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Textile Research Journal 2006 76: 587
DOI: 10.1177/0040517506067375

Textile Research Journal Article

Fabric Selection for a Liquid Cooling Garment

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Abstract The selection of an inner fabric layer is an important aspect in the development of a liquid cooling garment (LCG). The desired characteristics of an inner fabric layer in LCGs include good thermal conductivity, moisture management, and tactile properties. Good thermal conductivity can improve cooling efficiency, and good moisture management and tactile properties can make the wearer more comfortable. Eighteen fabrics that differed in fiber content, fabric structure and thickness were investigated in this study for their suitability for use as an inner fabric layer for a LCG. Thermal resistance, evaporative resistance, wicking, and water distribution were measured. Correlation among the three moisture management tests was studied. The effects of metal-containment and fabric thickness on thermal and evaporative resistance were determined. The most suitable fabric among the 18 tested fabrics was selected in this study.

Key words liquid cooling garment (LCG), inner fabric layer, thermal resistance, evaporative resistance, moisture management, wicking, water distribution

Cooling vests can play an important role in reducing heat stress of workers wearing various kinds of protective clothing by keeping the workers' body temperature at safe levels. Based on different cooling mechanisms, cooling vests can be divided into passive and active systems [1]. One type of passive cooling vest uses ice or chemical-based frozen gel packs [2]. The focus group research carred out by the authors found that first responders perceive the disadvantages of phase change gel pack devices to be initial overcooling and difficulty inserting the solid gel packs into vest pockets, especially in a short time period as is often required for response calls [3].

The most common active cooling system is a liquid cooling garment (LCG). In a LCG, cool liquid is circuited inside tubes embedded in a garment with the help of a battery-powered pump. Once the liquid is warmed by the body, it is circulated to a heat sink or cooler where it is recooled [1]. The concept of a LCG was first suggested by Billingham in 1958 and the first prototype suit was constructed at the Royal Aircraft Establishment in the United Kingdom in 1962 [4]. The early-stage LCGs were developed for astronauts to alleviate heat stress in hostile aerospace environments, and Nunneley [4] and Shvartz [5] provided detailed reviews for these LCG developments. For aerospace applications, warm water may also be circulated in tubing in specific segments of the garment for astronauts performing extravehicular activities with extreme cold conditions [6, 7]. Young et al. evaluated the effectiveness of cooling different body areas during upper and lower body exercise and found that cooling the arms does not provide any advantage during upper body exercise while cooling the thigh surfaces during lower body exercise does provide an advantage [8]. When warm water was circulated, Koscheyev et al. found that it was possible to transport heat from more distant areas of the body such as the upper torso, arm and head to the fingers through blood flow [6].

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Textile Research Journal Vol 76(7): 587–595 DOI: 10.1177/0040517506067375
Figure 1 appear in color online: http://trj.sagepub.com

Previous LCG researches focused on the effectiveness of cooling different body areas [5, 8], intermittent and regional cooling [9], tubing pattern, liquid flow rate in tubing, liquid inlet temperature [4], efficiency of whole garment [10], and using separate multi-loop control [11]. The fabrics used in the LCG garments have not been investigated. Cotton fabrics are still dominant in LCGs.

Many LCGs are constructed with tubing sewn to one fabric layer such that the tubing rests directly on the skin. However, the authors envisioned a three-layer system with the tubing sandwiched between two fabric layers for wearer comfort. An inner fabric layer with high thermal conductivity can enhance the heat exchange between body and the cool liquid and thus improve the efficiency of the cooling garment. Workers wearing protective clothing in hot environments typically are under heat stress, and therefore produce considerable sweat. The sweat should be transported away from the skin surface in the form of liquid or vapor such that the fabric touching the skin feels dry for wearer comfort. The transport of both moisture vapor and liquid away from the body is called moisture management [12]. Therefore, the inner textile layer that is designed to be worn next to the skin should have the following characteristics: good thermal conductivity, good moisture management, and good tactile properties.

During the past two decades, new fabrics have been engineered to possess enhanced moisture transport properties. Yet, there is no comparison among these materials. To provide better electrical conductivity, some metal-containing fabrics were developed [13] and they may also provide higher thermal conductivity because metals usually have higher thermal conductivity than cellulose or other polymer materials used in fabrics.

Moisture management is a complicated process influenced by a variety of fabric characteristics such as fiber (hydrophilic or hydrophobic), porosity, and thickness. Water transport in fabrics can be in the form of liquid and vapor. For liquid transport within fabrics, textile researchers distinguish two phenomena – wetability and wickability [14]. Wetting is the displacement of a fiber–air interface with a fiber–liquid interface and wicking is the spontaneous flow of a liquid in a porous substrate, driven by capillary forces [15]. Many test methods have been developed to measure liquid water take up and water vapor transport in fabrics [12, 14, 16–19]. These methods measure different aspects of moisture management characteristics of fabrics. However, these tests still do not account for the breadth of possibilities of moisture transportation in fabrics such as liquid water transportation through multi-layered fabrics. This is an important factor in fabric evaluation and selection in LCG development. Some companies developed their own methods to evaluate moisture transport in fabrics of interest. One example is Malden Mills' water distribution test that examines liquid water transport from one side of a fabric to the other side.

Two standards, ISO 11092 [20] and ASTM F1868 [21], were developed to measure the thermal and water vapor resistance of a material under steady state conditions. Thermal resistance, denoted as R_{ct}, is the temperature difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. Evaporative resistance, denoted as R_{et}, is the water vapor pressure difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. These two standard methods are used to measure R_{ct} and R_{et} of textiles using specified equipment and procedures developed in accordance with these two standards.

The purpose of this study was to select a fabric with good thermal conductivity and moisture management properties that is suitable for use as a next-to-the-skin fabric layer for a LCG. Eighteen fabrics that varied by fiber content, fabric structure and thickness were investigated to assess their thermal and moisture management properties. Three moisture tests were used in this study and the correlations between these tests were determined. Analysis of variance (ANOVA) was used to determine the effect of metal-containment in fabrics and fabric thickness on R_{ct} and R_{et}. The fabric with the optimum thermal conductivity and moisture management properties among these 18 fabrics was also determined by ANOVA.

Experimental

Materials

Eighteen fabrics were used in this study and their fiber contents, fabric structures, and thicknesses are listed in Table 1. Fabric thicknesses were measured using a thickness gage in accordance with ASTM D1777-64. For each fabric, ten thickness measurements were made and their mean was calculated and listed in Table 1.

Thermal Resistance and Evaporative Resistance Measurements

Thermal resistances and evaporative resistances were measured using a sweating guarded hot plate (model SGHP-8.2) manufactured by Measurement Technology Northwest in accordance with ASTM F1868-98. Three measurements were made for each fabric.

Wicking Test

A "strip" wicking test described by Harnett and Mehta [16] was conducted in this study. A strip of the test fabric, 2.54 cm × 15.24 cm, with the 15.24 cm side in the lengthwise direction, was suspended vertically with 1 cm of its

Table 1 Fabrics tested in this study.

Fabric no.	Fiber content	Fabric structure	Thickness (mm)
1	80% polyester, 20% spandex	Knit	0.585
2	90% cotton, 10% cotton coated stainless steel	Woven	0.304
3	100% nylon	Woven	0.136
4	100% silver coated nylon	Knit	0.597
5	cotton outside, copper silver inside	Woven	0.255
6	100% cotton	Knit	0.559
7	polyester, copper	Woven	0.126
8	75% metal, 25% nylon	Woven	0.136
9	95% polyester, 5% silver coated nylon	Knit	0.742
10	100% polyester	Knit	0.756
11	100% polyester	Knit	0.907
12	100% silver coated nylon	Nonwoven	0.345
13	95% polyester, 5% silver coated nylon	Knit	0.820
14	23% polyester, 63% nylon, 14% spandex	Knit	0.974
15	97% polyester, 3% silver coated nylon	Knit	0.760
16	96% polyester, 4% spandex	Knit	0.731
17	100% polyester "face", 100% nylon "wrong"	Knit	0.826
18	100% polyester	Knit	1.416

lower end immersed in a beaker of dark green food-dye-colored distilled water. After 5 minutes, the height reached by the water in the fabric above the water level was measured. Three measurements were made for each fabric.

Water Distribution Measurement

Malden Mills' water distribution test, with some modifications, was used in this study. When water was applied to the wrong side (usually the next-to-the-skin side) of a fabric, the ratio of water transport to the right side of the fabric in total water reflected the water distribution value. A wetted fabric sample was sandwiched between two layers of filter paper horizontally, such that the absorbent face on both top and bottom layers of paper were in contact with the fabric sample. The water absorbed by the top and bottom layers was equated to the right and wrong side fabric absorption.

The configuration of wrong-side-up water distribution test is in Figure 1. Two 10.16 cm × 10.16 cm square pieces of filter paper, labeled L and U, were weighted and recorded as $W_{L,dry}$ and $W_{U,dry}$ respectively. Paper L was placed, absorbent side up, on an impermeable plexiglass flat surface. A 7.62 cm × 7.62 cm square fabric sample was centered on paper L with the wrong side of the fabric up. Using a syringe, 1.3 ml of water was delivered uniformly over the surface (wrong side) of the sample and set aside for 2 minutes for stabilization. Filter paper U was placed with absorbent side in contact with the fabric sample (absorbent side down). A plexiglass square was centered on top of the paper–sample–paper stack and a 500 g cylindrical metal weight was placed in the middle of the plexiglass. After 1 minute, the weight and plexiglass were removed. The paper L and U were weighed and recorded as $W_{L,wet}$ and $W_{U,we}$, respectively.

Water absorbed by filter paper L, calculated by equation (1):

$$W_L = W_{L,wet} - W_{L,dry} \qquad (1)$$

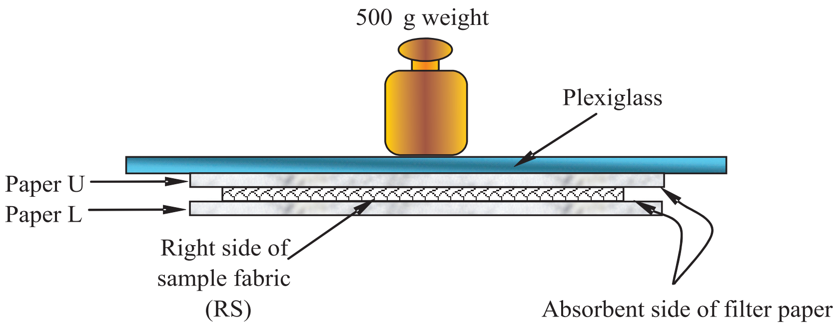

Figure 1 Configuration of wrong-side-up water distribution test.

was the amount of water transported to the *right* side of the fabric. The water absorbed by filter paper U, calculated by equation (2),

$$W_U = W_{U,wet} - W_{U,dry} \tag{2}$$

was the amount of water that remained on the *wrong* side of the fabric sample. Then, the total absorbed water (W_{WT}) was obtained from equation (3).

$$W_{WT} = W_L + W_U \tag{3}$$

The ratio of right-side water (W_L) to total water (W_{WT}) was defined as *wrong-side-up water distribution value* (WD_W), and calculated by equation (4).

$$WD_W = \frac{W_L}{W_{WT}} \tag{4}$$

The *right-side-up water distribution value* (WD_T) was obtained using the same protocol by orienting the fabric right side up, while 1.3 ml of water was uniformly applied on the wrong side of the fabric sample. WD_T can be calculated by equation (5).

$$WD_T = \frac{W_U}{W_{WT}} \tag{5}$$

Three measurements of wrong-side-up water distribution and right-side-up water distribution were made for each fabric.

Results and Discussion

Correlation between Evaporative Resistance, Wicking and Water Distribution

Three tests, evaporative resistance (R_{et}), water distribution (WD_W and WD_T), and wicking, were used to determine the selected fabrics' moisture transport properties. Table 2 shows their estimated correlation coefficient ρ and the p value to test the null hypothesis of $\rho = 0$ (no significant correlation).

From Table 2, one can see that there is no significant correlation between R_{et} and the other three test values since all of the p values in the last column or last row are greater than 0.05, and the null hypotheses $\rho = 0$ cannot be rejected. However, there is significant correlation between the wicking and water distribution results. This is possibly because R_{et} reflects vapor transport through fabric while wicking and water distribution tests reflect liquid water transport through fabric. All of the estimated correlation coefficients among the wicking test results and two water distribution test results are greater than 0. Therefore, the three testing results are positively correlated. For a fabric with high wicking value, the corresponding water distribution values are also high, whereas the water distribution values are low for fabrics with low wicking value.

The Effect of Metal-containment, and Fabric Thickness on Thermal Resistance

The general linear model $y_{i,j} = \mu + \alpha_i + \varepsilon_{i,j}$ was used to test whether metal containment in fabrics influenced thermal resistance R_{ct}. Here the dependent variable y is thermal resistance, and α is the effect of metal containment. The following null hypotheses H0 was tested and Table 3 presents the ANOVA results for this model.

H0: $\alpha_i = 0$, there is no significant effect on R_{ct} due to whether the fabric contains metal

From Table 3, one can see that the null hypothesis ($\alpha_i = 0$) is not rejected because $p > 0.05$. So it can be concluded that the presence of metal in these selected fabrics did not significantly influence thermal resistance.

The linear regression $y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$ was used to test the effect of fabric thickness on thermal resistance. Here the dependent variable y was thermal resistance and the independent variable was fabric thickness. The following

Table 2 Correlation among the three moisture tests.

(correlation coefficient ρ) (p value under H0: ρ = 0)	Wicking	WD_w	WD_r	R_{et}
Wicking		0.67601 < 0.0001	0.73088 < 0.0001	0.05993 0.6761
WD_w	0.67601 < 0.0001		0.87446 < 0.0001	–0.22580 0.1006
WD_r	0.73088 < 0.0001	0.87446 < 0.0001		–0.13566 0.3280
R_{et}	0.05993 0.6761	–0.22580 0.1006	–0.13566 0.3280	

Table 3 ANOVA table – effect of metal-containment on R_{ct}.

Source	DF	Sum of squares	Mean square	*F* value	Pr > *F*
Model	1	0.00002993	0.00002993	0.40	0.5294
Error	52	0.00388175	0.00007465		
Corrected total	53	0.00391168			

null hypotheses H0 was tested and Table 4 presents the ANOVA results for this model.

H0: $\beta_1 = 0$, there is no linear relationship between R_{ct} and fabric thickness

From Table 4, one can see that fabric thickness has a significant effect on R_{ct} ($p < 0.05$). Since the parameter estimate of β_1 is greater than 0 ($\beta_1 = 0.26441$), R_{ct} increases when fabric thickness increases. The R^2 value of this model is only 0.1673 and so the linear relationship between R_{ct} and fabric thickness is weak, although it is significant.

The thermal resistance of a homogeneous solid material is determined by the thermal conductivity of the material and its thickness. Their relationship can be given as

$$R_{ct} = L/k \qquad (6)$$

where R_{ct} is thermal resistance, L is thickness and k is thermal conductivity. From equation (6), it can be seen that there are two ways to lower thermal resistance. One is to use a thin layer material (lower L), and the other is to use a high conductivity material (increase k). However, the above discussion about thermal resistance and thermal conductivity is only suitable for a homogeneous solid material. The thermal property of fabrics is more complicated because of the complex structure of fiber, yarn and fabric.

As the idea of using a metallic fiber to increase k, thus reducing R_{ct}, was found to be ineffective, and so the authors did not focus further on metal-containing fabrics to find low thermal resistance fabrics. Instead, the following fabric properties appeared to play a role in reducing the thermal resistance of the tested fabric. The properties are tight fabric structure, smooth yarn, thin fabric, and sufficient fabric weight to adhere to the skin. All of these properties reduce the air gap between the fabric and skin, or reduce the air within the fabric. As air has a much lower thermal conductivity than a polymer fiber, reducing entrapment of dead air was again found to be critical for minimizing thermal resistance.

The Effect of Metal-containment and Fabric Thickness on Evaporative Resistance

Similar to R_{ct}, the general linear model $y_{i,j} = \mu + \alpha_i + \varepsilon_{i,j}$ was used to test whether metal containment in fabrics affected evaporative resistance R_{et}. Here the dependent variable y was evaporative resistance, and α was the effect of metal containment. The following null hypothesis H0 was tested and Table 5 presents the ANOVA results for this model.

H0: $\alpha_i = 0$, there is no significant effect on R_{et} due to whether the fabric contains metal.

From Table 5, one can see that the null hypothesis ($\alpha_i = 0$) is not rejected because $p > 0.05$. So it can be concluded that

Table 4 ANOVA table – effect of fabric thickness on R_{ct}.

Source	DF	Sum of squares	Mean square	*F* value	Pr > *F*
Model	1	0.00065433	0.00065433	10.45	0.0021
Error	52	0.00326	0.00006264		
Corrected total	53	0.00391			
Variable	**DF**	**Parameter estimate**	**Standard error**	***t* value**	**Pr > |*t*|**
Intercept	1	0.01532	0.00224	6.84	< 0.0001
Thick	1	0.26441	0.08181	3.23	0.0021

Table 5 ANOVA table – effect of metal-containment on R_{et}.

Source	DF	Sum of squares	Mean square	*F* value	Pr > *F*
Model	1	3.08324354	3.08324354	2.16	0.1474
Error	52	74.12646879	1.42550902		
Corrected total	53	77.20971233			

Table 6 ANOVA table – effect of fabric thickness on R_{et}.

Source	DF	Sum of squares	Mean square	*F* value	Pr > *F*
Model	1	17.81939	17.81939	15.60	0.0002
Error	52	59.39033	1.14212		
Corrected total	53	77.20971			

Variable	DF	Parameter estimate	Standard error	*t* value	Pr > |t|
Intercept	1	2.40419	0.30234	7.95	< 0.0001
Thick	1	43.63423	11.04682	3.95	0.0002

the presence of metal in these tested fabrics did not make a significant difference for the evaporative resistance data.

The linear regression $y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$ was used to test the effect of fabric thickness on evaporative resistance. Here the dependent variable y was evaporative resistance and the independent variable was fabric thickness. The following null hypotheses H0 was tested and Table 6 presents the ANOVA results for this model.

H0: $\beta_1 = 0$, there is no linear relationship between R_{et} and fabric thickness

From Table 6, one can see that fabric thickness has a significant effect on R_{et} ($p < 0.05$). As the parameter estimate of β_1 is greater than 0 ($\beta_1 = 43.63423$), R_{et} increases when fabric thickness increases. The R^2 value of this model is only 0.2308. Therefore the linear relationship between R_{et} and fabric thickness is weak, although it is significant.

R_{ct} and R_{et} Values of the 18 Tested Fabrics

The R_{ct} values of the 18 fabrics are shown in Figure 2. The authors used the general linear model $y_{i,j} = \mu + \alpha_i + \varepsilon_{i,j}$ to test whether there was a significant difference in R_{ct} among them. Here the dependent variable y was R_{ct}, and α was the effect of fabric.

H0: $\alpha_i = 0$, there is no significant difference in R_{ct} among these 18 fabrics

Table 7 is the ANOVA table for this test. From Table 7, one can see that there was a significant difference in R_{ct} among these 18 tested fabrics ($p < 0.05$). Fisher's LSD test was used to test where the difference lies and Table 8 shows the results of the Fisher's LSD test. There are eight groups with no significant difference among fabrics in the same group, but there is a significant difference between the groups. The three fabrics in group 1 have the lowest R_{ct} for the 18 fabrics tested.

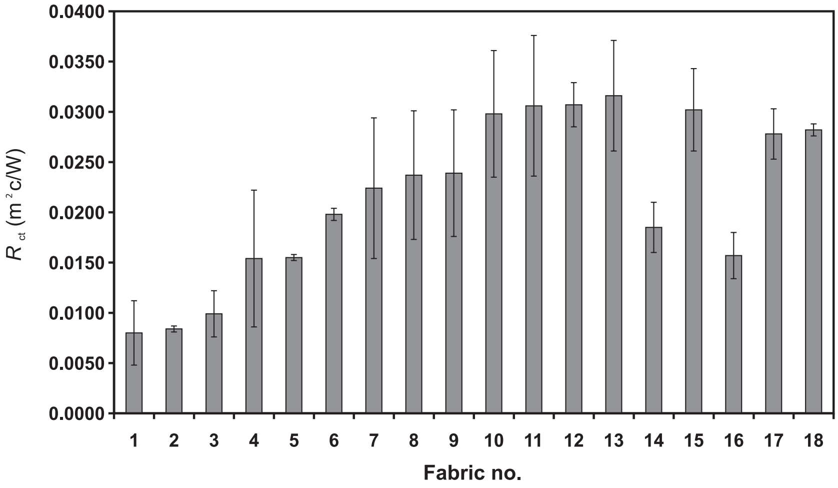

Figure 2 The R_{ct} values of the 18 fabrics.

Table 7 ANOVA table to test the difference in R_{ct} among the 18 tested fabrics.

Source	DF	Sum of squares	Mean square	*F* value	Pr > *F*
Model	17	0.00336522	0.00019795	13.04	< 0.0001
Error	36	0.00054646	0.00001518		
Corrected total	53	0.00391168			

Table 8 Fisher's LSD test on R_{ct}.

Group	Fabric no.
1	1, 2, 3
2	3, 4, 5, 16
3	4, 5, 16, 14, 6
4	14, 6, 7, 8, 9
5	7, 8, 9, 17, 18
6	8, 9, 17, 18, 10
7	9, 17, 18, 10, 15
8	17, 18, 10, 15, 11, 12, 13

The R_{et} values of the 18 fabrics are shown in Figure 3. A general linear model $y_{i,j} = \mu + \alpha_i + \varepsilon_{i,j}$ was used to test whether there was a significant difference in R_{et} among them. Here the dependent variable y was R_{et}, and α was the effect of fabric.

H0: $\alpha_i = 0$, there is no significant difference in R_{et} among these 18 fabrics

Table 9 is the ANOVA table for this test. From Table 9, one can see there is a significant difference in R_{et} among these 18 tested fabrics ($p < 0.05$). Fisher's LSD test was used to test where the differences lie and Table 10 presents the results of Fisher's LSD test, showing that there are eight groups. The seven fabrics in group 1 have the lowest R_{et} for the 18 fabrics tested.

Wicking and Water Distribution Values of the 18 Tested Fabrics

The results of the wicking test for the 18 fabrics tested in this study are shown in Figure 4 and the results of the water distribution test for the 18 fabrics are shown in Figure 5. From Figure 4, one can see that some metal-containing fabrics, such as fabrics 4, 7, 8, and 12, have no wicking ability. Their water distribution values are also low in comparison with others. Knit fabrics with a higher percentage of polyester, i.e., fabrics 1, 10, 11, and 16, usually have higher wicking values. This is because of the hydrophilic property of polyester and because there are more capillaries in knits than in woven fabrics. Not all fabrics are suitable for the "strip" wicking test. As fabric 3 has one hydrophilic side and one hydrophobic side, the fabric floated on the surface of the test solution and could not be immersed in the solution. The wicking value of this fabric was not obtained.

The water distribution test conducted in this study was a modified version of the water distribution test developed by Malden Mills. The authors modification included using the fractions of right side water in overall water (WD_W and WD_r) instead of weights of right side water (W_L in wrong-side-up test and W_u in right-side-up test) to reflect water distribution. Since water loss during the test was an error-prone characteristic of this test, the modification offsets water loss on both sides and thus improves accuracy and reliability of the test. This water distribution test is a simple test to measure how much water can pass through the tested fabric from next-to-skin side to the outside and the

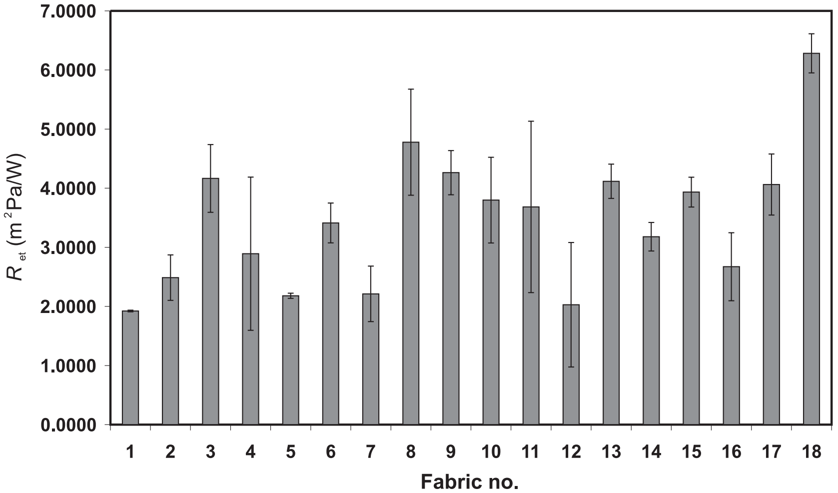

Figure 3 The R_{et} values of the 18 fabrics.

Table 9 ANOVA table to test the difference in R_{et} among the 18 tested fabrics.

Source	DF	Sum of squares	Mean square	*F* value	Pr > *F*
Model	17	64.60769806	3.80045283	10.86	< 0.0001
Error	36	12.60201427	0.35005595		
Corrected total	53	77.20971233			

Table 10 Fisher's LSD test on R_{ET}.

Group	Fabric no
1	1, 12, 5, 7, 2, 16, 4
2	7, 2, 16, 4, 14
3	2, 16, 4, 14, 6
5	14, 6, 11, 10, 15, 17, 13
6	6, 11, 10, 15, 17, 13, 3, 9
7	10, 15, 17, 13, 3, 9, 8
8	18

results of this test were significantly correlated to the results of the wicking test. Fabric 14 had the highest water distribution values among all tested fabrics because this fabric is designed to pick up body moisture and move it quickly to the upper surface of the fabric using a "push–pull" moisture control mechanism.

Conclusions

This study used three tests to measure the moisture transportation properties of the selected fabrics. The evaporative resistance test reflects vapor transport whereas the wicking test and water distribution test reflect liquid transport in fabrics. There was no significant correlation between vapor transport values and liquid transport values, whereas the liquid transport values were significantly correlated with each other.

Whether the fabric contained metal or not did not significantly affect R_{ct} and R_{et}. As metal containment in fabric did not improve thermal conductivity and most metal-contained fabrics do not have good liquid water transport (wicking and water distribution) ability and good tactile properties, metal-containing fabrics were considered to be poor candidates for use as an inner fabric layer in a LCG development.

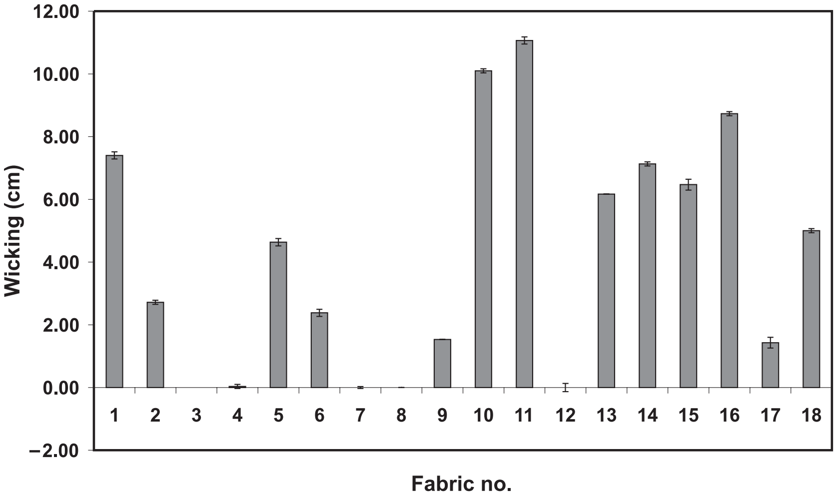

Figure 4 The wicking values of the 18 fabrics.

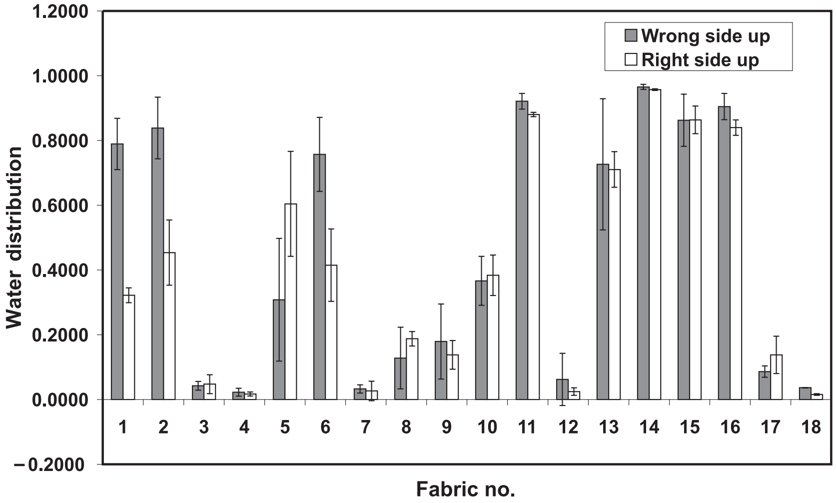

Figure 5 The water distribution values of the 18 fabrics.

Two fabrics, i.e., No. 1 and No. 2, were in the first group for both R_{ct} and R_{et}. They had the lowest R_{ct} and R_{et} among the 18 fabrics tested and there was no significant difference between these two fabrics in R_{ct} and R_{et}. There are several advantages of fabric 1 over fabric 2 as a candidate for the inner fabric layer. First, fabric 1 is a knit fabric whereas fabric 2 is a woven fabric, and the knit fabric is more suitable for next-to-the-skin application. Second, fabric 1 has better wicking and water transport properties, and thus better liquid water transport capability. Third, fabric 1 has better stretch property which will allow for creating a tighter fitting garment and thereby reducing the air gap between the fabric and the skin. Although the stretch property will be compromised after bonding with the tubing and outer layer fabric, there is still the potential for stretch to be an advantage depending on the design. Therefore, from the fabrics that were investigated and tested, the authors concluded that fabric 1 was the most advantageous fabric for the inner fabric layer in a LCG.

Acknowledgement

This research was supported under Award MIPT-106-113-2000-021 from the National Memorial Institute for the Prevention of Terrorism (MIPT) and the Office for Domestic Preparedness, U.S. Department of Homeland Security. Points of view in this document are those of the authors and do not necessarily represent the official position of the U.S. Department of Homeland Security or MIPT.

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