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Quantitative Study on the Relationship Between the Thermal Comfort Performance of Textile and Apparel Materials and Their Thermodynamic Properties

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ABSTRACT

With the growing demand for clothing comfort, the thermal comfort performance of textile and apparel materials has become a key research focus in the textile industry. Thermal comfort is not only closely related to the wearer's comfort and health but also plays a crucial role in clothing design and material selection. The thermodynamic properties of textile materials, particularly thermal resistance and the Predicted Mean Vote (PMV) index, significantly influence wear comfort. However, most existing studies primarily focus on individual thermodynamic properties, lacking a systematic quantitative approach. Moreover, current calculation methods fail to comprehensively account for the multidimensional thermodynamic characteristics of materials in assessing thermal comfort. Accurately evaluating the thermal comfort of textile materials based on thermodynamic principles remains a pressing challenge. Existing studies mainly rely on empirical calculations of thermal resistance and PMV values, often based on simplified assumptions that do not adequately adapt to various environmental conditions and textile material properties. While some models for thermal resistance and PMV evaluation have been proposed, they are largely dependent on experimental data or assumptions, lacking an integrated analysis of multiple thermodynamic characteristics. To address these gaps, this paper proposes a thermodynamics-based method for evaluating the thermal comfort performance of textile materials. By quantitatively calculating thermal resistance and PMV values, this study aims to provide a theoretical foundation for clothing design and material optimization.

1. INTRODUCTION

With global climate change and the continuous increase in the demand for comfort, the thermal comfort of textiles and apparel has become an important consideration in modern clothing design and production [1-4]. Awais et al. [5] mentioned that thermal comfort is not only related to the wearer's health and comfort but also directly affects the market competitiveness of textile products. Under different environmental conditions, the heat conduction performance and thermodynamic properties of textile and apparel materials play a decisive role in human thermal comfort [6, 7]. Therefore, how to scientifically evaluate and optimize the thermal comfort of textile and apparel materials has become an urgent problem in the field of textile science and clothing design.

References [8-11] mentioned that the thermal comfort of textile and apparel materials is closely related to their heat conduction and moisture absorption and perspiration properties, among other thermodynamic characteristics. By accurately calculating and analyzing parameters such as thermal resistance and PMV value (PMV index for thermal comfort in a uniform environment), a theoretical basis can be provided for clothing design, thereby improving the comfort and functionality of garments [12-16]. However, existing studies, such as those in references [17-19], mostly focus on the single thermodynamic properties of materials or simple empirical formulas, lacking comprehensive quantitative analytical methods and failing to fully consider the comprehensive impact of multidimensional thermodynamic properties of materials on the wearer's thermal comfort. Therefore, proposing a quantitative calculation method based on thermodynamics is of great significance for achieving an accurate evaluation of the thermal comfort of textile and apparel materials.

Although existing studies provide a certain theoretical foundation for evaluating the thermal comfort of textile and apparel materials, most methods have certain limitations [20-22]. For example, traditional thermal resistance calculation methods largely rely on empirical data, ignoring the complex interactions between thermodynamic properties of materials, while the calculation of PMV values mostly depends on experimental data and standard assumptions, lacking adaptability to different materials and environmental conditions. As a result, the computational models in existing studies often fail to accurately reflect the thermal comfort of actual wearing environments and urgently need improvement and refinement.

Over the past five years, significant progress has been made in thermal comfort evaluation methods with the deepening of research. In addition to the traditional PMV model based on thermodynamics and environmental parameters, new evaluation methods such as multi-scale thermal comfort modeling and the application of smart sensor technology have gradually been proposed. For instance, some studies have introduced thermal comfort assessment methods based on body temperature monitoring, where wearable devices continuously track the body temperature, providing a more personalized evaluation of thermal comfort. However, these new methods often have certain limitations, such as issues with sensor accuracy and insufficient consideration of individual differences. Therefore, integrated assessment methods combining thermodynamic properties and the PMV theory still hold significant application value and research importance.

The research content of this paper mainly includes two parts: first, quantitative calculation of the thermal resistance of textile and apparel materials based on thermodynamic principles, proposing a more precise thermal resistance calculation model; second, developing a thermal comfort evaluation method applicable to different textile materials based on the PMV value calculation theory combined with thermodynamic properties. Through these two studies, this paper aims to provide a more scientific and accurate thermal comfort evaluation tool for clothing design, promoting innovation in the textile and apparel industry in terms of comfort and functionality.

2. CALCULATION METHOD OF THERMAL RESISTANCE OF TEXTILE AND APPAREL MATERIALS BASED ON THERMODYNAMICS

In studying the quantitative relationship between the thermal comfort performance of textile and apparel materials and their thermodynamic properties, accurately calculating the thermal resistance value of materials is a crucial step. The thermal resistance value directly affects the heat exchange process between the human body and textile materials, thereby playing a decisive role in the thermal comfort of wearers. This paper selects three different calculation algorithms—thermal comfort standard algorithm, semi-contact algorithm, and non-contact algorithm—to comprehensively and accurately evaluate the thermal resistance value of textile and apparel materials. These three algorithms each have different applicable scenarios, advantages, and disadvantages, reflecting the thermal conduction performance of materials from different perspectives and revealing their impact on thermal comfort. The thermal comfort standard algorithm is the most common method, based on human thermal comfort standards, using idealized assumptions and empirical formulas to calculate thermal resistance values, suitable for basic evaluations under conventional environments. In contrast, the semi-contact and non-contact algorithms provide more flexible and refined measurement tools, particularly useful for accurately analyzing the thermal transmission characteristics of multilayer materials and complex environmental conditions. Figure 1 illustrates the research approach in this paper.

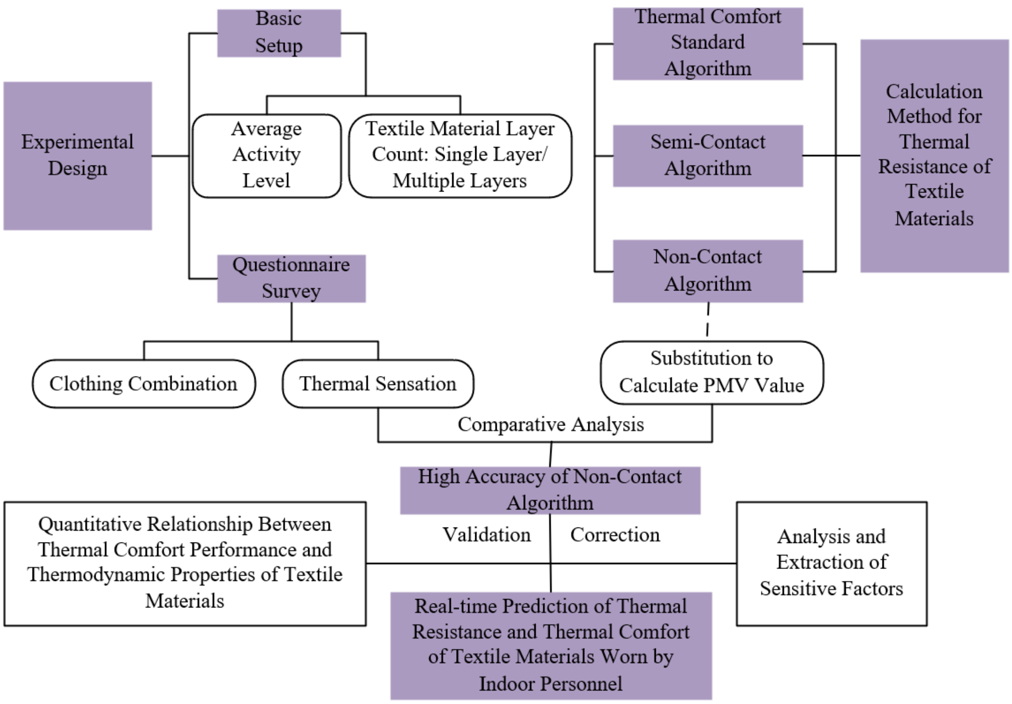


Figure 1. Research framework of this study

2.1 Thermal comfort standard algorithm

In this study, the thermal comfort standard algorithm, as a traditional thermal resistance calculation method, mainly relies on the international thermal comfort standard ISO 9920. It determines the thermal resistance value of a single piece of clothing through a lookup table and then calculates the total thermal resistance value of a complete clothing ensemble. The basic principle of this algorithm is to consider the thermal resistance value of textile and apparel materials as an essential parameter affecting heat exchange between the human body and the environment. Specifically, the thermal comfort standard algorithm classifies the thermal resistance of different textile materials and garment styles and integrates the basic thermal comfort needs of the human body to form a standardized evaluation system. According to this algorithm, the thermal resistance value of each piece of clothing is first determined through standard table lookup. Then, using simple weighted or additive calculations, the overall thermal resistance value of the entire clothing set is obtained. Suppose the thermal resistance value of a single piece of clothing is denoted as U_{DJ} and the overall thermal resistance value of a clothing set is denoted as U_{ZT}. The calculation formula is as follows:

$$U_{ZT} = 0.159 + 0.843\sum U_{DJ} \quad (1)$$

In practical applications, the relative velocity between the human body and the air changes in dynamic environments, leading to the attenuation of thermal resistance values. Especially during movement such as walking, the increased air movement relative to the body significantly affects the thermal resistance properties of textile and apparel materials. The thermal comfort standard algorithm, which determines thermal resistance values through a simple lookup method, does not directly account for the attenuation effect of thermal resistance in motion states. Therefore, when applied to movement scenarios, appropriate corrections must be made. This attenuation correction more accurately reflects the thermal exchange performance of textile and apparel materials under motion conditions, further revealing the close relationship between thermodynamic properties such as breathability, thermal conductivity, and humidity with thermal comfort during activity. Suppose a person's walking speed is denoted as n_{WA} and the thermal resistance attenuation value is denoted as ΔU_{ZT}. The calculation formula is as follows:

$$\Delta U_{ZT} = 0.511 U_{ZT} + 0.00321 n_{WA} - 0.21 \quad (2)$$

2.2 Semi-contact algorithm

Unlike the traditional thermal comfort standard algorithm, the semi-contact algorithm integrates multiple measurement instruments to obtain real-time data on textile surface temperature, human skin temperature, air temperature, and wind speed. This allows for the establishment of a more realistic and dynamic heat flow model. The core idea of this method is to calculate the thermal resistance of textile and apparel materials by utilizing the principle that the heat flux from the skin to the textile layer is equal to the heat dissipated from the textile layer to the environment. Specifically, by measuring the surface temperature of textile materials and the skin temperature at multiple body locations and combining these with environmental temperature and wind speed data, this method can more accurately reflect the thermal conduction performance of textile materials under various conditions. By comprehensively considering textile surface temperature, human skin temperature, environmental temperature, and wind speed, the semi-contact algorithm provides a more precise simulation of the heat exchange process between the human body and textile materials, revealing how properties such as thermal conduction and breathability influence thermal comfort in different environments.

In practice, the semi-contact algorithm employs various advanced measurement tools. An infrared thermal imager is used to obtain thermal distribution images of textile surfaces, and the AnalyzIR software processes the images to generate detailed textile surface temperature data. This data is used to estimate the thermal conductivity coefficient and thermal resistance value of textile materials. Furthermore, to accurately measure human skin temperature, the "nine-point method" is adopted, where miniature skin temperature sensors are placed on the forehead, chest, back, back of the left and right hands, left and right upper arms, and left and right thighs to capture the skin temperature of different body parts and calculate their average value. This approach provides an accurate representation of temperature variations across the body, improving the accuracy of thermal resistance calculations. For environmental data collection, a portable anemometer is used to measure dry-bulb air temperature and wind speed, while a black globe thermometer is employed to measure the black globe temperature. These data provide the necessary environmental parameters for subsequent thermal conduction calculations and effectively simulate the heat exchange process between the human body and the environment. Suppose the human body's heat transfer coefficient is denoted as g, the thermal resistance value of textile and apparel materials as U_{ZT}, textile surface temperature as s_{ZT}, average skin temperature as s_{tj}, indoor operative temperature as s_0, air dry-bulb temperature as s_x, and indoor mean radiant temperature as $\bar{s}_e$. The calculation formulas are as follows:

$$U_{ZT} = \frac{1}{0.161g}\frac{s_{tj} - s_{ZT}}{s_{ZT} - s_0} \quad (3)$$

$$\begin{aligned} s_{tj} &= 0.069 s_{Forehead} + 0.166_{Front\ chest} \\ &+ 0.166 s_{Back} + 0.024 s_{Back\ of\ the\ left\ hand} \\ &+ 0.024 s_{Back\ of\ the\ right\ hand} + 0.069 s_{Upper\ left\ arm} \\ &+ 0.069 s_{Upper\ right\ arm} + 0.192 s_{Left\ thigh} \\ &+ 0.192 s_{Right\ thigh} \end{aligned} \quad (4)$$

$$s_0 = X s_x + (1 - X)\hat{s}_e \quad (5)$$

Suppose the black globe temperature is denoted as s_h, the emissivity as γ_h, and the diameter of the black globe thermometer as F. The indoor mean radiant temperature calculation formula is as follows:

$$\bar{s}_e = \left[\begin{array}{l} (s_h + 273)^4 \\ + \dfrac{0.211*10^8}{\gamma_h}\left(\dfrac{|s_h - s_x|}{F}\right)^{1/4}(s_h - s_x) \end{array} \right]^{1/4} - 273 \quad (6)$$

2.3 Non-contact algorithm

In this study, the non-contact algorithm aims to accurately calculate the thermal resistance value of textile and apparel materials by utilizing non-contact measurement tools and integrating different heat transfer factors under dynamic and static thermal conditions, especially in changing environmental conditions and motion states. Under static thermal conditions, the total thermal resistance value of textile and apparel materials is defined as the thermal transfer resistance from the human body surface through clothing, enclosed air layers, boundary air layers, and into the environment. At this time, it is assumed that the human body and textile apparel materials are in a stable thermal state, with no significant external heat flow changes, and the thermal resistance value mainly reflects the physical insulation performance. However, in practical applications, the heat exchange between the human body and the environment is typically dynamic, making the static thermal resistance value unable to accurately reflect thermal comfort under dynamic conditions. To address this issue, the non-contact algorithm introduces correction coefficients to adjust the thermal resistance value under static conditions, thereby calculating the dynamic air thermal resistance $U_{x\text{-}D}$ and the dynamic total clothing thermal resistance $U_{T\text{-}D}$. Assuming that the clothing area coefficient is represented by d_{ZT}, we have:

$$U_{T-S} = U_{C-S} + \frac{U_{x-S}}{d_{ZT}} \quad (7)$$

d_{ZT} can be calculated based on the static clothing thermal resistance value $U_{C\text{-}S}$:

$$d_{ZT} = 1 + 1.969 U_{C-S} \quad (8)$$

$$U_{C-S} = 0.161 U_{ZT} \quad (9)$$

In summary, the total static thermal resistance value can be expressed as:

$$U_{T-S} = 0.161 U_{ZT} + \frac{U_{x-S}}{1 + 0.311 U_{ZT}} \quad (10)$$

In practical applications, the thermal state of textile and apparel materials is dynamic. In this case, correction coefficients $Z_{O,I}$ and $Z_{O,T}$ must be introduced to calculate the dynamic air thermal resistance $U_{x\text{-}D}$ and the dynamic total clothing thermal resistance $U_{T\text{-}D}$ under static conditions, respectively:

$$U_{x-D} = Z_{O,I} U_{x-S} \quad (11)$$

$$U_{T-D} = Z_{O,T} U_{T-S} \quad (12)$$

The correction coefficients of dynamic textile and apparel thermal resistance can be calculated by the following equation:

$$Z_{O,T} = \begin{cases} Z_{O,C} & U_{ZT} \geq 0.6 \\ \dfrac{(0.6 - U_{ZT}) Z_{O,I} + U_{ZT} Z_{O,C}}{0.6} & U_{ZT} < 0.6 \end{cases} \quad (13)$$

The correction coefficients for wind speed and human walking speed can be calculated by:

$$Z_{O,I} = e^{\left(-0.561(n_x - 0.15) + 0.0566(n_x - 0.15)^2 + 0.269 n_q - 0.0269 n_q^2\right)} \leq 1.0 \quad (14)$$

$$Z_{O,C} = e^{\left(-0.271(n_x - 0.15) + 0.0266(n_x - 0.15)^2 + 0.188 n_q + 0.131 n_q^2\right)} \leq 1.0 \quad (15)$$

The dynamic textile and apparel thermal resistance value is calculated as:

$$U_{Z-D} = U_{T-D} - \frac{U_{x-D}}{d_{ZT}} = \frac{s_{tj} - s_{ZT}}{Z + E} \quad (16)$$

When a person is in a sitting position, the convective Z and radiative E heat exchange between the skin and textile apparel materials can be quantified by:

$$Z + E = d_{ZT} \left\{ g_z \left(s_{ZT} - s_x \right) + 3.68 * 10^{-8} \left(s_{ZT}^4 - s_e^4 \right) \right\} \quad (17)$$

Furthermore, based on Eqs. (13) and (14), the dynamic textile and apparel thermal resistance value $U_{Z\text{-}D}$ is defined as the ratio of the temperature difference between the skin and textile apparel materials to the convective (Z) and radiative (E) heat exchange between the skin and the surrounding environment. The calculation formula is:

$$U_{Z-D} = \frac{s_{tj} - s_{ZT}}{Z + E} = \frac{1}{d_{ZT}} \left\{ \frac{s_{tj} - s_{ZT}}{g_z \left(s_{ZT} - s_x \right) + 3.68 * 10^{-8} \left(s_{ZT}^4 - s_e^4 \right)} \right\} = \frac{\beta}{d_{ZT}} \quad (18)$$

The advantage of the above calculation method is that it can incorporate multiple dynamic heat exchange factors and obtain relevant data through non-contact means. In specific operations, the non-contact algorithm acquires temperature distribution images of the human body surface using an infrared thermal imager. These images are processed using AnalyzIR software to obtain the clothing surface temperature s_{ZT} and the face-neck temperature s_t. The face-neck temperature is considered a key factor affecting overall human thermal sensation, making it particularly important. In addition to temperature data, a portable anemometer was used to measure the air dry-bulb temperature s_x and wind speed n_x, which provide necessary environmental parameters for the calculation of dynamic thermal resistance values. All these measurements were performed non-invasively, avoiding direct interference with the human body, thus improving both the comfort and accuracy of data collection. Specifically, assuming that the temperature gradient between the skin and the textile apparel material surface divided by the dry heat loss per unit human body surface area is represented by x, the following equation is derived to estimate the non-linear function of textile and apparel thermal resistance values under static and dynamic conditions:

$$0.311 U_{ZT}^2 + U_{ZT} - \frac{1}{0.162 Z_{O,T}} \left\{ \beta + U_{x-St} \left(Z_{O,I} - Z_{O,T} \right) \right\} = 0 \quad (19)$$

$$\beta = \frac{s_t - s_{ZT}}{g_z \left(s_{ZT} - s_x \right) + 3.64 * 10^{-8} \left(s_{ZT}^4 - s_e^4 \right)} \quad (20)$$

$$g_z = \begin{cases} 2.41 \left| s_{ZT} - s_x \right|^{0.25} & 2.41 \left| s_{ZT} - s_x \right|^{0.25} \geq 11.1 \sqrt{n_x} \\ 11.1 \sqrt{n_x} & 2.41 \left| s_{ZT} - s_x \right|^{0.25} < 11.1 \sqrt{n_x} \end{cases} \quad (21)$$

The correction factors for wind speed and human walking speed are represented by $Z_{O,I}$ and $Z_{O,C}$, respectively, and are calculated as follows:

$$Z_{O,T} = \begin{cases} Z_{O,C} & U_{ZT} \geq 0.6 \\ \dfrac{U_{ZT}\left(Z_{O,C} - Z_{O,I}\right)}{0.6} & U_{ZT} < 0.6 \end{cases} \tag{22}$$

$$Z_{O,Z} = e^{\left(-0.255(n_x - 0.15) + 0.0267(n_x - 0.15)^2 + 0.191 n_q + 0.133 n_q^2\right)} \leq 1.0 \tag{23}$$

In the derivation of the non-contact algorithm formulas, multiple dynamic factors are incorporated into the static thermal resistance calculation formula, forming a non-linear function model. This model integrates various factors such as skin temperature, textile and apparel material surface temperature, and air temperature. These factors collectively influence the heat exchange process between the human body and the environment under dynamic conditions, thereby determining the clothing thermal resistance value and thermal comfort. In this process, the face-neck temperature, as a representative of local body regions, has significant influence, as the face and neck are among the most sensitive areas for human thermal perception. Therefore, the non-contact algorithm particularly emphasizes the collection of face-neck temperature data, providing a more detailed basis for evaluating overall thermal comfort performance.

In summary, in the thermal resistance calculation methods, the standard algorithm is suitable for measurements under standard experimental conditions and is typically used for planar fabrics or materials with simple structures. In this method, the temperature difference and heat flux density are measured through direct contact, making it appropriate for stable heat sources and airflow conditions. The semi-contact algorithm is suitable for materials with certain irregular shapes or greater thickness. It requires partial contact with the material's surface during measurement, making it ideal for fabrics with surfaces that are not perfectly smooth. The non-contact algorithm uses infrared thermography to measure thermal images, making it suitable for dynamic thermal environments or materials that cannot be directly touched, such as certain functional fabrics or sensitive materials. Each algorithm has its limitations: the standard algorithm tends to have larger errors in fabrics with complex structures, while the semi-contact and non-contact algorithms may be affected by environmental temperature changes or sensor accuracy.

3. THERMODYNAMICS-BASED CALCULATION METHOD OF PMV VALUE FOR TEXTILE AND APPAREL MATERIALS

To more accurately assess the thermal comfort of different body parts, this study introduces a zoned PMV calculation model based on the traditional PMV model. This model takes into account the heat flux distribution and local thermal comfort differences across various body parts, using multi-point thermal resistance and local temperature differences for calculations. Through this model, the thermal comfort impact of different garments on various body parts can be more precisely evaluated, making it particularly suitable for the thermal comfort analysis of complex structures or functional fabrics. Figure 2 visually illustrates the schematic diagram of human body thermal balance when wearing textile apparel. In this study, the PMV value is used as an evaluation index for human thermal sensation, primarily to quantify and assess thermal comfort when wearing different textile and apparel materials. The calculation of PMV value integrates factors such as ambient temperature, humidity, wind speed, human activity level, and clothing thermal resistance, allowing for an accurate prediction of human thermal comfort under specific conditions. In this study, we combine the PMV calculation method with the thermodynamic properties of clothing materials to explore the impact of different textile materials on human thermal comfort under varying environmental conditions. Assuming the human metabolic rate is represented by L, the mechanical work done by the body is Q, the clothed human body surface temperature is s_{ZT}, the mean radiant temperature is s_e, the water vapor pressure in the air is O_x, the clothing area factor is d_{ZT}, the convective heat transfer coefficient between the human body and the environment is g_z, and the dry-bulb air temperature is s_x, the calculation formula is as follows:

$$PMV = \left(0.322 r^{-0.0331L} + 0.0274\right) SM \tag{24}$$

$$\begin{aligned} SM &= (L - Q) \\ &-3.011\left[5.712 - 0.006(L - Q) - O_x\right] \\ &-0.22(L - Q - 57.15) \\ &-0.0163L(5.57 - O_x) \\ &-0.0133L(34 - s_x) \\ &-3.986*10^{-8} d_{ZT}\left[(s_{ZT} + 273)^4 - (s_e + 273)^4\right] \\ &-d_{ZT} g_z (s_{ZT} - s_x) \end{aligned} \tag{25}$$

During the above calculations, the thermodynamic properties of textile materials, such as thermal conductivity, breathability, and humidity regulation, are quantified as clothing thermal resistance parameters, further affecting changes in the PMV value. In this way, the PMV value not only reflects pure environmental factors but also provides a comprehensive assessment of the thermal comfort of textile and apparel materials, offering quantitative guidance for optimizing clothing material design and thermal comfort.

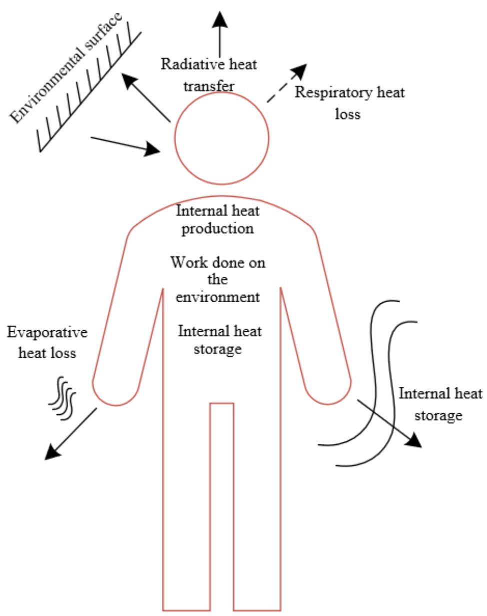
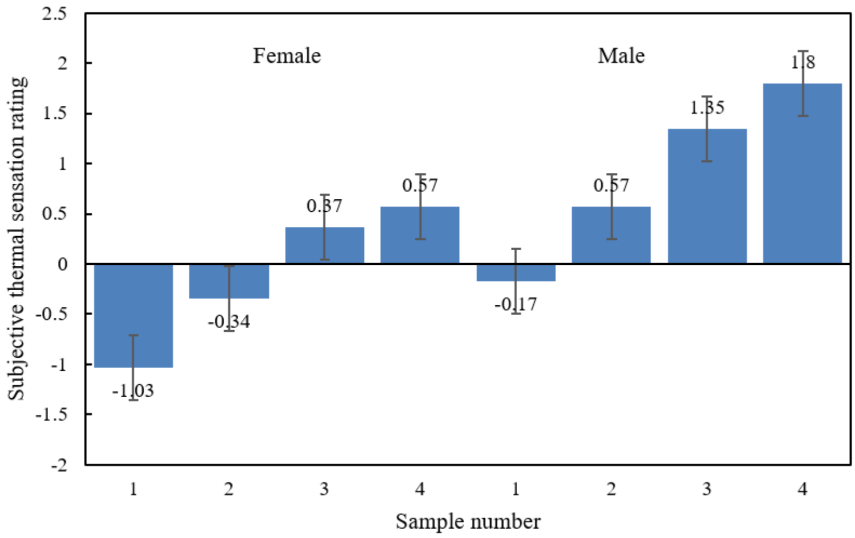


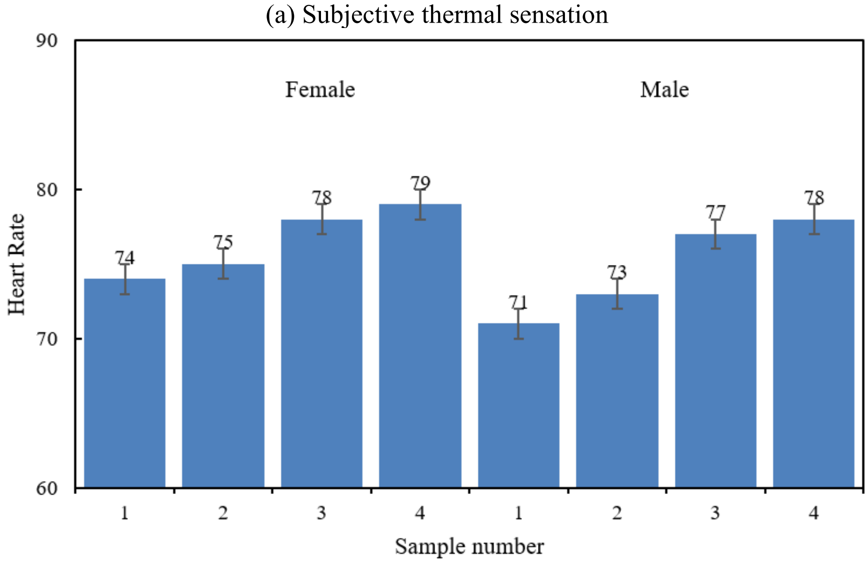
Figure 2. Schematic diagram of human body thermal balance wearing textile apparel

4. EXPERIMENTAL RESULTS AND ANALYSIS

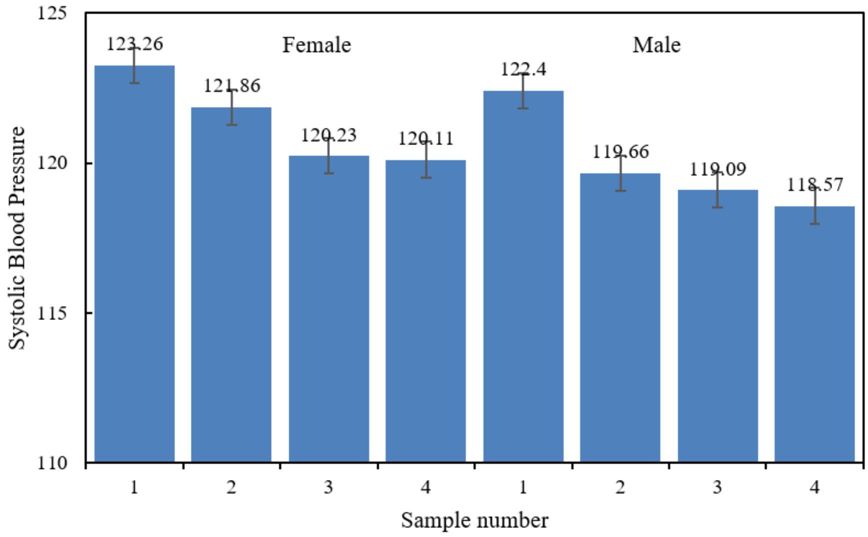
According to the experimental data in Figure 3, subjective thermal sensation scores of the test samples showed significant variations under different textile apparel conditions. For instance, the subjective thermal sensation scores of Sample 1 and Sample 2 were relatively low, at -1.03 and -0.34, respectively, indicating that subjects wearing these garments experienced a cooler environment. In contrast, the scores for Sample 3 and Sample 4 were higher, at 0.37 and 0.57, respectively, suggesting that subjects wearing these garments felt a warmer environment. This indicates that the thermal comfort of clothing changes accordingly with variations in textile materials. Heart rate data showed minor fluctuations under different samples, with an average heart rate ranging from 71 to 79, suggesting that the subjects' physiological responses did not exhibit excessive variations and remained within a normal physiological state. Systolic and diastolic blood pressure also demonstrated relatively stable trends across all samples, with systolic blood pressure fluctuating between 118.57 and 123.26 and diastolic blood pressure ranging between 79.25 and 80.77, indicating that changes in clothing materials did not significantly impact blood pressure levels. Combining thermodynamic principles with the PMV value calculation theory, the thermal comfort scores of the test samples were closely related to the thermal resistance of the materials. Low-thermal-resistance materials such as Sample 1 and Sample 2 effectively conducted heat, leading to lower thermal loads on the wearer, reflected in lower subjective thermal sensation scores (-1.03 and -0.34). In contrast, high-thermal-resistance materials such as Sample 3 and Sample 4 exhibited poorer thermal conductivity, causing heat accumulation and thus increasing the wearer's thermal comfort, as reflected in higher scores (0.37 and 0.57). However, despite the differences in thermal comfort scores, variations in heart rate and blood pressure data remained relatively small, indicating that clothing materials had a limited impact on the physiological responses of the subjects.



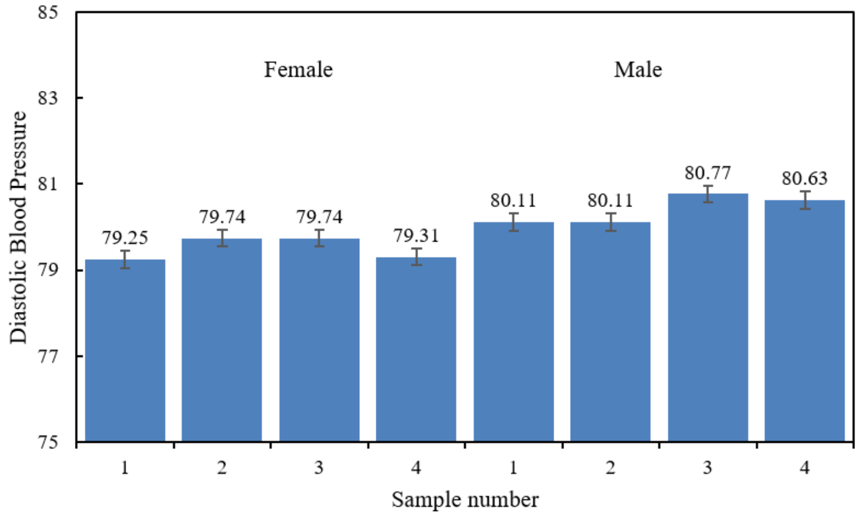
(a) Subjective thermal sensation



(b) Heart rate

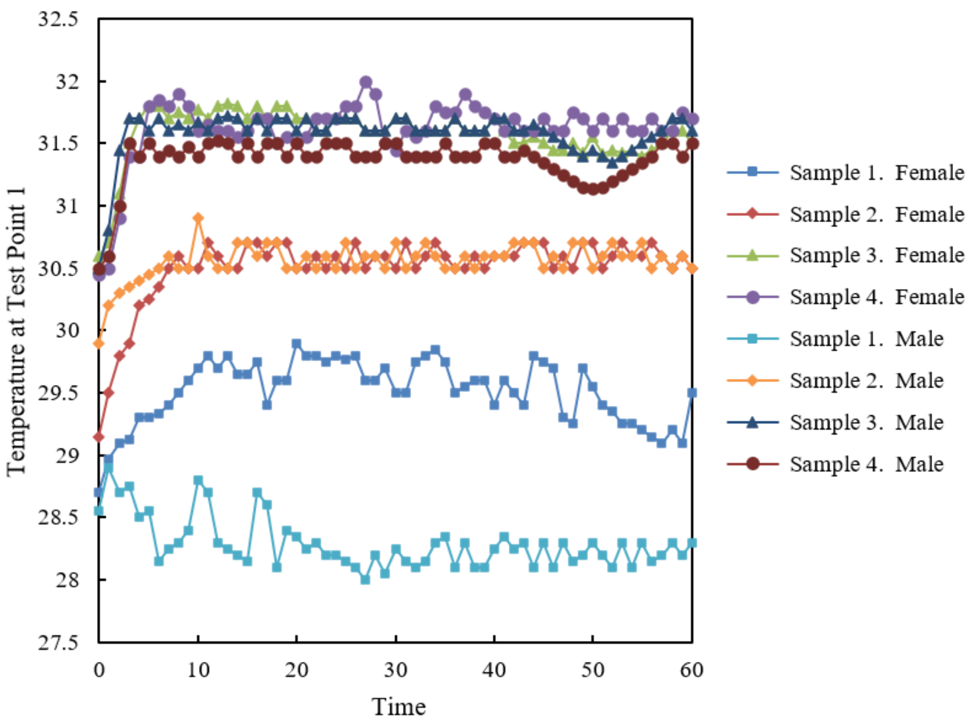


(c) Systolic blood pressure

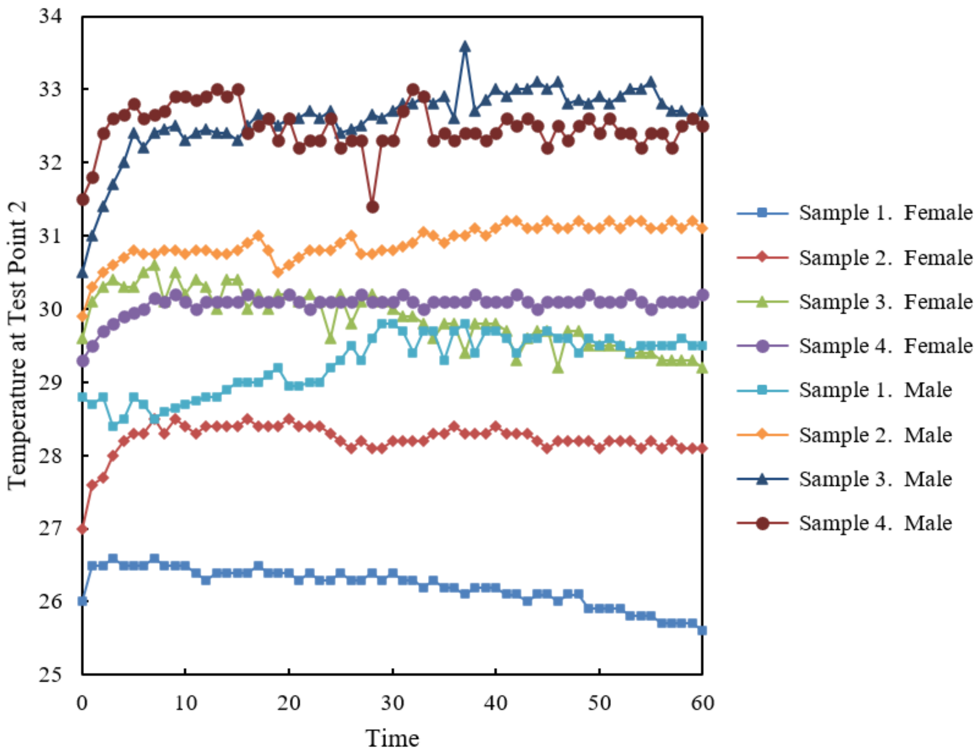


(d) Diastolic blood pressure

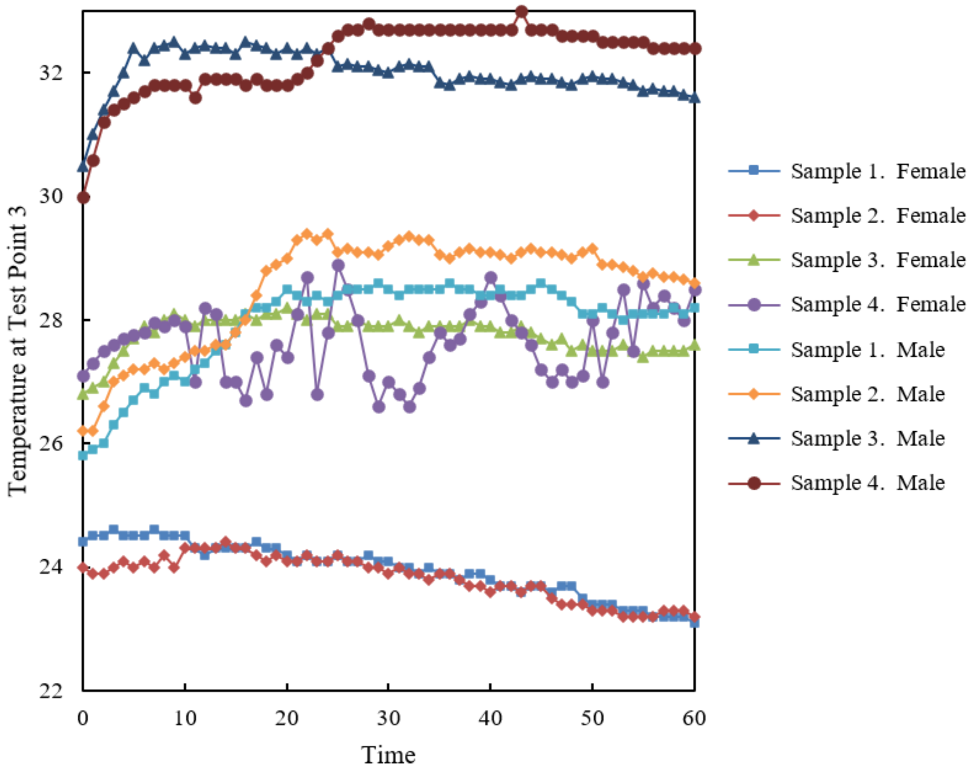
Figure 3. Thermal comfort test results of subjects wearing textile apparel



(a) Test point 1



(b) Test point 2



(c) Test point 3

Figure 4. Comparison of temperatures at different test points for subjects wearing different textile clothing materials

According to the data in Figure 4(a), it can be observed that the temperature variation trend at test point 1 for different samples is significant. In the female group, sample 1 (starting temperature of 28.7℃, ending at 29.75℃) shows a relatively slow and stable temperature change, with a slight upward trend. In contrast, the temperature of sample 2 (starting at 29.15℃, ending at 29.9℃) changes slightly more noticeably, with an overall increase of approximately 0.75℃. The temperature variations of sample 3 and sample 4 are more significant. The temperature of sample 3 rises from 30.6℃ to 31.6℃, while sample 4 increases from 30.45℃ to 31.7℃, with both samples exhibiting a temperature increase of over 1℃. This indicates that these materials have lower thermal resistance, causing their temperature to gradually rise, making the wearer feel a warmer environment. The temperature variation trend in the male group is similar to that in the female group. The temperature of sample 1 slightly increases from 28.55℃ to 29.8℃, with a change of less than 1℃. The temperature of sample 2 rises from 29.9℃ to 30.7℃, with an increase of about 0.8℃. The temperature of sample 3 rises from 30.5℃ to 31.7℃, and the temperature of sample 4 increases from 30.5℃ to 31.5℃. The male group data similarly indicate that samples 3 and 4, which show a greater temperature increase, may make the wearer feel warmer during the test, while samples 1 and 2, with smaller variations, result in a lower thermal load for the wearer.

According to the temperature data of the subjects at test point 2 provided in Figure 4(b), the temperature variation trends of different textile materials at various time points can be observed. The female and male samples show different temperature fluctuations during the test, with some variations. In the female group, the temperature variation of sample 1 is relatively small, maintaining around 26.0°C, indicating that the material has good thermal conductivity and can quickly reach thermal equilibrium over extended wear, keeping the temperature relatively stable. The temperature of sample 2 is relatively stable but shows a slight upward trend, rising from 27.0°C to about 28.2°C. This suggests that the material provides a certain level of thermal comfort while also possessing some thermal resistance. The temperature variations of sample 3 and sample 4 are more significant, especially for sample 4, where the temperature rises from 29.3°C to 30.2°C. This reflects the strong thermal insulation properties of the material, making it suitable for wear in cold environments. The temperature variation trends in the male group are similar to those in the female group. The temperature of sample 1 remains around 29.0°C, with little fluctuation. The temperature of sample 2 is higher, rising from 30.0°C to 31.0°C, with relatively stable fluctuations, showing a certain degree of thermal insulation. The temperature variations of sample 3 and sample 4 are more significant, particularly sample 3, where the temperature gradually rises from 30.5°C to 33.0°C, indicating that the material has strong thermal resistance and is suitable for providing warmth in lower-temperature environments.

From Figure 4(c), it can be seen that the temperature data of subjects at test point 3 show significant individual and material differences. In the female group, the temperature variations of sample 1 and sample 2 are relatively stable, remaining between 23℃ and 24℃, indicating that these two materials have low thermal resistance and can exchange heat with the external environment quickly. The temperatures of sample 3 and sample 4 are significantly higher, especially for sample 4, where the temperature reaches around 27.5℃ at test point 3. This reflects its strong thermal insulation properties, making it suitable for wear in cold environments. The situation is similar in the male group, where the temperature variations of sample 1 and sample 2 are relatively slow, fluctuating around 25℃. However, the temperature variations of sample 3 and sample 4 are larger, particularly sample 3, where the temperature gradually rises to 32℃. This indicates that the material has high thermal resistance, effectively reducing heat loss, making it suitable for insulation needs in cold environments.

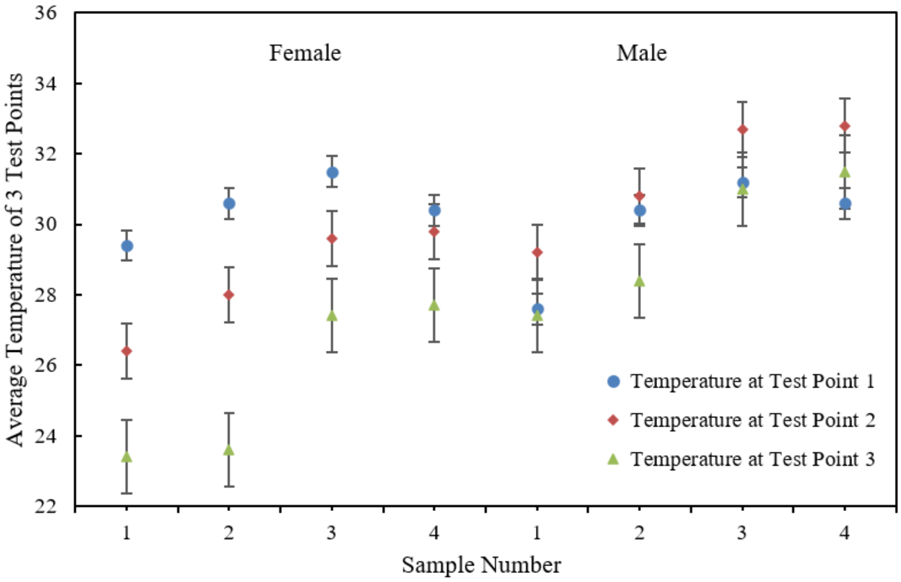
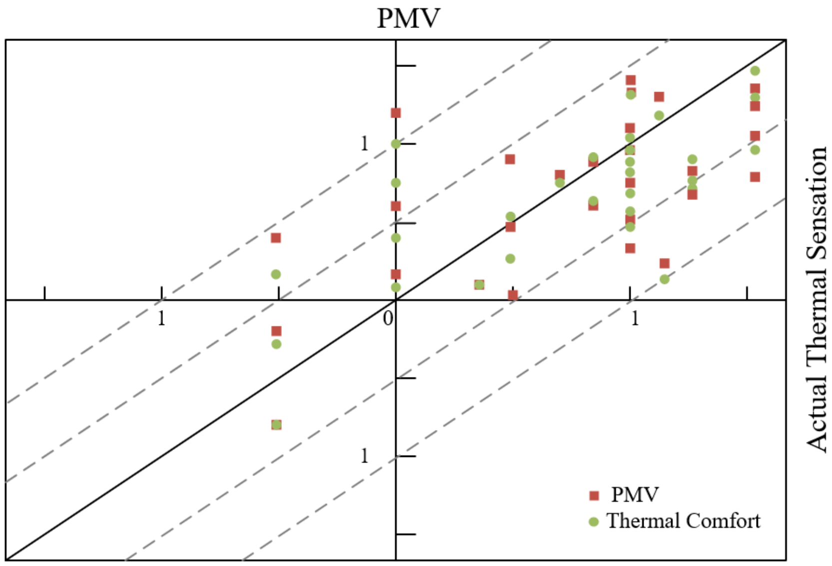


Figure 5. Average temperature at different test points for subjects wearing non-textile clothing

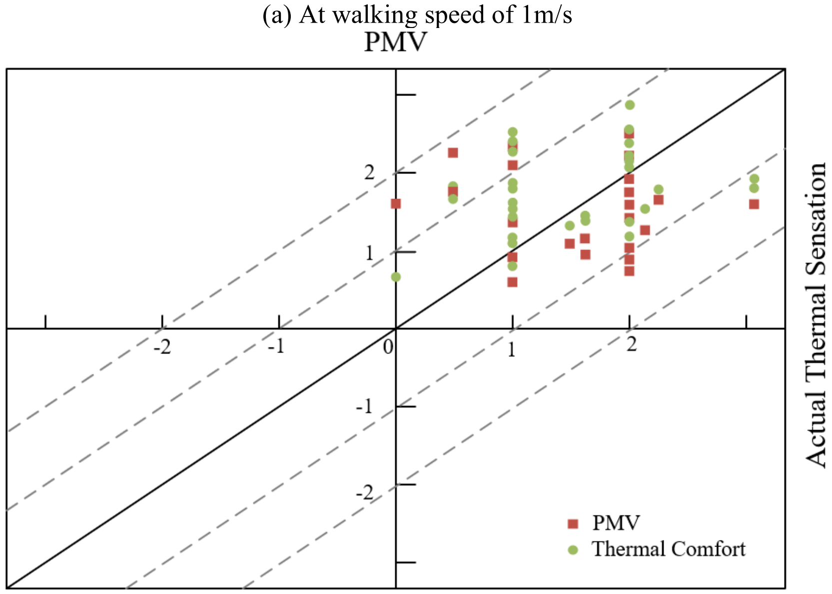
From these experimental data, it can be observed that the thermal resistance performance of textile materials directly affects the temperature variation trend. For materials with low thermal resistance, they can quickly reach thermal equilibrium with the external environment, maintaining a relatively stable temperature, making them suitable for warmer environments. In contrast, materials with high thermal resistance can better prevent body heat loss and maintain a higher temperature, making them more effective in providing warmth in cold environments. This result is consistent with the PMV calculation theory, where high thermal resistance materials can effectively improve thermal comfort in low-temperature environments, while low thermal resistance materials are suitable for hot or mild environments, providing a comfortable wearing experience.

According to the temperature data at different test points provided in Figure 5, significant differences exist in the temperature regulation effects of different textile materials. The temperature data at test point 1 show that sample 1 (female) and sample 2 (female) are relatively close, at 29.4℃ and 30.6℃, respectively, while sample 3 and sample 4 are relatively lower, at 30.4℃ and 27.6℃, respectively. At test point 2, the temperatures of sample 1 and sample 2 slightly decrease to 26.4℃ and 28℃, respectively, while the temperatures of sample 3 and sample 4 slightly increase, reaching 29.6℃ and 29.8℃. At test point 3, the temperatures of sample 1 and sample 2 continue to decrease, reaching 23.4°C and 23.6°C, indicating that these two materials have low thermal resistance and easily dissipate heat to the external environment. In contrast, the temperatures of sample 3 and sample 4 significantly increase, reaching 27.4°C, 27.7°C, 28.4°C, and 31.5°C, respectively. This demonstrates their strong thermal insulation properties, especially for sample 4 in the male group, where the temperature change is the most significant, reaching 31.5°C, showing its high thermal resistance characteristics.

From the data distribution in the two graphs of Figure 6, when the walking speed is 1m/s, the PMV values and thermal comfort data points are more scattered, with some points near the ideal zone, but still many deviations. The PMV values represented in red and the thermal comfort values represented in green do not show a clear concentration in their distribution. When the walking speed is increased to 1.5m/s, the data points are more concentrated, with most points closer to the ideal zone, indicating that at this speed, the consistency between the PMV values and thermal comfort has improved. Compared to the 1m/s speed, the overall dispersion has decreased. This difference in data distribution suggests that the walking speed has a significant impact on both the PMV values and thermal comfort. As the walking speed increases from 1m/s to 1.5m/s, the body's metabolism accelerates, heat production increases, making the relationship between thermal comfort and PMV values closer and the data distribution more concentrated. This means that when designing clothing, it is important to consider the thermal physiological responses of the body at different walking speeds. Especially for sportswear, the thermal comfort changes brought by walking speed variations should be fully considered to improve the functionality and comfort of the clothing and meet consumers' needs in different physical states. In the analysis of Figure 6, in addition to the impact of walking speed on the PMV value, we further investigate the variation patterns of the PMV value under different exercise intensities. During low-intensity exercise, the thermal load on the body is relatively light, and the PMV value changes only slightly. However, during high-intensity exercise, the body's metabolic rate and sweat evaporation increase, leading to a higher thermal load, and the PMV value rises significantly. Therefore, analyzing the effect of exercise intensity on the PMV value allows for a more precise assessment of thermal comfort under different exercise conditions.



(a) At walking speed of 1m/s



(b) At walking speed of 1.5m/s

Figure 6. Comparison of PMV values and thermal comfort under different walking speeds

In further experimental analysis, apart from temperature variations, the impact of humidity on thermal comfort is also significant. Changes in humidity not only affect the efficiency of sweat evaporation but also alter the permeability and thermal conductivity of materials. For example, in high-humidity environments, the permeability of fabrics decreases, and sweat evaporation is hindered, resulting in a higher thermal load on the body. Therefore, the variation in humidity is crucial for thermal comfort assessment, and we will supplement the analysis of how humidity affects the thermal resistance values of different fabrics and thermal comfort evaluation results.

In the analysis of experimental results, in addition to the macroscopic thermal resistance and comfort assessment, the influence of the material's microstructure on heat conduction performance should also be considered. Factors such as fiber arrangement, pore structure, and fabric density significantly affect the fabric’s thermal resistance and permeability. The microstructure of the fabric determines the conduction path and speed of heat flow between fibers, which in turn impacts thermal comfort. For instance, fabrics with higher porosity can provide better air circulation and vapor emission, thereby improving thermal comfort. Therefore, future research will place greater emphasis on the influence of microstructure on heat conduction to better reveal the thermal comfort properties of textile materials.

5. CONCLUSION

This study focuses on two aspects: first, based on thermodynamic principles, the thermal resistance of textile clothing materials was quantitatively calculated, and a more accurate thermal resistance calculation model was proposed; second, by combining thermodynamic properties and PMV value calculation theory, a thermal comfort evaluation method for different textile materials was developed. The first part of the study provides a scientific thermal resistance evaluation tool for clothing design by analyzing the thermal resistance characteristics of textile materials, helping designers make precise material choices to improve the functionality and comfort of the clothing. The second part provides a basis for evaluating the thermal comfort of different materials by combining thermodynamics and PMV theory, which helps predict wearer's comfort in different environmental conditions and optimize clothing design. Overall, this research provides a quantitative theoretical tool for the textile and apparel industry, aiming to promote innovation in comfort and functionality, particularly in the realization of intelligent and personalized clothing design.

In the conclusion of this study, we proposed a thermal comfort evaluation model that demonstrates good predictive accuracy. However, there are still certain limitations in its practical application. The model assumes specific environmental conditions and fabric characteristics, which may not accurately reflect the thermal comfort performance of all types of fabrics under different environmental conditions. Specifically, in extreme environments such as high humidity and high temperatures, the model’s accuracy may be limited. Additionally, the model's applicability under high-intensity exercise conditions requires further validation. Future research will focus on optimizing these limitations and validating the model in real-world application scenarios.

In this study, preliminary experiments used a relatively small sample size, which was insufficient to fully verify the model's general applicability. Therefore, future research will involve increasing the sample size, selecting fabrics with different structural characteristics, functional fabrics, and various thicknesses to ensure the model’s broad applicability and accuracy. In this study, we mainly considered the thermal comfort of single-layer fabrics, while the heat transfer properties of multi-layer fabrics were not explored in depth. Multi-layer fabrics, through air gaps between layers and thermal resistance effects, can effectively regulate the body’s thermal comfort. Therefore, future research will include the impact of multi-layer fabric structures on thermal comfort, especially when considering factors such as air circulation, inter-layer heat transfer, and moisture migration, to further refine this model and enhance its practicality.

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REFERENCES

[1] An, S.K., Kumphai, P., Alam, A.M., Eike, R.J. (2022). Traditional handwoven textiles: A case study of thermal comfort of Thailand’s traditional fusible and nonfusible linings. Textile Research Journal, 92(21-22): 3973-3981. https://doi.org/10.1177/00405175221097105

[2] Matusiak, M. (2010). Thermal comfort index as a method of assessing the thermal comfort of textile materials. Fibres & Textiles in Eastern Europe, 18(2): 45-50.

[3] Mandal, S., Mazumder, N.U.S., Agnew, R.J., Grover, I.B., Song, G., Li, R. (2021). Using artificial neural network modeling to analyze the thermal protective and thermo-physiological comfort performance of textile fabrics used in oilfield workers’ clothing. International Journal of Environmental Research and Public Health, 18(13): 6991. https://doi.org/10.3390/ijerph18136991

[4] Hes, L., Bal, K., Dolezal, I. (2021). Principles of clothing comfort and their use in evaluation of sensorial and thermal comfort of men’s casual jacket. Fibers and Polymers, 22(10): 2922-2928. https://doi.org/10.1007/s12221-021-0425-z

[5] Awais, M., Krzywinski, S., Wendt, E. (2021). A novel modeling and simulation approach for the prediction of human thermophysiological comfort. Textile Research Journal, 91(5-6): 691-705. https://doi.org/10.1177/0040517520955227

[6] Skrzetuska, E., Puszkarz, A.K., Pycio, Z., Krucińska, I. (2021). Assessment of the impact of clothing structures for premature babies on biophysical properties. Materials, 14(15): 4229. https://doi.org/10.3390/ma14154229

[7] Siddiqui, M.O.R., Sun, D. (2018). Development of experimental setup for measuring the thermal conductivity of textiles. Clothing and Textiles Research Journal, 36(3): 215-230. https://doi.org/10.1177/0887302X18768041

[8] Matusiak, M., Sikorski, K. (2011). Relative thermal

comfort index as a measure of the usefulness of fabrics for winter clothing manufacturing. Fibres and Textiles in Eastern Europe, 9(6): 94-100.

[9] Lei, L., Shi, S., Wang, D., Meng, S., Dai, J.G., Fu, S., Hu, J. (2023). Recent advances in thermoregulatory clothing: Materials, mechanisms, and perspectives. ACS Nano, 17(3): 1803-1830. https://doi.org/10.1021/acsnano.2c10279

[10] Mangat, M.M., Hes, L., Bajzík, V. (2015). Thermal resistance models of selected fabrics in wet state and their experimental verification. Textile Research Journal, 85(2): 200-210. https://doi.org/10.1177/0040517514545254

[11] Puszkarz, A.K., Machnowski, W., Błasińska, A. (2020). Modeling of thermal performance of multilayer protective clothing exposed to radiant heat. Heat and Mass Transfer, 56: 1767-1775. https://doi.org/10.1007/s00231-020-02820-1

[12] Ongwuttiwat, K., Sudprasert, S., Leephakpreeda, T. (2018). Determination of human thermal comfort due to moisture permeability of clothes. International Journal of Clothing Science and Technology, 30(4): 462-476. https://doi.org/10.1108/IJCST-09-2017-0138

[13] Bogdan, A., Sudoł-Szopińska, I., Szopiński, T. (2011). Assessment of textiles for use in operating theatres with respect to the thermal comfort of surgeons. Fibres & Textiles in Eastern Europe, 19(2): 65-69.

[14] Eryuruk, S. H. (2019). Effect of fabric layers on thermal comfort properties of multilayered thermal protective fabrics. Autex Research Journal, 19(3): 271-278. https://doi.org/10.1515/aut-2018-0051

[15] Zhang, Q., Cheng, H., Zhang, S., Li, Y., Li, Z., Ma, J., Liu, X. (2024). Advancements and challenges in thermoregulating textiles: smart clothing for enhanced personal thermal management. Chemical Engineering Journal, 488: 151040. https://doi.org/10.1016/j.cej.2024.151040

[16] Sybilska, W., Korycki, R. (2016). Analysis of thermal-insulating parameters in two-and three-layer textiles with semi-permeable membranes. Fibres & Textiles in Eastern Europe, 5(119): 80-87. https://doi.org/10.5604/12303666.1215532

[17] Wang, Y., Xu, Y., Xu, D., Fan, J. (2022). Optimization of multilayer clothing assemblies for thermal comfort in cold climate. International Journal of Thermal Sciences, 179: 107586. https://doi.org/10.1016/j.ijthermalsci.2022.107586

[18] Kaziur, P., Mikołajczyk, Z., Kłonowska, M., Woźniak, B. (2022). Design methodology and technology of textile footwear. Materials, 15(16): 5720. https://doi.org/10.3390/ma15165720

[19] Ullah, H.M.K., Lejeune, J., Cayla, A., Monceaux, M., Campagne, C., Devaux, É. (2022). A review of noteworthy/major innovations in wearable clothing for thermal and moisture management from material to fabric structure. Textile Research Journal, 92(17-18): 3351-3386. https://doi.org/10.1177/00405175211027799

[20] Kaya, D.D., Oglakcioglu, N., Sari, B., Yilmaz, H.A. (2023). Electromagnetic shielding and comfort properties of knitted fabrics produced by electrically conductive fibers. Fibers and Polymers, 24(7): 2451-2468. https://doi.org/10.1007/s12221-023-00200-0

[21] Jhanji, Y., Gupta, D., Kothari, V.K. (2024). Role of fibre, yarn and fabric variables in engineering clothing with required thermo-physiological properties. Indian Journal of Fibre & Textile Research (IJFTR), 49(1): 109-128. https://doi.org/10.56042/ijftr.v49i1.9536

[22] Matusiak, M., Kowalczyk, S. (2014). Thermal-insulation properties of multilayer textile packages. Autex Research Journal, 14(4): 299-307. https://doi.org/10.2478/aut-2014-0030