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# Thermophysiological Comfort Properties of Nonwoven Fabrics Developed for Apparel Industry

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## Abstract

Hydroentangled nonwoven fabrics were developed that have apparel like textile properties. In this study thermophysiological comfort properties of the developed nonwovens have been evaluated and compared with the standard woven and commercially available hydroentangled nonwoven fabrics. The developed hydroentangled fabrics were comprised of Tencel and thermoplastic bicomponent fibres and they were prepared by using the hybrid needlepunching and hydroentanglement processes. Moisture management and thermal comfort properties, which determine the warm-cool feeling of the fabrics, were determined and analysed. In this study, wicking and thermal properties of the fabrics were evaluated by using BS ISO 9073-6:2003 and BS ISO 11092:2014 standards, respectively. The attained results were compared with standard woven (cotton/polyester) and commercially available nonwoven fabric Evolon® (polyester/nylon splitable microfilament fibre)). The results indicate that developed hydroentangled fabrics exhibite the wearer. The developed hydroentangled fabrics exhibited 19.58 g/cm wicking value that is higher than the woven and Evolon® fabrics, which showed wicking values of 1.5 and 1.2 mg/cm respectively. Furthermore, the developed hydroentangled fabrics appears to be suitable for use as an outer fabric, next to skin in the apparel industry for multiple applications.

**Keywords:** Hydroentangled fabrics; Thermal properties; Moisture management; Thermophysiological

#### Introduction

Durable nonwoven fabrics have been developed that can be used in the apparel industry and the classic example is Evolon\*. Beside with other mechanical properties such as tensile and flexural rigidity, the thermo-physiological properties are also very important because these properties are directly linked to the wearer's comfort. Thermal comfort has a significant relationship with the moisture management, air permeability, water vapour permeability and the structure of the fabric. The moisture management in the fabric determines the cooling effect and therefore gives comfort to the wearer. Wearer comfort of clothing has continually assumed great importance during the last few decades. During exercise or working conditions, the human body wets because of sweating of the liquid (sweat), which does not evaporate from the skin to the atmosphere, as a result the wearer feels uncomfortable and tends to lose the working efficiency. Therefore, moisture transmission of the fabric is very important in order to optimise the wearer's comfort and for this, the wicking property of a fabric plays an important role in moisture transmission [1]. Wicking is an effective phenomenon that plays a pivotal role in maintaining the body comfort in sweat condition. Fabrics with higher wicking properties offering a dry feeling by spreading the moisture within the fabric structure coming from the body and tends to evaporate to the environment [2]. Fabric's higher moisture transmission is linked with the air permeability of the fabric.

Thermal comfort of the wearer is achieved when there is a thermal equilibrium between the human body and the environment. If the amount of the transmitted sweat is lower than that produced by the body, then the wearer will feel discomfort because of the excessive accumulation of the liquid within the structure of the fabric and that will resist the thermal transmission [3]. One of the fundamental functions of the clothing is to maintain thermal balance of the body, which depends on many factors including the textile material, environment and the clothing structure. Chen et al., also found in their research that liquid diffusion and structural properties of nonwoven materials are strongly interlinked. Fabrics with the lower thermal absorptivity values give "warm" feelings [4].

According to Mao and Russell, there are three ways through which heat is transferred through fabrics, by conduction, convection and thermal radiation [5]. Conduction is directly linked with the material properties and fibre-to-fibre contacts, convection depends on the fluid and the trapped air within the structure of the fabric and the thermal radiation is related to the heat transfer between two bodies by means of electromagnetic waves. It is known that nonwoven fabric consists of fibres and the air between the fibres, so the heat transfer from the body to the environment mainly depends on the convection and conduction process in nonwoven fabrics. Woo and Baker also found in their research that fibre and entrapped air conduction and radiation through the fabric are the primary mechanisms for heat transfer [6]. They also found that thickness of the fabric plays a pivotal role in thermal comfort; thicker fabric causes a reduction in heat transfer through the conduction and radiation processes. Conduction through the entrapped air is reduced because of the high amount of entrapped air in the thicker structure of the fabric. Fibre-to-fibre conduction is also reduced because of the tortuous path created by the fibres in the structure. Tortuous path causes an increase in the radiative absorption and scatter within the structure of the fabric.

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There are different factors that affect the absorption properties of the fabric such as, fabric area density, blend ratio, consolidation of fibres, fabric thickness, and fabric density [7]. The study reported in this paper is about characterisation and comparison the thermal comfort properties of the developed hydroentangled nonwoven fabrics for apparel applications with a woven and commercially available nonwoven fabrics for the apparel market.

## Materials and Methods

The fabrics were produced in collaboration with the Nonwovens Research Institute, University of Leeds. Two different types of fibres, Tencel® and bi-component sheath/core (PE/PET) staple fibres were used. Tencel® fibres were 1.4 dtex, 38 mm in length with a smooth surface, while the bi-component fibres were 2.2 dtex and 40 mm in length with a crimped surface. The required amount of each fibre was separately weighed and initially hand blended in preparation for the next process. The fibres were then carded (parallel laid) through the pilot carding machine and pre-needled by using 8 mm penetration and 100 strokes per min on the pilot needlepunching machine. The pre-needled substrates were then rolled and packed for use in the hydroentanglement process. The pre-needled fibrous webs were uniformly hydroentangled by using pilot hydroentanglement system and the nonwoven fabrics were prepared at hydroentanglement pressure of 125 bars with two passes, while the line speed was maintained at 3 m/min. The orifice of jet strip was 150 µm and the density of the jet orifice was 5.56/cm. All the fabrics were prepared from the same pre-needled web with nominal area density of  $150 \pm 5$  gm<sup>-2</sup>. Five samples were prepared with the blend ratio of 70/30% (Tencel/Bi-component). The details of the developed hydroentangled nonwoven, commercial nonwoven and the woven fabrics are given in Table 1.

The air permeability and wicking properties of the developed hydroentangled fabrics and the reference fabric samples were determined according to ISO 9237:1995 and ISO 9073-6:2003 standards (150  $\pm$  1 mm length and 30  $\pm$  1 mm width in machine and cross directions), respectively. The thermophysiological properties were evaluated according to ISO 11092:2104 standard. Thermophysiological properties were tested on SGHP apparatus. Thermal resistance (Rct) and water vapor resistance (Ret) properties of the nonwoven fabrics were also obtained by using the SGHP apparatus. The samples were conditioned at 20°C prior to testing. The samples were coated with gold and images were obtained by using the scanning electronic microscope [8].

## **Results and Discussion**

The air permeability results for the three fabrics tested are presented in Figure 1. It is apparent that the prepared hydroentangled nonwoven fabric showed air permeability values that are similar to the woven fabric but significantly higher than the commercial nonwoven fabric (Evolon). This is mainly due to the fact the developed hydroentangled fabric has a more porous structure as compared to the commercial nonwoven, as shown in Figure 2.

The results presented in Table 1 show that the commercial nonwoven and woven fabrics have lower thickness values than the developed hydroentangled nonwoven fabric, thus the developed hydroentangled fabric is not too compact as compared to the other two fabrics. The more open and loose structure of the developed fabric results in the higher air permeability values obtained. It has been reported by Guocheng et al., that the air permeability of the fabric affects the thermal characteristics of the fabric [4]. For example the higher air permeability results in the slower rate of heat transfer from the human body to the environment because of the large number of pores in the fabric structure. The researchers suggested that the higher number of pores mean higher number of entangling points in the fabric structure and this leads to more trapped air in the fabric structure that resist the heat transfer process. They also found that the air permeability is directly proportional to the thickness of the fabric, and it can be seen Table 1 that the developed hydroentangled fabric showed higher fabric thickness (0.88 mm) than the commercial nonwoven (0.43 mm) and the woven fabric (0.50 mm). The SEM images presented in Figure 2 demonstrate that the structure of hydroentangled fabric (B) is significantly more open as compared to the Evolon structure (A). Therefore, it can be determined that the developed hydroentangled fabric showed the higher air permeability value because of its porous structure, which could have a direct effect on the thermophysiological properties of the fabric because of the trapped air within the structure of the fabric. Varshney et al., also found that on increase in the volume of the air entrapped in the fabric structure causes a reduction in the heat flow through the fabric [9].

The developed hydroentangled fabric was prepared by using Tencel and bi-component (PE/PET) fibres. When the fabric after hydroentangled process, was subjected to the thermal process, the low melt part of the bicomponent fibre (PE sheath) melted and reduced the porosity of the fabric, which caused a lowering of the air permeability, leading to higher heat transfer from the human body to the environment. Since the lower porosity means that there will be less air trapped within the structure of the fabric and it allows more heat transfer.

Moisture circulation properties of the fabrics play a vital role in thermophysiological comfort around the body. As has been discussed above that there are many factors that are linked with the moisture circulation within the fabrics, such as the fabric structure, fibres content and finishing of the fabrics. Moisture circulation mostly depends on the wicking properties of the fabrics. The results presented in Figure 3 show that the developed hydroentangled nonwoven fabric (H1) exhibited the highest wicking values, both in the machine and cross machine directions.

The developed hydroentangled nonwoven fabric (24.48 g.cm and 14.56 g.cm) showed much higher wicking values as compared to the commercial nonwoven fabric (1.34 g.cm and 1.10 g.cm) in machine and cross machine directions. The higher wicking properties of the developed fabric are a result of its open fabric structure. It can be seen

Fabric Type	Manufacturing Process	Contents	Area Density (gm²)	Thickness (mm)	Bulk Density (gcm <sup>-3</sup> )	
H1	Hybrid process of pre-needled and hydroentanglement	Fibril Tencel and bi-component (sheath/ core) PE/PET	145	0.88	0.17	
E1	Spunlaid and hydroentanglement	Splitable bi-component (isle-land-in-sea) PET/PA6 filament	140	0.43	0.32	
W1	Weave	Cotton and PET	144	0.50	0.29	

Table 1: Physical properties of developed hydroentangled nonwoven, commercial nonwoven and woven fabrics.

in Figure 4 that the developed hydroentangled fabric showed presence of parallel and smooth strands that are absent in the structure of the commercial nonwoven fabric. The fine fibrils in the strands within the developed hydroentangled structure created very fine capillaries or tubes, which help to move the moisture away from the body and spread it within the structure of the fabric thus providing comfort to the wearer during intensive working condition. Mijovic et al., have reported that during the hot condition of the body (35°C), the heat flow mainly depends on the evaporation method of the fabric rather than the radiation and conduction processes (Figure 4) [10].



Figure 1: Air permeability of developed hydroentangled nonwoven, commercial nonwoven and woven fabrics.



Figure 2: Topical view of commercial hydroentangled (A), developed hydroentangled nonwoven (B) and woven (C) fabric structures obtained by SEM at 1 mm size.



commercial nonwoven (E1) and woven (W1) fabrics.



Figure 4 shows that the commercial nonwoven fabric exhibited haphazard distribution of filaments within the fabric structure, which resists the moisture circulation within the fabric structure causing discomfort for the wearer because of the clinging of the fabric to the body. Furthermore, the developed hydroentangled fabric is mainly composed of Tencel fibres (70%), which has good water absorption properties since the water is absorbed within its structure rather than just on the surface of the fibres. Secondly, because of their fibril structure, the fibres create a large number of capillaries, which also help to disperse the water within the fabric structure [11]. Figure 5 illustrates the different mechanism of heat transfer from the human body to the environment. It can be seen that with the increasing body temperature, the heat transfer mechanism changed from radiation at 20°C to evaporation at 35°C. At 20°C heat transfer mainly depends on the radiation process, where more airy structure can cause discomfort to the wearer because of the trapped air in the structure, which resists the heat flow from the body to the environment. But when the body sweats, then the water replaces the air in the structure and wicking of the liquid carrying the heat from the body evaporates to the environment (Figure 5).

It can be seen in Figure 3 that the developed hydroentangled fabric showed maximum wicking, both in the machine and cross directions. This suggests that the developed hydroentangled fabric will absorb maximum amount of liquid from the body because of the Tencel fibres, which absorb water within the fibre structure and then the excess water evaporates to the environment because of the forced convection method, which occurs with the help of the fresh air.

#### Thermal absorptivity (Dry)

Fabrics with lower thermal absorptivity values give a "warm" feeling [12]. The results presented in Table 2 show that the developed hydroentangled fabric (H1) has lower value of thermal absorptivity (b) in the dry condition as compared to the commercial nonwoven (H1) and woven (W1) reference fabrics. There appears to be two main reasons that the developed fabric showed a lower value of heat absorption. Firstly, the developed nonwoven fabric has a porous structure and the dead air can be trapped within the pores, which provides resistance to transfer of heat from the fabric to the environment (Figure 6). Secondly, the thickness of the developed nonwoven fabric is higher than both the reference fabrics. It was observed by Frydrych et al., that the heat diffusion depends on the thickness of the fabric, because the heat waves spend more time in a thicker fabric than in a thinner fabric structure (Table 2) [12].



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The results given in Table 2 also show that the reference plain woven fabric exhibited the highest dry thermal absorptivity value because of its systematic fabric weave and a lower thickness value. The commercial hydroentangled nonwoven exhibited a thermal absorptivity value of 104 w.m<sup>-2</sup>.S<sup>1/2</sup>. K<sup>-1</sup>, which was higher than the developed hydroentangled nonwoven fabric (77 w.m<sup>-2</sup>.S<sup>1/2</sup>. K<sup>-1</sup>) and lower than the reference woven sample (130 w.m<sup>-2</sup>.S<sup>1/2</sup>.K<sup>-1</sup>).

Firgo et al., found that the thermal absorptivity of 100% Tencel fibre was higher than that of 100% cotton fibre and an increase in the thermal absorptivity of Tencel fibre was observed as the air humidity was increased [13]. The hydroentangled fabric developed in this study is composed of 70% Tencel and 30% bicomponent sheath/core PE/PET fibre and it is the addition of the bicomponent fibre in the developed hydroentangled fabric that lowered the thermal absorptivity of the fabric, as shown in Figure 6.

In a compact structural material, the heat transfer occurs by the conduction through fibres [14]. Based on this motion as expected in the dry state, the commercial nonwoven and reference woven fabrics exhibited thermal absorptivity values that are higher than the



Figure 6: Microscopic image of hydroentangled fabric (H1) produced at 125 bars hydro pressure.





developed hydroentangled fabric. The developed hydroentangled has loose structure in which the air is trapped in the fabric interstices, resulting in a decrease in the conduction of heat within the developed hydroentangled fabric. Snezana et al., found that the heat transfer is also affected by the morphology and structure of the fibre [14]. More crystalline fibres give better heat conduction, and it is noted that the commercial hydroentangled fabric consisted of polyester and nylon fibres and that polyester shows higher crystallinity due to which the commercial nonwoven (E1) also has enhanced thermal absorptivity. These researchers also demonstrated that the loose structure consisted of entrapped air, which acts as an insulating medium and thus slows down the transfer of thermal energy within the fabric. Milenkovic et al., found that the fabric thickness and entrapped air are the major factors that influence the heat transfer from the body to the environment [15]. The developed hydroentangled fabric exhibited the highest thickness and loose structure; therefore, it was expected to show the lowest thermal conductivity in the dry condition (Figure 7).

Fabric density also has a significant effect on its thermal absorptivity. Kandhavadivu et al., have demonstrated that as the amount of fibre per unit area of the fabric increases, the thermal conductivity of the fabric also increases [16]. The fabric density has a direct effect on the thermal properties of the fabric. Figure 8 show that the commercial hydroentangled fabric exhibited higher thermal absorptivity as compared to the developed hydroentangled fabric because of its higher fabric density. The highest value of thermal absorptivity was exhibited by the woven fabric. The woven fabric has a set regular pattern of weave with an even distribution of pores and compactness, this helps in uniform conduction of heat by the fabric (Figure 8).

On the basis of these results, it can be concluded that the developed hydroentangled fabric keeps the body warm because of its low thermal absorptivity. However, because of its porous nature, the fresh air can enter the fabric structure and push the trapped air out and transfer the heat into the environment during any physical activity, thus giving the body cooling effect and comfort, as illustrated diagrammatically in Figure 9.



Figure 8: Effect of fabric density on the thermal absorptivity of the developed and commercial hydroentangled and woven fabric in dry condition.

S#	Fabrics	Thickness @ 5 g/cm² (mm)	Wt. g/m²	Density g/cm³	DRY		WET		% of loss in	9/ of receivery offer 4
					b	r	b	r	warmth to touch	min wetting
					(w.m <sup>-2</sup> .S <sup>1/2</sup> . K <sup>-1</sup> )	(K.m <sup>2</sup> .W <sup>-1</sup> )	(w.m <sup>-2</sup> .S <sup>1/2</sup> . K <sup>-1</sup> )	(K.m².W <sup>-1</sup> )		
1	H1	0.86	150	0.174	77	23.7	494	9.8	541%	44.58%
2	E1	0.43	140	0.325	104	20.9	484	7.7	365%	36.8%
3	W1	0.48	144	0.300	130	20.4	437	7.0	226%	34.31%

\*b: Thermal absorptivity, r: Thermal resistance

 Table 2: Comparison of thermal absorptivity of developed hydroentangled fabric nonwoven with commercial nonwoven and woven fabrics.

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## Thermal absorptivity (Wet)

The developed hydroentangled nonwoven fabric exhibited higher thermal absorptivity in the wet condition as compared to the commercial nonwoven and woven fabrics, as shown in Table 2. It was because of its higher wettability or absorption as compared to the other fabrics. Tencel fibres have higher water absorption rate than cotton (woven W1), and secondly, because of the fibril nature of Tencel fibres, the absorption and dispersion of water within the fabric structure is enhanced. Water is highly conductive medium and has the capability to absorb heat from the body and transfer it to the environment.

The higher thermal absorptivity value of the developed hydroentangled fabric can be related to the presence of Tencel fibres and their fine structure. The commercial hydroentangled nonwoven fabric also showed higher absorptivity than the woven fabric. The commercial hydroentangled fabric (E1) is composed of bicomponent polyester and nylon filaments, which do not absorb the water inside the fibres and therefore they transmit the water from the body and transport it to the environment.

The lowest value of thermal absorptivity was shown by the woven fabric. Although, the fabric is made of cellulose based fibres, but because of its compact weave structure, it has low moisture absorption from the body. Furthermore, because of its fine yarns, the fibres were not able to act as capillaries, due to which the fabric showed lower values of thermal absorptivity in the wet condition. Thermal absorptivity is a surface property and the finishing processes can affect this property considerably [3].

After the thermal bonding process, the thermal absorptivity in the dry state of the developed hydroentangled nonwoven fabric (H1) can be changed. During the thermal bonding process, the sheath part of the bicomponent fibres (PE) will melt and will create thermal bonding with the surrounding fibres and it will also have an effect on the porous structure of the fabric, which will result in the reduction of the amount of trapped air in the fabric structure.

## Conclusion

Hydroentangled nonwoven fabrics were manufactured by employing manmade and synthetic blends of fibres and then characterised for their thermophysiological comfort properties. Thermal comfort values of nonwoven fabrics can be engineered by the selection of appropriate fibres and manufacturing techniques. The thermal comfort in the dry state of the developed hydroentangled nonwoven fabrics are affected by their structure because of the trapped air within the fabrics. However, in the wet state the developed hydroentangled nonwoven fabrics give better comfort level to the wearer because of their higher moisture management properties. The moisture management and air permeability of the fabric are linked with the types and orientation of the fibres in the fabric structure. SEM images provide a good insight of the fibre placement and orientation within the structure of the fabrics.

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