PROCESS-STRUCTURE-PROPERTY RELATIONSHIPS
OF YARNS PRODUCED ON THE CARD-SPINNING
SYSTEM

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Dedicated to my parents
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SUMMARY

Traditionally, the process sequence for staple yarn manufacturing involves about ten steps. In this project, analysis and enhancement of carding and spinning, the research team works on a new technology to produce staple yarns in two major steps, namely, opening/cleaning, and yarn formation. The novel yarn formation system consists of a card fitted with a web dividing device and multiple spinning nozzles. This novel system represents a brand new approach to staple yarn manufacturing, and a fundamental analysis of certain aspects of the system is conducted in this study. The research objectives are: 1. To analysis and regulate fiber transport to the spinning heads with aim of achieving spinning reliability and product uniformity, 2. To study the limiting factors affecting the operating range and to develop solutions to overcome such barriers, 3. To characterize the structure of yarns from this spinning system and to analyze the yarn performance properties, and 4. To work with industry partners and identify unique applications for the new type of yarn.

Having successfully produced a novel yarn form the Card-spinning system, it is important for us to define the process-structure-property relationship of the yarns. These relationships will help us in improving yarn quality and in finding new applications for the yarns.

The yarn properties are influenced by many processing parameters such as ribbon width, web uniformity, fiber type, spinning speed, nozzle type and nozzle air pressure. In this study, the fiber linear density, web basis weight, and spinning nozzle pressures are varied. The resulting yarns are characterized for their linear density, geometric features, strength, elongation at break, and evenness by image analysis, yarn tensile test, and Uster evenness test. A statistical analysis of the test results is conducted to quantify the effect of processing parameters on yarn properties and to identify processing conditions for desirable yarn properties.
CHAPTER 1

Introduction

Staple yarn manufacturing generally involves about ten individual steps. In order to shorten the processing sequence, an experimental card-spinning system has been built at Georgia Tech, which combines carding directly with yarn spinning. In this system, fiber is fed through a fine opener to a carding machine, and the web from the card is divided into narrow ribbons that are then spun into yarns by air-jet nozzles.

The characteristics of the yarns are influenced by many processing parameters such as ribbon width, web uniformity, fiber type, spinning speed, nozzle type, and nozzle air pressures. In this experimental study, the fiber linear density, web basis weight, and spinning nozzle pressures are varied. The resulting yarns are characterized for their linear density, geometric features, strength, elongation at break, and evenness. Tensile and evenness testers and image analysis tools are used to characterize yarn properties. A statistical analysis is conducted to qualify the effect of processing parameters on yarn properties and to identify processing conditions for desirable yarn properties.
1.1 Development of card-spinning machine

Currently, the process sequence for staple yarn manufacturing performs four major functions: separation, parallelization, attenuation, and consolidation. As the tasks are performed in multiple steps, several machines (about 10) in sequence are needed for these tasks. For the production of yarns, the sequence comprises: bale opening, opening/cleaning (1 to 3 steps), blending, carding, drawing (2 to 3), and yarn formation (1 to 2). It has been the industry’s strong desire to shorten the sequence while maintaining acceptable product quality so as to reduce the costs associated with equipment, floor space, labor, material loss, and machine down time.

The Card-Spinning machine [1] combines carding directly with yarn spinning in one integrated unit, thus by-passing the separate drawing and materials handling/transport steps. The system is based on a Truetzschler card (DK-760) with a chute feed, and the fiber is supplied by a hopper feeder and fine opener system that is linked to the card. The developed system consists of a web-dividing device, spinning unit and a winding unit. A simple and versatile web-dividing device has been designed and fabricated to create a narrow ribbon from the card web, which is then transported to the spinning head, and an air-jet spinning nozzle spins yarn out of it. Integration of the card, web-splitting unit, yarn spinning unit, and the winding unit into a continuous processing line has been successfully achieved. The effect of processing conditions on the properties and operational characteristics of yarn produced on the Card-Spinning system have also been studied. The process is supported by a web-monitoring system, which is used to analyze the web non-uniformity. This will facilitate online monitoring of web mass density and the new web-splitting technique makes it possible for dynamic web splitting to automatically adjust ribbon width according to local web mass density.
1.2 Objective of Research

(1) To produce yarns from Card-spinning system, analyze their geometric structure and mechanical properties;

(2) To develop an understanding of process-structure-property relationship of the yarns;

(3) To characterize the card-spun yarns properties and find the internal relationship of yarn structure and yarn mechanic properties;

(4) To find the suitable process parameters to achieve better quality yarns;

(5) To work on the application and market for this new type yarns.
CHAPTER 2
Review of Literature

In this chapter, literature in the following areas is critically reviewed:

(a) Principle of air-jet spinning;
(b) Classification of the fasciated yarn structure;
(c) Effect of process variables on the structure of air-jet spun yarns;
(d) Relationship between yarn properties and structural parameters;
(e) Microdenier fibers.

2.1 Principle of air-jet spinning

Air-jet spinning, like friction and rotor spinning, is a relatively new spinning technology. Though the technology of producing fasciated yarns by using high pressure air has been available since the early 1960’s, only in the last two decades has it been commercially used mainly as a result of design improvements of the nozzle. The main advantage of air-jet spinning over other unconventional spinning systems is its ability to spin yarns in both the medium and fine count range. Also, the high productivity of air-jet spinning makes it possible to economically produce fine count yarns for the apparel industry. In contrast to rotor spinning, the lower limit on the number of fibers in the yarn cross-section is very close to that of ring spinning. The thread tensions that occur in air-jet spinning are very low when compared to ring and rotor spinning.

Air-jet spinning is essentially a pneumatic spinning method which consists of passing a drafted strand of fibers through one or two fluid nozzles located between the front roller of a drafting system and a take up device.

The MJS is provided with two air vortex nozzles, which rotate in opposite directions.
The N₂ nozzle is used to apply twist to the fiber bundle coming out of the front roller. This is the so-called false twist, thus no yarn can be produced by this nozzle alone. (Shown in Figure 2.1)

![Figure 2.1 Structure of MJS air-jet Nozzle](image)

The other nozzle N₁ is attached between the N₂ nozzle and the front roller. The air from this nozzle rotates in the opposite direction from that of N₂ nozzle. The operation and function of N₁ nozzle is represented as follows and in Figure 2.1.[1]

The fiber bundle coming out of the front roller is twisted by the back nozzle N₂. However, since the fiber bundle is turned in the opposite direction by the N₁ nozzle, the fiber bundle receives the untwisting action and some of the twists in the fiber bundle between the front roller and the N₁ nozzle are reduced.

Some of the fibers are separated from the fiber bundle, and wound around the fiber bundle by the force of the N₁ nozzle.

The yarn coming out of the N₁ nozzle is then twisted again at the N₂ nozzle. The air jet rotates at very high rate, about three million rpm (rotation per minute). The fiber bundle rotates between 200,000 and 300,000 rpm. Winding of the yarns is performed continuously at high speed. Future explanation of the process is provided in Figure 2.2.[13]
The yarn is in a stationary state. It is $S$-twisted in the zone $T$ and $Z$-twisted in zone $U$.

The yarn is moving here. $S$-twist is inserted before the nozzle $N2$ and removed after it, to give a net zero twist.

The separation of the fibers, $S2$, is shown here. The first nozzle has been added. The direction of yarn rotation in the first nozzle is $B$.

The winding of the fibers $S2$, is shown here. The pitch of the fibers is $L1$.

The untwisting of the fibers $S1$ and $Z$-twisting of the fibers $S2$ after the nozzle $N2$ are shown here. Note the pitch $L2 < L1$.

Figure 2.2 Principle of air-jet spinning\(^{123}\)
2.2 Classification of the fascinated yarn structure

The structure of a fascinated air-jet yarn consists of an untwisted core of parallel fibers and a surface wrapping of fibers, imparting radial forces to the yarn and preventing axial slippage amongst the core fibers when the yarn is stressed. On the basis of microscopic observations, various researchers have classified the structure of air-jet spun yarns differently.

Lawrence and Baqui\(^2\) have classified the structure of air-jet spun yarns into three basic classes as shown in Figure 2.3.

![Yarn Structure Diagram](image)

**Figure 2.3 Classification of fascinated yarn structural elements\(^4\)**

Class I: Figure 2.4 shows the main feature of this class to be a thin ribbon of fibers uniformly wrapped around a twistless core, forming a structure resembling that of a hollow spindle wrap spun yarn, in which a multifilament strand wraps a twistless core of staple fibers. As the figure shows, the wraps have a counterclockwise helix, i.e., they are of a Z
direction. From the tandem arrangement of the air jets, it appears that the first jet controls the direction of wrap of the Class I structure. The angle of wrap for this class varied between 40-45°.

![Image: Appearance of Class I and variations of the class]

Figure 2.4 Appearance of Class I and variations of the class

Class II: Figure 2.5 shows the wrapping feature of this class to be random, in that a number of different wrap helices occurred on the same length of core. The number of fibers having the same helix of wrap varied from 1 to 6, and the helix angles between 45 to 90°. Although predominantly of the Z direction, a number of the helices had an S direction. The core was also twistless with, at times, evidence of crimp, but the crimp was not as pronounced as in Class I.
Class III: As shown in Figure 2.6, there were sections of the yarn in which the core fibers were not wrapped. These sections at times showed a low level of Z twist.

As the frequency of the Class III places in the yarn increased, the breaking load and extension of the spun yarn decreased. Lawrence and Baqui\textsuperscript{[2]} have concluded that Class III gives the weak place in the yarn. Being wrapped structures, both Classes I and II should have imparted strength to the yarn. The parameters for the Class I structure were inversely related to those for Class III. Class II showed a direct relation to yarn neppiness. A significant improvement in yarn quality can be achieved if the structure of total length conforms to that of Class I.
2.3 Effect of Process Variable on the Structure of Air-Jet Spun Yarn

The properties of air-jet spun yarns greatly depend on the process parameters. The important process parameters affecting air-jet spin yarn properties include the front and back nozzle pressures, the spinning speed, the main draft ratio, the total draft, the thread tension, and inter-jet distance. [2]

Lawrence and Baqui [2] found that yarn strength decreased with increase in the front nozzle pressure. This finding is not consistent with other works. Chasmawala et al. [3] and Grosberg et al. [4] have reported that an increased in front nozzle pressure increases the yarn tensile strength. Nishimura et al. [5] showed that with increasing the front nozzle pressure the tensile strength of air-jet spun yarns increased and then decreased. The different range of front nozzle pressures used for these researches and the different levels of other parameters can be attributed to the different relationship between front nozzle pressure and yarn tensile strength. Rajamanickam et al. [6] reported that for a given back nozzle pressure, front nozzle pressure at which maximum yarn strength is achieved depends on yarn count. Optimum front nozzle pressure was lower for finer yarns than for
Lawrence and Baqui\textsuperscript{(5)} and Chasmawala\textsuperscript{(10)} et al. have reported that the yarn irregularity, hairiness and imperfections increase with increasing front nozzle pressure. Rajamanickam\textsuperscript{(7)} et al. have shown that with increasing front nozzle pressure, yarn irregularity and imperfection increased for all yarn counts and blend ratio. Lawrence and Baqui\textsuperscript{(5)} speculate that the increase in the imperfections could be due to the increase in the fly generated. Chasmawala\textsuperscript{(10)} et al. attribute the increase to the increase of concentration of mass brought about by the increasing number of wrapper fibers. While the increase in the number of wrapper fibers increases the yarn strength, it led to more unevenness.

The yarn tenacity decreases as the back nozzle pressure increases. The back nozzle pressure has no significant effect on the yarn irregularity, imperfections or hairiness. Lawrence and Baqui\textsuperscript{(5)} have shown that the tensile properties will improve with increasing spinning speed. With increasing spinning speed, yarn strength increased and then decreased, but the hairiness continuously increased. Rajamanickam\textsuperscript{(6)} et al. has shown that yarn hairiness increases with spinning speed and front nozzle pressure.

Rajamanickam\textsuperscript{(7)} investigated the effect of the interaction between process parameters on yarn tensile strength. For a given back nozzle pressure, the front nozzle pressure that yields maximum strength depends on the yarn count and yarn blend ratio. For a finer yarn, optimum front nozzle pressure decreased, while optimum back nozzle pressure increased.

2.4 Relationship between Yarn properties and Structural Parameters\textsuperscript{(7,10)}

Lawrence and Baqui\textsuperscript{(5)} have shown that the yarn breaking load increases with increase in Class I structure and a decrease in Class III structure. Also, through microscopic observation, they have shown that the neps in the air-jet yarns are less than 6 mm long and are associated with Class II wrapped structure. The number of neps in the yarn
showed an increase with increasing incidence of Class \textsuperscript{11} wrapped structure. An increase in the frequency and length of Class 1 structure is shown to improve yarn evenness and decrease yarn imperfections.

Chasmawala et al.\textsuperscript{[3]} have shown that the yarn tenacity decreases as the number of core fibers increase. They theorize that this could be because of the decrease in the number of wrapper fibers. The authors have also postulated that there is an optimum wrapper fiber content that provides enough transverse forces to overcome frictional slip of the core. An increase in the number of wrapper fibers after the elimination of frictional slip would be detrimental to the yarn breaking load because this implies fewer core fibers to support the applied load.

Chasmawala et al.\textsuperscript{[3]} have further shown that the yarn hairiness depends on the number of core and wild fibers. As the number of core fibers increases, the proportion of the protruding fibers is reduced, resulting in lower yarn hairiness.

Xie et al.\textsuperscript{[29]} analyzed the tensile behavior of wrap-spun yarns by their structure and by the properties of both the parallel-fiber core and the filament binder yarn. A general model of wrap-spun yarns is proposed, which, with appropriate assumptions, can be used to predict the relationship between yarn strength and structural parameters. Pillay et al.\textsuperscript{[26]} have researched the fiber configuration and migration in the open-end yarns. They concluded that fiber length and fiber fineness have a direct influence on yarn strength, yarn unevenness and yarn hairiness. There exists an optimum fiber length corresponding to yarn quality.

2.5 Microdenier fibers

Microfibers or microdenier fibers are the thinnest, finest of man-made fibers. The US and European standards for classifying fibers as micro denier are that they must be less than one denier per filament. The Japanese, who first brought out the microdenier fibers, define them as even finer (0.5 denier per filament or less). Almost all the microdenier fibers in the US market now are polyester fibers and this is expected to be the case for a
while [3]. Some of the advantages of these superfine fibers are: 1. They are flexible, soft, smooth and easy to twist; 2. They offer a large surface area per unit weight; 3. They have good blending affinity with other materials.

The main advantage of the microdenier fiber especially with respect to air-jet spinning is its superior feel. The hand of the fabric made from micodenier fibers, especially if the fabric is brushed, has received very high marks from consumers and is the primary reason for its success in the market. Microdenier fiber fabrics have other important characteristics, which other softer hand fabrics made from regular polyester fibers do not have namely, good resistance to wrinkling and soiling, and superior wash-wear performance [3].

The Blending rigidity of a fiber is given by the equation:

\[
Rigidity = EI = (\pi Ed^4) / 64
\]

Where E is the tensile modulus, d is the fiber diameter and I is the moment of inertia. Thus, the bending rigidity is directly proportional to the fourth power of the fiber diameter (and hence the square of fiber denier). Thus, by reducing the denier of the fiber from 1.2 for a typical conventional staple fiber to 0.6 for a microdenier fiber reduces the bending rigidity by a factor of 4. Also the surface area of the fiber increases with a decrease in the fiber denier. The increase in surface area has a big positive effect on the pilling of fabrics and in carding of staple fibers. The fiber breaking force reduces as the denier per filament is reduced. The fiber weight also decrease and this reduces the centrifugal forces on the fiber during carding which necessitates a change in the setting and speeds during subsequent processing.
CHAPTER 3
Experiment procedure

3.1 Yarn formation

3.1.1 Development of Card-spinning machine

3.1.1.1 Objective
Specific objectives of the project are:

1. To analyze and regulate fiber transport to the spinning heads to achieve better spinning reliability and product uniformity.
2. To characterize the structure of yarns from this spinning system and investigate the yarn performance characteristics.
3. To study the limiting factors affecting the operating range (e.g., yarn count range, types of raw material, etc.) and to develop solutions to overcome such barriers.

3.1.1.2 Statement of the problem

The main challenges associated with the idea of using card web directly for the yarn spinning are three fold.

a) Non-Uniformity of the card web

In a conventional carding system, the transverse direction card web uniformity is not considered very critical since the formation of sliver results in averaging of varying cross machine mass density. Also the processes of successive drafting and doubling further reduce the variability in the linear density of the sliver or roving, which are the ultimate inputs to the spinning machines. But in the Card-Spinning system web variability in both machine and cross-machine directions is critical. While the former induces variations within yarn, the latter introduces variability between different yarns or also within yarn if the variations in the cross directions
tend to shift. Thus it is very important to characterize the nature of web uniformity, for example as periodic or random, depending on which corrective measures can be implemented.

b) Splitting the card web into ribbons of uniform width

A typical card web mass density ranges between 8-15 g/m². The ribbon width required for a 59 tex (10 Ne) yarn is calculated to be less than a centimeter, provided no drafts are introduced in the system. Dividing such a delicate fiber web into small widths without unacceptable variations is a challenge. Not only this, narrow ribbons imply larger number of ribbons and therefore more spinning heads. Accommodating a large number of spinning heads in front of a card is again a challenge and will require a carefully designed arrangement of spinning heads.

c) High speed spinning technology

To obtain maximum productivity it is imperative to run the card at its highest speed. This means that a spinning technology, capable of spinning yarns at very high speeds, is required. The space requirement in front of the card for accommodating large number of spinning heads followed by corresponding winding units is also an important consideration. Moreover all this is required without hindering the access to the web. Thus a suitable candidate for the spinning technology should be small, capable of spinning at high speeds and be simple in design.

3.1.1.3 Problem solving approaches

The basic approach is to divide the web into narrow strips and feed each strip to a separate spinning unit, thereby reducing the processing line to two major steps:

- Opening/cleaning, and
- Yarn formation
Eliminating post carding steps can be expected to yield a more non-uniform yarn; perhaps less expensive yarn for some industrial purposes.

In order to implement this basic idea, the various problems stated above have been addressed using the following approaches:

- **Online card web monitoring and image analysis** [12]: Card-Spinning system employs an online web monitoring system, which scans the web online and analyzes it for web uniformity. This analysis can be used to characterize the web non-uniformity, e.g. a periodic non-uniformity may suggest wearing of some mechanical part in the machine. Along with a long-term solution it can also provide short-term solution by signaling the web dividing system to vary the ribbon widths according to varying web mass density. This system will also help in characterizing the amount of variability introduced by the spinning process, using image analysis algorithms that operate on web images to predict yarn non-uniformity.

- **Dividing card web into ribbons of uniform linear density**: A set of very fine air jet nozzles are employed to divide the web. The Jet Web Divider consists of a pair of very fine nozzles blasting compressed air against a moving cylinder. Using multiple jets on the same principle would create more ribbons that could be used to spin more than one yarn simultaneously with separate spinning units.

- **High-speed spinning technology**: The two good candidates for a fast spinning process are rotor spinning and air jet spinning. However the fact that the process requires several spinning heads directly in front of the card puts physical constraints on the size of the spinning system. Since rotor spinning requires a number of driving mechanisms and motors, the process is more complicated as compared to the air jet spinning. Given the speeds of new state-of-the-art carding machines, air jet spinning at very high speeds seems to be the best candidate. Therefore, air-jet spinning is selected for the Card-Spinning system.
3.1.1.4 Web dividing

Methods of web dividing

**Use of Belt Splitter**: (Designed by James Brazell, patent applied for)\(^{(11)}\)

A web splitter was designed based on the principles involving positive control of the web sections during division via belts that squeeze the web, and shear the web longitudinally in a short distance due to differential speeds (Figure 3.1). Initially the belts were divided into two groups with slower speeds and faster speeds, each set driven by a distinct servo motor with digital control. Timing pulleys and belts were used to avoid the influence of the faster moving pulleys on the slower pulleys.

![Shearing-Belt web dividing system](image)

*Figure 3.1 Shearing-Belt web dividing system*
Advantages

The main advantage of the system was its positive control on the web while dividing it, thereby maintaining uniform width.

Disadvantages/Limitations

- Bulky system: This system was bulky, and also made the card web much less accessible to the operator.
- It had many moving parts including a motor and a controller.
- There was no flexibility of changing the splitting widths as the width depends on the width of the belts, which were not easy to replace very frequently. Thus no option of varying ribbon widths dynamically was available.
- Since the system worked on the principle of shearing via differential speeds, it necessarily required spinning at least at two different speeds.
- It was difficult to compensate for web mass density while dividing the web since the ribbon width could not be changed.

Use of Air-knife:

To implement a simpler and less bulky system, an air knife was used. An air knife is a misnomer in the sense that it cannot be used alone to cut/divide the web. Instead it facilitates the web movement on a smooth aluminum plate surface using air to guide the web. The actual dividing device consisted of two high-pressure air jets which blasted the air on the web against the aluminum plate to divide it, Figure 3.2. The divided web was taken up by another set of take-up rollers and fed to the jet nozzle thereafter. The excess web was vacuumed from the sides and collected as waste.

![Figure 3.2 Air-knife splitter](image_url)
The main advantage of the system was that it was less bulky and very simple without any moving parts. It provided an easy access to the card web. Also since the spacing between the dividing jets could be changed, it offered the flexibility of changing the ribbon widths to spin different counts.

Disadvantages/Limitations
The Air-knife system was highly unstable. This was mainly because the air from the splitting jets reflected from the base surface, and could not get released freely due to a pair of take-up rollers at the other end. This forced the air to rise up above the rollers, taking the web along. The settings were very critical and posed serious doubts on practical implementations.

Use of Air Jet nozzles
The third attempt was made using air jet nozzles but without the Air-knife. This time a moving curved surface was used to support the web while splitting. In this system the web was positively gripped between the two rollers just after splitting. Also, the moving surface helped the air move forward rather than letting it rise straight up after reflecting from the surface. This resulted in a cleaner split. Not only this, it solved many other problems faced by other systems.

Advantages
- This system is much simpler and more versatile in functionality. It can divide web at various speeds, for various widths and it requires very small space to mount the splitting nozzles.
- Variable strip widths can be achieved, for spinning different yarn count simultaneously with almost no restrictions on number of counts at a time.
- Irrespective of different widths, all strips exit at the same speed, therefore the spinning speeds remain constant and no extra attention is required to setup the system again.
3.1.2 Yarn formation steps

As shown in the Figures 3.3, 3.4 and 3.5, splitters are placed on the curved surface of the first splitter roller, and a top roller resting on the two bottom rollers positively grips the web. The camera for online scanning has been installed right before the splitting section.

Figure 3.3 Schematic (Top View)

Figure 3.4 Schematic (Side view)
3.1.2.1 Pressure requirements

The splitter nozzle air pressure affects the splitting quality. Too high a pressure disturbs the web and it tends to fly away with the excess air. Too low a pressure does not split the web very cleanly and a lot of bridging fibers are seen. Various pressures were tried, and it was found that pressures about 200 kPa were the optimum. However the optimal pressure tends to vary when the nozzle position and direction are changed, either intentionally or unintentionally.

3.1.2.2 Practical problems faced

Splitting surface

The roughness of the splitting surface on the steel roller is very critical from the point of view of bridging fibers. Excessive friction results in a large amount of bridging fibers, which in turn results in ribbon breakages. Surface with almost no friction does not provide enough force to hold the web and thus the web sags between the card and the rollers due to its own weight. However using a top roller has solved the second
problem, but the first still exists.

- Bridging fibers and breakages
  Bridging fibers refer to the fibers protruding from the edge of the split ribbon. No matter how steady the process is, bridging fibers are bound to appear. This happens because the fibers in the web are not perfectly straight. Due to their crimp, they have a strong cohesion, and thus even a high-speed air jet cannot separate them, keeping them perfectly parallel. This results in bridging fibers at the edges. These bridging cause various problems. Firstly, since they are not parallel, they reduce the effective fiber length in the yarn, thereby deteriorating the yarn quality. Secondly, these fibers can still contact the excess web after the split and due to pressure of the top roller they get entangled and cause interference in the free movement of the ribbon. At some weak points the ribbon may not sustain its integrity, leading to strand breakage and reduced system efficiency.

- Limitations on using multiple nozzles
  Using multiple nozzles would require a carefully designed arrangement to ensure that all of the nozzles work well together without significant interference.

3.1.2.3 Synchronization of the Card Spinning System

Web take-up assembly
The web take-up assembly consists of two rollers, at the same level and running at the same speeds, with a top roller between the two rollers (Figure 3.6). The first roller is rubber coated to facilitate better gripping of the fiber web, and to provide a sufficiently smooth surface for the splitting to take place. The other roller is a metal roller with some surface roughness required to pull the web by frictional force. It also helps in removal of the unused web by holding on to it. The top roller is a PVC pipe, put on the web to help the splitting action, by positively gripping the web from the front end while air jet is splitting it. It also prevents the web from flying away due to the air currents being created.
in the region. The speed of this assembly is regulated using a separate DC motor controller. Fine adjustments are made to prevent the web from sagging too much or being broken due to excessive draft. In addition, this assembly needs to be synchronized with the card speed like other motors being used in the setup. The splitter nozzles are so oriented on the web that the air jets hit on the curved surface of the rollers. The moving curved surface of the roller does not directly reflect the air back, instead the air escapes easily from the gap between the two rollers below the web, leaving the ribbons undisturbed.

Since most of the web remains unused during the experiments, the extra amount of web needs to be removed continuously from the experimental area, to keep the area clean. To achieve this, a suction system has been implemented using a suction fan (Figure 3.6). The excess web is guided below the experimental table right after the splitter rolls, and fed to a pipe connected to the suction fan. The suction is sufficient to pull the excess web, without causing a break. Another pipe takes the vacuumed fiber to a distant location, where the fiber is collected as a waste. Thus, the system does not allow the excess web to interfere with the test setup while experimentation.

Figure 3.6 Excess web removal system
PID controller and synchronization

A PID controller is being used to synchronize the whole assembly. All the motors in the test setup except for the one used for web take-up assembly, were synchronized to the speed of the card (Figure 3.6). The carding machine was treated as the “Master”, while all other motors were setup as “Slave”. The speed of each motor can be specified individually as ratios of the card speed. The controller consists of a magnetic pickup, 2 M-Trim Contrex controllers, and 2 Ring Kits to provide feedback control capability to the system. One of the M-Trim controls the speed of the winder and the second pair of take up rollers, whereas the second one controls the first pair of take-up rollers which are located right before the spinning head and after the splitting zone.

Since the differential speeds in the system will lead to undesired drafts, it is very essential to control the speeds positively. Even a slight fluctuation in power supply may cause different speeds, resulting in the instability of the process. Therefore, a feedback system has been implemented to prevent such instabilities. In this setup the Carding machine is the most suitable candidate to run in the Master mode because it cannot be controlled from outside, and it being the source of fiber mass for the spinning, determines the process speeds. Thus a change in the carding speed automatically adjusts the process speeds and the process remains stable and synchronized.

The circuit diagram of the controller is provided in Appendix A and the circuit diagram of the motor drive in Appendix B.

Control Panel (for rollers’ speed)

The control panel is show in Figure 3.7:

The circuit diagram of the control panel is shown in Appendix C.

Function of “Power” switch: start/stop the relevant motors;

Function of “R-Start/Stop: turn on/off the relevant controller.

Function of “Manual Speed”: adjust the motor speed when the controller status is on Manual.

Function of “Manual/Auto”: change the controller status between manual and automatic running.
3.2 Fiber and Process Parameters

3.2.1 Fiber for yarn samples

Two different kinds of polyester staple fibers are used for making yarn samples. Type 1: Polyester fiber (1.5 denier, 1.66 dtex; Length: 1.50 inch, 38.1mm). Type 2: Polyester fiber (1.0 denier, 1.1 dtex; length: 1.25 inch, 32 mm). To achieve the same number of fibers per unit area, the draft ratio of the card should be different with Type 1 and Type 2. The weight of fiber class 1 should be about 30% lighter than that of fiber Type 2.

The web density of Type 1 fiber: 9.98 ± 0.2 g/m²
The web density of Type 2 fiber: 7.02 ± 0.3 g/m²
3.2.2 Nozzle pressure combination

By using different front and back nozzle pressure ($N_1$ & $N_2$) combinations, 25 yarn samples were made for each fiber type. The nozzle pressure combination table is shown in Table 3.1 and Figure 3.8.

Table 3.1 Nozzle pressure combination: ($N_1$: front nozzle, $N_2$: back nozzle)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$N_1$</th>
<th>$N_2$</th>
<th>Sample No.</th>
<th>$N_1$</th>
<th>$N_2$</th>
<th>Sample No.</th>
<th>$N_1$</th>
<th>$N_2$</th>
<th>Sample No.</th>
<th>$N_1$</th>
<th>$N_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>6</td>
<td>50</td>
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<td>50</td>
<td>45</td>
<td>21</td>
<td>50</td>
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<td>25</td>
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<td>30</td>
<td>45</td>
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<tr>
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<td>30</td>
<td>50</td>
<td>15</td>
<td>60</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

Unit: psi (1 psi = 6.9 kPa)
Figure 3.8 Pressure setting combinations for $N_1$ and $N_2$
3.3 Evaluation of Yarn Quality

3.3.1 Yarn count (Linear density):

The yarn count indicates the length of yarn in relation to the weight. Each yarn sample was measured from a test of 10 specimens.

\[
N_{\text{tex}} = \frac{G}{L} \times 1000 \\
N_{\text{ne}} = \frac{L}{G} \\
N_{\text{e}} = \frac{L'}{(840 \times G')}
\]

\(N_{\text{tex}}\): yarn count, \(N_{\text{ne}}\): English count; \(N_{\text{e}}\): Metric count  
\(G\): yarn weight (gram); \(L\): yarn length (meter); 
\(L'\): yarn length (yard); \(G'\): yarn weight (pound).

For the determination of the count of yarn, it is necessary to determine the mass of a known length of the yarn. In every test, 1.00 meter length of yarn was weighed. The balance resolution is 0.00001g.

3.3.2 Yarn strength and elongation:

Breaking strength, elongation, elastic modulus, and resistance to abrasion are some important factors that will determine the performance of the yarn during use or further processing.

Tensile strength of the yarn is one of the most important characteristics. Tensile strength is the highest unit tensile stress that a material can sustain before failure. The tensile strength is affected by many factors.
The yarn breaking mechanism is assumed to be as follows:
Either all wrapper fibers break simultaneously leading to catastrophic yarn failure, or
there is partial slippage and partial breakage of the fiber.

Consequently, the yarn strength has three components:
1. the wrapping fiber strength: the strength of the yarn decided through the
   restriction of the wrapper fibers;
2. the strength of the portion of the core fibers that actually break;
3. the strength of the portion of the core that offer frictional resistance to yarn
deformation.

Using an INSTRON machine to test tensile strength of the yarns, each sample is
tested 15 times.
Gauge length is fixed at 10 cm.
Sample: single yarn;
Testing speed is 2 cm/min;
Break time is 21±5 seconds (ASTM standard)
The test result is the maxima load of the yarn (N).

After testing, the results are converted to specific strength.

\[ P_0 \ (N/tex) = \frac{P(N)}{N_{tex}} \]
\[ P_0 \ (gf/den) = \frac{P(gf)}{N_{den}} \]

\( P_0 \): Specific Strength (N/tex, gf/denier); \( P \): Max load (N, cN, gf);
\( N_{tex}, N_{den} \): yarn count

Also, the elongation at break and break strain can be found from test.

An important factor, which will affect the test result, is the length of the specimen
actually used for carrying out the test. The strength of a test specimen is limited by
the weakest link in it. If the test specimen is longer, it is likely to contain more weak spot, than a shorter test specimen. Hence the test results will be different for different test lengths due to the weak spots. The gauge length of test is fixed at 10 cm for all samples.

3.3.3 Image processing of yarns

Image processing was used to measure the yarn diameter and the variance of the diameter.

Equipment: Olympus Camera Assembly 20X Lens;
Software: LEICA Qwin V2.3;
Calibration: 1 Pixel= 0.0173mm;
Number of specimens tested for each sample: 5;
Number of diameter measurements per specimen: 100.

3.3.4 Evenness test

There are a number of testers, of which the Uster Evenness Tester is the most widely used. A strand of textile material is passed at a constant speed between the two parallel plates of a capacitor. As the strand varies in linear density and displaces the air normally present, this produces a variation in capacitance that is related to the mass of textile material between the plates. This capacitor is included in circuits that transform the capacity variations into variations in electric current. This varying current can be used to operate a pen recorder that plots a record of the unevenness on a paper chart. It can also be fed into computers that calculate and display statistics characterizing the unevenness.

It is advisable that the strand to be tested should have uniform moisture regain throughout its length, and among all test specimens. It is therefore necessary that the atmospheric conditions in which the strand is stored should be stable for some time
immediately before testing. The packages should be conditioned in this way for 24 hours. [17]

Evenness test is used for testing the uniformity of the yarn. The mass per unit length variation due to variation in fiber assembly is generally known as “irregularity” or “unevenness”. There is a numerical value, which represents the mass variation. The mathematical statistics offer two methods:

1. the irregularity U%: It is the percentage mass deviation of unit length of material and is caused by uneven fiber distribution along the length of the strand;
2. the coefficient of variation CV%.

In handling large quantities of data statistically, the coefficient of variation (CV%) is commonly used to define variability and is thus well-suited for expressing yarn evenness. It is currently the most widely accepted way of quantifying irregularity. It is given by:

\[
\text{Coefficient variation (CV\%) = (Standard deviation/average)\times 100}
\]

The irregularity U% is proportional to the intensity of the mass variations around the mean value. The U% is independent of the evaluation time or tested material length with homogeneously distributed mass variation. The larger deviations from the mean value are much more intensively taken into consideration in the calculation of the coefficient of variation CV (squaring of the term). CV % has received more recognition in the modern statistics than the irregularity U. It can be considered that if the fiber assembly required to be tested is normally distributed with respected to its mass variation, a conversion possibility is available between the two types of calculation.

\[
\text{CV\% = 1.25\times U\%}
\]
Equipment: Uster Tester 3;
Number of runs per sample: 3;
Test speed: 22.9 m/min;
Test time: 3 min;
Measuring slot: 2 (coarse yarn).

Because some yarn samples were not long enough for continuous testing, it was necessary to piece together several segments of yarn for each run on the testers.
Chapter 4
Result and Discussion

4.1 Effect of front and back nozzle pressures on the structure of air-jet spun yarn

4.1.1 Summary of previous work \[^{[11]}\]

Spinning conditions change the structure of yarn very significantly; this changes the appearance, hand and performance of the final fabric. A study by Tyagi et al \[^{[9]}\] shows that the yarn properties steadily improve in all aspects with the decrease in yarn linear density, and all properties except the elastic recovery, are more sensitive to first nozzle pressure. The results show a significant increase in tenacity, breaking extension, rigidity and abrasion resistance with the increase in nozzle pressure from 200 kPa to 300 kPa. This increase is explained by the increase in incidence of the surface wrapping fibers and the wrapping length. An increase in spinning speed shows further improvement in tensile properties and the abrasion resistance, but affects the rigidity adversely. But increasing the nozzle pressure increases the yarn unevenness owing to concentration of mass in very short lengths due to greater incidence of wrapper fibers. The variation in the first nozzle pressure and spinning speeds is not reported to offer any advantage for the elastic recovery of the MJS yarn. However increasing the gap between the first nozzle and the nip of the front roller increases the elastic recovery proportionally.
As shown schematically in Figure 4.1, increasing the spinning speeds created more uniform structure as the wrapping is done over a longer length of the yarn. Decreasing the speed results alternate bulky and constricted regions because of non-uniform wrapping in yarns. However at higher speed, the yarn hairiness increases \cite{1}.

As discussed previously, increasing the N\textsubscript{1} nozzle pressure increases the number of wrapper fibers thereby improving the yarn tensile properties. (Figure 4.2)

![Figure 4.1 Effect of spinning speeds on yarn structure](image)

(a) High speed  (b) Low speed

![Figure 4.2 Effect of N\textsubscript{1} air pressure on yarn structure](image)

(a) High pressure  (b) Low pressure

35
Feed ratio represents the draft of the air-jet twisting zone, equal to the ratio of exit roll speed to the feed roller speed. Feed ratio changes the yarn appearance, as at lower feed ratio yarn gets uneven wrapping. At a higher feed ratio, yarns look more uniform, closer to ring yarn. Because at higher feed ratio the core fibers are pulled straight while being wrapped, the yarn spun at lower feed ratio shows constricted and bulky regions at regular interval as the core fibers being loose bulge out wherever they are not properly wrapped (Figure 4.5).

![Figure 4.3 Effect of feed ratio on yarn structure](image)

Figure 4.3 Effect of feed ratio on yarn structure
(a) High feed ratio (b) Low feed ratio

High front roller pressure grips the fibers positively up to the last point, there by creating tension in the fibers. As soon as those fibers are released they spring back and thus get detached from the main body of the strand under high air current. This results in more number of wrapper fibers but also in a more hairy yarn (Figure 4.4).

![Figure 4.4 Effect of front roller pressure on yarn structure](image)

Figure 4.4 Effect of front roller pressure on yarn structure
(a) High pressure (b) Low pressure
4.1.2 Effects of the front and back nozzle pressures on the appearance of the air-jet spun yarn

In this experiment, Image analysis is used to analyze the geometric feature of the yarn. The system includes Olympus Camera Assembly, 20x Lens, and LECIA Qwin V2.3 system software. The calibration of the image figure is set to be 1 Pixel=0.0173mm.

Lawrence and Baqui [2] have used SEM to identify the different structure of air-jet spun yarns from Murata air-jet spinning system. They classified the yarn structure into 3 basic classes.

- Class I: A twistless core, which at times is crimped, but wrapped uniformly by a thin fiber ribbon with a uniform helix angle and direction. (Figure 2.2)
- Class II: A twistless core randomly wrapped by fibers, in the singular state and in groups, showing Z and S directions of wrap with differing helix angles. (Figure 2.3)
- Class III: Unwrapped sections of yarn core, at times having residual twist. (Figure 2.4)

The Class I structure is formed by uniform fiber bundle and appropriate nozzle pressure.

The Class II structure is formed by a more bulky fiber bundle, which hinders the surface fiber from rotating around the core fibers, causing disorderly and random wrapping. The Class III structure is like that produced with low nozzle pressure, which prevents the surface fibers from wrapping the core fiber tightly.

By using this classification method, we can detect the different classes in the yarn image. Two examples are provided to show how the yarns from Card-Spinning system are classified.
a: Polyester 1 (1.5 denier, 38.1 mm in length) N1=30 Psi, N2=45 Psi

Figure 4.5 Yarn structure classification

From Figure 4.5, we can find that in the first sample, Class I, II, and III are one third of the sample length each. In sample 2, Class I is one third of the sample length and Class III is two third of the sample length.

Figures 4.6 and 4.7 show the appearance of yarn from card-spinning system. Each yarn was imaged 5 times in different sections. After analyzing the image sections by using the yarn structure classification method (by Lawrence and Baqui [25]), the percentages of Classes I, II, and III of each sample are obtained. The results are shown in Table 4.1.
<table>
<thead>
<tr>
<th>Type 1: Polyester fiber (1.5 diameter; Length = 38.1 mm)</th>
<th>55 psi</th>
<th>45 psi</th>
<th>35 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>30 psi</td>
<td>40 psi</td>
<td>50 psi</td>
</tr>
</tbody>
</table>

Figure 4.6 Appearance of Type 1 yarn
### Type 2. Polyester fiber 2 (1.0 denier; Length ~32 mm)

<table>
<thead>
<tr>
<th>$N_2$</th>
<th>$N_1$</th>
<th>35 Psi</th>
<th>45 Psi</th>
<th>55 Psi</th>
</tr>
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<tbody>
<tr>
<td>30 Psi</td>
<td></td>
<td><img src="image1.jpg" alt="Image" /></td>
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<tr>
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<tr>
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<td><img src="image7.jpg" alt="Image" /></td>
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<tr>
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*Figure 4.7 Appearance of Type 2 yarns*
<table>
<thead>
<tr>
<th>$N_1$</th>
<th>$N_2$</th>
<th>25 Psi</th>
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<th>45 Psi</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Class I (%)</td>
<td>Class II (%)</td>
<td>Class III (%)</td>
<td>Class I (%)</td>
</tr>
<tr>
<td>30 Psi</td>
<td></td>
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<td>80</td>
<td>10</td>
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<tr>
<td>40 Psi</td>
<td></td>
<td>35</td>
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<td>55</td>
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<td>50 Psi</td>
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<tr>
<td>$N_1$</td>
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<td>45 Psi</td>
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<td></td>
<td>Class I (%)</td>
<td>Class II (%)</td>
<td>Class III (%)</td>
<td>Class I (%)</td>
<td>Class II (%)</td>
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</table>
From Table 4.1 we can find that when $N_2$ is fixed and $N_1$ varies, the portion of Class III section the yarn will evidently decrease in the range for $N_1$ from 30 to 60 psi. And the portion of Classes I and II will increase accordingly. This relation is shown in both types of yarns.

Under the same process condition ($N_1$, $N_2$), the portion of Class II (disorderly/random wrapped) section in polyester 2 yarns is more than that in polyester 1 fiber yarns. The reason can be trace to the fiber length. Polyester 2 (1.0 denier; 32 mm in length) fiber is shorter than polyester 1 (1.5 denier; 38.1 mm in length). The shorter fiber is more difficult to be bended than longer fibers. So the shorter fibers tend to form disorderly wrapped section during process.
4.1.3 Effect of the font and back nozzle pressures on the diameter variation of the air-jet spun yarns

In this experiment, yarn image was taken with a 20X lens. One pixel corresponds 0.0173 mm in length. A typical 1-cm yarn section was first imaged and for each image, the yarn widths (diameter) were determined automatically at 100 equally spaced sections using the LEICA Qwin V2.3 software. The figure below shows a 1-mm section that was divided into 10 equally spaced sections. The diameter of the yarn is the distance between two vertical dots on the same line.

![Yarn image in 20X Lens](image)

The variation of the diameter in yarns is different for each sample. The reasons for diameter variation are obvious. They can be traced to the web and equipment. Variation of the diameter is an indication of the uniformity of the yarn’s appearance. When the other conditions, such as spinning speed, fiber type, uniformity of strand fed to the nozzle are fixed, the variance of the yarn diameter could be attributed to the font and the back nozzle pressures.

During the spinning process, the back nozzle creates a false twist, and the front nozzle makes the surface fibers to wrap around the core fibers. When the air pressure of the font and back nozzles is changed, the force that makes the yarn rotate will change, and the wrapping effect will change. The wrapped fiber is the main feature of the structure of the yarn. We can see how yarn is affected by the wrapped fibers form Figure 4.9.
In this experiment, each yarn sample was measured 5 times. In each test, the Qwin software can help us calculate the diameter of the yarn in every section, the mean diameter, and the value of the variance. The results are shown in Tables 4.2 and 4.3.
Table 4.2 Diameter of class 1 yarns
Type 1. Fiber fineness =1.5 denier; Length =38.1 mm
Table 4.1

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Average Diameter (mm)</th>
<th>Standard Dev.</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.278</td>
<td>0.283</td>
<td>0.221</td>
</tr>
<tr>
<td>2</td>
<td>0.754</td>
<td>0.174</td>
<td>0.230</td>
</tr>
<tr>
<td>3</td>
<td>0.955</td>
<td>0.146</td>
<td>0.153</td>
</tr>
<tr>
<td>4</td>
<td>0.938</td>
<td>0.179</td>
<td>0.191</td>
</tr>
<tr>
<td>5</td>
<td>1.001</td>
<td>0.167</td>
<td>0.167</td>
</tr>
<tr>
<td>6</td>
<td>0.945</td>
<td>0.154</td>
<td>0.163</td>
</tr>
<tr>
<td>7</td>
<td>0.865</td>
<td>0.165</td>
<td>0.190</td>
</tr>
<tr>
<td>8</td>
<td>0.757</td>
<td>0.107</td>
<td>0.141</td>
</tr>
<tr>
<td>9</td>
<td>0.963</td>
<td>0.165</td>
<td>0.172</td>
</tr>
<tr>
<td>10</td>
<td>1.046</td>
<td>0.176</td>
<td>0.169</td>
</tr>
<tr>
<td>11</td>
<td>1.371</td>
<td>0.283</td>
<td>0.207</td>
</tr>
<tr>
<td>12</td>
<td>0.950</td>
<td>0.138</td>
<td>0.146</td>
</tr>
<tr>
<td>13</td>
<td>1.210</td>
<td>0.196</td>
<td>0.162</td>
</tr>
<tr>
<td>14</td>
<td>1.210</td>
<td>0.143</td>
<td>0.144</td>
</tr>
<tr>
<td>15</td>
<td>1.041</td>
<td>0.153</td>
<td>0.147</td>
</tr>
<tr>
<td>16</td>
<td>1.158</td>
<td>0.212</td>
<td>0.183</td>
</tr>
<tr>
<td>17</td>
<td>0.598</td>
<td>0.110</td>
<td>0.184</td>
</tr>
<tr>
<td>18</td>
<td>0.887</td>
<td>0.141</td>
<td>0.159</td>
</tr>
<tr>
<td>19</td>
<td>0.801</td>
<td>0.143</td>
<td>0.179</td>
</tr>
<tr>
<td>20</td>
<td>0.961</td>
<td>0.154</td>
<td>0.160</td>
</tr>
<tr>
<td>21</td>
<td>0.941</td>
<td>0.194</td>
<td>0.206</td>
</tr>
<tr>
<td>22</td>
<td>0.798</td>
<td>0.125</td>
<td>0.128</td>
</tr>
<tr>
<td>23</td>
<td>1.290</td>
<td>0.245</td>
<td>0.214</td>
</tr>
<tr>
<td>24</td>
<td>0.940</td>
<td>0.207</td>
<td>0.220</td>
</tr>
<tr>
<td>25</td>
<td>0.868</td>
<td>0.169</td>
<td>0.195</td>
</tr>
<tr>
<td>Average</td>
<td>0.981</td>
<td>0.173</td>
<td>0.177</td>
</tr>
</tbody>
</table>

*: Average number from three sections, each measured at 100 locations.
Table 4.3 Diameter of class 2 yarns

Type 2. Fiber fineness =1.0 denier; Length =32 mm

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Average Diameter (mm)</th>
<th>Standard Dev.</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.803</td>
<td>0.212</td>
<td>0.264</td>
</tr>
<tr>
<td>2</td>
<td>0.850</td>
<td>0.174</td>
<td>0.204</td>
</tr>
<tr>
<td>3</td>
<td>0.846</td>
<td>0.146</td>
<td>0.172</td>
</tr>
<tr>
<td>4</td>
<td>0.847</td>
<td>0.179</td>
<td>0.212</td>
</tr>
<tr>
<td>5</td>
<td>0.819</td>
<td>0.167</td>
<td>0.204</td>
</tr>
<tr>
<td>6</td>
<td>0.949</td>
<td>0.162</td>
<td>0.171</td>
</tr>
<tr>
<td>7</td>
<td>0.985</td>
<td>0.165</td>
<td>0.167</td>
</tr>
<tr>
<td>8</td>
<td>0.797</td>
<td>0.107</td>
<td>0.134</td>
</tr>
<tr>
<td>9</td>
<td>0.740</td>
<td>0.165</td>
<td>0.223</td>
</tr>
<tr>
<td>10</td>
<td>1.073</td>
<td>0.176</td>
<td>0.164</td>
</tr>
<tr>
<td>11</td>
<td>0.839</td>
<td>0.283</td>
<td>0.338</td>
</tr>
<tr>
<td>12</td>
<td>0.996</td>
<td>0.138</td>
<td>0.139</td>
</tr>
<tr>
<td>13</td>
<td>0.874</td>
<td>0.196</td>
<td>0.224</td>
</tr>
<tr>
<td>14</td>
<td>1.000</td>
<td>0.143</td>
<td>0.143</td>
</tr>
<tr>
<td>15</td>
<td>0.788</td>
<td>0.153</td>
<td>0.194</td>
</tr>
<tr>
<td>16</td>
<td>0.892</td>
<td>0.221</td>
<td>0.247</td>
</tr>
<tr>
<td>17</td>
<td>0.723</td>
<td>0.110</td>
<td>0.152</td>
</tr>
<tr>
<td>18</td>
<td>1.054</td>
<td>0.141</td>
<td>0.134</td>
</tr>
<tr>
<td>19</td>
<td>0.879</td>
<td>0.143</td>
<td>0.173</td>
</tr>
<tr>
<td>20</td>
<td>0.853</td>
<td>0.154</td>
<td>0.181</td>
</tr>
<tr>
<td>21</td>
<td>0.812</td>
<td>0.194</td>
<td>0.239</td>
</tr>
<tr>
<td>22</td>
<td>1.089</td>
<td>0.095</td>
<td>0.087</td>
</tr>
<tr>
<td>23</td>
<td>0.870</td>
<td>0.245</td>
<td>0.282</td>
</tr>
<tr>
<td>24</td>
<td>0.808</td>
<td>0.207</td>
<td>0.256</td>
</tr>
<tr>
<td>25</td>
<td>1.099</td>
<td>0.169</td>
<td>0.155</td>
</tr>
<tr>
<td>Average</td>
<td>0.889</td>
<td>0.166</td>
<td>0.194</td>
</tr>
</tbody>
</table>
From Tables 4.2 and 4.3, we notice that the average diameter of all 25 samples of Type 2 is smaller than that of Type 1. This tendency can also be found in the average standard deviation of Type 1 and Type 2 samples. Type 1 samples are made by 1.5 denier fibers, and Type 2 samples are made by 1.0 denier fibers. In the spinning process, the average number of fiber per unit web area is almost equal, and therefore the number of fibers in the cross section of Type 2 yarn should be equal to that of the Type 1 yarn, as the strip width is same. It is obvious that, if the number of fibers in cross section of yarn is equal, the yarn made by the finer fiber (Type 2) should be finer than the yarn made by fiber of Type 1.

Variance is one of several indices of variability that statisticians use to characterize the dispersion among the measures in a given population. To calculate the variance of a given population, it is necessary to first calculate the mean of the scores, then measure the amount that each score deviates from the mean and then square that deviation (by multiplying it by itself). Numerically, the variance equals the average of the squared deviations from the mean.

\[
\sigma^2 = \frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}
\]

\(\sigma^2\): variance; \(\sigma\): standard deviation; \(n\): sample size; \(\mu\): sample mean; \(x_i\): sample value

From an experiment, we can get the standard deviation of the sample. If the standard deviation of the yarn is small, it means that the yarn diameter does not change too much, and the yarn is quite uniform.

The average standard deviation of Type 1 yarn is 0.173 (the variance of Type 1 yarn samples should be 0.0299). And the variance of Type 2 yarn samples is 0.166^2=0.0276. The standard deviation of the Type 2 yarn is slightly less than that of Type 1 yarn.
Figure 4.10 shows typical appearance of the yarns with higher or lower diameter variance. It is obviously that the yarn with lower diameter variance looks much more uniform than the yarn with higher diameter variance. This led us to try to find some relationship between the yarn diameter variance and the process parameters.

In the card-spinning process, the front and back nozzle pressures ($N_1$, $N_2$) affect the yarn diameter variance. Figures 4.11 and 4.12 show the effect of $N_1$ and $N_2$ on yarn diameter variation. Figure 4.11 shows the diameter variation for different back nozzle pressure ($N_2$) at constant $N_1$. Figure 4.12 shows the diameter variation for different front nozzle pressure ($N_1$) at constant $N_2$. 

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Figure 4.11 Yarn diameter variation versus $N_2$
Figure 4.12 Yarn diameter variation versus $N_1$.
From Figures 4.11 and 4.12, we find that when the front nozzle pressure ($N_1$) is constant and the back nozzle pressure ($N_2$) varies, the diameter variance of the yarn shows random changes. But if we keep the back nozzle pressure ($N_2$) constant, when the front nozzle pressure ($N_1$) increases the yarn diameter variance decreases (Figures 4.12).

We can conclude that the front nozzle pressure ($N_1$) has a strong effect on the yarn diameter variance; the back nozzle pressure ($N_2$) has little effect on the yarn diameter variance. And increasing the front nozzle pressure ($N_1$) can increase the yarn uniformity.
4.1.4 Influence of fiber length and fineness on the structure and properties of Card-Spun yarns

Artzt et al.\textsuperscript{[19]} have studied the influence of fiber length and fiber fineness on processing performance and yarn quality. The results relating to the optimum fiber count and fiber length show that with the use of a 1.3 dtex 38mm fiber it is possible to spin a wide range of counts of air-jet spun yarns with optimum results. The staple length of 38 mm is also the optimum when using the finer count of 0.8 dtex fiber. When using the longer fiber (such as 45 mm), the expected increase in yarn strength with longer fiber length mostly turns out to be a decline. So the fiber length plays a main role on the yarn properties.

In section 4.2.1, we report that the Type 1 yarns (1.5 denier, 38.1 mm in length) have higher specific strength than Type 2 yarns (1.0 denier, 32 mm in length) in each process parameter combinations. It may be expected that Type 2 yarns will wrapped more tightly and have much higher specific strength than Type 1 yarns, because the Type 2 fiber is finer and the bend rigidity is lower, which can be twisted easily by air-jet nozzle. However, shorter fiber length leads to a lower specific strength in Type 2 yarns.

From Table 4.1 we can find that the Class II portion in the Card-Spun yarns does not change too much in different nozzle pressure combinations. Type 2 yarns have more Class II portion than Type 1 yarns (Class II portion is defined as disorderly / random wrapped yarn structure). The shorter fiber length results in more Class II portion in the yarn.
4.1.5 Influence of process parameters on the yarn twists

A yarn is twisted when fibers on the surface, which were originally parallel to the axis of the yarn, are now deformed (rotated) so that they make an angle \( \alpha \) with the axis, and the amount of twist is a function of this angle. This definition of twist only applies to the ideal case of an originally straight fiber assembly. However, in actual yarns, variability of yarn diameter, contraction because of twist, migration of fibers from zone to zone, radial compression of the yarn, and fiber slippage are some of the factors that tend to make the yarn geometry depart from the ideal.\(^{(20)}\)

In the card-spun yarns, the yarn twists show different appearance and distribute with different orderliness in different yarn structure classes.
In card-spun yarns, the twist distributes evenly and yarn shows uniform helix angle and direction. The twist angle is 35-40°, and the twist is 8-10 turns/cm. In conventional yarns, the twist angle rarely exceeds 30°. Comparing to typical air-jet yarns, the car-spun yarns have a larger twist angle.

![Yarn twist analysis](image)

The spinning nozzle used is designed to spin yarns at very high speeds, nearing about 80-200 m/min, but the current set-up runs at slower speeds of about 20 m/min, which puts a limitation on the spinning quality. The wrapper fibers do not wrap uniformly over the length. This happens because the slow speed of fiber strand in the nozzle tends to shorten the pitch of the helix formed by the wrapper fibers. This gives a unique yarn structure with a wavy appearance having bulky unwrapped fiber strand, heavily wrapped portions and larger twist angle. Figure 4.15 shows the different appearance of typical air-jet yarns and card-spun yarns.
It has been observed that a finer count yarn is relatively more uniform in its surface appearance and is less hairy (Figure 4.16). Since a crimped polyester fiber was used in this study, having a large amount of fibers inside the nozzle does not let air vortex perform wrapping effectively. Whereas for finer counts, there is plenty of free space for vortex to form and thus a more uniform yarn structure results.

In Section 4.2.1, we will discuss the relationship between yarn specific strength and yarn structure. Obviously, the Class I and II have more twist than Class III, and therefore yarns with more Classes I and II sections are stronger.
4.2 Effect of front and back nozzle pressures on the properties of air-jet spun yarn

4.2.1 Effect of front and back nozzle pressures on the tensile strength of air-jet spun yarn

According to studies on the fracture of air-jet spun yarns \(^{[7][14]}\), the yarn breaking load is dependent upon the following:

1. the number of wrapper, core and wild fibers;
2. the extent of wrapping;
3. the length and frequency of the three structural classes;
4. the evenness and the number of imperfections;

There is some evidence that the number of wrapper fibers increased with an increase in front nozzle pressure, as the present study confirms (Section 4.1). When the front nozzle pressure increases, vibration of the secondary balloon also increases and this causes more fibers to be detached from the main strand, which results in more wrapper fibers. The result of present investigation shows that with the increase in front nozzle pressure, the proportion of Class I structure increases, the proportion of Class II structure also increases, while the Class III structure decreases. The unevenness (CV\%) of the yarn decreases with the increase in the front nozzle pressure \((N_f)\).

Initially, as the front nozzle pressure increases, the number of wrapper fibers and the proportion of Class I structures increase. Also the number of Class III structures decreases. These two factors work together to increase the yarn strength. Moreover, as shown, the CV % and the imperfections also decrease with increasing front nozzle pressure.
It is expected that the front nozzle pressure will affect the yarn breaking load. When the front nozzle pressure \((N_1)\) increases, the yarn breaking load should also increase. The strength not only depends on the maximum load of yarn, but also on the yarn count. Thus specific strength is used in our discussion.

The effect of front and back nozzle pressure on the yarn tensile strength is shown in Figure 4.17.

![Figure 4.17 Yarn specific strength versus \(N_1\)](image)
In Figure 4.17, we keep back nozzle pressure ($N_2$) constant and change the front nozzle pressure ($N_1$). But the yarn specific strength did not display the relation we expected (when the front nozzle pressure ($N_1$) increases the yarn strength will increase for constant back nozzle pressure ($N_2$)). So the previous conclusions by other researchers can not explain the observed relations between yarn strength and air-jet nozzle pressure ($N_1$, $N_2$) for the Card-spinning system.

Using MINITAB software we can analyze the relationship among yarn strength, the front nozzle pressure, the back nozzle pressure and yarn linear density. The results are as follows.

<table>
<thead>
<tr>
<th>Correlations: Yarn Strength V.S. $N_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson correlation of Strength (N/Tex) and $N_1$ = -0.153</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Correlations: Yarn Strength V.S. $N_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson correlation of Strength (N/Tex) and $N_2$ = 0.177</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Correlations: Yarn Strength V.S. $N_{tex}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson correlation of Strength (N/Tex) and $N_{tex}$ = -0.192</td>
</tr>
</tbody>
</table>
The correlation between two variables reflects the degree to which the variables are related. A common measure of correlation is the Pearson Product Moment Correlation (called Pearson's correlation for short). Pearson's correlation reflects the degree of linear relationship between two variables. The value of the pearson correlation coefficient value can be calculated from the following equation. X and Y indicate the two variables, (X1, ..., Xn) and (Y1, ..., Yn).

\[ r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\frac{\sum X^2}{N} - \frac{\left(\sum X\right)^2}{N}\right) \left(\frac{\sum Y^2}{N} - \frac{\left(\sum Y\right)^2}{N}\right)}} \]

X, Y: variables; N: sample size; r: Pearson's correlation coefficient

The value of r ranges from +1 to -1. A correlation of "+1" means that there is a perfect positive linear relationship between variables. The scatter plot shown in Figure 4.14 depicts such a relationship. It is a positive relationship if high scores on the X-axis are associated with high scores on the Y-axis. A correlation of "-1" means that there is a perfect negative linear relationship between two variables. It is a negative relationship when high scores on the X-axis are associated with low scores on the Y-axis. A correlation of "0" means there is no linear relationship.
between the two variables.

Through the correlation analysis, we can find that the correlations of strength, front nozzle pressure \( (N_1) \), back nozzle pressure \( (N_2) \) and linear density of yarns are -0.153, 0.177 and -0.192. The linear relations of \( N_1 \) to strength, \( N_2 \) to strength and yarn linear density to strength are not very high. All absolute values of the correlations are less than 0.5. There is no clear indication that yarn strength will increase or decrease with \( N_1, N_2, \) or \( N_{\text{lin}} \) during the spinning process.

**Regression Analysis:**
During the yarn spinning process for each type of yarn, the spinning speed, draft ratio and fiber type are kept constant. The variable parameters are the front nozzle pressure, back nozzle pressure and yarn linear density. The yarn strength is a dependent variable in the spinning process. We are interested in finding a relationship between yarn strength and the spinning parameters using multivariable analysis.
YarnStrength(N/ tex) = f(N1, N2, N_m)

Because the linear relations of yarn strength vs. N_1, yarn strength vs. N_2, yarn strength vs. N_m, are not very high, we have added several non-linear terms, N_1^2, N_2^2, ln(N_1), ln(N_2), N_1/N_2 and N_2/N_1, to improve the accuracy of the regression.

The regression result shown below is obtained using MINITAB software.

Yarn Strength (N/tex) = -8.0 - 0.250 N_1 + 0.012 N_2 + 6.76 \frac{N_1}{N_2} - 6.68 \frac{N_2}{N_1} + 0.00136 N_1^2 - 0.00059 N_2^2 - 8.21 ln(N_1) + 11.6 ln(N_2) + 0.000063 N_m

Type 1 (1.5 denier, 38.1mm) \ (R^2=0.791)

Yarn Strength (N/tex) = -6.78 + 0.228 N_1 - 0.0915 N_2 - 0.782 \frac{N_1}{N_2} + 0.745 \frac{N_2}{N_1} - 0.00118 N_1^2 + 0.000420 N_2^2 - 3.81 ln(N_1) + 0.83 ln(N_2) + 0.000485 N_m

Type 2 (1.0 denier, 32mm) \ (R^2=0.789)

These two equations show how the front nozzle pressure (N_1), back nozzle pressure (N_2) and yarn linear density (N_m) affect the yarn tensile strength. The R^2 of regression is around 0.8, and the regression is fitting is reasonable.
Figure 4.19 illustrates one example of regression result versus experimental values. The $N_1$ is fixed at 60 Psi, yarn material is Type 2 fiber (1.0 denier, 32 mm in length). The different linear densities are marked beside the experiment values. The reason why the regression line is above all experiment values is that the regression equation is based on all nozzle pressure combinations but this figure only shows the data for $N_1=60$ Psi.

From these two equations, we may calculate the appropriate nozzle pressure for the desired yarn strength and yarn count. Also we may estimate the yarn strength with given nozzle pressure and the yarn count. The yarn count is determined mainly by the web density and ribbon width, and nozzle pressures can be adjusted easily. So the two equations are useful for selecting processing parameters.

We also observed that under the same spinning condition, the yarn specific strength of Type 2 (polyester fiber 2: 1.0 denier; 32mm in length) is lower than that of Type 1 (polyester fiber 1: 1.3 denier; 38.1mm in length). The reason can be traced to the fiber length. The longer fibers can form more twist than shorter fibers.
Note that, however, the regression equations have limitations because they are based on one set of test of test data, and some condition are not take into consideration (For example: environment conditions and machine conditions).

**Structure-Strength relationship:**

According to Lawrence and Baqui [2], Class III portion in the yarn increases, the breaking load of spun yarn decreases. Class III presents weak places in the yarn. In Section 4.1, we classified the 3 different classes of yarn structure. Figure 4.20 shows the relationship of yarn strength and the percentage portion of each class.

![Type 1 (1.5 denier, 38.1 mm in length)](Figure 4.20 (a) Relationship of yarn strength and the percentage portion of each class)

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Figure 4.20(b) Relationship of yarn strength and the percentage portion of each class

Figure 4.20, we see that the Class III portion decreases while Class I portion increases as the yarn strength increases. Class II portion does not change significantly. These results are consistent with the conclusion of Lawrence and Baqui[21].
4.2.2 Effect of front and back nozzle pressures on the break strain of air-jet spun yarn

The breaking elongation of the air-jet spun yarn depends not only on the yarn breaking load and the fiber modulus, but also on the proportion of fibers that slip or break. If all the core fibers in the yarn were to break without slipping, then the breaking elongation of the yarn will depend on the breaking load and the fiber elastic properties. However, in reality some core fibers slip and others break. In our experiments, most of yarns break due to the fiber slippage.

![Graph showing load vs. elongation](image1)

**Figure 4.21** Catastrophic failure

![Graph showing load vs. elongation](image2)

**Figure 4.22** Non-catastrophic failure

66
Catastrophic yarn failure occurs when all fibers at the point of failure break or slip completely at the same load. The load elongation curve of a yarn, which undergoes catastrophic failure, is shown in the Figure 4.21. A yarn is said to have failed non-catastrophically when fibers at the point of failure do not break or completely slip at the same load. When a few fibers fail, the remaining fibers continue to take up the load with different sets of fibers failing at different loads. The load elongation curve for a yarn, which fails non-catastrophically, is shown in Figure 4.22. A special case of non-catastrophic failure is when all fibers at the point of yarn failure slip completely at low loads (Figure 4.23).

Figure 4.24 illustrates conventional yarn failure mechanism:

Figure 4.24 Stress-strain curve for a conventional staple yarn [31]
The mechanism of yarn failure is usually explained in the basis of stress-strain characteristics of yarns. Figure 4.24 reveals the nonlinear mechanical behavior of a yarn with linearity restricted for low stress only (region I), where slippage is prevented by friction. In region II, fibers start to slip, and at higher stress (region III), both slippage and breakage of fibers take place.

In our experiment, most yarns fail due to non-catastrophic failure, and most yarns display failure due to the fiber slippage. Figure 4.25 shows some the stress-strain curves of one yarn sample.

Type 1 (1.5 denier, 38.1 mm in length) \(N_1 = 35\) Psi; \(N_2 = 40\) Psi

Figure 4.25 Stress versus strain

Figure 4.25, we see that the fibers in the yarn do not break at the same time, and the yarns break due to the slippage of the fibers. This figure represents the most typical behavior of yarns in tensile test.

In these yarns, because of the processing conditions, the wrapped fibers did not twist the core fibers tightly. So when the yarns are stretched, the core fibers will slip due to the low level of friction.
Figures 4.26 and 4.27 show the relation between yarn tensile strength and yarn breaking elongation.

Figure 4.26 Breaking elongation versus specific strength of Type 1 yarns

Figure 4.27 Breaking elongation versus specific strength of Type 2 yarns
From Figures 4.26 and 4.27, we can find a decreasing frequency for breaking elongation when the yarn strength increases.

**Card-Spinning yarn failure behaviors**

The Figures 4.28 and 4.29 compare the yarn stress-strain behavior of yarns with low and high strength.

**Type 1** (1.5 denier, 38.1 mm in length) \( N_1=35 \text{ Psi} \) \( N_2=40 \text{ Psi} \)

![Specific Stress versus Strain graph](image)

**Figure 4.28 Low strength yarns failure behavior**

**Type 1** (1.5 denier, 38.1 mm in length) \( N_1=40 \text{ Psi} \) \( N_2=55 \text{ Psi} \)

![Specific Stress versus Strain graph](image)

**Figure 4.29 High strength yarns failure behavior**
From Figure 4.28 and 4.29 we see that yarns with low and high strength show different failure behavior when they are stretched. The reason can be traced to the structure of the yarns.

Figure 4.30 shows the yarn geometric feature for the two samples in Figures 4.28 and 4.29.

a:

Type 1 (1.5 denier, 38.1 mm in length) N1=35 Psi  N2=40 Psi
(low strength)

b:

Type 1 (1.5 denier, 38.1 mm in length) N1=40 Psi  N2=55 Psi
(high strength)

Figure 4.30 Geometric features of low and high strength yarns

By comparing the structures of low strength yarns and high strength yarns, we can find that low strength yarns have less twist than the high strength yarns. And the high strength yarns are twisted much more tightly than the low strength yarns.

One effect of twist in a yarn is to cause contraction as a result of the longer path (because of helical geometry) followed by the fiber. The contraction behavior of spun staple yarn is discussed by Landstreet et al. [27]
As seen from Figure 4.28, the low strength yarn fails gradually, and the modulus of the yarn does not change much. During the test, all the yarns break due to fiber slippage. Figure 4.29 shows the failure behavior of high strength yarns. The high strength yarns have more twist which causes yarns to contract more than low strength yarns. When stretched, the high strength yarn will first extend to remove yarn contraction and the modulus at the beginning of test is low. After the yarns totally extended, the surface fibers twisted around the core fibers are tightened more and more, and the modulus of the yarn show an increase. As the tensile force continues to increase, more and more surface fibers will slip. At some point, there are not enough surface fibers, holding the core fibers tightly, and the yarn will break suddenly. This is the reason why the high strength yarns break more quickly than the low strength yarns, and as a result, the high strength yarns have lower break strains than the low strength yarns.
Failure Mechanism

The structure of an air-jet spun yarn is highly irregular. Usually it has been assumed that the air-jet spun yarn consists of a core created by untwisted fibers, which are wrapped together by wrapper fibers. The core axis is assumed to be a straight line, with the diameter of the wrapper fiber helix equaling the diameter of the yarn core. However, when analyzing the yarn image, we notice that generally these assumptions are not satisfied for yarns from the card-spinning system.

Figure 4.31 Air-jet yarn image

Wrapper fibers are randomly distributed along the yarn length, and they create wrapping ribbons consisting of random numbers of fiber. We can characterize a wrapping ribbon by the value of the wrapping angle $\alpha$, the width of the ribbon $w_r$, and the distance between successive wraps $w_d$. All these parameters can fully characterize the structure of an air-jet spun yarn. \[\text{Figure 4.32 Yarn structure characterize}\]
In different yarn structure classes, the $w_1$, $w_d$ and $u$ are different.

<table>
<thead>
<tr>
<th>Class</th>
<th>$W_1$</th>
<th>$W_d$</th>
<th>$u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>long</td>
<td>short</td>
<td>large</td>
</tr>
<tr>
<td>Class II</td>
<td>long</td>
<td>short</td>
<td>random</td>
</tr>
<tr>
<td>Class III</td>
<td>short</td>
<td>long</td>
<td>small</td>
</tr>
</tbody>
</table>

Since $w_d$ is the untwist portion in the yarn, it is more likely to break than other areas. The diameter of the failure region of a yarn was observed to be lower than the mean value for the whole yarn sample. The failure region can be characterized by low number of fibers in the wrapping ribbons, and relatively long distances between successive wraps. Therefore Class III portion in the yarn is the weak section.

In the low strength yarn, the Class III portion of the yarns is more than that in high strength yarns (Figure 4.30), and so the low strength yarns are easier to break and display lower yarn strength.

In most cases, yarn failure was caused by slippage of the core fibers. From the image of card-spun yarn specimens before and after breaking, the break region shows loose fiber bundle, and the break point is often located in a section with small yarn diameter.

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In rare cases, the card-spun yarns break due to wrapper fiber breaking. It happens in only the high strength yarns and the break region is located in Class I or Class II portion instead of Class III in the yarns. During yarn tensile test, fiber breaking sound ("click") can be heard when the wrapper fibers break. After the test we can find some short fibers in the yarn break region. Also, the yarn break edge shows the shape of a fiber bundle wrapped by residue wrapper fibers. (Figure 4.34)
4.2.3 Effect of front and back nozzle pressures on the evenness of air-jet spun yarn

Yarn evenness is commonly measured by the variation in mass per unit length. It can influence many other properties of the yarn and the fabric made out of it. A certain minimum mass variation in the yarn principally arises from the basic properties of the fiber and hence cannot be totally avoided. The measurement of unevenness is only a quantification of the differences between different yarns in this aspect. The measurement principle evolved from the conventional cut-and-weigh-method, in vogue as early as the 1920s. Since then, considerable developments have taken place in the techniques of evenness measurement. The current generation testing equipment aims not merely at measuring the yarn evenness but also providing additional information to correct and improve the process as well as specific machine elements. In this experiment, the yarns were tested on Uster3 machine. Before Uster tests, we first measured the variation of the yarn diameter by image analysis, the purpose was to assess the effect of front and back nozzle pressure on the variance of yarn diameter.

There exist many factors that influence yarn evenness (CV %). During the card-spinning process, if the ribbon width is fixed, the unevenness of the ribbon created by carding will influence the yarn unevenness; web dividing can cause bridging fibers that will influence the yarn unevenness; the air-jet spinning nozzle makes the surface fibers twist around the core fibers also has an effect on the yarn evenness. Although it is difficult to see which factor has the greatest effect on the yarn evenness, we can get some quantitative information about yarn unevenness by comparing the yarn unevenness corresponding to different processing parameters such as nozzle pressures.
Table 4.4 shows the evenness (CV %) of yarns produced with the different nozzle pressures.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Type 1 (CV %)</th>
<th>Type 2 (CV %)</th>
<th>N₁ (psi)</th>
<th>N₂ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.3</td>
<td>25.25</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>27.5</td>
<td>21.76</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>29.11</td>
<td>19.73</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>16.9</td>
<td>24.54</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>24.34</td>
<td>28.69</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>24.33</td>
<td>24</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>28.85</td>
<td>16.66</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>8</td>
<td>19.75</td>
<td>22</td>
<td>60</td>
<td>49</td>
</tr>
<tr>
<td>9</td>
<td>22.05</td>
<td>30.98</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>24.24</td>
<td>23.3</td>
<td>39</td>
<td>50</td>
</tr>
<tr>
<td>11</td>
<td>17.36</td>
<td>21.74</td>
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<td>30</td>
</tr>
<tr>
<td>12</td>
<td>24.64</td>
<td>38.3</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>13</td>
<td>20.77</td>
<td>22.97</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>14</td>
<td>21.46</td>
<td>22.54</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>15</td>
<td>26.17</td>
<td>24.62</td>
<td>60</td>
<td>55</td>
</tr>
<tr>
<td>16</td>
<td>21.37</td>
<td>22.18</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>17</td>
<td>28.47</td>
<td>31.62</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>18</td>
<td>18.74</td>
<td>21.5</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>19</td>
<td>19.67</td>
<td>24.6</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>22.08</td>
<td>36.48</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>21</td>
<td>27.3</td>
<td>26.41</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>22</td>
<td>19.41</td>
<td>21.63</td>
<td>60</td>
<td>35</td>
</tr>
<tr>
<td>23</td>
<td>37.9</td>
<td>21.63</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>24</td>
<td>26.12</td>
<td>23.23</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>25</td>
<td>29.39</td>
<td>26.65</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>23.6568</strong></td>
<td><strong>24.8204</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Standard Dev.</strong></td>
<td><strong>5.19897</strong></td>
<td><strong>4.677354</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
From the Table 4.4, we see that the average CV % of Type 1 yarn is slightly less than that of Type 2. However, the standard deviation of Type 2 yarns is less, indicating a lower mass variation in Type 2 yarns.

Figure 4.35 shows the effect of front nozzle pressure ($N_1$) on evenness of the card-spun yarns when the back nozzle pressure ($N_2$) is fixed.

![Figure 4.35 CV % versus $N_1$](image)

Figure 4.36 shows the effect of back nozzle pressure ($N_2$) on evenness of the card-spun yarns when the front nozzle pressure is fixed.
Figure 4.36 CV% versus N₂
When $N_1$ is fixed at 50 and 60 Psi, the curves of evenness (CV %) versus $N_2$ for the two types of yarns are similar. Therefore, fiber geometry has little effect on the evenness of the yarns, and the process conditions play a main role on the quality of the yarns.

Also, we can see that when the front nozzle pressure ($N_1$) is fixed, the lowest CV% of the yarn occurs when the back nozzle pressure is 45 - 50 psi. But in the first series of figures ($N_2$ is fixed and $N_1$ varies), such trend is not easily seen.

Figure 4.37 provides three-dimensional plots showing how the CV % value changes with the front and back nozzle pressure ($N_1$ and $N_2$).
We can see that when $N_1$ is in the 35-45 (psi) range and the $N_2$ is in the 45-55 (psi) range the graph is concave, which means in this area the CV % value is the smallest. At this time, the yarn evenness is the best. On the contrast, when $N_1$ is in the 45-55 (psi) range, and $N_2$ is in the 35-45 (psi) range, the evenness of the yarns is the worst.

Similarly, we can also plot the 3-D graphs of CV % value for Type 2 yarns.
Figure 4.38 3-D plots of class 2 yarn evenness

When $N_1$ is in the 40 -50 (psi) range and $N_2$ is in the 45 -55 (psi) range, the value of CV % is the smallest. In this area, the evenness of Type 2 yarn samples is the best. In contrast, when $N_1$ is in the 30 -40 (psi) range and $N_2$ is in the 35 - 45 (psi) range, the evenness of Class 2 yarn is the worst. These results are summarized in Table 4.5.
Table 4.5 Evenness results of the yarns

<table>
<thead>
<tr>
<th>Evenness results</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Range</td>
<td>( N_1(\Psi) )</td>
<td>(35,45)</td>
</tr>
<tr>
<td></td>
<td>( N_2(\Psi) )</td>
<td>(45,55)</td>
</tr>
<tr>
<td>Worst Range</td>
<td>( N_1(\Psi) )</td>
<td>(45,55)</td>
</tr>
<tr>
<td></td>
<td>( N_2(\Psi) )</td>
<td>(35,45)</td>
</tr>
</tbody>
</table>

**Relationship of yarn structure classes and yarn evenness**

If we compare the 3 different yarn structures, it can be seen that the Class I and Class II\(_R\) are much more uniform than Class II. Class II has more disturbed fibers which wrap around the core fibers randomly. By this reason, we are trying to find the relationship between Class II portion in the yarn and yarn evenness.

![Class II portion vs CV](image)

Figure 4.39 Class II vs CV (%)

From Figure 4.39, we see that the CV value and Class II portion in the yarn have a direct positive relationship.

**Conclusion:**

With different fiber types, the front and back nozzle pressures show different effects on the evenness of the yarn. The effect of the back nozzle pressure \( N_2 \) remains within the same range on the Type 1 and Type 2 yarn samples, but the front nozzle
pressure \((N_1)\) has a different range. From Table 4.5, we can find that when \(N_1\) nozzle pressure increases, the evenness of the Type 1 and Type 2 yarns becomes worse. The font nozzle pressure \((N_2)\) for the best yarn evenness depends on the yarn material (fiber fineness and fiber length). Optimal back nozzle pressure \((N_2)\) for yarn evenness does not depend on the yarn material.

To produce even yarns, we should adjust the back nozzle pressure \((N_2)\) to the range of 45 - 55 (psi) and then adjust the front nozzle pressure to find the suitable nozzle pressure combination for the best evenness. The yarn evenness is directly related Class II structure in the yarn.
4.3 Conclusion

From the previous analysis for the effect of the front nozzle pressure ($N_1$) and back nozzle pressure ($N_2$) on the structure and properties of the yarns, we can draw the following conclusions.

- **Effect of nozzle pressure on the structure of air-jet spun yarns from the card-spinning system**

  - The air-jet spun yarn structures from the card-spinning system are more sensitive to the front nozzle pressure ($N_1$) than the back nozzle pressure ($N_2$). When the front nozzle pressure goes up, the portion of unwrapped section (Class III) will decrease, and the orderly and disorderly wrapped sections (Class I and II) will increase accordingly.

  - The front nozzle pressure ($N_1$) has a stronger effect on the yarn diameter variation than the back nozzle pressure ($N_2$). The back nozzle pressure has little effect on the yarn-diameter variance. Increasing the front nozzle pressure can make the yarn look more uniform.

  - The twist configuration of card-spun yarns can be classified into 3 basic structure classes. The configuration is affected by the spinning condition (such as ribbon uniformity, spinning speed and nozzle pressure).

  - The fiber length and fiber fineness have an influence on the structure of yarns. The shorter fiber more likely form Class II structure in the yarn.
Effect of nozzle pressure on the properties of air-jet spun yarns in card-spinning system

- The effect of nozzle pressure on the strength of the air-jet spun yarns from the Card-spinning system can be described using the following regression equations:

Yarn Strength (N/ tex) = \(-8.0 - 0.250N_1 + 0.012N_2 + 6.76 \frac{N_1}{N_2} - 6.68 \frac{N_2}{N_1} + 0.00136N_1^2 - 0.00059N_2^2 - 8.21\ln(N_1) + 1.16\ln(N_2) + 0.000063N_{sw}\)

Type 1 (1.5 denier, 38.1mm) \((R^2=0.791)\)

Yarn Strength (N/tex) = \(6.78 + 0.228N_1 - 0.0915N_2 - 0.782 \frac{N_1}{N_2} + 0.745 \frac{N_2}{N_1} - 0.00118N_1^2 + 0.000420N_2^2 - 3.81\ln(N_1) + 0.831\ln(N_2) + 0.000485N_{sw}\)

Type 2 (1.0 denier, 32 mm) \((R^2=0.789)\)

- The yarn specific strength is directly related to the Class III structure portion in the yarn, which represents the weak area in the yarn.

- In the card-spinning system, the yarn breaking elongation decreases as the yarn strength increases.

- The effect of nozzle pressure on the evenness of the yarns from the card-spinning system: with different materials (fiber fineness), the best and worst yarn evenness corresponds to the same range of back nozzle pressure \((N_2)\). When the front nozzle pressure \((N_1)\) increases, the yarn evenness have a tendency to become worse. The yarn evenness has a direct correlation with to the Class II structure in the yarn.

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Chapter 5
Suggestions For Future Work

In future studies, the card-spinning system needs to be improved to reduce interruption due to yarn breakage. The web dividing needs to be and the nozzle angle to the web should be precisely controlled. The spinning speed should be increased. After synchronizing the whole system, the machine can now run at 45 yards/min. But this speed is still lower than the normal air-jet spinning speed. Shortening the distance between the spinning nozzle and the web take-up assembly may decrease the probability of ribbon break.
Appendix A: Controller Diagram
Appendix B: Motor Drive Diagram
Appendix C: Control Panel Diagram
REFERENCES


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