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DIFFERENT APPROACHES FOR PREDICTING AIR JET SPUN YARN STRENGTH

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SUMMARY OF THE THESIS

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Abstract

Air jet spinning process has reached an industrial acceptance stage having developed through half a century. This study aims to contribute to the knowledge of air-jet yarn formation process by investigating the influence of selected technological parameters of the Rieter air-jet spinning machine on yarn properties, especially its strength. Furthermore, to shed light on the problem of the prediction of yarn strength. A three-dimensional numerical simulation of the airflow field inside Rieter air jet spinning nozzle has been presented. The velocity and pressure distribution were analyzed to describe the principle of yarn formation. The analysis of velocity components and static pressure revealed how the air vortices are created inside the nozzle as well as how the yarn is spun.

A numerical simulation along with experimental verification were performed to investigate the influence of nozzle pressure on air jet yarn tenacity and the results were in good agreement. The results show that increasing nozzle pressure resulted initially in improving yarn tenacity, but at high-pressure, tenacity deteriorates.

Different approaches have been used to predict the tenacity of air jet yarn. One of these approaches is a statistical model, where the effect of yarn linear density, delivery speed and nozzle pressure on yarn strength were investigated and a multiple regression model was used to study the combined effect of these parameters and response surfaces were obtained. Based on the different combinations of processing variables, optimal running conditions for tested materials were obtained.

As a second possible approach to predict yarn strength, a mathematical model that predicts the strength of Viscose and Tencel air jet spun yarn at short gauge length has been presented which is based on an earlier model. The model is based on calculating the core fiber strength as a parallel bundle of fibers. Also, calculating the wrapper fiber strength as a bundle of fibers in the form of helical path and considering the interaction effect between the wrapper and core fibers. Fiber parameters in addition to yarn structural parameters were used to obtain the theoretical yarn tenacity at short gauge length. Results showed that the accuracy of the proposed model is satisfactory for the tested yarns set.

As an alternative approach to predict air jet yarn strength, a statistical model has been presented. By using this model, the influence of the tensile tester gauge length on the ring, rotor, and air jet spun yarn tenacity and its coefficient of variation has been investigated. The model correlates yarn tenacity and coefficient of variation of yarn tenacity to gauge length. The model is based on Peirce model and assuming the 3-parameter Weibull distribution of yarn strength values. A reasonable agreement has been shown between the experimental and the predicted values. The model successfully captured the change in yarn strength and its coefficient of variation at different gauge lengths. Results confirmed that at longer gauge lengths, yarn strength decreases and its coefficient of variation decreases as well.

Keywords

Numerical simulation; mathematical modeling; statistical modeling; fibers; Rieter air jet spinning; airflow; wrapper ratio; strength prediction; Viscose; Weibull distribution; gauge length; linear density; nozzle pressure; delivery speed; structure.

Anotace

V současné době tryskové dopřádání dosáhlo po půlstoletí svého vývoje průmyslového uznání a zaujalo své místo na trhu. Cílem této práce je přispět k poznání procesu tvorby příze, zmapovat vliv vybraných technologických parametrů tryskového dopřádacího stroje na vlastnosti příze, zejména její pevnost a především poskytnout širší náhled na problematiku predikce pevnosti tryskové příze. V práci je provedena trojrozměrná numerická simulace průtokového pole vzduchu uvnitř spřádací trysky tryskového dopřádacího stroje Rieter Air-jet. Byla analyzována distribuce rychlosti a tlaku vzduchu s cílem popsat princip tvorby příze. Analýza složek rychlosti a statického tlaku vzduchu ukázala, jak jsou uvnitř trysky tvořeny vzduchové víry, a jakým způsobem se příze formuje.

Byla provedena numerická simulace spolu s experimentální verifikací, která zkoumala vliv tlaku kroutícího vzduchu na pevnost příze. Výsledky simulace přinesly dobrou shodu s experimentem. Výsledky ukázaly, že zvyšující se tlak v trysce vedl zpočátku ke zlepšení pevnosti příze, ale při vysokém tlaku vzduchu se pevnost zhoršila.

Ve stěžejní části práci jsou prezentovány a popsány různé možnosti přístupů k predikce pevnosti příze. Jedním z nich je statistické modelování založené na experimentálních měřeních. V rámci tohoto přístupu byl sledován vliv délkové hmotnosti příze, odtahové rychlosti a nastaveného spřádního tlaku vzduchu. Pro analýzu kombinovaného vlivu těchto parametrů pomocí responzních povrchů byl použit vícenásobný regresní model. Na základě různých kombinací mezi sledovanými technologickými veličinami byly získány optimální parametry nastavení pro testovaný materiál.

Jako druhý z možných přístupů k predikci pevnosti tryskové příze je navržen matematický model. Pomocí tohoto modelu lze predikovat pevnost 100% viskozové a 100% tencelové tryskové příze na krátkých upínacích délkách. Model je založen na výpočtu pevnosti jádra příze, jakožto paralelního svazku vláken, výpočtu pevnosti obalové vrstvy vláken jakožto svazku vláken ovinutého ve šroubovici kolem jádra příze. V modelu je rovněž zohledněn interakční účinek mezi vlákny v obalu a vlákny v jádru příze. Jako vstupní parametry modelu pro výpočet teoretické pevnosti příze na krátkých upínacích délkách jsou použity parametry vláken i strukturální parametry příze. Výsledky ukázaly, že přesnost navrhovaného modelu je uspokojivá pro soubor experimentálních přízí.

Jako další z možných přístupů k predikci pevnosti příze (na krátkých úsečkách) je prezentován statistický model. Pomocí modelu je zkoumán vliv upínací délky příze v trhacím přístroji na pevnost a variační koeficient pevnosti tryskové, prstencové a rotorové příze. Model vychází z Peirceova modelu a předpokládá tříparametrové Weibullovo rozdělení hodnot pevnosti příze. Mezi experimentálními a predikovanými hodnotami byla zaznamenána přiměřená shoda. Model úspěšně zachytil změny pevnosti příze a její variační koeficient při různých upínacích délkách. Výsledky potvrdily, že při větších upínacích délkách pevnost příze klesá a její variační koeficient se rovněž snižuje.

Klíčová slova

Numerická simulace; matematické modelování; statistické modelování; vlákna; tryskové dopřádání Rieter; proud vzduchu; podíl obalových vláken; predikce pevnosti; viskóza; Weibullovo rozdělení; upínací délka; jemnost; tlak spřádního vzduchu; odváděcí rychlost; struktura

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1. Introduction

Air jet spinning process has reached an industrial acceptance stage having developed through half a century. Known as Fasciated spinning, air jet yarn was first introduced by DuPont Company in 1971 using the principle of air vortices to form a yarn. In 1982, Murata jet spinning "MJS" was introduced and achieved more commercial success. In this system, some control was achieved over the distribution of the wrapper fibers leading to better yarn quality. MJS has a major disadvantage of not being able to produce acceptable 100% cotton yarns. Furthermore, MJS is restricted to finer counts, since yarn tenacity reduces as the yarn becomes coarser. In 1997, Murata jet spinning "MVS" was introduced. The MVS system uses a single nozzle with an inner needle and this system became able to produce 100% carded cotton yarns [1]. In 2009, Rieter Company presented the latest method in air jet yarn production. Both Rieter and MVS systems are based on a similar principle, but the nozzle block in Rieter system does not contain the needle holder that works as a twisting guide [2].

2. Overview of the Current State of the Problem

2.1 ***Literature review***

Since the yarn structure and properties in air jet spinning technology depend on the airflow field distribution and its intensity inside the air jet nozzle, therefore, it is necessary to study this airflow. The early system of air jet spinning was introduced by MJS. Investigations were carried out to simulate numerically the airflow field on this system using computational fluid dynamics "*CFD*" software [3]–[6]. Other researchers performed a numerical computation of the airflow field in MVS in order to explain the principle of yarn formation [7], [8]. Also, different numerical along with experimental investigations were carried out to study the influence of MVS production and nozzle parameters on yarn structure and properties [9]–[21]. There are differences in nozzle design between Murata and Rieter nozzle. Therefore, it is interesting to simulate the airflow field inside the Rieter nozzle as this could give a better understanding of this new technique. Furthermore, since the pressure is an important air jet spinning process parameter, therefore its influence on airflow should be investigated. In this way, the change in yarn strength as nozzle pressure changes can be predicted.

Also, experimental investigations were carried out on the influence of MVS machine production parameters on yarn properties in order to optimize yarn quality. Those parameters are nozzle (pressure and orifice angle), the distance between spindle and front roller nip point, draft, spindle (cross-section, working period and diameter), yarn (linear density and delivery speed) and fiber composition. Most of these parameters proved to have a significant effect on final yarn properties [22]–[25]. Although these parameters have been investigated, the slight differences in nozzle design for both Rieter and MVS systems may lead to a different trend. Along with these experiments, response surface equations were obtained using multiple regression that relates process parameters to yarn structure and its properties [26]–[28]. Yet no regression model has been presented for Rieter air jet spun yarns. A possible model can be presented that predicts yarn tenacity based on nozzle pressure, delivery velocity and yarn linear density, which are considered as very important air jet spinning parameters.

There is no doubt that the strength is considered as a very important yarn property that significantly influences its post-processing performance and final fabric quality. To engineer air jet yarns aiming better quality, this requires knowing the relationship between fiber properties, yarn structure, and yarn properties. The mathematical models are usually used to describe and explain such relationships [29]. Numerous researchers presented a good contribution to this topic. Many of them presented mathematical models for ring spun yarn [30]–[42] and rotor yarn [32], [43]–[46]. Nevertheless, mathematical models of air jet spun yarn are limited [47]–[50]. Rajamanickam et al. [51], [52] presented mathematical models that describe the air jet yarn fracture behavior, including the failure mechanism of core and wrapper fibers and predict the air jet yarn strength accordingly. They obtained a mathematical relationship between yarn breaking load, its structural parameters, and fibers properties. However, their model is a bit complicated as well as they obtained a prediction error which was quite high. So, it is necessary to develop a model which can be simpler and more accurate.

Generally yarn strength is measured at 500 mm gauge length, however, in fact, the yarn is exposed to stresses at longer lengths in post-spinning processes particularly in sizing, warping, and weaving. Therefore, it is interesting to know how yarn strength varies at different gauge lengths. Substantial researches have been done to study experimentally the effect of gauge length on different spun yarn tensile properties [53]–[59]. Some other researchers studied this phenomenon theoretically and developed a model that relates yarn tenacity to gauge length [38], [60]. Zurek et al. proposed empirical relationships between yarn tenacity and gauge length [31], [56], [61]–[65]. Peirce proposed the weak link theory and concluded that yarn strength decreases with the increase of gauge length [66]. By studying Peirce model, it can be seen that it is based on Gaussian distribution, nevertheless, by analyzing the model, it is observed that it is valid only on short gauge lengths. Therefore, a new model can be established if another type of distribution for the yarn strength values is assumed. If this distribution fits the data well, this could achieve more accurate model.

2.2 ***Purpose and aim of the thesis***

The main aims of this thesis are to contribute to the knowledge of the air jet yarn formation process, particularly Rieter air jet spinning technology, to investigate the influence of selected technological parameters of the spinning machine on yarn properties, especially its strength. Furthermore, to shed light on the problem of the prediction of yarn strength by trying different approaches to establish models that can be used for prediction of air jet spun yarns strength. Each model, whether statistical, mathematical or numerical could contribute to understanding the air jet spinning process, yarn structure, yarn strength and the relationship between fibers and yarns.

The first part of this work includes a 3-dimensional simulation of the airflow field inside the Rieter air jet spinning nozzle using ANSYS software which is based on the finite volume method. So, before embarking on prediction process, the principle of yarn formation is initially explained using the numerical simulation approach. Afterward, the effect of nozzle pressure has been studied using the simulation process, then experiments have been conducted to verify the results obtained from the simulation process. Furthermore, predicting the change in the air jet yarn strength as nozzle pressure changes.

The second part aims to investigate some process parameters in Rieter air jet spinning technology, namely, yarn linear density, nozzle pressure, and delivery speed. These parameters were proved to influence fiber configuration and yarn structure significantly. Along with the experiment, a statistical model had been established based on multiple regression to study the combined effect of process parameter on yarn tenacity as well as to predict the air jet yarn strength.

In the third part, a mathematical model to predict the air jet yarn strength at short gauge length is presented. An earlier mathematical model for air jet yarn strength has been modified targeting simpler and more accurate model. And in the last part, an attempt has been made to establish a statistical model to predict the air jet yarn strength at different gauge lengths. The model is based on an earlier model but used a different type of the distribution function to fit yarn strength values at all gauge lengths, hence, obtaining the more accurate model. Moreover, the validation of the model was extended to include ring, rotor, and air jet yarns.

3. Description of Principle of Yarn Formation Using Numerical Modeling

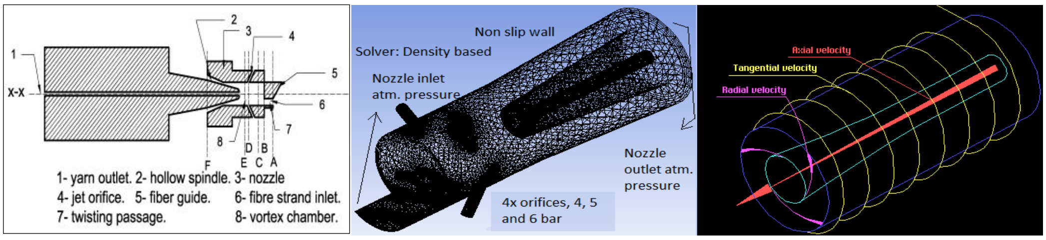
In this chapter, a 3D simulation process has been carried out to study the principle of yarn formation of the Rieter air jet spinning machine. Along with the theoretical study, an experimental investigation was carried out to study the effect of the nozzle pressure on yarn tenacity.

3.1 ***Numerical computation***

All dimensions of a Rieter air jet nozzle unit were measured and the cross-sectional view of the nozzle is shown in *Figure 3.1-a.* The simulated region consists of all regions occupied by the air (the existence of yarn was ignored seeking simplification). The mesh of the fluid field was constructed using an unstructured tetrahedral grid. The computational grid of the airflow field in Rieter air jet spinning nozzle is shown in *Figure 3.1-b.* Afterward, the mesh quality was adjusted using inflation sizing and edge sizing. The steady state was employed in the modeling process.

The characteristics of the flow in this nozzle pertain to the high swirling instruments which have anisotropic airflow. Therefore, the realizable k-ε model was used to simulate this turbulent airflow. Since nozzle inlet pressure is very high and the internal airflow speed is very high, the air density change cannot be ignored (compressible fluid). Therefore, the solution method in the Fluent module was density based. The governing equations are as follows; the mass conservation equation in the differential form, the momentum conservation equation in the form of Navier-Stokes equation for compressible flow and the ideal gas law. The realizable k-ε turbulence model was adopted and combined with the implicit solver to obtain the simulation results.

The boundary conditions were set as follows; the solid wall has the non-slip boundary condition, nozzle outlet pressure is equal to the outside atmospheric pressure, nozzle inlet pressure is equal to the external atmospheric pressure, hollow spindle outlet pressure is equal to the external atmospheric pressure. Different pressures were applied for the four jet orifices inlets; 0.4, 0.5 and 0.6 MPa. To simplify the modeling process, the process is assumed adiabatic.



(a) (b) (c)

Figure 3.1 Rieter nozzle, (a) 2D cross-sectional view, (b) the computational grid of the airflow field, (c) velocity components.

3.2 *Experimental verification*

100% Viscose fibers of 1.3 dtex and 38 mm length were spun to produce air jet spun yarns. The drawn sliver with 3.5 ktex was spun using Rieter air jet spinning machine J20 to produce 23 Tex yarns with different nozzle pressure; 4, 5 and 6 bar. Yarn tensile properties were tested using Instron 4411 instrument. One-way ANOVA test was performed to check the significance of nozzle pressure on yarn tenacity. To verify the simulation process in a better way, yarn structure was analyzed using scanning electron microscope SEM, where the yarn wrapper ratio W was calculated for each yarn as shown in *Figure 3.2*.

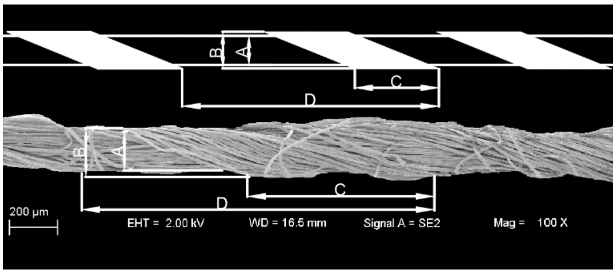


Figure 3.2 30 Tex Viscose yarn longitudinal view under SEM.

According to the ideal yarn structure, the volume of the core fibers can be calculated as a cylindrical segment from both sides (also called a truncated cylinder). The volume of one cylindrical section can be obtained by imagining that two sections are fitted together to form a cylinder of diameter A and height D [67], Therefore, the wrapper ratio (%) can be obtained.

$$W = \frac{C(B^2 - A^2)}{C(B^2 - A^2) + A^2 D} \cdot 100 \tag{3.1}$$

As shown in *Figure 3.2*, the longitudinal yarn view under the microscope for 70 yarn section was captured, then merged to create the whole yarn image. The images were then analyzed and parameters A, B, C and D were obtained.

3.3 ***Numerical modeling results***

3.3.1 Vortex creation

Figure 3.3 shows the velocity vectors for the x-x axial cross-section. The air stream is ejected from the 4 jet orifices at a speed exceeding 650 m/s. This speed decreases when it reaches the vortex chamber to become less than 320 m/s. As a result, a swirling airflow is generated in a thin layer near the vortex chamber wall. This airflow whirls inside the nozzle and move downstream and finally is expelled from the nozzle outlet. In the twisting passage, a suction airflow is created and flows into the vortex chamber enabling the drafted fiber strand to enter the nozzle. It can be noticed also that another airflow is created inside the hollow spindle and flows from the hollow spindle outlet upstream to the vortex chamber and this can help in controlling the trailing ends of the spun yarn. Afterward, these two mentioned airflows meet and become a single airflow. At this stage, the velocity of the airflow reduced to approximately 80 m/s near the nozzle inlet and 200 m/s near the hollow spindle inlet. Finally, the vortex is created inside the nozzle.

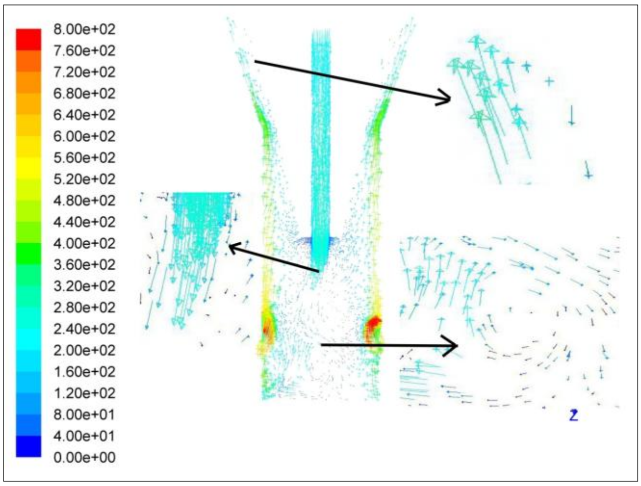


Figure 3.3 Velocity vectors (m/s) for the x-x axial cross-section (at 0.5 MPa pressure).

As shown in *Figure 3.1-a*, because of the specific geometry of the Rieter nozzle, the fiber strand is not sucked uniformly at the nozzle inlet where fibers strand enters the nozzle inclined to the nozzle axis so a certain number of fibers are separated from the main fiber strand. These fiber ends are then twisted around the non-rotating yarn core at the entry of the hollow spindle by the action of the mentioned air vortex [68].

3.3.2 Principle of yarn formation

The velocity magnitude is the resultant velocity of three velocity components; the axial velocity, the tangential velocity, and the radial velocity. Results revealed that the tangential velocity component has the maximum value, followed by the axial velocity, then the radial velocity and this is ascribed to a big inclination angle of the jet orifices to nozzle axis (around 60^{o}). The quality of the air jet yarn depends mainly on the wrapping process, i.e. higher number of wrapper fibers along with tighter and regular wrapping contribute to better yarn structure. After the wrapping process takes place inside the vortex chamber, the yarn is formed and drawn through the hollow spindle.

3.3.2.1 Tangential velocity distribution

Figure 3.4-a shows the tangential velocity at different nozzle cross-sections. It can be remarked that the value of the tangential velocity in the vicinity of the hollow spindle outer wall is high while the tangential velocity value inside the hollow spindle is low and its direction is opposite to the former. Because of this difference in value and direction, the hairs on yarn surface could be embedded into the yarn body or blown away, consequently, yarn hairiness and tenacity improve. This justifies that the air jet yarn is known for its relatively low hairiness [69].

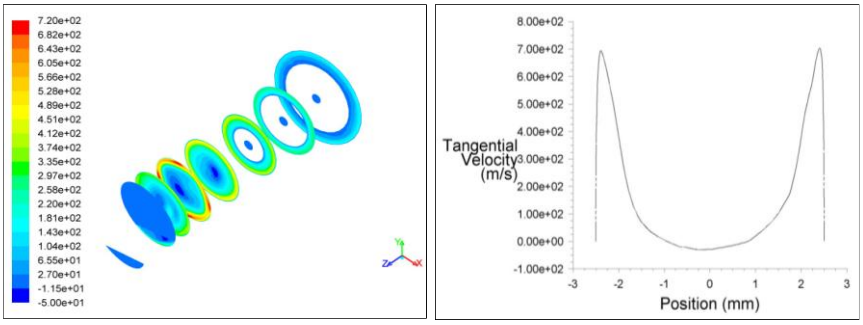


Figure 3.4 The tangential velocity; (a) contours (m/s) at different nozzle cross-sections, (b) distribution curve at section D.

Figure 3.4-b shows the tangential velocity distribution curve at section D. It can be seen that the tangential velocity increases slowly from the nozzle axis towards outside in both directions, then a sudden and sharp increase in the tangential velocity takes place near the edges of the nozzle wall. In the inner region, the core fibers strand is exposed and affected slightly by this slow airflow, therefore, the core fibers in the final spun yarn have almost no twist. While the fibers in the periphery of the strand are affected greatly by the high tangential velocity that forces them to twist.

3.3.2.2 Radial velocity distribution

Figure 3.5 shows the radial velocity distributions at section D. The fiber separation process is more likely in this zone. Results showed that the values of the radial velocity near the nozzle wall are higher than that in the vicinity of the nozzle axis and this forces the fibers in the strand periphery to be embedded towards the yarn axis. It is also clear that the values of the radial velocity are less than the corresponding tangential velocity and its distribution is not symmetric as the tangential velocity and this is due to the influence of the vortex.

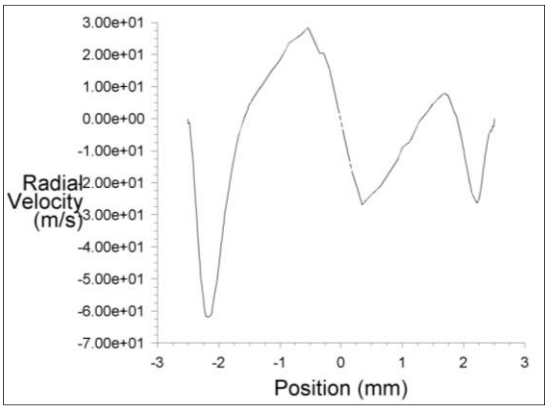


Figure 3.5 The radial velocity distribution at section D.

3.3.2.3 Axial velocity distribution

Figure *3.6* shows the axial velocity for the x-x axial cross-section. Similar to the tangential velocity distribution, the axial velocity direction inside the hollow spindle is in the opposite direction of the axial velocity direction outside the hollow spindle. The reverse flow is evident inside the hollow spindle from its inlet to its outlet.

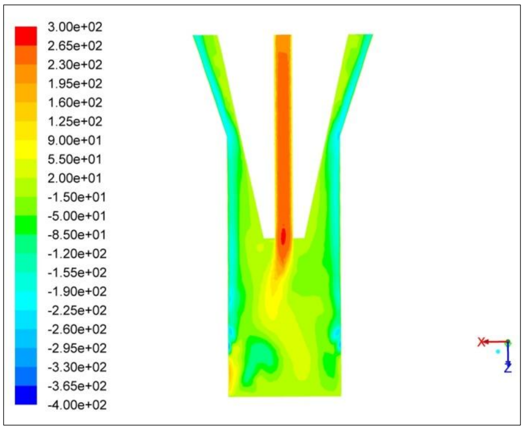


Figure 3.6 Contours of the axial velocity (m/s) for the x-x axial cross-section.

3.3.3 Effect of nozzle pressure on structure and strength of the air jet yarn

Figure 3.7 shows the contours of the axial velocity distribution at different nozzle pressure. It can be seen that the intensity of above-mentioned reverse flow in the hollow spindle which contributes to the vortex creation increases with the increase of the nozzle pressure from 4 to

6 bar. When the pressure became 6 bar, it is obvious that the reverse flow reached the nozzle inlet which obstructs the spinning process because its direction is opposite to the strand movement direction. *Figure 3.8* shows the contours of the tangential velocity distribution at different nozzle pressure. The fiber separation process takes place in the region near the nozzle entrance. By increasing nozzle pressure, the tangential velocity in this area increases gradually which is good for fiber separation and twist. But at high pressure, the tangential velocity becomes very high and fiber control could be deteriorated as the number of regular wrapper fiber decreases while the irregular wrapping increases. Also, by increasing the nozzle pressure to 6 bar, the tangential velocity in the region between the wall of the hollow spindle and the inner wall of the nozzle increases and its area enlarges. This can lead to turbulence in this zone, which consequently could affect yarn quality. This trend is also found similar when MVS nozzle was investigated [11].

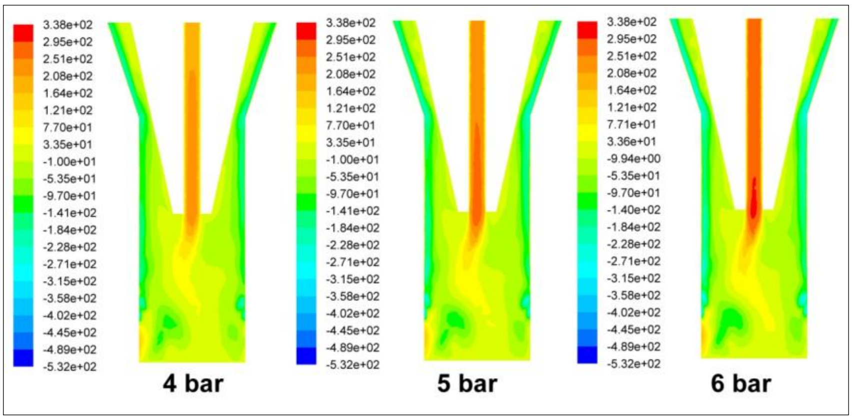


Figure 3.7 Contours of the axial velocity distribution (m/s) for the x-x axial cross-section at different nozzle pressure.

The contours of the static pressure distribution at different nozzle pressure are shown in *Figure 3.9*. By increasing the nozzle pressure, the negative pressure in the area in the vicinity of the vortex chamber outlet increases and its area shifts towards outside, this is beneficial to the fiber separation process. On the other hand, increasing the nozzle pressure resulted in increasing the positive air pressure exists in the area between the outlets of the jet orifices toward the hollow spindle outer wall. This could obstruct the fibers movement influencing yarn formation process negatively. By combining the results presented in *Figure 3.7*, *Figure 3.8*, and *Figure 3.9*, the optimum yarn strength is anticipated when using a nozzle pressure of 5 bar.

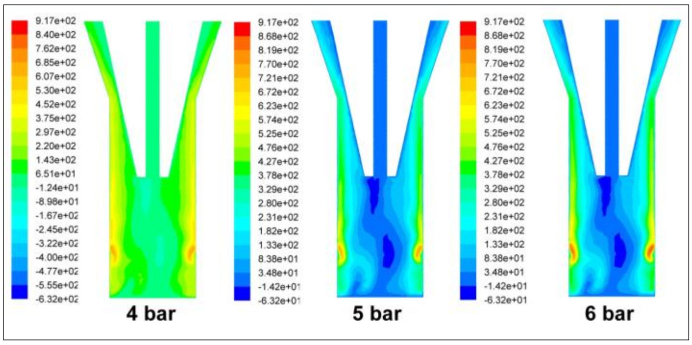


Figure 3.8 Contours of the tangential velocity distribution (m/s) for the x-x axial cross-section at different nozzle pressure.

Figure 3.10 shows the experimental results of the yarn tenacity at different nozzle pressure. Statistical analyses showed that the differences in yarn tenacity are statically significant at 95% confidence level. It is clear that yarn tenacity increases when nozzle pressure increases from 4 to 5 bar, then tenacity decreases gradually when it reaches 6 bar.

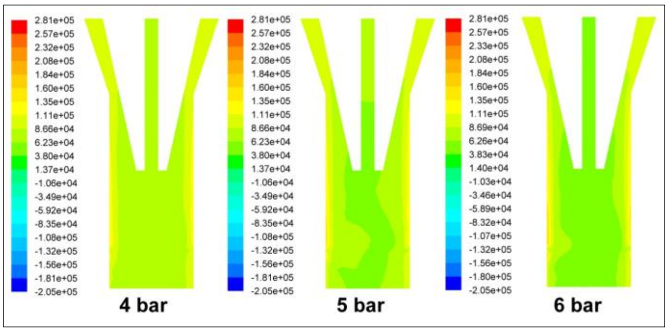


Figure 3.9 Contours of the static pressure distribution (Pa) for the x-x axial cross-section at different nozzle pressure.

The structural analyses shown in *Table 3.1* revealed that when spinning using nozzle air pressure of 4, 5 and 6 bar, the corresponding wrapper fiber ratio is 30.7, 32.7 and 29.3% respectively. The statistical analyses showed that the differences in wrapper ratio are statically significant at 95% confidence level. However, the coefficient of variation is quite high (24.51-29.44%). Nevertheless, considering the values of C and D, it can be seen that the coefficient of variation is less (08.93-19.59%). Therefore, C/D ratio was calculated (it is the ratio between one wrap width to the pitch at this yarn section). The values of C/D support the previous results of wrapper ratio where it followed the same trend. When spinning using nozzle air pressure of 4, 5 and 6 bar, the corresponding C/D ratio is 21.81, 33.33, and 26.94% respectively.

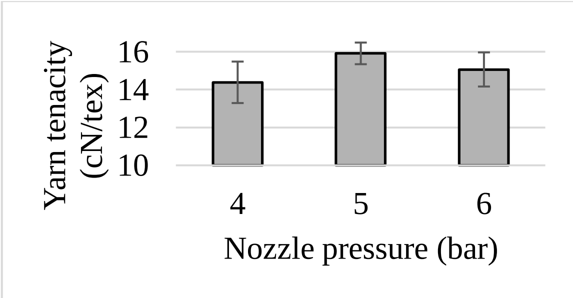


Figure 3.10 Effect of nozzle pressure on 23 Tex yarn tenacity.

The initial increase in air pressure (4 and 5 bar) increases the intensity of the above-mentioned reverse flow in the hollow spindle which contributes to the vortex creation, the tangential velocity in the region near the nozzle entrance increases gradually, the negative pressure in the area in the vicinity of the vortex chamber outlet increases and its area shifts towards outside. All these factors contribute to fiber separation process and the regular twist. Consequently, the yarn structure has tight regular wrappings and more wrapped portions (more wrapper ratio 32.7%).

On the other hand, When the pressure reaches 6 bar, it is obvious that the reverse flow reached the nozzle inlet which could obstruct the spinning process because its direction is opposite to the strand movement direction, the tangential velocity becomes very high, the tangential velocity in the region between the wall of the hollow spindle and the inner wall of the nozzle increases and its area enlarges. This can lead to turbulence in this zone. All these factors contribute to less fiber control and obstruction of fibers movement influencing yarn formation process negatively. Consequently, the yarn structure contains wild fibers, irregular wrapping, and less wrapped portions (less wrapper ratio 29.3%). By comparing the above-mentioned results, it can be concluded that the experimental findings agree with the numerical simulation results.

Table 3.1 Yarn structural parameters at different nozzle pressures.

Nozzle pressure	4 bar		5 bar		6 bar	
	Average (μm)	CV%	Average (μm)	CV%	Average (μm)	CV%
A	175	32.29	105	36.82	168	34.17
B	241.5	31.74	133	36.04	207.9	24.29
C	287	18.12	273	9.16	431.9	16.23
D	1316	13.11	819	8.93	1603	19.59
C/D (%)	21.81		33.33		26.94	
Wrapper ratio (%)	30.7	29.39	32.7	29.44	29.3	24.51

4. Prediction of Air Jet Yarn Strength Based on Statistical Modeling

In this chapter, some process parameters of Rieter air jet spinning machine, namely, yarn linear density, nozzle pressure, and delivery speed have been investigated. Along with the experiment, a statistical model had been established based on multiple regression to study the combined effect of those parameter on yarn tenacity as well as to predict the air jet yarn strength.

4.1 *Materials and methods*

100% Viscose fibers were spun to produce air jet yarns with different counts and machine parameters. The Box-Behnken factorial experimental design was used to obtain the combination of yarn count, delivery speed, and nozzle pressure. *Table 4.1* shows the chosen parameters and their levels. It is notable to mention that spinning one sample with the level coded (-1, 1, 0) was impractical because the end breakage rate was very high which obstructed the spinning process. A total of 12 yarns were spun then placed in the standard conditions prior to testing.

Table 4.1 Spun yarn production parameters.

	The levels and their codes		
Parameters	-1	0	1
Yarn count (Tex)	16	23	30
Delivery speed (m/min)	350	400	450
Nozzle Pressure (bar)	4	5	6

The yarn tenacity was tested using Instron 4411. Ordinary least squares regression model was used to analyze the test results and to obtain the regression equation (4.1).

$$Y = \beta_0 + \beta_i X_i + \beta_j X_j + \beta_k X_k + \beta_{ij} X_i X_j + \beta_{ik} X_i X_k + \beta_{jk} X_j X_k + \beta_{ii} {X_i}^2 + \beta_{jj} {X_j}^2 + \beta_{kk} {X_k}^2 \quad (4.1)$$

Where Y is the dependent variable, X_i, X_j, X_k are independent variables, β_0 is the regression equation constant, $\beta_i, \beta_j, \beta_k$ are the linear coefficients, $\beta_{ij}, \beta_{ik}, \beta_{jk}$ are the interaction coefficients and $\beta_{ii}, \beta_{jj}, \beta_{kk}$ are the quadratic coefficients.

4.2 *Regression model*

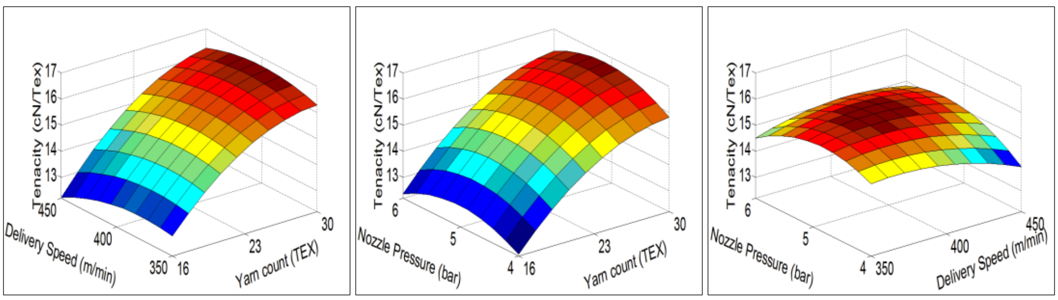
Equation (4.2) Indicates the response surface equations for yarn tenacity obtained by using multiple regression (the squared multiple regression coefficient R^2=95.5%).

$$
\begin{aligned}
Z = -22.4652 + 0.7800X_1 + 0.0808X_2 + 4.1643X_3 \\
+ 0.0005X_1X_2 + 0.0079X_1X_3 + 0.0068X_2X_3 \\
- 0.01637{X_1}^2 - 0.0002{X_2}^2 - 0.6931{X_3}^2
\end{aligned}
\qquad (4.2)
$$

By using this model, it is possible to predict air jet yarn tenacity Z based on yarn count X_1, yarn delivery speed X_2 and nozzle pressure X_3.

4.3 ***Effect of process parameters on yarn strength***

Figure 4.1 shows the influence of linear density, delivery speed and nozzle pressure on yarn tenacity. It is obvious that the linear density has the maximum effect on yarn tenacity. As shown in *Figure 4.1-a* and *b*, coarser yarns 30 Tex have higher tenacity by about 29% than finer yarns 16 Tex and this is due to the increase in the number of fibers in yarn cross-section, thus, the number of core and wrapper fibers in yarn cross section that bear the load exerted on the yarn. Nevertheless, results shown later in *Table 5.3* reveal that wrapper ratio increases slightly at coarser counts. The same trend also exists for MVS yarn [27]. Increasing the yarn delivery speed from 350 to 400 m/min results in increasing yarn tenacity, but when using high delivery speed of 450 m/min a deterioration in yarn tenacity occurs by about 3.5% and this is a consequent of the insufficient time for the whirling action to take place in the vortex chamber which could result in an increment of the number of the wild fibers and the regions of unwrapped core fibers [26]. This effect is more obvious when producing 16 Tex yarn at 400 and 450 m/min where yarn tenacity is very low. Yarn tenacity increases when nozzle pressure increases from 4 to 5 bar, then decreases gradually when it reaches 6 bar and this is because the increase in air pressure initially causes tight regular wrappings and more wrapped portions of the yarn (more wrapper ratio), but higher air pressure creates irregular wrappings and increases the wild fibers (less wrapper ratio), (elaborate explanation is given in section 3.3.3). The same trend is also confirmed for MVS yarn [27].



(a) (b) (c)

Figure 4.1 Effect of (a) yarn linear density and delivery speed, (b) yarn linear density and nozzle pressure, and (c) nozzle pressure and yarn delivery speed, on yarn tenacity.

5. Prediction of Air Jet Yarn Strength Based on Mathematical Modeling

In this chapter, a prediction of air jet spun yarn strength at short gauge length has been presented. Different models have been modified, combined and a new model has been proposed and validated.

5.1 *Model for the failure of the air jet spun yarn*

Air jet yarn structure can be divided into the core which is almost parallel fibers and the wrapper which is in a helical form. In the current model, the core strand strength has been calculated as a parallel bundle of fibers. This strand is also subjected to the normal forces of the wrapper fibers. Therefore, the frictional forces applied to the core fibers strand have been calculated. In addition, the strength of the wrapper fiber strand has been calculated.

It is worth mentioning that the strength of the core fiber strand has been calculated based on the assumption that the fibers are gripped between two jaws and the gauge length of the yarn tensile tester is less than fiber length. Consequently, to verify the model, the air jet yarn strength has been measured at a gauge length shorter than the fiber length. The yarn structure is assumed to be ideal as shown in *Figure 5.1*. It is assumed that; wraps width and height are constant and distributed regularly along the yarn axis, helix angle is constant, and core fibers are straight and parallel to yarn axis.

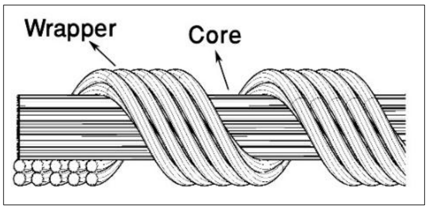


Figure 5.1 Simplified model of short staple air jet spun yarn.

5.1.1 Determination of core fiber strength

The strength of the core fiber strand is the summation of the strength of a parallel bundle of fibers gripped between two jaws of the tensile testing instrument and the strength of that bundle originated from a fiber-to-fiber frictional force caused by the normal forces from the wrapper fiber strand during the extension process.

Assuming a short staple spun yarn is gripped between tensile tester jaws with a gauge length less than fiber length. This yarn is spun using short staple fibers. Assuming that these fibers are straight, parallel to yarn axis, have equal circular diameters, no slippage occurs between core fibers due to the usage of short gauge length, inter-fiber friction is so small that can be ignored and individual fiber position in the yarn is random. Therefore, Neckář theory of parallel fiber bundle can be used to find the strength of this parallel fiber bundle [61]. During the tensile testing process, and due to the random distribution of fibers in the bundle, some fibers are gripped between the jaws while some others aren't. By using the same derivation steps, it is valid that,

$$\eta = \begin{cases} \int_0^{l_{max}} \left(1 - \frac{h}{l}\right) \gamma(l)\, dl \,, h < l_{max} \\ 0 \qquad\qquad\qquad\qquad\qquad , h \geq l_{max} \end{cases} \tag{5.1}$$

Where η is fiber length utilization factor, $\gamma(l)$ is the mass fraction function, h denotes the gauge length, l is fiber length and l_{max} is maximum fiber length. Thus, we can deduce the core fibers strength σ_1 as a parallel bundle gripped between two jaws using equation (5.1) as follows,

$$\sigma_1 = f \frac{(100 - W)}{100} \frac{X_1}{T_i} \eta \tag{5.2}$$

Where f denotes fiber breaking load and W denotes wrapper fibers percentage, X_1 is yarn linear density and T_i is fiber linear density. Assuming that the yarn cross-section is circular and remains circular till break. To obtain the normal forces on core fibers, Krause et al. model [47] was used and modified. By analyzing the forces acting on an element of a wrapper fiber as shown in *Figure 5.2*, and using the same derivation steps,

$$sin\,\alpha = \left(\frac{1 + e_r}{1 + e_f}\right) sin\,\alpha_o \tag{5.3}$$

$$e_r = -e_y \tag{5.4}$$

$$e_y = 2(sin\,\alpha_o)^2 - 1 + \sqrt{(2(sin\,\alpha_o)^2 - 1)^2 + e_f(2 + e_f)} \tag{5.5}$$

Where α is the average strained wrapper fiber helix angle, e_f is fiber breaking elongation, e_y expresses yarn longitudinal strain, e_r represents yarn lateral strain, and α_o is the average unstrained wrapper fiber helix angle. We can then deduce the total frictional forces on core fibers σ_2 as a result of the total normal forces exerted by wrappers fiber strand as follows,

$$\sigma_2 = v_f \mu \frac{f(sin\,\alpha)^2}{r} \frac{W}{100} \frac{X_1}{T_i} pi \tag{5.6}$$

Where μ is the fiber friction coefficient, pi is the average strained pitch of wrapper fibers, r is the average strained yarn radius, and v_f is yarn packing density (assumed constant=0.6 [61]).

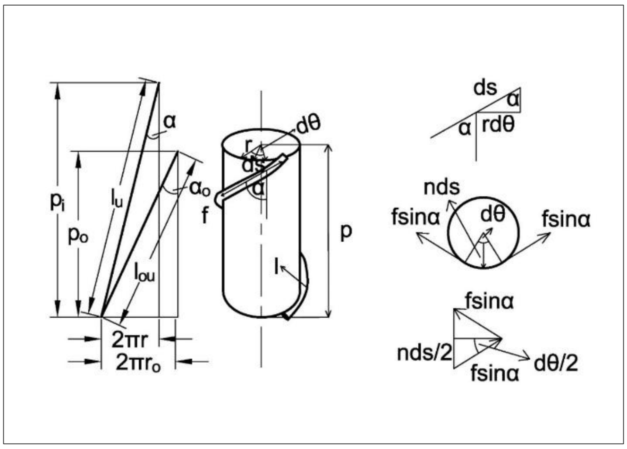


Figure 5.2 Force analysis of air jet yarn before and during axial tensile loading (adapted and reproduced [47]).

5.1.2 Wrapper fiber strength component

Hypothesizing the existence of uniform normal pressure on core fibers due to the wrapping effect, constant wrapping angle and fibers are breaking simultaneously due to extension at a gauge length less than fiber length, total wrapper fibers strength σ_3 can be deduced from Krause et al. model [47].

$$\sigma_3 = f\, cos\, \alpha \frac{W}{100} \frac{X_1}{T_i} \tag{5.7}$$

Therefore, for a tensile drawing in a short nip gauge, the total tensile strength of air jet yarn is contributed by the core fiber strength, the wrapper fiber strength and the friction force between fibers. According to the proposed assumptions in the current model and using equations (5.2), (5.6) and (5.7), it is possible to obtain yarn strength p (cN) as follows,

$$p = \sigma_1 + \sigma_2 + \sigma_3 \tag{5.8}$$

5.2 *Experimental verification*

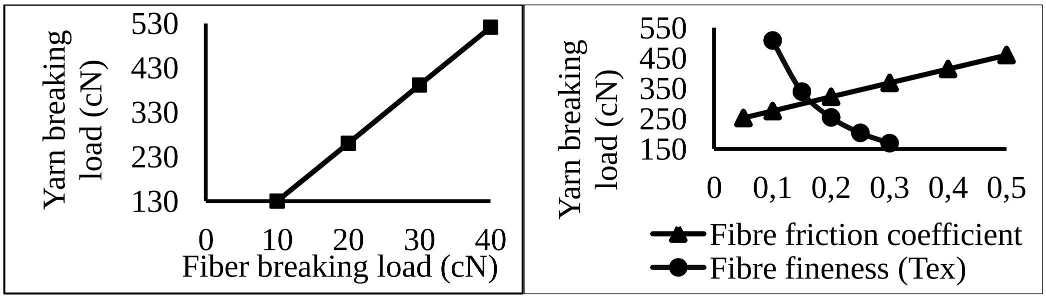
Air jet yarns were spun using different materials and machine parameters as shown in *Table 5.1*. Fibers strength and fineness were measured using Lenzing Vibrodyn-400 according to EN ISO1973 [70]. Fiber length distribution was obtained using Sinus instrument according to ASTM D1447 [71]. SEM analyses were performed to analyze the yarn structure. Yarn number of wraps per meter, helix angle and parameters A, B, C and D were obtained. Yarn diameter was measured using Uster tester according to ASTM D1425 [72]. Yarn strength was measured at short gauge length using Labortech instrument according to ASTM D2256 [73].

Table 5.1 Yarn production plan.

Sample No.	Material type	Yarn count (Tex)	Delivery speed (m/min)	Nozzle pressure (bar)
1	Viscose	16	350	5
2	Viscose	30	350	5
3	Viscose	30	450	5
4	Viscose	16	400	4
5	Viscose	30	400	4
6	Viscose	16	400	6
7	Viscose	30	400	6
8	Viscose	23	350	4
9	Viscose	23	450	4
10	Viscose	23	350	6
11	Viscose	23	450	6
12	Viscose	23	400	5
13	Viscose	20	400	6
14	Viscose	25	400	6
15	Tencel	23	400	6

5.3 ***Results of the mathematical model***

By using the proposed model, it is possible to investigate theoretically the effect of both fibers and yarn parameters on yarn breaking load as shown in *Figure 5.3* and *Figure 5.4*. *Figure 5.3-a* depicts the direct proportionality between fiber strength and yarn strength. It can be seen from *Figure 5.3-b* that yarn strength improves significantly with the increase of interfiber friction coefficient. Because the increase in friction reduces the slippage in the wrapper and core fibers, hence, increases the number of the wrapper and core fibers that resist loading then break during the extension process [74]. When spinning air jet yarn using coarser fibers, the overall number of fibers in yarn cross-section decreases and yarn strength drops significantly.



(a) (b)

Figure 5.3 Influence of fiber (a) breaking load, (b) friction coefficient and fineness, on predicted yarn breaking load.

Results in *Figure 5.4-a* show that yarn strength improves by increasing the wrapper ratio as this increases the total number of wrapper fibers that exert the above-mentioned normal forces on the core fiber strand causing more frictional forces that resist the tensile load. Generally, higher wrapper fiber ratio is desired, but it is mainly limited to the spinning technology. Results also show that when the yarn gets coarser the breaking load increases.

As shown in *Figure 5.4-b*, when wraps per meter increase, yarn breaking load increases. However, unlike ring and rotor yarns, the strength of air jet yarn does not decrease much, but it levels off at high twist (wraps per meter). This is because approximately 70% of the yarn structure is untwisted core fibers, this result also agrees with the finding of Krause et al. [47].

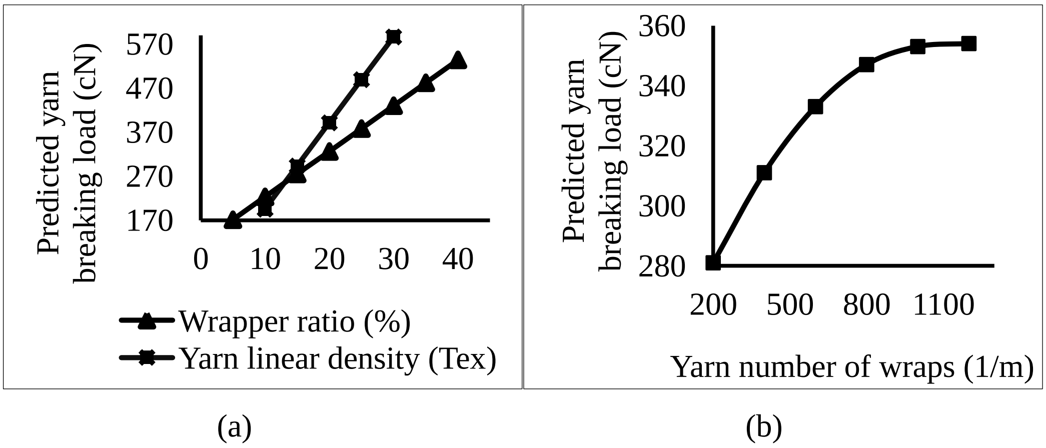


Figure 5.4 Influence of yarn (a) linear density and wrapper ratio, (b) number of wraps per meter, on predicted yarn breaking load.

The 15 yarn samples theoretical strength was calculated by obtaining the fiber length distribution, fiber properties, yarn parameters under SEM and using equations (3.1), (5.1), (5.2), (5.3), (5.4), (5.5), (5.6), (5.7) and (5.8). Fiber parameters, measured yarn parameters under the microscope along with the predicted and experimental values of yarn strength are shown in *Table 5.2* and *Table 5.3*.

Table 5.2 Viscose and Tencel fiber properties.

Property	Viscose	Tencel
Fiber friction coefficient (-)	0.35	0.21
Fiber breaking elongation (%)	19.40	8.10
Fiber fineness (Tex)	0.13	0.13
Fiber breaking load (cN)	3.28	5.20
Fiber length utilization factor (-)	0.199	0.188

Results presented in *Table 5.3* show that the proposed model exhibited good agreement with the experimental results of yarn breaking load where the prediction error varies from (1.62-16.17%). The higher values of prediction error could be ascribed to the variation (*CV%*) in the measured values of wrapper fiber helix angle (*CV%*=08-31%), the measured values of pitch (*CV%*=05-43%) and wrapper fiber ratio (*CV%*=09-42%).

Table 5.3 Theoretical and experimental yarn results.

Sample	Actual yarn count (Tex)	Wrapper fiber ratio (%)	Yarn diameter (mm)	Average unstrained wrapper fiber helix angle (rad)	Average unstrained pitch (mm)	Yarn wraps per meter	Predicted yarn breaking load (cN)	Experimental yarn breaking load (cN)	Prediction error (%)
1	15.9	33.36 (19)	0.20	0.45 (23)	1.17 (42)	825	224.41	237.85	5.65
2	15.6	28.82 (42)	0.23	0.40 (31)	1.38 (40)	714	195.42	214.95	9.09
3	16.4	33.25 (18)	0.21	0.45 (19)	1.45 (18)	700	237.64	241.55	1.62
4	22.4	34.3 (21)	0.24	0.55 (13)	1.46 (34)	668	347.37	401.99	13.59
5	22.6	31.82 (27)	0.23	0.53 (18)	1.29 (43)	698	329.07	370.19	11.11
6	22.6	32.85 (28)	0.28	0.51 (22)	1.56 (38)	635	323.97	372.39	13.00
7	22.7	37.01 (20)	0.25	0.54 (16)	1.34 (29)	658	366.74	377.68	2.89
8	22.4	37.74 (15)	0.25	0.55 (15)	1.34 (30)	685	366.83	404.85	9.39
9	29.4	37.14 (18)	0.27	0.59 (17)	1.45 (35)	629	490.97	552.92	11.20
10	29.4	39.42 (9)	0.29	0.61 (18)	1.64 (24)	562	525.39	551.58	4.75
11	29.5	35.96 (18)	0.29	0.62 (19)	1.74 (22)	545	502.52	522.89	3.89
12	29.4	36.4 (21)	0.27	0.64 (10)	1.45 (37)	619	502.49	562.38	10.65
13	20	35.92 (25)	0.23	0.47 (20)	1.05 (15)	692	303.13	361.60	16.17
14	25	37.36 (21)	0.28	0.56 (16)	1.24 (5)	634	404.79	453.21	10.68
15	22.6	34.56 (18)	0.25	0.66 (8)	1.26 (24)	515	566.97	612.53	7.43

* The values in brackets indicate the coefficient of variation (*CV%*) of the measured parameter.

6. Prediction of Air Jet Yarn Strength at Different Gauge Lengths Based on Statistical Modeling

In this chapter, step by step derivation of a statistical model that predicts air jet yarn strength at different gauge length has been presented. The model has been derived by [75] in which, the yarn strength, as well as its coefficient of variation at different gauge length, are being calculated. Moreover, the model has been validated by [76].

6.1 *Yarn strength in relation to gauge length*

The current model uses the same assumptions of Peirce model which implies that the principle of weakest link theory is valid and the probability that one short part of yarn breaks is independent to the probabilities of breakage of all other short parts, i.e., the probability of breakage of all short parts is mutually independent. But unlike Peirce model, it is assumed that the yarn strength p (cN) at a short gauge length l_o (mm) follows the Weibull distribution [75]. Let us assume a yarn is gripped between two jaws as shown in *Figure 6.1*. And let us assume that the function $F(p, L)$ is the probability that a yarn of a given length L (mm) breaks by a force p and this function is non-decreasing function because if the value of p is high, $F(p, L)$ value becomes high as well.

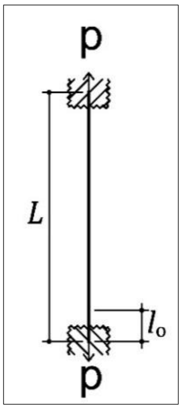


Figure 6.1 A yarn is gripped between the jaws of a tensile tester.

The probability of non-breaking of the long length L can be formulated as follows,

$$1 - F(p, L) = \left(1 - F(p, l_o)\right)^{L/l_o} \tag{6.1}$$

Where, $F(p, l_o)$ is the cumulative distribution function of yarn strength at gauge length l_o (i.e. the probability that a yarn with a given (short) gauge length l_o breaks by a force p). Since $F(p, L)$ is a non-decreasing function ranges from $F(p \leq p_{min}, L) = 0$ to $F(p \geq p_{max}, L) = 1$, so, $1 - F(p, L)$ is non-increasing function ranges from $1 - F(p \leq P_{min}, L) = 1$ to $1 - F(p \geq P_{max}, L) = 0$. In addition, equation (6.1) is a function of p only. Thus, let us introduce the risk function $R(p)$ in the way that,

$$\left(1 - F(p, L)\right)^{L/l_o} = e^{-LR(p)}, \qquad L > 0 \tag{6.2}$$

And,

$$R(p) = \left(\frac{p - p_{min}}{Q}\right)^c \tag{6.3}$$

Where $R(p) \in (0, \infty)$, $p_{min} \geq 0$, $Q \geq 0$ and $c \neq 0$ are constants for a yarn. Then the cumulative distribution function can be formulated by using equation (6.2) and (6.3),

$$F(p,L) = 1 - e^{-L\left(\frac{p-p_{min}}{Q}\right)^c} \tag{6.4}$$

The unit of p_{min} and p is (cN) and the unit of Q is $(cN.m^{1/c})$, consequently, the cumulative distribution function is a dimensionless unit. Let us assume a parameter of gauge length q where,

$$q = \frac{Q}{L^{1/c}} \tag{6.5}$$

Furthermore, the probability density function $f(p,L)$ is the differentiation of the cumulative distribution function $F(p,L)$, therefore, by differentiating equation (6.4) in respect to p, and using equation (6.5),

$$f(p,L) = \frac{c}{q}\left(\frac{p-p_{min}}{q}\right)^{c-1} e^{-\left(\frac{p-p_{min}}{q}\right)^c} \tag{6.6}$$

Equation (6.6) characterizes the distribution of random variable p by the parameters p_{min}, q and c which can be expressed by 3-parameters Weibull distribution. Where p_{min} represents location, c is shape and q is scale. The variable p also can be transformed in the way that,

$$u = \left(\frac{p-p_{min}}{q}\right)^c, u \in (0,\infty) \tag{6.7}$$

The random variable p can be calculated using equation (6.7),

$$p = qu^{1/c} + p_{min} \tag{6.8}$$

By differentiating equation (6.8),

$$dp = \frac{q}{c}u^{\frac{1}{c}-1}du \tag{6.9}$$

In Peirce model, the probability density function for the transformed value u was obtained assuming a Gaussian distribution. This distribution can't fit the data at all cases of gauge length. On the other hand, the Weibull distribution is one of the most widely used distribution in survival and life time analyses because of its flexibility and versatility among other distributions by changing the value of its shape parameter. Therefore, in the present model, the 3-parameter Weibull distribution was assumed which could be valid at most of the cases, hence, giving better accuracy [76].

6.1.1 Calculating the mean yarn strength

The m^th^ non-central statistical moment can be calculated as follows,

$$\overline{p^m} = \int_{p_{min}}^{\infty} p^m f(p,L)dp \tag{6.10}$$

By using equations (6.6), (6.7), (6.8), (6.9), and the binomial theorem yields,

$$\overline{p^m} = \sum_{i=0}^{m} \left(\binom{m}{i} q^{m-i} p_{min}^{i} (1)^i \int_0^\infty u^{\frac{m-i}{c}} e^{-u}\, du \right) \tag{6.11}$$

As Gamma function $\Gamma x = \int_0^\infty u^{x-1}\, e^{-u} du$, Therefore,

$$\Gamma(x+1) = \int_0^\infty u^x\, e^{-u} du \tag{6.12}$$

By substituting equation (6.12) in (6.11), the mean value of yarn strength $\overline{p^1}$ can be obtained,

$$\overline{p^1} = q\Gamma\left(\frac{1}{c} + 1\right) + p_{min} \tag{6.13}$$

As $\Gamma(x+1) = x\Gamma x$, hence,

$$\overline{p^1} = \frac{q}{c}\Gamma\frac{1}{c} + p_{min} \tag{6.14}$$

Based on equation (6.5) and (6.14), the mean yarn strength (cN) can be expressed also as follows,

$$\overline{p^1} = \frac{QL^{-1/c}}{c}\Gamma\frac{1}{c} + p_{min} \tag{6.15}$$

6.1.2 Calculating the standard deviation of yarn strength

Assume that $\omega(u)$ is the probability density function of the transferred value u, therefore it is valid that,

$$\omega(u)du = f(p, L)dp \tag{6.16}$$

Using equations (6.6), (6.7), (6.9) and (6.16), the probability density function can be obtained,

$$\omega(u)du = e^{-u}du \tag{6.17}$$

Analogically, the non-central moments of the transferred value u is,

$$\overline{u^x} = \int_0^\infty u^x e^{-u} du \tag{6.18}$$

From equation (6.12) (6.17) and (6.18),

$$\overline{u^x} = \Gamma(x+1) \tag{6.19}$$

And the mth central moment of yarn strength $\overline{(p - \overline{p_l})^m}$ can be calculated using equation (6.8) and applying the expectation operator E of mean value as follows,

$$(p - \overline{p_l})^m = E\{(p - \overline{p_l})^m\} \tag{6.20}$$

By using equation (6.14) and by using the same logic in equation (6.19),

$$(p - \overline{p_l})^m = q^m \left(\sum_{j=0}^{m} \left((-1)^j \binom{m}{j} \Gamma\left(\frac{m-j}{c} + 1\right) \left(\Gamma\left(\frac{1}{c} + 1\right) \right)^j \right) \right) \tag{6.21}$$

The dispersion σ^2, which is the 2nd central moment of yarn strength can be obtained, and finally, the standard deviation of yarn strength can be calculated,

$$\sigma = q\sqrt{\frac{2}{c}\Gamma\frac{2}{c} - \frac{1}{c^2}\Gamma^2\frac{1}{c}} \tag{6.22}$$

6.1.3 Calculating the coefficient of variation of yarn strength

Using the values of σ and p from equation (6.14) and (6.22), the coefficient of variation of yarn strength CV (%) can be obtained then expressed by Q parameter using equation (6.5),

$$CV = \frac{\sqrt{\frac{2}{c}\Gamma\frac{2}{c} - \frac{1}{c^2}\Gamma^2\frac{1}{c}}}{\frac{1}{c}\Gamma\frac{1}{c} + \frac{p_{min}}{QL^{-1/c}}} \tag{6.23}$$

6.1.4 Mathematical model validation

100% Tencel fibers of 1.3 dtex and 38 mm were spun to produce 23 Tex ring, rotor and air jet spun yarns. Instron 4411 was used to measure yarn tensile properties at different gauge lengths namely, 60, 100, 200, 300, 400, 500, 600 and 700 mm. The structure of rotor and air jet spun yarns was investigated by analyzing the longitudinal view and the yarn cross-section of these yarns using optical microscope according to the standard test method [77]. To validate the model, the values of yarn strength at 300 mm gauge length were obtained and the Weibull distribution along with its 3-parameters, p_{min}, c and q were obtained using the modified weighed least square estimators method [78]. Then the Weibull distribution was obtained using the following equation,

$$f(t) = \frac{c}{q}\left(\frac{t - p_{min}}{q}\right)^{c-1} e^{-\left(\frac{t-p_{min}}{q}\right)^c} \tag{6.24}$$

Afterward, the parameter Q was calculated using equation (6.5), then yarn tenacity, $\overline{p^1}$ and coefficient of variation of yarn strength, CV were obtained at each gauge length by using equation (6.15) and (6.23).

6.2 *Results of the model*

6.2.1 Yarn strength

To understand the behavior of the probability density function of the linearly transformed yarn strength as defined according to Peirce model [66], it was calculated at different values of $^{L}/_{l_o}$. It can be seen from *Figure 6.2* that the distribution shape changes at different gauge lengths and it follows the Gaussian distribution approximately only at L equal to l_o.

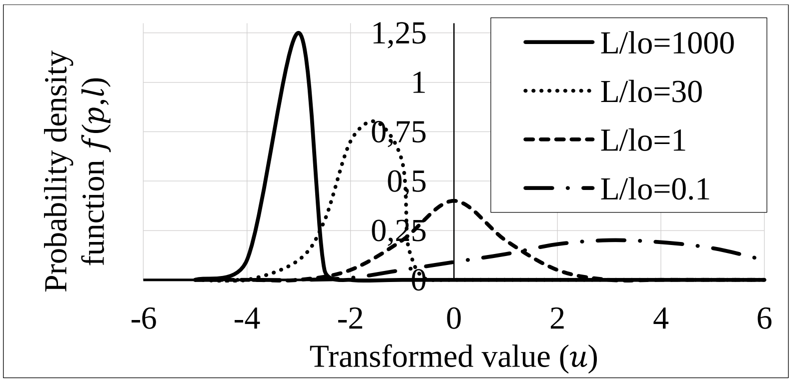
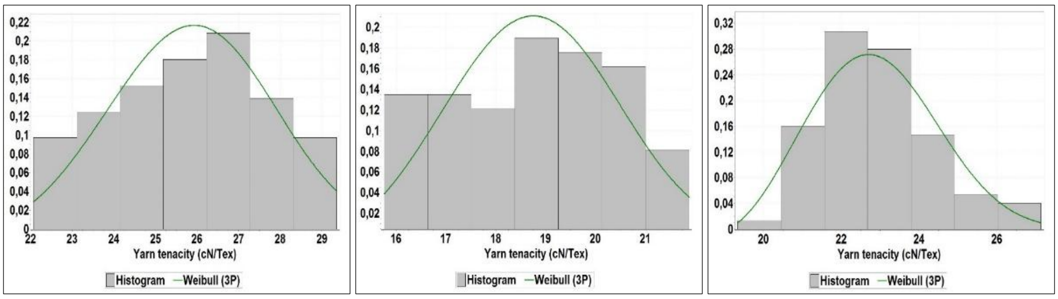


Figure 6.2 Probability density function of the linearly transformed yarn strength.

Figure 6.3 shows the histogram and the equivalent 3-parameter Weibull distribution for yarn tenacity measured at 300 mm gauge length. The values of p_{min}, c and q for each yarn were obtained and used for predicting yarn strength and its coefficient of variation. It is clear that the Weibull distribution fit well the yarn strength values at 300 mm gauge length. By observing *Figure 6.3-b*, it is obvious that the irregular nature and the variability in rotor yarn structure causes difficulty in obtaining the Weibull distribution accurately.

Figure 6.4 shows the theoretical and experimental values of yarn strength at different gauge lengths. It is evident that the predicted and experimental strength values are in a good agreement for all tested spun yarns. It can be observed also that the ring spun yarn tenacity is the strongest yarn followed by the air jet yarn then rotor yarn.



(a) (b) (c)

Figure 6.3 The probability density function of yarn tenacity at 300 mm gauge length; (a) ring, (b) rotor, (c) air jet.

The high tenacity of ring spun yarn is attributed to the uniform twist which improves fiber gripping, interlocking and migration characteristics [79]. By comparing both air jet and rotor yarns longitudinal and cross-sectional view shown in *Figure 6.5*, and in case of the rotor yarn, the thin strand of fibers (before twisting) has hooked ends as well as fibers migration is high, therefore, the fiber length is not fully utilized. In case of the air jet yarn, the structure consists of two layers – a core bundle without twist, in which fibers are arranged parallel to the yarn axis, and the wrapping layer, which is twisted around the core. Fibers in wrapping layer are formed so that the top end of fibers converges to the center of the yarn while the trailing end together with other fibers wrap the core due to swirling air [80].

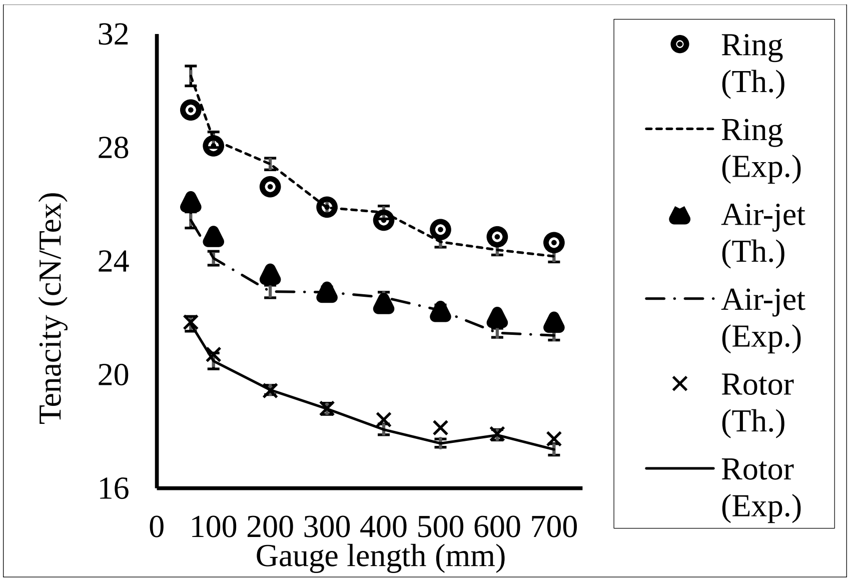


Figure 6.4 Theoretical and experimental values of yarn strength at different gauge lengths.

It is also noted from *Figure 6.4*, that the strength of all yarns decreases with increasing gauge length from 60 mm to 700 mm and this is because the probability of the existence of weak links in yarn structure is greater at higher gauge length as explained by the weak link theory [66]. At long gauge length, yarn thin places more likely exist which can't bear the tensile load. And most yarn failures take place when there is a sudden reduction in yarn mass [81].

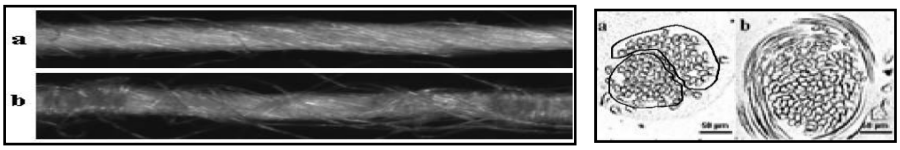
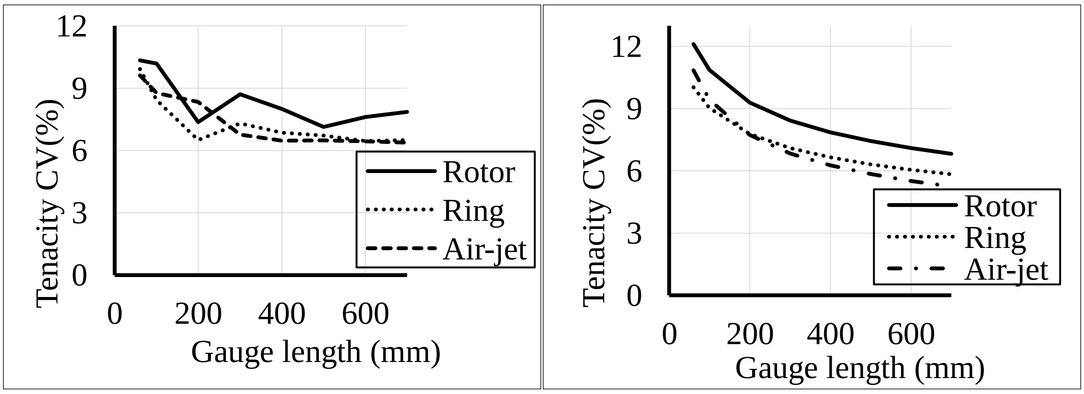


Figure 6.5 Longitudinal and cross-sectional view of yarns; (a) air jet, (b) rotor.

6.2.2 Coefficient of variation of yarn strength

The experimental and predicted relationship between the coefficient of variation of yarn tenacity (*CV%* tenacity) and gauge length is presented in *Figure 6.6*. It is observed from *Figure 6.6-a* that *CV%* tenacity of rotor yarn is the highest, followed by the air jet yarn and ring yarn at most gauge lengths. It is also clear that *CV%* tenacity for all yarns is higher at shorter gauge length.

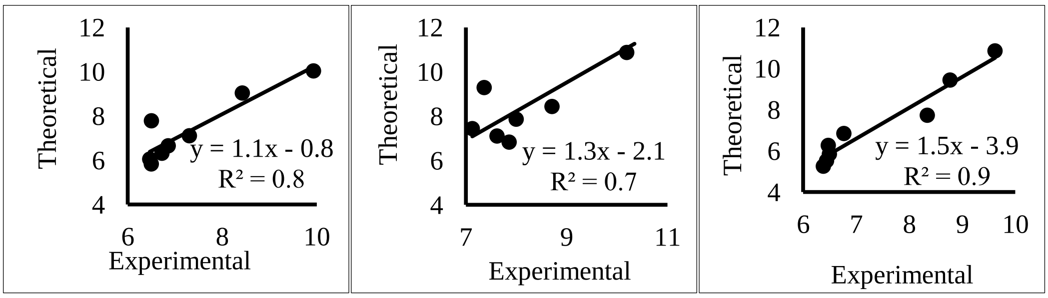
Figure 6.7 reveals the correlation between the experimental and theoretical *CV%* tenacity. Results reveal that the proposed model captured well the change in *CV%* tenacity over different gauge lengths for all tested yarns. The R-squared value is the highest in case of air jet yarn followed by ring spun yarn, then rotor yarn. The low R-squared value of rotor yarns may be explained by their high experimental values of *CV%* tenacity (08-11%) as well as the irregular nature of rotor yarn structure.



(a) (b)

Figure 6.6 Coefficient of variation of yarn strength at different gauge lengths; (a) experimental, (b) theoretical.

However, generally, the difference between experimental and theoretical values of coefficient of variation is attributed to the assumption that the probability of breakage of all short yarn segments is mutually independent. Another model that hypothesizes the dependency of each segment on the adjacent segments may be developed to obtain more precise results.



(a) (b) (c)

Figure 6.7 Experimental versus calculated results of coefficient of variation of yarn strength at different gauge lengths; (a) ring, (b) rotor, (c) air jet.

7. Evaluation of results and new findings

This thesis contributed to the knowledge of the air jet yarn formation process, particularly Rieter air jet spinning technology by investigating the influence of selected technological parameters of the spinning machine on yarn properties, especially its strength. Furthermore, it shed light on the problem of the prediction of yarn strength by trying different approaches to establish models that can be used for prediction of air jet spun yarns strength.

In the first part, a 3D simulation process was carried out to study the principle of yarn formation of the Rieter air jet spinning machine. Along with the theoretical study, an experimental investigation was carried out to study the effect of the nozzle pressure on yarn tenacity. In the second part, the effect of yarn linear density, nozzle pressure and delivery speed on Rieter air jet spun yarn tenacity was investigated and a statistical model that predicts the yarn tenacity was presented.

In the third part, a prediction of air jet spun yarn strength at short gauge length was presented. In the fourth part, a new statistical model based on Peirce model was validated which is capable of capturing the change of ring, rotor, and air jet yarn strength and its coefficient of variation at different gauge lengths.

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1. **Eldeeb M.**, Sayed Ibrahim, Ismael Rakha, Fawkia Fahim, and Eman Elshahat, “Effect of finishing process on plied compact and conventional ring spun yarn properties”, 20th Conference STRUTEX (proceedings), Liberec: Technical University in Liberec, 2014. Not paged 4 pages. ISBN 978-80-7494-139-9.

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Quotation

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Curriculum Vitae

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Nationality	Egyptian	
Marital status	Married	
Date of birth	23.11.1983	

Work Experience		
Textile Technology Department, Faculty of Textile Engineering, Technical University of Liberec, Liberec, Czech Republic.	PhD scholar	2013-2017
Textile Technology Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.	Teacher	2011-2013
	Teaching assistant	2009-2011
K.C.G Textile Egypt S.A.E Company for home textiles, El Asher men Ramadan, Egypt.	Quality assurance supervisor	2008-2009
Oriental Weavers Company for carpets, El Asher men Ramadan, Egypt.	Maintenance and production Engineer	2006-2008
El Gazar Company for ready-made garments, Mansoura, Egypt.	Planning Engineer	2005-2006

Academic Profile and Fellowship Period			
Mansoura University, Mansoura, Egypt	Textile Engineering Department, Faculty of Engineering	*MSc Degree*, Awarded	2011
Küçükçalık company for home textiles, İnegöl, Turkey	Quality control	Training	2008
Mansoura University, Mansoura, Egypt	Textile Engineering Department, Faculty of Engineering	*BSc* Degree, Very Good with honor (First of class)	2005
Masr Company for spinning and weaving, El Mahala El Kobra, Egypt.	Maintenance	Training	2004
El Nasr Company for spinning, weaving and dying, El Mahala El Kobra, Egypt	Production	Training	2003

Brief Description of the Current Expertise, Research, and Scientific Activities

Doctoral Studies: Full-time student at the Faculty of Textile Engineering, Department of Textile Technology, Specialization: Textile Technics and Material Engineering

Exams:	Heat and Mass Transfer in Porous Media KHT/D17,	21.02.2014
	Textiles Projection KMI/D20,	13.03.2014
	Structural Theory of Fibrous Assemblies KTT/D11,	02.06.2014
	Numerical Methods KAP/D40,	09.12.2014
	Experimental Technique of the Textile DFT/D33,	13.02.2017

State Doctoral Examination: Completed on 16.05.2017 with the overall result passed.

Research projects:

1. **Eldeeb M.** (leader), Shoaib Iqbal, and Zuhaib Ahmed, A project entitled, "Effect of plying process on air jet yarn properties", supported by "Student Grant Competition 2015", Technical University of Liberec, Czech Republic, project no. 21086.
2. Zuhaib Ahmed, **Eldeeb M.** (member), and Shoaib Iqbal, A project entitled, "3D construction and structure of woven fabric", supported by "Student Grant Competition 2015", Technical University of Liberec, Czech Republic, project no. 21153.

Record of the state exam

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

Jméno a příjmení doktoranda: **Moaz Ahmed Samy Moustafa El Deeb**

Datum narození: **23. 11 1983**

Doktorský studijní program: **Textilní inženýrství**

Studijní obor: **Textile Technics and Material Engineering**

Termín konání SDZ: **16. 5. 2017**

prospěl ~~**neprospěl**~~

Komise pro SDZ:

		Podpis
Předseda:	prof. Ing. Bohuslav Neckář, DrSc.	
Místopředseda:	doc. Ing. Maroš Tunák, Ph.D.	
Členové:	prof. Ing. Michal Šejnoha, Ph.D., DSc.	
	prof. Ing. Ladislav Ševčík, CSc.	
	doc. Ing. Martin Bílek, Ph.D.	
	doc. Ing. Pavel Rydlo, Ph.D.	
	Ing. Gabriela Krupincová, Ph.D.	OMLUVENA

V Liberci dne 16. 5. 2017

O průběhu SDZ je veden protokol.

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Recommendation of the supervisor

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Recommendation of the supervisor

Supervisor´s opinion on Ph.D. thesis

Ph.D. candidate: Moaaz Ahmed Samy Moustafa El Deeb

Title of the work: Different Approaches for Predicting Air Jet Spun Yarn Strength

Doctoral study program: Textile Engineering

Supervisor: Ing. Eva Moučková, Ph.D.

Currently, yarns produced on air-jet spinning machines are increasingly applied, especially in the field of garment products. The process of forming the air-jet yarn in the spinning box is completely different from rotor and ring spinning technology. Thanks to it, air-jet yarns are featured by a different, specific structure (fasciated yarn). This, in case of optimally set machine process variables, makes these yarns stronger compared to rotor spun yarns. Concurrently, the air-jet yarns exhibits lower hairiness. Although there are many research works focused on air-jet yarn, they are primarily deals with the influence of the technological parameters on the properties of the air-jet yarns produced on Murata Vortex spinning machine (MVS) or simulation of air flow field in the MVS nozzle chamber. However, Rieter company introduced its air-jet spinning machine in the year 2009. It differs from the MVS by the machine concept, the nozzle geometry and fiber guide in front of spinning tip placed in the nozzle house. Therefore, the study of forming process of Rieter air-jet yarns together with the problematics of yarn strength and possibility of its prediction is an up-to date subject.

At presented Ph.D. thesis, the candidate focuses on the issue of yarn strength on a wider scale, which is in line with the objectives of the work. Therefore, the work is divided into 4 main chapters. The research part of the dissertation thesis includes current knowledge in the area of air-jet spinning and the prediction of the air-jet yarn strength. In the first main chapter, the student tries to clarify the process of yarn formation using the numerical modeling of airflow field in the nozzle. He points out the importance of nozzle pressure, which affects the arrangement of wrapper fibers in yarns and hence the structure of the yarn, which, to some extent, reflects in the yarn strength. In the second part, based on experimental measurements, the student compiled a multiple regression model of yarn strength in dependence on the yarn count, the nozzle air pressure and delivery speed. In the third part the student proposed and experimentally verified the mathematical model of yarn strength on short gauge lengths. During the model creation, he proceeded logically with regard to the specific yarn structure and the use of research work. Yarn strength predicted using the proposed mathematical model fits to experimental yarn strength very well. Within the work, the student suggested new method of calculation wrapper fiber ratio and was able to critically evaluate its weaknesses. In the last main part he presented statistical model for prediction of air-jet yarn strength at different gauge lengths based on Neckar´s model. In this part he compared obtained results with results of ring and rotor spun yarn.

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His publication activities are in very good level. The candidate is a main author or a co-author of:

- 5 papers published in the impact factor journals indexed in WOS database,
- 1 paper published in a journal indexed in Scopus database only and
- 2 papers in other journals.

Today, 3 next papers are in press in the impact factor journals. He also published 6 articles at conferences and seminars.

Ph.D. student Moaaz El Deeb worked out the thesis with interest and initiative. During work solution, he clearly demonstrated both the ability to work independently and the ability of logical thinking in connection with the application of models and their derivation.

Therefore, I recommend this Ph.D. thesis for the defense.

V Liberci 8. 6. 2017

Ing. Eva Moučková, Ph.D.
KTT

Opponent's reviews

Dissertation Review
DIFFERENT APPROACHES FOR PREDICTING AIR JET SPUN YARN STRENGTH

Author: **Moaaz Ahmed Samy Moustafa Eldeeb M.Sc.**
Technical university of Liberec
Faculty of Textile Engineering

In accordance with the internal "Study and Examination Rules" of the Technical university in Liberec Liberci" article 22 , I have worked up following Dissertation Review of the dissertation of PhD. Student Mr. Moaaz Ahmed Samy Moustafa Eldeeb M.Sc.

The production of air jet yarn is, in the first place, thanks to the Japanese company Murata, firmly anchored among the industrially recognized staple yarn production technologies. Murata launched its first jet spinning machine MJS already in 1982 and then in 1997 the MVS machine, which was able to process 100% cotton fibers. Murata gradually managed to persuade the conservative textile manufacturer about the benefits of this new spinning process.

Rieter, as currently the leading spinning machine manufacturer, could not neglect this trend and therefore, in 1999, has been developing its own unique jet spin technology. This technology is now available for customers around the world using a J26 jet spinning machine. Compared to other yarn manufacturing technologies, especially ring and rotor, this technology is still new and some patterns of yarn production in the spinning nozzle are not yet exactly described. The significance of the presented dissertation thesis is above all in that it tries to answer some open questions in connection with this new spinning technology.

The content of literary research faithfully reflects the current state of the problem and creates a solid base for the author's further work. The aim of the thesis is quite precisely defined in chapter 2.2. As a contribution to the problem of forming yarn yarns, and the content and form of work to that end correspond.

The work brings three approaches to the problem of predicting the strength of staple yarn, produced by the air-jet spinning technology:

1. Numerical (CFD) airflow simulation in the FLUENT program.
2. Statistical model based on experiments and regression model
3. Mathematical model

I have the following comments to the individual methods
:

1. Numerical (CFD) airflow simulation in the FLUENT program.

The problem of numerical simulation of air flow is that there is not freely available computing apparatus for simulating the behavior of textile fibers in the air flow so it is only possible to judge their behavior from the course of air flow and combine them with experimental results. The author of the work in this area probably reached the maximum possible. By comparing with the experimental results, it is at least possible to estimate the yarn strength trends caused by changes in the airflow in the nozzle.

2. Statistical model based on experiments and regression model

This approach is probably the most reliable way to predict the yarn's strength as it is based on practical measurements and evaluates them statistically. However, it is not clear how far this model would provide results for yarns outside the regions that were used to create the regression model.

3. Mathematical model

Personally, I like this approach very much, it works with real physical and geometric quantities, and although it is considerably simplified, it provides relatively good results when compared to experiments.

The achieved results are confronted with the knowledge known from the literature directly in the text of the thesis. In many cases similarities or directly conclusions are identified. From this point it is obvious that the doctoral student did not deviate from the real state of the problematics, and the willingness of this work in the field of the analysis of air- jet yarns can be uniquely identified.

The work shows that the best results for prediction of yarn strength are provided by a statistical model based on the processing of a number of experiments.

The formal aspect of the work and its graphic design is very high. Also, on a linguistic basis, I cannot blame anything, the work is written in plain English and I did not identify any typing or grammar mistakes in it.

The list of publications on the pages 81 and 82 contains a total of 20 entries and consists of articles, presentations on workshops and other research activities. Most of the work is related to the issue of staple yarns delivered by air-jet technology, so it is obvious that the author deals systematically with this issue.

Over all, the dissertation work is describing very complicated process of the forming of air- jet yarn including the relevant influences to this process. Everything is supported via practical experiments with adequate explanation. In few cases the used terminology was not absolutely precise from the point of view of industrial application, but it has no negative influence to the understandability of the text.

I suggest that the doctoral student answer the following questions during his defense:

1. Does the doctoral student have any knowledge of any numerical tools combining airflow simulation with the behavior of the textile fibers?

2. What are the limits of the statistical model in the yarn segments that were not used directly to determine regression coefficients?

3. Would it be possible to combine the statistical and mathematical model in a suitable way to achieve greater confidence in predicting yarn strength?

I recommend the dissertation for defense.

in Usti nad Orlici 22nd of August 2017

doc. Ing. Jiří Sloupenský, CSc.
Rieter CZ s.r.o. Ústí nad Orlicí

Thesis Review Report

Title of Thesis: Different Approaches for Predicting Air Jet Spun Yarn Strength
Name of the Candidate: Moaaz Ahmed Samy Moustafa Eldeeb

Air-jet spinning is one of the promising technologies for manufacturing of staple fiber yarns. The resulting yarn, called air-jet spun yarn, has a specific fasciated structure which is manifested by the fiber materials used and the process parameters maintained during spinning. This yarn is popularly used for production of woven shitting fabrics as well as knitted interlock, pique, and jersey fabrics. Nevertheless, the strength of air-jet spun yarns is always lower than the strength of the traditional ring-spun yarns. Why is it so? What roles do the fiber materials and the spinning parameters play to decide this? Is it possible to predict the strength of air-jet spun yarns? The current thesis studies different approaches for prediction of strength of air-jet spun yarns.

At the beginning of this research work, the candidate carried out numerical simulation to investigate the influence of nozzle pressure on the structure and strength of air-jet yarns. An attempt was made to explain the experimental findings on the basis of simulation results. In my opinion, this piece of work was an original contribution to knowledge and it was presented nicely and thoroughly in the thesis.

Then, the candidate made an attempt to predict the strength of air-jet yarns with the help of statistical modelling technique. The experiment was conducted in accordance with a response surface design and the results were analysed by means of statistical regression technique. The candidate obtained a very good correlation between the experimental and model results. Though the response surface design is generally used for optimization of processes and products, the candidate did not try to maximize the strength of the yarns. As this can be interesting, it is suggested that the candidate may like to use the same experimental data for maximising the strength of the yarn and report the same in the thesis.

Afterwards, the candidate attempted to develop a mathematical model for prediction of air-jet yarn strength. The developed model was quite simple and it was presented clearly in the thesis. However, the model was found to underpredict the strength of all air-jet yarns studied in this work. Why was it so? A tentative reason for this behaviour may be stated in the thesis. Also, it is suggested that in Figure 6.4, the experimental points should be shown by circles owing to their discrete character and the theoretical results could be displayed by continuous lines.

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At the end, the candidate reported on a statistical model for predicting the strength of air-jet yarns at different gauge lengths based on Weibull distribution of yarn strength. Though the candidate started this chapter with Peirce's model of yarn strength, however, this model was not used to explain the experimental results. Instead of this, the candidate chose Weibull model to predict yarn strength. Why the candidate did not choose Perice's model? Was it so that the strength of air-jet yarns followed Weibull distribution more closely than the Gaussian distribution (one of the assumptions of Peirce's model)? The candidate may like to cast some light on this in the thesis. Further, it was found that the thesis reported a low correlation between the experimentally obtained CV of tenacity and the theoretically determined CV of tenacity. Was there any specific reason for this what the candidate could think of?

Also, the candidate can make an attempt to further improve the language of the thesis. It is better to follow a particular tense, rather than a mix of past tense and present perfect tense. Also, some sentences require modification. For example, the last sentence of the second paragraph in page number 10 is not completed and it requires to be corrected. Further, the phrase "statistically significant at 95% confidence level" needs to be changed as "statistically significant at a level of significance of 0.05".

Overall, I find the quality of the thesis very good. The research work carried out by the candidate is well documented and coherently presented in the thesis. The research problem has been introduced in a very logical way and the objectives are found to be very well defined. The survey of literature has been carried out very critically and exhaustively with mentioning the state of the art in-detail and highlighting the gaps in literature. The overall flow of presentation of the thesis is excellent; especially continuation of one chapter to the next one has been maintained very carefully. The systematic and in-depth study carried out by the candidate on the present research topic demonstrates that the candidate is competent enough to carry out independent research work. As mentioned in the thesis, this work led to 14 publications (11 Published and 3 Communicated) in journals and 6 presentations in conferences. This further demonstrates the research quality and productivity of the candidate. Based on the above observations, I strongly recommend the thesis for the award of Ph.D. degree.

Das 01/11/17

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