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Study of the Stress Relaxation Property of Vortex Spun Yarn in Comparison with Air-jet Spun Yarn and Ring Spun Yarn

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Abstract
The structure of vortex spun yarn made by the Murata vortex spinning machine is different from that of other yarns, such as ring spun yarn, air-jet spun yarn and so on. The stress relaxation model is constructed by a generalized Maxwell model connected in a row to a Hook's spring in order to predict and analyse the stress relaxation property of vortex spun yarn. Based on the stress relaxation model, the stress relaxation properties of vortex spun yarn, ring spun yarn and air-jet spun yarn are compared and analysed. The factors influencing the stress relaxation property of vortex spun yarn, such as the tensile strain, tensile rate and yarn count are discussed. The research results show that the stress relaxation model can be used for describing the stress relaxation mechanism of vortex spun yarn. The elasticity of vortex spun yarn is better than that of air-jet spun yarn, but worse than that of ring spun yarn. When the tensile strain is lower and the tensile rate is larger, vortex spun yarn has a more obvious stress relaxation phenomenon. The stress relaxation phenomenon of finer yarn is more obvious than that of coarser yarn.

Key words: *Murata vortex spinning, vortex spun yarn, stress relaxation.*

Introduction

Murata vortex spinning (MVS) is promising new spinning technology developed from Murata jet spinning It uses whiled airflow in the nozzle block to twist the open-trail end fibres into vortex spun yarn. So far as Murata vortex spinning is concerned, previous research can be summarised as follows:

1. Discussion on the yarn formation principle based on the process of yarn formation and flow field rule inside the nozzle block. For example, Gray described the process of vortex spun yarn formation [1]. The flow pattern of airflow inside the nozzle block is analysed by constructing a Computational Fluent Dynamic (CFD) Model by Zou et al. [2, 3] and Pei et al. [4], which is used to interpret the yarn formation principle of vortex spun yarn.
2. The influence of the spinning process on the structure and properties of vortex spun yarn. For example, Basal discussed the influence of fibre characteristics, such as short fibre and neps in cotton fibres on the quality of vortex spun yarn [5]. Other process parameters, such as nozzle angle, nozzle pressure, spindle diameter, yarn delivery speed, draft ratio and distance from the nip of the front rollers and hollow spindle were also investigated and analysed to establish the structure and properties of vortex spun yarn [6 - 10]. Ortlek studied the effect of the hollow spindle diameter and spindle working period on the properties of 100% viscose MVS yarns and found that various properties of MVS yarns are significantly affected by the spindle diameter and spindle working period [11]. Zou explained the generation of yarn thin places of MVS yarn and the high fibre loss rate by making a force analysis of a separated fibre in the twist chamber [12].
3. Research on the structure and properties of vortex spun yarn as well as a comparison of the structure and properties of yarns produced by different spinning systems, such as conventional ring spinning, air-jet spinning and open-end rotor spinning. For example, the structure of vortex spun yarn consists of a core of parallel fibres held together by wrapper fibres [13, 14], which was illustrated

Table 1. *Fibre properties.*

Fiber properties		Fibre type		
		Colored cotton	White cotton	Bamboo pulp fibre
Upper quartile length, mm		26.8	29.3	-
Fibre length, mm		-	-	40.1
Fineness,	dtex	1.46	1.74	1.56
	micronaire	3.14	4.81	-
Tenacity, cN/dtex		1.9	2.83	2.21
Elongation, %		5.7	7.6	19.3

Table 2. *Yarn formation process parameters*

Yarn type	Vortex spun yarn			Air-jet spun yarn	Ring spun yarn
Case	1	2	3	4	5
Spinning Machine	Murata vortex spinning			Air-jet spinning	Ring spinning
Delivery speed, m/min	320	400	400	167	19
Total draft	129	218	128	98	27
Main draft	40	35	30	23	-
Nozzle type	75, Holder 130d, 9.3	75, Holder 130d, 8.8	75, Holder 130d, 8.8	H26	-
Condenser/ Hollow spindle, mm	Hollow spindle 1.4			Condenser 4	-
Spindle speed, r.p.m.	-	-	-	-	15000
Ring diameter, mm	-	-	-	-	40
Feed ratio	1	0.96	0.96	1	
Take up ratio	0.99	1.013	1.013	0.99	-
Air pressure, MPa	0.4	0.6	0.6	N1 0.3, N2 0.4	-
Distance between front roller and spindle/N2 nozzle, mm	19	20	20	39.5	-
Yarn count, tex	18.2	18.2	32.4	18.2	18.2

by the fibre spatial trajectory in vortex spun yarn based on the yarn formation process [15]. Compared with ring and open-end rotor spun yarns, vortex spun yarns have lower hairiness and better pilling resistance [14, 16 - 18]. Basal et al. found that vortex spun yarns have tenacity advantages over air jet yarns, particularly at high cotton contents [13].

4. Investigation of the fabric characteristics produced by vortex spun yarn in comparison with ring and rotor spun yarn knitted fabrics [18 - 20]. These investigations found that fabrics made from MVS yarn had a more even appearance and lower pilling tendency.

This paper will further discuss the properties of vortex spun yarn. As we all know, the properties of fabric are greatly affected by the yarn properties, such as tenacity, hairiness, evenness, viscoelastic property and so on. The viscoelastic behavior, such as stress relaxation under constant deformation and creep elongation at constant stress, which is also one of the most important yarn properties , will affect the dimensional stability of a fabric. The viscoelastic behaviour of yarns with the same fibre components are affected by the yarn type, yarn count, different tensile strains and rates. The creep elongation property of vortex spun yarn has already been investigated by Zou [21]. Therefore this paper will focus on the stress relaxation property of vortex spun yarn.

Experimental

Materials

Table 1 shows the properties of the coloured cotton, white cotton and bamboo pulp fibres used in this study. The cotton and bamboo pulp fibres were provided by Dezhou Huayuan Eco-Technology Co., Ltd. and Henan Xinye Textile CO., Ltd. in China, respectively. The process parameters used to produce different experimental samples are shown in ***Table 2***. The 18.2 tex white cotton/coloured cotton blend yarns with an 85% white cotton ratio, in cases 1, 4 and 5 of ***Table 2***, were spun by Murata vortex spinning, air-jet spinning and ring spinning. The vortex spun yarns of 18.2 tex and 32.4 tex in cases 2 and 3 of ***Table 2,*** respectively, were spun from a bamboo pulp fibre/white cotton blend with a 70% bamboo pulp fibre ratio on Murata vortex spinner.

Stress relaxation test

Stress relaxation tests were carried out on test samples in cases 1 - 5, which were subjected to relaxation for 300 seconds at different test conditions. The stress relaxation properties of the yarns were measured by a YG061 electronic single-yarn tensile tester. Tests were conducted in a conditioned atmosphere of 20 ± 2 °C and 65 ± 2% relative humidity. 10 tests per sample were performed and their mean values were used to describe the stress relaxation behaviour of vortex spun yarn. For all tests, an ample gauge length of 500 mm was chosen. The pre-tension for measuring creep elongation was 0.5 cN/tex.

Stress relaxation model

The internal stress of a yarn under a fixed tensile strain is a function of the relaxation time, which can be described by constructing a stress relaxation model with Hook’s springs and Newton’s dashpots. The stress relaxation model with more Hook’s springs and Newton’s dashpots can more accurately describe the stress relaxation phenomenon of a yarn. This paper will adopt the modified generalised Maxwell model in ***Figure 1***, used to describe the viscoelastic behaviour of *Agave Americana L.* fibres by Oudiani et al. [22], to analyse the relaxation property of the vortex spun yarn. The mechanical behaviour of this model is expressed by ***Equation 1*** as follows

$$\frac{\mu_2}{E_2E_3}\ddot{\varepsilon}+\left(\frac{E_1}{E_2}+\frac{\mu_2}{\mu_1}+1\right)\dot{\varepsilon}+\frac{E_1}{\mu_1}\varepsilon= =\frac{\mu_2}{E_2E_3}\ddot{\sigma}+\left(\frac{1}{E_3}+\frac{E_1}{E_2E_3}+\frac{\mu_2}{\mu_1E_3}\right)\dot{\sigma}+\left(\frac{E_1}{E_3\mu_1}-\frac{1}{\mu_1}\right)\sigma \quad (1)$$

Where E_1, E_2, and E_3 are the elastic coefficients of Hook’s springs, μ_1 and μ_2 - the viscosity coefficients of Newton’s dashpots, σ - the stress action on a yarn, and ε is the elongation of a yarn under stress σ.

When the elongation $\varepsilon = \varepsilon_c$, ***Equation 1*** can be modified as follows

$$\frac{\mu_2}{E_2E_3}\ddot{\sigma}+\left(\frac{1}{E_3}+\frac{E_1}{E_2E_3}+\frac{\mu_2}{\mu_1E_3}\right)\dot{\sigma}+\left(\frac{E_1}{E_3\mu_1}-\frac{1}{\mu_1}\right)\sigma=\frac{E_1}{\mu_1}\varepsilon_c \quad (2)$$

where the value of ε_c is a constant elongation.

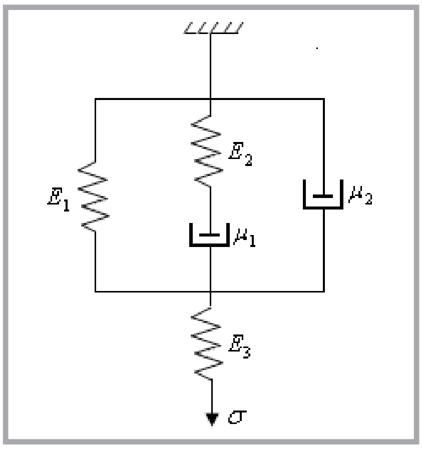

Figure 1. *Modified generalised Maxwell model [22]; E1, E2, and E3 - elastic coefficients of Hook’s springs, μ1 and μ2 - viscosity coefficients of Newton’s dashpots.*

If $A=\frac{\mu_2}{E_2E_3}$; $B=\frac{1}{E_3}+\frac{E_1}{E_2E_3}+\frac{\mu_2}{\mu_1E_3}$;

$C=\frac{E_1}{E_3\mu_1}-\frac{1}{\mu_1}$; $D=\frac{E_1}{\mu_1}\varepsilon_c$

Equation 2 can be simplified as

$$A\ddot{\sigma}+B\dot{\sigma}+C\sigma=D \quad (3)$$

thus the general solution of ***Equation 3*** is expressed by ***Equation 4*** as follows

$$\sigma(t)=\left(\frac{E_1E_3}{E_1-E_3}\right)\varepsilon_c+c_1e^{\left(\frac{-B+\sqrt{A^2-4AC}}{2A}\right)t}+c_2e^{\left(\frac{-B-\sqrt{A^2-4AC}}{2A}\right)t} \quad (4)$$

where c_1, c_2 are undetermined coefficients, and t is the time variable. When $t = 0$, $\sigma(0)=E_3\varepsilon_c$ and $\dot{\sigma}(0)=0$, which are substituted into ***Equation 4***, parameters c_1, c_2 can then be obtained as

$$c_1=E_3\varepsilon_c-\frac{D}{C}+-\frac{\left(-B+\sqrt{A^2-4AC}\right)\left(E_3\varepsilon_c-\frac{D}{C}\right)}{2\sqrt{A^2-4AC}} \quad (5)$$

$$c_1=E_3\varepsilon_c-\frac{D}{C}-\frac{\left(-B+\sqrt{A^2-4AC}\right)\left(E_3\varepsilon_c-\frac{D}{C}\right)}{2\sqrt{A^2-4AC}} \quad (6)$$

Therefore, the simplified form of ***Equation 4*** is described by the following equation

$$\sigma(t)=c_0+c_1e^{-t/\tau_1}+c_2e^{-t/\tau_2} \quad (7)$$

where $c_0=\left(\frac{E_1E_3}{E_1-E_3}\right)\varepsilon_c$,

$$-\frac{1}{\tau_1}=\frac{-B+\sqrt{A^2-4AC}}{2A},$$

$$-\frac{1}{\tau_2}=\frac{-B-\sqrt{A^2-4AC}}{2A},$$

and τ_1 and τ_2 are the stress relaxation time.

Results and discussion

Stress relaxation property of vortex spun yarn compared with other yarn types

Different yarns made by different spinning machines have different yarn structures, which results in discrepancies in their stress relaxation properties. The vortex spun yarn in case 1 has the same yarn counts and same material composition as the air-jet and ring spun yarns in cases 4 and 5, respectively. The stress relaxation properties of these yarns are tested under a 200 mm/min tensile rate and 4% tensile strain. The stress relaxation properties of the vortex spun yarn in case 1 compared with the air-jet spun and ring spun yarns in cases 4 and 5 is shown in ***Figure 2***. Based on test data of the yarns' stress relaxation behaviour, theoretical curves of the stress relaxation behaviour for cases 1, 4 and 5 are fitted using ***Equation 7*** by means of Origin 8.0 software. The stress relaxation curves are characterised by parameters presented in ***Table 3*** together with correlation coefficients. The high correlation coefficient validates the effectiveness of the stress relaxation model. The parameters of the stress relaxation model for every yarn type are also shown in ***Table 3***.

For ***Figure 2***, when the vortex, air-jet and ring yarns are all at a 4% tensile strain, the internal stress action on the vortex spun yarn is greater than that on the air-jet spun yarn and less than that on the ring spun yarn. For every yarn type the stress relaxation phenomenon taking place in approximately 10 seconds is very significant, which then gradually weakens with time until it reaches a plateau. As shown in ***Table 3***, values of the stress relaxation time τ_1 and τ_2 of vortex spun yarn are larger than those of air-jet spun yarn and less than those of ring spun yarn, which is caused by their different structure; this can be used to illustrate the elasticity of ring spun yarn being greater than that of vortex spun yarn, followed by air-jet spun yarn. The stress relaxation of a yarn under fixed tensile strain reaches a balance earlier for a loose yarn structure, like that of air-jet spun yarn. Compared with air-jet spun yarn, vortex spun yarn has more wrapper fibres, which restricts the slippage of core fibres. Therefore the stress relaxation time of vortex spun yarn is longer than that of air-jet spun yarn under fixed tensile strain.

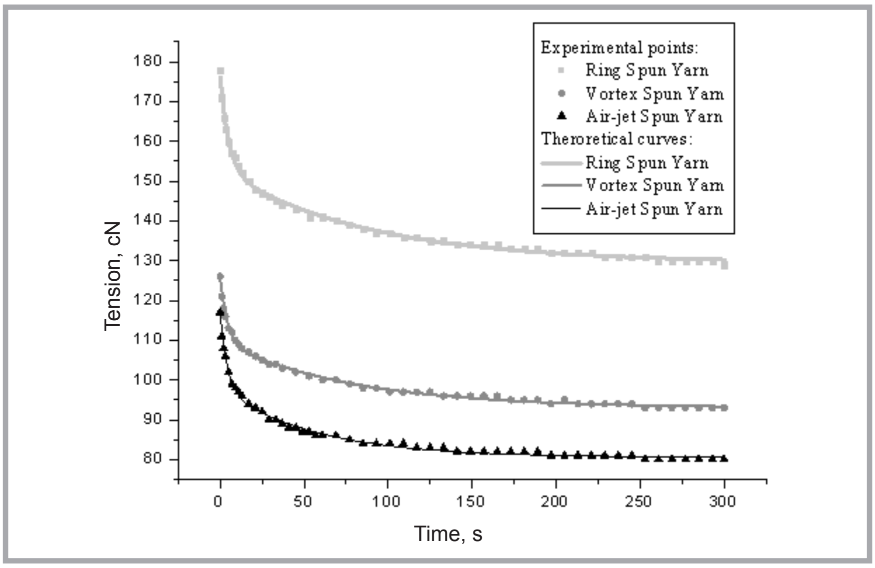

Figure 2. *Stress relaxation curves of vortex spun yarn compared with air-jet and ring spun yarns for cases 1, 4 and 5. Parameters of curves of the stress relaxation model according to* ***Equation*** *7 are given in* ***Table 3*** *together with correlation coefficient* R^2.

Table 3. *Parameters of the stress relaxation model for different yarn according to* ***Equation*** *7 for curves presented in* ***Figure 2*** *and correlation coefficient* R^2.

Yarn types	Parameters of stress relaxation model					R^2
	c_0	c_1	c_2	τ_1	τ_2	
Vortex spun yarn	92.98	16.74	15.43	78.09	4.05	0.9959
Air-jet spun yarn	80.53	17.19	18.27	56.96	4.34	0.9963
Ring spun yarn	129.51	23.46	23.12	86.69	4.88	0.9955

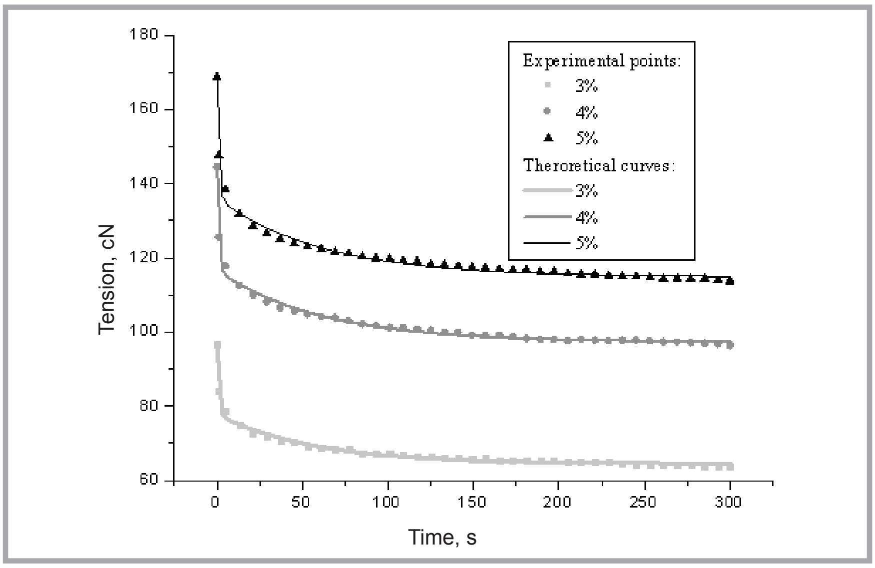

Figure 3. *Stress relaxation curves under different tensile strain levels for vortex spun yarn in case 1. Parameters of curves of the stress relaxation model according to* ***Equation*** *7 are given in* ***Table 4*** *together with correlation coefficient* R^2.

Table 4. *Parameters of the stress relaxation models under different tensile strain levels for vortex spun yarn in case 1according to* ***Equation*** *7 for curves presented in* ***Figure 3*** *and correlation coefficient* R^2.

Tensile strain, %	Parameters of stress relaxation model					R^2
	c_0	c_1	c_2	τ_1	τ_2	
3	64.48	13.38	18.71	56.46	0.95	0.9933
4	97.31	19.36	27.89	60.82	0.92	0.9942
5	114.89	21.28	32.53	61.31	1.01	0.9906

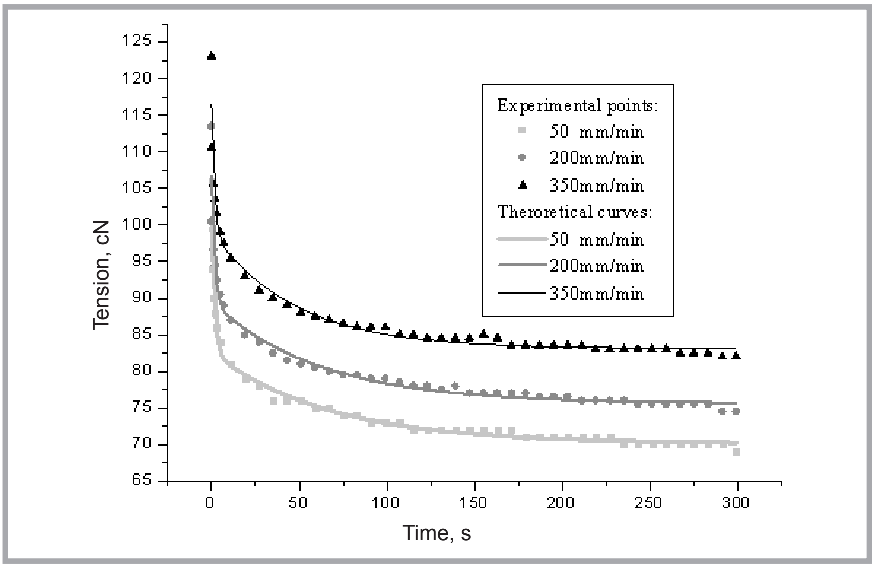

Figure 4. Stress relaxation curves under different tensile rates for vortex spun yarn in case 1. Parameters of curves of the stress relaxation model according to ***Equation*** *7 are given in* ***Table 5*** *together with correlation coefficient* R^2.

Table 5. Parameters of stress relaxation models under different tensile rates for vortex spun yarn in case 1 according to ***Equation*** *7 for curves presented in* ***Figure 4*** *and correlation coefficient* R^2.

Tensile rate, mm/min	Parameters of stress relaxation model					R^2
	c_0	c_1	c_2	τ_1	τ_2	
50	70.10	12.49	17.03	66.84	1.74	0.9595
200	75.59	13.89	17.15	61.55	1.63	0.9591
350	83.07	16.03	17.35	47.57	1.45	0.9673

Effect of tensile strain on the stress relaxation property of vortex spun yarn

Changing the tensile strain will affect the stress relaxation property of vortex spun yarn. The stress relaxation tests for case 1 were carried out for 300 seconds after being drawn at different tensile strain levels from 3% to 5%. ***Figure 3*** shows data of the relaxation stress with a change in the time under different tensile strain levels for case 1. According to the stress relaxation test results, the theoretical stress relaxation curves of case 1 are fitted using the stress relaxation model by means of Origin 8.0 software, shown in ***Figure 3***. The stress relaxation curves are characterised by parameters presented in ***Table 4*** together with correlation coefficients. The correlation between the theoretical predicting value and the experimental one is very high.

It is clear from ***Figure 3*** that the internal stress of vortex spun yarn decreases with the prolongation of the stress relaxation test time. At the initial stage (after approximate 10 seconds), the internal stress of vortex spun yarn falls rapidly, then decreases gradually, and finally it is close to a constant value at a stress relaxation test time over 300 seconds. ***Figure 3*** also shows that a higher tensile strain level will lead to bigger internal stress action on the vortex spun yarn. When the tensile strain level action on vortex spun yarn is higher, the values of τ_1 and τ_2 are larger, as shown in ***Table 4***. Thus the elasticity of vortex spun yarn at a higher tensile strain level is more obvious, the reason for which is that the larger centripetal force yielded by the wrapper fibres is exerted on the core fibres of vortex spun yarn when the tensile strain level is higher, restricting the slippage of core fibres of the vortex spun yarn stretched.

Effect of tensile rate on the stress relaxation property of vortex spun yarn

The tensile rate plays an important role in the stress relaxation property of yarn. Stress relaxation tests were conducted on the vortex spun yarn in case 1, which was subjected to relaxation for 300 seconds after being drawn at a 4% tensile strain at different tensile rates. According to the stress relaxation experimental test results, the stress relaxation curves under different tensile rates for vortex spun yarn in case 1 were fitted using ***Equation 7*** by means of Origin 8.0 software, as shown in ***Figure 4***. The stress relaxation curves are characterised by parameters presented in ***Table 5*** together with correlation coefficients. ***Table 5*** also shows that the high correlation coefficient validates the effectiveness of the stress relaxation model.

The internal stress of vortex spun yarn sharply decreases initially in approximate 10 seconds, and then slowly falls with the stress relaxation test time approaching constant stress, as can be shown in ***Figure 4***. ***Figure 4*** also shows that the internal stress of vortex spun yarn becomes high when the tensile rate increases from 50 mm/min to 350 mm/min. Values of the stress relaxation time τ_1 and τ_2 are lower at a higher tensile rate, as shown in ***Table 5***. Therefore the stress relaxation phenomenon for vortex spun yarn is more obvious at a higher tensile rate.

Effect of yarn count on the stress relaxation property of vortex spun yarn

Stress relaxation tests of yarns with counts of 18.2 tex and 32.4 tex for cases 2 and 3 were done after the yarns had been drawn up to a 4% tensile strain at a rate of 200 mm/min. According to the stress relaxation test results, stress relaxation curves for different yarn counts (counts 18.2 tex and 32.4 tex) were drawn based on ***Equation 7*** using Origin 8.0 software, as shown in ***Figure 5*** (see page 32). The stress relaxation curves are characterised by parameters presented in ***Table 6*** together with correlation coefficients. The high correlation coefficient shows that the stress relaxation model can effectively describe the stress relaxation behaviour of vortex spun yarns with different yarn counts.

The internal stress attenuates rapidly at first and then slowly decreases with an increase in the stress relaxation test time until tending towards a stable condition. The internal tension is high when the vortex spun yarn becomes fine, which may be caused by the difference in the proportions of wrapper fibres for cases 2 and 3. It shows that the fine count yarn of vortex spun yarn has more wrapper fibres than coarse count yarn, validated by Tyagi et al. [8], resulting in less slippage between fibres for vortex spun yarn with a 4% tensile strain. However, the stress relaxation times τ_1 and τ_2 are bigger for coarse count yarn in ***Table 6*** (see page 32), which shows its relaxation phenomenon is not obvious.

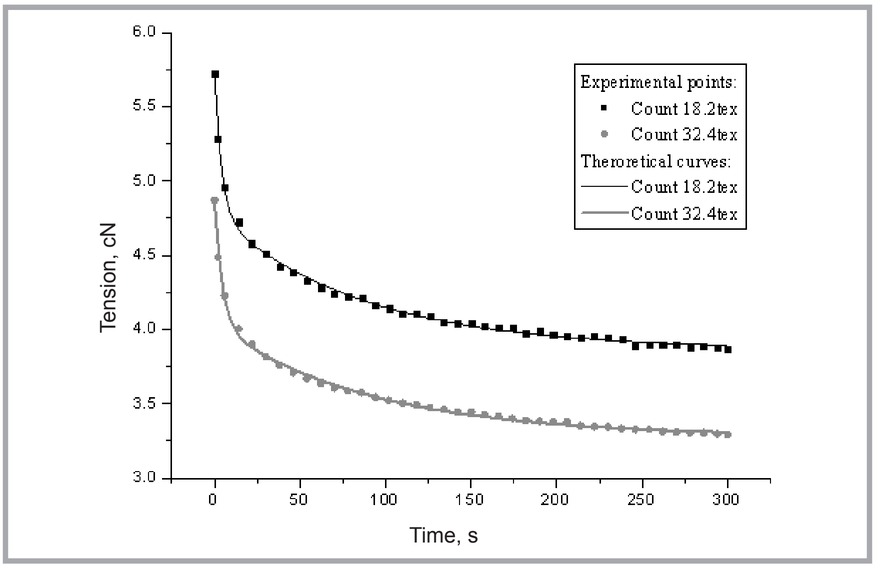

*Figure 5. Stress relaxation curves under different yarn counts for vortex spun yarns in cases 2 and 3. Parameters of curves of the stress relaxation model according to **Equation** 7 are given in **Table 6** together with correlation coefficient R^2.*

*Table 6. Parameters of the stress relaxation models under different yarn counts for vortex spun yarns in cases 2 and 3 according to **Equation** 7 for curves presented in **Figure 5** and correlation coefficient R^2.*

Yarn Count, tex	Parameters of stress relaxation model					R^2
	c_0	c_1	c_2	τ_1	τ_2	
18.2	3.87	0.91	0.93	85.35	4.15	0.9974
32.4	3.28	0.75	0.81	90.24	4.61	0.9969

Conclusions

In this study, a stress relaxation model was developed to describe the relaxation behaviour of vortex spun yarns at different external conditions which best simulated the tension and relaxation behaviour of the vortex spun yarn.

The research shows that the stress relaxation behaviour of yarn is influenced significantly by the yarn type, tensile strain level, the tensile rate and yarn count. The internal stress for all test conditions decreases sharply initially and slowly attenuates with prolongation of the relaxation test time until approaching a constant stress. At the same tensile strain, as compared with air-jet and ring spun yarns, the internal stress action on vortex spun yarn is between the values of the internal stress action on air-jet spun yarn and those for ring spun yarn. Moreover the elasticity of vortex spun yarn is better than that of air-jet spun yarn, but worse than that of ring spun yarn. For vortex spun yarn at a larger tensile strain level, higher tensile rate and finer count, the internal stress action thereon is high. When vortex spun yarn is at a lower tensile strain level, higher tensile rate and is finer, the relaxation time is shorter, as shown by the fact that vortex spun yarn has a more obvious stress relaxation phenomenon.

Acknowledgments

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