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Comparisons of Thermal and Evaporative Resistances of Kapok Coats and Traditional Down Coats

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Abstract
The main aim of this paper is to contribute to finding a good solution to the ethical problem of live plucking. The use of new eco-environmental kapok fibres as a coat filler substitute for traditional duckling down was reported. The physical structures of kapok fibre were studied by scanning electron microscopy (SEM). The thermal and evaporative resistance properties of twelve sets of traditional duckling down coats and kapok coats were measured and compared using a novel sweating thermal manikin called "Walter". The results showed that there are no significant statistical differences in thermal and evaporative resistances among traditional duckling down coats and kapok coats. It was also found that there is the best mix rate of material and air trapped inside, which provides the best thermal resistance for the coat. Finally, we proposed that kapok fibres be used as a coat filling to lower the product price. Most importantly, the use of kapok fibre results in as good thermal and evaporative resistances of a coat as with traditional duckling down.

Key words: *live plucking, kapok fibre, down, thermal resistance, evaporative resistance, thermal manikin.*

Introduction

Down is a good thermal insulator widely used in winter jackets, pillows, sleeping bags, quilts, fashion accessories etc. However, it is often obtained by subjecting ducks, geese, swans or even penguins to the cruelty of live plucking. Gregory and Grandin [1] reported that live plucking was practised in Hungary, Poland, France and Germany. Gentle and Hunter [2] studied the physiological and behavioural responses associated with feather removal in birds and found that feather removal is likely to be painful and removal by flockmates can be categorised as an ethical problem. Many veterinarians and bird experts call live plucking extremely cruel. As a result, it is necessary to find a good substitution for traditional down, providing pain relief for poultry. A potential alternative to down insulation inside clothing is fibre from the kapok tree - a tropical tree of the Malvales variety and Malvaceae family, native to Central America and the Caribbean, northern South America, southern Asia and to tropical West Africa [3, 4].

Previous studies on kapok fibre have presented a great deal of knowledge concerning its properties. A yarn blend ratio of 3:2 (kapok/cotton) was successfully spun by Bisanda [5], which produced and exhibited mechanical properties similar to those of most short staple fibres. Mwaikambo [6] used kapok/cotton fabric as a reinforcement for conventional polypropylene and anhydride grafted polypropylene resins. Xiao and Yu [7] studied the structures and performances of kapok fibres, in which they found that kapok fibre has good heat resistance, and the structure of the cell wall is looser than that of cotton. Huang and Lim [8] investigated the performance and mechanism of a hydrophobic-oleophilic kapok filter for oil/water separation. Liu and Wang [9] studied the tensile and bending properties of kapok fibres using a tensile tester and the Kawabata Evaluation System (KES). It was found that the tensile curve of kapok fibre was similar to that of cotton. They also found that the bending rigidity of a single kapok fibre is small, but the relative bending rigidity is high due to its low linear density. Nilsson and Bjordal [10] explored the possibility of using kapok fibres for enriching cultures of lignocellulose-degrading bacteria. Recently, Cui et al. [11] investigated the thermal, bulk and compression properties of two types of kapok/down blended wadding, in which they found that the comprehensive ability of wadding to retain warmth increases with an increased content of kapok. However, the use of kapok fibres as filler material for winter coats has not been reported nor investigated yet.

In this study, kapok fibres were used as a filler inside six polyester layer coats to compare the thermal and evaporative resistance properties with those of six other traditional duckling down coats in a climate chamber representing a common outdoor winter climate in south-eastern China (the air temperature being about 4.5 °C and relative humidity around 65%). The effect of different filler quantities inside the coats on thermal and evaporative resistance properties was investigated. In addition, the possibility of using a kapok coat to substitute a traditional down coat in winter as a main garment for cold protection was also discussed.

Methodology

Kapok fibre

Kapok fibre is a silky fibre obtained from the seed of a tree indigenous to tropical zones. SEM images of the kapok fibre are shown in ***Figure 1***. It has a hollow lumen (or structure) and a sealed tail [12] with an external radius of 8 ± 3 μm, in-

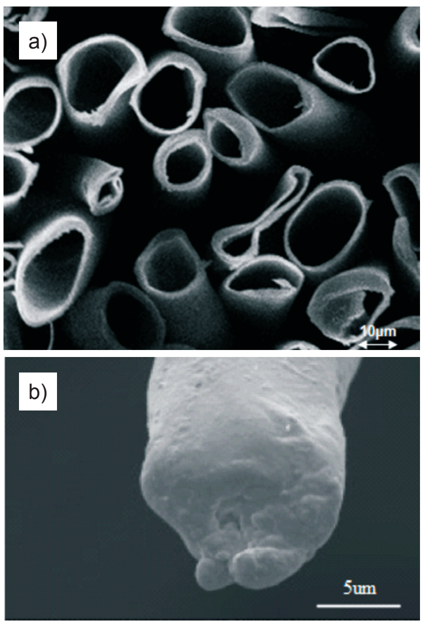

Figure 1. *SEM images; a) fibre cross-sections, b) the end of a kapok fibre.*

Table 1. Clothing ensembles.

Clothing ensembles Descriptions		
coat	**underwear**	**trousers**
Down coats 1-6 (160, 170, 175, 186, 201 and 226 g) Kapok coats 7-12 (170, 189, 197, 214, 225 and  (Size: M, color: Black)	 Northface™ long sleeve polyester shirt, (Size M, color: red with black)  pure cotton underpants (color: navy blue)	 Duckling down trousers (outer layer: pure polyester, filler: 100% down, color: black)

ternal radium of 7 ± 3 μm, and a length of 20 to 32 mm, which indicates that the lumen makes up 77% of the fibre volume [13]. Kapok fibre has good thermal resistance, which decomposes at a temperature of 296 °C. Kapok fibre is comprised of 43% alpha cellulose, 24% pentosan, 15% lignin, and 6.6% Uronic anhydride [7].

Clothing ensembles tested

To determine their thermal and evaporative resistances, six sets of coats filled with different quantities of kapok fibres were compared to six sets of coats with different down quantity fillings as defined by mass in g. The mass of duckling down inside the six down coats were 160, 170, 175, 186, 201 and 226 g for garments 1 to 6, respectively. Similarly, the mass of kapok fibre inside the coats were 170, 189, 197, 214, 225 and 431 g for garments 7 to 12, respectively. The outer woven fabrics of these coats were all made up of coated polyester. All twelve coats had the same size and were specially manufactured to fit on a "Walter" thermal manikin. In order to simulate real winter in eastern China, long sleeve polyester knit underwear, pure cotton underpants and duckling down trousers were put on the "Walter" thermal manikin. Each clothing ensemble was tested three times, and their mean value was reported. Details of the clothing ensembles are listed in ***Table 1***.

Thermal manikin

A novel sweating fabric thermal manikin called "Walter" (***Figure 2***) was used to test the thermal and evaporative resistances of these garments [14].

With this manikin the total thermal resistance can be measured and calculated using the following equations:

$$R_t = \frac{A \times (t_s - t_a)}{H_d} \tag{1}$$

$$H = H_d + H_e \tag{2}$$

$$H_e = E \times Q \tag{3}$$

where, R_t is the total thermal resistance of the garment in m^2·°C/W; A is the body surface area in m^2; t_s and t_a are the skin and ambient temperature, respectively in °C; H, H_d and H_e are the total, dry and evaporative heat loss, respectively in W; E is the latent heat of evaporation of water at skin temperature in W·h/g; Q is the sweating rate in g/h.

Figure 2. Fabric sweating thermal manikin "Walter".

The total evaporative resistance of a garment can be calculated by Equation 4,

$$R_e = \frac{A \times (p_s - p_a)}{H_e} = \frac{A \times (p_{sf} \times RH_s - p_{af} \times RH_a)}{E \times Q} \tag{4}$$

where, R_e is the evaporative resistance in Pa·m^2/W; p_s and p_a are the water vapor pressure on the skin and the environment temperature, respectively in Pa; p_{sf} and p_{af} are the saturated water vapour pressure at skin temperature and ambient temperature, respectively in Pa; RH_s and RH_a are the relative humidity on the skin and ambient, respectively in %.

Test conditions

The core temperature of the "Walter" thermal manikin was set at 37 °C. The area of the climatic chamber was 4.0 × 2.5 × 2.1 m, and all tests were conducted at an ambient temperature of 4.5 ± 0.5 °C, relative humidity 65 ± 5%, and air velocity of 0.4 m/s. Two Pt-100 RTD temperature sensors, two humidity sensors (HIH-3610) and an air velocity sensor (Swema 3000) were used in the climatic chamber. Fifteen RTD temperature sensors were attached to the surface skin of different body parts (head, chest, back, tummy, hip, right upper arm, tight lower arm, left upper arm, left lower arm, anterior thigh (right), posterior thigh (right), anterior thigh (left), posterior thigh (left), right calf, left calf) of the manikin to measure the skin surface temperatures. The average temperature value of these 15 points was used as the mean skin surface temperature. All clothing ensembles were put inside the climatic chamber 24 hours before measurement in order to stabilise. Each of the tests was repeated three times for one condition, and average values were used for the final analysis. The recordings were considered satisfactory and correct if the coefficient of variance of all the values measured for each clothing ensemble stayed below 10%.

Results and discussion

The calculated thermal resistance R_t, and evaporative resistance R_e, of the twelve sets of clothing ensembles are shown in ***Table 2***. The mean skin temperature t_s, ambient temperature t_a, ambient humidity RH_a, heat power W, and sweat rate Q, measured on the manikin are also listed. It can be seen from ***Table 2*** that the manikin's average skin temperature was stable, ranging from 34.6 to 34.8 °C. The total heating power ranged from 251.6 to

262.5 W/m². Hence, the final results are accurate and stable for all the tests.

The independent samples t-test was used to determine whether there was a significant difference between the average thermal resistance values of the same measurement made for duckling down coats and for kapok coats. The results were considered significant at $p \leq 0.05$. Statistical results are listed in ***Table 3***. The 2-tailed t-test significance probabilities are 0.809 and 0.810. Thus, there are no significant differences in the average thermal resistance values of the duckling down and kapok coats at a significance level of 5%.

Figure 3 shows that the thermal resistances of the down (1 - 6) and kapok (7 - 12) ensembles ranged from 0.330 to 0.366 m²·°C/W. Obviously, a clothing ensemble with a high value of thermal resistance is preferred in winter because it ensures less heat loss from the human body to the environment. For duckling down coats 1 to 6, the thermal resistance increased as the duckling down weight inside the coat rose from 160 to 186 g, which provided the best thermal resistance. On the other hand, too much duckling down in a coat, for example 201 or 226 g, started to reduce the thermal resistance, most probably due to the fact that the volume available at a certain down quantity decreased the amount of air trapped inside the coat. Thus our findings indicate that the highest thermal resistance can be achieved with an economically optimum filling and static air ratio inside the coat. This result is similar to that obtained for down sleeping bags investigated in an earlier study [15].

Similarly, increased thermal resistance was obtained by increasing the kapok fibre inside the coat from 170 to 197 g,

Table 2. *Test results. Filling weight: Coats1-6: 160, 170, 175, 186, 201 and 226 g.; Coats 7-12: 170, 189, 197, 214, 225 and 431 g.*

Clothing ensembles		t_s, °C	t_a, °C	RH_a, %	W, W/m²	Q, g/h	R_t, m²·°C/W	R_e, m²·Pa/W
Down coats	1	34.6	4.3	66.0	252.2	128.2	0.335	71.89
	2	34.8	4.5	59.4	258.3	142.2	0.344	64.16
	3	34.6	4.2	71.3	256.9	139.0	0.344	63.49
	4	34.7	4.2	65.6	253.7	143.9	0.359	61.32
	5	34.6	4.2	68.4	260.1	148.2	0.350	57.71
	6	34.8	4.0	65.2	256.3	135.3	0.343	62.00
Kapok coats	7	37.7	4.7	69.9	257.1	133.4	0.330	68.09
	8	34.7	4.4	62.8	262.5	143.8	0.337	67.59
	9	34.7	4.5	61.6	253.7	141.8	0.349	64.81
	10	34.7	4.5	66.0	256.2	139.1	0.344	64.79
	11	34.7	4.5	61.4	251.6	131.3	0.340	70.74
	12	34.6	4.3	64.7	252.4	147.4	0.366	58.85

Table 3. *Results of an independent-samples t-test of total thermal resistances.*

Down-kapok	Test for Eq. of Var.		t-test for Equality of Means						
	F	Sig.	t	df	2-tailed Sig.	Mean Diff	Std. Error Diff	95% Conf Int	
								Lower	Upper
Eq	0.629	0.446	0.249	10.00	0.809	0.0015	0.0060	-0.0119	0.0149
Uneq			0.249	8.568	0.810	0.0015	0.0060	-0.0123	0.0153

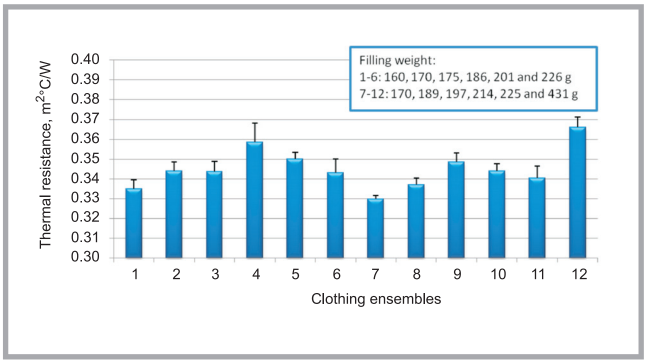

Figure 3. *Clothing thermal resistances of the twelve down and kapok coats.*

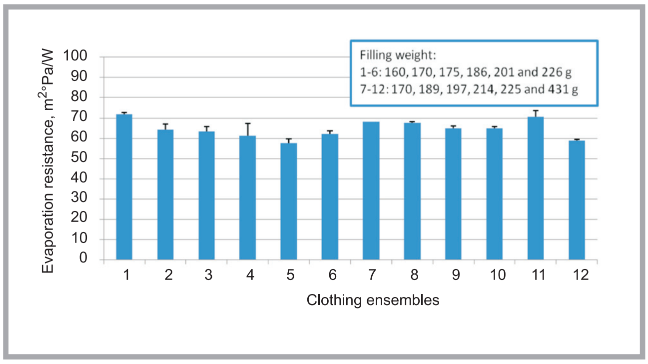

Figure 4. *Total evaporative resistances of clothing ensembles.*

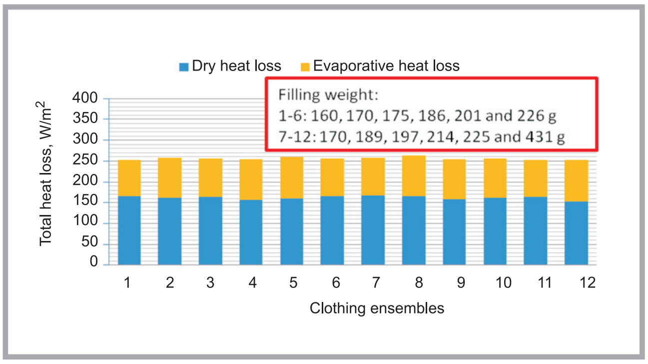

Figure 5. *Dry heat losses and evaporative heat losses.*

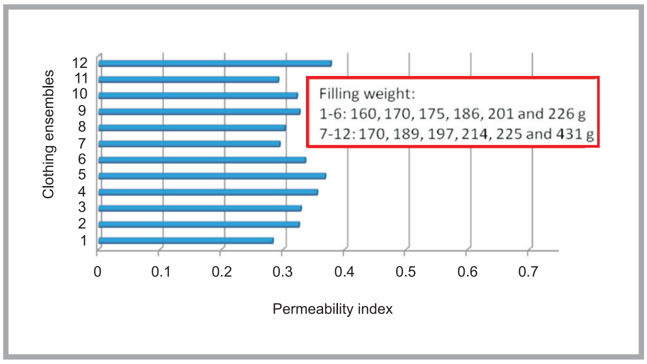

Figure 6. *Permeability indices of clothing ensembles.*

which provided the best thermal resistance, the thermal resistance reaching 0.366 °C m^2/W when the quantity of kapok fibres inside the coat was greatly increased - to 431 g. This amount of filling is about 1.9% higher than that in the best down ensemble, 4 (186 g), and also 4.3% higher than the next best kapok ensemble - 9 (197 g). However, the price of a kapok coat with such an amount of kapok fibre will be considerably increased.

Figure 4 shows the total evaporative resistances of the twelve down and kapok coats. It is well known that low evaporative resistance indicates that water vapour can easily pass through the garment layers. Hence, clothing with low evaporative resistance is preferred by wearers in any weather condition. The evaporative resistances ranged from 57.71 to 71.89 m^2·Pa/W, which are much lower than the values for cold weather windproof and waterproof protective clothing reported in an earlier study [16].

The dry heat loss of twelve sets of clothing ensembles varied from 153.6 to 167.7 W/m^2, as seen in ***Figure 5***. This corresponded to about 61 to 66% of the total heat losses. Hence, evaporation corresponded to about 34 to 39%, which clearly demonstrates that kapok and down fillings have nearly the same permeability. We also calculated the permeability index for all the kapok and down coats. The permeability index of all twelve clothing ensembles ranged from 0.28 to 0.36 (***Figure 6***). The permeability index i_m (dimensionless) of clothing ensembles can be calculated [17] by Equation 5.

$$i_m = 60.65\frac{R_t}{R_e} \qquad (5)$$

These findings are in line with those of McCullough [18, 19], who found that the average permeability index for conventional indoor ensembles was about 0.4, and Havenith [17, 20], who set the permeability index for one- or two-layer permeable clothing to 0.38. The clothing ensembles tested in this study remain below this level. For winter ensembles these values are relatively good and can thus be classified as permeable [19, 21].

Finally, the findings point to kapok as a cost-effective alternative to duckling down filler. While the study found no significant statistical differences in the thermal and evaporative resistances of duckling down coats and kapok fibre coats, the price of duckling down per ton is 5 to 10 times higher than that of kapok fibres currently on the market. Based on this, kapok fibres could be proposed to be used as a substitute for traditional duckling down filling inside coats. This may reduce production and product costs, which would be favourable for both coat manufacturers and consumers. And most importantly, the thermal and evaporative resistance properties of equivalent products of down and kapok were nearly the same.

Conclusions

The physical structures and properties and thermal and evaporative resistances of six sets of down coats and six kapok coats were investigated in this study. No significant differences in thermal and evaporative resistances were found. It was observed that there is an optimal air and filling rate inside the coat, which gives the highest thermal resistance. For a duckling down coat 186 g gave the best thermal resistance, while 189 g of kapok fibres had the highest thermal resistance for the same design and size of garment within a filling range of 160 to 226 g. The evaporative heat loss comprises about 34 to 39% of the total heat loss in the garment ensembles tested. The permeability index of these clothing ensembles ranged from 0.28 to 0.36, which can be deemed permeable cold protective clothing. The price of kapok fibre per ton is only one fifth to one tenth of that of down, which could reduce production costs, favourable for both manufacturers and consumers. It is proposed that kapok fibres be used as a filler inside coats to replace traditional duckling down.

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