EFFECTS OF LOW TEMPERATURE PLASMA TREATMENT ON THE WETTABILITY OF BAMBOO/COTTON BLENDED FABRICS

C. W. KAN and Y. L. LAM

Institute of Textiles and Clothing, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China
✉ *Corresponding author: C. W. Kan, tccwk@polyu.edu.hk*

Received November 26, 2014

This paper investigates the influence of low temperature plasma, under various treatment conditions, on the wettability of bamboo/cotton blended fabric. Low temperature plasma treatment can modify the surface of the polymers and change substrate characteristics, such as wettability, and more importantly, the process is an environmentally friendly finishing. In this paper, bamboo/cotton blended fabric was treated with low temperature plasma under different treatment conditions, such as different oxygen flow rate, jet-to-substrate distance and plasma treatment time, to evaluate how these parameters influence the characteristics of treated fabrics. After the plasma treatment, evaluation tests, such as topography by scanning electron microscopy, wettability, whiteness and yellowness, were conducted to evaluate the properties of plasma-treated fabric under different parameters. The study concluded that there was a desirable change in the wettability of the bamboo/cotton blended fabric due to the plasma treatment.

Keywords: plasma treatment, bamboo, cotton, blended fabric

INTRODUCTION

Environmentally friendly textile production using natural fibers and eco-friendly dyeing methods, with low energy requirements, high percentage dye exhaustion and less dyeing waste are hot research topics. Cotton is the most popular cellulosic fiber nowadays. It is a natural vegetable seed fiber obtained from mature capsules of the cotton plant. Cotton is soft and comfortable to touch since its surface is smooth. It also has good absorbency, strength, resistance to high temperature, strong alkali and chlorine.[1] On the other hand, bamboo fiber, which is also a biodegradable cellulosic fiber, has become common in recent years, and it is believed that it can become as popular as cotton fiber, since bamboo fiber is more environmental than cotton fiber regarding the plant's growing process. Moreover, bamboo has good absorbance and breathability, it is anti-static and anti-UV.[1] It is currently used in a wide range of textile applications.

To make the coloration process of bamboo/cotton blended fabric more environmentally friendly, plasma treatment before coloration is used. The concept of plasma was introduced by Langmuir in the early 1920s.[2] Plasma, in general, refers to the excited gaseous state consisting of atoms, molecules, ions metastables and electrons, such that the concentration of positively and negatively charged species is roughly the same. Plasma treatment provides increased bond strength, wettability, permeability and biocompatibility.[3-7] After oxygen plasma treatment, the bamboo and cotton fabric surface becomes rougher, and the fabric structure has more hydroxyl groups.[4,5] These physical and chemical changes increase the wettability of fabric.[4] In this paper, the effect of low temperature plasma treatment on the wettability of bamboo/cotton blended fabrics was studied.

EXPERIMENTAL

Material

The fabric used was a 3/3 twill woven fabric with cotton warp (27.8 tex) and bamboo weft (35.3 tex). The warp density was 80 ends/inch and weft density was 64 picks/inch. It weighed 2.078 g/cm².

Pretreatment of blended fabric

Before plasma treatment, the fabric was washed with 10 g/L non-ionic detergent (Diadavin EWN-T

200%) with liquor-to-goods ratio 100:1, for 10 minutes to remove dirt, and rinsed by running deionized water for 10 minutes. The washed fabrics were dried completely in an oven at 70 °C and then the fabrics were conditioned at a temperature of 21±1 °C and humidity of 65±2% for 24 hours, according to BS EN ISO 139: 2005.

Plasma treatment

The plasma treatment of bamboo/cotton fabrics was carried out in Surfx Atomflo 400-Series Atmospheric Plasma. Helium (99.95% purity) and oxygen (99.7% purity) were used as carrier and reactive gases for the plasma treatment. The treatment was carried out using a rectangular nozzle, which covered an active area of 1 x 25 mm^2 and was mounted vertically above the substrate. The helium flow rate was kept at 10 L/min during the treatment and the output power used was 150 W. The parameters used were jet-to-substrate distance (1 mm, 3 mm, 5 mm), oxygen flow rate (0.1 L/min, 0.3 L/min, 0.5 L/min) and treatment time (0.1 s, 0.5 s, 1 s), as shown in Table 1. The plasma-treated fabrics were stored under standard conditions (*i.e.* temperature of 21±1 °C, humidity of 65±2%) for 24 hours prior to further evaluation.

Longitudinal wicking test

Longitudinal wicking test (BS 3424-18) was applied to evaluate the hydrophilicity of the fabrics. Fabric strips of 2 cm x 11 cm in warp and weft direction, respectively, were cut. The fabric strips were marked with a scale from 1 cm to 10 cm on the surface by using a water soluble pen. Next, the fabric strips were suspended vertically with the lower edge of 0.5 cm immersed in a beaker with 500 ml distilled water. The time of water uptake was recorded at 1 cm intervals from 1 cm to 10 cm. Each specimen was tested for a maximum of 30 min. Both the warp and weft directions of the fabrics were measured. 3 measurements were taken for each direction of the specimens and then averaged. Equation (1) shows the calculation of the maximum wicking rate:

$$\text{Maximum wicking rate (cm/min.)} = \frac{\text{Maximum wicking height (cm)}}{\text{Time to reach maximum wicking height (min.)}}$$

Table 1
Plasma treatment conditions

Treatment conditions	Oxygen flow rate (L/min)	Jet-to-substrate distance (mm)	Treatment time (s)
1	0.1	1	0.1
2	0.1	1	0.5
3	0.1	1	1.0
4	0.1	3	0.1
5	0.1	3	0.5
6	0.1	3	1.0
7	0.1	5	0.1
8	0.1	5	0.5
9	0.1	5	1.0
10	0.3	1	0.1
11	0.3	1	0.5
12	0.3	1	1.0
13	0.3	3	0.1
14	0.3	3	0.5
15	0.3	3	1.0
16	0.3	5	0.1
17	0.3	5	0.5
18	0.3	5	1.0
19	0.5	1	0.1
20	0.5	1	0.5
21	0.5	1	1.0
22	0.5	3	0.1
23	0.5	3	0.5
24	0.5	3	1.0
25	0.5	5	0.1
26	0.5	5	0.5
27	0.5	5	1.0

Drop test

The drop test was applied according to AATCC Test Method 193, to evaluate the wettability of the fabrics. The plasma-treated fabrics were cut into 5 cm x 5 cm pieces and both the face and the back of the specimens were tested. An amount of 0.1 g Methylene Blue in 100 ml distilled water was used as solvent. A drop of Methylene Blue solvent (10 μl) was dropped from a 1 cm height on the surface of the fabric specimen using an auto-pipette. After 20 minutes, the dispersion area (cm^2) was measured and recorded. Three measurements were taken on each side of the sample and averaged.

Measurement of fabric yellowness and whiteness

The whiteness and yellowness indexes were measured using a spectrophotometer (ColorEye 7000A) to evaluate whether any color change of the bamboo/cotton blended fabric was induced by the plasma treatment. The untreated and plasma treated specimens were inserted into the specimen holder, and the illuminant, observer angle and standard were as specified. For the whiteness test, illuminant D65, ASTM E313, with 2^o and 10^o observer angles was used. For the yellowness test, illuminant D 65, ASTM E313 and ASTM D1925 with 2^o and 10^o observer angles were used. Each parameter with 2 specimen samples with 4 measurements was taken to obtain average results.

RESULTS AND DISCUSSION

Wettability

Wicking can only occur when a liquid wets fibres assembled with capillary spaces between them, which results in the capillary forces driving the liquid into the capillary spaces.[8] Figure 1 shows the wicking time of bamboo/cotton blended fabrics required for upward movement of water measured at each 1 cm interval for maximum 30 minutes. Figure 1 shows that the maximum wicking height of all the specimens, in warp direction and weft direction, is around 9 cm and 7 cm, respectively. This means the warp yarn of fabrics had a higher maximum wicking height than that of the weft yarn. In other words, the cotton fiber had a better liquid transport capability, *i.e.* hydrophilic property, than that of bamboo fiber.

When the fabrics were treated with different oxygen flow rate, the result proved that the average wicking rate of the warp and weft yarns increased when the oxygen flow rate increased, *i.e.* control < 0.1 L/min < 0.3 L/min < 0.5 L/min. The maximum improvement in wicking rate was of 21.0%, 26.4% and 30.1% for 0.1 L/min, 0.3 L/min and 0.5 L/min oxygen flow rates used in the plasma treatment, respectively. Plasma-treated fabrics had a faster wicking rate than that of the control fabric as the number of polar groups formed on the fabric surface increased with increasing oxygen flow rate. Also, after the plasma treatment, the fabric surface became rougher, with more grooves and cracks, which helped increase the contact area between water and the fabric surface. The higher the contact area between water and the fabric surface, the higher the water uptake rate. Also, the wicking rate is inversely proportional to the capillary pressure.[2] The capillary pressure decreases with increasing capillary radius. The plasma treatment causes fiber fineness to decrease, which can increase the capillary radius. Therefore, the capillary pressure is reduced and hence the wicking rate will be increased. In addition, it is found that the maximum wicking rate (average of warp and weft yarns) increases for 15.9%, 26.4%, 30.1%, when the fabrics are treated with plasma for 0.1 s, 0.5 s and 1.0 s, respectively. The result proves that more reactive species could be created and accumulated on the fabric surface, resulting in more polar groups formed on it, *i.e.* leading to increased wettability of the fabric.

Moreover, when comparing specimens treated under different jet-to-substrate distance, it can be found that 3 mm distance shows the best improvement in wicking rate (30.1%), while 1 mm distance shows the least (23.5%). In general, when the distance between the plasma jet nozzle and the substrate surface is too small, the flow of the plasma gas from the nozzle is almost blocked by the fabric and the gas can only be bounced off the surface and flows out in a more parallel to the fabric surface direction, which greatly reduces the effectiveness of the treatment.[9] On the other hand, when the distance between the plasma jet nozzle and the substrate surface is too large, plasma gas from the nozzle is unable to hit the fabric surface, which means less surface modification is achieved.[10] Hence, in this case, 3 mm jet-to-substrate distance exhibits the highest effect in enhancing the wettability of the fabric.

Table 2 shows the drop test results (area in cm^2) of bamboo/cotton blended fabrics with or without plasma treatment. The control fabric shows a larger dispersion area at the back side of the fabric (0.86 cm^2) rather than that of the face side (0.77 cm^2). Also, from Table 2 it may be remarked that all the plasma-treated fabrics, both on their face and back side, presented a larger dispersion area than that of the control fabric.

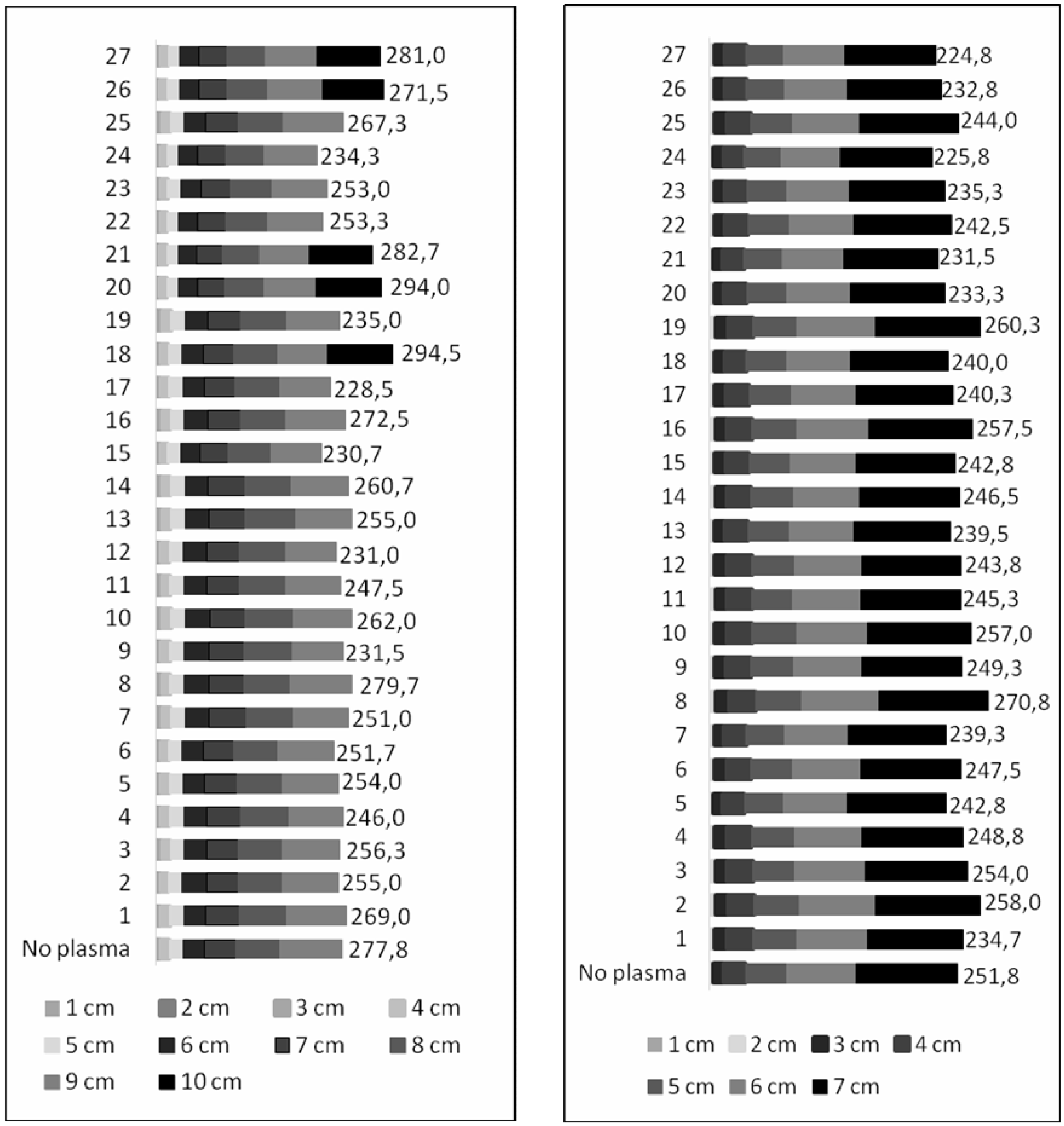

Figure 1: Wicking test results for plasma-treated and untreated bamboo/cotton fabrics in (a) warp direction and (b) weft direction (numbers on the right side of the chart indicate the time to reach the maximum wicking height)

Considering the different oxygen flow rates used, the sequence of the dispersion area on the face side of plasma-treated fabrics was the following: 0.1 L/min < 0.5 L/min < 0.3 L/min. As mentioned before regarding the wicking test, the plasma gas changes the fabric surface roughness. There appear more grooves in the specimen surface, which increase the contact area between water and the surface. This allows faster penetration and absorption of water. Thus, 0.3 L/min and 0.5 L/min plasma-treated fabrics have a larger dispersion area.

When comparing the dispersion area of the 0.3 L/min and 0.5 L/min plasma-treated fabrics, the 0.3 L/min one has a better result because, on the liquid-substrate interface, the water droplet is ‘riding’ on the rough surface of the substrate.[11] On the relatively rougher surface, the contact between the surface and the droplet is minimized, resulting from the much higher energy barriers for the rearrangement of liquid molecules at the liquid-substrate interface.[12-14] In addition, since the plasma treatment was applied on the face side of the fabric, the physical and chemical properties of the fabric changed mainly on the face side.[15] From the dispersion results, it is clear that the dispersion of the fabric increased more significantly on the face side.

Generally speaking, the dispersion area on the face side increases with increasing treatment time. An increase in the treatment time will increase the concentration of active species reacting with the fabrics and hence decrease the surface tension of the fabric's surface, *i.e.* improving wettability.

Table 2
Drop test results (area in cm^2) for plasma-treated and untreated bamboo/cotton fabrics on face and back side

Plasma treatment	Face	Back	Plasma treatment	Face	Back	Plasma treatment	Face	Back
No plasma	0.77	0.86						
1	0.87	0.89	10	1.18	1.11	19	1.02	1.14
2	0.94	1.01	11	1.13	1.11	20	0.99	1.00
3	0.99	1.00	12	1.23	1.22	21	1.20	1.05
4	1.13	1.17	13	1.10	1.10	22	1.01	1.17
5	0.91	0.96	14	1.11	1.10	23	1.06	0.94
6	1.09	1.11	15	1.24	1.16	24	1.19	1.11
7	0.90	1.02	16	1.11	1.07	25	1.02	1.10
8	1.01	0.90	17	1.16	1.10	26	1.10	1.09
9	1.00	1.05	18	1.10	1.19	27	1.10	1.02

Table 3
Yellowness and whiteness of bamboo/cotton fabrics with or without plasma treatment

Treatment condition	Whiteness		Yellowness			
	ASTM E313 (D65/10°)	ASTM E313 (D65/2°)	ASTM E313 (D65/10°)	ASTM E313 (D65/2°)	ASTM D1925 (D65/10°)	ASTM D1925 (D65/2°)
No plasma	63.65	63.88	4.01	2.25	4.21	2.93
1	62.84	63.08	4.18	2.42	4.38	3.04
2	61.55	61.82	4.54	2.77	4.79	3.49
3	61.48	61.75	4.57	2.80	4.83	3.53
4	63.14	63.14	4.18	2.41	4.37	3.02
5	62.38	62.62	4.23	2.46	4.43	3.15
6	61.72	62.01	4.50	2.73	4.74	3.43
7	63.58	63.79	4.00	2.28	4.17	2.89
8	63.02	63.24	4.02	2.25	4.20	2.92
9	62.33	63.48	4.03	2.46	4.48	3.21
10	61.74	62.00	4.38	2.58	4.62	3.33
11	62.14	62.42	4.53	2.76	4.77	3.47
12	61.18	61.45	4.72	2.90	4.95	3.65
13	62.01	62.65	4.35	2.34	4.51	3.22
14	62.52	62.73	4.47	2.71	4.36	3.08
15	61.69	61.95	4.45	2.68	4.70	3.40
16	63.86	64.09	4.07	2.30	4.41	3.13
17	63.20	63.43	4.18	2.56	4.33	3.09
18	62.66	62.57	4.40	2.63	4.61	3.31
19	61.80	62.03	4.32	2.56	4.58	3.30
20	61.43	61.70	4.67	2.90	4.95	3.65
21	61.35	61.63	4.72	2.95	4.98	3.67
22	62.43	62.62	4.21	2.45	4.42	3.13
23	62.26	62.02	4.39	2.62	4.63	3.34
24	61.44	61.70	4.66	2.89	4.89	3.59
25	63.27	63.50	4.02	2.26	4.22	3.04
26	62.68	62.91	4.40	2.36	4.31	3.02
27	62.31	62.56	4.48	2.71	4.44	3.44

For different jet-to-substrate distance used in the plasma treatment, the results of the dispersion area on the face and back of the specimens are more or less similar. No considerable difference among the results shows that there is a relationship between jet-to-substrate distance and dispersion area of the fabrics.

Fabric yellowness and whiteness

Whiteness is the measure of how close the surface color of a substrate matches the color of a perfect white. The perfect reflecting diffuser has a whiteness index of 100, whereas materials treated with a fluorescent whitening agent give values as high as 150. However, this would not happen on this bamboo/cotton blended fabric as no fluorescent whitening treatment was applied. The preferential absorption of the white light in the short wavelength region, ranging from 380 nm to 440 nm, by the material usually causes an appearance of yellowness. Yellowness is considered to be associated with high temperature treatment and product degradation by exposure to atmospheric gases, light and other chemicals. Thus, yellowness can be used to indicate color degradation after plasma treatment by making a comparison between untreated specimens and plasma-treated ones. The whiteness index and yellow index of the fabrics are shown in Table 3.

For both observer angles of 10^o and 2^o, the whiteness index of the untreated control specimen was of about 63, showing that the surface of the untreated fabric is acceptable white, as 100 means perfect white. In addition, the whiteness of the plasma-treated fabrics decreased when the fabrics were treated with (i) 0.1 L/min > 0.3 L/min > 0.5 L/min oxygen flow rate, (ii) 0.1 s > 0.5 s > 1.0 s treatment time and (iii) 5 mm > 3 mm > 1 mm jet-to-substrate distance for both observer angles of 10^o and 2^o. The specimen treated with plasma at 0.5 L/min oxygen flow rate or 1.0 s treatment time or 1 mm jet-to-substrate distance showed the least white surface because of the increased amount of active species that increased the heat produced during the reaction.

During the plasma treatment, heat is produced due to the action of active species. The transfer of heat to the fabric surface causes overheating of the fabric, and, as known, overheating of cellulosic fabrics leads to yellowing. The longer the treatment time or the higher the oxygen flow rate, the more serious the overheating of the fabric, and hence more serious yellowing. Moreover, when the jet-to-substrate distance increased, the amount of gases reaching the fabric surface decreased, as fewer gases could reach the fabric surface. Less heating was generated during the reaction to cause overheating. Thus, less yellowing was observed on the fabric surface.

On the other hand, as may be noted from Table 3, the overall yellowness index at observer angle of 10^o is higher than at that of 2^o. The result also shows that the yellowness index is inversely proportional to the whiteness index. Therefore, the yellowness index results further confirmed that the increased active species generated by plasma would increase the heat produced during reaction and hence causing yellowing of fabric.

CONCLUSION

In this paper, low temperature plasma treatments were conducted for bamboo/cotton blended fabric in order to determine any influences of plasma treatment on the fabric. It was treated with oxygen plasma with different oxygen flow rate (0.1 L/min, 0.3 L/min and 0.5 L/min) jet-to-substrate distance (1 mm, 3 mm and 5 mm) and treatment time (0.1 s, 0.5 s and 1 s). The results confirmed that there were enhancements in the performance of the bamboo/cotton blended fabrics after the plasma treatment, such as wicking, dispersion and surface modification.

ACKNOWLEDGEMENTS: The authors wish to express their gratitude towards The Hong Kong Polytechnic University for providing the financial support for this work.

REFERENCES

[1] Hong Kong Cotton Spinners Association, "Textile Handbook", Hong Kong Cotton Spinners Association, 2007.

[2] C. W. Kan and C. W. M. Yuen, *Text. Prog.*, **39**, 121 (2007).

[3] K. K. Samanta, T. N. Gayatri, S. Saxena, S. Basak, S. K. Chattopadhyay *et al.*, *Cellulose Chem. Technol.*, **50**, 745 (2016).

[4] C. W. Kan, in "Sustainable Apparel. Production, Processing and Recycling", edited by R. Blackburn, Woodhead Publishing Series in Textiles, 2015, Chapter 3 – Plasma treatments for sustainable textile processing, pp. 49-118.

[5] C. W. Kan, C. F. Lam, C. K. Chan and S. P. Ng, *Carbohyd. Polym.*, **102**, 167 (2014).

[6] S. Sousa, C. Gaiolas, A. P. Costa, C. Baptista and M. E. Amaral, *Cellulose Chem. Technol.*, **50**, 711 (2016).

[7] Z. J. Wang, Y. Chen and X. Li, *Surf. Coat. Technol.*, **228**, Suppl. 1, S198 (2013).

[8] A. Patnaik, R. S. Rengasamy, V. K. Kothari and A.

Ghosh, *Text. Prog.*, **38**, 1 (2006).
[9] C. X. Wang and Y. P. Qiu, *Surf. Coat. Technol.*, **201**, 6273 (2007).
[10] Y. L. Lam, C. W. Kan and C. W. M. Yuen, *J. Appl. Polym. Sci.*, **124**, 3341 (2012).
[11] C. Yang, U. Tartaglino and B. N. J. Persson, *Phys. Rev. Lett.*, **97**, 116103 (2006)
[12] C. Yang, U. Tartaglino and B. N. J. Persson, *Eur. Phys. J.*, **25**, 139 (2008).
[13] R. N. Wenzel, *Ind. Eng. Chem.*, **28**, 988 (1936).
[14] A. B. D. Cassie and S. Baxter, *Trans. Faraday Soc.*, **40**, 546 (1944).
[15] W. Rakowski, M. Okoniewski, K. Bartos and J. Zawadzki, *Melliand Texibrichte*, **63**, 301 (1982).