Suleiman Ndaro Mbwana,
***Xiang-yu Jin,**
Ting Chen,
Chongwen Yu

Optimum Water Jets Inclination Angle for Better Tensile Strength in Hydroentanglement Process

Department of Textile Engineering,

***Department of Nonwoven,**
Donghua University,
Shanghai, 201620. P. R. China
E-mail: mbwanasul@yahoo.co.uk

Abstract
An experimental set up was developed to evaluate the role of the water jet inclination angle during the hydroentanglement process. Hydroentangled bicomponent nonwoven fabrics were made using the inclined water jet apparatus designed. The effects of water jet inclination angles are discussed and evaluation was made on the basis of the fabric tensile strength. The experimental results revealed that the use of inclined water jets increases the fabric's tensile strength. An inclination angle of 10 degrees was the optimum, showing higher tensile strength for all nonwoven fabrics tested. These results confirmed that with an optimum water jet inclination angle in the hydroentanglement process, the fabric's tensile strength can be improved.

Key words: *hydroentanglement, inclined water jets, optimum inclination angle, splittable bicomponent fabrics.*

Introduction

Each nonwoven manufacturing system involves the following: fibre/raw material selection, web formation, web consolidation, as well as web finishing and converting. It has been reported that the technologies expected to gain more importance are spun bonding, melt blowing, and hydroentanglement [1]. No matter how hydroentanglement systems may vary from one manufacturer to another, the entanglement of fibre web requires the following: a web supporting substrate, water jet nozzles, water extraction, water circulation and filtration [1 - 5]. In this study, a hydroentanglement unit was designed to provide inclined water jets.

The study of hydroentanglement units has been ongoing for many years, and many researchers have shown that nozzle parameters and their configurations play a great role in the hydroentanglement process [6 - 11]. However, other researchers[12 - 17] have studied the effect of specific energy and jet pressure on the tensile strength of hydroentangled fabrics and concluded that there is an optimum pressure and specific energy to be considered for obtaining the maximum tensile strength of fabrics. All of those studies used perpendicular water jets. In the case of diverging water jets, experiments were conducted by Bunting of DuPont in 1964, as well as Zolin and Sternlieb [18 - 20]. Bunting [21] set the manifold oblique to the linear direction of the woven cloth, but his method was never commercialised since it was totally impractical and costly. Zolin [20] replaced Bunting's oblique strip with a multivane jet strip, each vane being discontinuous from the adjoining vane and consisting of 3 or more holes per vane. From their work they concluded that diverging water jets can improve the performance of woven fabrics.

Their methods were used for woven fabrics, but they were very complicated and costly since they referred to the change in the manifold setting and did not specify the angles used. Webster and Longmire [22] studied the vortex dynamics of jets from inclined nozzles and found that the radial spreading of jets increased with the nozzle's inclined angle; they concluded that as the inclination angle increased, the coherent structure rapidly broke down.

Recently, Oathout, J. M. et al [23] used angled water jets to study the anisotropic nature of nonwoven fabrics. From their study they concluded that when using angled jets, the isotropy of hydroentangled fabrics was improved. Furthermore, they reported that relatively low water jet pressures were sufficient to achieve low strength ratios compared to higher water jet pressures ,which can achieve good strength ratios but tended to cause jet washing, resulting in less fabric uniformity. In their work the water jet pressure ranged from 40 - 1800 psi, and angle jets of 0 - 30 degrees and a jet density of 16 jets/cm were used. The fibre type used in this study was mainly 100% polyester. However, after careful review of the literature, there appears to be nothing about the use of inclined water jets for splittable bicomponent fibres, hence research is needed to form a deep understanding of the effect of inclined water jets on such fibres. Optimisation of the hydroentanglement process leads to low energy and low water consumption during it; as a result, the running cost can be reduced. In order to enhance the hydroentanglement process, it is good practice to increase the fibre bonding points. By doing this, an increase in the tensile strength is expected. To attain this goal, the use of inclined water jets was considered as a possible solution due to their long path distance within the fibre web. In this paper we investigate the use of inclined water jets using different inclination angles. We evaluate changes in the tensile strength of nonwoven fabrics and make a comparison to find out the optimum inclination angle for obtaining maximum tensile strength.

Experimental

Materials

The island in sea bicomponent fibre, 70%PET/30%COPET of 4 dtex linear density with 37 PET islands, and 70%PA6/30%PET pie segment fibre of 2.77 dtex linear density with 8 segments were used in this study. Carded webs of 100 grams per square meter (gsm) for each fibre type were produced using a conventional sampling carding machine.

Mbwana N. S., Jin X., Ting C., Yu C.; Optimum Water Jets Inclination Angle for Better Tensile Strength in Hydroentanglement Process.
FIBRES & TEXTILES in Eastern Europe 2009, Vol. 17, No. 4 (75) pp. 82-86.

The fibre length for all fibres was 51mm and each sample of carded web was cut into small pieces of 55 mm (width) by 175 mm (length). Five samples were obtained corresponding to machine directions and crosswise directions, respectively, all of which were marked to avoid mixing them. This allowed for greater accuracy in the processing of carded webs using small jet plates during hydroentanglement.

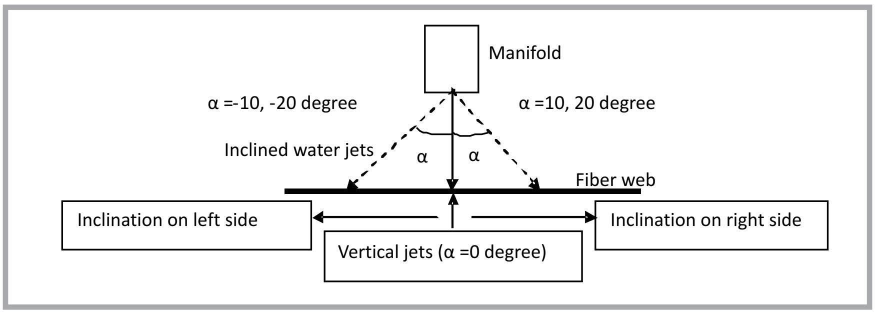


***Figure 1.** Inclination modes of water jets. Note: The fabric flow was directed in the front or back with respect to the manifold and water jets perpendicular or angled from the perpendicular with respect to the fibre webs.*

Preparation of hydroentangled samples

The inclined water jet apparatus designed was used for the preparation of hydroentangled nonwoven fabrics. The -20, -10, 0, 10, and 20 degrees of inclination of nozzle orifices on the jet plates (see ***Figure 1***) and pressure levels of 3, 5, 7 and 10 bars were used to process the fabrics. Figure 1 clearly shows the meaning of the negative sign (-) as an inclination on the left side of the web.

Two passes for each side of the fibre webs were used during hydroentanglement, and the standoff distance between the nozzle orifice and fibre web was fixed at 20 mm. Other processing variables were a jet density of 3 jets/cm, a nozzle orifice diameter of 0.3 mm and web velocity of 0.72 m/min. The water in the pressure water tank was driven by air pressure from the air compressor downwards through the hydraulic hose pipe, and eventually the water jets were forced through the orifices, striking the fibre web fixed on the screen mesh. Since the jet plate was small, the shifting of the fibre web along its width was carried on to cover a small area of the carded fibre webs until the sample was totally hydroentangled.Webs in the machine direction (MD) were hydroentangled lengthwise and in a crosswise direction (CD) width wise. ***Figure 2*** shows a flow diagram of the process, and ***Figure 3*** is an example of a jet plate in the small manifold of the inclined nozzle orifice at an angle of 10 degrees used in this study.

The preliminary stage of this work was done in a laboratory, from which it was derived that the processing variables, such as the water jet pressure, jet density, nozzle orifice diameter are much different from the ones usually used in industrial/commercial hydroentangling units.

Measurements

The preparation of all samples and tests were carried out according to ASTM D 5035-95 (strip method) [24]. The tensile strength of hydroentangled non-woven fabrics was measured using a Universal Material Tensile Testing Machine (AGS-500ND) at a constant rate of 250 mm/min and gauge length of 100 mm. The dimensions of the samples was 50 mm by 170 mm in the machine (MD) and crosswise directions (CD). Five samples were tested in the machine direction and crosswise direction , and the average values of their tensile strength at break were recorded.

Results and discussions

The tensile strengths at break of hydroentangled fabrics tested in accordance with their processing variables are given in ***Tables 1*** & ***2***.

Trends in tensile strength depending on the inclination angle of the water jet

The ***Figure 4*** shows the trend in tensile strength depending on inclination angles. The curves in ***Figure 4*** clearly show that the tensile strength at break increased up to the maximum value and then started to decrease. ***Figure 4*** confirmed the optimum inclination angle of 10 and -10 degrees as the best for providing higher tensile strength at constant pressure levels, followed by -20 and 20 degrees as their tensile strength was higher than that of perpendicular water jets. As can be seen from ***Tables 1*** & ***2***, other values of tensile strength at the different pressure levels of 3.5, and 7 bars show the same trend as that for 10 bars, as shown in ***Figure 4***.

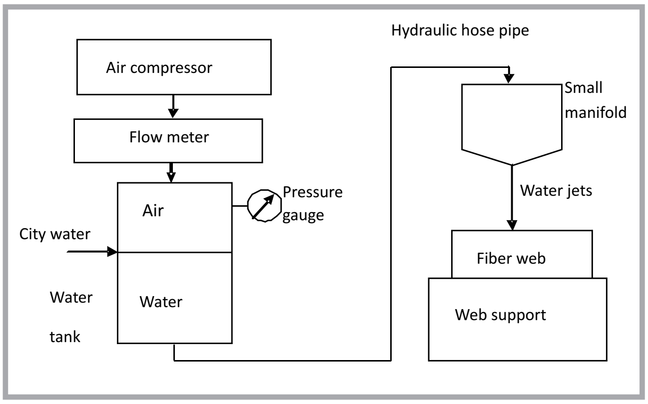


***Figure 2.** Flow diagram of the hydroentanglement process.*

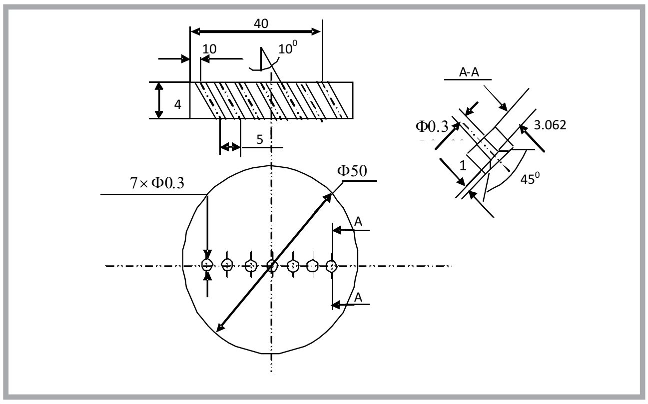


***Figure 3.** Jet plate of nozzle orifices of 10 degree angle of inclination. **Note**: All dimensions are in millimeters (mm) and the figure is not drawn to scale.*

Table 1. Tensile strength at break (N/5 cm) of PET/COPET fabrics after hydroentanglement. ***Note:*** *Pg-Pressure, MD-Machine direction, CD-Crosswise direction.*

Pg		Inclined angle of the nozzle (α) in degrees									
		-20		-10		0		10		20	
Bars		MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
3	Average	0.494	0.119	0.549	0.121	0.326	0.088	0.546	0.121	0.495	0.118
	Cv %	10.92	9.62	14.51	13.06	13.18	14.3	22.4	11.83	15.36	16.09
5	Average	0.579	0.158	0.682	0.209	0.484	0.134	0.681	0.206	0.579	0.159
	Cv %	17.57	24.23	12.33	10.65	18.2	19.45	11.94	16.84	15.57	15.06
7	Average	1.254	0.289	1.575	0.358	0.831	0.252	1.576	0.354	1.25	0.281
	Cv %	16.09	19.24	11.45	8.18	6.3	20.19	23.69	22.35	16.08	15.11
10	Average	4.257	0.874	5.17	4.327	2.796	0.887	5.218	4.675	4.369	0.9
	Cv %	9.56	7.55	6.55	8.75	17.95	7.02	8.92	4.69	4.73	1.71

Table 2. Tensile strength at break (N/5 cm) of PA6/PET fabrics after hydroentanglement. ***Note:*** *Pg-Pressure, MD-Machine direction, CD-Crosswise direction.*

Pg		Inclined angle of the nozzle (α) in degrees									
		-20		-10		0		10		20	
Bars		MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
3	Average	7.13	2.046	10.53	2.426	3.946	0.914	10.67	2.438	7.09	2.096
	Cv %	18.22	7.26	14.78	12.91	18.88	17.58	18.28	12.37	17.48	12.72
5	Average	17.068	3.666	22.806	6.744	10.992	3.002	22.58	4.772	17.72	3.982
	Cv %	20.28	21.45	29.69	28.85	11.61	10.46	23.27	21.68	10.39	10.87
7	Average	39.312	11.768	42.463	17.658	33.202	10.452	42.494	17.982	39.228	11.604
	Cv %	14.93	16.16	15.98	11.45	27.07	23.32	11.37	24.5	9.18	7.6
10	Average	50.34	13.17	64.57	35.12	45.89	12.18	65.42	35.05	51.27	13.38
	Cv %	7.436	9.564	5.482	5.764	2.321	6.163	1.982	2.288	2.641	4.378

Influence of the perpendicular water jet (0 degree) on the tensile strength at break

As indicated in ***Tables 1*** & ***2***, it was proved that the tensile strength of PET/COPET fabrics were in the range of 0.326 to 2.796 N/5 cm in the machine direction (MD) and 0.088 to 0.887 N/5 cm in the crosswise direction(CD).

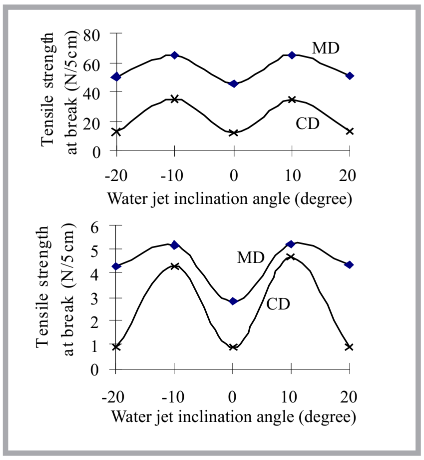


Figure 4. *Effect of water jets inclination angle on the tensile strength of bicomponents fabrics. a) PA6/PET FABRICS, 100 gsm, b) PET/COPET FABRICS, 100 gsm. 10 bars.*

However, the tensile strength of PA6/PET fabrics was higher, (3.946 to 45.887 N/5 cm for MD and 0.914 to 12.176 N/5 cm for CD) than that of island in sea (PET/COPET) fabrics for the same pressure levels and inclination angles.The reason for this is possibly due to the low linear density of PA6/PET fibres, which caused the fibres to bend and move easily within the fibre webs during hydroentanglement, resulting in more entanglement, thus increasing the tensile strength. Furthermore, as the pressure increased from 3 bars to 10 bars, the tensile strength at break of PA6/PET fabrics was dramatically higher than that of PET/COPET fabrics in both the machine (MD) and crosswise directions (CD). It is probable that this reflected the splitting of PA6/PET fibres, which means a reduction in fibre diameter, causing a better and more efficient entanglement of fibres to produce more bonding points, thus affecting an increase in the tensile strength. ***Figure 5*** shows SEM photos of fibre webs after being hydroentangled, which confirmed the splitting behaviour of PA6/PET even though low pressures were used. The PET/COPET fibres in ***Figure 5.a*** were not split at all due to the strong interfacial bonding between polyester and co polyester.

The value of tensile strength when using perpendicular water jets (at an inclination angle of 0 degrees) was lower than other values of tensile strength in the same processing conditions when using inclined water jets. This maybe due to the shortest path of water jets through the fibre webs (see ***Figure 6***), which means the water jets strike very few fibre segments along its path during hydroentanglement, resulting in few bonding points compared to the inclined water jets.

Effect of an inclination angle of -10 and 10 degrees on the tensile strength at break

As can be seen in ***Tables 1*** & ***2***, the highest tensile strength values occurred when using an inclination angle of -10 and 10 degrees. This may be attributed to the long path distance of water jets through the fibre webs during the hydroentanglement process. In this case, many fibres were displaced, twisted, deflected or bent to form many bonding points, which improved the tensile strength. The decrease in impact force in the -10 and 10 degree inclined mode of impact during hydroentanglement may not have had a significant effect on fibre movement within the fibre webs due to the low water jet inclination angle compared to water jets of -20 and 20 degrees. The comparison of tensile strength, depending on the fibre types used (see ***Table 1*** & ***2***), can be explained by the mechanical properties of the fibres, such as the bending modulus, fibre tenacity, linear density, coefficient of friction, cross-section area, fibre splitting (see ***Figure 5***) etc. The results confirmed that angles of inclination of -10 and 10 degrees proved to be the best in this study.

Effect of an inclination angle of -20 and 20 degrees on the tensile strength at break

Tables 1 & ***2*** indicate that the tensile strength of PET/COPET fabrics was in the range of 0.494 to 4.369 N/5cm for the machine direction and 0.118 to 0.9 N/5cm for the crosswise direction, while for PA6/PET the range was 7.09 to 51.272 N/5cm for the machine direction and 2.046 to 13.380 N/5cm for the crosswise direction. The values of tensile strength for a -20 and 20 degree inclination angle were generally higher than those obtained using perpendicular water jets but lower than the values obtained using a -10 and 10 degree inclination angle. This can probably be explained

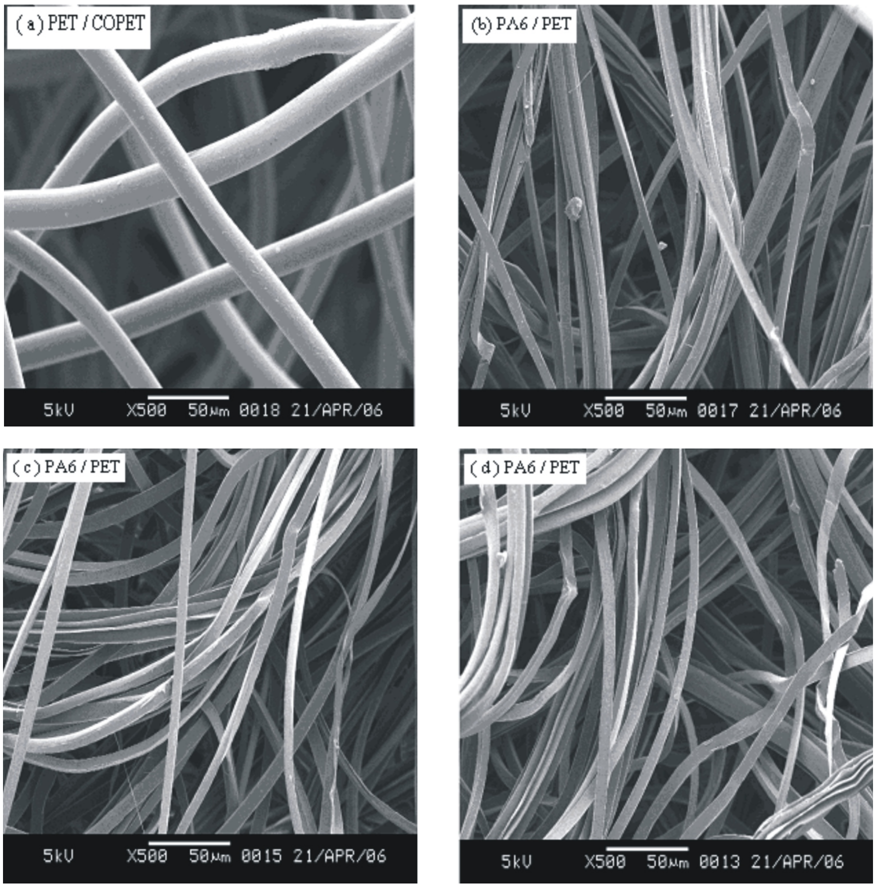


Figure 5. *SEM photomicrographs of splittable bicomponent fibre webs after hydroentanglement.* ***Note:*** *1. a), and c) Treated with 10 bars at a water jets inclination angle of 10 degree. 2. b) Treated with 10 bars and vertical water jets (0 degree). 3. d) Treated with 10 bars and water jets of inclination angle of 20 degree*

by the fact that as the angle of inclination increased up to 20 or -20 degrees, there was a significant development of vortex rings within the water jets compared to water jets with an inclination angle of 10 degrees. Even if the water jets acquired a longer path distance than all other angles used, we expected more bonding points, which increase the tensile strength; however, this may be the effect of vortex rings making the structure of the constricted water jets unstable, leading to a decrease in the specific energy or impact force as a result of the less turbulent effect within the fibre webs. Another problem is that as inclined water jets of a higher degree than -10 or 10 degrees strike the fibre webs, the jets tend to reorient the individual fibres severely, the effect of which may be a decrease in the cohesion and bonding strength of entangled fibres as well as the uniformity of the web structure becoming impaired. The explanations mentioned may be the reasons for the reduction in tensile strength, but the tensile strength was still better than that obtained using perpendicular water jets. Results for the tensile strength based on opposite angles, such as 10 and -10 degrees as well as -20 and 20 degrees, are in fact almost the same; a small difference is inevitable.

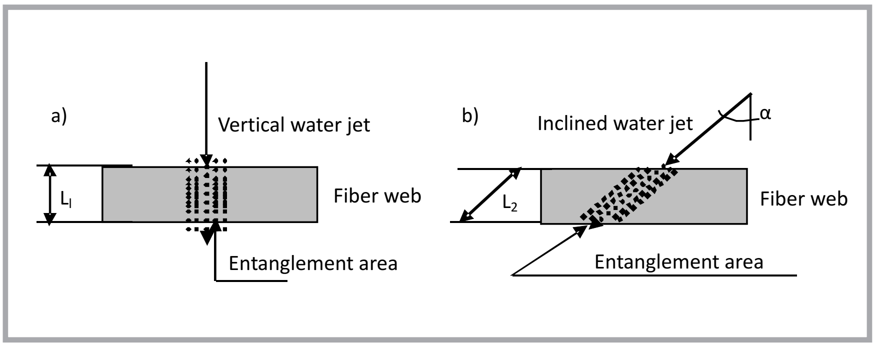


Figure 6. *Path distance of water jets through fibre webs a) in vertical mode b) in inclined mode. Note: L_1 is the shortest path distance due to the vertical water jets, L_2 is the longest path distance due to the inclined water jets and the web thickness is assumed to be the same. (L_1 is obvious greater than L_2).*

Conclusion

This study was undertaken to evaluate a suitable water jet inclination angle for splittable biocomponent fibres in the hydroentanglement process . The inclined water jet apparatus was designed and used to attain this goal: making test samples and then making a comparison to find out which inclination angle is more suitable. The results showed that inclination angles of 10 and -10 degrees were the optimum, followed by inclination angles of 20 and -20 degrees; the least suitable being for perpendicular water jets (at an inclination angle of 0 degrees). It is hoped that the results from this study reflect the role of inclined water jets in the hydroentanglement process and will instigate further research using the same parameters as those used in the commercial industrial hydroentanglement process with inclined water jets taken into consideration.

Acknowledgments

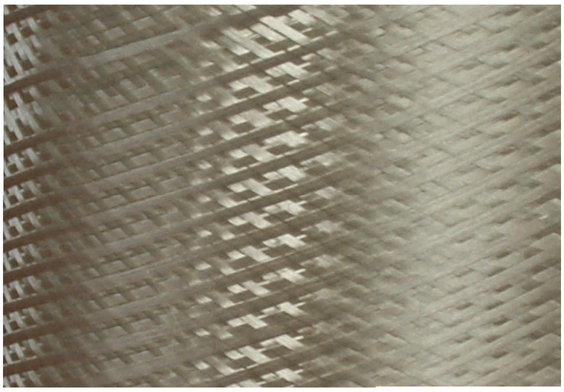
The author would like to acknowledge the financial support received from the China Scholarship Council (CSC) and the Tanzania Industrial Research and Development Organisation (TIRDO).

References

1. *Fechter Th. A., Münstermann U., Watzl A.; "Latest Developments in Hydroentanglement," International Fibre Journal, February 2001, Vol. 16, No. 1, pp 50-51.*
2. *Weng W.; "Hyper punch Technology for Artificial Leather and Paper maker Felts," The 8th Shanghai International Conference Papers, Shanghai, P. R. China,22-23 Sept. 1999, pp 198-205.*
3. *Turbak A. F.; "Nonwovens: Theory, Processing, Performance, and Testing,"Tappi Press, USA, 1993, pp 168-169.*
4. *Medeiros F. J.; "Spunlace / Hydroentanglement Methods and Products," International Non-woven Conference, Virginia, USA, 11-13 September 1996, INDA-TEC 1996, pp. 5.1-5.15.*
5. *Barnard W. S., Osborne R. J., Dayton N. J.; "Spunlace Processes Worldwide," The International Non-woven Technological Conference, Book of Papers, Marriott's Hilton Head Resort Association of the Non-woven Fabric Industry, USA, 18-21 May 1987, INDA.TEC 87, pp. 501-512.*

6. Tafreshi H. V., Pourdeyhimi B., Holmes R., Shiffler D.; "Simulating and Characterizing Water Flows Inside Hydroentangling Orifices," Textile Research Journal, 2003, Vol. 73, No. 3, pp. 256-262.
7. Ghasemieh E., Versteeg H. K., Acar M.; "Effect of Nozzle Geometry on the Flow Characteristics of Hydroentangling Jets," Textile Research Journal, 2003, Vol. 73, No. 5, pp. 444-450.
8. Tafreshi H. V., Pourdeyhimi B.; "Simulating the Flow Dynamics in Hydroentangling Nozzles: Effect of Cone Angle and Nozzle Aspect Ratio," Textile research Journal, 2003, Vol. 73, No. 8, pp. 700-704.
9. Begenir A., Tafreshi H. V., Pourdeyhimi B.; "Effect of Nozzle Geometry on Hydroentangling Water Jets: Experimental Observations," Textile Research Journal, 2004, Vol. 74, No. 2, pp. 178-184.
10. Tafreshi H. V., Pourdeyhimi B.; "Simulating Cavitation and Hydraulic Flip Inside Hydroentangling Nozzles," Textile Research Journal, 2004, Vol. 74, No.4, pp 359-364
11. Anantharamaiah N., Tafreshi H. V., Poudeyhimi B.; "A study on flow through hydroentangling nozzles and their degradation," Chemical Engineering Science, 2006, Vol. 61, pp. 4582-4594.
12. Begnir A.; "The Role of Orifice Design in Hydroentanglement," Master of Science Thesis, NCSU, 2002.
13. Hwo C. C., Shiffler D. A.; "Non-woven forum PTT (staple) Fibres," Corterra Polymer, Copyright Shell, 2000, (http:// www.shellchemicals.com/chemicals/pdf/corterra/0053.pdf), viewed at October 11, 2006
14. Berkalp O. B., Pourdeyimi B., Seyami A.; "Texture Evolution in Hydroentangled Nonwovens," International Nonwoven Journal, 2003, Vol. 12, No. 1, pp. 28-35.
15. Zheng H.; "The impact of input Energy, Fibre Properties, and Forming Wires on the Performance of Hydroentangled Fabrics," Ph.D. Thesis, NCSU, 2003.
16. Timble N. B., Gilmore T. F., Morton G. P.; "Spunlace Fabric Performance of Unbleached Cotton at Different Specific Energy Levels of water," International Non-woven Conference, Hyatt Regency Crystal City, Virginia, USA, 11-13 September 1996, INDA-TEC 1996.
17. Pourmohammadi A., Russell S. J., Höffele S.; "Effect of Water Jet Profile and Initial Web Geometry on the Physical Properties of Composite Hydroentangled Fabrics," Textile Research Journal, 2003, Vol. 73, No. 6, pp. 503-508.
18. U.S Pat. 4,967,456, 1990-11-06.
19. U.S Patent 5,791,028, 1998-08-11.
20. U.S Patent 6,253,429B, 1998.
21. Australian Patent 287,821 September, 1964.
22. Webster D. R., Longmire E. K.; Vortex Dynamics in Jets from Inclined Nozzles, Phys. Fluids, 9(3), March 1997, pp. 655-666
23. J. M. Oathout, P. O. Staples, D. F. Miller, Process and Apparatus for Increasing the Isotropy in Nonwoven Fabrics., US. Patent 6,877,196, 2005-12-04.
24. ASTM Standard D 5035-1995, Standard Test Method for Breaking Force and Elongation of Textile Fabrics (strip method), Annual Book of Standards, Vol. 7, ASTM International, West Conshohocken, PA, 1995.

Received 07.01.2007 Reviewed 24.04.2009



Multifilament chitosan yarn