

Engineering Weft-Knitted Spacer Structures for Enhanced Wicking in Menstrual Underwear

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I. INTRODUCTION

Reusable menstrual underwear is an undergarment that is designed to absorb and hold blood during the menstrual cycle. They are usually made with multiple layers consisting of wicking and absorbing fabrics, including an additional barrier layer for leak-proofing [1]. In published literature [2], the function of the skin-contact or wicking layer is to promptly wick and transfer the fluids into the subsequent absorbent layers. Additionally, consumer reviews of existing reusable menstrual underwear emphasized the need to minimize the spread of fluid and prevent rewetting of the skin contact surface [3].

Wicking can be defined as the natural flow of liquid through a porous material that is triggered by capillary pressure. Contact angle and capillary radius play a significant role in determining the vertical, horizontal, and transverse wicking. When the contact angle and capillary radius are lower, capillary pressure becomes greater. Furthermore, when the contact angle is lower while the capillary radius is higher, the horizontal spread of the liquid becomes higher. Thus, how the moisture spreads and travels within a porous material can be engineered by controlling the above two parameters [4]. Higher net capillary pressure through the fabric ensures one-way fluid transfer. Simultaneously, higher horizontal spread in the outer surface compared to the inner surface can be achieved by making that surface more hydrophilic while lowering its capillary radius [5].

Only a few published studies were present on reusable menstrual underwear, especially with a focus on design and development [1]. Additionally, most of the research [2] and patents [6] did not disclose the technical specifications of the wicking layers. Moreover, no publications were available on wicking fabrics designed specifically for menstrual fluid transfer without the use of zonal or engineered finishes.

Several studies have focused on wicking fabrics that focused on achieving unidirectional liquid transfer and increased horizontal diffusion for sweat management applications, which could potentially be adapted for menstrual underwear products. Those studies investigated three-thread fleece fabrics [8, 9] and plated weft-knitted fabrics [9, 10] that had layered structures. The skin-contact surfaces of those fabrics had less hydrophilic yarns with lower yarn counts and higher filament counts compared to their outermost surfaces to achieve the above-mentioned properties.

Weft-knitted spacer fabric structures could also satisfy that requirement by incorporating yarns with different

hydrophilicity, as well as yarn and fiber counts to the face, back, and spacer yarns. Spacer fabrics also possess the advantages of low area density, low bulk density, freedom of thickness modifications, layered structure capability, and design flexibility [12 - 14]. However, the use of spacer fabrics with the above-mentioned principles for enhanced wicking function has not been explored in any of the published literature. Therefore, the present study aims to address the knowledge gap in that area.

In this study, fifteen weft-knitted spacer fabrics were developed following the aforementioned yarn and fiber requirements. The unidirectional liquid transfer and horizontal wicking performance of their outermost surfaces were evaluated to determine their suitability as the wicking layer in menstrual underwear.

II. MATERIALS AND METHODS

A. Spacer Structure Design and Development

The identified layered effect was achieved by using two sets of nylon (ContiFibre, Italy: Bright trilobal PA66, 40D/20f) and polyester (Toung Loong Textile MFG, Taiwan: Round hollow cross-section, 100D/100f) yarns with different yarn and fiber counts, as well as different hydrophilicities for the face and back yarns. A high moisture-wicking polyester Coolmax yarn (ContiFibre, Italy: Four channel cross-section, 2-fold 78D/88f) was selected for the spacer yarn to promptly transfer the fluids through the fabrics into the back layer.

Fifteen three-thread flat weft knitted spacer fabric structures were selected and divided into groups A and B according to the stitch formation type of spacer yarns. In both groups, face and back yarns create only knit loops. Group A included structures in which the spacer yarn created tuck stitches in the front bed and knit stitches in the back bed instead of tuck stitches compared to conventional spacer fabrics [12, 13]. The purpose of this selection was to assess the effect on wicking from having more area of hydrophilic Coolmax yarn in the reverse side of the fabric through the knit loops. Conversely, group B included structures in which the spacer yarn connected to both face and reverse layers through tuck stitches. The variations within the two groups were obtained by varying the consecutive knit, tuck, or miss stitches along a course or a wale. The details of the structures are illustrated in Table 1.

Fifteen structures were developed using a fully computerized flat knitting machine (Shima Seiki N. SVR123SP, Japan). The SDS-ONE KnitPaint software was used to design and program the fabric structures. During development, the machine gauge was set to 14E, and the take-down tension was maintained within the 30-35 range. Digital

Stitch Control System (DSCS) mode was employed, with the loop length setting fixed at 3.8 mm for all structures.

B. Testing and Evaluation

The developed fifteen fabric structures were tested using the Moisture Management Test (MMT: AATCC 195), Fabric Weight Test (GSM: ASTM D3776), and Fabric Thickness Test (ASTM D1777-96).

The Moisture Management Test (MMT) was conducted with SDL ATLAS Moisture Management Tester model M290 MMT for both sides of each structure, with five specimens for each side. Mean values for the properties of wetting time, absorption rate, maximum wetted radius, accumulative one-way transport index, spreading speed, and overall moisture management capacity (OMMC) were obtained for each side of the fabric structures. In this test, the side of the specimen onto which the liquid is dropped is referred to as the top surface, while the other side is referred to as the bottom surface. Additionally, the face side of the fabric structures was considered as the skin contact surface. For validating the effectiveness of the developed spacer fabrics for menstrual underwear applications, a commercially available wicking fabric was used for comparison. This fabric had a mesh jersey structure along with a zonal-wicking finish, a GSM of 140, and a thickness of 1.1 mm. In the results section, this fabric is denoted as “R”.

B2	-	v [^]					176
	v [^]	-					
B3	2 -	2 -	2 -	2v [^]			182
	2 -	2 -	2v [^]	2 -			
	2 -	2v [^]	2 -	2 -			
	2v [^]	2 -	2 -	2 -			
B4	2 -	2v [^]					233
	2v [^]	2 -					
B5	2 -	2 -	2v [^]	2v [^]			244
	2v [^]	2v [^]	2 -	2 -			
B6	2 -	2 -	2 -	2v [^]	2v [^]	2v [^]	174
	2v [^]	2v [^]	2v [^]	2 -	2 -	2 -	
B7	-	v [^]	-	v [^]			143
	v [^]	-	-	-			
	-	v [^]	-	v [^]			
	-	-	v [^]	-			
B8	^	v					180
	v	^					

^aOne square represents one set of needles of front and back needle beds. -: Miss stitch, v[^]: Tuck stitches in both beds, vΩ: Tuck stitch in front bed and knit stitch in back bed, v: Tuck stitch with only front bed, ^: Tuck stitch with only back bed, 2: creates stitches in two consecutive courses in same wale.

TABLE I. SELECTED SPACER STRUCTURES

Structure	Repeat Unit of Spacer Yarn ^a						GSM
A1	-	-	-	vΩ			137
	-	-	vΩ	-			
	-	vΩ	-	-			
	vΩ	-	-	-			
A2	-	vΩ					153
	vΩ	-					
A3	2 -	2 -	2 -	2vΩ			174
	2 -	2 -	2vΩ	2 -			
	2 -	2vΩ	2 -	2 -			
	2vΩ	2 -	2 -	2 -			
A4	2 -	2vΩ					229
	2vΩ	2 -					
A5	2 -	2 -	2vΩ	2vΩ			197
	2vΩ	2vΩ	2 -	2 -			
A6	2 -	2 -	2 -	2vΩ	2vΩ	2vΩ	223
	2vΩ	2vΩ	2vΩ	2 -	2 -	2 -	
A7	-	vΩ	-	vΩ			135
	vΩ	-	-	-			
	-	vΩ	-	vΩ			
	-	-	vΩ	-			
B1	-	-	-	v [^]			152
	-	-	v [^]	-			
	-	v [^]	-	-			
	v [^]	-	-	-			

III. RESULTS AND DISCUSSION

As shown in Fig. 1, all fabric structures had positive values (>1) for the one-way-transport capacity index grade (grade = index/100) of the face-to-reverse direction while having a value higher than the index of the reverse-to-face direction. A lower index in the reverse-to-face direction is a good indicator of reduced rewetting potential. Furthermore, values greater than 100 (grade 1) for the one-way-transport capacity index could be considered fabrics with good one-way transport ability [15]. Thus, it can be concluded that all the developed weft-knitted spacer fabrics successfully achieved the identified one-way fluid transfer requirement for the menstrual underwear application. It was also observed that group B (mean grade value 3.169, variance 0.660) outperformed group A (mean grade value 2.178, variance 0.103) in the one-way-transport capacity index considering the face-to-reverse direction. Structure B2 of group B showed the highest value with a grade of 4.688 (index 468.81). Meanwhile, the reference fabric showed a grade of 3.986, placing it second compared to the developed 15 structures. It is noteworthy that B2 managed to outperform R in both face-to-reverse and reverse-to-face direction one-way-transport capacity indices without any additional finishes.

All structures of group A had equal wetted radii for both top and bottom surfaces, while all structures of group B had higher wetted radii in their bottom surfaces compared to their top surfaces as shown in Fig.2. Thus, it can be concluded that only group B was able to satisfy the required fluid spread requirement. B2 also had the highest ratio of maximum wetted radii between the bottom and top surfaces with a value of 2.40. Furthermore, it also had the lowest value for the maximum wetted radii of the top surface with a value of 10 mm. Moreover, B2, B4, and B8 of group B showed a higher wetted radii ratio compared to R (1.500).

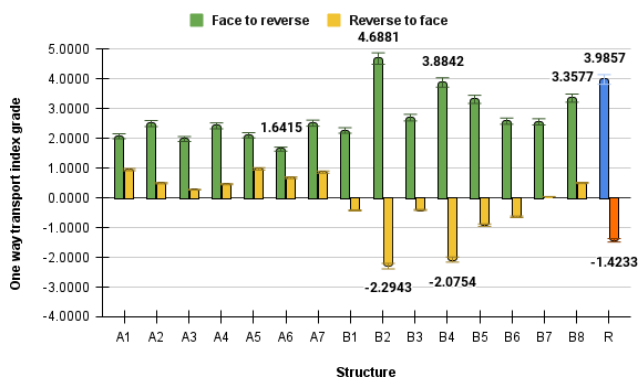


Fig. 1. One-way-transport-capacity index grade

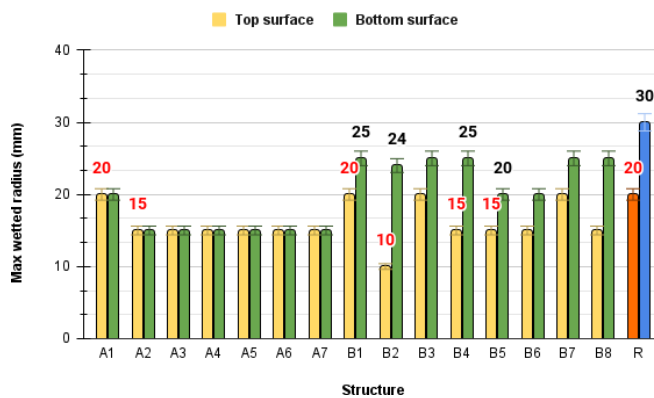


Fig. 2. Max wetted radius

With these results, it can be concluded that fabric structure B2 of group B was the best-performing spacer fabric in terms of the one-way-transport capacity index and fluid spreading radius. When examined under a counting glass, it was identified that B2 had larger openings on the face side than other structures in the group. This could be linked to the higher performance of B2. However, further analysis was not conducted, as it was beyond the scope of this study. In addition, it was evident that the spacer structures of group A, in which the spacer yarn formed knit stitches in the back bed as opposed to tuck stitches, performed worse compared to structures of group B. This could be linked to the fact that the knit loops of Coolmax spacer yarns on the reverse side are hidden behind the knit loops of polyester back yarns due to the effect of tension. However, further analysis is required to conclude this hypothesis.

Several structures in group B outperformed reference fabric R, further validating the performance of the developed spacer fabrics against commercial menstrual underwear applications.

IV. CONCLUSION

The use of spacer fabrics with the principles for enhanced wicking function: the inner (skin contact) surface of the fabric being more hydrophobic than its outer surface, and the yarn diameter of the inner surface being smaller than the yarn diameter of the outer surface, has not been explored in any of the published literature. Thus, this study established the ability of the developed spacer structures' one-way-transport capacity with the above yarn requirements.

The spacer structures of group B where the spacer yarn formed tuck stitches in the back needle bed as opposed to knit stitches outperformed the spacer structures of group A. It was identified that structure B2 was the best-performing fabric across the fifteen developed spacer fabrics in terms of the one-way-transport index and fluid-spreading radii. It was also identified that several structures in group B performed better or similarly to the reference fabric R, validating the superior performance of the fabric developments against commercial menstrual underwear applications. The findings in this study can serve as a guideline for developing an effective wicking layer for menstrual underwear. Future testing with synthetic menstrual blood stimulant liquid could be conducted to further validate the performance of the identified effective structures.

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