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On the Design and Specifications of Fibrous Wadding Materials for Maintaining Human Body Comfort at Different Room Temperatures

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ABSTRACT

In the present work, we propose a simple method of obtaining the optimal weight of wadding for cold protective clothing to maintain human thermal comfort. Using the self-developed testing device, we established the experimental relation between the thickness and thermal conductivity of the fibrous wadding materials. Then, according to the distribution of the thermal insulation of a multi-layer clothing system, we derived the relationship between the engineering thickness and the effective insulation of the fibrous wadding, which is subsequently used to obtain the analytical expression for the weight of wadding as a function of the effective insulation of fibrous wadding material. Eventually, we deduced the analytical expression for the optimal weight of wadding as a function of temperature, which keeps the human body under the thermal equilibrium condition at different temperature environments. As such, we developed a scheme to rationally design fibrous wadding materials for cold protective clothing to maintain human body comfort.

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KEYWORDS

Multi-layer clothing; thermal conductivity; engineering thickness; the weight of wadding; thermal comfort

1. INTRODUCTION

There is an increasing demand for thermal comfort at different temperature environments since clothing that is poorly insulated from the cold or too warm can cause discomfort. This is especially crucial at low temperatures when clothing is expected to properly balance the heat generated by normal metabolism to maintain the body's thermal balance[1, 2]. Fibrous wadding material is one of the major fibril assemblies used as thermal insulation materials for cold protective clothing. The heat transfer in fibrous wadding occurs through conduction, convection and radiation[3, 4]. At low wind velocity, the heat transfer through convection is negligible; therefore, the conductivity is the primary heat transfer mechanism in fibrous wadding materials[5]. For fibrous wadding materials, a large amount of air is trapped inside the pores between fibers, providing a natural barrier to the cold environment. For example, the conductivity coefficients of cotton and wool are 0.071-0.073 (W/m·°C) and 0.052-0.055 (W/m·°C), respectively, which are much smaller than that of the immobile air; therefore, the amount of air trapped inside the fibrous wadding materials determines the thermal comfort of cold protective clothing, which is associated with weight of wadding. The greater the weight of wadding is, the less air is contained in fibrous wadding.

According to national (GB/T24254-2009) and international (ISO11079-2007) standards, the thermal insulation of the clothing system in different indoor environments is

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essential for human body comfort. Cold-protective clothing prevents heat loss from the human body and makes the person feel comfortable for as long as possible in low-temperature environments. There are a number of studies that examine the relation between thermal insulation of clothing system and temperature environments[6-10]. Meinander et al. [7] reported that the thermal insulation values measured by thermal manikins need to be corrected at -25℃. Wang et al. [6] found that the moisture management property of multi-layer clothing ensembles shows a significant influence on moisture diffusion and temperature distributions in the clothing system. These research works provide the necessary grounding for engineering clothing system that provides the specifications for cold-protective clothing.

On the other hand, cold-protective clothing increases the physical workload by increasing metabolic energy consumption. In particular, the weight of clothing has the greatest influence on energy consumption, and the stiffness of clothing is the second most important influential factor. Dorman and Havenith found that metabolic energy consumption is increased by 2.7% per clothing kilogram[11]. In addition, the friction between clothing layers hinders the extremity movement of a person, which further increases the physical workload. Therefore, lightweight and bulky clothing materials are beneficial for reducing the weight of clothing while still providing sufficient protection against cold. Fibrous wadding is a material having such merits. However, it is labor-intensive and costly to manufacture fibrous waddings due to the unknown thermal resistances of waddings at the specific ambient temperature. Under such circumstances, we may need several trials to adjust the weights of waddings in the production line before finalizing the specifications for a particular temperature environment. For each trial production, the waddings are made into clothing that is subsequently tested with a thermal manikin to obtain the thermal insulation values.

In the past two decades, the theoretical researches on the thermal properties of fibrous assemblies have mainly focused on establishing and improving the theoretical model to accurately describe the heat transfer inside fibrous assemblies[12-15], whereas the experimental researches have primarily focused on blending different types of fibers to achieve a better thermal insulation performance for fibrous material[20-23]. In our previous work[15, 19], we presented combined experimental and theoretical studies on thermal physical properties of fibrous materials, in which we derived an analytical model which significantly improves the accuracy of calculated thermal conductivity of fibrous material. However, there have been very few literature reports on the relationship of occupants' comfort and insulation of clothing, especially regarding the specifications of fibrous materials that meet the requirement of the thermal comfort of the human body at different temperature environments.

In the present study, we measured the heat flows through down wadding and kapok/down blended wadding in different thicknesses using the self-developed device. Based on the relationship between engineering thickness and effective insulation of fibrous wadding, as well as the relationship between the weight and the engineering thickness of fibrous wadding, we derived an analytical expression of the weight of wadding as a function of effective insulation. Furthermore, by applying the national (GB/T24254 – 2009) standard, we obtain the optimal weight of wadding that meets the requirements of human thermal comfort in different temperature environments.

2. MATERIAL AND METHOD

2.1 Theoretical Model

2.1.1 Thermal insulation in a multi-layer clothing system

In general, there are three types of insulation that can be found in the literature[20], i.e., the total insulation, the effective insulation and the basic insulation.

The total insulation refers to the thermal insulation from the skin surface to the environment, which is written as[21]

$$I_t = \frac{(t_s - t_a)}{K_{clo} \cdot Q} \tag{1}$$

where I_t is the total insulation (clo); Q is the heat loss per square meter of skin surface area (W/m^2); t_s is the average skin temperature; t_a is the ambient temperature (℃); K_{clo} is a constant, 0.155 (m^2·℃/W·clo). The Q, t_s and t_a can be measured by the thermal manikin. Subsequently the I_t is calculated.

The effective insulation refers to the thermal insulation from the skin surface to the outer surface of clothing without excluding the influence of increasing body surface area after dressing, which is written as follows[21]:

$$I_{cle} = I_t - I_a = \frac{(t_s - t_a)}{(K_{clo} \cdot Q)} - I_a \tag{2}$$

where I_{cle} is the effective insulation of clothing (clo); I_a is the impedance of the boundary air layer on the thermal insulation of dressed human body surface (clo); The basic insulation refers to the thermal insulation from the skin surface to the outer surface of clothing [21], which can be written as follows:

$I_a = [[0.61((t_a + 273)/298)^3 + 1.9\sqrt{(v_a)}((t_a + 273)/298)]]^{(-1)}$ [20], v_a is the wind speed (m/s).

$$I_{cl} = I_t - \frac{I_a}{f_{cl}} = \frac{t_s - t_a}{K_{clo} \cdot Q} - \frac{I_a}{f_{cl}} \qquad (3)$$

where I_{cl} is the basic insulation of clothing (clo); f_{cl} is the clothing area factor (no unit). According to ISO 7730-1994 standard, f_{cl} can be written as follows:

$$f_{cl} = 1.0 + 0.25 I_{cl} \qquad (4)$$

Both I_t and I_a can be evaluated with a thermal manikin. Therefore, we can calculate the effective insulation I_{cle} and the basic insulation I_{cl} according to Equations (1) to (4).

It is well known that the relationship between the thermal resistance R ($m^2 \cdot ℃/W$), the thickness d (m) and the thermal conductivity λ ($W/(m \cdot ℃)$) is $R = d/\lambda$. The relationship between the insulation value I and the thermal resistance R is $I = R/K_{clo}$. Therefore, the relationship between effective insulation I_{cle} and thickness d can be expressed as follows:

$$d = \lambda \cdot R = \lambda \cdot K_{clo} \cdot I_{cle} \qquad (5)$$

Here, the clothing is a multi-layer system composed of the inner wears, the fabric cover, the fibrous wadding and the coat. The basic insulation of inner wears can be directly evaluated by using a thermal manikin, according to Equations (1) – (4). The thermal conductivity of fabric cover can be measured by using a KES-F7 instrument[22]; subsequently, the effective thermal insulation can be obtained by using Equation (5). Therefore, only the effective insulations of fibrous wadding and coat are to be solved.

The insulation distribution formula of multi-layer clothing system in the reference [20] is used to calculate the basic insulation of clothing system, which is shown as follows:

$$I_{cl} = 0.835 \sum I_{clei} + 0.161 \qquad (6)$$

where I_{cl} is the basic insulation of a multi-layer clothing system (clo), I_{clei} is the effective insulation of a single layer of clothing system (clo).

We substitute the basic insulation of the multi-layer clothing system into the left side of Equation (6), and the effective insulations of inner wears, the fabric cover and the fibrous wadding into the right side of Equation (6). Since only the effective insulation of the fibrous wadding is unknown in the equation, it can be solved. In the same way, after obtaining the effective insulation of fibrous wadding, we substitute the basic insulation of the clothing system into the left side of Equation (6), and the effective insulations of the inner wears, fabric cover, fibrous wadding and coat into the right side of Equation (6) to calculate the effective insulation of the coat.

2.1.2 Relationship between the insulation and engineering thickness

The thickness of fibrous wadding is severely affected by external pressure. Under the normal wearing condition, the thickness of fibrous wadding is smaller than its original thickness during the compression, i.e., the engineering thickness. This paper assumes that the engineering thickness of the wadding material is proportional to the weight of wadding, which is generally applicable to the fibrous material s[23], and the relationship between the engineering thickness and the weight of wadding is established accordingly.

Replacing d and λ in Equation (5) with the engineering thickness engineering and the thermal conductivity $\lambda_{engineering}$ at the corresponding thickness, respectively, we get:

$$d_{engineering} = \lambda_{engineering} \cdot K_{clo} \cdot I_{cle} \qquad (7)$$

where the physical meanings of K_{clo} and I_{cle} are the same as in Equation (5). According to the discussion above, the effective insulations of the fibrous wadding material can be evaluated using a thermal manikin, while the engineering thickness and thermal conductivity remain unknown. Therefore, we establish the experimental relationship between the engineering thickness and the thermal conductivity under that thickness.

2.1.3 Experimental relationship between engineering thicknesses and thermal conductivities of fibrous wadding

The heat flows of two wadding materials in different compressed thicknesses are measured by the KES-F7 instrument in conjunction with a height-adjustable system, as shall be demonstrated below. For evaluating the thermal conductivities of two wadding materials, a more accurate formula of the thermal conductivity of the fibrous assembly established by our group is adopted herein[15, 19]. The thermal conductivities of two wadding materials in different thicknesses are shown in Figure 1.

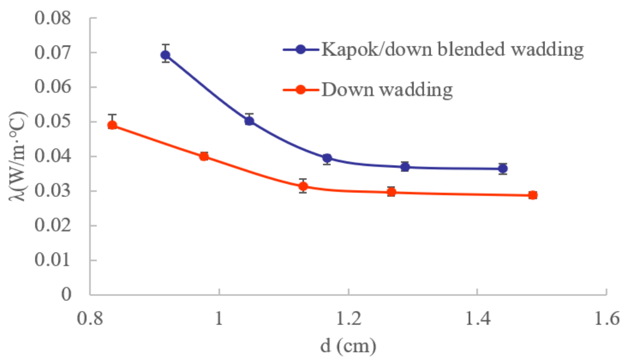

Figure 1. The thermal conductivities of two wadding materials in various thicknesses

According to the test data in Figure 1, the statistical relationships between the thicknesses of the two wadding materials and their thermal conductivities are obtained by performing the nonlinear regression fitting procedures, as shown in Equations (8) and (9).

Substituting Equations (8) and (9) into Equation (7), respectively, the engineering thicknesses of the two wadding materials can be solved. Subsequently, the engineering thickness is expressed as a function of the weight of wadding based on the assumption that the engineering thickness is proportional to the weight of wadding. The general relationships between the weights and the engineering thicknesses of the kapok/down blended wadding and down wadding are as follows:

Obviously, with the same weight, the engineering thickness of kapok/down blended wadding is greater than that of down wadding, because the down wadding can be compressed to a smaller thickness under a certain pressure due to its unique structure [16].

2.1.4 Relationship between weight and effective insulation of fibrous wadding

The relationship between the thermal conductivity λ and the weight G of the kapok/down blended wadding and down wadding can be obtained by combining Equations (8) to (11), as shown in Equations (12) and (13), respectively

$$\lambda_{Kapok/down} = -0.3341d^3 + 1.3781d^2 - 1.9121d + 0.9208, \qquad R = 0.9998 \tag{8}$$

$$\lambda_{down} = -0.0678d^3 + 1.3050d^2 - 0.4587d + 0.2585, \qquad R = 0.9997 \tag{9}$$

$$d_{kapok/down} = 0.009474G \tag{10}$$

$$d_{down} = 0.007207G \tag{11}$$

$$\lambda_{kapok/down} = -0.3313 \times (0.0095G)^3 + 1.3781 \times (0.0095G)^2 - 1.9121 \times 0.0095G + 0.9208 \tag{12}$$

$$\lambda_{down} = -0.0678 \times (0.0072G)^3 + 0.3050 \times (0.0072G)^2 - 0.4587 \times 0.0072G + 0.2585 \tag{13}$$

$$I_{cle} = \frac{6.1275G}{-2.8405 \times 10^{-3}G^3 + 1.2437G^2 - 1.8165 \times 10^2 G + 9208} \tag{14}$$

$$I_{cle} = \frac{4.644G}{-2.5306 \times 10^{-4}G^3 + 0.1581G^2 - 33.0264G + 2585} \tag{15}$$

Substituting Equations (12) and (13) into Equation (7), we can get Equations (14) and (15).

2.2 Methods

2.2.1 Clothing

To explore the specifications of wadding materials required in different low-temperature environments, two types of cold protective clothing with the same specifications were made with kapok/down blended wadding and down wadding, respectively. The cold protective clothing consists of a heat-insulating lining and a detachable fabric sheet. The structure of the thermal insulation lining is shown in Figure 2.

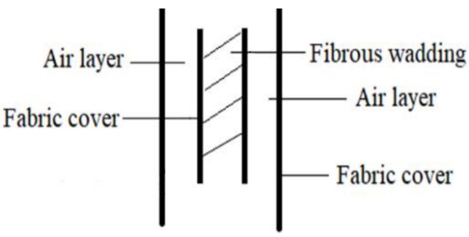

Figure 2. The schematic diagram illustrating the thermal insulation lining

The thermal insulation lining is made of the kapok/down blended wadding or down wadding, wrapped around by a polyester fabric cover. The composition of kapok/down blended wadding is 40% duck down + 20% kapok + 40% polyester, and the weight of wadding is 85.5g/m^2. The down wadding is made up of 90% duck down and 10% silk with a weight of wadding of 88.8g/m^2. The two fabric covers are made of the same materials.

The specifications of customized clothing systems are shown in Table 1. In line with the permitted working conditions of the thermal manikin and the customized combination of clothing in winter, the inner wears consist of stocking cap, shirt, sweater, knitted cotton trousers, outer pants, and cotton socks. The thermal insulation value of each garment is listed in table 2. Coat A and B are made of the same materials with the same styles, the length of which reaches to the middle of the thighs of the thermal manikin, and are equivalent to a windbreaker with lining in it. The coat consists of two sub-layers: the inner one is woven nylon fabric, and the other layer is waterproof polyester fabric. The detailed information of fabrics is shown in table 3. A layer of cotton is sandwiched in the hat of the suit, and the length of the detachable thermal insulation lining is 5cm shorter than that of the coat.

Table 1. Customized clothing systems with five different configurations

Serial number	Configuration
1#	Inner wears
2#	Inner wears + kapok/down lining + fabric cover
3#	Inner wears + down lining + fabric cover
4#	Inner wears + kapok/down lining + fabric cover + coat A
5#	Inner wears + down lining + fabric cover + coat B

Table 2. Thermal insulation for individual garment

Garment description	Thermal insulation (clo)
stocking cap	0.050±0.003
shirt	0.086±0.005
sweater	0.170±0.01
knitted cotton trousers	0.070±0.001
outer pants	0.165±0.01
cotton socks	0.020±0.004

Table 3. Physical properties of fabrics

Layer	Fabric cover	The inner layer of the coat	The outer layer of the coat
Materials	Woven polyester	Woven nylon	Wool-cotton blend
Thickness (mm) at 0.6 kPa	0.860±0.01	0.442±0.01	0.993±0.01
Weight (g/m^2)	110.1±10.2	70.8±0.5	304.9±5.9
Thermal conductivity(W/m·℃)	0.1613±0.002	0.10±0.004	0.068±0.006
Air permeability (mm·s^{-1})	2.30±0.01	25.3±0.6	63.4±3.2

2.2.2 Climate

All experiments were conducted in a climate chamber at an ambient temperature of 3±0.5 °C. The wind speed was 0.4 m/s. The relative humidity was 50 ± 5%. The average skin temperature of the thermal manikin was 33 °C.

2.2.3 Measurements

To evaluate the thermal insulation performance, the KES-F7 instrument[18] was used to measure the thermal conductivities of down wadding, kapok/down blended wadding and fabric cover, as shown in Figure 3 (a). To measure the thermal conductivities of fibrous wadding materials at different thicknesses, a height-adjustable system is employed to adjust the height of the hot plate, as shown in Figure 3 (b). The details of the test system can be found in our previous work[14].

For thermal manikin testing, the body core temperature of thermal manikin was 37±0.5℃[24]. The skin temperature is the mean value of temperatures measured at different surface body area. The skin temperatures were measured by attaching thirty-two PT100 patch sensors all over the surface area of the manikin. The actual skin temperature may vary from 32 to 36℃[24], depending on the amounts of clothing ensembles worn by the manikin.

3. RESULTS AND DISCUSSION

Table 4 shows the calculated total, effective and basic insulations and clothing area factors for the as-prepared clothing systems. The effects of conduction, convection and radiation are included in the calculated insulations. However, the experimental studies show that the effect of convection is very small for a multi-layer clothing system[23]. In particular, the temperatures of the air layers between each layer of clothing is mildly decreased from the body surface to the surrounding environment, which means the temperature difference between the two sides of the fibrous wadding material is so small that the radiation has a negligible effect on heat transfer. Therefore, the thermal conductivity of fibrous wadding material is the main factor contributing to the thermal comfort of the human body.

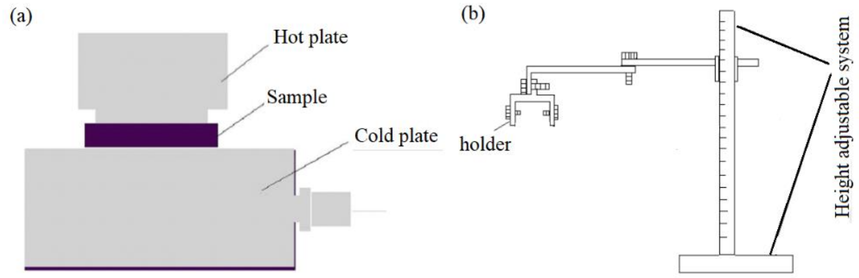

Figure 3. Schematic diagram illustrating (a) KES-F7 instrument and (b) height-adjustable system

Table 4. The total, effective and basic insulations and clothing area factor for each clothing system

	1#	2#	3#	4#	5#
I_t	1.626±0.02	1.991±0.01	1.989±0.01	2.552±0.02	2.715±0.01
I_a	0.626±0.001	0.626±0.001	0.626±0.001	0.626±0.001	0.626±0.001
I_{cle}	1.000±0.01	1.365±0.02	1.363±0.01	1.926±0.01	2.089±0.02
f_{cl}	1.285±0.03	1.378±0.02	1.384±0.02	1.536±0.01	1.580±0.01
I_{cl}	1.139±0.02	1.512±0.01	1.537±0.01	2.144±0.02	2.319±0.02

Table 5 shows the calculated effective insulation of each layer in the customized clothing system. The calculated engineering thicknesses of the kapok/down blended wadding and down wadding are listed in Table 6. As can be seen from Table 5, the effective insulations of coat A and B are much higher than those of the others. There may be two reasons accounting for the higher effective insulations of the coat A and B. Firstly, the cuff and neckline of the coat are fastened during the test, and the manikin is put on the hood of the jacket, which has a layer of cotton in it; secondly, these two coats are equivalent to the windbreaker with lining since it reaches to the middle of the thigh, which leads to a more excellent insulation of the coat. The effective insulation of coat B is slightly higher than that of coat A because the thermal insulation lining of coat B is made by filling the down manually, resulting in a bread-like structure, as shown in Figure 4. The bread-like structure contains still air at the suture after the lining is added with the coat, resulting in greater effective insulation of coat B.

The effective insulations corresponding to different wadding densities are calculated according to eqn. (14) and (15), as shown in Figure 5. By the data in Figure 5, the relationships between the effective insulations of the two wadding materials and the wadding densities are obtained, as shown in Equations (16) and (17).

When the effective insulation of the wadding material is less than 3.12 clo, the required weight of wadding for kapok/down blended wadding is less than that of down wadding. This is because the certain air can be stored by the closed hollow structure of the kapok fiber in the kapok/down blended wadding, while the interior of the fiber assembly is divided into numerous small spaces for air storing by the kapok fiber. Since conductivity is the most important form of heat transfer in wadding[16,25], the hollow structure of kapok benefits the heat preservation of the clothing system due to the conductivity of immobile air is much smaller than those of fibers[16]. Such a unique structure of kapok fiber provides better thermal insulation for kapok/down wadding. In contrast, when the effective insulation of the inner lining material is greater than 3.12 clo, the required weight of wadding of kapok/down blended wadding is greater than that of down wadding, which indicates that, with a mounting increase in demand for warmth, the heat preservation of kapok fibers is gradually exceeded by that of down fiber with the same weight of wadding. This is because the down possesses a superb thermal insulation capacity due to its unique structural characteristics [26]. The down cluster is made of a large number of subunits composed of small fibrils with divergent branch structures[26]. With the increase of the weight of wadding, the large number of subunits of the down fiber helps to maintain a great loftiness and low volume fraction for thermal insulation purposes [26], which ultimately makes heat preservation of down cluster higher than that of the kapok fiber assembly.

Table 5. The effective insulation of each layer in a multi-layer clothing system

	Fabric cover	Kapok/down blended wadding	Down wadding	Coat A	Coat B
I_{clei}	0.034±0.001	0.550±0.02	0.580±0.02	0.757±0.02	0.936±0.01

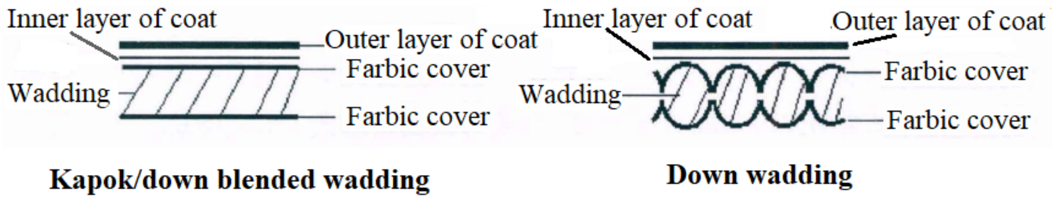

Figure 4. Schematic drawings summarizing the overall features of the clothing systems made of kapok/down blended wadding and down wadding, respectively

Table 6. The calculated engineering thicknesses and measured actual thicknesses of kapok/down blended wadding and down wadding

Fibrous wadding	G (g/m^2)	$d_{engineering}$ (cm)	d (cm)
Kapok/down blended wadding	85.5±1.2	0.81±0.003	1.43±0.02
Down wadding	88.8±2.2	0.64±0.002	1.48±0.01

$$G_{\frac{kapok}{down}} = 8.9253I_{cle}^3 - 39.606I_{cle}^2 + 80.82I_{cle} + 51.249, \quad R^2 = 0.9991 \tag{16}$$

$$G_{down} = 4.3468I_{cle}^3 - 25.949I_{cle}^2 + 83.796I_{cle} + 48.79, \quad R^2 = 1 \tag{17}$$

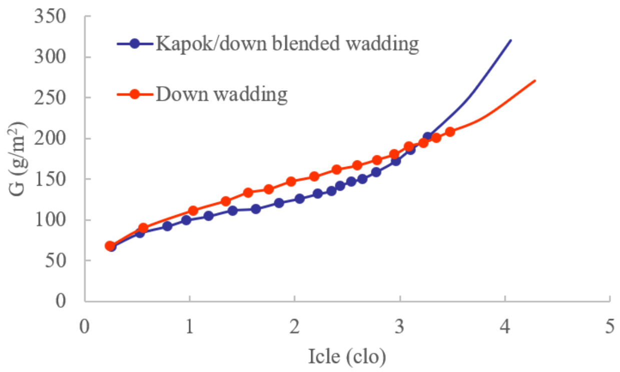

Figure 5. The nonlinear regression fitting of the weight of wadding as a function of effective insulation

Based on the research above, we propose a method of quickly and efficiently obtaining the optimal weight of the wadding of fibrous wadding materials required to maintain human thermal comfort at different temperatures in this paper. In the following, we use an example to illustrate our algorithm. The way of wearing is as clothing system 4#, coat A is adopted as the outfit, and the airflow rate is assumed to be 0.4m/s.

(1) According to GB/T24254 – 2009 standard, the metabolic rate of physical labor is found to be 90W/m^2. When the ambient temperature is t, the basic insulation of the clothing required to maintain the thermal comfort of the human body is:

$$I_{cl} = -0.087t + 2.46 \tag{18}$$

(2) Based on Equation (6), i.e., I_{cl}=0.835×(I_{cle}(inner wears) +I_{clex}+2×I_{cle}(fabric cover)+I_{cle}(coat))+0.161, the relationship between the basic insulation of the clothing system and the effective insulation required by the wadding material is obtained:

$$I_{cleX} = 1.198I_{cl} - 2.018 \tag{19}$$

(3) Substituting Equation (19) into Equation (18), we can get the relationship between the effective insulation of wadding materials and the ambient temperature:

$$I_{cleX} = -0.104t + 0.929 \tag{20}$$

(4) The effective insulation of wadding material I_{cleX} is substituted into Equations (16) and (17) to obtain the wadding densities corresponding to the effective insulation, i.e., the optimal amount of wadding filled in the thermal insulation lining to maintain human thermal comfort at the temperature of t, as shown in Equations (21) and (22).

Several temperatures are selected as examples to illustrate the relationship between the ambient temperature and the optimal weight of wadding of the fibrous wadding in the required lining materials, as shown in Figure 6.

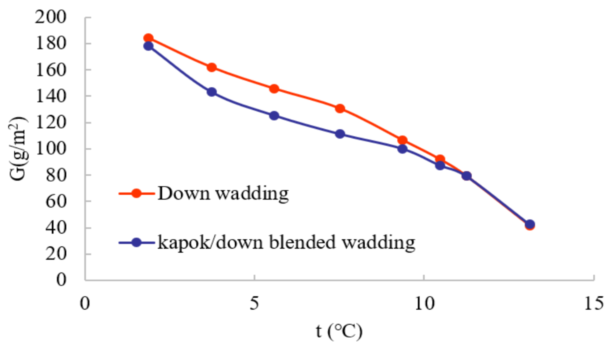

Figure 6. The optimal wadding densities in different temperatures

According to the actual production data[27] provided by Zhejiang Sanhong international feather Co Ltd, the weight of wadding of the filled duck down in the thermal insulation lining sold to Shanghai is 100g/m^2, while the weight of wadding of the filled duck down in the thermal insulation lining sold to the north is 140g/m^2, which is consistent with the weight of wadding of the down wadding in Figure 6, thus verifying the accuracy of the relationship between the ambient temperature and the optimal weight of wadding required to maintain human thermal comfort obtained in this study. In addition, under the same temperature, the weight of wadding of down wadding is generally larger than that of kapok/down wadding, suggesting that adding kapok fiber into the fibrous wadding can reduce the weight of cold-protective clothing while maintaining the same thermal insulation performance, which is consistent with our previous work[14].

$$G_{\frac{Kapok}{down}} = 8.9253 \times (1.024 - 0.101t)^3 - 39.606 \times (1.024 - 0.101t)^2 + 80.82 \times (1.024 - 0.101t) + 51.249 \tag{21}$$

$$G_{down} = 4.3468 \times (1.024 - 0.101t)^3 - 25.949 \times (1.024 - 0.101t)^2 + 83.796 \times (1.024 - 0.101t) + 48.79 \tag{22}$$

4. CONCLUSION

In this work, we proposed an intelligent prediction algorithm in which one can easily acquire the specifications of fibrous wadding at different temperatures by studying the relationship between the thermal comfort of the human body and the thermal insulation of clothing. In particular, we derived the analytical expression for the weight of wadding as a function of effective insulation, which is achieved by establishing the experimental relationship between the thermal conductivity and the thickness. The thermal conductivities of fibrous wadding under different thicknesses were measured with the KES-F7 instrument in conjunction with a height-adjustable system. Following the national standard, we obtain the optimal weights of kapok/down wadding and down wadding required to maintain the thermal comfort of the human body at the specified temperatures. We found that the thermal insulation of kapok/down blended wadding is generally better than that of down wadding due to the hollow structure of kapok fiber; however, with the increase of weight of wadding, the three-dimensional skeleton structure of down fiber divides the fiber assembly into numerous small spaces, which stores more still air than does the hollow structure of kapok fiber, leading to a better insulation performance of down wadding than that of kapok/down blended wadding.

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