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Modification and Validation of a Dynamic Thermal Resistance Model for Wet-State Fabrics

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Abstract: To investigate the dynamic thermal resistance of woven fabrics in different wetting states, ten commonly used clothing fabrics were selected and tested for fabric thermal resistance under different levels of water saturation in accordance with Chinese national standards. Based on Mangat's eight thermal resistance prediction models, the study improved the models by replacing the original moisture content with water content saturation. The suitability of the eight models in predicting the thermal resistance of woven fabrics in wet states was compared using the sum of squared deviations (*SSD*), sum of absolute deviations (*SAD*), and correlation coefficient (R^2). The results showed that during the process from initial wetting to complete immersion, the measured thermal resistance values of the ten fabric samples were consistent with the predicted values from Model 5 in the theoretical model of thermal resistance ($R^2 > 0.955$). The characteristic of Model 5 is that the air thermal resistance and water thermal resistance are first connected in parallel and then connected in series with the fiber thermal resistance. The corrected predicted values from Model 5 were highly consistent with the experimental measurement values and can be used to approximate the thermal resistance of woven fabrics in wet states.

Keywords: wet state; ultradry state; thermal resistance; thermal comfort; empirical model

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1. Introduction

As the "second skin" of the human body, clothing is the most important barrier for maintaining thermal stability [1]. Clothing should help maintain the body's thermal and moisture balance, enabling the body to be in a state of psychological, physiological, and sensory comfort during long periods of work and activity. When factors such as sweating, rainwater, and accidental immersion cause clothing to become wet, both the thermal resistance and moisture resistance of the clothing will change, affecting its comfort. Fabric thermal resistance is influenced by factors such as the fabric structure, density, humidity, and surface treatment and is closely related to fabric thickness, yarn density, fabric surface friction coefficient, and fabric type [2–4]. In wet conditions, the moisture absorption and release of the fabric will cause a constant change in the proportion of water and air in the fabric, and the thermal resistance of the wet fabric will also dynamically change [5]. The three key factors affecting fabric moisture absorption are thickness, porosity, and fiber type, and thicker and higher-porosity fabrics can absorb more water, with natural fibers having greater moisture absorption than synthetic fibers. In wet conditions, due to the participation of water, the structure and composition of the fabric will undergo small changes, making the thermal performance of clothing more complex than in dry conditions.

There have been numerous studies on fabric thermal resistance in wet conditions worldwide. Hes et al. [6] tested the thermal resistance of fabrics per unit thickness in dry and wet conditions, and the results showed that the thermal resistance of fabrics in wet conditions was significantly lower than in dry conditions. Oğlakcioğlu et al. [7] tested the thermal resistance of 10 kinds of knitted pure cotton fabrics in wet conditions; the conclusion was that increasing the moisture content of the fabric significantly increased its heat transfer capability. Wang et al. [8] tested the thermal resistance of seven different thicknesses of cotton and polyester fabrics in fully saturated conditions, confirming that fabric thickness and fiber material have a significant impact on thermal resistance. Akckgun et al. [9] tested the thermal resistance changes in wool and wool/polyester blend fabrics at different levels of moisture, and the results showed that fabric porosity also has a significant impact on thermal resistance. Yang et al. [10] tested the thermal resistance of three typical clothing items in saturated conditions and found that the thermal insulation performance was significantly reduced compared with dry conditions. Therefore, the fundamental factors affecting fabric thermal resistance in wet conditions are fabric fiber type, the water in the fabric, and the distribution of water in the fabric. Establishing a theoretical model for the thermal resistance of wet fabrics based on fabric composition and structure is scientifically significant for analyzing complex wet thermal resistance.

In the past few decades, many researchers have studied the prediction of thermal resistance models for fabrics, both theoretically and experimentally. Nake et al. [11] were the first to propose a three-parameter theoretical model of air, water, and fiber polymers, including series, parallel, and combined usage, some of which could be used for thermal resistance prediction; however, these models were very complex and limited to the dry state. Hes [12] assumed that the thermal resistance of the fabric was parallel to the thermal resistance of water in his proposed thermal resistance model, which had higher predictability. Mangat et al. [3] proposed a theoretical model for the combination of series and parallel air, water, and fiber polymer thermal resistance under wet conditions. They tested the thermal resistance of cotton knitted fabrics at different moisture levels, and the results showed that two sets of models had the best consistency with experimental data. In addition, the experimental conclusion also suggested that the model may be applicable to other types of fabrics; this conclusion needs to be verified by subsequent experiments. In addition to the above thermal resistance models, the literature also mentions six thermal resistance models [13]. Through the comparison of experimental data and models, it is believed that these models have poor correlation with the thermal resistance of wet fabrics. Although individual thermal resistance models involve the influence of moisture, they do not consider the dynamic thermal resistance changes of fabrics due to moisture increase. In summary, previous studies mostly involved the prediction of thermal resistance of knitted fabrics, lacking the prediction of the thermal resistance of woven fabrics as a large category. In order to more comprehensively analyze the thermal resistance changes in various types of fabrics under wet conditions, this study refers to national standards to test the thermal resistance values at each moisture level and analyzes the effect of fabric humidity on thermal resistance by studying the thermal resistance changes in different fabrics after wetting. Based on the test results, the theoretical model of fabric thermal resistance is modified and verified more accurately.

2. Thermal Resistance Theoretical Model

Fabric is typically composed of fiber polymers, stagnant air within the fabric, and absorbed water molecules [3]. The material that provides warmth is primarily the stagnant air, and the main role of the fiber polymers is to provide storage space for this air. Under natural conditions, the water content in fabrics is minimal and mainly achieved through the binding of hydrophilic groups within the fiber polymers to water vapor in the air or in the form of adsorption onto the fabric surface. The thermal resistance of fabrics is a critical parameter for measuring their ability to insulate heat transfer, is an important indicator of fabric thermal comfort, and primarily dependent on fabric thickness and thermal conductivity [14,15] (see Equation (1)),

$$R_t = \frac{h}{\lambda} \tag{1}$$

where R_t is the thermal resistance of the fabric in $m^2 \cdot °C/W$, h is the fabric thickness in m, and λ is the thermal conductivity of the fabric in $W/(m \cdot °C)$.

The thermal resistance of fabric is largely dependent on the amount of stagnant air within it. Therefore, it can be concluded that factors affecting the air content in fabrics determine their thermal resistance. These factors include fabric fiber type, thickness, surface density, organizational structure, and porosity, all of which are critical in determining clothing thermal resistance. Fabric thickness and surface density can be directly measured, and there are many methods for measuring fabric porosity. Studies have used fabric surface density, fabric thickness, and fabric fiber density to calculate porosity [3] (see Equation (2)).

$$\varepsilon = 1 - \frac{m}{h \cdot \rho_{fib}} \tag{2}$$

where ε is the porosity of the fabric in percentage, ρ_{fib} is the fiber density under standardized moisture regain in g/m^3, and m is the measured areal density of the fabric in g/m^2.

The dry fabric system is composed of fibers and air, with the air uniformly distributed in the voids of the entire fabric system, including the interstices between the fabric structure and yarns, the interstices between fibers, and the internal voids of the fibers. Assuming a constant capacity of the fabric system, when the external environment is humid, the dry fabric continuously absorbs moisture from the outside. Unlike air, the interaction between water molecules and fibers is more complex, which Hes [16] describes in four forms: after the fabric absorbs water, water molecules first enter the micro-pores of the fibers and quickly form strong hydrogen bonds with the hydrophilic groups in the fiber polymers, whereas the remaining water molecules quickly occupy all the voids in the entire fabric system outside the fiber polymers until almost all the air in the fabric system is driven out. Finally, some of the water molecules are adsorbed on the fabric surface and the fabric reaches the state of saturation absorption, with the maximum water content. Sugawara and Yoshizawa [17] proposed that the thermal conductivity of porous materials depends on the thermal conductivity of the fluid and the solid. For fully saturated porous fabrics, the fabric thermal resistance can be regarded as the combination of fiber thermal resistance and water thermal resistance. Since the thermal conductivity of water is 22 times higher than that of air (0.57/0.026) [18], as the proportion of water in the fabric increases, the overall thermal conductivity of the fabric will significantly increase, resulting in a decrease in the fabric's insulation ability.

Many scholars have constructed theoretical and empirical models of fabric thermal resistance under different humidity levels through practical experiments and theoretical analyses. Among them, Mangat et al. [3] proposed a theoretical model for the wet-state thermal resistance of single-layer fabrics based on previous theories, which macroscopically considers the wet-state thermal resistance of fabrics as consisting of fiber thermal resistance, air thermal resistance, and water thermal resistance. The following assumptions were made: (1) the voids are uniformly distributed throughout the fabric system, and the moisture content contained in the fabric is constant. When the fabric is soaked, the water entering the fabric replaces some of the air in the voids; (2) when the hygroscopic fabric expands after absorbing water, the fabric undergoes changes and the thickness and area of the fabric increase, whereas the voids between the fibers and yarns decrease. However, since the macroscopic changes are still relatively minor, the changes can be ignored; (3) when the fabric is completely immersed, the water in the voids can be regarded as countless water columns, and the height of the water columns in the voids can be regarded as the thickness of the fabric. If the fabric has not reached complete wetting, the height of the water columns and air columns cannot be measured; (4) this model is based solely on thermal conduction and does not consider the effects of convection, radiation, and evaporation.

This series of models defines wet-state fabrics as a mixed system of fibers, water, and air, and the total thermal resistance of the fabric is jointly determined by the thermal resistance of the fibers, air, and water. The thermal resistance calculation formulas for the three factors are [3] (see Equations (3)–(5)):

$$\text{Fiber thermal resistance}: \ R_f = \frac{h(1-\varepsilon)}{\lambda_f} \tag{3}$$

$$\text{Air thermal resistance}: \ R_a = \frac{h\varepsilon}{\lambda_a(1-\mu)} \tag{4}$$

$$\text{Water thermal resistance}: \ R_w = \frac{h\varepsilon}{\lambda_w \mu} \tag{5}$$

where R_f, R_a, and R_w represent the thermal resistance of fibers, air, and water, respectively, $m^2 \cdot ^\circ C/W$. λ_f is the thermal conductivity of fiber polymers, $W/(m \cdot ^\circ C)$. λ_a is the thermal conductivity of air, in $W/(m \cdot ^\circ C)$, whereas λ_w is the thermal conductivity of water, $W/(m \cdot ^\circ C)$. μ is the moisture content of the fabric, %.

The thermal resistance of a fabric in a wet state can be predicted by combining the thermal resistance of its fiber, air, and water components in series, parallel, or a combination of both. Based on different serial and parallel configurations in practice, Mangat et al. [3] summarized eight thermal resistance models for wet fabrics (see Equations (6)–(13)). By comparing the predicted results of these models with actual measurements, the thermal resistance model with the best correlation was finally selected as the theoretical prediction model for thermal resistance. The eight thermal resistance models are as follows:

$$\text{Model 1}: \ R_t = R_f + R_a + R_w \tag{6}$$

$$\text{Model 2}: \ R_t = \left(R_f^{-1} + R_a^{-1} + R_w^{-1}\right)^{-1} \tag{7}$$

$$\text{Model 3}: \ R_t = \frac{R_a \cdot R_f}{R_a + R_f} + R_w \tag{8}$$

$$\text{Model 4}: \ R_t = \frac{R_f \cdot R_w}{R_f + R_w} + R_a \tag{9}$$

$$\text{Model 5}: \ R_t = \frac{R_a \cdot R_w}{R_a + R_w} + R_f \tag{10}$$

$$\text{Model 6}: \ R_t = \frac{R_w(R_a + R_f)}{R_a + R_w + R_f} \tag{11}$$

$$\text{Model 7}: \ R_t = \frac{R_a(R_w + R_f)}{R_a + R_w + R_f} \tag{12}$$

$$\text{Model 8}: \ R_t = \frac{R_f(R_w + R_a)}{R_a + R_w + R_f} \tag{13}$$

Among the eight models summarized by Mangat et al. [3], Models 1 and 2 represent the predicted thermal resistance values for fiber, air, and water in direct series and in parallel and therefore should be excluded from consideration when selecting the optimal thermal resistance model. In their subsequent experiments, Mangat et al. validated the accuracy of the above models in predicting the thermal resistance of a single-layer knitted fabric at different levels of moisture content. The results showed that Model 3 in their model group had a good correlation with a certain twill cotton fabric tested, whereas Models 5 and 7 exhibited the best consistency with all experimental data and were applicable to different types of knitted fabrics.

It should be noted that Mangat et al. used the moisture content μ and $1-\mu$ to represent the ratio of water and air in the interstices of the fabric, respectively, in the calculation formulas for air and water thermal resistance. According to the formula for moisture content, it represents the proportion of water in the wet fabric. Therefore, using moisture content to represent the ratio of water and air in the fabric interstices is not rigorous. The thermal resistance prediction curve in Mangat et al.'s results often underestimated the actual measurement values, which may be caused by the definition of moisture content. In this study, we followed the thermal resistance prediction model framework of Mangat et al. and used water content saturation to represent the ratio of water and air in the fabric interstices, which is the maximum water content that the fabric can absorb. The water content saturation was calculated as the ratio of the weight of water measured during the test to the maximum water absorption weight of the fabric. The maximum water absorption of the fabric was calculated based on the weight of the sample before and after immersion, using the Formulas (14) and (15):

$$WAC = \frac{m_{water}}{SA} \times 100\% \tag{14}$$

$$\eta = \frac{m_{wet} - m_{dry}}{WAC} \times 0.09 \tag{15}$$

where WAC is the maximum water absorption of the fabric in g/m^2, SA is the fabric area in m^2, m_{water} is the maximum water weight that the fabric can absorb, g, m_{wet} is the weight of the wet fabric, g, m_{dry} is the weight of the ultradry fabric, g, and η is the water content saturation, %. The fabric samples are all large samples with a size of 0.3 m $\times$ 0.3 m; the total area of the samples is 0.09 m^2.

3. Experimental

3.1. Materials

Previous research on the thermal performance of wet fabrics has primarily focused on porous and highly moisture-absorbent knitted fabrics. In this study, we investigated the thermal performance of various types of woven fabrics commonly used in clothing, including natural fiber fabrics such as cotton, linen, silk, and wool, as well as synthetic fiber fabrics such as nylon and polyester. We also included blended fabrics such as polyester/cotton, nylon/spandex, polyester/viscose, and polyester/ammonia. To prevent moisture evaporation from the fabric during thermal resistance testing, we sealed the fabric samples in flat bags (0.4 m $\times$ 0.3 m). The fabric samples were wetted with laboratory-made deionized water to ensure consistency across all samples. See Table 1 for details on all fabric parameters.

Table 1. Fabric specifications.

Symbol	Composition	Structure	Thickness (mm)	Weight (g/m^2)	Porosity
CO	Cotton 100%	Plain	0.78	121.87	0.8985
JU	Jute 100%	Twill	0.93	249.25	0.8213
SI	Silk 100%	Plain	0.63	72.94	0.9148
WO	Wool 100%	Twill	1.02	175.39	0.8697
PO	Polyester 100%	Plain	0.66	90.05	0.9011
NY	Nylon 100%	Plain	0.72	161.06	0.8037
PE	Polyester 90% + Elastane 10%	Plain	0.89	155.37	0.8739
PC	Polyester 65% + Cotton 35%	Plain	1.41	227.26	0.8877
AV	Acrylic 70% + Viscose 30%	Plain	0.89	200.62	0.8047
NE	Nylon 85% + Elastane 15%	Plain	0.77	136.69	0.8748

3.2. Sample Preparation

Measuring the maximum water absorption of a fabric sample is the first step in evaluating a fabric's ability to absorb and store moisture. The experimental method followed that by Tang et al. [19]. To ensure that the fabric was completely dry before measurement, all test fabrics were dried in an oven at 105 °C for 30 min to remove any excess moisture and achieve an "ultra dry state" as proposed by Naka et al. [11]. Then, the fabric sample was soaked in deionized water for 3 min and hung vertically until there were no liquid droplets falling for 30 s, indicating complete wetting of the fabric.

Based on the maximum water absorption of the fabric, the fabric saturation level, and the area of the fabric sample, the amount of water added to the fabric sample is determined. The fabric saturation level is defined as the percentage of the added water to the maximum water absorption of the fabric, reflecting the degree of water content saturation in the fabric. Since the testing time of the thermal resistance tester is relatively long, the evaporation of water from the test fabric during the test will not only affect the temperature and humidity of the surrounding environment but also cause a decrease in the moisture content of the fabric. To address this issue, the method proposed by Raccuglia et al. [20] was adopted to seal the wet fabric. Specifically, the ultradry fabric was placed flat in a sealed bag and a certain amount of deionized water was measured and poured into a humidifying spray bottle. The spray bottle was then suspended about 2 cm above the center of the fabric sample and sprayed evenly with deionized water. After 5 min of standing, the bag is sealed once the fabric is fully wetted.

In addition, the thermal resistance tests were conducted on the ultradry fabric and on fabrics with saturation levels of 20%, 40%, 60%, 80%, and 100%. If the saturation level of the test sample exceeded 100%, i.e., there is excess water between the fabric and the simulated skin, the humidification procedure is performed in two steps to avoid insufficient water due to excess water adhering to the inner wall of the sealed bag. First, the added water is determined based on the maximum water absorption of the sample, followed by adding the excess water using a micro pipette to the center of the sample before the thermal resistance test is performed.

3.3. Equipment and Methods

The thermal conductivity, thermal resistance, and insulation properties of fabric samples were measured using a textile heat transfer performance tester (Ningbo Textile Instrument Co., Ltd., Ningbo, China, YG606E, see Figure 1) in accordance with GB/T 11048-2018 (Textiles—Physiological effects—Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test)) [21]. The instrument provides rapid measurement of both steady-state and transient thermal performance. To some extent, this instrument simulates the heat flow density q (W/m^2) from human skin to fabric when the fabric is initially in contact with the skin in an environment without forced convection. The fabric thickness was determined using a digital fabric thickness gauge (Wenzhou Interco Testing Instruments Co., Ltd., Wenzhou, China, YG(B)141D) in accordance with GB/T 3820-1997 (Determination of thickness of textiles and textile products) [22], whereas the surface density was determined using an electronic balance with an accuracy of ±0.1 g in accordance with GB/T 4743-2009 (Textiles—Yarn from packages—Determination of linear density (mass per unit length) by the skein method) [23]. The fabric samples were dried in a ventilated oven (Wenzhou Baien Instrument Co., Ltd., Wenzhou, China, Y802K) and sealed using a hand-press sealing machine; a humidifier was used.

When two fibers are blended during the fabric weaving process, the density of the blended fibers cannot be directly obtained. However, it can be estimated using the following equation proposed by Militky [24].

$$\rho_{ab} = r\rho_a + (1 - r)\rho_b \tag{16}$$

where a and b represent the types of fibers, ρ_a and ρ_b represent their fiber densities, r represents the proportion of fiber a, and ρ_{ab} represents the density of the blended fiber. All tests were conducted under laboratory conditions with a temperature of 20 ± 1 °C, relative humidity of 50 ± 5%, and wind speed < 0.4 m/s.

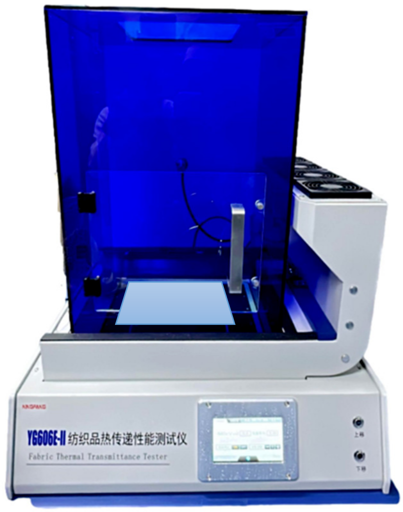


Figure 1. Textile heat transfer performance tester (test plate to do highlighting effect).

3.4. Thermal Properties Characterization

The thermal properties of textiles, such as the heat transfer coefficient (U), thermal resistance (R_t), and thermal insulation (Q), are influenced by factors such as the fabric type and environment. In this study, a textile heat transfer performance tester was used to measure these properties in a constant temperature and humidity room. The laboratory temperature was set at 25 ± 1 °C, with a humidity of 65 ± 5% and a wind speed less than 0.4 m/s. The temperature of the test plate was set at 35 °C, and square fabric samples measuring 0.3 m × 0.3 m were prepared for each fabric type. Before each day's experiment, a blank test was conducted, then the instrument chamber was opened and the sealed bag with the wetted fabric was laid flat onto the test plate of the thermal resistance tester. During the experiment, care was taken to maintain stable air inside the instrument as much as possible. After a period of testing, the thermal properties of the fabric could be read from the instrument panel. Each experiment was performed three times and the results were averaged, with a coefficient of variation between the test results being less than or equal to 3%.

The heat transfer coefficient of a fabric refers to the heat flux passing through a unit area of fabric when there is a surface temperature difference of 1 °C [25]. The formula for calculating the heat transfer coefficient is as follows:

$$U = \frac{U_{bp} \times U_1}{U_{bp} - U_1} \tag{17}$$

where U is the heat transfer coefficient of the fabric, W/(m^2·°C), U_{bp} is the heat transfer coefficient of the experimental plate without specimen, W/(m^2·°C), and U_1 is the heat transfer coefficient of the experimental plate with specimen, W/(m^2·°C).

The thermal resistance is the reciprocal of the heat transfer coefficient, and its conversion formula for thermal resistance is:

$$R_t = \frac{1}{U} \tag{18}$$

$$R_{tm} = R_{ct} - R_{ct0} \tag{19}$$

where R_{tm} is the actual measured thermal resistance of the fabric in m^2·°C/W; R_{ct} is the final thermal resistance test reading of the thermal resistance tester, which is the sum of the fabric thermal resistance and the sealing bag thermal resistance in m^2·°C/W; and R_{ct0} is the thermal resistance of the sealing bag in $m^2 \cdot °C/W$, which can be directly tested by the thermal resistance tester. The thermal resistance of the sealing bag R_{ct0} is 12.8×10^{-3} $m^2 \cdot °C/W$.

The thermal insulation rate is the percentage of the difference between the heat dissipation with and without the sample to the heat dissipation without the sample. It is related to the thermal conductivity and porosity of the fibers and reflects the ability of the fabric to prevent the loss of body heat. According to the latest textile thermal insulation testing standard GB/T 35762-2017 (Textiles—Test method for thermal transmittance—Flat plate test), the equation for calculating the thermal insulation rate is as follows [26]:

$$Q = \frac{W_2 - W_1}{W_1} \times 100\% \quad (20)$$

where W_1 is the heat dissipation of the blank test plate (W/°C) and W_2 is the heat dissipation of the sample test plate (W/°C).

4. Result and Discussion

4.1. Effect of Water Content Saturation on Fabric Thermal Resistance

In this study, the thermal performance changes of ten different fiber types of woven fabrics were measured at various humidity levels. The measurement results of thermal resistance and insulation rate in dry and wet states are shown in Figures 2 and 3; each sample was measured three times. The coefficient of variation (CV) for the measurement results was less than 3%. As shown in the figures, the fabrics deteriorated in thermal performance after wetting and the thermal resistance and insulation rate both decreased as the water content saturation level of the fabric increased. Compared with the thermal resistance of all fabrics in the ultradry state, when the water content saturation level reached 20%, the thermal resistance significantly decreased in the range of 8.3~12.1 $\times 10^{-3}$ $m^2 \cdot °C/W$, with an average decrease of 42.5%. Subsequently, when the water content saturation level reached 40%, 60%, 80%, and 100%, the average decreases in thermal resistance were 61.8%, 71.5%, 74.9%, and 77.8%, respectively. It was observed that the degree of decrease in thermal resistance gradually decreased as the water content saturation level of the fabric increased; this ultimately decreased to 22.2% of the thermal resistance in the ultradry state. This may be because a small amount of water in the fabric provides a shortcut for heat transfer when the water content saturation level of the fabric is low, significantly increasing the thermal conductivity of the fabric. As the water content saturation level increases, water molecules gradually enter the interior of the fabric until all the voids in the fabric system are occupied [27]. The thermal conductivity of fabric fibers generally ranges from 0.033 to 0.100 W/(m·°C) according to literature [17]. Air, as a poor conductor of heat, has a stable thermal conductivity of only 0.026 W/(m·°C) at 20 °C, whereas the thermal conductivity of still water at 20 °C is 0.57 W/(m·°C), which is 22 times higher than that of air. The specific heat capacity of water is 3431 times that of air at 37 °C [28]. When water occupies the entire fabric system, it not only destroys the loose structure of the fabric but also significantly reduces the thermal resistance of the fabric due to its higher thermal conductivity. When a large number of water molecules are adsorbed on the surface of the fabric, the fabric surface becomes moist [29]. As the proportion of adsorbed water in the fabric increases, the impact on thermal resistance gradually becomes less significant because the adhesion force and the action force of adsorbed water are weak [10]. For blended fabrics, due to the different blending proportions of hydrophilic and hydrophobic fibers, it can be found that the proportion of hydrophilic fibers is greater than hydrophobic fibers in materials such as NE (Nylon 85% + Elastane 15%), whose thermal resistance loss after complete wetting is 84.21% of the ultradry-state thermal resistance, whereas the proportion of hydrophobic fibers is greater than hydrophilic fibers in materials such as PC (Polyester 65% + Cotton 35%), whose thermal resistance loss was 68.70% of the ultradry-state thermal resistance. This finding may indicate that the thermal resistance loss after wetting is greater for blended fabrics with a higher percentage of hydrophilic fibers.

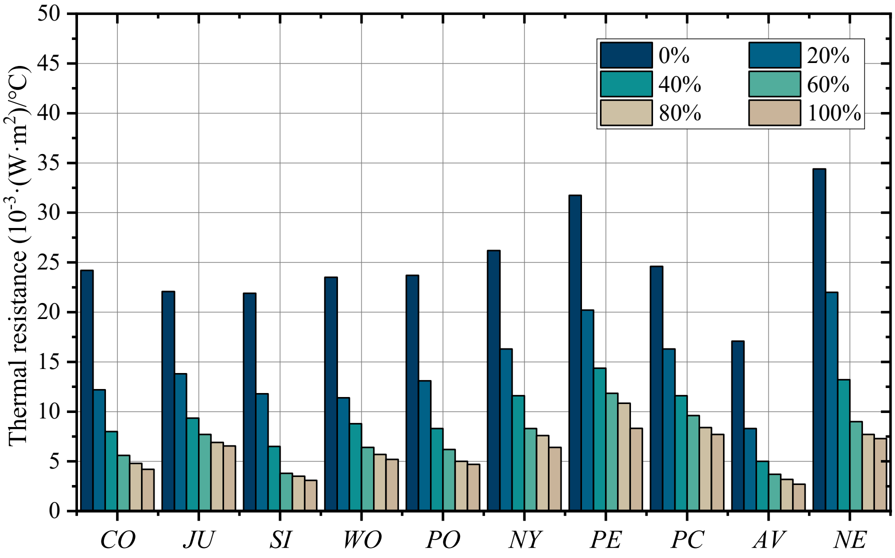


Figure 2. Thermal resistance of the fabrics at different water content saturation.

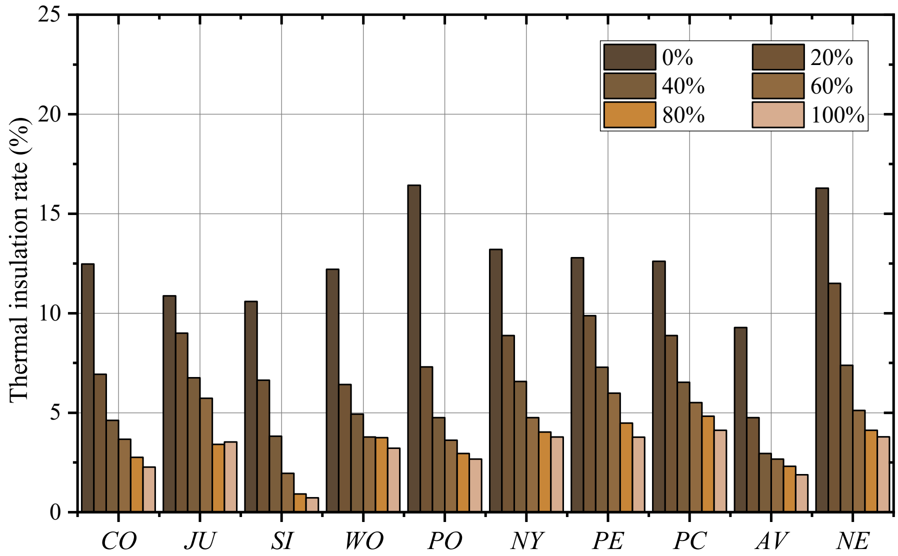


Figure 3. Thermal insulation rate of the fabrics at different water content saturation.

4.2. Selection of a Theoretical Model for Thermal Resistance

Exploring the accuracy of different models in predicting the thermal resistances of wet fabrics, we conducted statistical comparisons between the predicted values from each model and the experimental values. We used three methods: sum of squared deviations (*SSD*), sum of absolute deviations (*SAD*), and coefficient of determination (R^2), according to standard procedures, to analyze the accuracy of the model predictions. Tables 2–4 compare the predicted thermal resistance values and actual test values for Model 1 to Model 8, with the two best results highlighted in bold. The results show that all three evaluation methods gave consistent results and that Model 5 was the closest to the actual test values for all ten fabric samples ($R^2 \geq 0.955$). This model's characteristics are that the air resistance and water resistance are connected in parallel, followed by a series connection with the fiber resistance. Although Model 7 did not perform as well as Model 5 ($R^2 \geq 0.917$), it still demonstrated good predictive ability. This model's characteristics are that the water resistance and fiber resistance are connected in series, followed by a parallel connection with the air resistance. Therefore, we consider that the predictions of Model 5 and Model 7 for the thermal resistance of moist fabrics have some reference value. This finding is similar to the results of Mangat et al. [3], indicating that the use of woven fabric samples is also applicable to Model 5 in this study.

Table 2. Sum of squares of deviations of each model.

Symbol	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
CO	0.933199	0.000101	0.000904	0.928485	**0.000002**	0.000021	**0.000008**	0.000085
JU	1.219922	0.000149	0.000977	1.212564	**0.000007**	1.212564	**0.000019**	0.000048
SI	1.22135	0.001666	0.000076	0.000462	**0.000003**	0.000027	**0.000012**	0.000056
WO	0.859346	0.011524	0.005531	0.859995	**0.000009**	0.010149	**0.000023**	0.011331
PO	1.001217	0.000123	0.000901	0.998148	**0.000011**	0.000015	**0.000013**	0.000121
NY	0.774761	0.000105	0.000676	0.770626	**0.000012**	0.000019	**0.000021**	0.000097
PE	0.639571	0.000084	0.000565	0.637524	**0.000008**	0.000012	**0.000011**	0.000821
PC	0.605522	0.000072	0.000581	0.602423	**0.000005**	0.000017	**0.000009**	0.000061
AV	0.843322	0.005482	0.001254	0.598752	**0.000014**	0.000017	**0.000027**	0.000121
NE	0.755424	0.000382	0.000951	0.754122	**0.000022**	0.000017	**0.000034**	0.000201

Table 3. Sum of absolute deviations of each model.

Symbol	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
CO	1.101330	0.019659	0.033001	1.053953	**0.003696**	0.010501	**0.005818**	0.015354
JU	1.255706	0.025461	0.036638	1.202308	**0.004415**	1.202308	**0.008084**	0.015765
SI	1.263636	0.008987	0.018391	1.024102	**0.003267**	0.012435	**0.006348**	0.012336
WO	1.089659	0.154268	0.106831	1.120350	**0.005283**	0.145965	**0.009126**	0.146836
PO	1.139877	0.017560	0.034325	1.094537	**0.006141**	0.007583	**0.007124**	0.017053
NY	1.005387	0.016181	0.031567	0.961944	**0.007786**	0.008308	**0.009639**	0.016016
PE	0.909487	0.015569	0.027219	0.873232	**0.005527**	0.007134	**0.006164**	0.014718
PC	0.886296	0.016374	0.027933	0.847941	**0.004618**	0.009027	**0.006348**	0.013441
AV	0.756122	0.022356	0.032515	0.235551	**0.003155**	0.004655	**0.008759**	0.012581
NE	0.842523	0.015666	0.012111	0.616515	**0.004235**	0.023151	**0.007989**	0.014587

Table 4. Correlation between the measured and predicted values.

Symbol	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
CO	−0.365	0.880	0.958	−0.400	**0.985**	0.883	**0.979**	−0.038
JU	−0.382	0.838	0.914	−0.410	**0.999**	0.811	**0.956**	−0.046
SI	−0.349	0.841	0.951	−0.346	**0.987**	0.876	**0.961**	−0.059
WO	−0.292	0.816	0.894	−0.324	**0.976**	0.933	**0.939**	−0.066
PO	−0.310	0.839	0.921	−0.344	**0.958**	0.858	**0.961**	−0.068
NY	−0.310	0.850	0.920	−0.344	**0.984**	0.856	**0.959**	−0.070
PE	−0.384	0.860	0.937	−0.418	**0.972**	0.871	**0.971**	−0.094
PC	−0.441	0.850	0.907	−0.473	**0.997**	0.846	**0.939**	−0.182
AV	−0.522	0.872	0.891	−0.423	**0.965**	0.817	**0.921**	−0.132
NE	−0.221	0.897	0.905	−0.373	**0.955**	0.873	**0.916**	−0.061

The coefficient of determination (R^2), sum of squared deviations (SSD), and sum of absolute deviations (SAD) were calculated as follows:

$$R^2 = S_{xy}^2 / S_x^2 S_y^2 \tag{21}$$

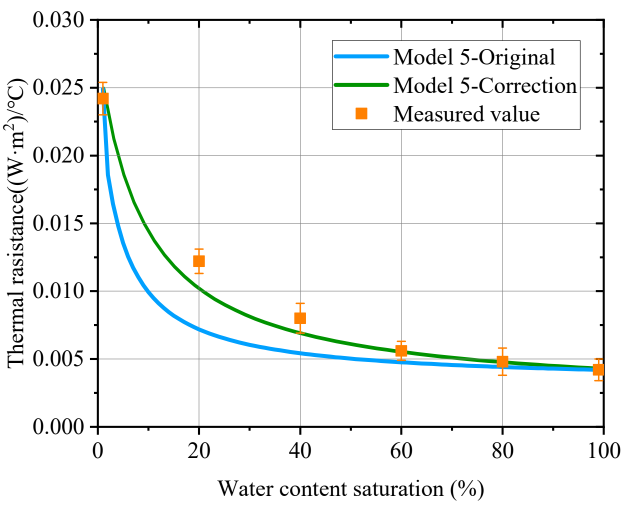
$$SSD = \sum_{i=1}^{n} \left(R_{tm,i} - R_t\right)^2 \tag{22}$$

$$SAD = \sum_{i=1}^{n} \left|R_{tm,i} - R_t\right| \tag{23}$$

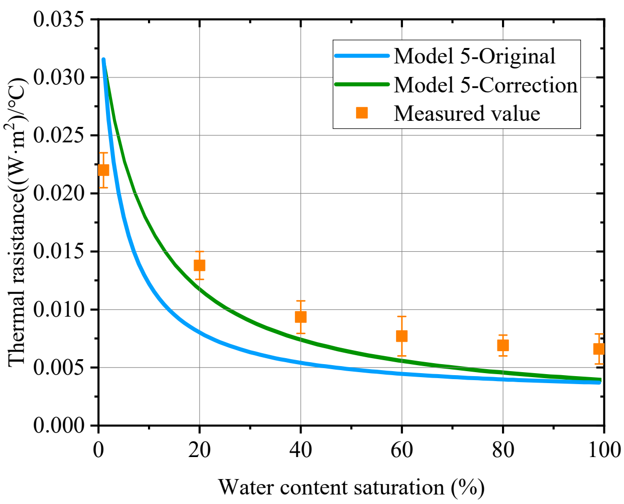
where $R_{tm,i}$ represents the actual thermal resistance of the fabric measured by the experimental instrument, in units of $(W{\cdot}m^2)/{}^{\circ}C$, i indicates the order of the actual thermal resistance test, and R_t is the predicted thermal resistance value of the model, in units of $(W{\cdot}m^2)/{}^{\circ}C$.

4.3. Modification of Thermal Resistance Model

According to the assumptions of the theoretical model (i.e., the voids in the fabric are uniform and constant), the model was revised by using the water content saturation instead of the moisture content to characterize the proportion of water in the fabric system voids. The study compared the fitting relationship between the prediction curve and experimental measurements before and after the revision of Model 5, as shown in Figure 4. From the figure, it can be clearly seen that the prediction curve is generally lower than the measured value, especially when using the original model. The revised model can obtain results closer to the measured value than the original model. Among the 10 sets of revised model prediction curves, 8 sets (80%) had R^2 values ranging from 0.95 to 0.99. Only one set of the revised model (NE group) had an R^2 value lower than 0.90 (R^2 = 0.896), which was higher than the original model (R^2 = 0.824) by 0.072. However, this was still higher than the acceptable range of R^2 values required by correlation analysis ($R^2 > 0.8$) [30]. It was also found that, especially at low water content saturation levels, the slope of the prediction curve of the revised model was smaller than that of the original model and the downward trend was more gentle, which was in line with the experimental test results. Comparison of the model prediction curve with the experimental results by Mangat et al. [3] also revealed that the original model always underestimated the thermal resistance compared with the actual measurement. Using water content saturation instead of moisture content can effectively improve the prediction accuracy of the model. The experimental results support the applicability of the model in predicting the wet-state thermal resistance of single-layer woven fabrics, indicating a great consistency between the measured and predicted values. Therefore, this study suggests that the revised Model 5 be used as the optimal model for predicting the wet-state thermal resistance of fabrics.



CO



JU

Figure 4. *Cont.*

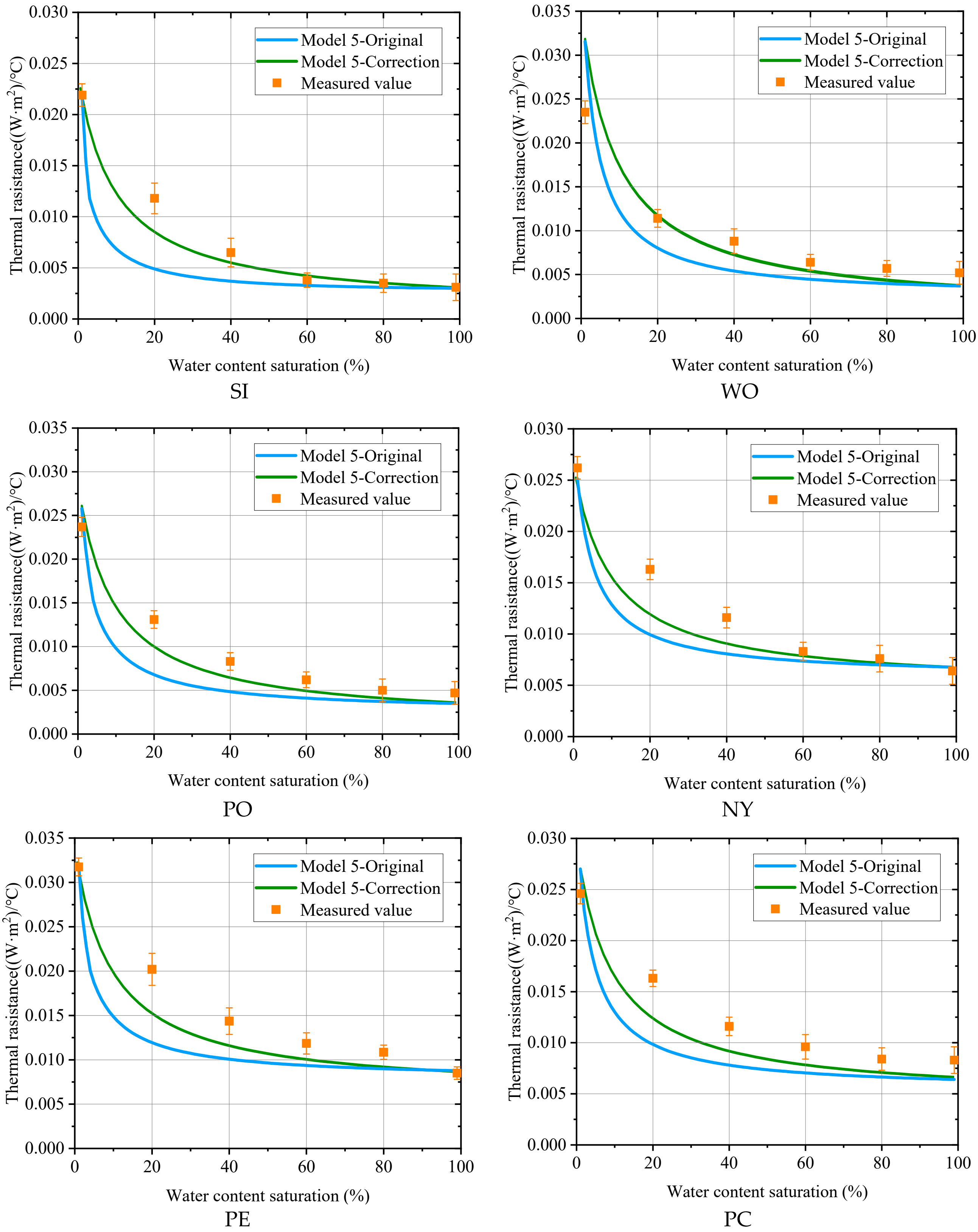


Figure 4. *Cont.*

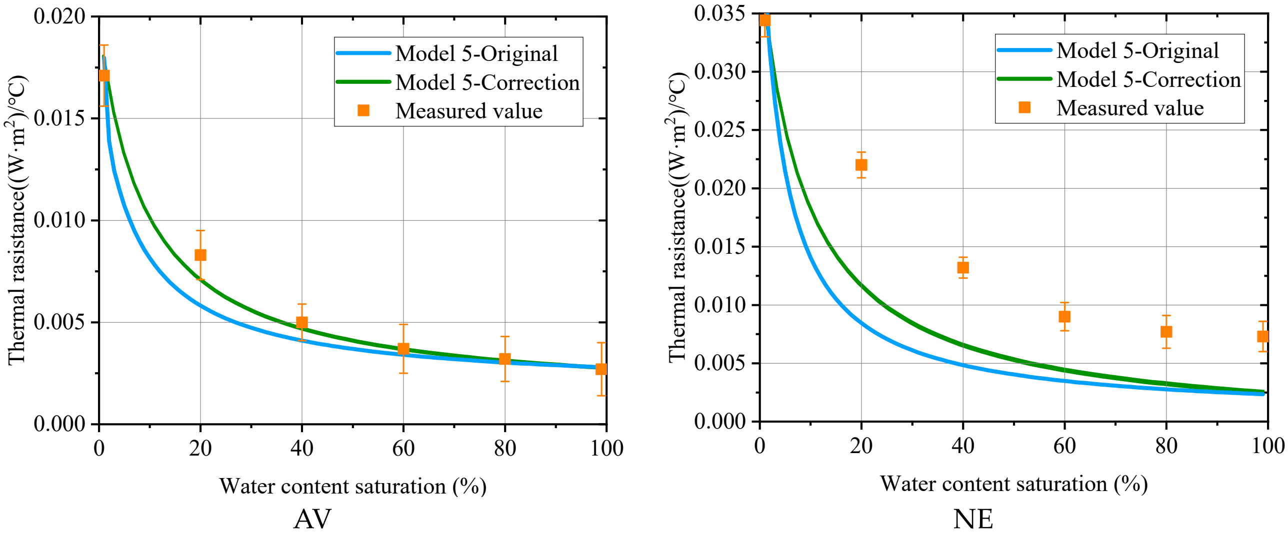


Figure 4. Simulated and measured values of the thermal resistance.

4.4. Relationship between the Theoretical Models and Test Results

Exploring the composition of the fabric thermal resistance and the effect of moisture on fabric thermal resistance, we explain the changes in thermal resistance observed in our experiments based on a theoretical model. As shown in Figure 4, the prediction curve of Model 5 more clearly illustrates the rate at which fabric thermal resistance deteriorates after absorbing moisture. According to the trend of Model 5's curve, we found that as the fabric's water saturation level increases, its thermal resistance significantly decreases. Moreover, we observed that the thermal resistance curve changes significantly around a water saturation level of 20%. Therefore, the fabric moisture absorption can be roughly divided into two processes: the initial stage of moisture absorption when the water saturation level is between 0~20% and the later stage of moisture absorption when the water saturation level is above 20%. The initial stage is characterized by a rapid decline in thermal resistance, with a decrease of approximately 51.92% to 64.28% compared with the ultradry state. The later stage is characterized by a slow decline in thermal resistance, with a decrease of only approximately 23.08% to 27.14% compared with the ultradry state.

According to the thermal resistance composition analysis of Model 5, the air thermal resistance and water thermal resistance are parallel components, whereas the fiber thermal resistance is a series component. The primary factor that affects fabric thermal resistance is the composition of the filler in the fabric's void spaces. The reason for the abrupt decline in the first half of the thermal resistance curve during the initial stage of moisture absorption is that the air content in the fabric's void spaces gradually decreases, whereas the water content gradually increases. Therefore, the factors that determine the amount of void space in the fabric, such as fabric thickness and porosity, become critical in affecting the thermal resistance of the wet fabric. When humidity changes, the fiber thermal resistance in the fabric's total thermal resistance does not change, but the composition of air thermal resistance and water thermal resistance does change. Therefore, the fiber's ability to adsorb water is also an important factor affecting the change in thermal resistance of wet fabrics. When the fiber becomes wet, its physical and chemical properties change, leading to significant microscopic effects on the system's internal energy, which manifests as a significant change in thermal conductivity. When a small amount of water enters the fabric, it first forms strong hydrogen bonds with hydrophilic fibers and then penetrates into the microporous structure of the porous fibers [31]. With an increase in moisture content, the water gradually fills the large pores formed by the fabric's tissue, forming numerous water columns that provide many transmission channels to accelerate heat transfer. After filling the void spaces of the fabric with water, excess water will accumulate on the fabric's surface due to its adsorption effect, resulting in a slow decline in the fabric's thermal resistance.

However, the effect of water absorption on thermal resistance is significantly smaller than that of moisture absorption, as indicated by the gentle slope of the curve in the latter stage.

4.5. Limitations and Applications

The theoretical model of fabric thermal resistance is not a perfect simulation of the real fabric structure due to the inherent complexity of the fabric itself. When the filling material in the fabric is only water or air, the thermal resistance of the fabric is composed of only two components: fiber thermal resistance and filling material thermal resistance, with the total fabric thermal resistance being the sum of the two. When the wetting is incomplete, the distribution of water and air inside the fabric becomes more complex. Water, which possesses surface tension and viscosity compared with air [32], has a more complicated contact situation with the fibers, and the number and position of the contact points have an impact on the overall thermal resistance of the fabric. This is difficult to measure or calculate; instruments can only measure the average thermal resistance of the fabric. As a part that is favorable for heat transfer is added to the filling material, the overall thermal resistance of the fabric decreases. However, as the proportion of one component continues to increase, the rate of change of the overall thermal resistance with respect to that component also increases, reflecting the heat conduction ability of that component [33]. In summary, the thermal resistance with respect to changes in water content cannot ignore the influence of the various components in the filling material. Such situations are difficult to predict and can only be derived from empirical models. The modified Model 5 can be used to approximate the thermal resistance of fabrics in the wet state and is a good alternative empirical model.

5. Conclusions

The thermal resistance of ten typical fabrics at different moisture levels was measured in this study to observe the changes in thermal resistance of woven fabrics as they are gradually humidified. The study found that as the humidity of the fabric increased, the thermal parameters including thermal resistance and thermal insulation rate deteriorated. The thermal resistance and thermal insulation rate of completely wetted fabrics were only 22.2% and 23.4% of that in the ultradry state. Based on Mangat et al.'s model, a model was selected and improved to predict the thermal resistance of woven fabrics at different moisture levels. After replacing the moisture content with water content saturation, the thermal resistance prediction model showed a more accurate prediction ability. The modified model had a significant improvement compared with the original model, as demonstrated by the correlation coefficient (R^2) test. The improved Model 5 fills the gap in predicting the thermal resistance of woven fabrics in a wet state. These results indicate that the modified Model 5 can be used to predict the thermal resistance of various types of woven fabrics under different moisture levels. This method provides an effective reference for quantifying the impact of moisture on the thermal resistance of woven fabrics and provides a theoretical basis for evaluating the thermal and moisture comfort of fabrics. Future research will consider using physiological saline to humidify fabrics to predict the thermal resistance of fabrics after being humidified by human sweat and to test other types of mathematical models using this method.

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