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Thermal Comfort Performances of Double-face Knitted Insulation Fabrics

Sibel Kaplan* and Bilge Yilmaz

Textile Engineering Department, Suleyman Demirel University, Isparta 32260, Turkey

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Abstract: Thermal comfort parameters of knitted fabrics such as thermal resistance and liquid transfer can be enhanced by combining hydrophilic and hydrophobic functional yarns as double-face fabrics. This study aims to investigate thermal conductivity (Alambeta Parameters), permeability (air permeability and Permetest Parameters) and liquid management characteristics of double-face knitted fabrics for which functional yarns such as Thermosoft®, Nilit Heat®, Viloft® and wool were combined with standard polyester (PET) and polypropylene (PP) by a false rib structure. According to the results of 11 fabrics-s is necessary, Nilit Heat®/PP (inner/outer) fabric has advantages for breathability, warmer sensations as a result of its minimum thermal absorption, conductivity and diffusion. Wool/PET can be suggested more for liquid management properties with its branched structure besides its higher thermal resistance and air permeability values. Both structures including hydrophilic or functional inner surfaces touching the skin can be suggested for a cold protective clothing to enable stable insulation and dryness.

Keywords: Double-face fabric, Insulation, Liquid transfer, Wool, Functional yarn

Introduction

Comfort, which is a necessity for all kinds of clothing, is very important for sports and protective garments. Main parameters of thermal comfort, such as insulation, breathability and liquid transfer are crucial for a cold-environment clothing. Sports textiles market, which also include cold protective components such as cycling and ski clothing, had a growth of 8.15 % in 2019, being one of the biggest market increments [1] as people are paying more attention to sports activities. Therefore, many researchers and industries have engaged to develop more comfortable fabrics and garments by functional materials and structures.

Synthetic fibers are generally considered to be the best choice for sportswear as they are able to provide a good combination of moisture management, softness, weight, insulation and quick drying; parameters improving muscle performance and delaying exhaustion. Knitted fabric appears to be the ideal base for active sportswear to combine functions of modified synthetic fibers and natural fibers supported with developments in fabric construction [2]. Standard synthetics (polyester, polyamide, polypropylene), natural fibers (cotton, wool) and regenerated cellulosics (viscose, lyocel, modal, micromodal, bamboo) are used as blends or layers/regional components of sports clothing [3,4]. Some modifications about synthetic fibers to improve comfort include cross section changes in filament or staple forms, microfibers and functional particle reinforcements [5-8].

Focusing on mid- base layer of cold weather (air temperature less than 15.6 °C) [9] protective or sports clothing, combined heat and sweat transfer mechanisms should be controlled for to delay the onset of chilling and prevent insulation decrease. As it is known, fabric insulation is governed by fabric thickness (the most important), porosity, bulk density, stiffness and drapeability [9-17]. Some researchers state fibers' influence directly, while others claim that fibers can only influence insulation indirectly by their effect on fabric structure. Insulation decrease and wetness sensation occurs by displacement of still air trapped within the microsized air pockets with liquid sweat [5,18].

Fabric porosity controls also evaporative heat transfer [12, 18] as it determines the path for vapor transfer. The effect of fiber is more evident for moisture transfer that highly hygroscopic fibers such as wool can absorb water, buffers microclimate and delays moisture build-up at fiber surface [14]. Material blending for better breathability and moisture management may be in yarn form such as composite core and sheath yarns or staple yarns made of hydrophobic and hydrophilic components [19-21]. With exceptional insulation and buffering features, wool blends with polyester and bamboo as single jersey fabric [22], with polyester as interlock fabric [14], wool with polyester and cotton as plating yarns [23] and wool/polyester double layer fabric for inner/outer layers [24] were investigated for their permeability, thermal resistance and moisture management features. All results indicated better performances of blended or multi-component fabrics. Double face or double layer fabrics are another solution for thermal comfort enhancement that, knitted fabrics including microfilaments or higher yarn counts on the external surface to reduce porosity activate the capillary phenomenon, in which moisture is discharged from the larger pores to the smaller pores from inner to the outer surface of the fabric [2,20,25]. Most of the studies [20,26-34] suggest a hydrophobic inner layer with good moisture transfer properties with a properly reduced stitch density and a hydrophilic outer layer. Fibers used for outer layer were bamboo, cotton, cotton/polyester, viscose, modal, lyocel; inner layer were polypropylene, polyamide, polyester, micro-polyester, acrylic, Coolmax® and lyocel/polyester

*Corresponding author: sibelkaplan@sdu.edu.tr

combined as double-layered/face fabrics knitted in plain plated or standard/pique double jersey structures [26,27,30-34]. Synthetic fibers can also be combined for fabric layers that Park *et al.* [25] compared thermal parameters of polypropylene/Coolmax® (inner/outer) with 100 % forms. Use of natural or hydrophilic fibres such as wool or comfort yarns such as Cupron and Cocona fibres for inner layer that offer natural anti-bacterial and anti-odour capabilities, enhanced ventilation, natural UV and skin soothing properties is also an option for functional fabric structures [29].

Besides double-layer/face fabric systems, garments including different materials or structures for different body parts where more liquid transfer or insulation is required combine advantages of both material and fabric structure [2,35,36]. The mentioned partial material/structure combinations help for comfort improvement as heat loss and sweating rates are not uniform over the body surface because of thermoregulation mechanism and non uniform environments [9]. Seamless knitting technology allows production of different stitches such as rib, net, jacquard, etc., as well as double face fabrics using two different yarns for keeping skin perfectly micro-climate controlled [29]. Lower thickness is also a desirable feature particularly for outdoor active people like workers and athletes [18]. The plain plated weft knitted structures were reported to give better dryness sensations as compared to double-layer combined structures knitted with the same yarns [27].

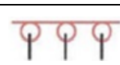
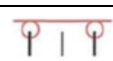
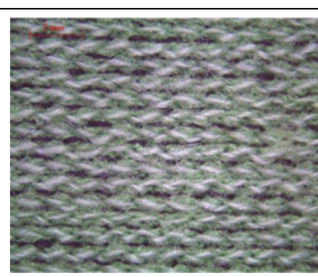
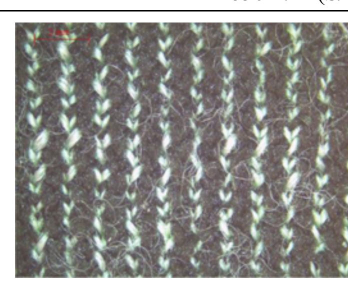
In this study, functional man-made fibers such as ThermoSoft®, Viloft®, Nilit Heat®, and wool were combined with standard polyester and polypropylene filaments by false rib structure with the existence of polyamide based elastomeric inlay yarn by a seamless knitting machine. Functional fibers developed for higher insulation/liquid transfer and wool were mainly located on the inner surfaces of the fabrics as miss stitches and as loops on outer surfaces creating a branched structure. Alambeta, Permetest, liquid absorption and transfer parameters of 11 fabric samples were tested and results were put forward about suitability of the investigated double face fabrics for different seamless clothing parts for insulation or sweat transfer as the aim of the study was to find the optimum material combinations for a thin insulation layer. Intended end use areas of the mentioned clothing are inner-mid layer of a cold protective or cold weather sports clothing.

Experimental

Material

Duffel jersey or false rib structures were produced with wool, Viloft®, Nilit Heat® and ThermoSoft® inner, and standard polyester (PET) and polypropylene (PP) outer surfaces. Functional materials, mostly located on technical back or inner sides of the fabrics were in staple form except for Nilit Heat®. ThermoSoft® is a staple yarn consisting of microacrylic and cellulose enabling high insulation and good liquid transfer by trapping more air within the yarn as a result of specific helical and layered fiber arrangement [37]. Wool yarn having a blend ratio of 90/10 % Wool/Polyamide (17.2 μm fiber diameter) has 'Total Easy Care' certificate [38]. Viloft® is the only flat viscose fiber having a unique cross-section increasing fibre surface by more than 50 % and trapped air by 70 % of yarn volume which makes it light and breathable. It also has advantages about softness and absorbency that it absorbs liquid quickly and gives a a dry

Table 1. Yarn properties and fabric structure

		Blend ratio	Yarn count	Twist/Form
Needle diagram		100 % PET	83 dtex/72 f	Texturised
		100 % PP	70 dtex/72 f	Texturised
		100 % Nilit Heat®	78 dtex/68 f (Ne 76)	Texturised
		100 % PET	83 dtex/72 f	Texturised
		100 % PP	70 dtex/72 f	Texturised
		100 % Thermosoft®	Ne 50	700 T/m (S/Z)
		90/10 % Wool/Polyamide	Ne 50	750 T/m (S/Z)
		Viloft®	Ne 50	650 T/m (S/Z)
Fabric Photos (8 x)	 Technical Back (Inner)		 Technical Face (Outer)	

feeling [39]. Nilit Heat® is a Nylon 6.6 based bacteriostatic and odor-free yarn including coffee charcoal together with an oxide additive. It absorbs and captures body heat for a certain period which creates superior insulation and moisture management properties [40]. 44dtex/34f PA elastomeric inlay yarn including elastane of 17dtex was used for the fabric samples as full plating.

Method

Fabric Production

Fabrics were knitted by a Santoni SM8 Seamless Knitting Machine having a gauge of 28 E, diameter of 14 inches and 248 needles. Microscopic photos (8x) of technical face and back of a fabric sample with needle diagram and yarn properties can be seen in Table 1. As can be seen in Table 1, functional synthetics/wool (green/white) in miss stitch form combined with PA based elastomeric yarn are located on inner side (technical back) of the fabric touching the skin. Functional synthetics/wool loops were located also on the outer surface combined with standard PET or PP filament yarns (black) creating a branched structure. Fabric samples were coded with material names located on 'technical back (inner)/technical face (outer)'.

All samples were piece dyed at 98 °C for 45 minutes, washed at 60 °C for 30 minutes, treated with a softener at 50 °C and a final warm rinse for 10 minutes. Only Viloft® yarn was obtained as dyed. All fabrics were washed according to TS EN ISO 6330:2012 in a Wascator FOM71 CLS washing machine (James Heal and Co. Ltd., Halifax, UK). All samples were conditioned under standard atmospheric conditions (20±2 °C, 65±2 % RH) in accordance with ASTM D1776-08e1 (2009) before the tests.

Thermal and Permeability Properties

Areal density and loop length tests were carried out according to standards TS EN 12127 and TS EN 14970 in turn. Air permeability values were tested according to TS 391 EN ISO 9237 by FX Textest 3300 under 100 Pa pressure (James Heal Corp., UK).

Thermal properties of the double-face knitted fabrics were carried out with Alambeta Instrument by Sensora (Czech Republic) and tests were performed according to standard ISO EN 31092-1994. Alambeta Instrument was used for thermal conductivity, resistance, absorptivity, thermal diffusivity, as well as the material thickness results of the samples. Water vapor permeability characteristics were tested by Permetest Instrument, according to ISO 11092 [15].

Liquid Absorption and Transfer Properties

Absorbency of the samples were tested by drop test according to AATCC 79:2018. Immersion period test investigating both wetting and wicking performances of the fabrics was conducted according to AATCC 79-Method B. Absorbtion capacities of the samples (10×10 cm) were calculated from the formula $((W_{wet}-W_{dry})/W_{dry}\times 100)$ according to the modified version of ISO 20158:2018. Drying performances were determined according to a preceding study [41] under standard atmospheric conditions with weight measurements at every 30 minutes for a certain period (6 hours). Weight losses (%) were calculated from the formula $((W_0-W_6)/W_0)\times 100$ where (W_0) and (W_6) are the weights recorded at the beginning and after 6 hours in turn.

Statistical Analyses

IBM SPSS 21.0 Statistics Software (SPSS Inc. USA) was used for ANOVA Analyses of the investigated parameters. Duncan and Student Newman Keuls (SNK) tests were used to examine significant differences among measured parameters. Correlation analysis was conducted to determine relationships among the investigated parameters.

Results and Discussion

Physical, Conductivity and Permeability Properties

Physical properties of double-face knitted fabrics are compiled in Table 2 with their ANOVA summaries. ANOVA results were summarized in Table 3. As can be seen, significantly minimum areal density values belonged to the fabrics including Heat® filament yarn (4 and 5) including cofee charcoal as a result of its lower linear density values among other functional yarns. Maximum areal density values belonged to Thermosoft® staple yarn including fabrics (6 and 7) and PET/PP (2). Wool and Viloft® including fabrics (8-11) had generally identical areal density values. When thickness and areal density are considered together, the bulkiest structures belonged to Viloft®/PET, Viloft®/PP and Thermosoft®/PET. While PET created a low thickness when used alone (1), it increased fabric thickness values when combined with other fibers except for wool (8 and 9). As a general look, staple yarn fabrics had higher thickness values as a result of their bulky structures and surface hairiness besides their higher fiber rigidities as thickness depends on number, size and resilience of the surface loops [13].

Air permeability is mainly affected by the characteristics (shape and size) of the pores in the fabric influenced by yarn linear density, course and wale densities [17]. Besides, Cuden and Elesini [42] pointed out the importance of air-fiber friction and stated that air permeability does not correlate closely with structural porosity, since the resistance to air passage also depends on surface textures on either side of fabric. Therefore, air permeability values can not be explained by only fabric densities, but also combined effects of fiber surface area [13] and roughness which changes friction behaviour with air. Air permeability values (Figure 2) are the maximum for the fabrics including Viloft® and wool staple yarns (8, 9, 10 and 11) creating higher pore volumes and area for air flow as a result of their irregular cross-sections or crimp. The mentioned result does not obey the hypothesis about effect of the fiber surface features, or in

Table 2. Fabric physical properties

Material (fabric code)	Areal density (g/m^2) [S.D.]	Thickness (mm) [S.D.]	Fabric density (g/cm^3) [S.D.]	Loop length (mm) [S.D.]
PET/PET (1)	237.56^{d} [9.41]	0.38^{f} [0.03]	0.62 [0.36]	3.76 [0.25]
PET/PP (2)	258.71^{a} [3.02]	0.98^{c} [0.06]	0.27 [0.05]	4.55 [0.11]
PP/PP (3)	237.16^{d} [3.48]	0.60^{e} [0.04]	0.40 [0.09]	4.30 [0.07]
Nilit Heat®/PET (4)	226.28^{e} [8.50]	0.56^{e} [0.08]	0.41 [0.10]	4.53 [0.08]
Nilit Heat®/PP (5)	227.9^{e} [2.97]	0.32^{g} [0.05]	0.71 [0.06]	3.77 [0.13]
Thermosoft®/PET (6)	253.55^{ab} [2.43]	1.22^{a} [0.02]	0.21 [0.10]	4.32 [0.26]
Thermosoft®/PP (7)	256.66^{a} [1.87]	0.78^{d} [0.07]	0.33 [0.02]	4.04 [0.23]
Wool/PET (8)	248.06^{bc} [7.86]	0.58^{e} [0.02]	0.43 [0.34]	4.08 [0.08]
Wool/PP (9)	248.56^{bc} [2.55]	1.01^{c} [0.04]	0.25 [0.05]	3.70 [0.13]
Viloft®/PET (10)	244.26^{c} [3.15]	1.16^{b} [0.03]	0.22 [0.11]	4.35 [0.07]
Viloft®/PP (11)	242.35^{cd} [3.02]	1.02^{c} [0.05]	0.24 [0.06]	4.37 [0.07]

*: Different superscript letters show statistically significant differences.

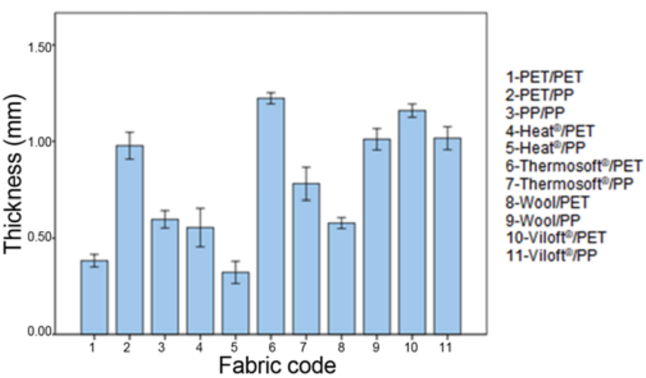


Figure 1. Thickness values of fabrics.

this case, pore volume increase might have compensated the negative effects of rough surfaces of Viloft® and wool yarns on air permeability. Among staple yarn fabrics, Thermosoft®/PP (7) had identical air permeability values with PET/PET (1) and PP/PP (3), despite yarn linear density differences between Thermosoft and synthetic filaments (Table 3). Minimum values belonged to Heat®/PET (4), despite moderate density values of the fabric and lower linear density of Heat® yarn, followed by Thermosoft/PET (6) having lower fabric density. This result confirms a preceding statement [13] about unexplainability of air permeability by only fabric density.

Thermal conductivity is an intensive property of a material

Table 3. Post-hoc test results of fabric properties

Fabric property	SNK/Duncan analysis results
Areal density	**4-5**<3-1-11-10<11-10-8<8-9-6<6-7-2
Thickness	**5**<1<4-8-3<7<2-9-11<10<6
Air permeability	4<6<1-3-7<2-5<11-9<**9-8-10**
Thermal conductivity	**5**<1-8<4<3<7-9<9-2<10-11<6
Thermal resistance	3<1<7-4<11<2-5<6<10-9<**8**
Thermal diffusion	**5-8-1**<8-1-4<3-7-9<2<11<10<6
Thermal absorption	**5-6**<6-10-1<8-11-3<11-3-4-2<4-2-7<7-9
Ratio of the max and stationary heat flux	1-3<3-5-6<6-10<10-4-11<4-11-7<2-8<**8-9**
Relative WVP	7-9<10-6-8<8-11<2-4-1<4-1-5<**1-5-3**
Water vapor resistance	**3-5**<5-4-1<4-1-2<11-10-8-6<9-7
Absorption period (drop) test	**8-6**-5-11-10<6-5-11-10-9<7<2-4<3
Immersion period	**8-6**<10-11-5-7<9
Absorption capacity	9<3-1<1-7-11<7-11-8<**5-6-2-4-10**
Weight loss during drying	4-2<6-10-5<10-5-11<5-11-8<11-8-9-7<**1-3**

1: PET/PET
2: PET/PP
3: PP/PP
4: Nilit Heat®/PET
5: Nilit Heat®/PP
6: Thermosoft®/PET
7: Thermosoft®/PP
8: Wool/PET
9: Wool/PP
10: Viloft®/PET
11: Viloft®/PP

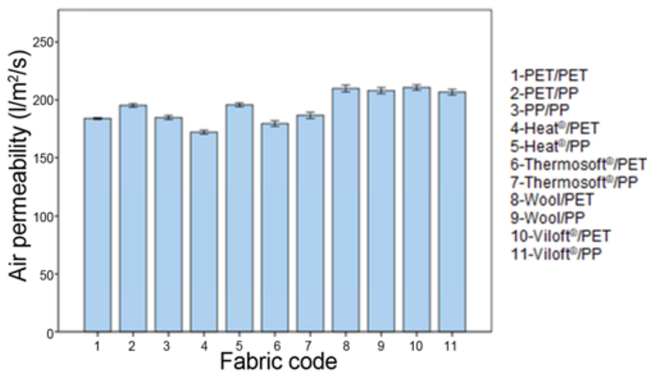


Figure 2. Air permeability values of fabrics.

that represents the heat transfer process through a fabric. Thermal resistance values are not inversely proportional to thermal conductivity values as a result of significant thickness differences among fabrics, not in harmony with a preceding study [17]. According to the results, maximum conductivity belonged to Thermosoft®/PET (6), followed by Viloft®/PET (10) and Viloft®/PP (11) (Figure 3). Thermosoft®/PET's (6) minimum fabric density but maximum thermal conductivity values is not in harmony with a preceding study [17] stating contribution of fabric density to thermal conductivity. Viloft®'s lower thermal conductivity among cellulosic fibers is not the case among synthetics and wool including fabrics as a result of higher thermal conductivity of cellulose. Minimum thermal conductivity, a desirable property for an insulation fabric was obtained for Heat®/PP (5), despite their lowest yarn linear densities, followed by identical performances of PET/PET (1) and Wool/PET (8). Lower thermal conductivity values can not be explained by fabric thickness or density values of the mentioned fabrics (1, 5 and 8). The coffee charcoal content of Heat® with an oxide additive [40] that may create a high specific heat [16] and evidently lower thermal conductivity of PP [43], may be the reasons of this result. Considering synthetics in 100 % form, PET/PET (1) has lower thermal conductivity than PP/PP (3) although PP/PP's higher thickness but when they are combined with other fibers as double-face fabrics, PP created lower conductivity for Heat® and Thermosoft®. Maximum thermal resistance was obtained for Wool/PET (8) which is also among lower thermal conductivity fabrics group. Higher thermal resistance values were obtained for fabrics including staple yarns (except for Thermosoft®/PP) due to an increase in number of hairy projections [9] and bulkier structures confirming the significant relationship between thermal resistance and air permeability (R^2=0.681*). Fiber orientation also plays a role on insulation that fibers oriented parallel to heat flow create higher thermal conductivity [9,13]. Miss stitches changing the direction of the fibers on inner surface might have an influence on higher insulation of the investigated fabrics. Significant correlations of max and stationary heat flux ratio with both thermal resistance (R^2=0.627*) and thermal absorption (R^2=0.677*) confirms a preceding study result [15].

Thermal diffusivity is the ability related to heat flow through the fabric structure. Thermal diffusivity results have relationships with thickness (R^2=0.894**) and results can be ranked as Thermosoft®/PET (6), Viloft®/PET (10), Viloft®/PP (11) and PET/PP (2), from the maximum. The expected higher results for denser fabric structures are not the case for this study that these fabrics have lower fabric densities ranging from 0.21 to 0.27 g/cm^3. Lower and statistically identical values were recorded for PET/PET (1), Heat®/PP (5) and Wool/PET (8).

Thermal absorptivity, which represents a transient heat conduction phenomenon, is the objective measurement of warm-cool feeling of fabrics and is a surface-related characteristic. It is related to fabric conductivity, density and specific heat capacity [17]. Thermal absorptivity values, obtained from inner sides of fabrics ranged from 111-159 Ws$^{1/2}$/m^{2}K. Significantly lower values, meaning warmer feelings were obtained for Heat®/PP (5) and Thermosoft®/PET (6) (Figure 5). Heat®/PP's lower thermal absorption performance can be explained by lower thermal conductivity

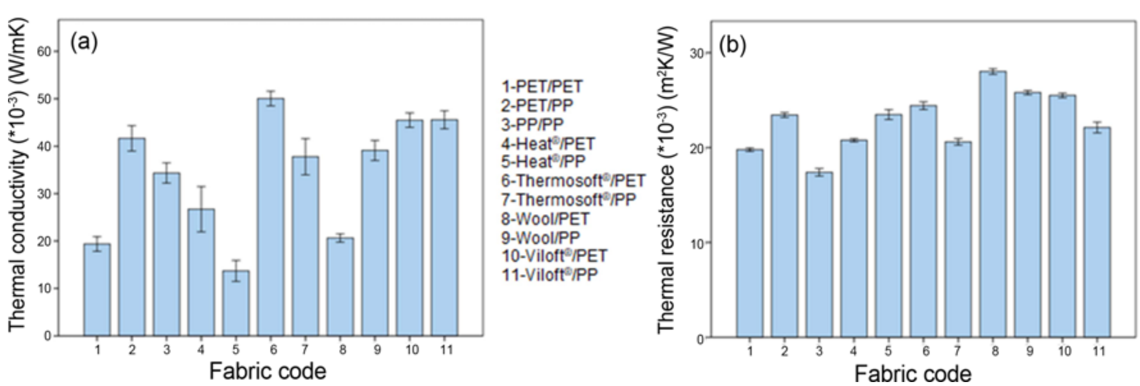


Figure 3. Thermal conductivity (a) and thermal resistance (b) values of fabrics.

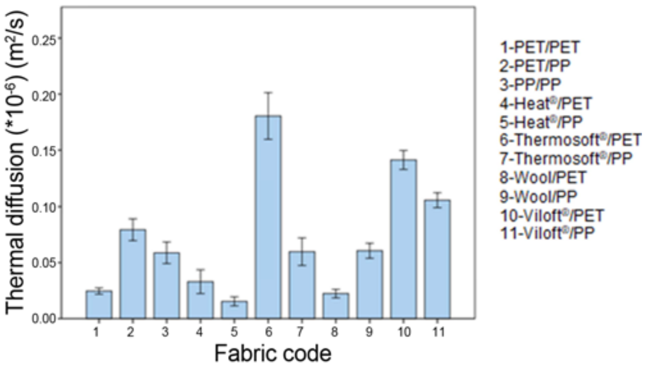


Figure 4. Thermal diffusion values of fabrics.

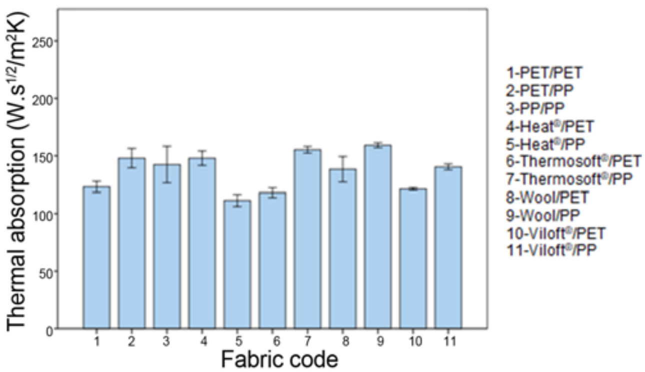


Figure 5. Thermal absorption values of fabrics.

values of polyamide based Heat® including fabrics (4 and 5) (Figure 3) and relatively lower thermal conductivity of standard polyamide than PET and PP [43]. Thermosoft®/PET's performance can be explained more by surface features of the Thermosoft® staple yarn including crimped acrylic. Significantly higher thermal absorption values of the fabrics having PP outer surfaces (except for Nilit Heat®) show the effect of standard filaments located on outer fabric surfaces. Identical performances of PET/PET (1), Thermosoft®/PET (6) and Viloft®/PET (10) confirms that yarn type (staple or filament) did not have an influence on thermal sensations of the fabric. Maximum values, meaning cooler sensations belonged to Thermosoft®/PP (7) and Wool/PP (9).

Relative water vapor permeability is a characteristic related to the pores where water vapor molecules can pass through and largely independent of fiber hygroscopicity. Whereas the time required for the microclimate humidity to return to the original level following exposure was considered a function of fabric porosity, thickness and possibly fiber hygroscopicity [44]. Confirming relationships with fabric structural features, permeability had negative correlations with fabric weight (R^2=-0.607*) and thickness (R^2=-0.670*). According to the results (Figure 6), maximum and statistically identical water vapor permeability results were obtained for PET/PET (1), PP/PP (3) and Heat®/PP (5). Despite moderate or high fabric densities of these fabrics, lower fabric thicknesses and less hairy or bulky structures of the constituting filament yarns may be the reason of higher breathability. Minimum values belonged to Thermosoft®/PP (7) and Wool/PP (9) despite their lower fabric densities. As a general look, fabrics including staple yarns in their inner surfaces allowed less water vapor passage because of the hairy structures preventing passage of water vapor [19] and increasing tortuocity. Probable swelling of hydrophilic fibers, wool and Viloft® may also contribute lower breathability values as stated before [45]. Identical performances of PET/PET (1) and PP/PP (3) were also valid for their combinations with other fibers that there is not a certain trend about their contribution to breathability. Water vapor resistance values gave an opposite ranking of relative water vapor permeability values as expected (R^2=-0.991) that minimum resistance values belonged to PP/PP (3) and Heat®/PP (5) fabrics. Resistance values are negatively correlated with immersion period results (R^2=-0.991) that fabrics having more porous structures enabled better water vapor transfer but worse wetting/wicking behaviours, probably because of the higher pore diameters. Summing up, only functional yarn, Heat® showed a distinctive positive performance in case of breathability besides standart PET and PP.

The first condition of liquid transfer, wetting or absorption

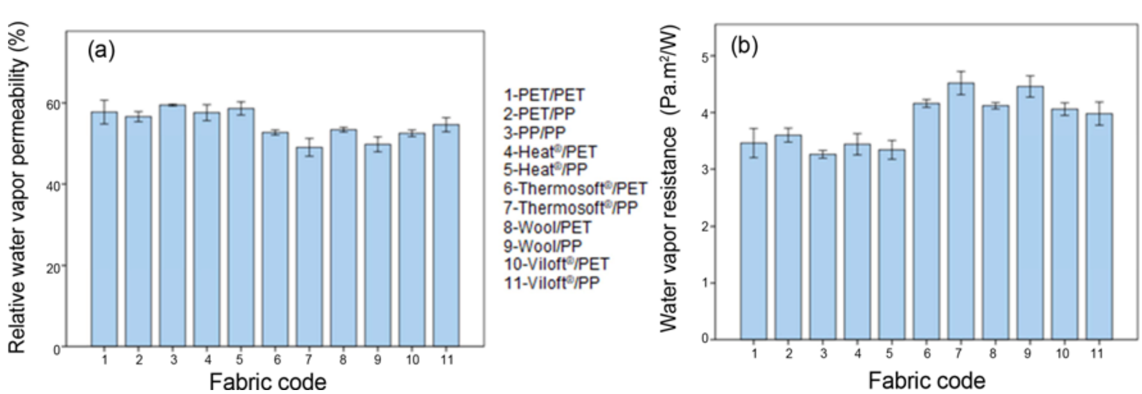


Figure 6. Relative water vapor permeability (a) and water vapor resistance (b) values of fabrics.

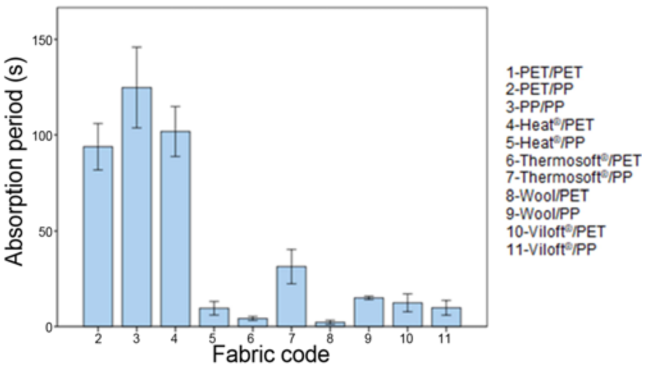


Figure 7. Absorption period values of fabrics.

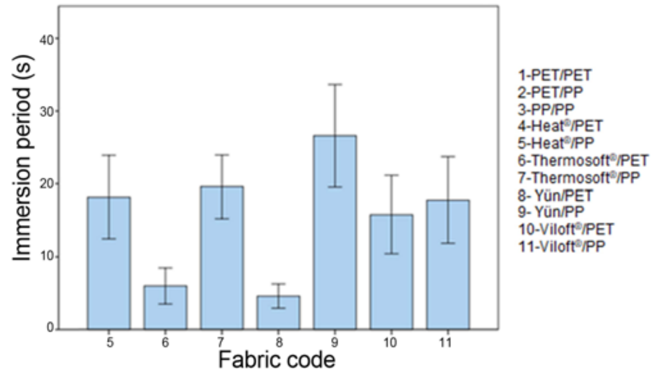


Figure 8. Immersion period values of fabrics.

of the liquid by the inner sides of double-face fabrics were investigated by drop test. Wetting is the initial process of fluid spreading where the fiber-liquid interface replaces the fiber-air interface. Wicking is due to fiber-liquid molecular attraction at the surface of fiber materials, which is determined by the surface tension and the effective capillary pathways and pore distribution [17]. According to the results, PET/PET (1) fabric did not absorb water within acceptable period. Heat®/PP (5), Thermosoft®/PET (6), Wool/PET (8), Viloft®/PET (10) and Viloft®/PP (11) fabrics absorbed water within 2.20-15 seconds. But only Wool/PET (2.20 seconds) and Thermosoft®/PET (4.20 seconds) fabrics absorbed water within a 5-second limit according to Moisture Management Tester Scale [46]. Wool's better performance as PET/Wool plated fabric [23] and as Wool/PET blend than 100 % wool for moisture management properties were reported before [27]. PP/PP (3) fabric absorbed water within the maximum period followed by PET/PP (2) and Heat®/PET (4). This result may be attributed to their hydrophobic natures, higher contact angles [17] and smoother surfaces. As a general look, all staple yarn fabrics (6-11) except for Thermosoft®/PP (7) had better wetting abilities than filament yarn fabrics as a result of hydrophilic components of the fabric inner layers (wool, Viloft®) and their rougher or inhomogenious surfaces [47] increasing their surface energies. Better performances of Wool/PET and Thermosoft®/PET can be explained by the faster wicking capacity of PET before swelling of the hydrophilic components takes place. The only exception of filament yarn fabrics is Heat®/PP (5) which created narrowing capilary holes through the thickness of fabric, a phenomenon reported in a preceding study with the better wicking by reduced stitch density for inner layer [20]. Is not the case for Heat®/PET (4) fabric as pores have identical diameters through fabric thickness with identical filament counts of PET and Nilit Heat®. PET/PP (2) having a similar narrowing capilar pore structure did not obey the mentioned rule probably because of insufficient hydrophilicity of the components.

Immersion or sinking periods of the fabrics giving idea about both wetting and wicking characteristics are given in Figure 8. Fabrics having codes 1-4 did not sink within an acceptable period, as they could not be wetted confirming their absorption period results. Sinking time of about 5 seconds is generally considered satisfactory for well prepared cellulosic materials [42] which can be accepted as a limit for thermal comfort. Confirming absorption period results, trademark label for Thermosoft/PET (6) (6 seconds) and Wool/PET (8) (4.60 seconds) had immersion periods within the limits, meaning a better liquid transfer capability. Thermosoft®'s acrylic/cellulosic content had also good performance before as blend form [19]. Wool's and Thermosoft®'s performances were better with PET (6 and 8) than PP (7 and 9). Better performances of PET combined fabrics than PP may be attributed to the capillaries among the branched structure: pores are narrower for PP and can be closed easily (preventing transfer) by swelling of wool or cellulosic component of Thermosoft®. In a preceding study [23] PP/Wool fabric had better liquid transfer performance than PET/Wool. Heat®/PP (5), Thermosoft/®PP (7), Viloft®/PET (10) and Viloft®/PP (11) having identical immersion periods between 15.8-19.6 seconds did not have sufficient wetting and wicking performances. Viloft®'s worse performance than wool although its chanelled structure as a cellulosic fiber confirms a preceding study result of wool/cotton fabric where wool was used as a transfer layer other than an absorption layer when compared with cotton [27]. The effect of pore size was proved by the correlations of immersion period with relative water vapor permeability (R^2=-0.681*) and water vapor resistance (R^2=0.635*). As wetting and wicking for all directions are valid for immersion test, worse performances of fabrics (5, 7, 9, 10 and 11) can be explained by PP's hydrophobic nature that prevents wetting although its slightly lower filament count.

Absorption capacity values of the double-face fabrics (ranged from 199 % to 287 %), a property related to the macromolecular structures of the fibers besides physical features are given in Figure 9. Maximum and statistically identical values belonged to PET/PP (2), Heat®/PET (4),

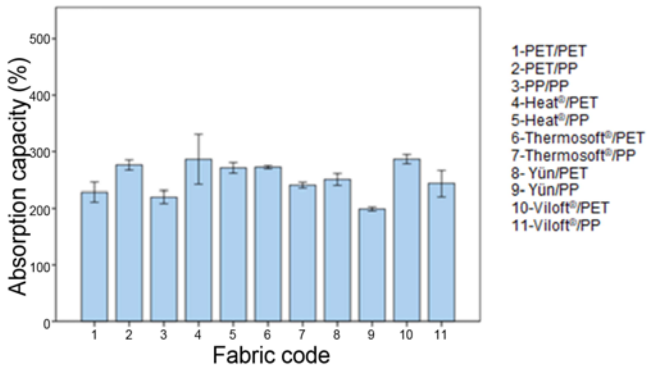


Figure 9. Absorption capacity values of fabrics.

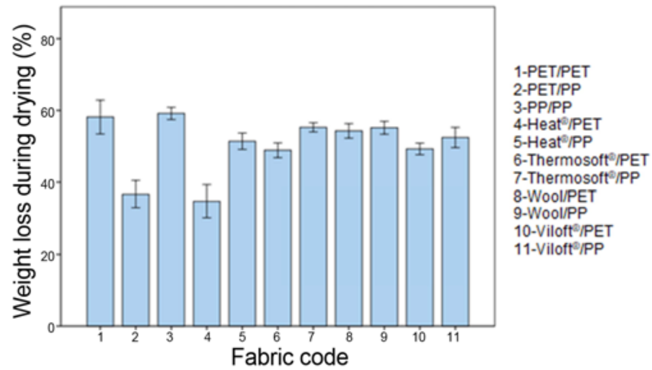


Figure 11. Weight loss values of fabrics.

Heat®/PP (5), Thermosoft®/PET (6) and Viloft®/PET (10). Is interesting to note that Wool/PET (8) and Wool/PP (9) had moderate and minimum absorption capacity values in turn and their difference is statistically significant. While PET/PET (1) and PP/PP (3) had identical absorption capacity performances, PP combinations of Thermosoft®, wool and Viloft® all had significantly lower absorption capacities than their combinations with PET. Fibers behaved different for absorption capacity values as a component of a double-face knitted fabric than their 100 % form. This result can be explained by the big difference in moisture affinities of wool and PP which changed their combined water holding capacity [41].

Weight changes of the double-face knitted fabrics consisting of both hydrophilic and hydrophobic components show similar drying behaviours within 6 hours (Figure 10). Slightly faster drying rate of Viloft®/PET (10) can be observed on the graphic.

When weight losses within 6 hours were analyzed in detail (Figure 11), maximum weight losses (%) belonged to PET/PET (1) and PP/PP (3) fabrics followed by Thermosoft®/PP, Wool/PET, Wool/PP and Viloft®/PP. Drying period was shown to be a direct function of absorption capacity [41,48] but as synthetic fibers lost higher amounts (percentage of wet weight) of moisture within 6 hours, weight loss had an indirect correlation with absorption capacity (R^2=-0.787*).

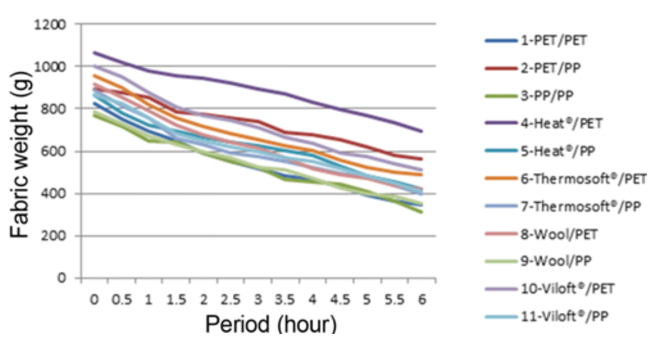


Figure 10. Drying behaviours of fabrics.

As the fabric absorbs more liquid, desorption and drying takes longer periods [14], therefore, weight losses during a certain period are lower. Minimum weight losses belonged to PET/PP (2) and Heat®/PET (4) having high absorption capacities.

Conclusion

Wool and functional yarns were combined with standard polyester and polypropylene filaments as double-face knitted fabrics for an insulation layer of a cold weather clothing. Alambeta, Permetest parameters giving idea about thermal and water vapor transfer features, wetting and wicking performances of 11 fabrics were tested. According to the results, Heat®/PP and other filament yarn fabrics had lower areal density and thickness. Staple yarns, mainly Viloft® and wool had higher air permeability but PP's performance is generally better considering all fabrics. Heat®/PP and Wool/PET had better insulation performances according to thermal conductivity/resistance and thermal difussion results. Besides Thermosoft®/PET, Heat®/PP also had lower thermal absorption, creating warmer sensations despite its filament nature, probably because of the coffee charcoal reinforcement enabling higher heat storage. Besides PP/PP, Heat®/PP gave better results also for water vapor transfer features. Thermosoft®/PET and Wool/PET were better for both sweat absorption and transfer, crucial functions for an insulation layer.

Summing up, despite the general trend for using hydrophobic fibers for inner faces/layers of knitted fabrics, wool and other functional man-made yarns such as Thermosoft®, Heat® and Viloft® can also be used for the inner faces touching the skin also for sensorial enhancements. It is thought that, results of this study can be useful for seamless garment producers that; Heat®/PP, Thermosoft®/PET and Wool/PET can be suggested for body parts where more insulation is required with also their better breathability, wetting and wicking performances. PP/PP is also better for permeability, wetting and wicking performances.

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