 studied in this paper, the thermal sensation of indoor personnel can be predicted in real time, and the terminal equipment in the air conditioning system can be adjusted to maintain a comfortable indoor environment synchronously. This method only verified the sitting state of indoor personnel, which has certain limitations. The applicability of people in different levels of activity such as uniform clothing, solar radiation, standing and walking still needs to be investigated or corrected further.

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