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STUDY ON THERMAL COMFORT OF WOOD TABLETOP MATERIALS

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ABSTRACT

The purpose of this study is to investigate the contact temperature and thermal comfort when the upper extremity touches a wooden table top, and to seek an efficient accurate simulation device instead of human testing. Therefore, three parts of this paper were conducted. First, 20 subjects were selected for the temperature test experiment. Secondly, the perceptual thermal comfort evaluation was quantified by recording the thermal comfort evaluation at a specific moment. Finally, a device was developed to replace the human forearm for upper limb thermal comfort study. The results show that the ambient temperature, type and thickness of material all have significant effects on the local contact temperature. In terms of thermal comfort evaluation, the correlation between temperature and thermal comfort was significant. The simulation device in the study is not only simple to operate, but also can continuously and stably replace the heat transfer process of the upper limb.

KEYWORDS: Wooden tabletop, thermal comfort, contact temperature, subjective evaluation, device simulation.

INTRODUCTION

As a major category of furniture, tables and chairs account for a very large proportion of the time used in work study and life. Temperature affects workers' thermal comfort and work concentration (Maula et al. 2016). Prolonged exposure to uncomfortable thermal sensations such as coldness and stuffiness, not only affects the physiological and psychological comfort at the time, but also may cause health problems in long-term use (Xiong et al. 2016). Some scholars have even suggested that ambient temperature is closely related to human mortality (Keatinge et al. 2000). Thermal sensation is a subjective description of the surroundings. Although people often evaluate how cold or warm a room is, they cannot actually feel the ambient temperature directly. People can only feel the temperature of the nerve endings located on the surface of their skin. Thermal comfort is a comfortable state in which the environment, neither feels hot nor cold, and is used to describe the degree of satisfaction expressed by indoor personnel with the thermal environment (Dear et al. 2013). An individually controlled microenvironment providing local heating or cooling has the potential to satisfy more occupants in a space compared to a centrally controlled total volume environment (Melikov et al. 1998, Tsuzuki et al. 1999, Akimoto et al. 2003). Skin temperature change gradients of fingers, hands and forearms correlate very similarly with overall human thermal sensation (Wang et al. 2007). It has even been proposed that the skin temperature of the hand can be used to predict the thermal comfort of people in a building instead (Humphreys et al. 1999). Therefore, it is important to study the thermal comfort of human upper limbs in contact with the wooden tabletop to study the overall thermal comfort of the human body.

The study of the local contact, thermal comfort of furniture usually uses methods such as subjective thermal comfort evaluation and instrumental measurements. The subjective evaluation of thermal comfort is mainly expressed with reference to the temperature sensory evaluation PMV (Predicted Mean Vote). PMV, also known as predicted mean evaluation, is an indicator that predicts the mean value of a large group of people voting on a 7-point heat sensory scale based on the heat balance of the human body (UNE-EN ISO 7730: 2006). Tiller et al. (2010) in their study of the effect of temperature on the comfort of office employees found that the thermal perception of office temperature was investigated by questionnaires for men and women. Park et al. (2011) discussed the relationship between the local thermal comfort and the overall thermal comfort of passengers in the passenger cabin through a questionnaire. It can be said that the subjective thermal comfort survey is the most common method used in indoor thermal comfort evaluation. This method allows the subjective degree of thermal sensation to be recorded digitally. Instrumental measurement means that the contact temperature at the contact point is measured directly to respond to the temperature sensory change. Sales et al. (2017) introduced infrared thermographic display to measure the temperature change at the test point in their study of seating thermal comfort. Cannon and Denhartog (2019) tested the temperature transfer performance on three different mattresses, using an inverted heating plate heated to 35°C. A combination of anthropometric and subjective evaluations was the most common approach. Some researchers used a combination of subjective anthropometric and experimental methods to evaluate the thermal comfort of different office chairs in five secondary schools (Vlaović et al. 2011). Xu and Guan (2017) studied the thermo-sensory properties of six desktop materials from 14°C to 17°C by a combination of thermal comfort evaluation and temperature testing. In order to test the thermal comfort of temperature-controlled mattresses, Li et al. (2020) recorded the sleep temperature changes in six regions of the whole body using a data acquisition instrument and used the subjective body temperature method to understand the thermal comfort of sleep in order to understand the effect of temperature-controlled water beds on human thermal comfort.

Although thermal comfort can be quantified by means of thermal comfort questionnaires, the process of human testing is time-consuming and labor-intensive and is also limited by the experimental environment. Therefore, many scholars hope to replace human experiments with experimental device simulation. Conceição et al. (2010) used four virtual mannequins to study the thermal comfort of a desk with four personalized ventilation (PV) systems. Sakoi et al. (2007) used a human model with the same local skin temperature as the human body through human model experiments to measure skin temperature distribution and sensible heat loss in various asymmetric radiation field distribution in a seated statue. Hu et al. (2020) studied the heat generation from forearm touching the tabletop material by simulating the local heat emitted by the human body through aluminum alloy U-slot plus heat generating pad and adding silicone rubber to simulate human skin.

This paper further investigates the contact of human upper limbs with wooden desktop materials, and tests the temperature change and thermal comfort change of upper limbs after contact with the desktop by combining human contact measurement and subjective evaluation method, and finds the interrelationship and change law between local temperature and thermal comfort. At the same time, a simulation device was developed to replace the human body for contact experiments, which can continuously and stably simulate the heat generation of upper limbs. And the device has high precision, small error, simple operation, and high practical value.

MATERIAL AND METHODS

Test materials and experimental environment

Three materials commonly used for desktop were selected for this study, including medium density fiberboard (MDF), single-ply structural particle board (SPB), and poplar multilayer board (PMB) (Zhen and Wang 2021). All samples were placed in a humidity chamber for two weeks prior to the start of the experiment, with the ambient temperature being the corresponding temperature in Tab. 1 and the relative humidity (RH) being 50% ± 3%. The size of the test piece refers to the regulations on the size of the test piece in the classification of formaldehyde emission grading for wood-based panel and finishing products in China (GB 39600: 2021).

Tab. 1: Experimental material and experimental conditions.

No.	Ambient temperature T_a ± 0.5°C (°C)	Size δ (mm)	Material type
1	20	500 × 500 × 20	MDF
2	20	500 × 500 × 20	SPB
3	20	500 × 500 × 20	PMB
4	25	500 × 500 × 20	MDF
5	25	500 × 500 × 20	SPB
6	25	500 × 500 × 20	PMB
7	25	500 × 500 × 15	MDF
8	25	500 × 500 × 25	MDF

When the human body is suitably dressed, adequately warmed and in a quiet state, an indoor temperature of 20°C is more comfortable, and for general civil buildings, such as residential, office and commercial, the interior design temperature is generally within the range of 24-28°C in summer and 18-20°C in winter (GB 50736: 2012). Therefore, the experimental temperature was set at two indoor temperatures of 20°C and 25°C.

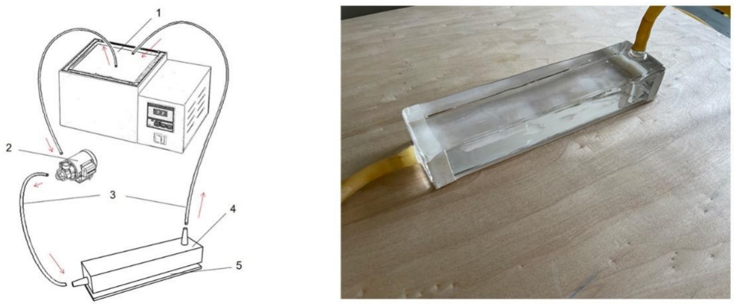
The laboratory is located in Nanjing, with a floor plan of 5.2 × 4.5 × 3.0 m. The indoor air temperature and humidity are controlled by air conditioners and humidifiers respectively. The experimental location needs to be separated from the air conditioner at a certain distance to avoid non-essential convective heat exchange caused by direct blowing of the air conditioner as much as possible (Prek 2005).

Subjects

10 adult males and 10 females were selected as test subjects, aged between 20 and 30 years, with regular daily activities such as eating and sleeping, and activities that may cause drastic changes in body metabolism such as stimulating diet and strenuous exercise were eliminated before the experiment. The subjects were required to take a 30 min break upon arrival at the laboratory and were trained on temperature testing and subjective experiments within 30 min.

Instruments and equipments

Temperature acquisition using Topaz PT100 multiplexed temperature data acquisition parameters to measure the temperature of the human-desktop contact interface with an accuracy of ± 0.3°C, a range of -200°C to 660°C, and a test frequency of 6 s once.



(a) (b)

Fig. 1: Simulation device diagram (a), and physical diagram (b).

Fig. 1 shows the device developed in this study to simulate the forearm of a subject to the external dimensions of 200 × 30 × 20 mm. It consists of five parts: *(1)* digital display thermostatic water bath (HH-2), *(2)* adjustable speed peristaltic pump, *(3)* latex tube, *(4)* quartz square bottle for simulating human upper limbs, *(5)* elastic silicone rubber sheet 2 mm for simulating human skin. The device works by circulating the temperature of water to simulate the temperature of the upper limb and using the surface of the elastic silicone rubber sheet to simulate the skin of the forearm.

Temperature test method

The test points for temperature acquisition were selected from the tip of the middle finger (T_1), the large cleft of the palm (T_2) and the side of the forearm palm (T_3), as shown in Fig. 2. Referring to Wang and Powen (2008) for the test experiments of thermal properties of interior decoration materials with sensory contact cold and warm, the test points need to be in close contact with the test material.

The temperature sensor on the test apparatus was connected at the test point, and the contact temperature at the three points was tested separately, and the contact between the human body and the wooden desktop material was shown in Fig. 3. After the test started, the subject's upper extremity was in contact with the test material for 30 min in a natural fit.

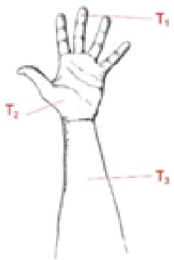


Fig. 2: Schematic diagram of temperature test points.

Fig. 3: Schematic diagram of temperature test.

Subjective experimental test methods

The subjective method was used to test the thermal comfort of the wooden desktop, that is, the subjects in contact with the human upper extremity of the wooden desktop material, the temperature perception of the material at certain intervals scored "cold (-3 points), cool (-2 points), slightly cool (-1 point), neutral (0 points), slightly warm (1 point), warm (2 points), hot (3 points)" seven levels of scoring (Lan et al. 2019). The rating was evaluated to obtain the curve of thermal comfort of the wooden desktop material over time. While collecting the temperature, the subjects were asked to evaluate the local thermal comfort according to seven levels within a specified period of time. The temperature changed rapidly in the first minute, so it was necessary to record the thermal comfort level for 12 s, 30 s and 60 s, respectively. After one minute, the data were recorded at 60 s intervals. The temperature consciousness evaluation data were recorded to obtain the curve of PMV change with time.

Device test methods

The device developed for this study replaces the subject's forearm, and therefore needs to make the temperature of the elastic silicone rubber sheet must be as close as possible to the temperature of the forearm skin. Before the experiment started, the temperature of the constant temperature water bath (HH-2) was set to 39.5°C with temperature fluctuations ≤ 0.5°C. After the temperature of the constant temperature water bath reached 39.5°C, the adjustable speed peristaltic pump was turned on and the volume flow rate was set to 2.52 $m^3 \cdot h^{-1}$. Water flows through the quartz square bottle from the bottom and out from the top. The temperature of the silicone rubber surface increases with the water flow temperature for a period of time and then reaches stability. The temperature receiver of the data collector was attached to the silicone rubber surface and in contact with the test material as in Fig. 4, and the temperature was recorded for 30 min.

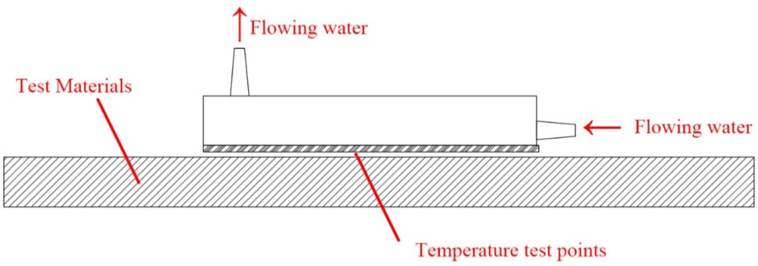


Fig. 4: Device simulation temperature test schematic.

RESULTS AND DISCUSSION

Temperature test analysis

Observation of 20 mm thick three materials at different ambient temperatures for human contact experiments, observed that the three test points of the upper extremity for 30 min showed different change characteristics from Fig. 5.

The temperatures at the fingers and palms were relatively close to each other, and the temperature at the arms was lower, showing an overall trend of $T_1 > T_2 > T_3$. From the fluctuation trend, the temperature change at the arm is more stable, and the temperature fluctuation at the finger is the largest. The temperature fluctuation of the three materials in the low room temperature is large, especially in the fingers. This may be due to more human nerve endings at the fingers, poor blood supply within the lower room temperature leading to stiffness of the limbs and a relatively small contact area. Fingers are rich in thermo-sensory sensors and are sensitive in the sensation of thermal comfort. When temperature changes are sensed, the temperature regulation mechanism of the fingers is faster and the fluctuation is more obvious, that is to say, the greater the temperature difference between the material temperature and the body temperature, the more drastic the temperature fluctuation at the fingers.

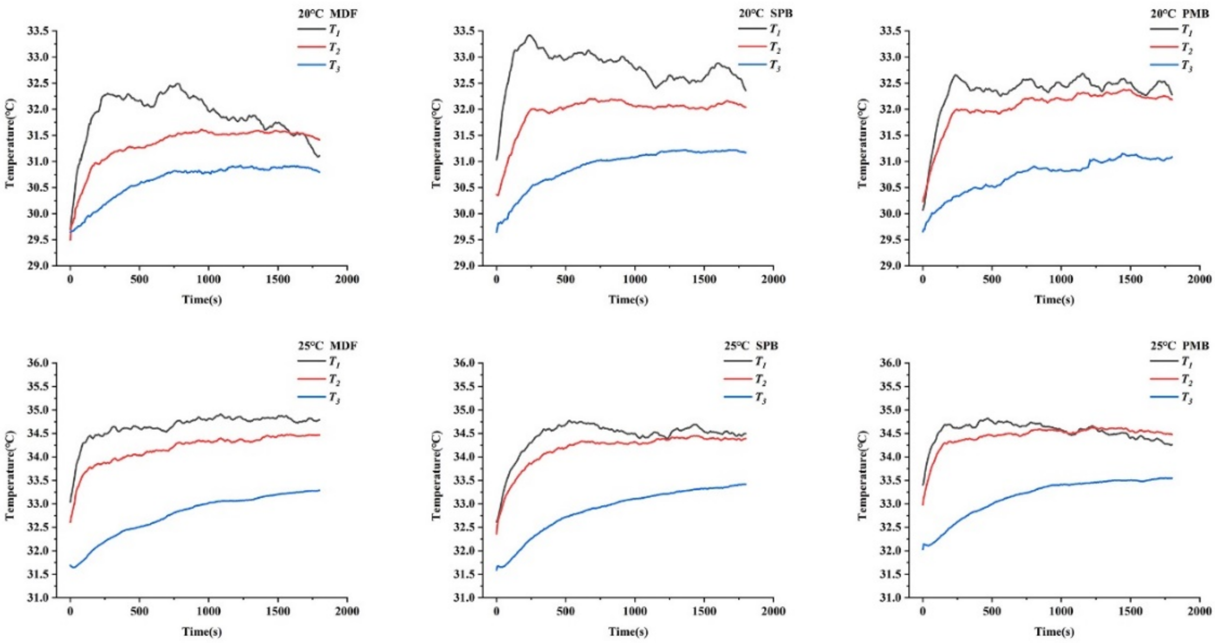


Fig. 5: Comparison of temperature changes at test points.

Since the temperature of the three test points differed significantly, but the thermal comfort of the forearm was evaluated as a whole, the average temperature of the upper extremity needed to be calculated. Regarding the calculation of the average temperature of the human body after contact with the wooden tabletop can be analogous to the average skin temperature of the human body, the calculation method of area-weighted average is used, and the weighting factor of each part is the percentage of its surface area to the surface area of the whole body (Dear et al. 1997):

$$T = 0.211T_1 + 0.211T_2 + 0.578T_3 \quad (1)$$

where: T - average temperature of the upper limb, °C; T_1 - finger temperature, °C; T_2 - palm temperature, °C; T_3 - arm temperature, °C.

After calculating the average temperature of the upper limb contact according to the above method, contact temperature changes of fiberboard, particleboard and multilayer board were compared under the conditions of 20°C and 25°C. Fig. 6 shows that the contact temperature rise process of the three materials has a similar trend, with the temperature rising sharply at the beginning of the contact and leveling off with time. There is a significant difference in the temperature change of human contact with different materials due to the different thermal conductivity of different materials. The human body has different rates of temperature transfer in the process of exothermic heat transfer of the material. The trend of temperature curve PLY > SPB > MDF was shown at both 20°C and 25°C ambient temperature conditions, which showed a negative correlation with thermal conductivity of the material. At 20°C, the temperature change curve fluctuates more and shows the characteristic of contact temperature decreasing at the end of the contact, the higher thermal conductivity of material, the more obvious this situation is. The higher thermal conductivity of material, the more pronounced this situation is. In contrast, the fluctuation of the temperature curve at room temperature of 25°C is relatively small, and the temperature drop at the end of is also relatively rare, and the temperatures of the three materials gradually converge.

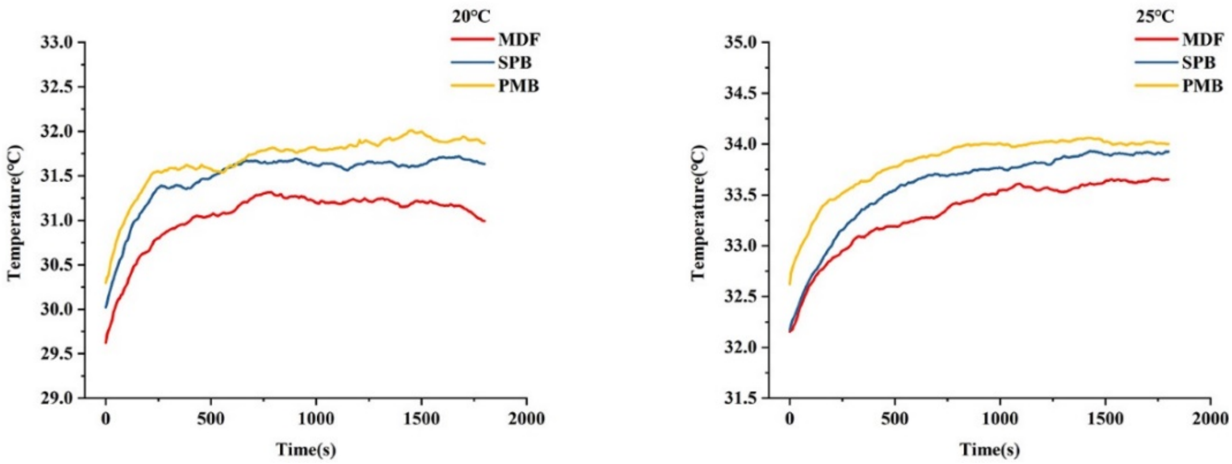


Fig. 6: Average temperature variation of different materials.

Fig. 7 responds to the trend of temperature change in 15 mm, 20 mm and 25 mm fiberboard in human contact experiment at 25°C. The same trend of temperature change for the same material, the overall temperature shows a trend of 15 mm > 20 mm > 25 mm. Therefore, the contact temperature shows a negative correlation with the thickness of the sheet.

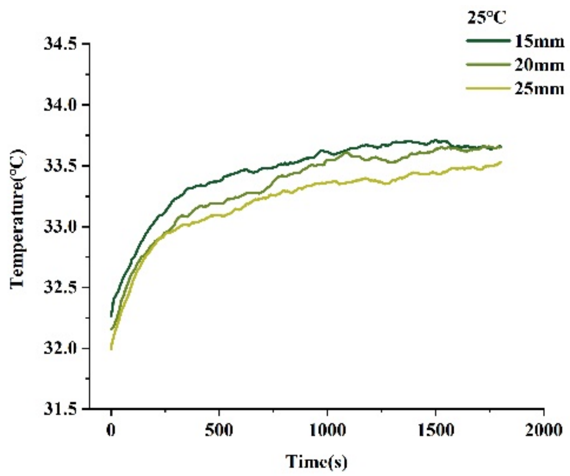


Fig. 7: Average temperature variation of MDF with different thickness.

Subjective experimental analyses

Comparing the test temperature with the subjective evaluation as in Fig. 8 and Fig. 9, the trend of PMV change is basically the same as the trend of temperature change, so there is a direct relationship between the local contact temperature T and the thermal comfort PMV. After correlation analysis by SPSS, $P = 0 < 0.01$ and the correlation coefficient were 0.444, and the relationship between the two was relatively close.

Under the ambient temperature condition of 20°C as in Fig. 8, the initial contact temperature is low, so the thermal comfort evaluation is low. As the contact temperature rises rapidly, the thermal comfort evaluation also rises rapidly and finally plateaus.

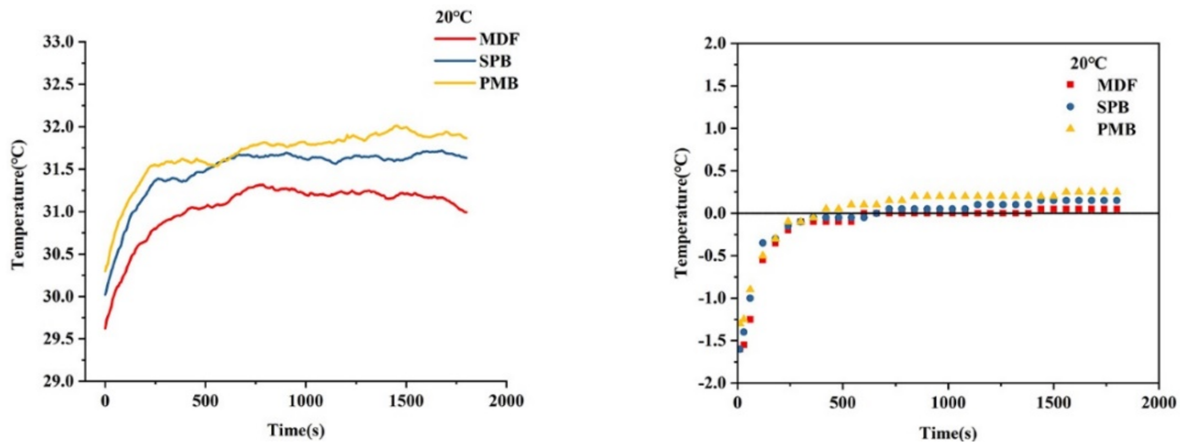


Fig. 8: Comparison of average contact temperature and thermal comfort in 20°C.

The thermal comfort evaluation also showed a similar trend of the temperature change in the ambient temperature condition of 25°C as in Fig. 9. The overall thermal comfort rating is also relatively higher than the ambient temperature of 20°C ambient condition due to the higher initial temperature of the material as the ambient temperature increases.

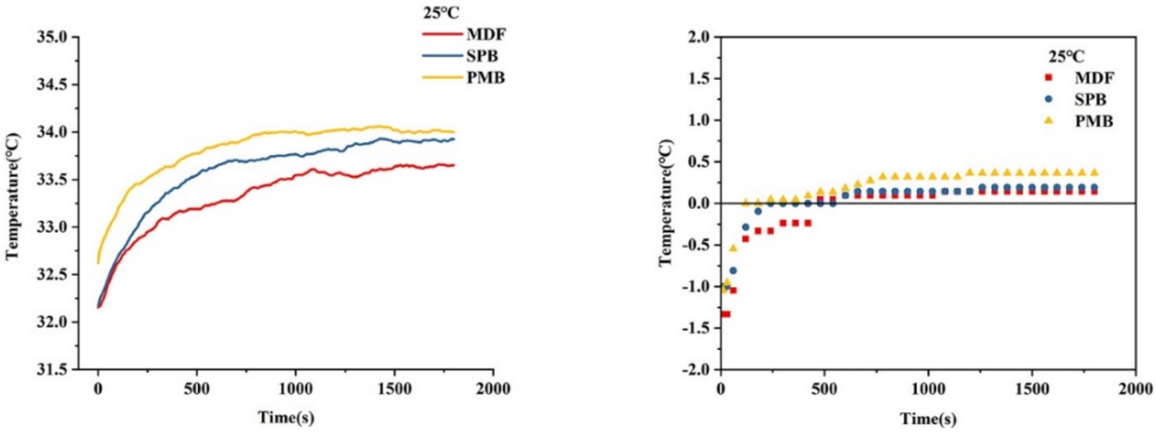


Fig. 9: Comparison of average contact temperature and thermal comfort in 25°C.

After plotting the scatter plot of the values of subjective evaluation and human exposure temperature as in Fig. 10, it was found that PMV at 20°C and 25°C were dispersed in two fixed regions and showed a linear distribution in the respective regions. Thus PMV is not only influenced by the exposure temperature, but also by the ambient temperature. A partial correlation analysis was performed on the three, that is, the ambient temperature (T_a) was used as the control variable and its influence on the subjective evaluation (PMV) was excluded, and the correlation between the exposure temperature (T) and the subjective evaluation (PMV) was analyzed. The partial correlation coefficient obtained after the analysis is 0.895, which is greater than the original correlation coefficient of 0.444, so there is a linear relationship between the three. The probability value of the partial correlation coefficient was further observed at $P = 0 < 0.01$, indicating a relatively high significance of the linear relationship.

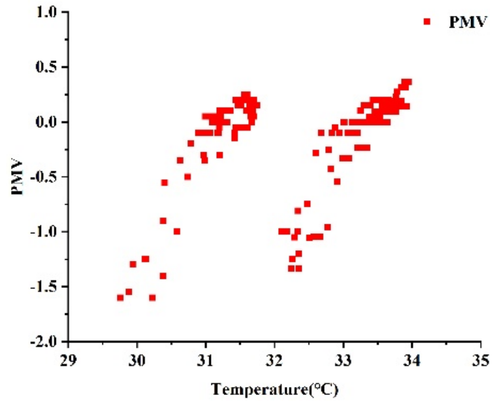


Fig. 10: Scatter plot of PMV with temperature.

A stepwise linear regression analysis of T and T_a as impact PMV worthy variables was performed, and $R^2 = 0.804$ was obtained, and the model was found to pass $P = 0 < 0.01$ when the F-test was performed on the model, and the linear regression equation obtained was：

$$PMV = 0.789T - 0.328T_a - 18.198 \quad (2)$$

where: *PMV* - subjective thermal comfort evaluation; *T* - local temperature of the human body in contact with the material, °C; T_a - ambient temperature, °C.

Once the linear regression equation is obtained, the perceptual thermal comfort can be represented by a measurable physical quantity, and the subjective interference can be reduced in subsequent studies. According to the definition of thermal comfort (Franger 1972), subjects feel thermal comfort, when condition is not too hot or cold. The recommended value of PMV indicator is -0.5 to +0.5 (UNE-EN ISO 7730: 2006). During long-term exposure, there will be parts beyond the recommended value, such as Δt (t_1, t_2) in Fig. 11 where the PMV value of thermal comfort evaluation for this period is within the recommended value, while other parts are no longer within this range. When the human body is exposed to the wooden desktop for a long time, to evaluate whether it is comfortable or not, it is necessary to compare how much of the range of the optimal thermal comfort time, which is the size of Δt.

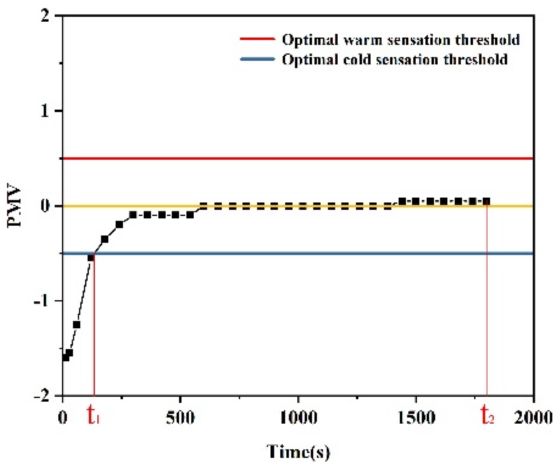


Fig. 11: Schematic diagram of optimal thermal comfort time.

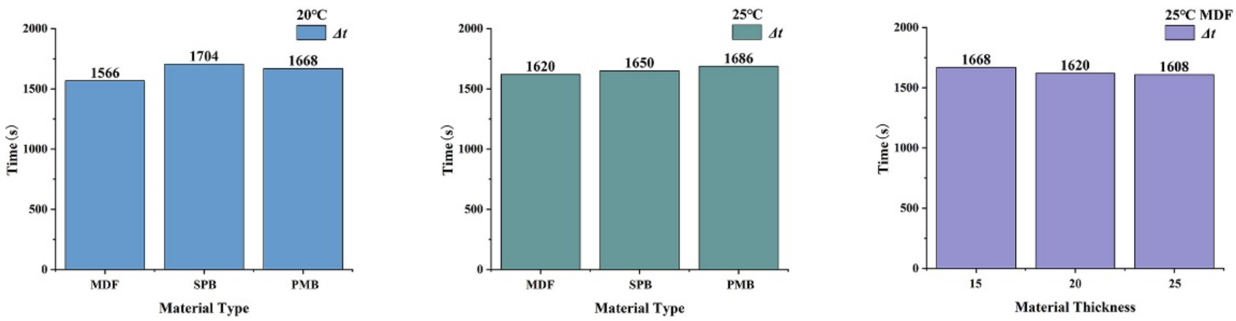


Fig. 12: Comparison of thermal comfort.

Based on Eq. 2 and the temperature change values tested in the temperature test, the change in PMV values at 6-second intervals was derived. It was found in Fig. 12 that the thermal comfort of different materials under the room temperature condition of 20°C: SPB > PLY > MDF; the thermal comfort of different materials under the room temperature condition of 25°C: PLY > SPB > MDF; the thermal comfort of different thicknesses of MDF at 25°C: 15 mm > 20 mm > 25 mm; the thermal comfort of different room temperature conditions of 20 mm MDF: 25°C > 20°C; the thermal comfort of 20 mm SPB Thermal comfort under different room temperature conditions: 20°C > 25°C; PLY of 20 mm under different room temperature conditions: 25°C > 20°C.

Comparison of experimental data and simulation data

A comparison of the measured results of the three different material subjects with the simulated results of the device after exposure to the three test materials at 20°C and 25°C environment is shown in Fig. 13.

The temperature-time curves of the test and simulated values follow a similar trend, with the test temperature being greater than the device temperature in the initial phase and the simulated device temperature exceeding the test temperature after a gradual approach. In contrast, the results of the instrument measurements were closer to the test temperature in the 25°C environment for the simulated data. The relative error means and standard deviations for comparing the subject and device temperatures at each measurement time point in the 20°C and 25°C environments are shown in Tab. 2.

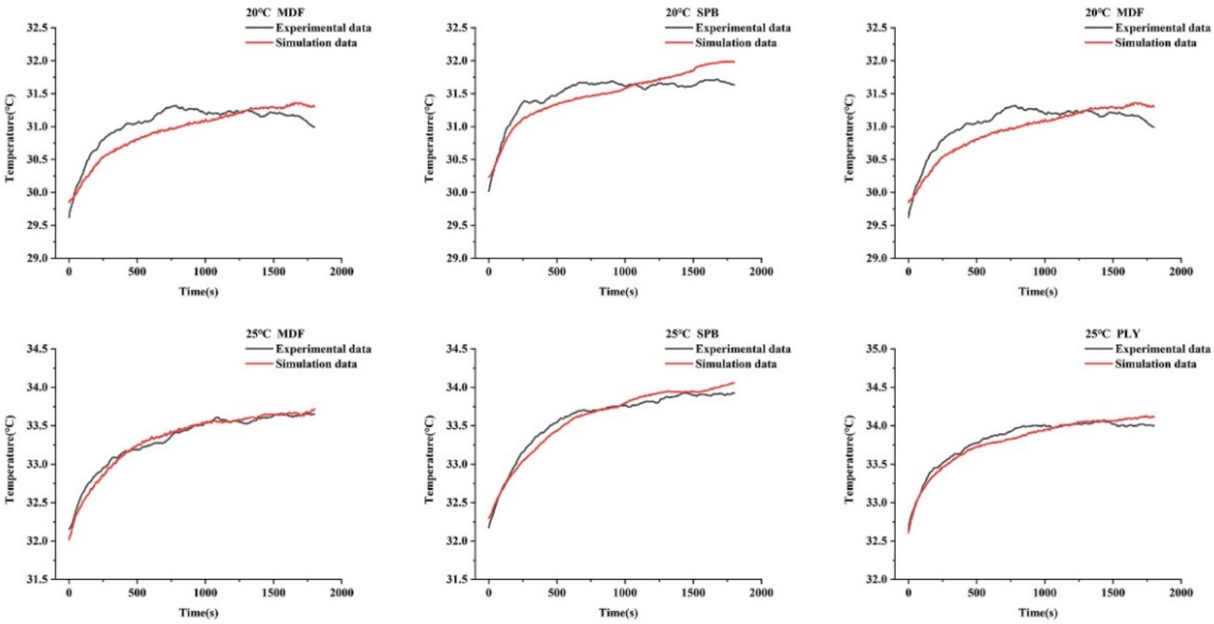


Fig. 13: Comparison of temperature change between human experimental data and device simulation data.

Tab. 2: Temperature error of simulation device.

Materials	20°C	25°C
MDF	0.586% (0.003)	0.139% (0.001)
SPB	0.437% (0.002)	0.207% (0.001)
PLY	0.417% (0.003)	0.174% (0.001)

The errors between the subject's measurement results and the instrument's measurement results were within 0.6%, indicating that the instrument developed in this study can stably measure the temperature between the forearm and the table. Also constant temperature water baths, peristaltic pumps, and quartz instruments are commonly used laboratory instruments, so simulating human flow through water flow is both stable and economical.

CONCLUSIONS

Investigation of thermal comfort of three wood desktop materials at 20°C and 25°C using thermometric and subjective evaluation methods, and came to the following conclusions: *(1)* The finger and palm contact material temperatures were similar, while the arm contact temperature was generally lower than the other two test points. However, the trend of temperature change was the same for all three test points. *(2)* For different desktop material, material for human contact temperature change trend has a great impact on the impact of the thermal conductivity of the material, contact temperature and material heat transfer coefficient is negatively correlated; for desktop material commonly used thickness, size, contact temperature and the size of the material thickness is negatively correlated. *(3)* Local thermal comfort during long-term contact with a material can be measured by the optimal thermal comfort duration, i.e., the longer the time occupied by the optimal thermal comfort the more comfortable the material is. According to this method of calculation, it is found that the thermal comfort of different materials under the room temperature condition of 20°C: SPB > PLY > MDF; the thermal comfort of different materials under the room temperature condition of 25°C: PLY > SPB > MDF; the thermal comfort of different thicknesses of MDF at 25°C: 15 mm > 20 mm > 25 mm; the thermal comfort of different room temperature conditions of MDF at 20mm: 25°C > 20°C; thermal comfort of SPB of 20 mm under different room temperature conditions: 20°C > 25°C; thermal comfort of PLY of 20 mm under different room temperature conditions: 25°C > 20°C. *(4)* Ambient temperature T_a and local contact temperature T have certain influence on the evaluation of thermal comfort, and the relationship between the three can be expressed in the form of linear equation, which makes the perceptual thermal comfort can be expressed by the physical quantity of objective temperature. *(5)* A device was developed to replace the front heat dissipation through the heat dissipation of water, and the contact experiment was conducted instead of the human body, and it was found that the simulated data of the device not only had stable data, but also had less error between the data and the human body test. The simulated device is simple and easy to operate, which can save a lot of time for human body testing and can be used for the study of local thermal comfort.

The study of human thermal comfort is a complex process, and if the local thermal comfort of the upper limbs in contact with the wooden desktop can be thoroughly studied, it is of great significance for the selection of materials and structure of the wooden desktop, and also has prospective significance for the design of furniture.

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