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Skin temperature measurement method

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Abstract: To improve the accuracy of skin temperature measurements in thermal comfort research, a new measurement method based on a new thermometer is proposed. A platinum film resistance (Pt1000) sensor of the thermometer is welded on a printed circuit board to eliminate the heat loss from the leads and avoid the influence of the surrounding thermal environment. In order to determine the suitable thickness of the board, a steady heat conduction model is established. The simulation results reveal that when the thickness of the board is 0.2 mm, the influence of the surrounding air can be effectively prevented and the skin temperature does not obviously increase. The experimental results of verification show that the maximum measurement error of the skin temperature measured by the thermometer is 0.24 ℃, and the average measurement error of the skin temperature is 0.04 ℃. The proposed method provides an effective and reliable option for the skin temperature measurement in thermal comfort research.

Key words: thermal comfort; skin temperature; measurement; platinum film resistance

Skin temperature, which indicates the physiological state produced by the heat exchange between a human body and the surrounding thermal environment, is an important index for thermal comfort evaluation. Studies show that the predicted mean vote (PMV) model[1] can evaluate thermal comfort accurately in a steady, uniform environment when the measured mean skin temperature (MST) is replaced by the fixed MST[2]. Liu[3] proposed that thermal comfort was directly assessed with the measured MST and concluded that the MST varied in the range of from 32.49 to 33.66 ℃ when people felt thermal comfort. Zhang et al.[4-6] presented that the skin temperature was one of the most important physiological parameters for thermal comfort evaluation in a transient and non-uniform thermal environment. Great attention has been paid to the accurate measurement of skin temperature in recent years. In this paper, a new measurement method of skin temperature is proposed.

1 Measurement Method

1.1 Skin temperature measurement

There are two categories of methods for skin temperature measurement: the indirect method and the direct method[7]. With the indirect method, the infrared radiation emitted by the skin is measured and the average skin temperature is deduced over the emitting area with an assumed average emissivity of the skin surface. The indirect measurement has an advantage in convenience, but its accuracy is poor because a precise emissivity of the skin is hard to obtain. Moreover, it is difficult to measure the parts covered by clothes with infrared instruments in thermal comfort experiments when the participants wear clothes.

In the direct method, the skin temperature is measured by a sensor which is directly contacted with the skin surface. The accuracy of the measurement greatly depends on how closely the temperatures of the sensor and the skin in the thermal equilibrium approach the temperature of the uncovered skin. Contact thermometers are widely used in thermal comfort researches due to their good accuracy, low costs and high sensitivity in skin temperature measurement. Skin temperature is usually measured by a thermocouple, which is connected to a copper plate with a solder joint to reduce the heat losses of the wires. Although the thermocouple can contact with the skin well and respond quickly, there are several shortcomings as follows:

1) The thermocouple has a poor stability and a great measurement error.

2) The thermocouple made by a thin wire is very tiny, so the error reduced by the heat losses of leads is relatively great.

3) The thermistor is subjected to randomly varying temperature fluctuations in air even when the surface temperature is a constant[7]. This kind of influence also affects the thermocouple when it is taped to the skin by surgical tape.

4) The temperature difference between the skin and the thermocouple exists, although the thermal resistance of the copper plate is low.

5) The solder joint produced by the welding procedure can affect the measurement results.

6) The conventional thermometers inevitably press the skin to obtain a good contact, which hence alters the blood flow distribution of the dermal microcirculation and obviously increases the skin temperature at the contact point[7].

1.2 New thermometer

To overcome the shortcomings of the thermocouple, a new thermometer, designed for skin temperature measurement, is proposed (see Fig. 1). The sensor is made of platinum film resistance (Pt1000), which is widely used for surface temperature measurement. In order to protect the sensor from being damaged by sweat, an insulating compound is painted on the thermometer. Compared with the thermocouple, the platinum film resistance contacts with the skin better and responds more quickly because of its film coat and the micro-grade thickness of, platinum. Moreover, the platinum film resistance is more stable and can measure the skin temperature with a higher accuracy than the thermocouple. The size of the platinum film resistance is 2.08 mm × 1.32 mm × 0.36 mm.

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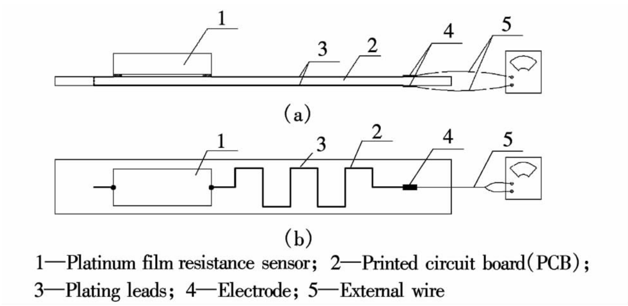

Fig. 1 Structure diagram of new thermometer. (a) Side view; (b) Vertical view

The platinum film resistance is welded on a printed circuit board(PCB) and connected with external wires through two plating leads on the board. The new thermometer has several advantages as follows:

1) The sensor welded on the circuit board is not easily broken.

2) The error caused by the heat losses of the leads can be ignored because the plating leads indirectly connect to the external wires.

3) The thermometer can contact well with the skin because the thickness of the platinum film resistance is so small (0.36 mm) that it can sink into the skin when the thermometer is taped to the skin.

4) The thermal resistance of the board can prevent the thermometer from being influenced by the surrounding thermal environment.

5) The pressure imposed on the skin by the film resistance with a thickness of 0.36 mm is very low and can be controlled in a narrow range because the board only contacts with a small area of the skin.

2 Thermal Analysis

The thermal analysis results indicate that the thermolysis changes when the platinum film resistance thermometer contacts with the skin. Due to the difference in the initial temperatures between the thermometer and the skin, the temperature of the skin changes immediately as soon as the skin comes in contact with the thermometer. The steady heat transfer rate from the skin to the surrounding air also changes because the normal radiation and convection between the skin and the environment is obstructed when the skin is covered by the thermometer. When a thermal equilibrium is obtained, the skin temperature can be measured.

2.1 Heat conduction model

Insulation is added at the top of the film resistance sensor to prevent the influence of the environmental temperature on the sensor during the skin temperature measurement. If the insulation is high, the local skin temperature increases. Contrarily, if the insulation is low, the thermometer may be inevitably influenced by the air temperature. Therefore, a steady heat conduction model is developed to determine the appropriate insulation level. The schematic representation of the heat exchanges among the skin, the thermometer and the ambient air is shown in Fig. 2. At the skin-air interface, the heat exchange from the skin surface generally includes three parts: convection, radiation and evaporation. At the board-air interface, the heat exchange is composed of convection and radiation as evaporation is prohibited. Below the skin surface, the heat exchange contains the conduction between the tissues, the conduction between the tissues and the blood, and the heat generated by metabolic activity.

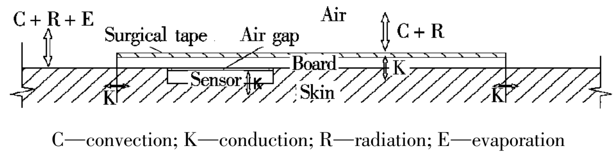

Fig. 2 Schematic representation of heat exchanges

In this study, although the heat conduction model cannot precisely predict the skin surface temperature and the temperature profile in tissues, it is concentrated on evaluating the double thermal influence of the skin surface and the surrounding air on the thermometer. The model is developed based on the assumptions as follows:

1) A section of the skin is idealized as a flat plate. It is exposed to the air on one side and to a heat flux on the other side. The conduction analysis results show that when the size of the skin flat plate is 50 mm × 50 mm, the heat conduction between the model skin and the peripheral skin can be ignored. So the other four sides of the flat plate can be treated as adiabatic boundaries in the model.

2) The skin is divided into three layers: the epidermis, the dermis and the subcutaneous region (see Fig. 3)[8]. The epidermis can be ignored because its thickness is only 80 μm. Wilson et al.[9] indicated that the skin surface temperature was maintained mainly by heat transfer, to a lesser extent by perfusion, and to a small extent by superficial tissue metabolism. Therefore, it is appropriate to assume that all the heat is generated in the subcutaneous region and only the dermis is considered in the model. Because the heat generation of the human body does not change when the thermometer is taped to the skin with an extremely limited contact area, the heat flux in the subcutaneous region can be treated as a constant.

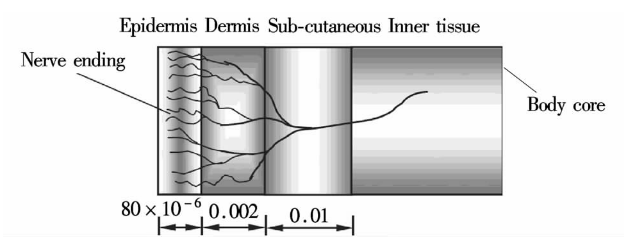

Fig. 3 Schematic geometry of three-layer skin structure (unit: mm)

3) The heat transfer rate of evaporation and radiation is simplified to an integrated convective coefficient at the skin-air and board-air interfaces.

4) The density ρ, the specific heat C and the thermal conductivity K of the skin are constants.

5) The thermal contact resistances in this model are ignored. The self-heating of Pt1000 is not taken into account.

The heat transfer process of the conduction model is calculated by the Fluent software. Three structure models are built to decide the appropriate thickness of the board. The size of the board is 12 mm × 2.5 mm, and the thicknesses of the boards are 0.1, 0.2 and 0.3 mm, respectively. Considering the influences of the heat flux and the integrated convective coefficient on the results, three kinds of heat fluxes (46.67, 50, 58 W/m²) and three kinds of integrated convective coefficients (4.6, 5.5, 6.4 W/(K·m²)) are taken into consideration in each model.

2.2 Simulation results

The temperature of the thermometer (T_1) is calculated by averaging the middle surface temperatures of the platinum-film resistance sensor. Five faces of the sensor are contacted with the skin, and thus only one face is affected by the surrounding air (see Fig. 2). The influence of the surrounding air can be judged based on the temperature difference (ΔT_1) between the average temperature of the five faces (T_2) and T_1. The simulation results show that ΔT_1 is always small and does not change with the thickness of the board. The reason is that there is an air gap with a thickness of 0.1 mm between the sensor and the air and the thermal conductivity of the air is 0.023 W/(K·m) which is one-tenth of the board. When the heat flux is 46.67 W/m² and the convective coefficient is 6.4 W/(K·m²), $\Delta T_1 = 1.53 \times 10^{-3}$ ℃.

The average skin temperature rise (ΔT_2) is the temperature difference between before and after the thermometer is taped to the skin. The variation in ΔT_2 with different heat fluxes and thicknesses of the board with a convective coefficient of 6.4 W/(K·m²) is shown in Fig. 4. The average skin temperature rise is only 0.004 3 ℃ when the thickness of the board increases from 0.1 to 0.2. Compared with the board with a thickness of 0.1 mm, the thermometer with the 0.2 mm-thickness board is more structurally stable. Therefore, the board with a thickness of 0.2 mm is used in this study, with which the influence of the surrounding air can be effectively prevented and there is no obvious increase in the skin temperature.

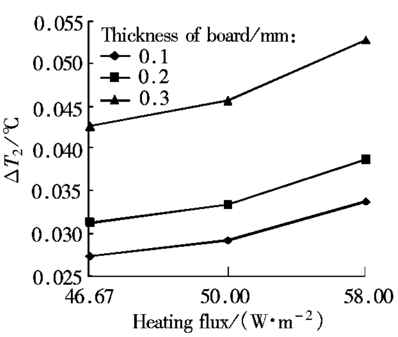

Fig. 4 Variation in ΔT_2 with different heat fluxes and thickness of board

T_3 refers to the real skin surface temperature without any covering, and ΔT_3 is the temperature difference between T_1 and T_3. When the thickness of the board is 0.2 mm, the variation in ΔT_3 with different heat fluxes and convective coefficients is shown in Fig. 5. It can be seen that ΔT_3 increases with the decrease in the convective coefficient and the increase in the heat flux. When the heat flux is 46.67 W/m² and the convective coefficient is 6.4 W/(K·m²), ΔT_3 is 0.11 ℃.

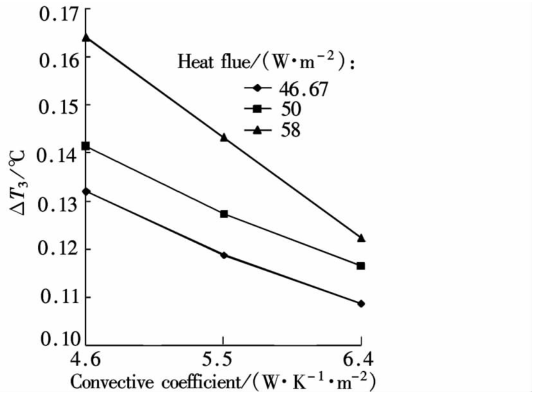

Fig. 5 Variation in ΔT_3 with different heat fluxes and convective coeffcients

2.3 Experimental results

To verify the accuracy of this new thermometer, two sets of skin temperature measurements are carried out for the new thermometer and the standard thermometer, respectively. Eight healthy subjects are recruited for the experiments. The skin temperatures are measured at the right upper arm, the left chest, the right thigh and the right leg. The mean skin temperature (MST) can be calculated by[10]

$$T_{\mathrm{MST}} = 0.2T_{\mathrm{right\_leg}} + 0.3T_{\mathrm{left\_chest}} + 0.2T_{\mathrm{right\_thigh}} + 0.3T_{\mathrm{right\_upper\_arm}} \quad (1)$$

The results are shown in Fig. 6. It can be seen that the new thermometer can accurately measure the skin temperatures. The maximum measurement error of the skin temperature is 0.24 ℃ and the mean skin temperature difference is 0.04 ℃.

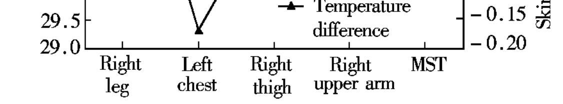

Fig. 6 Comparison of measuring results of two thermometers

3 Conclusion

A new measurement method based on a new platinum-film resistance thermometer is proposed. With the platinum-film resistance sensor welded on the printed circuit board, the heat losses of the leads are reduced and the sensor is insulated from the surrounding thermal environment. The board with a thickness of 0.2 mm is recommended for the thermometer based on the thermal analysis and simulation results. The experimental results confirm that the new thermometer can accurately measure the skin temperature. And it is a useful tool for the skin temperature measurement in thermal comfort research.

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皮肤温度测量方法

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摘要:针对热舒适研究中皮肤温度测量精度不高的问题,提出了一种采用基于薄膜铂电阻(Pt1000)传感器的新型温度计测量皮肤温度的方法.该温度计把传感器焊接在印刷电路基板上,以消除引线导热产生的传热误差,并隔绝周围热环境的影响.为确定合适的基板厚度,建立了一种稳态传热模型.模拟结果表明,厚度为 0.2 mm 的基板可有效隔绝空气影响,同时不会造成基板下皮肤显著温升.实验验证结果表明,测量皮肤温度时该温度计的最大测量误差为 0.24 ℃,平均测量误差仅为 0.04 ℃.因此,该方法是一种有效可靠的、适用于热舒适研究的皮肤温度测量方法.

关键词:热舒适;皮肤温度;测量;薄膜铂电阻

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