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Evaluation and Prediction of the Effect of Fabric Wetting on Coolness

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Abstract: As an important parameter of garment comfort, the thermal sensation of fabrics changes with factors such as sweat-induced humidity, making it a crucial area of research. To explore the coolness sensation of fabrics under different humidities, we tested heat transfer between fabrics and skin for 20 different fabrics with varying thermal absorption rates using fuzzy comprehensive evaluation to objectively assess their coolness levels. Subjective evaluation was then obtained by having subjects touch the fabrics and provide feedback, resulting in a subjective evaluation of their coolness levels. We compared the objective and subjective evaluations and found them to be highly consistent (R^2 = 0.909), indicating accurate objective classification of fabric coolness levels. Currently, random forest regression models are widely used in the textile industry for classification, identification, and performance predictions. These models enable the prediction of fabric coolness levels by simultaneously considering the impact of all fabric parameters. We established a random forest regression model for predicting the coolness of wet fabrics, obtaining a high accuracy between predicted and tested thermal absorption coefficients (R^2 = 0.872, RMSE = 0.305). Therefore, our random forest regression model can successfully predict the coolness of wet fabrics.

Keywords: wet state; coolness sensation; sensory evaluation; thermal absorptivity; random forest regression model

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1. Introduction

Clothing is an important barrier to maintaining thermal and moisture balance in the human body. Choosing the right clothing can help people maintain a state of psychological and physiological comfort during work and activities, which is why consumers pay more attention to the thermal and moisture comfort of clothing [1]. When the skin comes into contact with fabric, heat on the skin surface will quickly diffuse to the cooler fabric surface, causing a brief decrease in skin temperature, stimulating skin temperature receptors, and forming a cool or warm sensorial judgment in the human brain [2]. The thermal sensation of fabrics is influenced by factors such as fabric type, structure, thickness, density, and surface treatment, and is also closely associated with fabric humidity [3]. The skin surface of the human body is constantly perspiring, including visible and invisible perspirations that affect the humidity of the fabric. In summer, high temperatures accelerate human sweat production to regulate body temperature, with an average sweating rate of up to 1.5 L/h [4]. As a result, the fabric can become soaked with sweat, which significantly changes the thermal sensation of the fabric and affects the comfort of the clothing. Therefore, accurately assessing the strength of the thermal sensation of fabrics is of great significance in the research and development of clothing products.

A fabric can be regarded as a mixture of fibers, air, and water [5] and the factors affecting the coolness of contact are numerous and complex, making it a hot research topic. Many studies have investigated the factors influencing the coolness of fabrics. Atalie et al. measured the thermal parameters of fabrics before and after composite finishing with different counts, twists, variation of mass (CVm), thickness, and strength, and found that the thermal absorption coefficient of the fabric changed significantly [6]. Akcagun et al. measured the thermal sensation of wool/PET-knitted fabrics with different water contents, and the results showed that wool causes a slow decrease in thermal sensation as humidity changes, giving it good thermal comfort [7]. Qian et al. studied knitted fabrics and explored the effects of fabric structure and porosity on thermal absorption coefficient and other parameters [8]. Mansoor et al. used the Alambeta method to test the thermal absorption coefficient of socks before and after water absorption, and the results showed that the thermal absorption coefficient of the fabric significantly increased after moisture absorption [9]. In summary, objective evaluation of the coolness of the fabric based on a single physical index measured using experimental instruments has been the common approach in research on the thermal sensation of fabrics. Unfortunately, there is little consideration of the subjective perception of the fabric's contact with human skin, and subjective evaluation of the coolness of fabrics often requires a lot of time and high labor costs. Improving the connection between subjective and objective evaluation and proposing an effective prediction model is an important way of solving this problem.

In recent years, many researchers have studied prediction models of fabric thermal performance based on fiber, yarn, and fabric structural parameters. Dias and Delkumburewatte proposed a prediction model that can effectively predict the thermal conductivity of fabrics [10]. Mangat et al. proposed a thermal resistance prediction model based on the combination of air, water, and fiber polymer in series and parallel in the wet state [11]. Bhattacharjee and Kothari proposed a model for predicting heat conduction through woven fabrics and radiation through yarns [12]. Kanat et al. used an Artificial Neural Network (ANN) model to predict thermal resistance at different moisture levels [13]. To more accurately classify the coolness levels of fabrics in the wet state and establish a fabric prediction model for evaluating the coolness contact of fabrics with different water contents, this study tested the thermal absorption coefficients of 20 types of fabrics with different water content levels. The fuzzy comprehensive evaluation method was then used to study the level of cooling sensation offered by the fabric. Finally, a comparison with the subjective evaluation level of the subjects was conducted to determine the level of cooling sensation that is in line with the actual user experience. A Random forest regression model was established to effectively predict the coolness of fabrics based on objective evaluation of parameter characteristics and human sensory evaluation results.

2. Methods

2.1. Objective Evaluation Method

The objective evaluation method divides the thermal sensation characteristics of the fabric by measuring related parameters. The main evaluation method currently used is the thermal absorption coefficient method. The thermal absorption coefficient method characterizes the heat absorption capacity of the fabric based on the heat value absorbed by the test sample during transient heat transfer following skin contact based on the size of the thermal absorption coefficient. The thermal absorption coefficient is also commonly referred to as the heat storage coefficient or heat dissipation coefficient and was first proposed by Hes and Dolezal [14] to describe the instantaneous sensation felt when contact occurs between the skin surface and the fabric surface, reflecting the fabric's ability to absorb heat from the skin during contact with the human body. The thermal absorption coefficient is calculated based on the thermal conductivity of the sample. The thermal conductivity of the fabric represents the amount of heat passing through 1 m^2 of material at a distance of 1 m in 1 s and is calculated using the Fan formula [15]:

$$\lambda = \frac{Qh}{tS\Delta T} \quad (1)$$

$$b = \sqrt{\lambda\rho c} \quad (2)$$

where λ is the thermal conductivity of the fabric, W/(m·°C); Q is the heat passing through the body, J; h is the measured thickness of the fabric, m; S is the area through which the heat passes, m^2; t is the flow time, s; ΔT is the temperature difference in the direction of heat conduction, °C; b is the thermal absorption coefficient of the fabric, $Ws^{1/2}/(m^2 \cdot °C)$; c is the specific heat capacity of the fabric, J/(kg·°C); and ρ is the volume density of the fabric, kg/m^3.

As shown in Equation (2), the thermal absorption coefficient of the fabric is determined using three parameters: thermal conductivity, volume mass, and specific heat capacity. The larger the thermal absorption coefficient of the fabric, the stronger its heat absorption capacity, the more heat is lost when it comes into contact with the skin, and the better the coolness of the fabric. Conversely, if the thermal absorption coefficient of the fabric is small, the warming sensation of the fabric will be better. The actual thermal absorption coefficient of dry textiles usually ranges from 30 to 300 $Ws^{1/2}/(m^2 \cdot °C)$ while for wet fabrics, the thermal absorption coefficient can even exceed 500 $Ws^{1/2}/(m^2 \cdot °C)$ due to the high thermal conductivity and specific heat capacity of water [9]. The thermal absorption coefficient can only reflect the thermal transfer performance of the fabric in a steady-state environment and cannot reflect the dynamic heat transfer process when the fabric comes into contact with the skin.

2.2. Subjective Evaluation Methods

Objective evaluation methods have the advantages of strong repeatability and ease of operation. However, the coolness of fabrics is fundamentally a subjective sensation of human comfort, which can vary among individuals due to factors such as sensitivity to temperature and physical health conditions. Therefore, there is currently no accurate physical quantity that can directly measure the coolness of fabrics. Subjective evaluation is the most commonly used method for evaluating fabric comfort and mainly involves collecting subjects' feelings about fabric contact through questionnaire surveys and rating them based on subjective evaluation levels [16]. This can specifically express subjects' sensory perceptions of fabrics. Subjective evaluation methods mainly involve measuring the coolness sensation of a fabric when it comes into contact with the skin by directly touching the inner forearm of the subjects. Previous research has shown that the perception of heat sensation is similar between the forearm and the back, making it a more convenient option than directly measuring the coolness sensation by wearing the fabric. To accurately express the coolness of fabrics, a psychometric scale can be adopted to divide the human subjective sensation into levels and assign corresponding values, thereby quantitatively evaluating such qualitative issues [17]. In this study, the coolness levels of fabrics were divided into five levels based on a five-level psychometric scale. Level A indicated no coolness ($x_1 = 1$), level B indicated a slight coolness ($x_2 = 2$), level C indicated a general coolness ($x_3 = 3$), level D indicated an obvious coolness ($x_4 = 4$), and level E indicated a strong coolness ($x_5 = 5$). Subjects rated the fabric based on their feelings following contact between the fabric and the inner forearm. The number of ratings for each level was used as the weight for each level, which was denoted as ω_1, ω_2, ω_3, ω_4, and ω_5, respectively. The formula for the weighted average of the coolness of the fabric is:

$$x_i = \frac{x_1\omega_1 + x_2\omega_2 + x_3\omega_3 + x_4\omega_4 + x_5\omega_5}{\omega_1 + \omega_2 + \omega_3 + \omega_4 + \omega_5} \quad (i = 1, 2, \cdots, 20) \tag{3}$$

2.3. Coolness Sensation Level Classification

Fuzzy mathematics is based on fuzzy set theory [18], which is used to describe sets that are not clearly defined. The fuzzy comprehensive evaluation method is adopted to classify thermal absorption coefficient values of fabrics into membership degree levels. First, establish the evaluation factor object set $U = |u_1, u_2, u_3, \ldots, u_i|$ ($i = 1, 2, \ldots, n$), where the evaluation object u_i is the thermal absorption coefficient b_i. Second, establish the evaluation level set $V = |v_1, v_2, v_3, \ldots, v_j|$ ($j = 1, 2, \ldots, n$), where the evaluation level, v_i, is the coolness level of the fabric. Finally, by performing the membership degree function operation, the membership degree of the evaluation factors to the evaluation level is classified, making the fuzzy mathematical concepts more intuitive.

This study uses the trapezoidal distribution of fuzzy distribution. The mathematical model of the membership degree function is as follows:

$$\text{Level A}: \quad V_1(u_i) = \begin{cases} 1, & u_i < x_1 \\ \frac{1}{2}\left(1 + \frac{u_i - x_1}{x_2 - x_1}\right), & x_1 < u_i < x_2 \\ 0, & u_i > x_2 \end{cases} \tag{4}$$

$$\text{Level B}: \quad V_2(u_i) = \begin{cases} 0, & u_i < x_1 \\ \frac{1}{2}\left(1 + \frac{u_i - x_1}{x_2 - x_1}\right), & x_1 < u_i < x_2 \\ \frac{1}{2}\left(1 + \frac{u_i - x_2}{x_3 - x_2}\right), & x_2 < u_i < x_3 \\ \frac{1}{2}\left(1 - \frac{u_i - x_3}{x_4 - x_3}\right), & x_3 < u_i < x_4 \\ 0 & u_i > x_4 \end{cases} \tag{5}$$

$$\text{Level C}: \quad V_3(u_i) = \begin{cases} 0, & u_i < x_2 \\ \frac{1}{2}\left(1 + \frac{u_i - x_3}{x_3 - x_2}\right), & x_2 < u_i < x_3 \\ \frac{1}{2}\left(1 + \frac{u_i - x_3}{x_4 - x_3}\right), & x_3 < u_i < x_4 \\ \frac{1}{2}\left(1 - \frac{u_i - x_5}{x_5 - x_4}\right), & x_4 < u_i < x_5 \\ \frac{1}{2}\left(1 - \frac{u_i - x_5}{x_6 - x_5}\right), & x_5 < u_i < x_6 \\ 0 & u_i > x_6 \end{cases} \tag{6}$$

$$\text{Level D}: \quad V_4(u_i) = \begin{cases} 0, & u_i < x_4 \\ \frac{1}{2}\left(1 + \frac{u_i - x_5}{x_5 - x_4}\right), & x_4 < u_i < x_5 \\ \frac{1}{2}\left(1 + \frac{u_i - x_6}{x_6 - x_5}\right), & x_5 < u_i < x_6 \\ \frac{1}{2}\left(1 - \frac{u_i - x_7}{x_7 - x_6}\right), & x_6 < u_i < x_7 \\ 0 & u_i > x_7 \end{cases} \tag{7}$$

$$\text{Level E}: \quad V_5(u_i) = \begin{cases} 0, & u_i < x_6 \\ \frac{1}{2}\left(1 + \frac{u_i - x_6}{x_7 - x_6}\right), & x_6 < u_i < x_7 \\ 1, & u_i > x_7 \end{cases} \tag{8}$$

2.4. Random Forest Regression Model

Random Forest is a machine learning classification algorithm based on statistical theory, first proposed by Leo Breiman [19]. It combines Breiman's "Bootstrap aggregating" idea [20] and Ho's "random subspace" method [21] and can be used for both classification and regression. The Random Forest algorithm is a predictive tool that has high classification accuracy and is a new research hotspot in the field of data analysis. The principle is to generate a strong learning model by combining multiple weak learning models to improve the accuracy of the prediction model, a process called classifier combination. The Random Forest regression model can establish a complex nonlinear relationship between multiple independent variables and the dependent variable. Multiple sub-training sample sets are formed by using Bootstrap sampling to randomly extract data samples from the original training dataset, and each sub-training sample set has the same number of samples as the original training dataset. A decision tree model is then constructed. Due to randomness, hundreds or even thousands of decision trees can be generated, and the tree with the highest repeatability is selected as the final result. The prediction result of the Random Forest regression model is the average of all decision tree results. The specific process of constructing a Random Forest is as follows: first, randomly select m samples with replacement from the original sample set of n samples to construct m sub-sample sets. By training m sub-sample sets, m regression trees are constructed and the remaining samples are used as the test set to verify the prediction effect of the model. Then, set the regression model parameter "m_{try}". Assuming that there are k evaluation features of the fabric sample, randomly select a subset of m_{try} features (m_{try} < k) as the splitting node and determine the best splitting based on the optimal branching criterion. Finally, each regression tree stops growing based on the number of trees (n_{tree}), and after training, m decision trees are generated to form a Random Forest regression model. The arithmetic mean of the training results of the m decision trees is taken as the final model prediction result. The Random Forest prediction model is shown in Figure 1. The prediction effect of the model is evaluated using the root mean square error (*RMSE*) and the coefficient of determination (R^2) of the test set as shown in the following formula:

$$RMSE = \sum_{n=1}^{i} \left(y_i - y_i'\right)^2 / n \quad (9)$$

$$R^2 = 1 - RMSE/Y^2 \quad (10)$$

where y_i represents the true value of the test sample in the test set, y_i' represents the predicted value of the regression model, Y^2 represents the variance of the predicted value, and n is the number of samples in the test set.

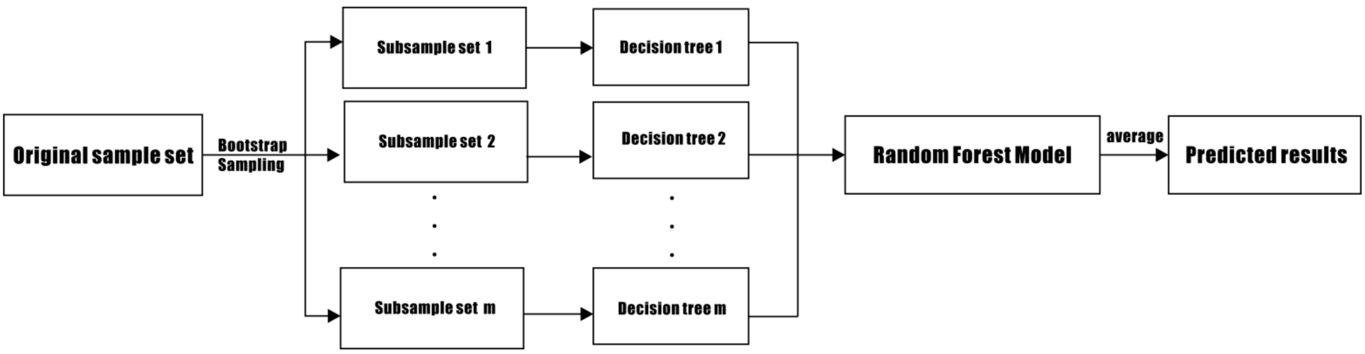

Figure 1. Random Forest regression model.

3. Experimental Section

3.1. Materials

This study involves analyzing the thermal contact coolness of multiple types of wet fabrics. All samples were selected from commonly used clothing fabrics in the market, and included fabrics of different materials and types. The parameters of all the fabrics are shown in Table 1. Before the experiment, the fabrics were subjected to low-temperature ironing to ensure a smooth surface. Then, the samples were cut into pieces with a length and width of 0.3 m and stored for later use after being placed in a room with a temperature of 24 °C and relative humidity of 65% for 24 h. Ionized water made in the laboratory was used to wet the fabrics.

The fabric thickness and surface density can be directly measured. There are many methods for measuring fabric porosity. In this study, fabric surface density, fabric thickness, and fabric fiber density were used to calculate the porosity [22] (see Equation (11)).

$$\varepsilon = 1 - \frac{m}{h \cdot \rho_{fib}} \quad (11)$$

where ε is the porosity of the fabric, %; ρ_{fib} is the fiber density at the stipulated regain, g/m^3; and m is the measured surface density of the fabric, g/m^3.

Table 1. Fabric specifications.

Symbol	Composition	Structure	Thickness (mm)	Weight (g/m^2)	Fiber Density (kg/m^3)	Porosity
#1	60S Cotton 100%	Plain	0.78	121.87	1540	0.90
#2	60S Cotton 100%	2/1 Twill	1.08	226.86	1540	0.86
#3	24S Jute 100%	2/1 Twill	0.93	249.25	1500	0.82
#4	21S Ramie 100%	3/1 Twill	1.13	208.55	1510	0.86
#5	60S Silk 100%	Plain	0.63	72.94	1360	0.91
#6	100S Wool 100%	2/2 Twill	1.02	175.39	1310	0.87
#7	40S Polyester 100%	Plain	0.66	90.05	1380	0.90
#8	21S Nylon 100%	Plain	0.72	161.06	1140	0.80
#9	120S Viscose 80% + Polyester 20%	Plain	0.90	130.44	1500	0.90
#10	60S Polyester 90% + Elastane 10%	Plain	0.89	155.37	1370	0.87
#11	60S Polyester 65% + Cotton 35%	Plain	1.41	227.26	1270	0.89
#12	40S Acrylic 70% + Viscose 30%	Plain	0.91	200.62	1142	0.80
#13	60S Nylon 85% + Elastane 15%	Warp knit	0.77	136.69	1419	0.87
#14	45S Polyester 98% + Elastane 2%	Warp knit	0.95	125.70	1378	0.90
#15	12S Nylon 70% + Polyester 30%	Warp knit	0.91	115.34	1212	0.89
#16	80S Polypropylene 65% + Polyester 35%	Weft knit	0.82	108.92	1068	0.87
#17	40S Cotton 80% + Polyester 20%	Weft knit	0.95	263.15	1508	0.81
#18	60S Polyester 58% + Cotton 42%	Weft knit	1.15	215.06	1447	0.87
#19	21S Wool 75% + Polyester 25%	Weft knit	1.16	133.69	1328	0.91
#20	32S Acrylic 80% + Polyester 20%	Weft knit	1.20	166.89	1196	0.88

When the fabric is made of two types of fibers blended together, the blended fiber density cannot be obtained directly but can be estimated using the following equation proposed by Militky [23].

$$\rho_{ab} = r\rho_a + (1 - r)\rho_b \tag{12}$$

In the formula, 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 at a temperature of 20 ± 1 °C, relative humidity of 50 ± 5%, and wind speed of less than 0.4 m/s.

3.2. Experimental Preprocessing

The study required measuring the maximum water absorption of each sample and dividing the fabric water content level based on the maximum water absorption. The experiment was conducted according to the method described by Tang et al. [24] and the pre-treated samples were ironed at low temperature and then dried in a 105 °C oven for 30 min before measurement to remove excess moisture inside the fabric and achieve the "ultra dry state" mentioned by Naka et al. [25]. The fabric samples were then soaked in deionized water for 3 min until completely wet, and then hung vertically to dry until there was no more liquid dripping for 30 consecutive seconds, indicating that the fabric was in a fully wet state. The weight difference between the fabric before and after soaking represents the maximum water content. The amount of humidity in each sample was determined based on the maximum water absorption. The study used fabric water content as the parameter for characterizing fabric moisture level, with the water content as the percentage of the sample's humidity level to the maximum water absorption reflecting the saturation level of the water content in the sample. The specific steps for adding humidity to the samples were as follows: the ultra-dry fabric was laid flat on a tabletop and a certain amount of deionized water was weighed using an electronic scale and poured into a humidifying spray bottle. The spray bottle was suspended about 2 cm above the center of the sample and the deionized water sprayed evenly over the fabric surface. The test was conducted after waiting for 5 min for the fabric to be fully wet. The study was conducted under conditions of ultra-dry state and water content levels of 20%, 40%, 60%, 80%, and 100%.

3.3. Objective Measurement Experiment

The experiment referred to the ISO 22007-2 [26] and ASTM D7984 [27] standards and was conducted at a constant temperature and humidity of 20 ± 0.5 °C and 60 ± 5%, respectively. A TPS 2500S thermal constants analyzer (Hot Disk AB., Co., Ltd., Göteborg, Sweden) was used to measure thermal conductivity and specific heat capacity of 20 fabrics with different water contents. Thermal absorption coefficient, which characterizes the thermal sensitivity performance of the fabric, was then calculated. The fabrics' thermal sensitivity levels were objectively evaluated based on the evaluation criteria. The instrument was turned on in advance and preheated for 30 min. The probe temperature was set to 35 °C, the same as the temperature of human skin. The resistance of the probe changed after contact with the sample. The thermal conductivity and thermal absorption coefficient of the fabric can be accurately calculated based on the change in probe resistance. The sample had to be in the same thermal state before each test and consecutive measurements were not allowed. Adequate time was required to ensure that the previously measured samples returned to their initial thermal states.

3.4. Subjective Measurement Experiment

Subjective evaluation was carried out in a laboratory at constant temperature and humidity (temperature setting of 20 ± 0.5 °C, humidity of 60 ± 5%, and wind speed less than 0.4 m/s) to ensure that the subjects' physiological functions were at their best state and their senses were more sensitive. At the same time, the psychological state was adjusted to ensure the smooth progression of the experiment. Subjects evaluated the coolness sensation of the fabric using the inside of their forearms [2]. Twelve college students—six males and six females—with an age of 21.8 ± 1.3 years (range 20–23), a height of 1.65 ± 0.04 m (range 1.52–1.82), and a weight of 55.6 ± 10.4 kg (range 43.3–82.4) volunteered to participate in this study. The subjects received relevant experimental training before the test, including an explanation of the definition of the thermal sensation from the fabric, the method for touching the samples during the test, and the rating method in the questionnaire. To avoid different scales, the same researcher explained the method for rating thermal sensation before each experiment to ensure smooth progression of the experiment and reliability and accuracy of the experimental results. Before touching the test samples, the subjects needed to sit quietly in the laboratory for 10 min to adapt to the surrounding environment and adjust their mental state. During the test, the subject extended their forearm forward with the inside of their forearm facing upwards, and the researcher placed the fabric on the forearm and pressed it appropriately to simulate the pressure exerted by clothing on the skin. As heat is conducted to the fabric when it comes into contact with human skin, to avoid errors, samples from the previous test were tested at an interval of 2 min to allow the fabric to return to its initial thermal state before the next test. The two forearms were covered alternately, and the test was completed when the two sensory evaluations given were consistent. If any inconsistency occurred, the process was repeated until all samples gave consistent evaluation results. The subjects filled out the questionnaires based on the warm/cool sensation felt by the forearm when it came into contact with the fabric. The coolness level was divided based on the individual's subjective feeling.

3.5. Statistical Analysis

The SPSS software (Version 27.0, IBM Co., Ltd., Armonk, NY, USA) was used to analyze the correlation between factors affecting the coolness sensation of wet-state fabrics using one-way analysis of variance and Pearson correlation analysis, with the significance level set at $p < 0.05$. Origin software (Version 2023, OriginLab Co., Ltd., Northampton, MA, USA) was used to compare the objective and subjective measurements by fitting the analysis and determining the linear relationship between the two.

4. Results and Discussion

4.1. Coolness via Objective Measurement

A study was conducted on 20 commonly used clothing fabrics as experimental samples. Before the experiment, all fabrics were pretested to ensure a smooth surface. The fabrics were then analyzed using a fabric thermal conductivity analyzer to measure the thermal absorption coefficient of different water contents. The thermal absorption coefficient of each sample is shown in Table 2. The coolness of the fabric was characterized based on the measured thermal absorption coefficient. A higher thermal absorption coefficient indicates a more significant coolness sensation upon contact with the fabric. Statistical analyses were conducted to identify factors that may affect the coolness of the fabric. The results showed that there were no significant differences in the coolness of different samples under dry conditions. A one-way ANOVA test showed that the water content of the fabric is the key factor affecting its coolness ($p < 0.05$). Pearson coefficients were used to characterize the relationships between the factors. The results showed that the type of fiber in the fabric (*Pearson* = 0.556), the thickness (*Pearson* = 0.157), the surface density (*Pearson* = 0.433), and the porosity (*Pearson* = −0.349) all affect the coolness of the fabric. Of these factors, water content was found to be the critical factor determining the thermal absorption coefficient of the sample. This is because the thermal conductivity of fabric fibers generally ranges from 0.03 to 0.10 W/(m·°C), while the thermal conductivity of still water at 20 °C is 0.57 W/(m·°C) and the thermal conductivity of water is generally 2–6 times higher than that of fiber polymers. At 37 °C, the volumetric heat capacity of water is 4200 J/(kg·°C), while the specific heat capacity of fiber polymers is approximately 1400–3300 J/(kg·°C). The volumetric heat capacity of water is generally 1.3–3 times higher than that of fiber polymers. Therefore, the thermal absorption coefficient of the fabric increases significantly when soaked in water [28,29]. The study also measured the thermal absorption coefficient of fabrics at moisture levels of 20%, 40%, 60%, 80%, and 100% (see Table 2). For each sample, each wet condition was analyzed in triplicate and outliers were removed to ensure that the coefficient of variation was less than 3%. The average result was rounded to two significant figures.

Table 2. Effect of water content on thermal absorptivity ($Ws^{1/2}/(m^2{\cdot}°C)$).

Symbol	Ultra-Dry State	20%	40%	60%	80%	100%
#1	100.43	141.45	174.68	248.78	325.51	441.08
#2	112.72	161.58	184.66	253.77	330.31	455.97
#3	95.23	126.32	178.51	242.83	277.65	354.97
#4	70.33	111.54	157.80	267.90	302.14	326.57
#5	91.98	125.30	168.83	220.80	230.07	344.47
#6	95.30	136.83	155.74	232.62	293.51	402.60
#7	83.82	112.74	141.64	213.88	252.48	328.22
#8	109.49	138.81	164.54	224.52	253.28	321.52
#9	96.86	137.18	164.96	248.94	273.78	373.60
#10	111.40	139.66	165.65	222.35	260.57	317.49
#11	124.06	152.41	180.66	198.59	212.30	321.74
#12	118.97	148.77	192.06	232.60	251.46	358.26
#13	75.03	125.35	177.46	222.54	346.82	377.57
#14	89.56	97.29	137.43	190.10	243.79	284.75
#15	87.60	127.40	131.02	192.90	273.35	293.35
#16	85.89	101.75	106.39	194.50	220.74	331.11
#17	92.07	118.58	148.53	260.84	294.85	309.52
#18	83.01	149.91	207.67	312.59	331.89	344.66
#19	99.11	124.50	135.91	184.37	294.63	371.40
#20	91.08	130.89	117.35	179.77	303.61	374.26

4.2. Coolness Level Classification Results

The fabrics' thermal absorption coefficient values obtained during experimental testing were classified into different levels based on the fuzzy comprehensive evaluation method, giving a more scientifically reasonable range of coolness levels for the fabric. Fabrics were classified into different coolness levels based on the fuzzy mathematical model, as shown in Figure 2. Fabrics with thermal absorption coefficients of $\leq$100 $Ws^{1/2}/(m^2{\cdot}°C)$ were defined as having no coolness (Level A), fabrics with thermal absorption coefficients ranging from 100 to 200 $Ws^{1/2}/(m^2{\cdot}°C)$ were defined as having general coolness (Level B), fabrics with thermal absorption coefficients ranging from 200 to 300 $Ws^{1/2}/(m^2{\cdot}°C)$ were defined as having slight coolness (Level C), fabrics with thermal absorption coefficients ranging from 300 to 340 $Ws^{1/2}/(m^2{\cdot}°C)$ were defined as having obvious coolness (Level D), and fabrics with thermal absorption coefficients of $\geq$ 340 $Ws^{1/2}/(m^2{\cdot}°C)$ were defined as having strong coolness (level E). Level A fabrics mainly contain 100% water, while Level B fabrics contain 80–100% water, Level C fabrics contain 60% water, and Level D fabrics contain 40% water. Level E fabrics mainly include ultra-dry fabrics and fabrics with a water content of 20%. As most dry fabrics had a thermal absorption coefficient of no more than 100 $Ws^{1/2}/(m^2{\cdot}°C)$ (14/20), it can be concluded that fabrics conduct non-coolness only in the dry state.

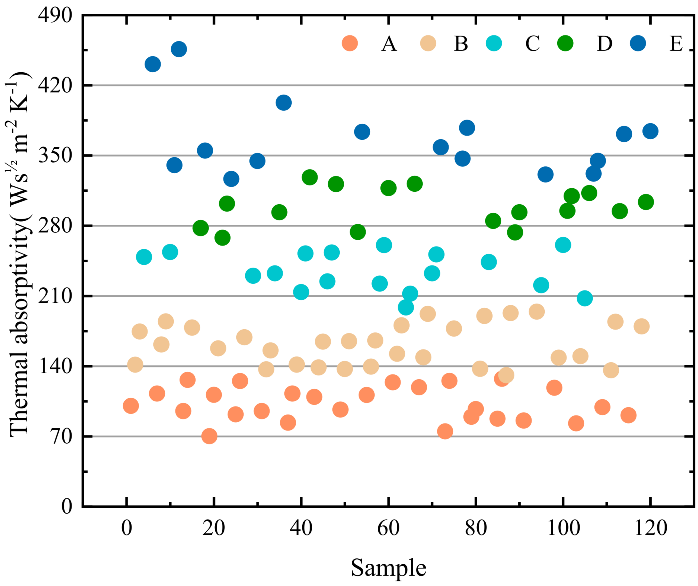

Figure 2. Thermal absorption coefficient class classification results.

By comparing the thermal absorption coefficient values of different types of fabrics, it was found that most fabrics have a thermal absorption coefficient of 100–300 $Ws^{1/2}/(m^2{\cdot}°C)$. Sample #2 (100% Cotton) had the highest thermal absorption coefficient at different water contents, indicating the strongest coolness effect. Sample #16 (98% Polyester + 2% Elastane) had the lowest thermal absorption coefficient at different water contents, indicating the least obvious coolness effect. This may be due to the fact that pure cotton fabrics are hydrophilic materials, whereas polyester fibers are hydrophobic. Polyester fibers have a stronger drying sensation after water absorption compared with other fabrics; a similar phenomenon was observed in the study by Mansoor et al. [9]. Comparison of the thermal absorption coefficients of fabrics with different water contents showed that the thermal absorption coefficient of most fabrics increased by 200–300% from dry to completely wet, while Sample #15 (85% Nylon + 15% Elastane) had the highest increase of 403% and Sample #13 (65% Polyester + 35% Cotton) had the lowest increase of 159%, which may be associated with the degree of water absorption. Sample #12 (90% Polyester + 10% Elastane), which has a composition similar to Sample #13, also demonstrated a similar phenomenon, with only an 185% increase.

4.3. Coolness via Subjective Measurement

The subjective evaluation experiment was conducted in a laboratory under constant temperature and humidity, where 12 graduate students of different sexes evaluated 20 different types of fabrics for their coolness. The constant temperature and humidity environment ensured that the human sensory organs were in the best state and the psychological state was stable, which was conducive for the smooth progression of the experiment. The air velocity was set to not exceed 0.04 m/s to simulate a still environment, thereby increasing the accuracy and reliability of the subjective evaluation results and reducing experimental errors. The results showed that fabrics that were more compressible and more easily bent (had lower stiffness) tended to have higher coolness levels against the inner side of the forearm during subjective evaluations. When fabrics were wet, they tended to have a stronger tactile sensation due to the tighter contact with the skin, resulting in higher coolness levels and a feeling of stickiness that made the experience uncomfortable. To test the consistency of the subjects' evaluations, Spearman rank correlation coefficient was used to analyze the correlation between the coolness evaluations of the fabrics by the subjects. The results are shown in Table 3 and indicate that there was a significant positive correlation between the subjective evaluations of the coolness effects of the fabrics, with most significance levels having $p < 0.05$. This suggests that the subjects' evaluations were consistent and reliable and had a certain reference value. The evaluation levels were determined by taking the most common level for each sample among the subjects. The weighted average range for Level A was l–1.5, for Level B was 1.5–2.5, for Level C was 2.5–3.5, for Level D was 3.5–4.3, and for Level E was 4.3–5. The subjective evaluations were based on personal experiences and subjective judgments of the subjects, and due to individual differences, their experiences of coolness may differ.

Table 3. Spearman's rank correlation coefficients between coolness evaluations for each pair of subjects.

Subjects	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Mean	0.951 *	0.852 *	0.854 *	0.765 *	0.865 *	0.758 *	0.876 *	0.875 *	0.876 *	0.858 *	0.855 *	0.890 *
S1		0.958 *	0.876 *	0.872 *	0.875 *	0.524	0.582	0.874 *	0.587	0.878 *	0.734 *	0.854 *
S2			0.912 *	0.654 *	0.756 *	0.675	0.847 *	0.784 *	0.875 *	0.914 *	0.821 *	0.587
S3				0.758 *	0.958 *	0.687	0.678	0.774 *	0.882 *	0.555	0.659	0.847 *
S4					0.707 *	0.879 *	0.911 *	0.768 *	0.745 *	0.576	0.879 *	0.861 *
S5						0.875 *	0.875 *	0.734 *	0.616	0.754 *	0.758 *	0.688
S6							0.758 *	0.548	0.702 *	0.662	0.725 *	0.651
S7								0.599	0.857 *	0.785 *	0.889 *	0.854 *
S8									0.798 *	0.714 *	0.854 *	0.741 *
S9										0.624	0.678	0.752 *
S10											0.758 *	0.732 *
S11												0.818 *

Note: * $p < 0.05$ (i.e., highly significant).

4.4. Consistency of Subjective and Objective Evaluations

Comparisons between the subjective evaluations and objective tests of the fabrics' coolness levels are shown in Table 4. Based on statistical analysis, there was a significant correlation between the subjective and objective evaluations of the coolness levels of the fabrics ($p < 0.05$). Additionally, the fitting curve in Figure 3 indicates good consistency between the subjective and objective evaluations of the fabrics' coolness levels ($R^2 = 0.909$; i.e., the closer R^2 is to 1, the higher the degree of fitting). The proportion of samples with consistent subjective and objective levels was 75.8%, validating the effectiveness of the thermal absorption coefficient method for evaluating the coolness performance of fabrics. It is worth noting that some samples showed differences between subjective and objective evaluations. For instance, samples #10, #11, and #12 in an ultra-dry state and samples #3 and #7, with a water content of 20%, had an objective evaluation level of B, while their subjective evaluation level was A. Sample #16, with a water content of 20%, and samples #1, #2, #11, and #14, with a water content of 40%, had an objective evaluation level of B, while their subjective evaluation level was upgraded to C. Samples #3, #5, and #9, with a water content of 60%, had an objective evaluation level of C, while their subjective evaluation level was B. Samples #1, #2, #5, and #14, with a water content of 60%, had an objective evaluation level of C, while their subjective evaluation level was B. Samples #12, #15, #17, and #19, with a water content of 80%, had an objective evaluation level of C, while their subjective evaluation level was D. Samples with different subjective and objective evaluation results can also be explained using their thermal absorption coefficients. Most of the measured results lie around the boundary of the objective classification, thus the differences in subjective and objective evaluations between different samples will not exceed one grade. In addition, when observing the results of subjective evaluation, it was found that more subjects tended to choose grades B or C. After questioning the subjects afterward, it was discovered that when the subjects did not feel the fabric's characteristics clearly or experienced sensory fatigue due to the experiment lasting too long, they would choose a more moderate grade to avoid making mistakes. Thus, grades A and E were rarely chosen, which could easily cause errors in the subjective evaluation experiment. However, the subjective and objective evaluations maintained a high degree of consistency for samples with obvious characteristics.

Table 4. Objective and subjective evaluations of fabric coolness levels.

Symbol	Ultra-Dry State		20%		40%		60%		80%		100%	
	Ob	**Sub**	**Ob**	**Sub**	**Ob**	**Sub**	**Ob**	**Sub**	**Ob**	**Sub**	**Ob**	**Sub**
#1	A	A	B	B	B	C	C	C	D	D	E	E
#2	B	B	B	B	B	C	C	C	D	D	E	E
#3	A	A	B	B	B	B	C	B	C	C	E	E
#4	A	A	B	A	B	B	C	C	D	C	D	E
#5	A	A	B	B	B	B	C	B	C	C	E	E
#6	A	A	B	B	B	B	C	C	C	C	E	E
#7	A	A	B	A	B	B	C	C	C	C	D	E
#8	B	B	B	B	B	B	C	C	C	C	E	E
#9	A	A	B	B	B	B	C	B	C	C	D	D
#10	B	A	B	B	B	B	C	D	C	C	D	D
#11	B	A	B	B	B	C	C	C	C	C	D	E
#12	B	A	B	B	B	B	B	C	C	D	E	E
#13	A	A	B	B	B	B	C	C	E	D	E	E
#14	A	A	A	B	B	C	B	C	C	C	C	E
#15	A	A	B	B	B	B	B	C	C	D	C	C
#16	A	A	B	C	B	B	B	B	C	C	D	D
#17	A	A	B	B	B	B	B	B	C	D	D	D
#18	A	A	B	B	B	B	D	C	D	D	E	E
#19	A	A	B	B	B	B	B	B	C	D	E	E
#20	A	A	B	B	B	B	B	B	D	D	E	E

Note: Ob and Sub represent objective and subjective evaluations, respectively.

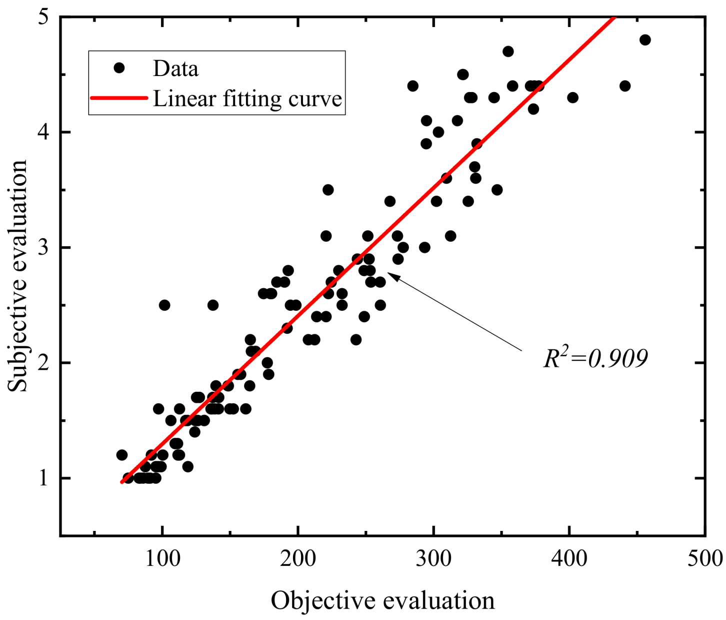

Figure 3. Fitting curves for subjective and objective evaluations.

4.5. Random Forest Model Predicts Coolness

A random forest regression model was used to predict the coolness of fabrics with different water contents. Five indicators, including the density of fiber bodies, the thickness of fabrics, the surface density, the porosity, and thermal conductivity in the dry state, were used as evaluation features in the random forest regression model. The original fabric sample set contained 100 samples, with 3/4 used as the training set and 1/4 used as the testing set. Combined with the subjective evaluation results, a random forest regression model was established, with the training set used for building the random forest algorithm and the testing set used for evaluating the remaining data. When the accuracy of the testing set is much higher than that of the training set, there is underfitting, while the opposite indicates overfitting. After analyzing the parameters of the random forest regression model, a random forest regression model for fabric coolness was established, and the model was used to predict the coolness level of fabrics with different water contents. The predicted results were compared with the measured values, as shown in Figure 4. The evaluation index of the model, R^2, was 0.872 and the RMSE was 0.305 (an RMSE of 0.2–0.5 indicates that the model can accurately predict the data and the smaller the value, the better the prediction effect). The low R^2 may be caused by a low sample size, although it still indicates that the model has good predictive performance and is effective at predicting and evaluating fabric coolness.

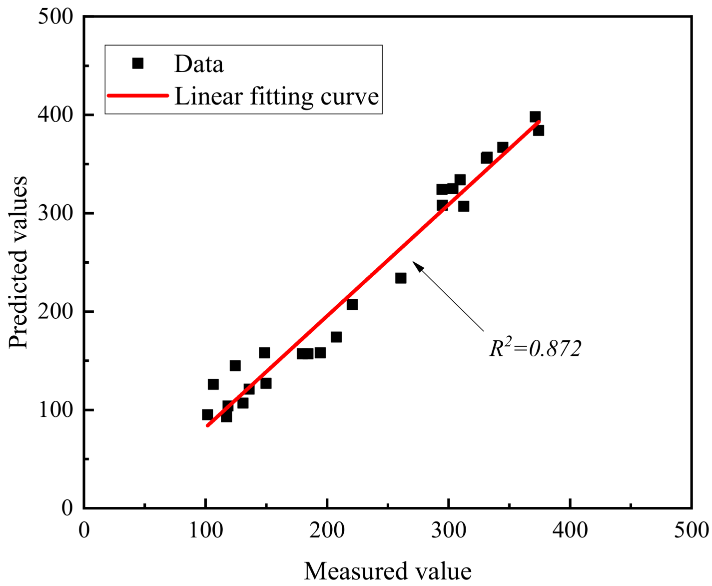

Figure 4. Comparison of the consistency between predicted and measured values.

4.6. Limitations

This study had its limitations. First, because the TPS 2500S thermal constant analyzer has different testing principles from Heat flux sensor-based instruments such as Alambeta, the thermal conductivity of the sample may be underestimated, which may also lead to the low thermal absorption coefficient of the sample. Second, the subject experiments are affected by steady-state heat conduction when the contact time between the skin and the sample exceeds 2 s. Even though emphasis was placed on the subjects to evaluate the instantaneous contact coolness of the fabric during the experiment, they are inevitably affected by steady-state heat conduction. We must admit that the above errors will occur during the experiment.

5. Conclusions

A thermal constant analyzer was used to test the thermal absorption coefficients of 20 commonly used clothing fabrics—including natural fibers, synthetic fibers, and blended fabrics—at different levels of water contents. The fabrics were objectively classified into five levels of coolness using fuzzy comprehensive evaluation and subjectively classified using participant evaluations. The results are as follows:

(1) The five levels of coolness classification provided by the fuzzy comprehensive evaluation method can give specific level indicators. For example, fabrics with a coolness level of A have a thermal absorption coefficient lower than 100 $Ws^{1/2}/(m^2 \cdot °C)$ and the coolness upon contact with the fabric is defined as none. Fabrics with a coolness level of B have a thermal absorption coefficient of 100–200 $Ws^{1/2}/(m^2 \cdot °C)$ and the coolness upon contact with the fabric is defined as general. Fabrics with a coolness level of C have a thermal absorption coefficient of 200–300 $Ws^{1/2}/(m^2 \cdot °C)$ and the coolness upon contact with the fabric is defined as slight. Fabrics with a coolness level of D have a thermal absorption coefficient of 300–340 $Ws^{1/2}/(m^2 \cdot °C)$ and the coolness upon contact with the fabric is defined as obvious. Fabrics with a coolness level of E have a thermal absorption coefficient greater than 340 $Ws^{1/2}/(m^2 \cdot °C)$ and the coolness upon contact with the fabric is defined as strong.

(2) Analysis of the consistency between the subjective and objective coolness levels of the fabrics indicates that using the thermal absorption coefficient as the objective evaluation index for perceived coolness is reliable. A comprehensive evaluation of fabric coolness based on both subjective and objective aspects can accurately reflect the real perception of the fabric when in contact with the skin. This can provide reliable data support for consumers when purchasing related products in the future and can also serve as a reference for developing fabric coolness level standards.

(3) The thermal absorption coefficient of the fabric made of 100% cotton under wet conditions is high, ranging from 112.72 to 455.97 $Ws^{1/2}/(m^2 \cdot °C)$, while the thermal absorption coefficient of the blended fabric made of 98% polyester + 2% elastane under wet conditions is low, ranging from 85.89 to 331.11 $Ws^{1/2}/(m^2 \cdot °C)$. This is because the fabric made of 100% cotton has more water absorption than the 98% polyester + 2% elastane blend fabric, resulting in stronger contact coolness.

(4) The established random forest regression model can effectively predict the coolness of fabrics at different water content levels. The evaluation indicators for the training set prediction results show that the R^2 is 0.872 and the *RMSE* is 0.305, indicating that the model has good predictive performance.

(5) Water content is the most important factor affecting the coolness of fabrics. As the water content of the fabric increases, the coolness of the fabric continuously improves. However, the corresponding humidity of the fabric also increases, potentially causing discomfort to the wearer. Therefore, when choosing summer clothing, it is important to consider fabric coolness upon contact under humid conditions and try to avoid the decrease in clothing comfort due to sweat-soaking.

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