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Warm - cool feeling relative to the state of a fabric surface

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Abstract : The thermal behavior of fabrics depends on many morphological and structural parameters. In this paper, an experimental device for measuring heat absorption of textile materials in transient state, is developed. The heat absorbed in transient state by a fabric is connected to the warm or cool feeling during the handle. When the human skin touches a garment which is at a different temperature, heat exchange occurs between the two bodies and the warm or cold feeling is the very first sensation. The experiment simulates this transfer of energy. Moreover, the influence of some tribological aspects, on fabric thermal behavior is analyzed. The cotton variety, the yarn structure (single or plied yarn) and the stitch length of the knitted fabrics used are the parameters of the study. The results bring into light that transient thermal properties and surface state characteristics are influenced by parameters on three scales : fiber (microscopic scale) , yarn (mesoscopic scale) and fabric (macroscopic scale), whose importance will be discussed.

1. INTRODUCTION

Heat transfer through textile materials has been one of the important interests since studies of textiles properties have begun [3,8]. The most essential thermal characteristic was the insulating ability determining the prime function of a garment. Thus, studies in the literature were about devices for measuring fabric thermal properties in steady state [4,5,7].

More recently, during the seventies and eighties, what people feel when touching a cloth has become a significant selling point. Then, the textile manufacturers have tried to meet the consumer requirements and a new field of research has appeared, called the "hand" of a fabric. The aim is to find objective criteria to quantify and qualify the human touch of a textile structure, on a mechanical and thermal point of view.

The state of a fabric surface and the warm-cool feeling are very important for the fabric handle. Kawabata *et al.* were the first to study these two aspects of the tactile feeling; but the link between these parameters was not established [6,9,10].

Nevertheless, textile material and fabric surface are morphological and structural parameters which influence simultaneously thermal properties in terms of warm-cool feeling, and fabric surface state in terms of friction behavior and pile quantity. The aim of this paper is to show the influence of the three scales of a fabric, i.e. the cotton variety (microscopic scale), the yarn structure (mesoscopic scale) and the cover factor of knitted fabrics (macroscopic scale), on warm-cool feeling and on surface state. After a description of the experimental devices used, the results of the transient thermal and tribological behaviors of a fabric will be brought out. Finally, a link will be established between these two physical aspects.

2. EXPERIMENTAL

2.1 Thermal device

2.1.1 Apparatus

When the human hand touches a fabric which is at a lower temperature, heat flows from the hand to the fabric through the skin. The warm-cool feeling is mainly a transient heat conduction phenomenon [9]. Heat conduction is the transfer of energy as a result of molecular interactions under a non-homogeneous temperature distribution. In order to simulate this physical phenomenon in an ambient atmosphere, an apparatus based on a hot guarded plate is developed (figure 1). It is made up of a square and thin central aluminum test plate (of a 100 mm^2-area) surrounded by a coplanar ring aluminum plate (of a 292 mm^2-area). These elements are set on two adiabatic boxes in order to avoid heat underneath exchanges with the environment. The central plate and the guard ring, separated by a thin polystyrene band (of a 2 mm-width), are heated by two independent assemblies of heater wire cemented resistances. The test plate is at the temperature corresponding to the hand skin, about 33°C at a standard climate and for a subject in good health. The ring plate is at a temperature 0.5°C higher than the test plate, i.e. 33.5°C, to avoid lateral heat loss from the central test plate.

The system has two independent proportional integral derivative (PID) process controllers, one for each heater resistance assembly. The device includes several thin and flat packaging platinum film probes (Pt 100 Ω) to control and measure the temperature in different points.

Figure 2 shows the axial symmetry of the plate arrangement. The latter is more accurate, indeed, the heat is flowing symmetrically to the upper and to the lower plates. So, it is possible to know the rate of the heat flowing only through the upper plate with the value of the rate of electrical power supplied by the heater resistances.

In order to ensure constant and reproducible environmental conditions, i.e. natural convection in a calm atmosphere, the process is inside a large non-airtight box. It prevents draft and allows the standard ambient temperature of 20°C to be obtained.

2.1.2 Measurement procedure

After bringing the test plate and the guard ring plate to the desired operating temperature, respectively 33°C and 33.5°C, it is necessary to wait to the equilibrium between the system and the ambient environment. When the equilibrium state is reached, the electrical power supplied by the resistances remains constant. At this moment, the fabric sample, which is conditioned to standard atmosphere 20°C and 65% RH, is placed on the surface of the test plate. Immediately, heat is lost by the plate and a temperature gradient exists through the fabric. The signal of the electrical power required by the system (plate plus sample) to reach again 33°C is recorded according to time. The guard ring avoids lateral heat loss, so, the measurement concerns the vertically heat flow between the test plate and the sample. The thermal energy lost by the test plate is equal to the energy absorbed by the fabric plus a constant C_1, and the heat flow witch heats the test plate is equal to the electrical power supplied by the heater wire resistances plus a constant C_2. The constants C_1 and C_2 are independent of the fabric, they only depend on the imposed temperature gradient ΔT. In our study this gradient is constant and equal to 13°C, i.e. the temperature difference between the atmosphere temperature (20°C) and the operating temperature (33°C).

Under these conditions, the thermal power transferred to the fabric is the difference between the power measured at the equilibrium state without sample and the power measured with a sample on the test plate,

$$P_f(t) = P_{pf}(t) - P_p \tag{1}$$

where P_f : power absorbed by the fabric, in Watt (W),

P_{pf} : power lost from the test plate when a sample covers it, in Watt (W),

P_p : constant power lost from the test plate without fabric at equilibrium state, in Watt (W).

The energy, absorbed by the sample is calculated by multiplying the instantaneous power absorbed by the fabric by the step of the time :

$$E = P_f(t) * \Delta t \tag{2}$$

where E : energy absorbed by the fabric, in Joule (J),

Δt : step of the acquisition time, in second (s).

2.2 Measurement devices for fabric surface state

Friction behavior is measured with a multi-directional tribometer [1]. The hairiness which quantified globally the number, the length and the cross section of the emergent fibers of the fabric surface is measured by a pilemeter developed by Bueno *et al.* [2].

2.2.1 Multi-directional tribometer

The multi-directional tribometer includes three parts : the drive for the sample, the sensor and the signal-processing unit [1]. The sample-carrier is a 140-mm-diameter rotary disk. The sensor is positioned at one end of a balance arm with counterweight at the other and this arm is fixed on the frame which supports the sample-carrier (Figure 3). The sensor is a piezo-electric accelerometer. The probe fixed on this sensor is a steel wire (0.5 mm in diameter and 5 mm in length) with its axis radial to the sample-carrier. The scanned surface on the rotary disk is a 110-mm-diameter ring. Measurements are performed at a rotation speed of 0.258 rps ; therefore the linear speed is 89 $mm.s^{-1}$.

The Fourier analysis of the electrical signal from the sensor consists in computing the autospectrum relative to frequency by a spectrum analyzer. The autospectrum is the average of several instantaneous spectra during at least a sample carrier rotation. Each spectrum is expressed in power spectral density (PSD) relative to frequency. The power spectrum density is :

$$PSD(f) = \frac{|X(f)|^2}{K * \Delta f} \tag{3}$$

where f : frequency in Hertz (s^{-1}),

X(f) : Fourier transform of the temporal signal x(t), which corresponds here to the signal from the sensor,

PSD : power spectrum density,

Δf : step in frequency domain, $\Delta f = 1$ Hz,

K : Coefficient relative to the windowing. In our case, we used a Hanning window, then K = 1.5.

The power spectrum density shows one or several peaks corresponding to the periodicity of the fabric structure. The number of peaks in the autospectrum depends on the structure of the fabric and their frequency depends on the fabric density, i.e. on the size of the stitches. For plain jersey fabrics, the power spectrum density has one peak which corresponds to the wales. The maximal magnitude of each peak yields information on the fabric surface, i.e. on the height of surface asperities and friction behavior of the surface.

2.2.2 Optical pilemeter

By lighting a textile fabric with a laser beam tangential to the material, the structure and the surface hairiness can be detected. Then structure and hairiness have to be separated. In fact, some hairs are smaller than 0.1 mm but are significant for tribological behavior.

The pilemeter includes two parts (Figure 4) : the drive of the sample and the optical assembly [2], including a diode laser. In front of the fabric, a beam expander gives a 20 mm-diameter beam, which is cut to 10 mm wide to have clear boarders. Then, the beam illuminates the fabric and an image of fibers is obtained. The use of a high-pass filter in the back focal plane of the first lens allows the direct component and the low-frequency component of this image corresponding to the fabric structure to be removed. The hairiness information is directed onto a photodiode. The electrical signal resulted from the photodiode is then proportional to the "hair quantity" Q, that is the projection area of the hairs onto the photodiode plane :

$$Q = \sum_{i=1}^{i=n} a_i = n \cdot A = n \cdot L \cdot w \propto n \cdot L \qquad (4)$$

where a_i : projection area of the i^{th} hair,

n : number of hair,

A : mean area of the projected hair,

w : mean width of the projected hair,

L : mean length of hair.

Q can be related to a hair mean length with the hypothesis of all fibers having the same diameter. If the fabric is made up with just one material, Q is proportional to the hairiness mass M.

$$M \propto s \cdot \rho \cdot Q \qquad (5)$$

where s : hair mean cross-section area,

ρ : material density.

The parameter used is the mean light energy received by the photodiode, i.e. the mean signal from the photodiode during the measurement.

3. RESULTS

Figure 5 shows the fabrics manufactured and used in order to study the influence of several structural and geometric parameters, at different scales, on thermal and tribological properties of the textile structure.

Two types of cotton, a Pima and one of Benin varieties, are tested, on both these aspects. Their morphological values (in terms of length, fineness, maturity,...) are measured with Uster Afis Maturity and Fineness and listed in Table I. With each cotton variety, two different structures of yarn are processed : a single yarn and a balanced two plied yarn (Figure 6). The yarn count is the same for both kind of yarns, i.e. 36 tex, to study the importance of the fiber arrangement in the yarn. From these yarns, plain jersey samples are knitted with three different stitch lengths, in order to determine the effect of the fabric cover factor (Table II). The cover factor is proportional to the ratio between the area covered by the yarn in the loop and the area covered by the loop in the fabric.

3.1 Thermal results

The warm-cool feeling is perceived just after the skin touches a fabric, which is at a different temperature, but it can be only perceived at the very first moments.

Let's set the hypothesis that the fabrics tested are assumed to be continuous media. For homogeneous materials, the equation 6 (Fourier's equation) shows that at a given temperature gradient, the heat flow increases with the thermal conductivity of the material. Then, the more a material absorbs thermal energy, the more it is thermal conductor and the cooler it seems at the very first moments of the contact with a warmer body.

$$\vec{\varphi} = -\lambda \, \vec{\nabla} T \qquad (6)$$

where $\vec{\varphi}$: heat flow density in the normal direction of the surface, in W/m^2,

λ : thermal conductivity of the structure of the material in the heat flow direction, in W/m/°K,

T: temperature field depending on the time, in °K.

For a fibrous material the thermal conductivity is a combination of thermal conductivity of the air and of the fiber (weighted respectively by the fraction of the volume took up by each component).

The quantity of heat energy absorbed by the different kinds of samples during 0.8 second are shown in Figure 7. The latter value has been chosen because at this time the power supplied by the heater resistances is at its maximum value, necessary for the test plate to reach the temperature set point ; this maximum depends on the fabric. For each type of knitted fabrics, twenty samples are tested. The data, first, point out that the Pima cotton fabrics absorb more energy than the ones made of Benin's cotton, for a given yarn structure and stitch length. Secondly, the fabrics knitted with the two plied yarn absorb more heat than the single yarn fabrics whatever the cotton variety and the stitch length. Lastly, the lower the fabric density is, the less the fabric absorbs energy.

Considering the previous reasoning, it can be pointed out that, on the one hand, fabrics made up of Pima cotton are cooler than the ones made up of Benin's cotton, for the same structural parameters, and on the other hand, fabrics knitted with the two plied yarns are cooler than the ones with single yarns, for the same other structural and morphological parameters.

The yarn structure and the cotton variety are less influent parameters in the warm-cool feeling when the stitch length is high. In fact, when the rate of air quantity raises in the stitch for a given tested area, the fraction of material density is lower (Table II). Then the natural convection phenomenon of heat transfer increases while the conduction phenomenon decreases. This explains why the structural and morphological parameters are less significant in this case, and thus proves that the warm-cool feeling is mainly heat transferred by a conduction phenomenon.

3.2 Tribological results

Figure 8 and 9 show respectively the friction and the hairiness results of the tested samples. The friction behavior of a fabric depends on the materials and the global roughness (the structure roughness plus the hairiness). In this study the material is cotton, so it can be considered that the friction behavior is the same for the two cotton variety. Therefore, the height of the peak resulting from the autospectrum depends on both roughness of the structure and pile quantity. The rougher is the structure, the higher the frequency peak is. Nevertheless, the hairier the fabric is, the lower is the frequency peak.

The pile quantity is the mean of the electrical signal resulting from the photodiode.

From these two measurements, it can be noticed that fabrics made up of Pima cotton are less rough and less hairy than the ones made up of Benin's cotton : Pima fiber is longer, so the yarn is more regular and less hairy after spinning. Moreover, the fabric roughness and pile quantity are lower for two plied yarn fabrics than for the ones made of single yarns. In fact, the spinning process for a balanced two plied yarn tends to parallelize the fibers (Figure 10), then the fabric has fewer asperities on the surface. Finally, fabric roughness and hairiness increase with the fabric stitch length : the knitted structure is looser and the air permeability increases (Table II), then the fabric surface presents wider range in the surface levels.

4. Link between transient thermal behavior and STATE OF fabric SURFACE

The results of the experimentation show the link between the thermal and the surface fabric properties at the microscopic scale (fiber), mesoscopic scale (yarn) and macroscopic scale (fabric). A variation of one structural or morphological parameter generates some modifications on tribological aspects and thermal behavior : a fabric seems all the warmer as its surface is rough and/or hairy.

The hairiness encapsulates air between the emergent fibers and the fabric surface. So, when the skin comes into contact with the fabric, a thin air layer appears at the contact interface and thus the heat transfer is reduced and the fabric seems warmer. In fact, the air is imprisoned, so it cannot transport energy by convection (heat convection is a transport of energy resulting from fluid movements generated by changes in fluid density) ; moreover, the thermal conductivity of the air is low (at 300°K, $\lambda_{air} = 0.0262$ W/m/°K), then air transports a low quantity of energy by conduction. That's the case for the Benin's cotton fabrics whatever the structure of the yarn, and for the single yarn fabrics whatever the variety of cotton, because both of them are hairy.

However, the air quantity encapsulated by the hairiness can not be the only explanation ; roughness also plays a large part. In fact, the two plied yarn fabrics are less rough than the ones in single yarn. Then, the contact interface area between skin and fabric is wider, therefore heat conduction transfer is higher and two plied yarn fabrics is felt cooler.

It brings into light that structure roughness and hairiness are two influent parameters. They play an independent role in the heat transfer phenomena, although they are intrinsically linked because of the proper fabric way of production.

5. Conclusion

Both the surface state and the thermal behavior of a fabric depend on the chosen fibers and the spinning and knitting or weaving processes. Therefore, in order to produce a fabric with precise tactile aspects, it is necessary to study simultaneously these two physical aspects, at the three scales : fiber, yarn and fabric.

Here, a thermal device based on a hot guarded plate has been developed to estimate the sensation of warm-cool feeling in relation to fabric surface state.

The morphological and structural parameters studied in this paper are the cotton variety, the kind of the yarn and the stitch length of the knitted fabrics. Fabrics seems all the cooler as it made up with fineness fibers. Fabrics knitted with two plied yarns are cooler than the ones with single yarns. Lastly, the lower the cover factor of the knitted fabric is, the more the fabric seems cool.

The thermal results, linked to surface state results in terms of roughness and pile quantity, first show that a rougher fabric has a smaller contact surface and so seems warmer. Secondly, it brings into light that a hairier fabric encapsulates a higher air quantity on its surface and then seems also warmer.

However, it is difficult to identify independently the part of the hairiness and the structure roughness concerning their influence on thermal behavior. More experimentation are in progress to ponderate the role played independently by hairiness and structure roughness.

Acknowledgment

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Figure 1 :

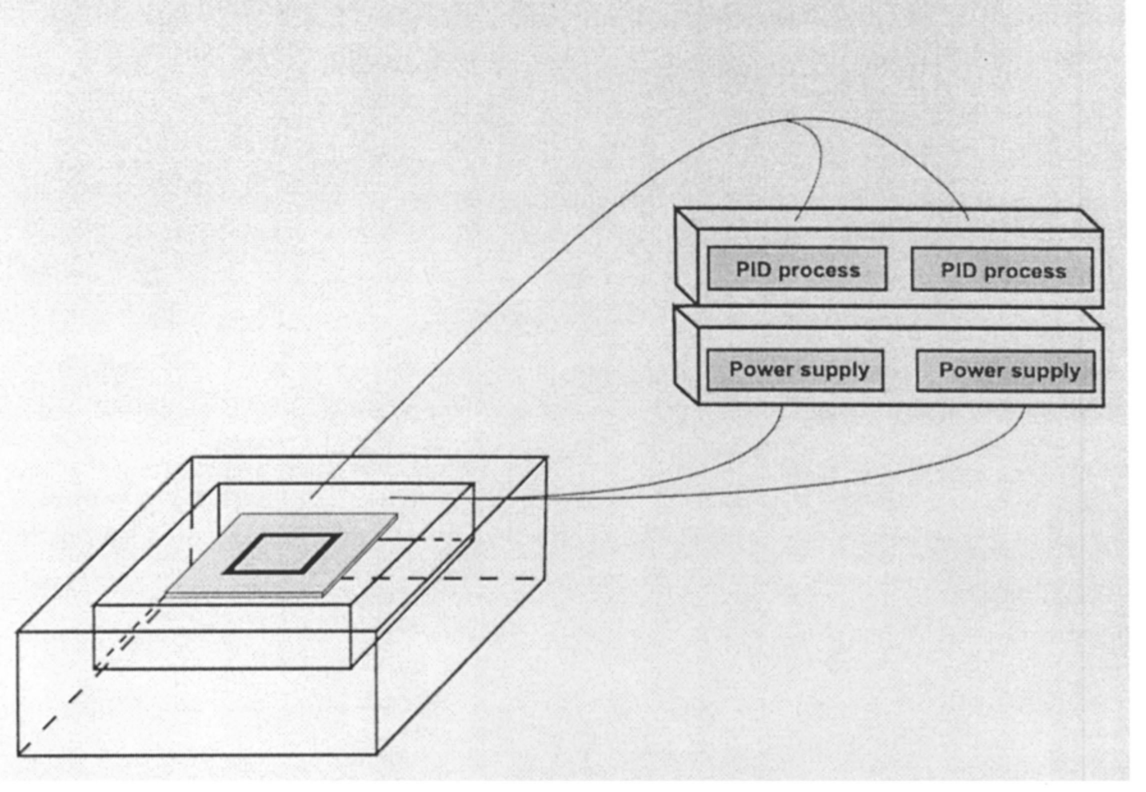


Figure 2 :

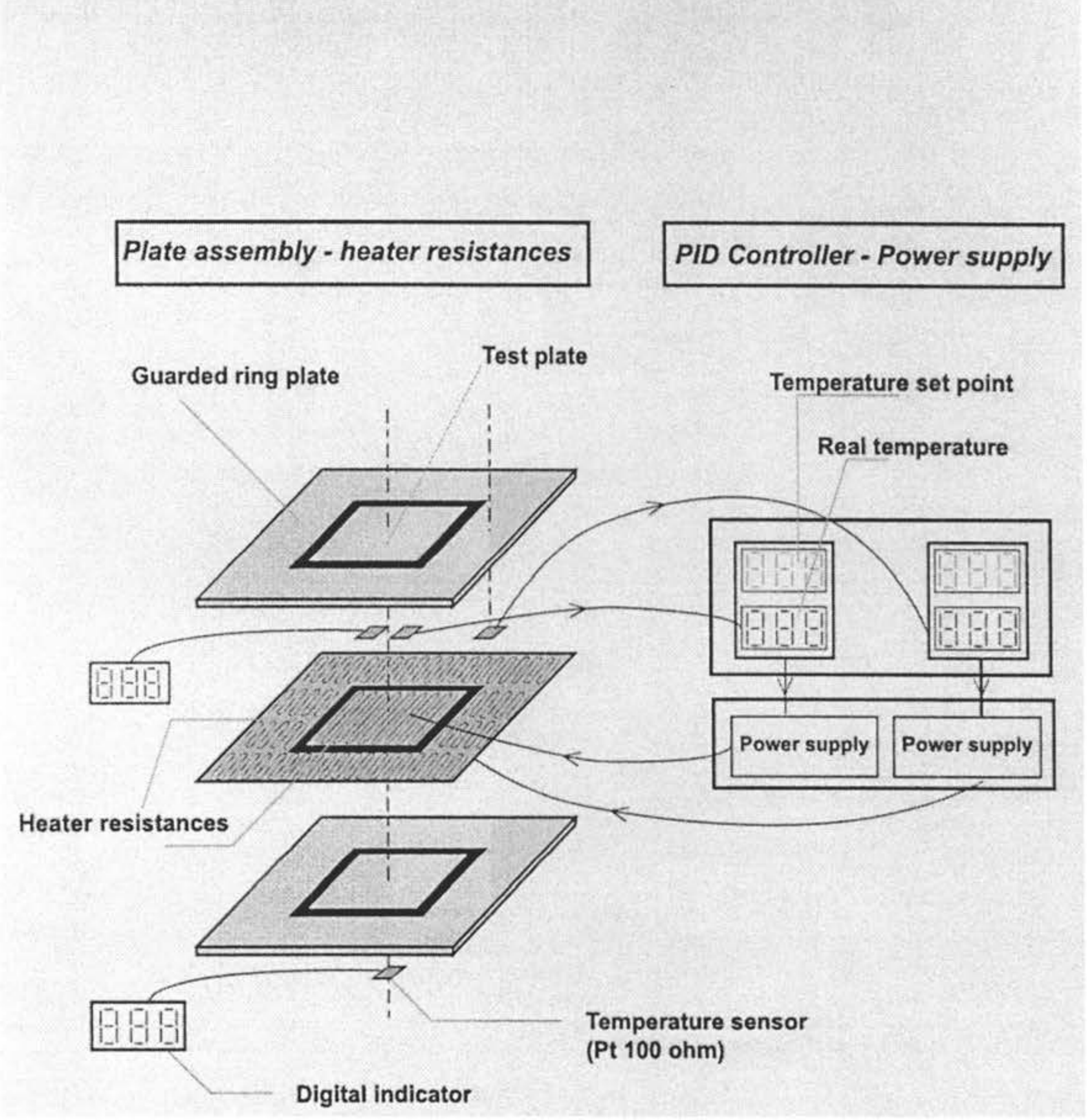


Plate assembly - heater resistances
PID Controller - Power supply
Guarded ring plate
Test plate
Temperature set point
Real temperature
Power supply
Power supply
Heater resistances
Temperature sensor
(Pt 100 ohm)
Digital indicator

Figure 3 :

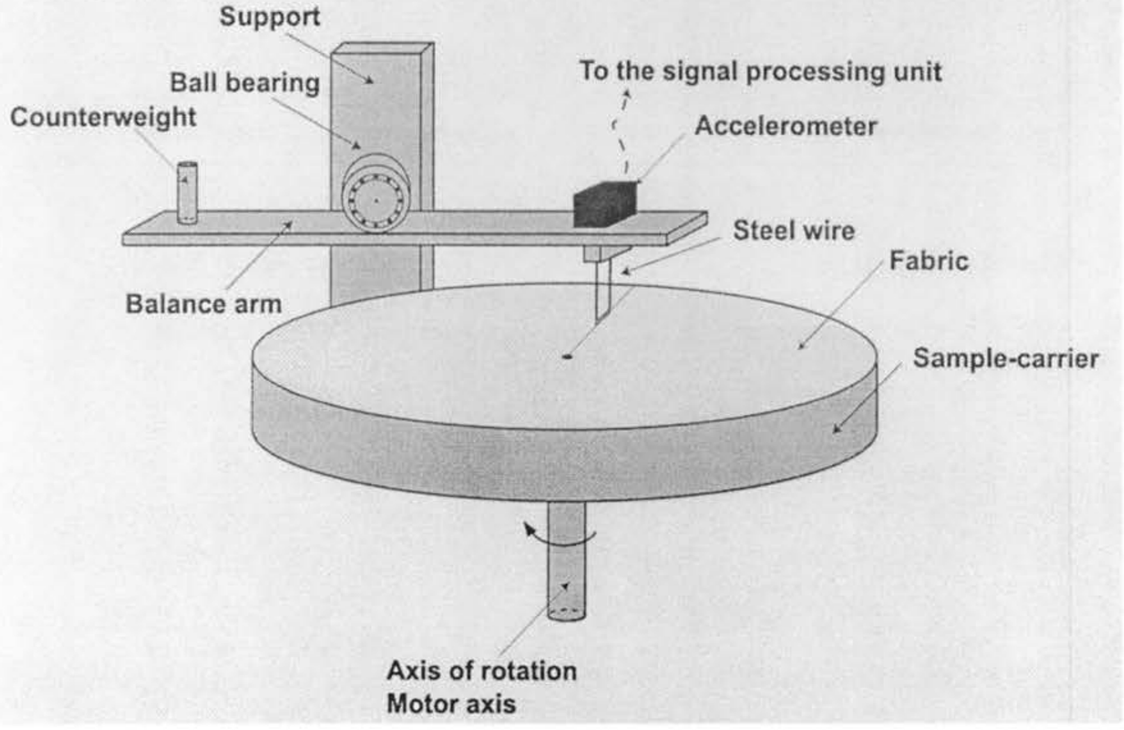


Figure 4 :

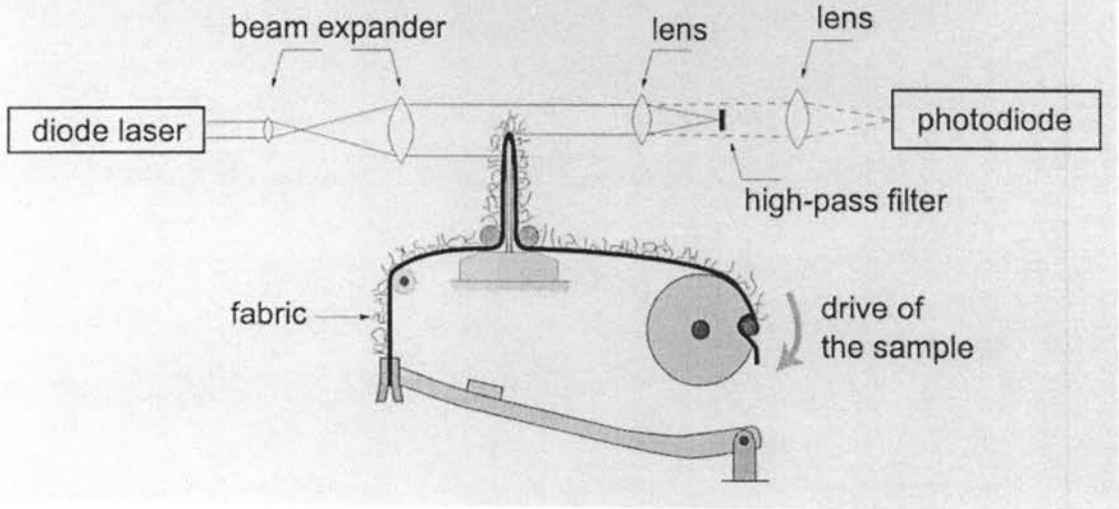


Figure 5 :

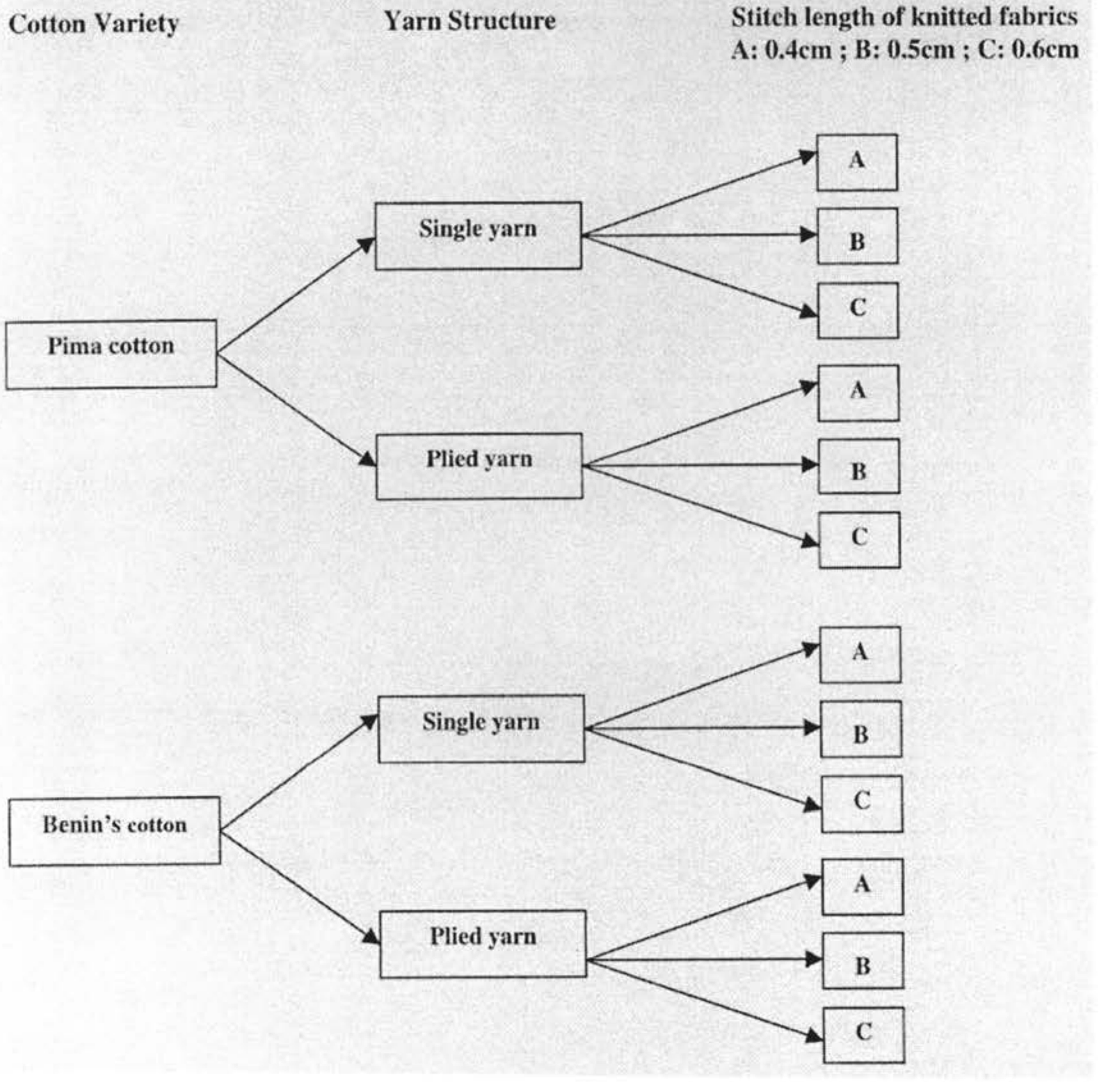
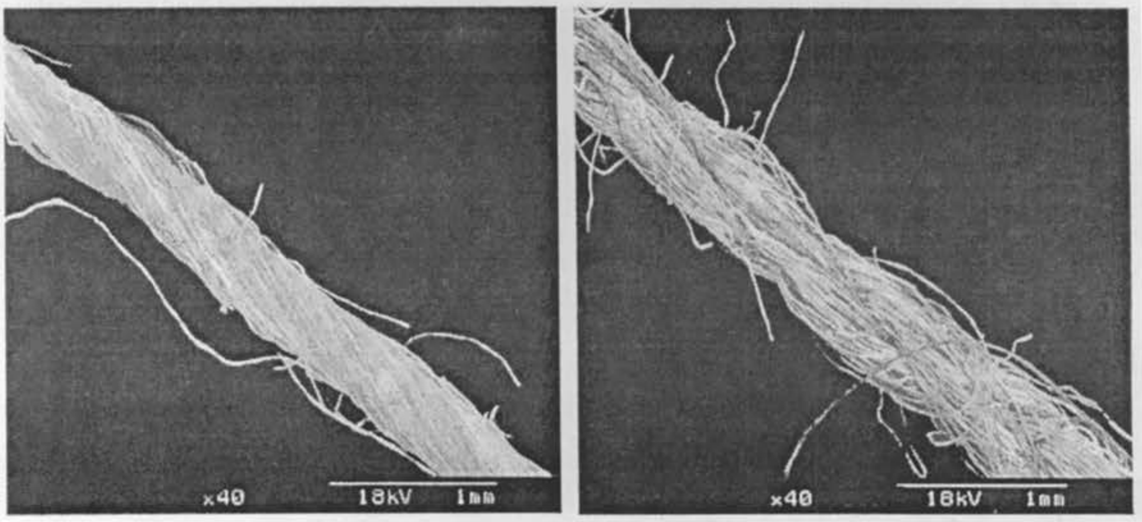

Cotton Variety
Yarn Structure
Stitch length of knitted fabrics
A: 0.4cm ; B: 0.5cm ; C: 0.6cm
Pima cotton
Single yarn
Plied yarn
Benin's cotton
Single yarn
Plied yarn
A
B
C
A
B
C
A
B
C
A
B
C

Figure 6 :



a) b)

Figure 7 :

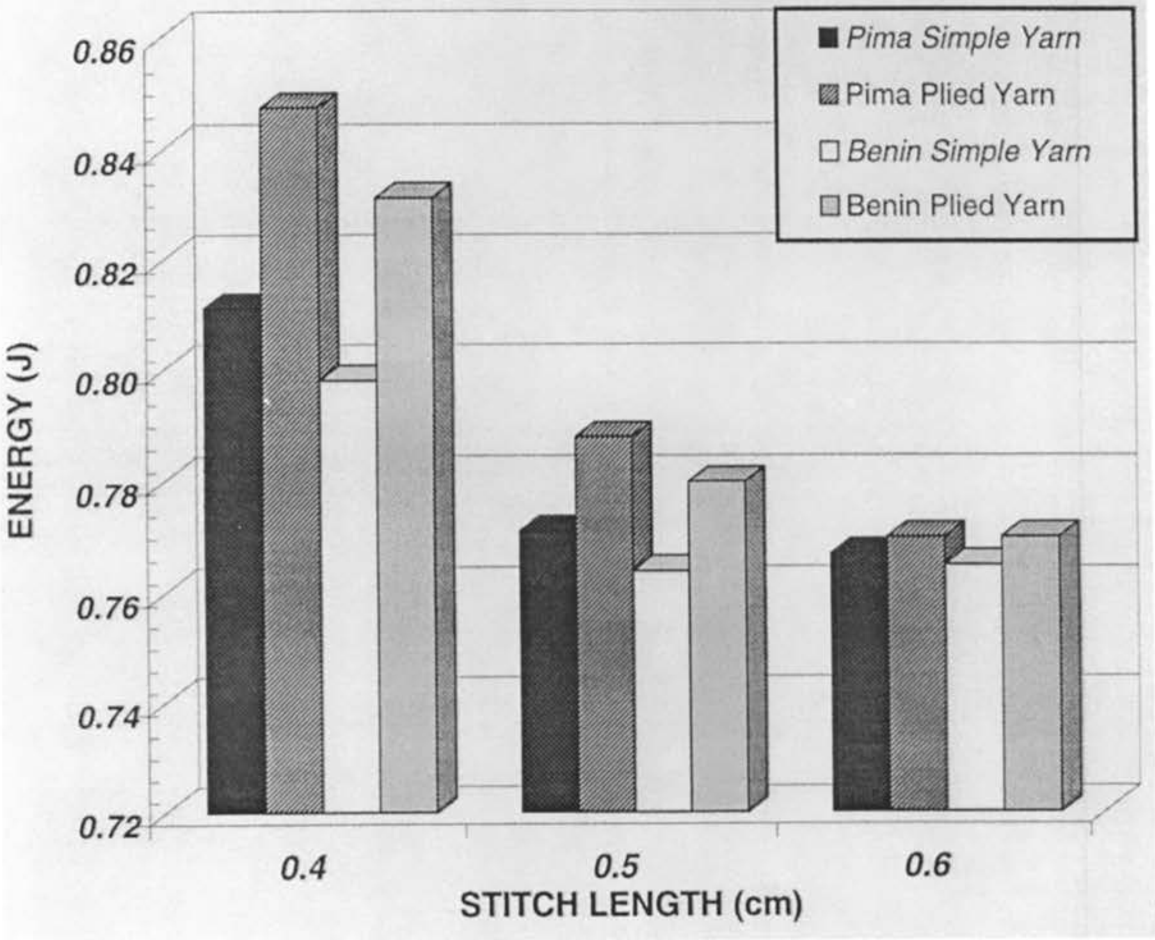


Figure 8 :

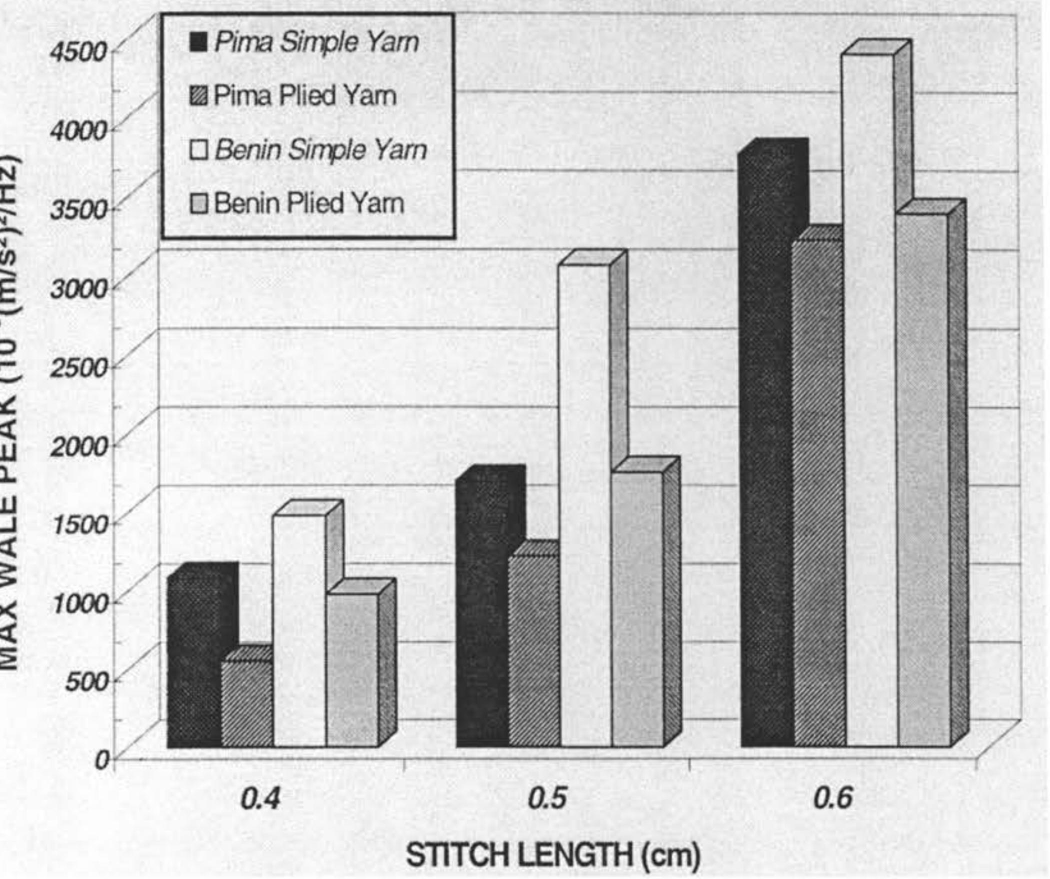


Figure 9 :

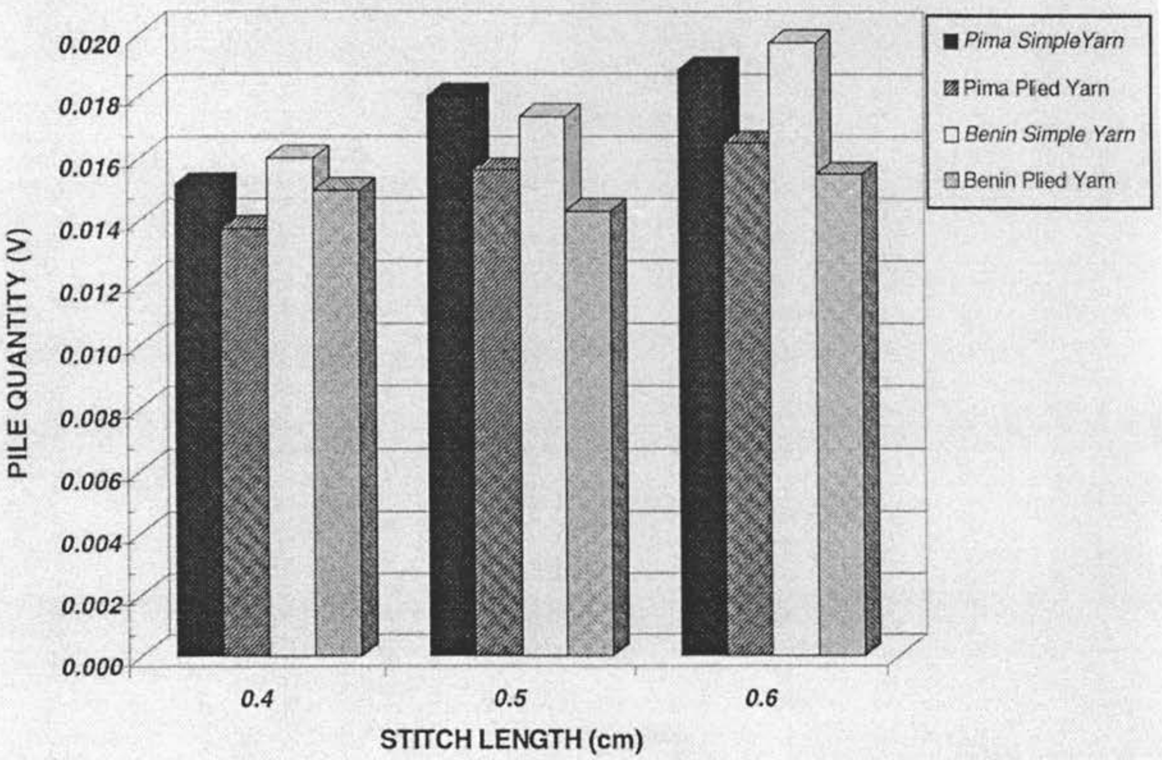
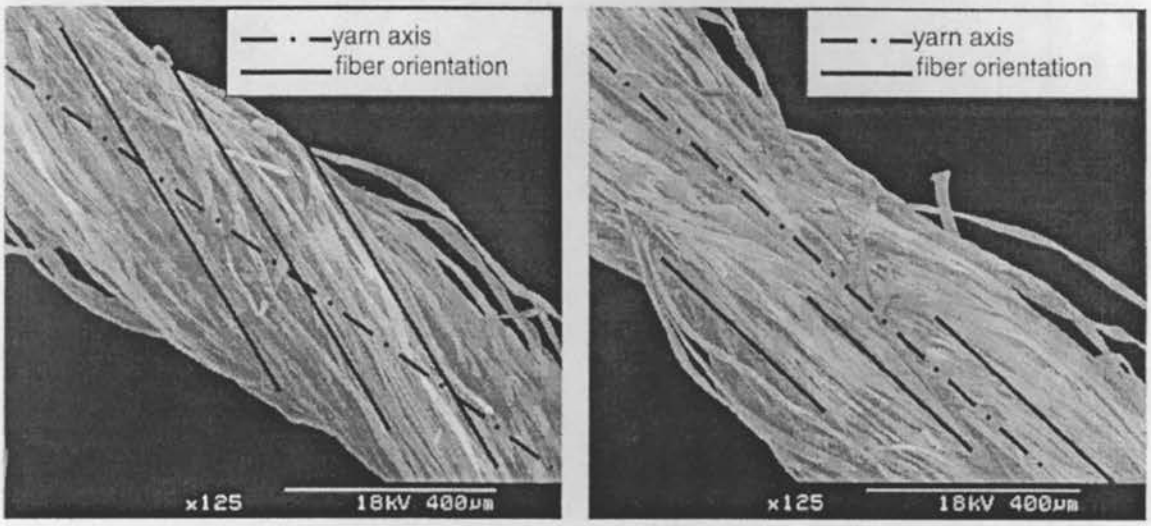


Figure 10 :



a) b)

Table I :

	L (w) [mm]	L (n) [mm]	Fineness [mtex]	IFC [%]	Maturity Ratio
	Pima Cotton				
Mean	29.8	23.9	140	12.2	0.88
Standard deviation	0.5	0.8	3.0	1.3	0.02
% CV	1.7	3.2	2.1	11.0	1.7
	Cotton from Benin				
Mean	25.9	20.9	166	8.9	0.91
Standard deviation	0.4	0.4	2.0	1.1	0.01
% CV	1.5	1.8	1.2	12.0	0.9

Table II :

		Stitch length (cm)	0.4	0.5	0.6
		Cover factor	15	12	10
AIR PERMEABILITY* **L/m²/s**	**Pima cotton**	**Single yarn**	682	1326	2802
		Plied yarn	994	1713	3123
	Benin's cotton	**Single yarn**	775	1425	3623
		Plied yarn	808	1639	3786