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Down Wadding Thermal Insulation Performance in Different Placement Conditions

Han-Xin Liu, Xiao-Xin Yang, Shu-Qi Liu, Jing Guo*

Beijing Institute of Fashion Technology, Heping Street, Chaoyang District, Beijing, 100029, China

Abstract

Warmth is a key consideration for consumers when choosing products. Existing research has mostly focused on testing the warmth performance of down products in a horizontal state, neglecting the non-horizontal state during actual wearing. This study investigates the thermal insulation performance of down waddings under different placement conditions and their interrelationships. Four types of stitching spacing and five types of unit filling amounts are determined through market research, and 20 pieces of down waddings are made. Thermal resistance experiments are conducted in both horizontal placement and 24-hour suspension states. The experimental results show that under 24-hour suspension, the thermal resistance value of down waddings generally decreases; Under the same stitching spacing conditions, the unit filling amount corresponding to the maximum thermal resistance value in the 24-hour suspension state has decreased; There is a significant difference in thermal resistance values between the two placement states, with a Pearson correlation coefficient of 0.939, indicating a strong positive correlation; A mathematical regression model $y = 0.825x + 0.033$ is established through SPSS analysis to describe the relationship between the thermal insulation of down wadding in two different placement conditions. The findings of this study provide an important theoretical basis and practical guidance for further research, design, and production of down products.

Keywords: Down Wadding; Thermal Resistance Test; Thermal Insulation Performance; Placement Condition

1 Introduction

Down products, as an excellent type of warm clothing, are lightweight, warm, and soft [1-4] and have become one of the essential equipment for modern people in severe cold weather. People's requirements for the thermal insulation performance of down products are also constantly increasing. Temperature plays a crucial role in the thermal comfort value [5, 6]. Scholars have found that the main factors affecting the thermal insulation performance of down products include unit filling amount, type of filling material, velvet content, fluffiness, fabric, etc. [7-10]. Gong Yunyu found through experiments that the degree of influence on thermal insulation performance is in

*Corresponding author.
Email address: julia0224163@163.com (Jing Guo).

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the order of unit filling amount, type of filling material, and velvet content [11]. On this basis, some scholars have proposed that factors such as stitch spacing and stitch density also have a significant impact on the thermal insulation performance of down products [12-17], and some studies have found that the influence of stitch spacing is second only to the unit filling amount [17]. The measurement methods for the thermal insulation performance test of down products include the cooling rate method, constant temperature method, warm dummy method, wearing test method, etc. [18, 19]. The latter two methods are mostly used to test the thermal insulation performance of the entire down-product system. As one of the constant temperature methods, the evaporative hot plate method has high accuracy in measuring the thermal resistance value of down flocs and is convenient for in-depth analysis [20]. The research on the thermal insulation performance of down waddings is mostly conducted by conducting thermal resistance experiments in a horizontal placement state. Non-horizontal placement factors of clothing during daily wear can change the down distribution, thereby affecting the insulation effect [21, 22]. Some scholars [12] have also studied the thermal resistance values of down waddings in horizontal and hanging placement states, but only for the stitching factors of down wadding.

Based on literature and market research, this study determined four types of stitching spacing and five corresponding unit-filling amounts for down wadding. Twenty down waddings were made and subjected to thermal resistance experiments in both horizontal and 24-hour hanging states to analyze the effects of different placement conditions on the insulation performance of down waddings and the differences and correlations in insulation performance under different placement conditions. Providing a reference for enterprises in designing and producing down products can help consumers better understand and choose down products with different needs.

2 Method

2.1 Experimental Materials

The experiment uses down wadding as the carrier, composed of fabric and down. Due to the focus of this research on the influence of changes in down indicators on the thermal resistance of down products, a polyester cowhide fabric with a thickness of 0.08 mm and a weight of 60.82 g/m^2 is selected as the fabric for making down flocs. To ensure warmth, goose down with a velvet content of 90% is chosen as the filling material for down wadding. After a literature review and market research found that among various forms of quilting, horizontal quilting is the most common and provides the best insulation for down products. Therefore, the horizontal quilting form is chosen.

2.2 Experimental Equipment

The instruments used in this experiment include the M259B thermal and humidity resistance tester, electronic balance, and suspension device.

The M259B thermal and moisture resistance tester (Fig. 1) simulates the heat and moisture transfer on the surface of human skin. According to the national standard GB/T 11048-2018 "Determination of Thermal and Moisture Resistance under Steady State Conditions of Physiological Comfort of Textiles (Evaporative Hot Plate Method)", the climate chamber of the equipment is set to 1 standard atmosphere, the temperature of 20 °C, relative humidity of 65%, and wind speed of 1 m/s. After reaching a stable state, it measures various fabrics' thermal and moisture resistance. The down waddings are placed on the test board, maintaining a constant temperature at the part in contact with the down waddings, and the wind direction of the device is adjusted to be parallel to the down waddings so that temperature and humidity can only be dissipated through the down waddings. After stabilisation, the data is recorded, and the thermal and humidity resistance are calculated.

Fig. 1: M259B Sweating Guarded Hotplate (SDL Atlas, China)

The suspension device is self-made and includes a floor-standing bracket and a clothes hanger with movable clips at both ends. During production, it ensures that the A-pole and B-pole are parallel to the ground, as shown in Fig. 2. This equipment is used to simulate the state of clothing wearing. It facilitates the subsequent measurement of the thermal resistance value of the down comforter inside the down waddings after the distribution of gravity influence.

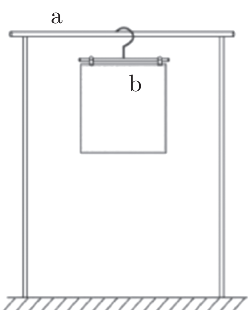

Fig. 2: Suspension device

2.3 Quilted Spacing and Filling Amount

Through literature research, it is found that the stitching spacing range of down waddings in related studies is 3-30 cm, and the unit filling amount range is 50-320 g/m^2. A study was conducted on 30 popular down jackets from three brands in the market, and it was found that the stitching spacing of lightweight products is 5-7 cm, with a unit filling amount of 61-78 g/m^2. The stitching spacing of ordinary products is 8-11 cm, with a unit filling amount of 84-130 g/m^2.

The stitching spacing of thick products is 11-15 cm, with a unit filling amount of 116-125 g/m^2. The stitching spacing of thickened products is 12-23 cm, with a unit filling amount of 130-200 g/m^2. Based on the results of two surveys, four types of stitching spacing, 5 cm, 7.5 cm, 10 cm, and 15 cm, and five unit filling amounts corresponding to the four types of stitching spacing, are selected as experimental variables. Detailed information on stitching spacing and filling amounts is shown in Table 1.

Table 1: Quilted spaces and unit filling weights of waddings

Quilted space/cm	Unit filling weight/(g·m^{-2})										
	80	90	100	110	120	130	140	150	160	170	180
5	1#	2#	3#	4#	5#	–	–	–	–	–	–
7.5	–	6#	7#	8#	9#	10#	–	–	–	–	–
10	–	–	–	11#	12#	13#	14#	15#	–	–	–
15	–	–	–	–	–	–	16#	17#	18#	19#	20#

2.4 Preparation of Experimental Samples

When making flocs, two factors, namely the stitch spacing and the unit filling amount, were selected as variable parameters for the experiment. Four types of stitching lines were determined based on the stitch spacing, namely 1, 2, 3, and 5, and the floc filling was completed according to the 5 filling amounts corresponding to each stitch spacing in Table 1. A total of 20 down wadding pieces were made, numbered 1#∼20#, using the method of first quilting and then filling to reduce drilling and improve flatness while ensuring the accuracy of grid filling. In making down wadding, hand stitching, and hand filling, produce down waddings with different stitching spacing and unit filling amount. The specific operation is as follows:

(1) After marking the canvas with lines, cut 40 pieces of 32 cm×32 cm fabrics along the warp and weft directions and iron them.

(2) Using an industrial sewing machine, select the DB9 needle and set the needle density to "2.5". Keep the fabric surface flat when sewing, and don't reverse the needle for both rise and fall. This minimises the shrinkage of the fabric caused by sewing. According to literature and market research, the horizontal stitching accounts for most down products and retains the best warmth. As we determined stitching spacing, horizontal stitching is used to sew 1, 2, 3, and 5 separate velvet threads on the canvas, with 5 pieces of each type sewn and reserved filling ports. The diagram is shown in Fig. 3.

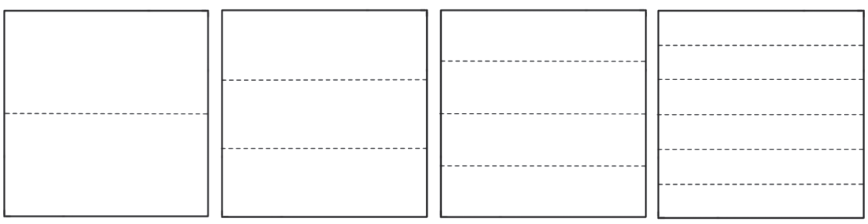

Fig. 3: The quilted space of the wadding (15 cm, 10 cm, 7.5 cm, 5 cm from left to right)

(3) The filling weight is determined based on the experimental plan's unit filling weight combined with the waddings' area, and the grid filling weight is calculated further. An electronic balance is used for manual filling. After filling, the waddings are tapped to make the internal waddings fully fluffy.

(4) After sewing the filling opening with a 1 cm seam allowance standard, gently tap the wadding with your hand again to ensure the internal wadding is fully fluffy and evenly distributed. The completed down wadding is shown in Fig. 4.

Fig. 4: Down waddings

2.5 Suspension Time

After hanging and placing, the wadding will gradually accumulate downwards over time under the influence of gravity. Dai [12] investigated the heat transfer coefficients of wadding in different placement conditions to investigate the effect of suspension time on the thermal insulation performance of down waddings. The suspension of wadding is placed for 0 h, 1.5 h, 3 h, 6 h, 12 h, 18 h, and 24 h. Heat transfer coefficients are measured separately. At the same time, compared with the heat transfer coefficients of wadding placed horizontally, the experiment found that the thermal insulation performance of wadding decreased with the increase of suspension time, and the decreasing trend also decreased with the increase of time. After 18 h to 24 h, the thermal insulation performance of wadding tends to flatten and reaches a stable state. The thermal insulation performance of the down wadding placed horizontally barely changes over time. Therefore, the suspension time for this experiment is determined to be 24 hours.

3 Experimental

3.1 Determination of the 'Steady State' Time

There is no clear explanation for "steady state" in GB/T 11048-2018, but the time it takes for different samples to reach a steady state varies. Depending on the thickness of the fabric, the steady-state time ranges from 30 minutes to 5 hours. To improve experimental efficiency and ensure data accuracy, a pre-experiment is conducted before formal measurement to determine when the floc reaches a steady state. Based on the filling coefficient, this experiment takes the four largest filling amounts of flocs for measurement. It is determined that it takes 45 minutes for the flocs with a 5 cm spacing to reach a stable state, 1 hour for the flocs with a 7.5 cm spacing, and 1 hour and 15 minutes for the flocs with a 10 cm spacing to reach a stable state; it takes 1 hour and 30 minutes for the 10 cm stitching spacing of the flocs to reach a stable state.

3.2 Measurement of the Thermal Resistance Value of Empty Board

Due to the machine's thermal resistance and the air layer's thermal resistance inside the testing chamber, the measured thermal resistance value of the fabric will be different from its actual thermal resistance value, and in general, the difference is a fixed value. An empty board test is required before formal measurement to calculate this value and reduce errors. Set the environment inside the test chamber to 1 standard atmospheric pressure, temperature of 20 °C, humidity of 65% RH, and wind speed of 1 m/s. Wait for the measurement results of each parameter to be within the tolerance range, take the average value, and calculate the empty plate's thermal resistance value (Rct0).

3.3 Thermal Resistance Experiment

The testing chamber of the thermal and humidity resistance meter is a closed climate chamber, and there is a test board inside the chamber to simulate the surface of human skin. By adjusting the temperature, humidity, and atmosphere inside the testing chamber to simulate the external environment, the thermal resistance value of fabrics in specific environments can be accurately measured. Before starting up, ensure that the wind speed sensor is 1.5 cm away from the testing platform, the drainage valve is open, and the water in the testing unit and liquid level sensor container has been drained. Then, turn on the machine, referring to GB/T 11048-2018 Textiles—Physiological effects—Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test), the environment in the test chamber is set to 1 standard atmospheric pressure, the temperature of 20 °C, the humidity of 65% RH, and wind speed of 1 m/s. The test plate's surface temperature (Tm) is adjusted to 35 °C. Adjust the height of the test board until the upper surface of the down waddings is level with the lower end of the air outlet while placing the down waddings in a "loop" shaped sponge at the same height as the down waddings and fully fits it. Adjust the temperature and humidity of the testing chamber, attach down waddings to the testing board, and close the chamber door once the instrument reaches a stable state. After the instrument is stable, 20 quilted spaces and unit filling weights of waddings are placed horizontally for 24 hours. They are sequentially placed in the test chamber on the Sweating Guarded Hotplate for testing. The calculation formula for the thermal resistance (Rct) of the waddings is:

$$R_{ct} = \frac{(T_m - T_a) \times A}{H - \Delta H_c} - R_{ct0} \tag{1}$$

In the formula: A is the area of the test board (m^2); T_a is the temperature of the air in the climate chamber (°C); T_m is the temperature of the test board (°C); H is the heating power provided to the test board (W); ΔH_c is the correction of heating power in thermal resistance measurement (W); R_{ct0} is the thermal resistance of the empty board.

After the instrument reaches stability, we record the test values. We take three valid data points as a set, calculate the waddings' thermal resistance, and record 60 times (20 sets) of data. After the measurement of 20 horizontally placed waddings is completed, we remove them and beat them evenly. We fix them on the suspension device and let them sit for 24 hours. We then repeat the measurement process of horizontally placed waddings and record 60 times (20 sets) of data. A total of 120 times (40 sets) of data are obtained in this experiment.

3.4 Statistical Analysis

After the thermal resistance tester reaches a stable state, each piece of wadding obtains 3 values as a valid data set. A total of 120 times (40 sets) of valid data are measured in this experiment. The normal Q-Q plot test shows that the data is roughly arranged along the line, indicating that the data follows a normal distribution. Excel is used to calculate the average and standard deviation of the collected data and organise the data for a descriptive analysis of the thermal resistance of the waddings in 2 placement conditions. Differential and correlation analysis of the data was then performed using SPSS16.0. At a significance level of $\alpha = 0.05$, if the significance P value is less than 0.05, the difference is considered statistically significant. By analysing the correlation coefficient r and significance P, the correlation between the thermal resistance of the waddings in two different placement conditions is explored.

4 Results and Discussion

Thermal resistance is the temperature difference ratio between two sides of a fabric and the heat flow rate per unit of area passing vertically through the fabric. It negatively correlates with the fabric's heat transfer coefficient and is critical for evaluating its thermal insulation performance. We take the average of the three data points to obtain 40 thermal resistance values, as shown in Table 2.

4.1 Descriptive Analysis of Thermal Resistance of Waddings in Two Different Placement Conditions

The measurement results of down waddings in Table 2 show that the experimental results are statistically analysed and organised. The variation of thermal resistance with the unit filling weight is plotted for two different placement conditions and 4 different quilted spaces, as shown in Fig. 5.

From the perspective of stitching spacing, the maximum thermal resistance value of down

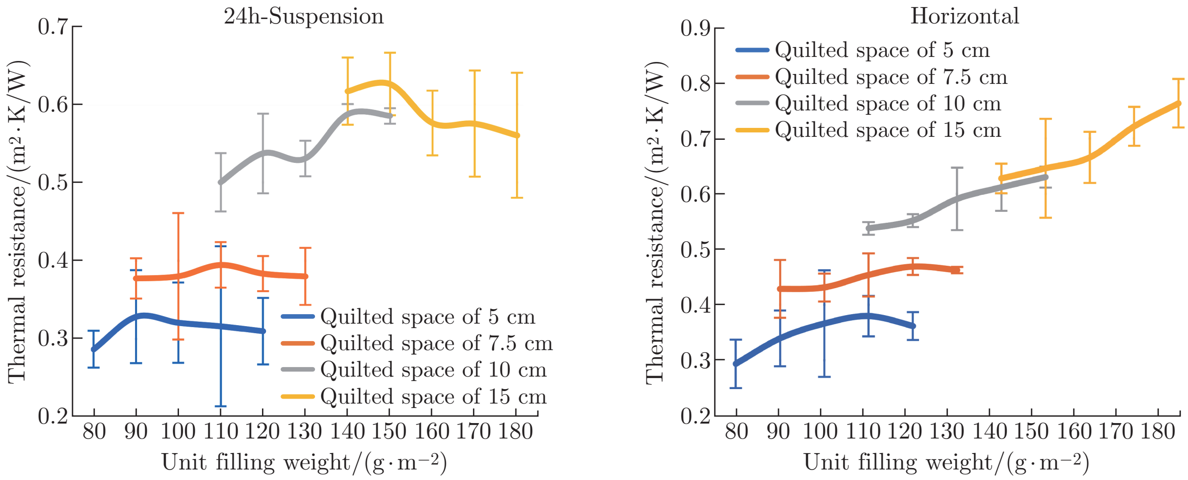

Fig. 5: Thermal resistance of down weddings in different placement conditions

Table 2: Thermal resistance test results of down waddings

Number	Quilted space/cm	Unit filling weight/g·m^{-2})	Thermal resistance/(m^2·k·w^{-1})			
			Horizontal		24h-Suspension	
			Mean	SD	Mean	SD
1#		80	0.293 8	0.043 6	0.286 9	0.023 5
2#		90	0.339 7	0.050 3	0.328 5	0.059 5
3#	5	100	0.366 4	0.096 1	0.320 9	0.051 4
4#		110	0.380 0	0.036 5	0.316 3	0.102 5
5#		120	0.362 0	0.025 2	0.310 1	0.042 5
6#		90	0.428 6	0.052 0	0.377 4	0.025 6
7#		100	0.431 4	0.025 2	0.380 1	0.080 9
8#	7.5	110	0.454 0	0.038 9	0.394 7	0.029 1
9#		120	0.469 1	0.015 3	0.383 6	0.022 5
10#		130	0.462 6	0.005 8	0.380 0	0.036 5
11#		110	0.537 8	0.011 5	0.500 2	0.037 3
12#		120	0.551 9	0.011 5	0.537 2	0.051 0
13#	10	130	0.590 9	0.056 1	0.530 7	0.022 8
14#		140	0.611 9	0.042 7	0.587 4	0.013 2
15#		150	0.630 3	0.018 9	0.585 2	0.009 9
16#		140	0.627 7	0.026 4	0.616 8	0.043 0
17#		150	0.646 1	0.089 2	0.626 1	0.039 8
18#	15	160	0.665 7	0.046 2	0.576 3	0.041 4
19#		170	0.721 5	0.034 9	0.575 3	0.067 8
20#		180	0.763 0	0.043 6	0.560 5	0.079 9

waddings varies with different stitching spacing. Under the same conditions, the thermal resistance value of down waddings increases with stitching spacing. When the spacing between the quilts is large, there is enough space inside the down waddings to interweave the down fibres, preventing the down waddings from piling up and hugging and increasing the static air content inside the down waddings. When the spacing between quilts decreases, the down-wadding fibres are squeezed and stacked against each other, decreasing warmth retention.

From the perspective of filling amount, in the horizontal placement state, when the stitching spacing is 5 cm and 7.5 cm, the thermal resistance value of down waddings shows a trend of first increasing and then decreasing with the increase of unit filling amount. When the stitching spacing is 10 cm and 15 cm, the thermal resistance value of down waddings shows an increasing trend with the increase of unit filling amount. In the 24-hour hanging and placement state, the thermal resistance value of down flocs mostly shows a trend of increasing and then decreasing with the increase of unit filling amount, and the maximum filling amount appears for each stitch spacing, as shown in Fig. 6.

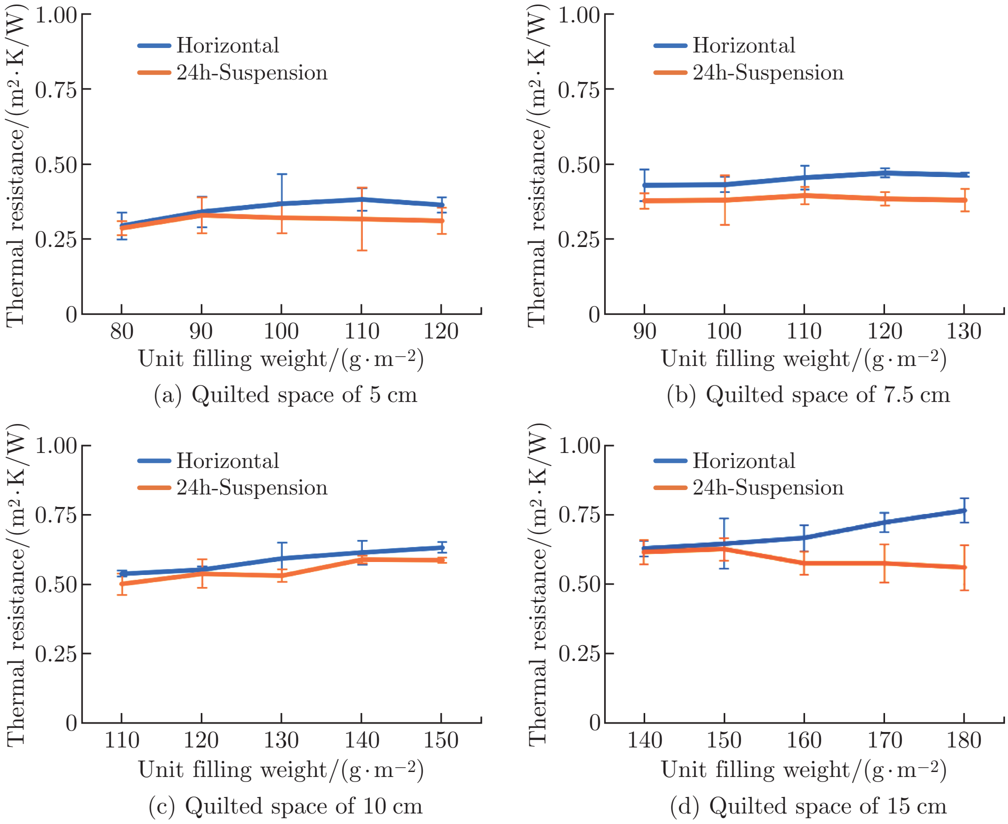

Fig. 6: The variation of thermal resistance with unit filling weight for 4 types of quilted spaces

When the stitching spacing is 5 cm, the thermal resistance value is maximum when the unit filling amount is 90 g/m^2; when the stitching spacing is 7.5 cm, the thermal resistance value is maximum when the unit filling amount is 110 g/m^2; when the stitching spacing is 10 cm, the thermal resistance value is maximum when the unit filling amount is 140 g/m^2; when the stitching spacing is 15 cm, the thermal resistance value is maximum when the unit filling amount is 150 g/m^2. Down fibres can fix more static air. As the filling amount increases, the number of down waddings increases, and the fixed static air also increases, resulting in improved insulation of down waddings; when the filling amount increases to a certain extent, the internal flocs of the down fibres squeeze each other, resulting in a decrease in the space between the down fibres, a reduction in the fixed static air, and a decrease in the warmth retention of the down fibres.

From the perspective of placement status, compared with the horizontal placement condition, the thermal resistance of the down waddings decreases after 24h-suspension placement. Under the same quilted space, the unit filling weight corresponding to the maximum thermal resistance of the waddings in the 24h-suspension condition is smaller than the horizontal placement condition. Specifically, when the quilted space is 5 cm, the unit filling weight corresponding to the maximum thermal resistance in the horizontal placement condition and the 24h-suspension placement condition is 110 g/m^2 and 90 g/m^2, respectively. When the quilted space is 7.5 cm, the unit filling weight corresponds to the maximum thermal resistance in the horizontal placement condition and the 24h-suspension placement condition of 120 g/m^2 and 110 g/m^2, respectively. When the quilted space is 10 cm, within the range of 110 g/m^2 $\sim$ 150 g/m^2, the unit filling weight corresponding to the maximum thermal resistance in the horizontal placement condition and the 24h-suspension placement condition is 150 g/m^2 and 140 g/m^2. When the quilted space is 15 cm, within the range of 140 g/m^2 $\sim$ 180 g/m^2, the unit filling weight corresponding to the maximum thermal resistance in the horizontal placement condition and the 24h-suspension placement condition is 180 g/m^2 and 150 g/m^2. The reason for the difference is that hanging and placing changes the distribution of down, causing the down to move downwards, resulting in an uneven distribution of down inside, leading to a decrease in thermal insulation performance.

4.2 Differential Analysis of Thermal Resistance of Waddings in Two Different Placement Conditions

From descriptive analysis, it can be concluded that the placement condition impacts the thermal resistance of down waddings. Therefore, further differential analysis is conducted on the thermal resistance in the 2 placement conditions. Conducting the paired sample T-tests on the thermal resistance in two different placement conditions. The results are shown in Table 3, with a significance level of $\alpha = 0.05$ and $p = 0.000 < 0.05$. There is a significant difference in the thermal resistance of the waddings in the 2 placement conditions, indicating that the placement condition significantly impacts the thermal insulation performance of down products.

Table 3: Paired sample T-test of thermal resistance in two different placement conditions

	Paired difference		t	df	Sig.
	Mean	SD			
Horizontal & 24h-Suspension	0.058	0.048	5.430	19	0.000

4.3 Correlation Analysis of Thermal Resistance of Waddings in Two Different Placement Conditions

To further clarify the relationship between the thermal resistance value in the horizontal placement state and the thermal resistance value after 24-hour suspension placement, a correlation analysis was conducted on the thermal resistance values of the flocs in the two placement states, and a scatter plot was drawn. As shown in Fig. 7, the scatter plot intuitively illustrates the linear relationship between the thermal resistance values of the flocs in 2 different placement conditions.

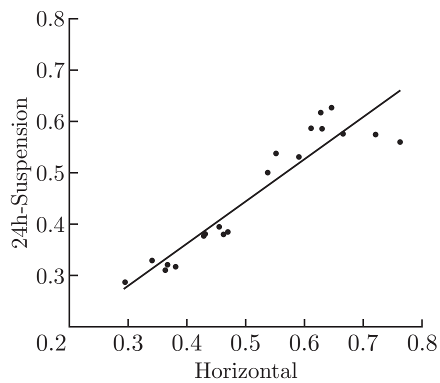

Fig. 7: Scatter plot

To further explore the correlation between the thermal resistance of the waddings in two different placement conditions, the results are shown in Table 4. The r (Pearson correlation coefficient) between the thermal resistance after horizontal placement and the thermal resistance after 24h-suspension placement is 0.939 > 0.9, $p < 0.01$, indicating a strong positive correlation between the thermal resistance of the waddings in both placement conditions.

Table 4: Correlation analysis

	Horizontal		24h-Suspension	
	Pearson correlation	Sig.	Pearson correlation	Sig.
Horizontal	1	–	0.939**	0.000
24h-Suspension	0.939**	0.000	1	–

4.4 Regression Model of Thermal Insulation Performance of Flocs in Two Different Placement Conditions

As shown in Table 4 to better predict the thermal insulation performance of down wadding, further univariate linear regression analysis was conducted to establish two regression models for the thermal insulation performance of down weddings in two different placement conditions, namely:

$$y = 0.825x + 0.033, R^2 = 0.881$$

Among them, x is the thermal resistance value of the floc placed horizontally, and y is the thermal resistance value of the sample placed in suspension for 24 hours ($m^2 \cdot K/W$).

The heat transfer coefficient of the samples in two different placement conditions shows a highly linear correlation, and the regression model prediction accuracy reaches 0.880, indicating that the regression model has a better fitting effect. Therefore, the thermal resistance value of the down waddings after 24 hours of hanging placement can be calculated through the above model based on the measured thermal resistance value of the down waddings in a horizontal placement state, which simplifies the experimental steps for studying the thermal insulation performance of the down wadding.

Table 5: Regression model of thermal insulation performance of flocs in two different placement conditions

Model	Nonstandardised coefficient		Sig.	R	R^2	Adjusted R^2
	B	Standard Error				
Constant	0.033	0.038	–	–	–	–
x	0.825	0.072	0.000	0.939	0.881	0.874

5 Conclusion

This paper explores the influence of different placement conditions on the thermal insulation performance of down wadding and the differences and correlations in the thermal insulation performance of down wadding in two different placement conditions. This study sets 4 types of quilted spaces and corresponding 5 types of unit filling weights, produces 20 down waddings and conducts thermal resistance tests in horizontal placement and 24h-suspension conditions. The experimental conclusions are as follows:

(1) The maximum thermal resistance value of the wadding increases with the increase of the quilted space. Compared with the horizontal placement condition, the thermal resistance of the down waddings decreases after 24 hours of suspension placement. Under the same quilted space, the unit filling weight corresponding to the maximum thermal resistance of the waddings in the 24 hours of suspension condition is smaller than in the horizontal placement condition.

(2) There is a significant difference in the thermal resistance of down wadding in 24h-suspension and horizontal placement. Conducting paired sample T-tests on the thermal resistance in two different placement conditions, the significance $p = 0.000 < 0.05$, indicating that different placement conditions impact the thermal insulation performance of down wadding.

(3) There is a strong positive correlation between the thermal resistance of down wadding in a 24-hour suspension condition and horizontal placement condition, as the Pearson correlation coefficient of thermal resistance in two different placement conditions is 0.939.

This study provides reference ideas for relevant personnel and enterprises in their research, design, and production of down products. This helps consumers better understand and choose products with different warmth needs. Meanwhile, this study suggests that future research can further clarify the relationship between the thermal insulation performance of down products in different placement conditions and digitise it to be more conducive to practical application.

(4) Using univariate linear regression analysis, the thermal resistance value under horizontal placement is defined as x, and the thermal resistance value under 24-hour hanging placement is defined as y. Two regression models for the thermal insulation performance of down waddings under two placement states are established: $y = 0.825x + 0.033$, $R^2 = 0.881$. This model can convert the thermal resistance values of down products in the two placement states. The thermal resistance value of down products in the vertical placement state can be estimated based on the thermal resistance value of down products in the horizontal placement state, predicting the thermal insulation performance of down products under human wearing state.

This study provides some ideas for relevant personnel and enterprises regarding the design of the stitching spacing and filling amount of down products. This helps to better develop down products that meet consumers' different insulation needs, thereby promoting the development and innovation of related industries.

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