Sinem Gunesoglu, Binnaz Meric, Cem Gunesoglu

The University of Uludag
Department of Textile Engineering
Bursa, Turkey

Thermal Contact Properties of 2-Yarn Fleece Knitted Fabrics

Abstract
When a person touches a garment, heat flow occurs between the human body and the fabric, with the resulting warm-cool feeling as the first sensation. This transient and dynamic thermal-contact feeling should be carefully investigated, since it strongly affects people's first impressions and subsequent choices when buying garments. It is possible to find papers on the thermal contact properties of various fabrics, from woven shirt fabrics to underwear types; in this paper, the warm-cool feeling of 2-yarn fleece knitted fabrics, which are widely used for outdoor garments, have been investigated, and to the best of our knowledge this has not been studied before. Four different fleecy fabrics were selected with varying ground and loop yarn combination, which is 100% cotton or PET/cotton blend in accordance with the most common, commercially available fleece-knitted fabric types. The fabrics are rinsed and subjected to raising treatment to produce typical fleecy fabric, and the influence of yarn type and raising treatment on warm-cool feeling is objectively determined by measurements performed by an instrument developed at the end of the 1990s. The measurements are taken in the dry and wet state of the fabrics. It is found that raising treatment is the primary factor determining the thermal contact feeling of fleecy fabrics; the yarn type and fibre blend is less important.

Key words: *fleece knitted fabric, raising, thermal absorptiveness, moisture absorptiveness.*

Introduction

Fabric thermal properties have been of great interest and importance for textile researchers, since they are among the major characteristics that determine wearing comfort. It is thus possible to find papers in the literature focused on the thermal comfort properties of textile fabrics and clothing. [9-12].

Traditionally, most measurements of fabric thermal properties were conducted in a state of equilibrium, analysing such easily measured properties as thermal conductivity, resistance and permeability. However, these steady-state methods cannot explain the heat-related subjective sensations that determine human comfort, because this approach does not reflect the real wearing situation, since the human body interacts dynamically with clothing. There are also dynamic- or transient-state thermal contact properties besides the steady-state thermal properties [14]. Thermal contact properties determine the feeling when the human skin touches an object for a brief period of time. The sudden mechanical contact of textile fabric with human skin causes a feeling of warmth or coolness due to the heat flow from the human body to the fabric that is at a lower temperature than the skin surface [5-7]. Pac expressed in his paper that at a given temperature gradient, the heat flow increases with the thermal conductivity of the material. The more a material absorbs thermal energy, the more it acts as a thermal conductor, and the cooler it seems at the very first moment of contact with a warmer body [11]. Which feeling is better depends on the customer: for hot summer garments a cooler (e.g. cotton) feeling is demanded, whereas in the north of Europe warmer clothing, based on PET or wool for example, is preferred.

This property, which is known as the 'warm-cool feeling', is included in the overall assessment of the handle of the textile materials with their low-stress mechanical properties, thus it contributes to the fabric handle. Hes states that the warm-cool feeling is involved in the fabric handle generally perceived by the hands, and this feeling strongly affects the choice of people when buying clothes or garments [8].

The aim of this study is to evaluate the warm-cool feeling of fleecy knitted fabrics, which are widely used as an outdoor garment for sports and active wear. The extent of the effects of the composition of two-yarn/fleecy knitted fabrics, as well as the role of the fabric type and raising treatment on this feeling, were examined in the study. The experimental device used is described and the contribution of each factor, covering fabric type with four treatment levels and raising treatment with two treatment levels, were assessed using a completely randomised two-way analysis of variance (ANOVA) for both the dry and wet state. The results were evaluated at 5% significance level.

Experimental

The single-sided fleecy fabrics, knitted in four different compositions on a 32'

Table 1. Constructional properties of the fleecy fabrics tested.

Fabric code	Yarn type and count	Area mass of fabric, g/m^2	Wales/ cm	Courses/ cm	Thickness, mm
CC	100% cotton 300 dtex (ground) 100% cotton 600 dtex (loop)	302.7	10	16	1.19
CCR		273.8			1.67
CP	87% PET/13% cotton 300 dtex (ground) 100% cotton 600 dtex (loop)	340.0	10	16	1.27
CPR		328.6			1.84
PP	87% PET/13% cotton 300 dtex (ground) 87% PET/13% cotton 600 dtex (loop)	313.0	10	16	1.10
PPR		295.5			1.36
PC	100% cotton 300 dtex (ground) 87% PET/13% cotton 600 dtex (loop)	321.8	10	16	1.22
PCR		320.0			1.78

E 22 circular knitting machine, were employed in this study. Each fabric type was knitted with the same course and wale count, and they were separated in accordance with the yarn type in both; ground and loop, marked as C or P, where C represents 100% cotton and P represents 87/13 PET/cotton blend open-end yarn. The first letter in the fabric codes stands for the back of the fabric, which touches the skin, and the second letter for the face. All the fabrics were rinsed, and then half of each one was subjected to raising in order to produce the common fleecy knitted fabric. R in fabric codes represents raised fabric from the backside. For example, CPR is the raised fleecy fabric with 100% cotton back, 87/13 PET/cotton blend face. Classification details are given in Table 1.

Apparatus

Kawabata and Yoneda were the first researchers to express the warm-cool feeling numerically; in 1983 they developed the Thermo-Labo, which was the first instrument able to evaluate thermal contact property objectively. They introduced the maximum level of the contact heat flow q_{max} (W/m^{2}K) as a measure of these transient thermal characteristics, and Kawabata has published the first objectively determined values describing the thermal-contact properties of textile fabrics. Their instrument was then commercialised and used in laboratories. The Thermo-Labo was processed by a differential circuit of temperature signals to approximate heat flow and a first-order integral circuit with a 0.2 second time constant to introduce a time lag [8,14,15].

Starting from the ideas of Kawabata, and from the model considering the ideal contact between two homogeneous semi-infinite solids, Hes introduced another parameter called thermal absorptiveness b (Ws$^{1/2}$/Km^2) to evaluate the warm-cool feeling. It was found that this parameter characterises perfection by the transient thermal feeling which one gets at the moment when one puts on an undergarment, a shirt or other textile product [6].

Thermal absorptiveness b (Ws$^{1/2}$/Km^2) is the heat flow q (W/m^2) which passes between the human skin and the contacting textile fabric. The human skin is considered of infinite thermal capacity and temperature t_1, and the contacting textile fabric is idealised as a semi-finite body of finite thermal capacity ρc (J/m^3) and temperature t_2 when the timeτ of thermal contact between human skin and a fabric is short. The transient temperature field between human skin and a fabric is given by the following partial differential equation, obtained by Fick's Second Law, to show that the relation between the temperature gradient depends on time ($\partial t / \partial \tau$) and on distance ($\partial^2 t$ / ∂x^2) [1,2]:

$$(\partial t / \partial \tau) = a\,(\partial^2 t / \partial x^2) \qquad (1)$$

where a (m^2/sec) is the so-called thermal diffusivity, and the equation can be used for calculating the initial level of transient heat flow q between human skin and a fabric. This is then given by the following relation:

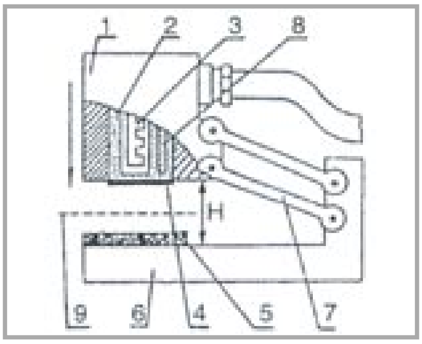

Figure 1. Functional scheme of the Alambeta instrument [3]: 1- measuring head, 2- copper block, 3 - electric heater, 4 - heat flow sensor, 5- measured sample, 6 - instrument base, 7 - head lifting mechanism, 8 - resistance thermometer, 9 - wetted textile interface simulating sweat discharge.

$$q = b(t_1 - t_2)/(\pi\tau)^{1/2} \qquad (2)$$

Thus the following relation gives derived thermal absorptiveness b:

$$b = (\lambda\rho c)^{1/2} \qquad (3)$$

where λ (W/mK) is thermal conductivity.

Hes developed an instrument in the Czech Republic named Alambeta to measure thermal absorptiveness. A simplified sketch of the Alambeta is shown in Figure 1. The measuring head 1 contains a copper block 2, which is heated to 32°C, simulating human skin temperature by means of an electrical heater 3. The temperature is controlled by a thermometer 8 connected to the regulator. The lower part of the heated block is equipped with a direct heat flow sensor 4. The sensor measures the thermal drop between the surfaces of a very thin non-metallic plate using a multiple differential micro-thermocouple. This sensor is 0.2 mm thick, and on contact with a subject of a different temperature, reaches the maximum heat flow qmax in 0.2 seconds. Thus, it simulates the human skin, which is approximately 0.5 mm thick and whose neutron ends, located in the middle, also take 0.1-0.3 second to reach qmax as the heat begins to flow through the contact subject. Before the measurement, the head is kept at a height H above the base plate 6 covered by the sample 5. The mechanism 7 ensures the correct movement of the measuring head. The pressure of the head onto the fabric can be adjusted within the range of 100 to 1000 Pa and substantially affects the results. It has been determined that the level of thermal absorptiveness depends on the contact pressure alone, which also corresponds to the real situation. The test starts by placing the head on the sample. The heat starts to flow through the sample; then the surface temperature of the sample suddenly changes, and the instrument's computer registers the heat flow course. This procedure is similar to putting a finger on a fabric to be selected. Simultaneously the sample thickness is measured [1,3].

An important aspect of evaluating the warm-cool feeling is the change of this feeling when textile products get wet. Since the thermal conductivity and thermal capacity of water is much higher than fibre polymers and the air is entrapped in the textile structure, fabrics moistened by sweat give a greatly changed warm-cool feeling when compared with the dry state. The resulting thermal contact is generally known as discomfort. For the objective evaluation of the warm-cool feeling, and to characterise the contact comfort felt by the wearer of a fabric that touches wetted skin, the experimental procedure described above could also be used. In this case, a special very thin interface fabric is prepared which should simulate the effect of a sudden sweat discharge on the skin. The sweat simulator should be as thin as possible in order not to influence the thermal capacity of the measured fabric in a dry state, but the interface fabric should absorb a certain amount of liquid injected, and it should distribute the liquid rapidly and uniformly. When the liquid distribution is stopped, the interface fabric is turned wet side down and inserted into the space between the tested fabric and the centre of the measuring head of the instrument. At the same time, the interface fabric and the measuring head of the instrument are dropped down towards the fabric being measured. Within a few seconds, the liquid from the interface fabric is more or less taken away by absorption into the measured fabric. When considering a simple parallel combination of thermal conductivity λ and λ_l of fabric and liquid respectively, and the same approach for their thermal capacities, the resulting thermal absorptiveness can be used to evaluate moisture absorptiveness. In the case of low absorption into the tested fabric, the thermal capacity of the interface fabric is kept rather high due to the higher relative moisture, and the resulting thermal absorptiveness b is significantly higher. The situation described above indicates that there is poor moisture absorptiveness of the tested fabric. When the liquid is rapidly distributed through the whole thickness of the tested fabric, the interface fabric becomes almost completely dry and the instrument shows a lower level of the thermal absorptiveness; this indicates good moisture absorptiveness, which is a required property for the sensation of comfort in a fabric in a wet state [3,4].

The validity of thermal absorptiveness as a new parameter expressing the warm-cool feeling of fabrics was confirmed by several tests, as stated in Hes's paper [4]. Hes compared the results of subjective feeling of nearly 100 persons with the values of thermal absorptiveness found by the means of the Alambeta of nine woven samples of similar structure (plain weave), thickness (from 0.22 to 0.33 mm) and fabric mass (from 0.120 to 0.165 kg/m^2), but made of nine different fibres and polymers. The results were treated statistically and evaluated by means of the Spearman's Rank Correlation Coefficient. He found that the level of this coefficient exceeded 0.9 when comparing the subjective warm-cool feeling and objective thermal absorptiveness.

The measurements of the thermal contact properties of the fabrics given above with the Alambeta in the dry and wet state have been undertaken in this study. For wet state measurements, we used an Coolmax fabric interface to fulfil all the requirements and injected 0.5 ml of water (containing detergent) into its surface. When the liquid had been uniformly distributed within a circle of 45-50 mm and stopped within one minute, we placed it in the instrument.

All the measurements were completed in an uncontrolled laboratory environment of about 24°C and 55% R.H. The measuring head temperature of the Alambeta is approximately 32°C, and the contact pressure is 200 Pa in all cases, as in the cited papers [3-6], to simulate the pressure of a finger on a fabric.

Results and Discussion

Thermal absorptiveness

Within various research projects, the thermal contact properties of all common textile products were experimentally investigated. It was found that the practical values of the thermal absorptiveness of dry fabrics range from 20-300 ($Ws^{1/2}/Km^2$) in a dry state, where the lowest (warmest) values are exhibited by nonwoven interlinings made by PET micro fibres. The higher this value, the cooler the feeling represented. Fibres and fibre polymers of higher equilibrium humidity also provide a cooler feeling. Therefore, the warmest feeling can be achieved in fabrics made from PVC, PP and PAN, whereas viscose, flax and cotton fibres show the coolest feeling [5,6].

Figure 2 shows the thermal contact feelings of the fabrics tested. The average results and coefficient variances of four measurements, for each fabric type, are also given in Table 2. The relatively low CV percentage values convinced us that the measurements are statistically regular and reliable.

These results first reveal that the CC fabric gives the maximum level of thermal absorptiveness among the samples, so it should feel cooler when touched. Secondly, the fabrics which have identical ground and loop yarn type in their structure also have higher thermal absorptiveness than the fabrics which are different. Thirdly, the raising process definitely reduces thermal absorptiveness, and the fabrics seem to have similar thermal absorptiveness after raising; all of them should have a warmer feeling as a function of hairy and bulky structure forming that entraps more air and increases the air gap between the skin and the fabric.

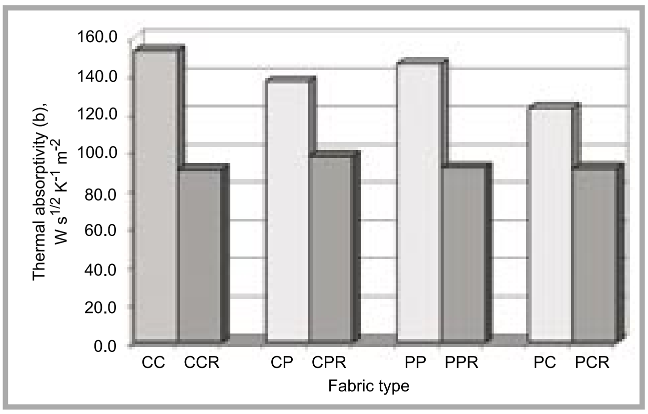

Figure 2. *Thermal absorptiveness of tested fabrics in dry state.*

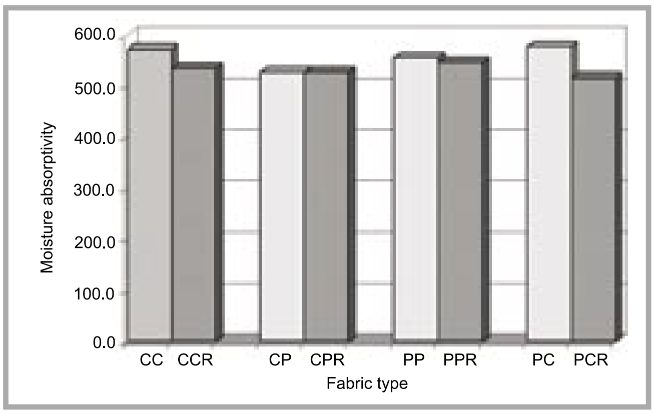

Figure 3. *Thermal absorptiveness of tested fabrics in wet state.*

Fibre type has a great influence on the warm-cool feeling. The CC and PP fabrics, which are similar in construction, weight and thickness (Table 1), differ in thermal absorptiveness, hence we found them statistically different. In the case of the CP and PC fabrics, the ANOVA reveals that the change of yarn type in the fabric side which touches the skin is insignificant on the level of thermal absorptiveness. For cotton, this level is higher, and thus it gives a cooler feeling. This is expected because the warm-cool feeling is mainly due to heat conduction, as pointed out in Pac's study [11]. Thermal conductivity is considered to be dominant in determining the heat transfer through fabrics and garments. Cotton represents higher thermal conductivity due to its higher equilibrium humidity, and this causes a cooler feeling at the first contact of fleece fabrics from cotton side. For the PET/cotton blend thermal conduction, the heat flow and consequently the thermal energy absorption is interrupted because of the existence of PET. However, the effect of fibre type on the warm-cool feeling seems to be almost negligible after raising. The ANOVA demonstrated that the influence of raising treatment is rather stronger, so that the interaction of two factors is still significant for thermal absorptiveness. All the raised fleece fabrics represent a similar level of thermal absorptiveness; they are not statistically different, but it is noted that the PCR fabric shows the lowest thermal absorptiveness among raised fleecy fabrics.

Moisture absorptiveness

Considering the samples of this study, when a cotton fabric comes into contact with wetted skin, it absorbs the liquid sweat rapidly and conducts it away from the fabric surface towards the fabric's interior. Due to high adhesion forces, the sweat is accumulated in the fabric close to the places where the sweat was generated. If the amount of sweat is not too high, within a short time the moisture concentration close to the fabric contact surface reduces, and the wearer feels the pleasant contact of nearly dry fabric. In the case of blended fabrics containing too much poorly absorbing PET fibres, the sweat remains adhered on the skin, and provokes an unpleasant cool feeling due to sweat evaporation. The fabric that exhibits good moisture absorptiveness lets the sweat distribute and reduces the unpleasant cool feeling. The thermal absorptiveness measurements which are performed in the presence of wetted interface fabric in the Alambeta enable the level of the unpleasant contact feeling to be evaluated. The level of thermal absorptiveness calculated in this state designates the level of liquid which is kept in the interface fabric due to the poor moisture absorptiveness of the tested fabric. The higher the level of thermal absorptiveness, the less the fabric shows moisture absorptiveness, and the more unpleasant the feeling.

Figure 3 shows the thermal absorptiveness measurements in the wet state. The average results and coefficient variances of four thermal absorptiveness measurements in the wet state for each fabric type are also given in Table 3. From this data, first of all we see that there is an increase in thermal absorptiveness in all cases. The ANOVA shows that all the constructions of fleece fabrics are at the same level of thermal absorptiveness (at 5% significance level) when they are wetted. Although the CC and CP fabrics which have cotton backsides exhibit a slightly lower thermal absorptiveness indicating better moisture absorptiveness, the fabric type is found to be insignificant. On the other hand, the raised fabrics exhibit too much increase between 440-495% in thermal absorptiveness, and show surprisingly better moisture absorptiveness properties than the fabrics without raising. The lowest thermal absorptiveness in the wet state is exhibited by the PCR fabric among the raised fleecy fabrics.

Considering the real wearing situation, a typical fleecy knitted garment is worn generally in colder climates to feel warmer. It also should give a pleasant feeling when wetted due to sweating after the wearer's strenuous activities. From this point of view, there is no difference between 100% cotton or PET/cotton blend fleecy fabric. The influence of the ground and loop yarn type on the thermal behaviour of a typical fleecy fabric is almost zero.

ANOVA Results

We performed the ANOVA for both the thermal and moisture absorptiveness of the fleece fabrics under discussion, in order to demonstrate the importance of each variable. We determined the contribution of the variables, fabric type and raising process, using all experimental data. We evaluated the results based on the F-ratio and the probability of the F-ratio. The lower the probability of the F-ratio, the stronger the contribution of the variation, and the more significant the variable. The result of variance analysis is given in Tables 4 and 5. Thus, the contribution of raising was highly significant in the thermal contact properties of fleece fabrics, especially in the dry state. To define the exact classification of tested fabrics, we also performed a single-factor, completely randomised ANOVA model, the variable of which is the fabric type; and we also used the Student-New-

Table 2. *Thermal absorptiveness of tested fabrics in dry state.*

Fabric code	b, $Ws^{1/2} K^{-1} m^{-2}$	CV, %
CC	153.00	3.3
CCR	90.70	8.1
CP	119.75	2.8
CPR	97.60	6.5
PP	144.00	3.7
PPR	91.58	15.3
PC	142.50	1.9
PCR	91.23	7.7

Table 3. *Thermal absorptiveness of tested fabrics in wet state.*

Fabric code	$b_{moisture}$, $Ws^{1/2} K^{-1} m^{-2}$	CV, %
CC	572.50	4.4
CCR	535.25	6.4
CP	527.75	5.5
CPR	527.25	4.6
PP	555.75	3.9
PPR	546.50	4.5
PC	577.50	7.9
PCR	516.50	5.7

Table 4. *The ANOVA results of variance analysis for thermal absorptiveness.*

Source		F-ratio	Probability (F-ratio)
Main level	Fabric type	3.95	0.200
	Raising	287.18	0.000
Interaction	Fabric type x raising	9.72	0.002

Table 5. *The ANOVA results of variance analysis for moisture absorptiveness.*

Source		F-ratio	Probability (F-ratio)
Main level	Fabric type	1.14	0.350
	Raising	4.92	0.036
Interaction	Fabric type x raising	2.31	0.102

Table 6. *The ANOVA results for the Student-Newman-Keuls (SNK) ranking at 5% significance level according to the single-factor ANOVA model.*

Fabric code	Thermal absorptiveness	Moisture absorptiveness
CC	a	a
CP	ab	a
PP	b	a
PC	ab	a
CCR	c	a
CPR	c	a
PPR	c	a
PCR	c	a

man-Keuls (SNK) range test to decide which fabric differs significantly from others (Table 6). The treatment levels were marked in accordance with the mean values, and any levels marked by the same letter showed that they were not significantly different. We found that the contribution of fabric type was only important in thermal absorptiveness before raising; the ANOVA revealed that it was insignificant in terms of thermal absorptiveness and moisture absorptiveness after raising.

Conclusion

The thermal contact feelings of fleecy fabrics in four different compositions were investigated in this study. The structural parameters studied in this investigation are the fibre type of ground & loop yarn, and the raising treatment. It is well known that the warm-cool feeling of a fabric depends on the chosen fibres, so here we observed the effect of the fabric construction process. We found that the thermal contact feeling of fleecy fabrics are strongly affected by the raising treatment which is the final process of an usual fleecy fabric. The influence of yarn type after raising seems to be insignificant. The role of fabric thickness is also ignored, since all the raised samples have a similar thickness. The feeling of fleecy fabrics wetted is much cooler; wetted raised fleecy fabrics exhibit a warmer (more pleasant) feeling than fabrics without raising.

Acknowledgement

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