(REFEREED RESEARCH)

AN INVESTIGATION OF HEAT FLOW THROUGH KAPOK INSULATING MATERIAL

KAPOK İZOLASYON MALZEMESİNDEN ISI AKIŞININ İNCELENMESİ

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ABSTRACT

The heat transfer process through kapok insulating material at different temperatures against wind speed was analyzed. A theoretical model of heat flow combined with conduction, convection and radiation was presented. The finite element method was used for detail study. Through the experiment, which was accomplished in an artificial climate chamber, it was found there was a good accordance between theoretical results and experimental results.

Key Words: Kapok, Finite element analysis, Heat transfer, Warm-keeping, Transient maximum heat flow.

ÖZET

Bu çalışmada, farklı sıcaklıklardaki kapok izolasyon malzemesinden gerçekleşen ısı akışı, rüzgar hızı karşısında analiz edilmiştir. Isı akışının bir teorik modeli; iletim, ısı yayımı ve ışıma ile kombine edilerek sunulmuştur. Sonlu elemanlar yöntemi, detaylı çalışma amacı ile kullanılmıştır. Çalışmada, teorik sonuçlar ile deneysel sonuçlar arasında iyi bir uyum olduğu görülmüştür.

Anahtar Kelimeler: Kapok, Sonlu elemanlar yöntemi, Isı transferi, Sıcak tutma, Geçici maksimum ısı akışı.

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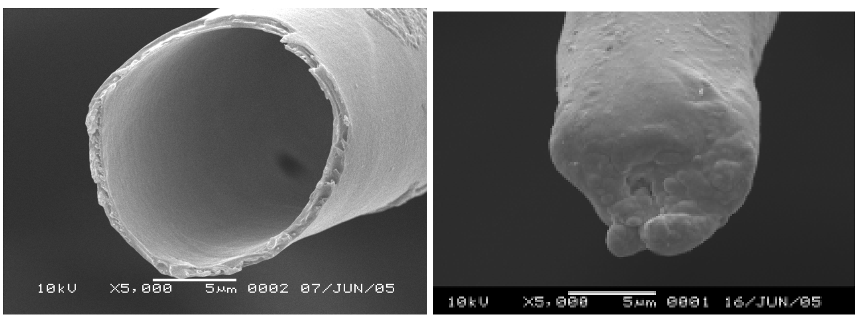
1. INTRODUCITON

Kapok fiber is one of the natural cellulostic fibers which grow on the kapok plant. It has a hollow body and a sealed tail, as shown in Fig.1, which are desirable features of candidates for functional textiles of this nature. However, the low volume weight of kapok is (specific density 0.29g/cm^3), and the short length and smooth surface of the fibers, causing poor inter-fiber cohesion, have prevented kapok from being processed by modern spinning machines.



(a) Body (b) Tail

Figure 1. Kapok fiber

The heat loss in cold environment is mainly done with three mechanisms

(1). First is the conduction, which is caused by temperature difference. Second is the radiation, which is concerned with the exchange of thermal radiation energy between two or more subjects. Third is the convection, which is worked on air flow. For the little air around the body, the warm air close to the body is removed and replaced by the air that has not to be warmed yet. So more frequent the warm air close to the body is replaced by the cool air, more heat loss from the body. This means there is an influence of temperature and wind speed on warm-keeping performance of fibrous insulating material.

In our earlier works (2, 3), multiple investigations on techniques of processing kapok fiber and the production technology of spinning, weaving and other products had been performed (2-4), so the kapok insulating material had already been used for the fabric. Through comparing the warm retain performance with those of the other fibrous insulating materials, it was found the thermal conductivity of the kapok insulating material was as low as that of the others (5). In this paper, for detail study of warm retain performance of kapok insulating material, three mechanisms of heat transfer were tripled together for analyzing the heat transfer process through the kapok insulating material, and the influence of wind speed on heat flow through the kapok insulating material at different temperatures was demonstrated.

2. MATERIAL AND METHOD

2.1 MATERIAL

The fabric made with kapok fibers was done with our own patent. Besides, the cotton fabric was done for compare. The properties of the materials and the structures of the fabrics are shown in Table 1 and Table 2. Because of roughness of skin and surface of yarn, a gap of 1mm is supposed between the skin and the fabrics in the analysis.

2.2 Model of Heat Transfer

In the former study, it had been proved that there was little convection and radiation (6) inside the fibrous insulating material, which means the heat are mainly delivered by conduction. This process can be expressed by the energy equation (7):

Table 1. Characteristic and configuration of fibers and yarns.

Materials	Characteristics and configuration
Kapok fiber	Average linear density: 0.064tex Average diameter: 20.5μm Average length: 20mm Moisture regain: 10%
Cotton fiber	Average linear density: 0.12tex Average diameter: 14μm Average length: 48mm Moisture regain: 8~13%
Air	Mass density:1.17kg/m^3 Thickness:1mm Specific heat:1027W·s/kg·K Conductivity:0.026

Table 2. Structure and properties of fabrics

Fabric	Materials: Duvetyn yarn	Materials: Plain cloth yarn	Fabric texture	Density	Mass density (kg/m^3)	Thickness (mm)	Specific heat (W·s/kg·K)	Thermal conductivity (W/m^2·K)
Kapok	Kapok yarn (36.4tex)	Cotton yarn (14.6tex)	Pile weave	90×72	179	2.19	1158	0.0486
Cotton	Cotton yarn (36.4tex)	Cotton yarn (14.6tex)	Pile weave	77×77	218	1.8	1187	0.0501

$$\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})-\rho c\frac{\partial T}{\partial t}=0 \quad (1)$$

Where T -temperature (°C); t -time (s); λ -conductivity $(W/m\cdot K)$; ρ -mass density (kg/m^3); c-specific heat $(W\cdot s/kg\cdot K)$.

For temperature difference between outer surface of fabric and adjacent air, the air close to the fabric is warmed up and mixed with the cooler air around, by which, the heat is transferred to the environment. Besides, because of the radiation energy exchanged between two subjects with different temperatures (8), the heat loss on the outer surface of the fabric by radiation should be tripled. So the boundary condition at the outer surface of the fabric could be described as:

$$-\lambda\frac{\partial T}{\partial x}=h(T_s-T_\infty)+\varepsilon\cdot\sigma(T_s^4-T_\infty^4) \quad (2)$$

where x -direction of heat transfer; q -heat flux $\left(W/m^2\right)$; h -convective heat transfer coefficient $\left(W/m^2\cdot K\right)$; T_s -outer-surface temperature of the fabric (°C); T_∞ -temperature of the ambient air (°C); ε -emissivity; σ - boltzmann constant, which is $5.67\times10^{-8}W/(m^2\cdot K^4)$.

Eq.(1) and Eq.(2) are the theoretical basis for heat transfer through fibrous insulating material.

From human body, the heat is transferred through fibrous insulating material to atmosphere. At the outer surface of the insulating material, the heat is exchanged with the environment by convection and radiation, for the physical parameters of the fabric is invariable, which means the conduction property of the insulating material is not changed, so the heat transfer is mainly influenced by wind speed and temperature of ambient air. On the basis of the theoretical models (Eq. (1) and Eq. (2)), which could be carried out by using the finite element software FLUENT, the influence of wind speed on heat flow at different temperature could be demonstrated. The average temperature of skin is 33.5°*C* (9).

2.3. Convective heat transfer coefficient

For the influence of environment on heat flow, the temperature of stream of air close to outer surface of fabric is

Table 3. Wind Speed and Convective Heat Transfer Coefficient at Different **Wind Scale**

Scale	Wind speed (m/s)	Average wind speed (m/s)	h $(W/m^2 \cdot K)$
0	0.00-0.20	0.10	4.000
1	0.30-1.50	0.90	7.874
2	1.60-3.30	2.45	12.99
3	3.40-5.40	4.40	17.41
4	5.50-7.90	6.70	21.48
5	8.00-10.7	9.40	25.45
6	10.8-13.8	12.3	29.11
7	13.9-17.1	15.5	32.68
8	17.2-20.7	18.9	36.08

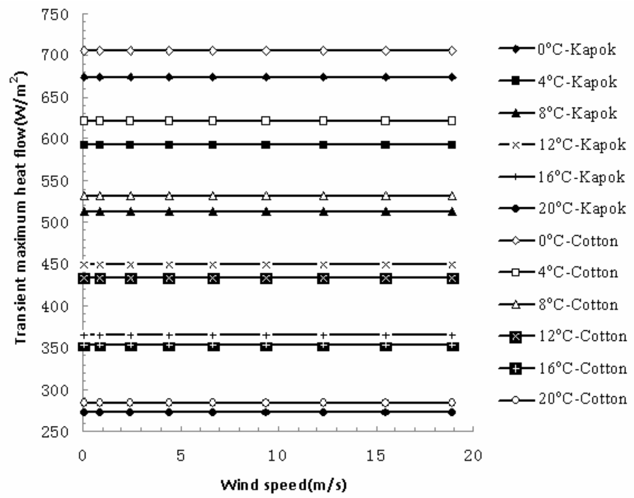


Figure 2. Relation between Transient Maximum Heat Flow and Wind Speed

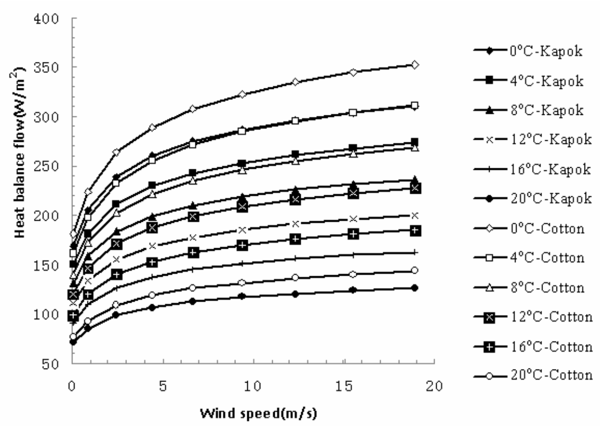


Figure 3. Relation between Wind Speed and Heat Balance Flow

chosen from the range of 2-20 °C and the wind scale changes from 0 to 8.

According to Rapp's result, the convective heat transfer coefficient could be got from experimental formula (9):

$$h = 4(W/m^2 \cdot K)$$

natural convection (wind scale 0) (3)

$$h = 8.3\sqrt{\upsilon}(W/m^2 \cdot K)$$

forced convection (wind scale 1-8) (4)

The convective heat transfer coefficient and wind speed at different wind scale are shown in Table 3.

2.4. Emissivity

The emissivity of a surface describes how effective it is at radiating energy compared with a black body. According to Dunkle and Wei's research, the emissivity of the outer surface of the fabric can be assumed to be 0.9 (9).

3. RESULTS AND DISCUSSION

Heat transfer process is characterized by two components: temperature and heat flow. Temperature represents thermal energy available, whereas heat flow represents the movement of thermal energy from one place to another. When fabric contacts with human body, there is energy transferred through the fibrous insulating material for the temperature difference between skin and environment. As time going on, the transfer process reaches dynamic balance gradually. Here, the heat balance flow, which is got when the heat transfer process reaches balance, is used to characterize the warm-keeping performance of the fibrous insulating material at different temperatures and wind speeds, and the transient maximum heat flow is used for describing the cool-warm feeling of the fibrous insulating material. Meanwhile, the temperature at the outer surface of the fabric is studied and tested and used as a criterion for the theoretical results.

3.4.1. Relation between Wind Speed and Transient Maximum Heat Flow

Fig.2 shows that the transient maximum heat flow varies with the temperature. The lower the temperature, the bigger the maximum heat flow is. This is to say, in the first few time, more energy is lost from human body in cold environment than warm environment. However, there is no influence of wind speed on transient maximum heat flow, even in the speed of 18.9 m/s. This is to say the wind could not penetrate the fibrous insulating material in a very short little time.

It also can be got from Fig. 2 that the transient maximum heat flow of the cotton insulating material is bigger than that of the kapok insulating material. This divergence become more apparent as the temperature gets lower. This means in a very quickly time, the kapok insulating material can prevent more energy loss from human body than that of the cotton insulating material.

3.4.3. Relation between Wind Speed and Heat Balance Flow and Temperature at Outer Surface of the Fabrics

Fig.3 shows the heat balance flow decreases uniformly with the increasing temperature at the same wind speed. This is to say the loss of

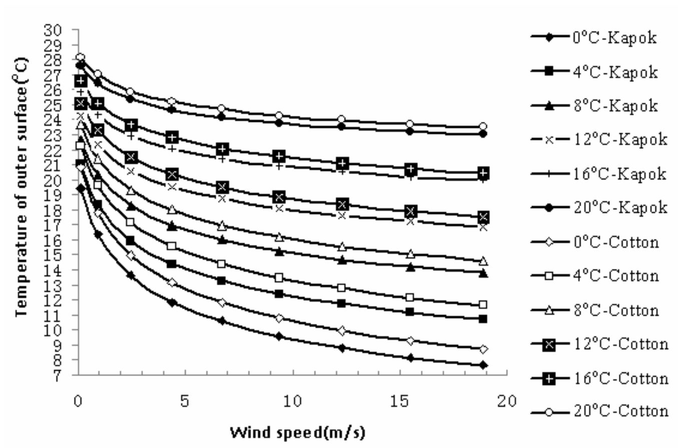


Figure 4. Relation between Wind Speed and Temperature at outer surface

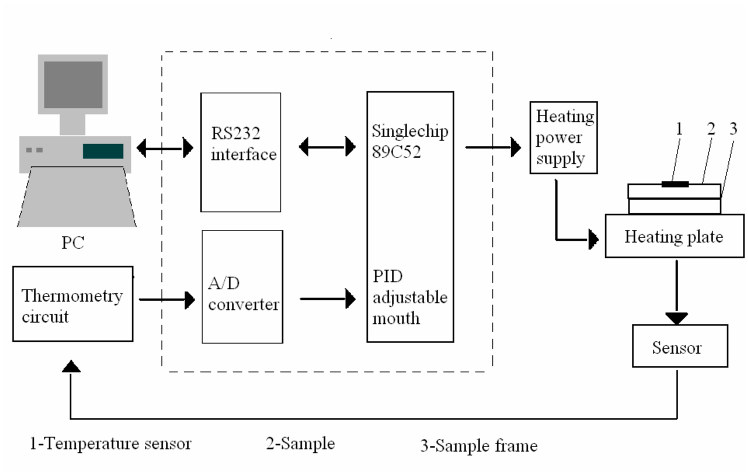


Figure 5. The sketch of the test system

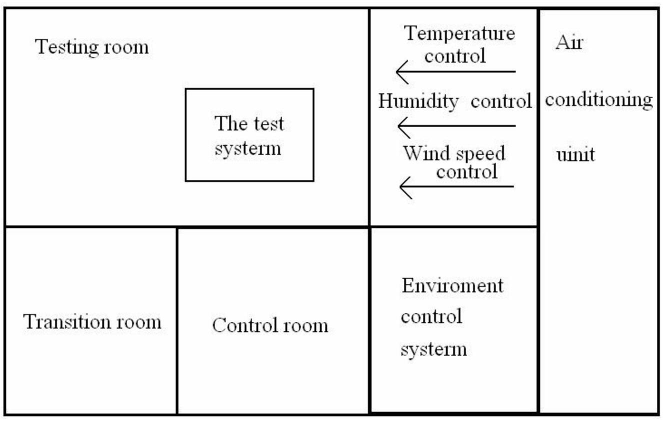


Figure 6. Artificial climate chamber

energy from human body increases equally when the temperature is lowered, this explains why people feel warmer in the environment of high temperature other than low temperature. It is also shown from Fig.3 that the heat balance flow increases with the wind speed, the bigger the wind speed, the smaller the slope of ascent curve is. This means the warm-keeping performance of the fibrous insulating material decreases rapidly with the increasing wind speed in the first few time, but when the speed exceeds the wind scale 4, the warm-keeping performance of the fiber insulating material descends slowly. Besides, the slope of ascent curve at different temperatures is distinct, the lower the temperature, the bigger the slope of ascent curve is. This is to say the influence of wind speed on the warm-keeping performance of fiber insulating material is more obvious as the temperature gets lower.

Seen from Fig. 3, it can be got the heat balance flow of the kapok insulating material is smaller than that of the cotton insulating material, and this divergence increases when the temperature becomes bigger. This is to say the kapok insulating material can prevent more energy loss from human body than the cotton insulating material. Perhaps, this is because the kapok fiber, which has a big lumen, contains more immobile air than that of the cotton fiber, for this reason the heat flow is restrained.

When the heat transfer process reaches dynamic balance, the temperature at outer surface of fabrics can be calculated. Fig.4 shows that the temperatures at the outer surface of the fabrics get smaller when the wind speed increases, and become bigger when the temperature increases. It can also be got from Fig.4 that the downtrend of temperature at outer surface against wind speed is more rapidly when the temperature gets lower. Compared the cotton insulating material with the kapok insulating material, it can draw a conclusion that the temperature at the outer surface of the kapok insulating material is lower than that of the cotton insulating material.

3.5. Compare of Theoretical and Experimental Results

For verifying the theoretical prediction, the temperature at the outer surface of the fabric is measured under various conditions of temperatures and wind speeds. The test system and the artificial climate chamber are shown in Fig.5 and Fig.6. The test system is mainly composed by two parts: the heating plate, which is used to simulate the skin at the fixed temperature of 33.5°C; the date recorder, which is used to test and record the temperatures at the outer surface of the fabrics through a temperature sensor. The test is carried out in the climate chamber where the humidity is 65% and the temperatures are 0°C, 4°C, 8°C, 12°C and 16°C respectively. The results of the experiment and the theoretical analysis are shown in Table 3.

From Table 3, it can be got that the experimental results are in good accordance with the theoretical results. This is to say the theoretical model used in the analysis truly reflects the

Table 3. Results of the Experiment and the Theoretical Analysis

Ambient temperature °C		Outer-surface temperature °C			
		Natural convection		Forced convection $v = 0.3 - 1.5(m/s)$	
		Experimental results	Theoretical results	Experimental results	Theoretical results
Kapok fabric	0	19.20	19.44	16.96	16.40
	4	20.56	21.00	17.85	18.35
	8	22.69	22.59	20.26	20.32
	12	23.85	24.21	22.98	22.32
	16	25.01	25.86	24.68	24.34
Cotton fabric	0	20.56	20.79	17.55	17.81
	4	22.35	22.20	19.21	19.60
	8	23.05	23.63	21.87	21.41
	12	25.46	25.1	23.45	23.24
	16	26.44	26.59	25.74	25.09

heat transfer process through the fabric.

4. CONCLUSIONS

The theoretical model combined with conduction, convection and radiation accounts for the experimentally observed heat transfer through kapok insulating material and cotton insulating material. The finite element method is an effective tool for solving the model. Through the analysis, it was found when the fabrics come to contact with the human body, the transient heat loss from human body didn't change with the wind speed. This means even when the wind speed reaches 18.9 m/s, the wind cannot penetrate the fibrous insulating material in a very short time. It was also found the transient maximum heat flow of kapok insulating material is smaller than that of the cotton insulating material. Considering the influence of temperature and wind speed on the heat balance flow, two conclusions can be got that the heat balance flow through the fibrous insulating material becomes smaller as the temperature gets bigger, and the heat balance flow increases with the wind speed, but the increasing trend becomes smaller when the wind speed gets bigger, which means the influence of increasing wind speed on warm retain performance of the fibrous insulating material is slow down, besides, it can be found the ascending trend is also influenced by the temperature, the lower the temperature, the more heat loss from human body when the wind speed increases. Compared the heat balance flow of the kapok fabric with the cotton fabric, it can be got that the kapok insulating material can prevent more heat losses from human body than those of the cotton insulating material.

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REFERENCES

1. Morton, W.E, Hearle, J.W.S., 1993, *Physical Properties of Textile Fibers*, The Textile Institute, Manchester, 5-15.
2. Sun, J.X., Wang, F.M., Liu, W., 2007, "*Test and Analysis of Java Cotton & Cotton Blending Yarn Property"*, Journal of Textile Research, 33(6): 35-36.
3. Zhao, K.W., Wang, F.M, 2007, "*Test Analysis of Twist and Elongation & Strength of Java Cotton Cotton Blended Rotor Yarn"*, Cotton Textile Technology, 35(3): 26-28.
4. Liu, W., Xu, G.B., Wang, F.M., 2007, "The Microbiological Properties of Kapok Battings". 2007 International Forum on Biomedical Textile Materials, Shanghai, China.
5. Sun, J.X., 2005, *Study on Shearing Property of Woven Fabric*, master's thesis, Shanghai, China, 36-55.
6. B. Farnworht, 1983, Textile Research Journal, 53(12): 717-725.
7. Liu, L.Y., 2002, *The Study of the Dynamic Heat and Moisture Comfort Properties of Garments*, doctoral dissertation, Shanghai, China, 12-30.
8. Zhao, Z.N., 2002, *Heat Transfer*, Higher Education Press, Beijing, 15-20.
9. McINTYRE, D. A., 1980, *Indoor Climates*, Applied Science Publishers LTD, London, UK, 10-50.

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