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Comparative Analysis of the Thermal Insulation Properties of Fabrics Made of Natural and Man-Made Cellulose Fibres

Abstract

Yarn made of natural and man-made cellulose fibres is nowadays commonly applied in textiles. It is already apparent that the type of raw material and fabric structure influences the properties of the finished goods. The main aim of this paper was to present a comparative analysis of thermal insulation properties (such as thermal conductivity, absorption and thermal resistance) of fabrics made of cotton and Tencel. 6 samples of cotton fabrics and 9 samples of fabrics from Tencel yarns were produced for the purpose of these tests. All fabrics had warp and weft yarns of nominal linear density of 20 tex. Three kinds of weaves were applied: plain, combined and twill with nominal warp and weft densities of 320/dm. The measurements were carried out on finished fabrics with the use of the ALAMBETA device. The results are presented graphically and discussed. The finished fabrics made of Tencel yarn showed lower values of thermal conductivity and thermal absorption than fabrics made of cotton yarns, and higher values of thermal diffusion and resistance. The influence of the type of weave on thermal properties was observed for all fabrics made of cotton and Tencel.

Key words: *thermal insulation, thermal conductivity, thermal absorption, thermal diffusion, thermal resistance, cellulose fabrics, cotton fabrics, fabric structure.*

Introduction

Thermal properties are among the most important features of textiles [1-3]. For instance, thermal insulation determines the elementary function of garments. Most of the studies hitherto carried out are devoted to measurements of static thermal properties such as thermal conductivity, thermal resistance, and thermal diffusion. Thermal insulation is a very important factor for estimating apparel comfort for the user. Thermal insulation properties are determined not only by the physical parameters of fabrics but also by structural parameters such as weave and drape.

Kawabata & Yoneda [4] pointed out the importance of the so-called 'warm-cool feeling''. This property tells us whether a user feels 'warm'' or 'cool'' at the first brief contact of the fabric with human skin. Hes [5,6] introduced the term of 'thermal absorption'' as a measure of the 'warm-cool feeling'' of textiles. Thermal absorption determines the contact temperature of two bodies. Its advantage consists in the peculiarity that thermal absorption does not depend on the conditions of the experiment, and is directly related to other thermal properties such as thermal conductivity and diffusion.

Nowadays, yarn made of cellulose fibres (natural and man-made) is commonly applied in textiles. It is apparent that the kind of raw material and the fabric structure will influence the properties of final goods.

The main aim of this paper is to present a comparative analysis of thermal

Table 1. *Physical and mechanical properties of cotton and Tencel yarns.*

Parameter	Unit	Tencel 100%, 20 tex	Cotton 100%, 20 tex
Breaking force	cN	514.0	248.4
Strain	%	8.7	6.9
Tenacity	cN/tex	26.2	12.5
Variation coefficient of tenacity	%	10.6	6.4
Variation coefficient of strain	%	8.4	7.2
Number of twist	1/m	771.0	803.0
Variation coefficient of twist	%	4.5	5.3
Metric twist coefficient		107.0	113.3
Linear density	tex	19.6	19.9
Variation coefficient of linear density	%	1.1	0.9
CV% Uster	%	15.2	15.6
Thin places	unit/1000m	12.0	18.4
Thick places/1000m	unit/1000m	72.0	24.0
Neps/1000m	unit/1000m	10.4	28.8

insulation properties such as thermal conductivity, absorption, thermal resistance and others for fabrics made of cotton and Tencel yarns, and also to study the influence of the type of weave and finishing on thermal properties.

Experimental Materials and Procedure

An assessment of thermal insulation was carried out for fabrics made of 100% cotton and 100% Tencel yarns with a nominal linear density of 20 tex. The physical and mechanical properties of Tencel and cotton yarns are presented in Table 1. All properties were determined according to Polish Standards. The fabrics examined were manufactured with three kinds of weaves: plain, canvas and twill, all with weft and warp nominal density of 32/cm (Figure 1).

The fabrics made of 100% Tencel yarn were processed according to three different kinds of finishing:

- Enzymatic desizing and removal of warp size before weaving; this was done by enzymatic treatment, by means of a-amylase and then intensive desizing in a solution of nonionic emulsion and desizing medium.
- Enzymatic treatment; this was carried out by a periodic method using enzymes of the cellulase type, which acted on the fibril ends and caused their shortening to obtain a slight pick-out surface. The effect depends on the mechanical activity of the enzyme used, as well as on the applied raw material components. 2% diazym 100 (Diamall) and acetate acid of pH=4.5-5.5 were applied for the enzymatic finishing process. The temperature of the process was in the range of 45-55°C and the reaction time was set to 60 minutes. Soft handle and in some cases the 'peach skin' effect can be obtained by using such enzymatic treatment.
- Resin treatment by the PAD-DRY-FIX method; 20% magnesium chloride and acetate acid of pH 4-4.5 were applied for this finishing process. The drying temperature was in the range of 110-150°C. Soft handle and fabric crease resistance was improved using this resin treatment.

Fabrics made of 100% cotton yarn were processed according to two kinds of finishing:

- Starch finishing, using natural starch at a drying temperature of 140°C.
- Ennoblement elastomeric finishing, which caused an improvement in fabric crease resistance; STABITEX GFA (resin), magnesium chloride and Heliofor PBO were used at a temperature of 150-160°C.

The physical and mechanical properties of all the types of finished fabrics made of Tencel and cotton yarns were assessed according to Polish Standards, and the results are shown in Tables 2 and 3. The fabric properties presented are the mean values of 20 measurements.

The measurements of thermal insulation parameters were performed on

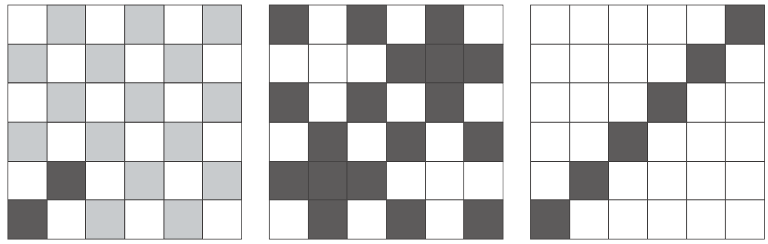

Figure 1. *Fabric weaves.*

Table 2. *Physical and mechanical properties of finished fabrics made of Tencel yarn (P - plain, C - canvas, T - twill).*

Parameters		Unit	Desizing			Enzymatic finishing			Resin finishing		
			P	C	T	P	C	T	P	C	T
Weight per square metre		g	151.6	155.6	138.9	147.8	148.1	139.1	154	152.5	142.9
Number of threads per 1 dm	warp	dm^{-1}	347.0	350.0	340.0	340.0	339.0	334.0	342.0	337.0	328.0
	weft	dm^{-1}	333.0	339.0	333.0	333.0	341.0	328.0	335.0	339.0	325.0
Breaking force in dry conditions	warp	daN	64.8	73.6	73.1	62.3	62.8	68.4	53.2	60.0	62.2
	weft	daN	45.5	64.8	67.2	44.8	59.9	61.7	37.4	53.8	58.6
Strain at break in dry conditions	warp	%	22.2	18.4	13.0	22.8	17.8	12.5	19.6	16.1	11.2
	weft	%	19.5	18.8	17.2	18.0	19.5	15.4	15.0	17.5	14.2
Thickness measured by thickness meter		mm	0.6	0.7	0.6	0.5	0.7	0.7	0.6	0.7	0.7
Shrinkage	warp	%	-4.4	-4.9	-2.7	-2.9	-4.1	-1.3	-4.3	-2.0	-2.0
	weft	%	-2.0	-2.0	-1.0	-1.0	0.6	0.5	-1.1	-1.0	-2.4
Crease resistance	warp	%	62.2	71.4	72.8	65.7	66.4	69.8	64.8	71.8	68.3
	weft	%	47.8	54.2	56.3	50.1	53.9	63.2	52.6	58.2	62.6
Air permeability		$dm^3m^{-2}s^{-1}$	308.1	937.1	1106.0	326.8	753.9	770.0	325.6	716.1	826.6

Table 3. *Physical and mechanical properties of finished fabrics made of cotton yarn (P - plain, C - canvas, T - twill).*

Parameter		Unit	Starch finishing			Elastomeric finishing		
			P	C	T	P	C	T
Weight per square metre		g	137.6	135.4	136.1	136.4	134.7	136.7
Number of threads per 1dm	warp		344.0	342.0	345.0	343.0	347.0	345.0
	weft		326.0	331.0	332.0	305.0	307.0	314.0
Breaking force in dry conditions	warp	daN	35.7	45.0	41.5	35.1	38.8	31.8
	weft	daN	33.3	43.8	37.8	33.6	31.8	24.3
Strain at break in dry conditions	warp	%	9.0	8.3	5.4	8.7	6.7	5.2
	weft	%	14.5	16.6	15.3	13.4	11.0	9.5
Thickness measured by thickness meter		mm	0.3	0.3	0.3	0.3	0.4	0.4
Shrinkage	warp	%	-3.7	-4.3	-4.2	-5.1	-4.2	-3.3
	weft	%	-3.4	-4.4	-4.5	-3.4	-4.3	-4.6
Crease resistance	warp	%	47.4	48.5	44.9	63.2	62.7	68.6
	weft	%	48.7	40.1	47.8	60.4	61.9	60.2
Air permeability		$dm^3m^{-2}s^{-1}$	104.5	462.1	262.2	198.6	496.4	340.5

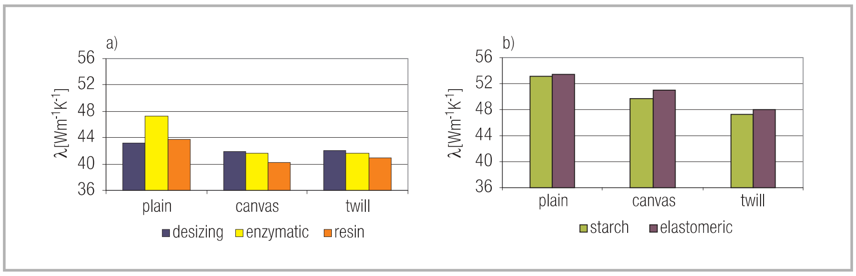

Figure 2. Thermal conductivity λ: a - Tencel, b - cotton.

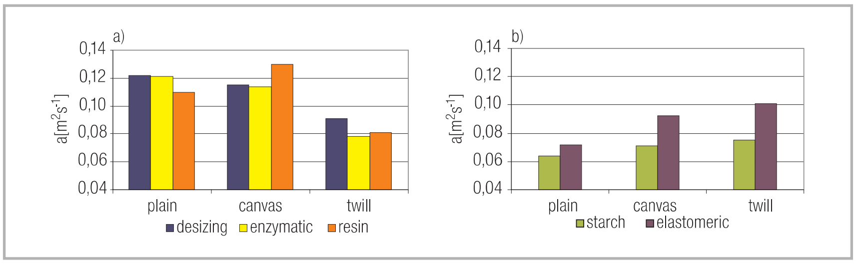

Figure 3. Thermal diffusion a: a - Tencel, b - cotton.

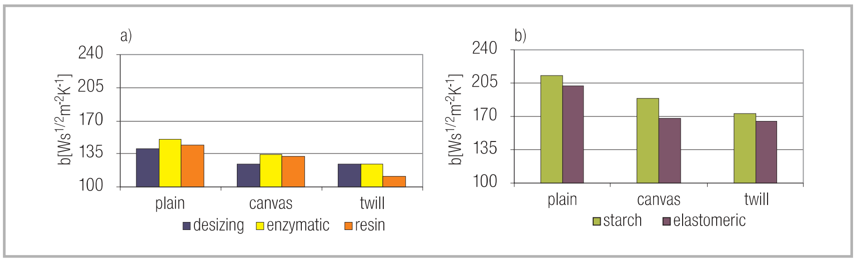

Figure 4. Thermal absorption b: a - Tencel, b - cotton.

finished fabrics with the use of the ALAMBETA device constructed by Hes (Czech Republic) [7]. Six parameters were determined: thermal conductivity λ, thermal diffusion a, thermal absorption b, thermal resistance r, the ratio of maximal to stationary heat flow density υ, and stationary heat flow density q_s at the contact point.

Five measurements for left and five for right sides for each fabric were made. The assessment of thermal properties was carried out based on the values of parameters calculated as the arithmetic mean of results obtained for both sample sides, which did not differ significantly. Unfortunately, the producer of the ALAMBETA device did not inform us exactly about the measurement accuracy of the particular properties measured. This device is probably in a state of ongoing development, and so the measurement results presented in the next chapter should be considered as rough estimates. However, when carrying out repeated tests with the same fabrics we obtained similar results to those presented in this paper.

While assessing the utility properties, we assumed that the fabrics produced (thin cotton and Tencel) are designed for summer clothing, and should ensure good heat transfer from the body to the environment.

Results

Thermal conductivity

The measurement result of thermal conductivity is based on equation (1):

$$\lambda = \frac{Q}{F\tau \frac{\Delta T}{\sigma}}, \quad Wm^{-1}K^{-1} \qquad (1)$$

where:

Q - amount of conducted heat,

F - area through which the heat is conducted,

τ - time of heat conducting,

ΔT - drop of temperature,

σ - fabric thickness.

Comparing the values of thermal conductivity in relation to the raw material used, we can state that fabrics made of cotton yarn have higher thermal conductivity than those made of Tencel yarn (Figure 2a,b).

If we consider this parameter according to the kind of weave, we can see that plain fabrics made of both cotton and Tencel yarns have the highest values.

When testing the influence of finishing on both cotton and Tencel fabrics, it can be noted that the influence of finishing is noticeable. We cannot make a comparison of the types of finishing between cotton and Tencel fabrics, because suitable finishing was used for the raw materials applied. In the case of canvas and twill weaves of Tencel fabrics, the fabrics with desizing finishing have in general the highest value of thermal conductivity, and those with resin finishing the lowest; however in the case of plain weave, the fabric after enzymatic treatment has the highest value.

Considering cotton fabrics, the difference between starch and elastomeric finishing is also apparent. In all cases, the fabrics with elastomeric finishing are characterised by a higher value of thermal conductivity than the fabrics with starch finishing. The results obtained show that all kinds of finishing and both kinds of raw materials influence thermal conductivity. Fabrics made of cotton have better thermal conductivity than fabrics made of Tencel.

Thermal diffusion

Thermal diffusion is defined by the relationship:

$$a = \frac{\lambda}{\rho c}, \quad m^2 s^{-1} \qquad (2)$$

where:

ρ - fabric density,

c - specific heat of fabric,

λ - heat conductivity.

Thermal diffusion is an ability related to the heat flow through the fabric structure. In the case of thermal diffusion, we observe the opposite situation to that noted previously. All types of weave fabrics made of Tencel have higher thermal diffusion than cotton fabrics (Figure 3a). Analysing the influence of the kind of finishing, it can be seen that cotton fabrics after elastomeric finishing are characterised by higher values of thermal diffusion than are fabrics after starch finishing (Figure 3b).

For Tencel fabrics, we can see no clear influence of finishing on thermal diffusion. While observing the influence of the kind of weave, we noted that Tencel plain fabrics have the highest value of thermal diffusion for desizing and enzymatic treatment (the canvas fabrics have the higher value for resin

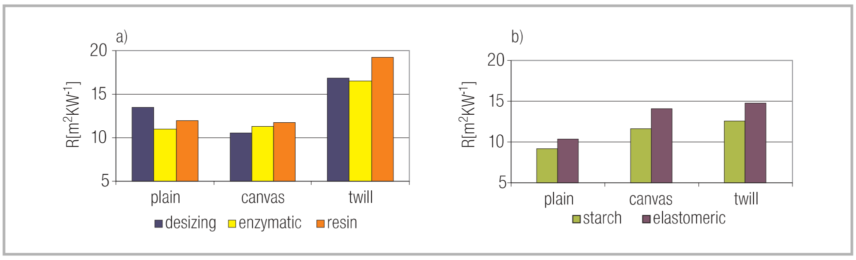

Figure 5. *Thermal resistance R: a - Tencel, b - cotton.*

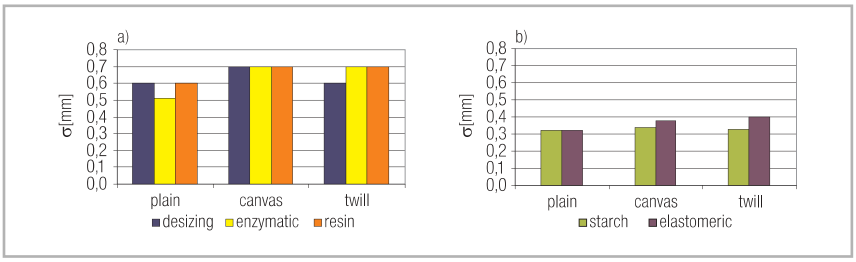

Figure 6. *Thickness σ : a - Tencel, b - cotton.*

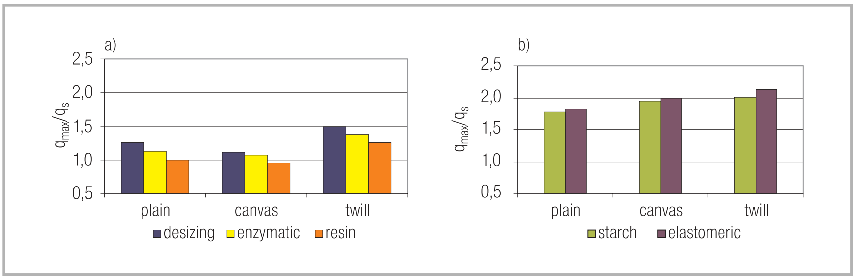

Figure 7. *Ratio of maximum and stationary heat flow q_{max}/q_s: a - Tencel, b - cotton.*

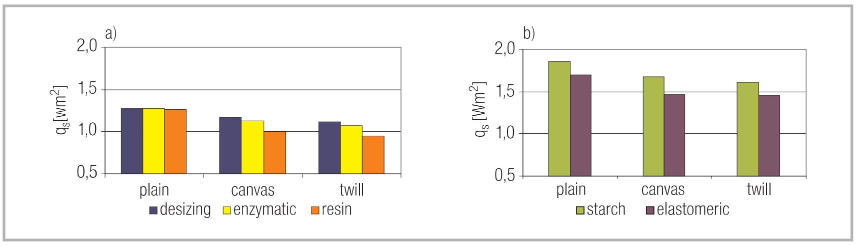

Figure 8. *Stationary heat flow density q_s: a - Tencel, b - cotton.*

processing), and the twill Tencel fabrics are characterised by the lowest value of this parameter. The opposite situation is noted for fabrics made of cotton yarns.

Thermal absorption

Thermal absorption can be expressed as:

$$b = \sqrt{\lambda \cdot \rho c}, \quad Ws^{1/2}m^{-2}K^{-1} \qquad (3)$$

where:
λ - thermal conductivity,
ρ - fabric density,
c - the specific heat of the fabric.

Thermal absorption is a surface property, and therefore the finishing processes can change it. This parameter allows assessment of the fabric's character in the aspect of its 'cool-warm" feeling. Fabrics with a low value of thermal absorption give us a "warm" feeling.

Tencel fabrics have a much lower value of thermal absorption, so they give us warmer feelings than fabrics made of cotton yarns (Figure 4a), which is not ideal for summer clothes. Fabrics after elastomeric finishing are characterised by lower thermal absorption than those after starch finishing, but the difference is not essential (Figure 4b). A clear dependence was observed between thermal absorption and the type of finishing for Tencel fabrics.

A small dependence was noted for the type of weaves for Tencel fabrics and a more prominent one for cotton fabrics. In both cases, plain fabrics have the highest absorption, and twill fabrics the lowest.

Summing up the above results, we have to say that fabrics with a regular, flat, smooth surface give a cooler feeling in comparison with fabrics of lower regularity and smoothness, and higher surface roughness.

Thermal resistance

Thermal resistance is connected with fabric thickness by the relationship (4):

$$R = \frac{\sigma}{\lambda}, \quad m^2KW^{-1} \qquad (4)$$

where:
σ - fabric thickness,
λ - thermal conductivity.

We stated that fabrics with twill weave for both kinds of yarn have the highest value of thermal resistance, whereas plain fabrics have in general the lowest value of this parameter (Figure 5).

Cotton fabrics after elastomeric finishing have higher thermal resistance than fabrics after starch finishing. In the case of Tencel fabrics, twill fabrics after all kinds of finishing have the highest thermal resistance. Fabrics made of Tencel with plain and canvas weaves have a value of thermal resistance at more or less the same level, apart from the fabric with plain weave after desizing finishing, in which this parameter is higher than after enzymatic and resin treatment.

Thermal resistance is a very important parameter from the point of view of thermal insulation, and is proportional to the fabric structure. Due to increase in thickness, we can observe the increase of thermal insulation, and in the same way the decrease of heat losses for the space insulated by the textile. Fabrics with twill and canvas weaves are characterised by a slightly greater thickness than plain fabrics, which results from the fabric structure. The influence of the type of finishing was also noted.

For Tencel fabrics the influence was not regular, whereas for cotton fabrics a higher value after elastomeric finishing could be observed. Considering the fabric structure, it is apparent that plain fabrics have the smallest thickness.

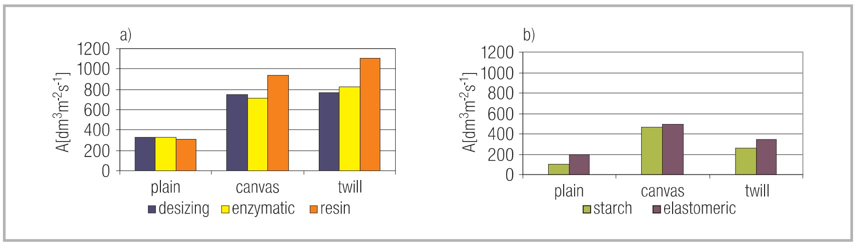

***Figure 9.** Air permeability A: a - Tencel, b - cotton.*

Ratio of maximum and stationary heat flow density

The maximum heat flow density (i.e., q_{max}) from the skin to the fabric appears at the moment of contact of the cold fabric with human skin. With time the heat flow stabilised itself at a determined level q_s, which is called the stationary heat flow density. The maximum heat flow is one of the parameters which characterise fabric thermal insulation, and similar to thermal absorption, is a surface property [5].

The ratio of maximum to stationary heat flow density for cotton fabrics is higher than for Tencel fabrics (Figure 7). Concerning the influence of finishing, we noted only a small influence of this factor on the ratio. Cotton fabrics after elastomeric finishing are characterised by a higher ratio value than fabrics after starch finishing. In the case of fabrics made of Tencel yarn, fabrics after desizing have the highest ratio value, and fabrics after resin finishing the lowest.

Stationary heat flow

The stationary heat flow density q_s is defined by the equation:

$$q_s = \frac{Q}{F \cdot \tau}, \quad Wm^{-2} \tag{5}$$

where:
Q - the amount of heat,
F - the area through which the heat is conducted,
τ - time of flow.

It was stated that cotton fabrics have a higher value of stationary heat flow density than fabrics made of Tencel (Figure 8). We have also observed the influence of the type of finishing. Cotton fabrics after starch finishing are characterised by a higher value of this parameter than after elastomeric finishing.

Fabrics of plain weave have the highest values of this heat flow density for Tencel fabrics, and those of twill the lowest -. The highest stationary density of heat flow characterises the plain Tencel fabrics, whereas twill fabrics have the lowest value. In the case of Tencel fabrics, a small influence of the kind of finishing is also apparent. Fabrics after desizing have the highest values, and those after resin finishing the lowest.

Air Permeability

Air permeability is a hygienic property of textiles which influences the flow of gas from the human body to the environment and the flow of fresh air to the body. Air permeability depends on fabric porosity, which means the number of canals in the textile fabric, its cross-section and shape. Thermal properties are essentially influenced by air permeability.

Air permeability is defined by the equation:

$$A = \frac{V}{F\tau(\Delta p)}, \quad dm^3 m^{-2} s^{-1}$$

where:
V - capacity of the flowing medium,
F - the area through which the medium is flowing,
τ - time of flow,
Δp - drop in pressure of the medium.

Air permeability was determined according to Polish Standard PN-EN-ISO 9297:1998. The measurement results are presented in Tables 2 & 3 and in Figure 9. It was noted that Tencel fabrics after resin treatment have in general the smallest values of air permeability, whereas after enzymatic and resin treatment the values of this parameter are more or less at the same level.

Considering the influence of the kind of weave of Tencel fabrics, the highest value was observed for fabrics with twill weave, and the lowest - for those with plain weave. Fabrics made of 100% cotton yarn of canvas weave have the highest value of air permeability, and fabrics of plain weaves - have the lowest value. Elastomeric treatment allows for higher values of this parameter than do fabrics with starch finishing.

Fabrics made of Tencel yarn have a higher value of air permeability than fabrics made of cotton yarn, so from this point of view they are more suitable for summer clothing.

Summary

On the basis of the results obtained, we can state that there are many possibilities for creating fabric properties which influence their comfort of use. The thin cotton and Tencel fabrics used for summer clothing which were the objects of research should ensure appropriate heat transfer between the human body and the environment. This can be achieved not only by the choice of thickness or the fabric cover factor, but also by applying appropriate weaves and appropriate finishing processes. Moreover, it was noted that the type of raw materials influences some fabric properties characterising their thermal and utility comfort. From the results obtained, we can state that fabrics made of cotton yarn have better thermal properties than those made of Tencel yarns when they are applied for summer clothing (from the point of view of thermal conductivity). But from the point of view of the 'warm-cool'' feeling and air permeability, Tencel fabrics are superior. Therefore, the choice of raw material depends on the subjective point of view of which property is more important for the user.

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References

1. Mecheels J., Körper-Klima-Kleideng, Melliand Textilberichte Part I, No 9, s 773 (1997).
2. Le C.V., Ly N.G., Heat and Moisture Transfer in Textile Assemblies, Text. Res. J. Part I, vol. 65, No 4, s 203, (1995).
3. Kawabata S., A Guide Line for Manufacturing Ideal Fabrics, International Journal of Clothing Science and Technology, Vol. 12, No 3, pp 134-140 (2000).
4. M. Yoneda, S. Kawabata, A Theoretical Consideration on the Objective Measurement of Fabric Warm/Cool Feeling, Objective Specification of Fabric Quality, Mechanical Properties and Performance, edited by S. Kawabata et al, the Textile Machinery Society in Japan 1982.
5. Hes l., Thermal properties of nonwovens. In: Congress Index 87, Geneva 1987.
6. Hes L., New achievements in the area of the objective evaluation of thermal insulation and thermal-contact properties of textiles, The 3rd Asian Textile Conference, Vol. II pp. 1201-1203 (1995).
7. Instruction manuals of the Alambeta instrument SENSORA Liberec Registered Company, Czech Republic, 1990.

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