Investigating Moisture Management Property of a Bi-layer Fabric Through Nanofiber-coated PET as a Novel Sewing Thread: Vertical Wicking Test

AfsanehValipouri*, Zahra Farzin, Seyed Abdolkarim Hosseini Ravandi

Abstract*- One of the common moisture management methods is to use a multilayer fabric structure which is capable to facilitate moisture transfer through fabrics. The present work aims at investigating the rate of liquid transfer through nanofiber-coated yarn as the sewing threads attaching two layers of fabric (hydrophobic/hydrophilic). Visual observations were carried out to make a comparison among vertical wicking rises in the nanofiber-coated yarns and the conventional yarns, The effects of voltage parameters, number of filaments per yarn and solution concentration on the height of wicked water were investigated. The highest rate of wicking belonged to the PAN nanofiber-coated yarn prepared at a voltage of 18 kV. Then, two layers of hydrophobic and hydrophilic fabrics were joined using nanofiber-coated yarns as the sewing threads to investigate the rate of liquid transfer through bilayer fabrics. The average liquid transfer in fabric was obtained by estimating the rate of reduction of the size of water droplet which was placed on the sewn thread on the hydrophobic fabric. The size of each droplet was measured at every 0.03 s, accurately. The coated yarn in compare to the conventional yarn showed higher rates of moisture transfer from the hydrophobic to the hydrophilic fabric.

***Keywords*: moisture management, bi-layer fabric, wicking, liquid transfer, nanofiber-coated sewing thread**

I. INTRODUCTION

Fabric moisture management possesses a great importance in fabric and textile applications [1, 2]. Wicking is an important factor affecting moisture transfer which has been a point of attention for many researchers [3, 4]. This phenomenon is strongly important in the case of clothes and apparel which determines comfort [5, 6]. As stated by Xu *et al.* (2016), the moisture wicking ability, diffusivity and evaporation ability of fabrics can greatly affect cooling efficiency and performance even in construction and building applications [7]. Moisture-management textiles are widely used in other applications that require water repellent property on one side and water absorbing property on the other, such as medical operation gowns, wound dressings, and hygienic products [8]. Other research studies were based on introducing novel fabrics with special structures to be used in many applications such as cloths [9], carpets, manmade grass, and geotextiles which could keep the under-covered area dry [10]. Zhu *et al.* (2016) found that bifacial fabrics (knitted/woven) could be used as moisture-management fabrics, without the need for any additional treatments [11].

In the case of apparel, according to Frackiewicz-Kaczmarek *et al.* (2014), the moisture content is not constant among body regions and is related to the regional fit of the clothing [12]. As the clothing fit control in high perspiration conditions is not applicable, the moisture management in the case of accelerating moisture transfer and spreading it as soon as possible is more appropriate choice. Mbise *et al.* (2017) have found that one of the factors affecting moisture transfer is the hydrostatic pressure difference between the two layers of spacer fabric [13]. However, the hydrostatic pressure, which is influenced by temperature, is not constant among body regions. Therefore, it can be concluded that regional temperature and fit should be also considered in apparel design to improve clothing comfort.

One concept is to assemble different fabrics with altered water absorption properties in different parts of the body [14]. Another concept is to use fabrics made from novel yarns with special abilities [15,16]. The ability of yarn could relies on enhancing the rate of moisture transfer through wicking phenomenon in one hand and spreading the moisture to the ambient air as soon as possible [17-19], in the other hand. However, less works have been done in the case of sewing threads. In the present work, novel sewing threads are used in a bilayer fabric structure to investigate the possibility of managing liquid transfer.

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TABLE I
TEST VARIABLES AND CHARACTERISTICS OF SAMPLES

Number of coated-yarn ply	Voltage (kV)	Solution concentration (wt%)	Type of yarn/coating solvent	Sample code
5	14	11	PET/ PAN	PAN5f/14v/11%
5	18	11	PET/ PAN	PAN5f/18v/11%
1	18	11	PET/ PAN	PAN1f/18v/11%
5	18	13	PET/ PAN	PAN5f/18v/13%
5	12	7.5	PET/ PVA	PVA1f/12v/7%
5	0	0	PET/ without coating	Pristine PET

To achieve an enhanced wicking ability of yarns, some previous researchers have introduced novel materials or techniques applicable on yarns. For instance, Valipouri *et al.* (2014) investigated the capillary rise in poly(L-lactic acid) nano/micro fiber yarns which were fabricated by electrospinning. According to their work, it was concluded that the surface porosity and fibers fineness in the electrospun yarn have a major effect on the capillary rise phenomenon [20]. Hajiani *et al.* (2014) investigated wicking rise in polyamide 66 twisted nanofiber yarns and concluded that with an increase in the yarn twist the vertical wicking of water was reduced significantly [21].

Ravandi et al. (2013) introduced another yarn using Nylon66 filament coated by nylon 66 nanofibers and showed that coating with nanofibers increases the height of wicked water [22]. Jad *et al.* (2011) investigated the vertical wicking in polyacrylonitrile (PAN) electrospinning nanofiber yarn and indicated that production parameters of nanofiber yarn should be chosen appropriately to obtain the desired properties of wicking rise [23]. However, there is still need of more scientific researches in this field to be used for further developing of novel yarns. The present work aims at increasing liquid transfer through a bilayer fabric which contains two layers of hydrophobic and hydrophilic fabrics.

Firstly, the effect of coating of the polyacrylonitrile nanofibers on the wicking rise of polyester yarn was investigated. Afterwards, the conventional and coated threads were used as the sewing threads to join two layers of hydrophobic and hydrophilic fabrics. Then, the liquid transfer of bilayer fabric on the sewn thread was investigated.

Previously, most of wicking tests based on image processing techniques included the strip test and the spot test [3, 24]. In the present work, vertical wicking test was used to investigate the effect of nanofibrous coating on thecapillary rise of water in yarns. Moreover, estimating the reduction rate of droplet size on the fabric surface is considered to be more appropriate technique in the case of point transfer.

II. MATERIALS AND METHODS

A. Preparation of nanofiber-coated hybrid yarn:

Polyacrylonitrile (PAN) polymer and polyvinyl alcohol (PVA) were used as the nanofiber materials for coating multifilament polyester yarn (PET). PVA with Mw=72000 g/mol was prepared from Merck Co, Germany. PET multifilament yarn (Mw=100000 g/mol) and PAN polymer (Mn=70000 g/mol) were prepared from Polyacryl Co. Dimethylformamide and double distilled water were used as the solvents of PAN and PVA, respectively. The samples characteristics are presented in Table I. To achieve the appropriate coating, all of the samples were prepared at a constant solution feed rate of 0.7 mm/h, twist of 168 TPM and the production rate of 1.52 m/h.

B. Electrospinning Coating of filaments:

The schematic of multifilament coating process setup is shown in Fig. 1. A bobbin was placed on a holder carrying the core filaments. An electrical field was applied between two nozzles with opposite polarity while a conductive half-sphere was employed near the electric field center to collect and guide the nanofibers onto the core filaments. The polymer solution fed by means of two syringe pumps, was subjected to the electric field system. Therefore, the

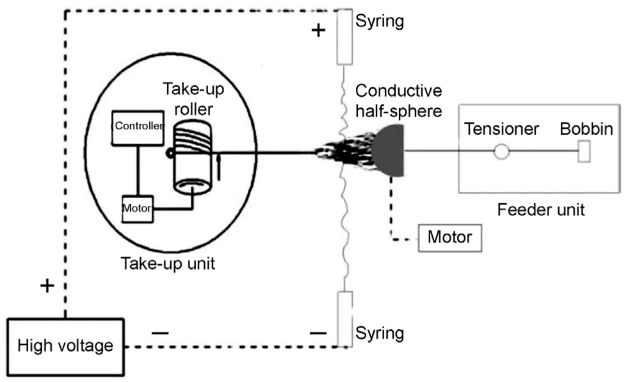


Fig. 1. Schematic of multifilament coating process setup [25].

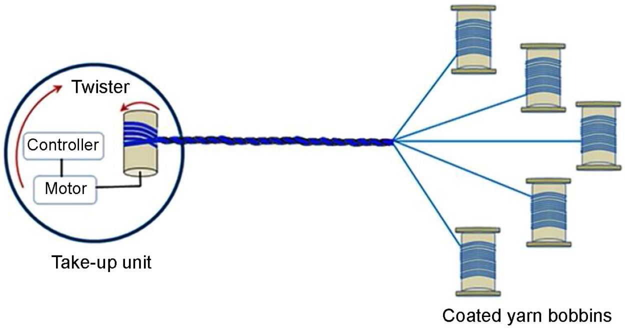


Fig. 2. Schematic of yarn plying setup.

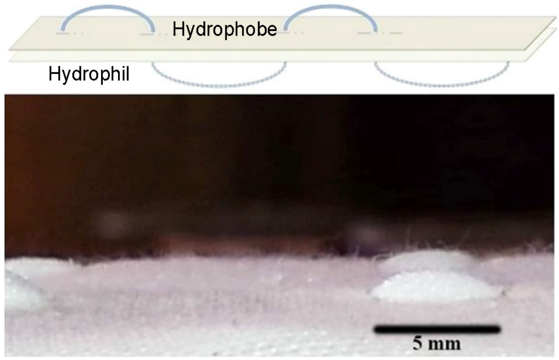


Fig. 4. Stitches in bi-layer fabric (hydrophobic side).

polymer solution was receiving an appropriate tension by the electrical forces and nanofibers collected on the half-sphere were pulled out onto the core filaments, forming a "spinning cone". This procedure let the nanofibers to cover the surface of the core filaments. Afterwards, the coated yarn was collected at a defined speed while receiving a defined value of twists. Also, to obtain multiplied coated yarn, 5 nanofiber-coated yarns were plied (see Fig. 2) to increase the yarn diameter to be suitable for transferring liquid water droplet through bi-layer fabric structure.

C. Wicking Test

To investigate the wicking phenomena in single ply and multiplied yarns, 0.05% of red acid dye was used to achieve a colored liquid. The molecular weight of the dye was 400.384 g/mol. All of the tests were carried out at the standard condition (i.e. RH: 65%, T: 20 °C).

An 8 Megapixel camera was used to record the heights of wicking rise with time. As shown in Fig. 3, one end of thread was attached to a holder and 10 mm of the other end was placed into the color solution (Acid Red AV), while slightly stretched by a defined weight (0.1 g/den). A ruler was used to show the height of the water wicked through thread. The average of 5 observations was recorded as the height of wicked water.

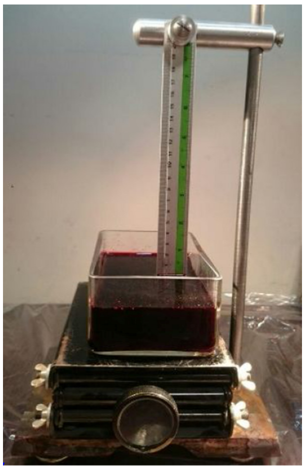


Fig. 3. Investigating the heights of wicking rises in threads.

C. Evaluating moisture transfer through sewing threads in fabrics

Woven cotton fabric was used both for the hydrophobic and hydrophilic fabrics. Hydrophobic property was achieved by using By-Guard water proof coating. Then, the hydrophobic fabric was joined to the hydrophilic one by sewing threads. The class 200-manual stitches were performed on the bi-layer fabric, as shown in Fig. 4. The stitch length at the hydrophobic and hydrophilic side was equal to 0.5 and 1.5 cm, respectively.

Afterwards, each bi-layer fabric was exposed under a droplet of colored water using a fixed syringe (Fig. 5). The water pressure in the syringe was accurately controlled to achieve a constant volume of every droplet. The droplet transfer was recorded and captured at every 0.03 s by the use of a fixed camera. Then, the images of droplets on the fabric surface were investigated using image processing techniques. The rate of water transfer was estimated for each sample by estimating the rate of reduction in droplet size. The average of 5 observations was determined as the rate of water transfer for each sample. Herein, side view

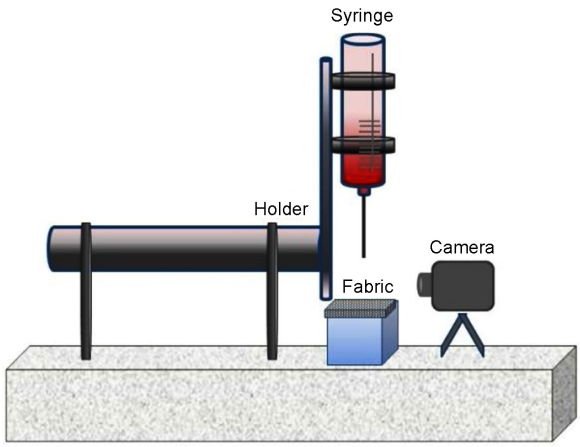


Fig. 5. Devices used to capture water droplets on the fabrics surfaces.

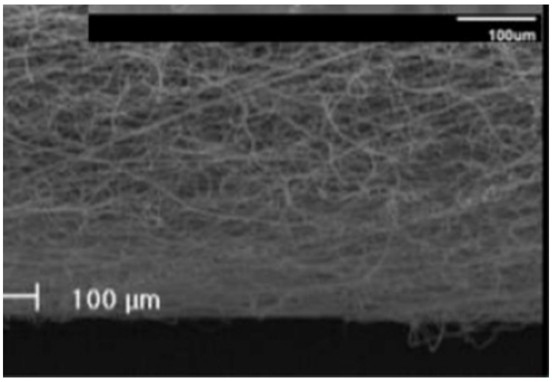


Fig. 6. A typical scanning electron microscopy (SEM) image of single-ply yarn.

observations were performed to make a better investigation in the case of shape of droplets.

III.RESULTS AND DISCUSSION

Fig. 6 shows a typical SEM image of electrospun yarn sample which was produced for capillary rise tests.

As shown in Fig. 7, the results showed that for both single-ply PAN and PVA nanofibers, the nanofiber-coated filaments had higher rate of moisture transfer in compare to the conventional sewing threads. This is due to the fact that the maximum height of wicked water in nanofibers having small capillariy radii is higher than that of micro fibers. Eq. (1) shows the relation between the height of wicked water and the capillary radii.

$$h = \frac{2\gamma\cos\theta}{\rho g R} \qquad (1)$$

Where, h is the maximum height of wicked water; is the contact angle and R is the capillary radii.

This means that the height of colored liquid penetrated through the nanofibers capillaries is higher in compare to that of colored liquid penetrated through the micro fibers.

Therefore, the yarns coated by nanofibers had higher equilibrium wicking heights in compare to conventional yarns. This is due to the fact that the large specific surface area of nanofibers could significantly absorb liquids.

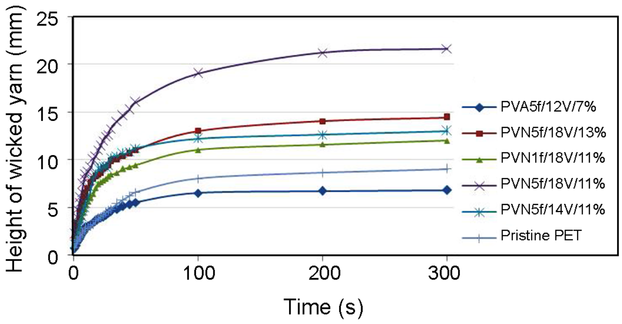


Fig. 7. Height of wicked water in different threads.

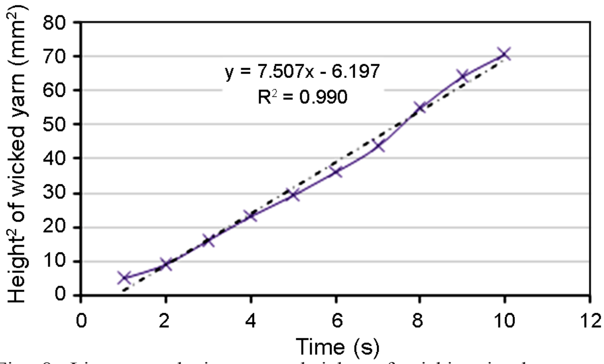


Fig. 8. Linear trends in square heights of wicking in the case of PAN5f/18v/11%.

However, the moisture transfer in the case of PVA was less compared to the PAN samples. In this case, the possible reason is the presence of hydrophilic group in PVA which could trap the moisture.

According to the results, the increase in the number of plies per yarn results in an increase of the capillary paths and the wicking height. In fact the transverse forces acting on yarn reduce the diameters of narrow paths and capillaries, which results in an increase of the height of wicked water.

Higher voltages result in higher rates of nanofiber production which indeed increase the number of fibers. As shown in Fig. 7, the height of wicking prepared at the voltage of 18 kV was higher than that prepared at 14 kV.The increase in the concentration of PAN solution from 11% to 13% results in the increase of the nanofiber diameter from 243±32 nm to 308±54 nm. It is expected that increasing concentration results in the increase of the electrical forces to keep constant tension on the electrospun jet. However, herein having a constant voltage, the number of fibers in 13% of concentration was higher than those in 11% of concentration. Therefore, increasing concentration reduces the number of capillaries, in one hand, and increasing the fibers diameters increases the capillary radius, in the other hand. It is concluded that the decrease in the concentration value results in the increase of the height of wicked water. Hence, the results are in agreement to the observations of Hosseini-Ravandi *et al.* (2013) which indicated that nanofibers with higher linear densities reduced the height of wicked water [22]. As shown in Fig. 8, the rise of wicking height for each sample showed a good correlation with the Lucas-Washburn equation.

According to the results, the higher rate of wicking was observed for the 5-ply nanofiber-coated yarn, with the voltage of 18 kV and the PAN concentration of 11% in compare to the other samples. Therefore, the best thread was considered for further investigations to study the fabrics structure.

TABLE II
SIZE OF WATER DROPLETS ON THE FABRICS SURFACES WHILE PASSING THROUGH THE CONVENTIONAL SEWING THREAD

As shown in Tables II and III, the images of droplets on the fabrics surfaces while passing through the sewn threads were captured every 0.03 s for conventional and nanofiber-coated yarn, respectively. It is clear that the water drop in the case of nanofiber-coated yarn is more pulled toward the surface in compare to the conventional yarn.

TABLE III
SIZE OF WATER DROPLETS ON THE FABRICS SURFACES WHILE PASSING THROUGH NANOFIBER-COATED SEWING THREAD

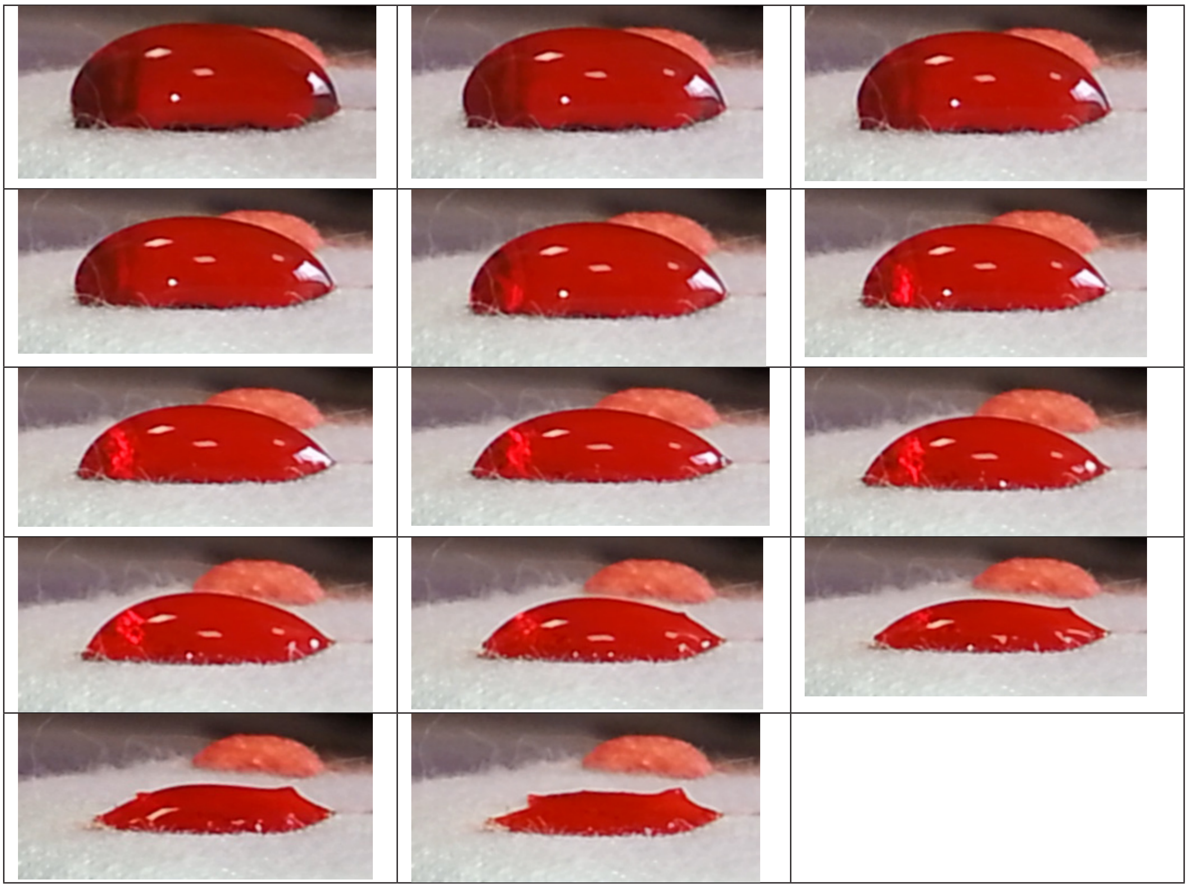
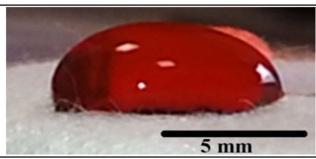
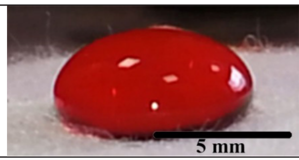


TABLE IV
STEPS OF IMAGE PROCESSING TECHNIQUES APPLIED ON EACH IMAGE OF WATER DROPLET

	Nanofiber-coated yarn	Conventional yarn
Original image		
Removing background		
Binary image		
Median filter (2.0 Pixel) to remove noises outside and maximum filter (10.0 Pixel) to remove noises inside		

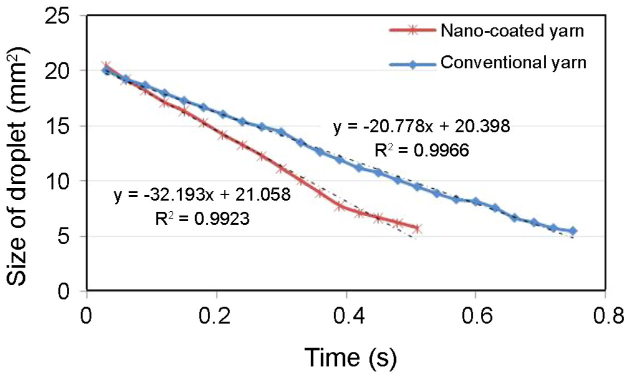


Fig. 9. Size of water droplet on the fabric surface versus time.

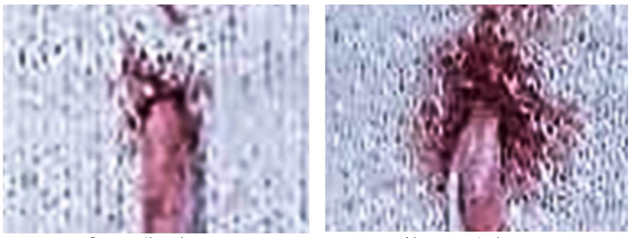


Fig. 10. Hydrophilic side of sample using conventional and nanofiber-coated yarns as the sewing threads.

Table IV shows the steps taken to estimate the reduction rate of droplet size while transferring through the sewn thread, using image processing techniques.

The size of water droplets was estimated by considering the total number of black pixels and converting them to the unit of area in mm^2. Fig. 9 shows the comparison between the rate of moisture transfer in the conventional and nanofiber-coated yarns.

Fig. 10 shows the hydrophilic side of bilayer fabric which was sewn by the conventional and nanofiber-coated threads after being wet by the droplet. It is concluded that not only the nanofiber-coated yarns have higher rates of moisture transfer, but also are capable to spread the moisture onto a wider area of the hydrophilic fabric in compare to the conventional sewing thread. Therefore, sewing nanofiber-coated yarns in some applications, which are exposed to the higher amounts of moisture, are better choices to enhance liquid transfer and make the fabric dry as soon as possible.

IV. CONCLUSION

The rate of liquid transfer in nanofiber-coated yarns being sewn in a bi-layer fabric was investigated. First of all, various threads were prepared by varying the type of coating (PAN, PVA or without coating), solution concentration (11% and 13%), number of plies (5 and 1) and the voltage of electrospinning (14 and 18 kV). The vertical rate of wicking height was investigated by the use of a digital camera. It was concluded that the yarns coated with 5 pliesat the voltage of 18 kV and the solution concentration of 11% showed the highest rate of wicking in all samples. Therefore, the mentioned condition was considered to be used in preparing the appropriate nanofiber-coated yarns for further investigations. The rise of wicking for the appropriate nanofiber-coated yarn showed a good correlation with the Lucas-Washburn equation. To investigate the rate of moisture transfer in a sewn thread in a fabric structure, two layers of fabric (hydrophobic/hydrophilic) were attached and sewn by both nanofiber-coated yarn and conventional yarn. The averages of moisture transfer in fabrics were obtained using a digital camera and image processing techniques. According to the results, the coated yarn in compare to the conventional yarn showed higher rates of moisture transfer from the hydrophobic side to the hydrophilic side. It is concluded that the nanofiber-coated yarns not only have higher rates of moisture transfer, but are also capable to spread the moisture to a wider area of a hydrophilic fabric in compare to the conventional threads. Therefore, sewing nanofiber-coated yarns in some applications which are exposed to the higher amounts of moisture are better choices to enhance moisture transfer and make the fabric dry as soon as possible.

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