Cotton Nonwovens with Unidirectional Water-Transport Properties Produced by Atmospheric Plasma Deposition

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Abstract

Cotton based nonwovens with unidirectional water-transport through the thickness of the fabric were prepared using atmospheric plasma technology. In controlling the plasma deposition parameters, a thin layer of polymerized Hexamethyldisiloxane was locally deposited onto a cotton nonwoven fabric, so that only the treated surface was hydrophobic, while the untreated surface remained hydrophilic. The water contact angle, surface morphology and chemical composition of the fabric surfaces were characterized, and the unidirectional water-transport performance, vapor transmission rate, thermal stability and durability of the treated nonwovens were tested. It was found that a super-hydrophobic surface could be durably achieved on one side of the fabric while maintaining a completely wettable surface on the other. The resulting asymmetric wettability enables the nonwovens to exhibit unidirectional water liquid-transport, without negatively affecting vapor transmission and air permeability. Such differential moisture management properties in sustainable cotton nonwovens are highly desirable for applications in hygiene, infection control and medical device applications.

Keywords

Nonwoven fabric, plasma treatment, amphoteric, unidirectional water-transport.

Introduction

Directional transport of liquids, whether relating to the management of bodily fluids in fabrics, transportation across biological membranes or nutrient transport in plants, is highly desirable in both nature and engineering applications (Zhao et al. 2017). Mechanical or capillary pressure and chemical potential are key driving forces governing the directional transmission phenomena of liquids, while fluid surface tension and wetting behaviour are also important factors. Amphoteric fabrics, also referred to as Janus materials, are those with the ability to direct the transport of liquid in one direction through differential surface functionalities. Asymmetric wetting properties include, for example, hydrophobic-hydrophilic, lipophilic-oleophobic, and amphoteric behaviour (Gore and Kandasubramanian 2018). Such materials in the form of membranes have been described by Zhou and Guo (2019) (Zhou and Guo 2019), and herein, we refer to amphoteric and Janus materials interchangeably.

A difference in the surface energies between the two sides (or regions) of the same fabric or membrane results in asymmetric wettability, and also affects the inherent driving forces responsible for unidirectional water-transport (Yang et al. 2018a). Generally speaking, Janus membranes can be divided into three categories: polymeric Janus membranes, polymeric-inorganic Janus membranes and inorganic Janus membranes (Zhou and Guo 2019). Textiles are valuable substrates for many Janus membranes because of their porous structure (Zhao et al. 2017). Such fibrous Janus membranes can be prepared as double-layer composite structures (Yang et al. 2017), for example using layer-by-layer electrospinning (Gore and Kandasubramanian 2018; Wang et al. 2018; Wu et al. 2012), or through single-sided modification (Yang et al. 2018a) using a surface treatment (Yang et al. 2019b). Owing to their unidirectional water-transport functionality, Janus fabrics have been widely applied in fields such as oil-water separation (Gore and Kandasubramanian 2018; Yue et al. 2018), fog collection (Ren et al. 2017), membrane distillation (Huang et al. 2017; Yang et al. 2017; Zhu et al. 2018) and blood plasma separation (Zhang et al. 2017) among others. In a fascinating new research paper, a “skin-like” fabric was demonstrated through controlled gradient wettability. The selectively treated hydrophilic channels amongst a hydrophobic substrate functioned like sweat glands in the human skin that repelled bulk liquid while allowing moisture transmission (Lao et al. 2020).

Although various strategies have been developed to modify the surface of membranes, the practical implementation of asymmetric modification of fabrics remains challenging. Wet chemistry easily penetrates through the thickness of many fabrics due to capillary effects, resulting in simultaneous chemical modification of both sides of the substrate. At least two methods can be implemented to address this: (a) introducing an extra interface on the surface of the fabric to separate the modified layer from the unmodified layer and (b) applying a reaction gradient along the fabric uniformly (Yang et al. 2018a). However, a simpler approach is needed that allows for cost-effective localised treatment of fabric surfaces.

Atmospheric plasma treatment has attracted considerable attention due to its ease of use at ambient conditions. Modification of fabric surfaces is possible without changing the internal composition of the fibre. Highly reactive particles that participate in the plasma reaction, such as ions, free radicals, electrons and so on (Davis et al. 2011; Yang et al. 2018a), can physically or chemically react with the substrate without causing damage to the bulk of the material (Dowling et al. 2011). The application of atmospheric pressure plasma jet processes also makes it possible to treat fabrics continuously (Li et al. 2017). Previously, researchers have prepared Janus membranes using vacuum plasma treatment (Airoudj et al. 2016; Teare et al. 2002; Yan et al. 2017), but continuous and large-scale production has not yet been achieved. In previous research, the continuous production of superhydrophobic cotton fabrics using HMDSO monomer by plasma treatment was demonstrated (Yang et al. 2019a; Yang et al. 2018b).

Herein, further research is reported exploring the preparation and behaviour of cotton nonwoven fabrics with amphoteric function, prepared by atmospheric pressure plasma treatment. By adjusting plasma jet treatment parameters, polymerized HMDSO was deposited on one side of the fabric, such that a continuous process compatible with industrial scale-up could be envisaged. The water contact angle, fibre surface morphology, and chemical composition of the two sides of the amphoteric fabric was analysed, and the directional water-transport behaviour, as well as vapor permeability, were characterized. To enable a fuller assessment of the utility of the resulting amphoteric effects, the thermal stability and durability of the treatments were also examined.

Experimental

2.1. Materials

Hexamethyldisiloxane (HMDSO, ≥ 99.0%, density=0.764 g/ml, boiling point=101 ℃) was purchased from Shanghai Aladdin Chemical Co., Ltd, China. Cotton spunlaced nonwovens (80 g/m^2, thickness=1 mm, density=80 kg/m^3) were supplied by CHTC Jiahua Nonwoven Co., Ltd, China. The cotton fibres were first bleached before the hydroentanglement process, so the final fabrics were free from any sizing agent on the surfaces.

2.2. Preparation of the Amphoteric Cotton Nonwovens

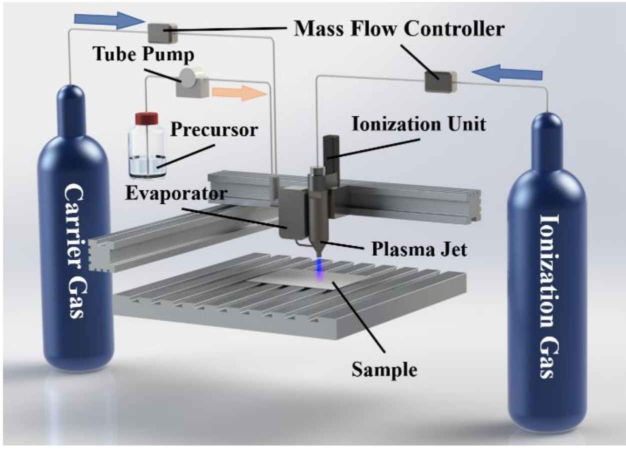

Fig. 1 Schematic Diagram of the Atmospheric Pressure Plasma System Operating with Computer-Controlled Motion and Velocity of the Plasma Jet

Amphoteric cotton nonwoven samples were prepared in a single step using an Atmospheric Pressure Plasma System (Model AS400 + PFW10, Plasma Treat GmbH, Steinhagen, Germany). The monomer (HDMSO) liquid was introduced into the afterglow region of the plasma by the carrier gas (Argon) after being heated to boiling point. HMDSO was polymerized by the energy provided by the plasma, and then deposited on to the surface of the nonwoven. By controlling the plasma process, the treated surface (TS) could be rendered hydrophobic while the untreated surface (UTS) remained hydrophilic. A schematic diagram of the Atmospheric Pressure Plasma System is shown in **Figure 1**, the gas was piped into the ionization unit, powered by an RF (21 kHz) power supply, to form the plasma. At the same time, the HMDSO precursor was piped into the evaporator via a tube pump. The temperature in the evaporator was slightly higher than the boiling temperature of the precursor. The carrier gas was directed to the evaporator and mixed with the vaporized precursor. The mixture was introduced into the afterglow region of the plasma and deposited on the surface of the nonwoven samples via the plasma jet after polymerization. The plasma jet was computer-controlled and traveled across the surface in an "S" shape. The plasma treatment is carried out under atmospheric pressure, and the movement of the plasma jet could be controlled. The precursor is directly introduced to the plasma jet for polymerization, so the sample can be prepared in one step. Industrialized large-scale production can be realized since the plasma jet is able to run continuously.

Compressed air was used as ionization gas; the voltage of the power supply was 300 V; the plasma cycle time (PCT), which influences the energy of the plasma was 60 %. Argon (Ar, 99.7%) was used as the carrier gas, and the flowrate was 300 L/h. In addition, the plasma jet scanning step distance was 2 mm and the distance between the nonwoven sample and jet nozzle was 40 mm.

2.3. Characterization

Water contact angle was measured by a contact angle goniometer (JY-PHb, Hebei, China). Scanning Electron Microscopy (SEM, Phenom Pro, Phenom-World B.V., Netherlands) was employed to characterize the surface morphology of fibres in the resulting amphoteric cotton nonwoven fabrics. The chemical structure of the fabrics was characterized by Fourier Transform Infrared Spectroscopy (FTIR Spectrometer, Nicolet iS5, Thermo Company, USA). The repeated liquid strike-through time of the fabric was tested by a LISTER AC Liquid Strike Through Time Tester (Lenzing Instruments GmbH & Co. KG, Austria) according to the ERT 153.0-02 standard. The wetback after a repeated strike-through time of the fabrics was tested by a WETBACK Nonwovens Wetback Tester (Lenzing Instruments GmbH & Co. KG, Austria) according to the ERT 154.0-02 standard. The water-vapor transmission rate was measured by a fabric moisture analyzer (YG601H-II, Zhejiang, China) according to GB/T 12704.2-2009. Air permeability was measured (Textest FX 3300-IV, Schwerzenbach, Switzerland) at a pressure of 200 Pa over an area of 20 cm^2. The pore size distribution was characterized by a pore size meter (Topas PSM 165, Dresden, Germany). Topor (perfluoro compound, Topas specific testing fluid, surface tension 16 $mN \cdot m^{-1}$) was used as the wetting fluid, and the cross-sectional area of measurement was 0.95 cm^2. Furthermore, fabric samples were stored at 90 °C and at -18 °C for one hour to determine the stability of the plasma treatment, and then for 2 months to assess the long-term durability.

Results and Discussion

Effect of Plasma Treatment Parameters on the Amphoteric Properties

Plasma treatment parameters are a major contributing factor to the modulation of amphoteric behaviour in fabrics. The face side of the cotton nonwoven fabric (treated surface, TS) was intended to be evenly coated by the treatment with HMDSO, whereas the reverse side (untreated surface, UTS) was expected to have remained untreated. The factors affecting the processing and penetrating performance of the plasma include the velocity of jet slide, the ionization gas flow rate and the precursor flow rate (Ekezie et al. 2019; Yang et al. 2018b). Therefore, the effect of these three parameters on the resulting amphoteric properties of the plasma treated cotton nonwovens was explored systematically, and the water contact angle was used to indicate a transformation to hydrophobic behaviour.

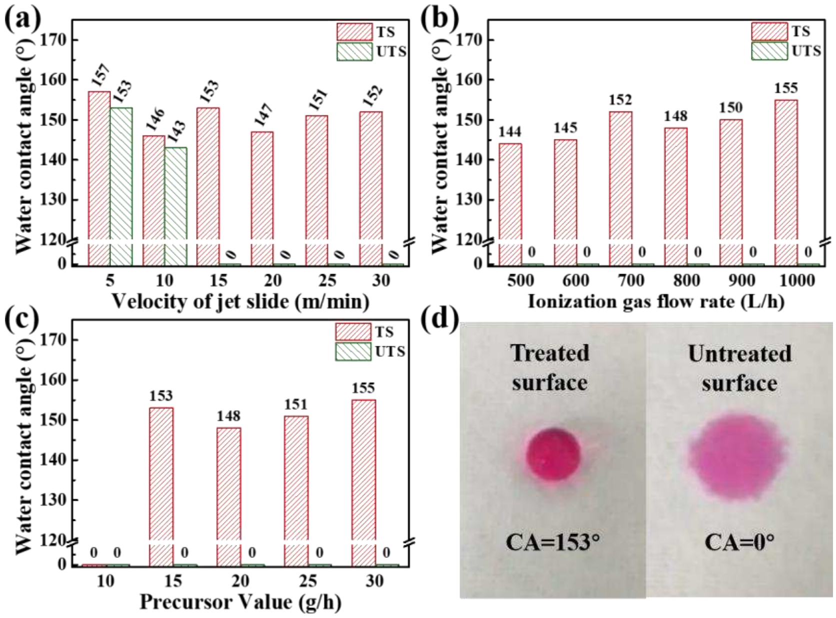

Fig. 2 Water contact angle of the treated surface (TS) and untreated surface (UTS) of the cotton nonwoven fabrics treated using different plasma parameters: (a) velocity of the jet slide; (b) ionization gas flow rate; (c) precursor value (flow rate). The droplet wetting characteristics of the TS and UTS, where CA=contact angle (d)

Figure 2 reports the water contact angle of the TS and the UTS of the cotton nonwoven fabrics, following modulation of three different plasma process parameters. Firstly, the ionization gas flow rate and the precursor value were set to 700 L/h and 30 g/h, respectively, and the velocity of the jet slide was gradually adjusted from 5 m/min to 30 m/min at an interval of 5 m/min. **Figure 2a** indicates that both sides of the treated fabric are hydrophobic when the jet slide ran at a low velocity, i.e., < 10 m/min, producing water contact angles of ~140-150°. As the jet velocity increased to higher than 15 m/min, while the jet facing side (TS) continued to exhibit high contact angles of around 150°, the contact of the reverse side (UTS) of the nonwoven retained its original wettability (contact angle of 0°). The lack of amphoteric effect at low jet slide velocity is the result of the polymerized HDMSO being able to penetrate the porous structure of the cotton nonwoven due to the longer jet dwell time. By increasing the jet slide velocity, the penetration of polymerized HDMSO to the reverse side of the fabric was inhibited.

Then, the velocity of the jet slide was fixed at 30 m/min and the precursor value was set to 30 g/h. As the ionization gas flow rate increased from 500 L/h to 1000 L/h, it was found that the treated cotton nonwovens were all amphoteric (**Figure 2b**). However, the plasma glow was unstable when the ionization gas flow rate was low, which may have an adverse impact on the uniformity of the hydrophobic coating. Finally, the effect of the precursor value on the amphoteric property was explored, wherein the velocity of the jet slide and the ionization gas flow rate were fixed at 30 g/h and 1000 L/h, respectively. As is evident in **Figure 2c**, while the precursor value was at 10 g/h, the hydrophobic modification of the TS was insufficient due to the small amount of precursor, leading to the hydrophilicity remaining on both sides of the fabric. However, amphoteric behaviour was obtained at a higher precursor value (≥15 g/h),

Based on these observations, to produce amphoteric cotton nonwoven fabrics, preferred values for the velocity of the jet slide, the ionization gas flow rate and the precursor were selected as 30 m/min, 1000 L/h and 15 g/h respectively. The water infiltration of the TS and UTS of the treated cotton nonwovens is shown in **Figure 2d** and clearly highlights differences in the wetting and rate of lateral spreading of the liquid droplets in the fabric, consistent with amphoteric behaviour.

3.2 Surface Morphology

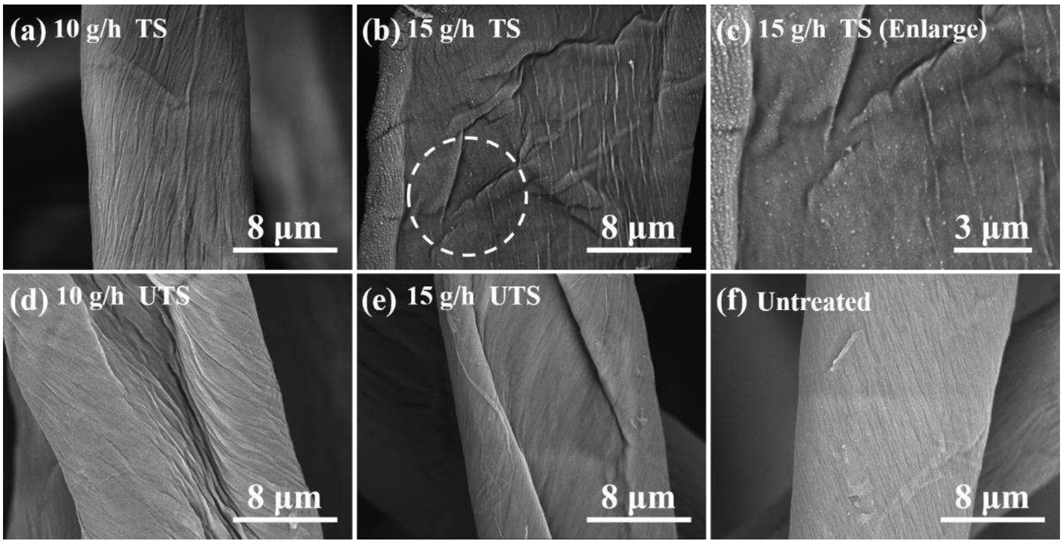

Fig. 3 SEM images of treated (TS) samples using different precursor values compared to the untreated cotton nonwoven fabric: 10 g/h TS (a); 15 g/h TS (b); 15 g/h enlarged TS (c); 10 g/h UTS (d); 15 g/h UTS (e); untreated control (f)

Plasma treatment applied to the surface of cotton nonwovens, may be expected to produce changes in fibre surface morphology, which could affect physical properties (Lee et al. 2000). **Figure 3** illustrates the resulting surface morphology of cotton fibres in each of the treated nonwoven fabrics, subjected to different precursor values (TS and UTS), together with the untreated cotton nonwoven control sample. It was found that for the treated fabric produced with a precursor value of 15 g/h, the fibres on the TS were evenly coated by the polymerized HMDSO. At higher magnification in the same sample (**Figure 3c**), uniform nano-protrusions on the fibre surfaces were observed. The formation of nano-protrusions is mainly due to the rapid replenishment of precursor in the plasma environment (Lazauskas et al. 2014). This coating was carefully scraped off the fibre surface and was found to be a white waxy coating. This polymer film is primarily responsible for the hydrophobic properties observed in the cotton nonwoven fabrics post plasma treatment, and the uniform nano-protrusions may also be expected to enhance hydrophobic properties (Kim and Lee 2019). The surface morphology of untreated fibres were very similar to that of TS fibre at a precursor value of 10 g/h, and features such as nano-protrusions were generally absent. According to Palaskar (2011) (Palaskar et al. 2011), the surface coverage of the TS mainly depends on the value of the precursor. A small amount of precursor brings about a thin hydrophobic coating on the treated surface, which may be insufficient to yield a significant change in hydrophobicity. The surface morphology of fibres in the UTS of fabric samples that exhibited amphoteric behaviour were the same as those in the untreated sample. This confirms that the plasma did not penetrate the fabric structure, and therefore no hydrophobic coating was deposited on the UTS.

3.3 Chemical Components

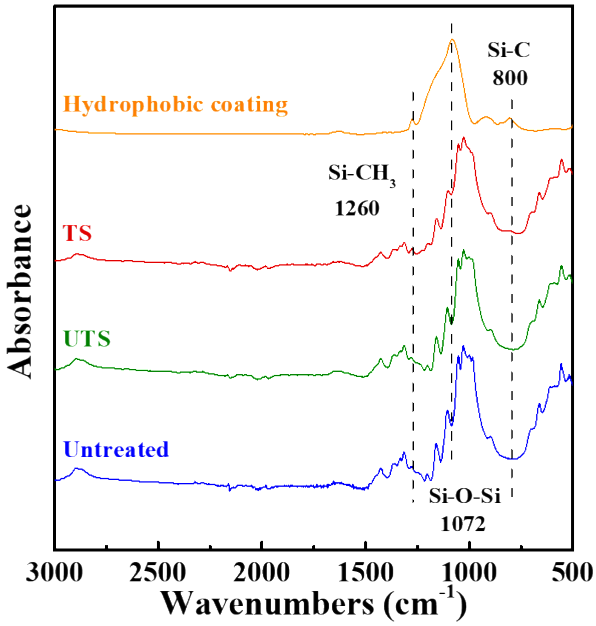

Fig. 4 FTIR Spectra of the HMDSO coating material, coated amphoteric cotton nonwoven fabric (TS and UTS) and the untreated control fabric

The hydrophobic behaviour of plasma treated cotton nonwovens is largely related to their surface chemical composition. The FTIR spectra of the hydrophobic coating, amphoteric cotton nonwoven (both sides) and untreated cotton nonwoven are shown in **Figure 4**. The peak at 1072 cm^{-1} is attributable to the stretching vibration of the Si-O-Si bond (Wallimann et al. 2018), present in the hydrophobic coating. It can also be observed that the infrared absorbance at this position in the TS of the amphoteric fabric is slightly higher than that in the UTS as well as in the untreated cotton nonwovens. Additionally, the peaks at 1260 cm^{-1} and 800 cm^{-1} are due to the bending vibration of the CH_3 and the Si-C rocking vibrations in Si-CH_3, respectively (Bashir and Bashir 2015; Raynaud et al. 2005). These two peaks appear in the spectra of both the hydrophobic coating and the TS of the amphoteric nonwoven sample. Si-CH_3 groups in the plasma polymerization are low surface energy groups, that can be expected to impart hydrophobic properties (Kale and Palaskar 2011). It is also evident in **Figure 4** that these characteristic peaks are not present in the spectra of the UTS of the amphoteric nonwovens, which is comparable to that of untreated cotton. Therefore, almost no polymerized HMDSO was found to be present on the UTS, enabling it to remain hydrophilic due to its cellulosic composition.

3.4 Unidirectional Water-Transport Behaviour

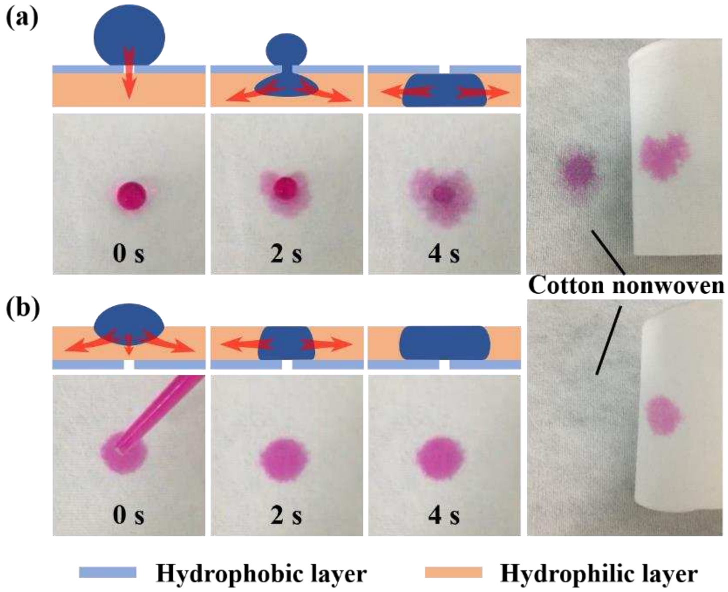

Fig. 5 Unidirectional through thickness water-transport behaviour of amphoteric cotton nonwoven fabrics

Janus fabrics have unidirectional water-transport functionality owing to their amphoteric properties (Wang et al. 2010). In other words, water can be transported from the hydrophobic surface to the hydrophilic surface but cannot be transported in reverse. Published literature has pointed out that the thickness of the hydrophobic coating has an influence on the performance of unidirectional water-transport in amphoteric fabrics. When the hydrophobic coating is too thin, the fabric has bidirectional transport behaviour, but when the hydrophobic coating is too thick, liquid transport can be impeded on both sides (Wang et al. 2019). Herein, treated cotton nonwoven fabrics produced using a precursor value of 15 g/h were found to have a hydrophobic coating with a suitable thickness to exhibit unidirectional water-transport functionality. The infiltration and penetration of water droplets in the TS and the UTS of the amphoteric cotton nonwoven fabric is shown in **Figure 5**. The water penetration is illustrated by placing an untreated cotton nonwoven fabric under the amphoteric cotton nonwoven fabric sample. When the water was placed on the hydrophobic layer (the TS), it penetrates the surface and transports to the reverse side, then laterally spreads on the UTS. (**Figure 5a**) In contrast, when water was placed onto the hydrophilic untreated surface (the UTS), the liquid just spreads laterally and does not transport through-thickness to the reverse side of the fabric. (**Figure 5b**) The unidirectional water-transport behaviour in amphoteric cotton nonwoven fabrics is linked to the asymmetric wettability. In the case where the hydrophobic layer is facing upward, the water droplet exhibits a large contact angle. The highly curved air/water interface is associated with pressure, as is known from the Young-Laplace equation (Zhou et al. 2020):

$$\Delta p = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (1)$$

In **equation (1)**, Δp denotes the pressure difference between the inside and outside of the liquid surface, it is influenced by the surface tension coefficient γ and the curvature radius of the liquid surface R_1 and R_2. This pressure and the hydrostatic pressure due to the gravity of water is enough to overcome the hydrophobic force on the surface of the hydrophobic layer. Due to the porosity of the amphoteric cotton nonwoven and the open pore structure at the surface, the hydrophobic coating is not continuous, which allows the water to reach the underlying hydrophilic layer (Zhou and Guo 2019). Capillary forces in the hydrophilic layer assist with the transport of the liquid, as well as with lateral spreading, depending on the fibre orientation within this fabric layer (Mao and Russell 2003a; Mao and Russell 2003b). In contrast, when the hydrophilic layer is upward, water is dropped on the hydrophilic layer, and the contact angle is 0. The resulting balance of forces means rapid liquid inlet, and capillary forces can spread the water within the hydrophilic layer. The hydrophobic layer effectively prevents full-thickness penetration through the fabric, so water is not able to penetrate through the hydrophobic side. This phenomenon is also akin to a “liquid diode” (Tian et al. 2012) and it makes amphoteric nonwovens valuable in many double-phase processes.

3.5 Repeated Liquid Strike-Through Time and Wetback Value

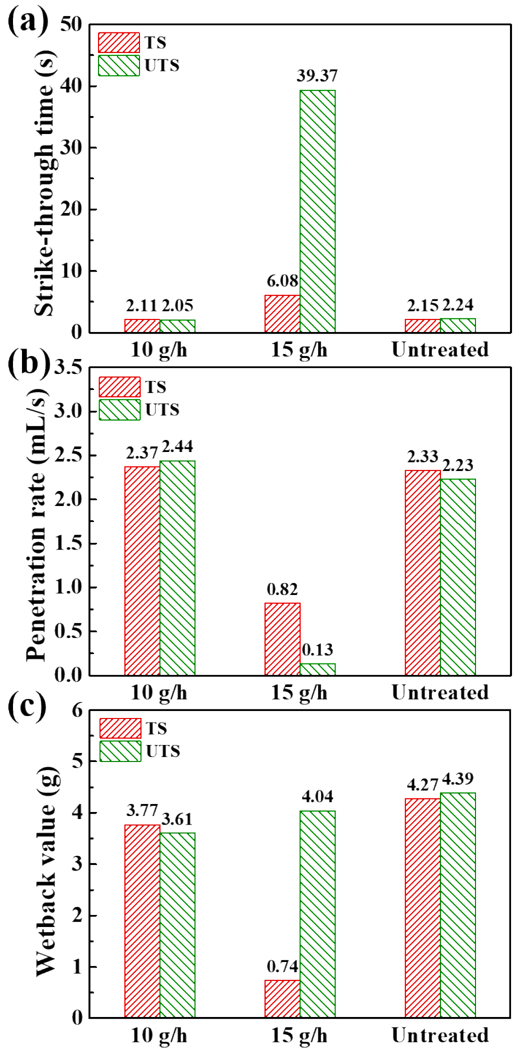

Fig. 6 Repeated liquid strike-through time (a), liquid penetration rate (b), and wetback (c) of the amphoteric and untreated cotton nonwoven fabrics

To characterize the unidirectional water-transport characteristics of the amphoteric cotton nonwoven fabrics quantitatively, the repeated liquid strike-through times and the wetback after repeated strikethroughs were measured. The mean strike-through times obtained are given in **Figure 6a**, based on a water volume of 5 mL. It was observed that for amphoteric cotton nonwovens (15 g/h), the mean strike-through time from the TS to the UTS was 6.08 s, which was much less than for the UTS to the TS. Owing to the unidirectional water-transport characteristics of the amphoteric cotton nonwoven fabric, water readily penetrated from the hydrophobic to the hydrophilic side, but penetration in reverse was markedly slower. The fabrics treated with a precursor value of 10 g/h, with a thin hydrophobic layer did not exhibit this unidirectional water-transport behaviour (Zhou and Guo 2019), so the strike-through time was almost the same as that of the untreated cotton nonwoven fabric, whether from the TS to the UTS or from the UTS to the TS. The strike-through time can be quantified as the water penetration rate (**Figure 6b**).

The wetback after repeated strike-through time is shown in **Figure 6c**, the mean wetback value on the TS of the amphoteric cotton nonwovens was 0.74 g, which is much smaller than that measured for the UTS, and untreated cotton nonwovens. With reference to the Washburn equation (Zhang and Luo 2020) in **equation (2)**:

$$h = \sqrt{\frac{cr\sigma \cdot cos\theta \cdot t}{2\eta}} \tag{2}$$

h denotes the wicking height of water, c is the capillary shape factor, r is the average capillary radius; cr is a fixed value referred to as the formal radius. σ denotes the surface tension of the liquid, θ denotes the contact angle and η is liquid viscosity. Thus, the wicking height is related to the contact angle and when the water reaches the hydrophobic layer of the TS, the wicking height and capillarity are reduced due to the large contact angle, which impedes wetback from the UTS to TS. As a result, little water remains on the TS after inlet, and the surface can remain dry. When this amphoteric cotton nonwoven fabric is used to make wearable hygiene products, for instance, diapers, the hydrophobic surface will be close to human skin, so that liquid could be quickly transported from the hydrophobic side to the hydrophilic side. The hydrophobic surface close to the skin will remain dry due to the low wetback characteristics of the hydrophobic side of this amphoteric cotton fabric. The low wet back is a valuable property in the top sheets of wearable hygiene products, as well as humidity-control clothing.

3.6 Water-Vapor Transmission Rate and Air Permeability

Table 1. Water-vapor transmission rate of amphoteric and untreated cotton nonwoven fabrics.

Sample	Water-vapor transmission rate (WVT)
TS to UTS	191.007 $g\cdot(m^2\cdot h)^{-1}$
UTS to TS	188.922 $g\cdot(m^2\cdot h)^{-1}$
Untreated	185.371 $g\cdot(m^2\cdot h)^{-1}$

The possible influence of the plasma treatment process on the water-vapor transmission rate and air permeability of the fabrics was also investigated. In Table 1 it is evident that the water-vapor transmission rate in the amphoteric cotton nonwoven fabric was not significantly different from that of the untreated fabric at ~188 $g\cdot(m^2\cdot h)^{-1}$. We believe the differences might have been caused by sample handling during the treatment and characterization steps instead of real structural change to the porous fabric structures. Meantime, cotton fabrics could expand after absorbing moisture, which would have a certain impact on the water-vapor transmission rate. However, this effect has an extremely limited influence on the fabric and has almost no effect on the water-vapor transmission rate. The pore size distributions and the Macro SEM image of the amphoteric cotton and the untreated cotton nonwoven fabrics were also almost identical (**Figure 7**). It can be seen that the fibrous assembling structure of the amphoteric cotton nonwoven and untreated cotton nonwoven were not different, and both of the average pore sizes were about 26 μm, confirming that plasma jet treatment resulted in no consolidation or structural modification of the geometric structure of the fabric. Given that there was no change in the fibrous structure, intrinsic permeability would not be expected to be modified, and since water vapor molecules are much smaller than the pore size, gas flow is highly unlikely to be affected by the hydrophobic layer and the change in surface energy (Chemetov and Cipriano 2014). Similarly, no significant difference in the air permeability between samples could be detected, with values of 1208 mm/s and 1126 mm/s being obtained for the amphoteric cotton and untreated cotton nonwoven fabrics respectively.

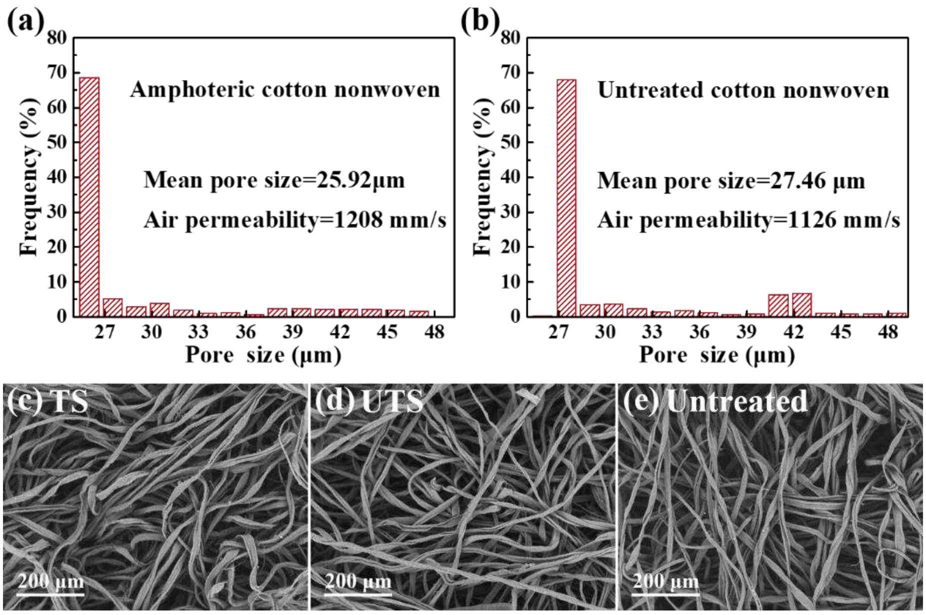

Fig. 7 Pore size distribution and air permeability of amphoteric cotton nonwoven fabric (a) and untreated cotton nonwoven fabric (b); Macro morphology of the treated surface (c), untreated surface (d) and untreated cotton fabric (e).

3.7 Thermal Stability and Durability

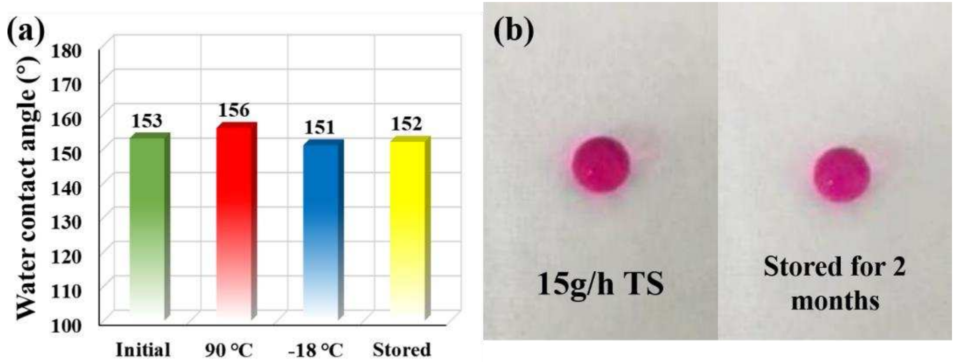

Fig. 8 Thermal stability and durability of the hydrophobic treatment in the amphoteric cotton nonwoven fabric (a). Photograph of water infiltration behaviour after 2 months storage

Fugitive amphoteric behaviour, i.e., where the differential moisture handling characteristics are not durable, would limit industrial utility, so basic stability testing was performed in respect of thermal and temporal conditions (Lin et al. 2019). The thermal stability and durability of the hydrophobic coating was characterized by measuring the water contact angle. As shown in **Figure 8**, following exposure to temperatures of 90 °C and -18 °C for one hour, and also storage in ambient conditions for two months, no marked differences were observed in the measured contact angles. Hydrophobicity remained quite consistent in the TS suggesting that cotton nonwoven fabrics treated in with HMDSO in the plasma jet process could be suitable for durable product applications in nonwovens where amphoteric behaviour is required.

Conclusion

Amphoteric cotton hydroentangled nonwoven fabrics with unidirectional water-transport functionality were successfully prepared by localised deposition of polymerized HMDSO through an optimised plasma jet process. Preferred treatment conditions were identified as 30 m/min, 1000 L/h and 15 g/h for the velocity of the jet slide, the ionization gas flow rate and the precursor rate, respectively. The treated side of the amphoteric cotton fabric was also characterised by the presence of nano-protrusions on the fibre surfaces. Asymmetric wetting and aqueous liquid transport were observed in amphoteric nonwoven fabric samples, and quantitatively characterized in repeated liquid strike-through and wetback studies. Liquid transport characteristics can be tuned by the modulation of plasma jet treatment process without affecting air permeability, vapor permeability or the pore size distribution of the nonwoven fabric. Furthermore, the polymerized HMDSO coating exhibited excellent thermostability and durability following storage, such that treated fabrics could be applied in a variety of industrial applications where moisture management is critical.

Authors’ Contributions

Yi Pu: Initial conceptualization, Experiment, Data curation, Formal analysis, Methodology, Writing-Original draft, Writing-Review & editing; **Jing Yang:** Experiment, Writing-Review & editing; **Stephen Russell:** Formal analysis; Writing-Review & editing; **Xin Ning:** Initial conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Writing-Review & editing.

Conflicts of Interest

All authors have given approval to the final version of the manuscript. The authors declare no conflicts of interest.

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