DEVELOPMENT OF AN EMPIRICAL MODEL FOR THE PREDICTION OF A FRICTIONAL INTERACTION FACTOR FROM PARAMETERS OF THE FIBER SEPARATION SECTION OF THE OPEN-END ROTOR YARN SPINNING MACHINE

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A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

Inter-fiber coefficient of friction, fiber feeding speed, and separation roll speed parameters influence frictional interaction in rotor yarn spinning by changing the fiber's surface and dynamic and static frictional characteristics. Hence, the chance of a fiber being deposited at outputs of the fiber separation section is influenced by changes in these parameters. The concept of a frictional interaction factor was adopted to explain the flow of fibers in changing frictional conditions. The objective was to develop an equation of the interaction factor through empirical methods of analysis.

Independent variables of inter-fiber friction and fiber feeding and separation roll speeds were manipulated in experimental tests using cotton fibers. The dependent variable was the interaction factor. Observed measurements of the mass of output and input material during the separation process were used to obtain the data for the dependent variable at three values of the independent variables.

A suitable regression model was developed from a consideration of linear, joint, and quadratic terms of the independent variables. Regression analysis was done using a method of weighted least squares due to heterogeneity in the variance of the observed data, which improved the precision of the model for practical application.

The linear terms of the independent variables were found to be adequate to develop the prediction model. Of the three independent variables, fiber feeding speed had the smallest contribution to the model and separation roll speed had the largest.

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Chapter I

INTRODUCTION

Open-end yarn spinning has been under development since the late 1960s [21,25]. Open-end spinning technologies include air-jet, vortex, friction, and rotor spinning. Rotor spinning in particular, is widely used in spinning a variety of staple fibers.

The open-end technology is of special interest because of its serial treatment of most of the yarn spinning operations (Figure 1). It offers high reductions in production costs over the conventional ring spinning. The process may be fully automated to include the cleaning of the rotor, yarn break repair, and replacement of the yarn package.

The open-end rotor machine has gone through technological design changes since its introduction in manufacturing, more than ten years ago [25,27]. The fiber transportation section of the machine has been of major interest to researchers [1,25,33,34,38,45]. This investigation focussed on the fiber separation system of open-end rotor spinning. The following discussion involves factors involved in the separation of fibers.

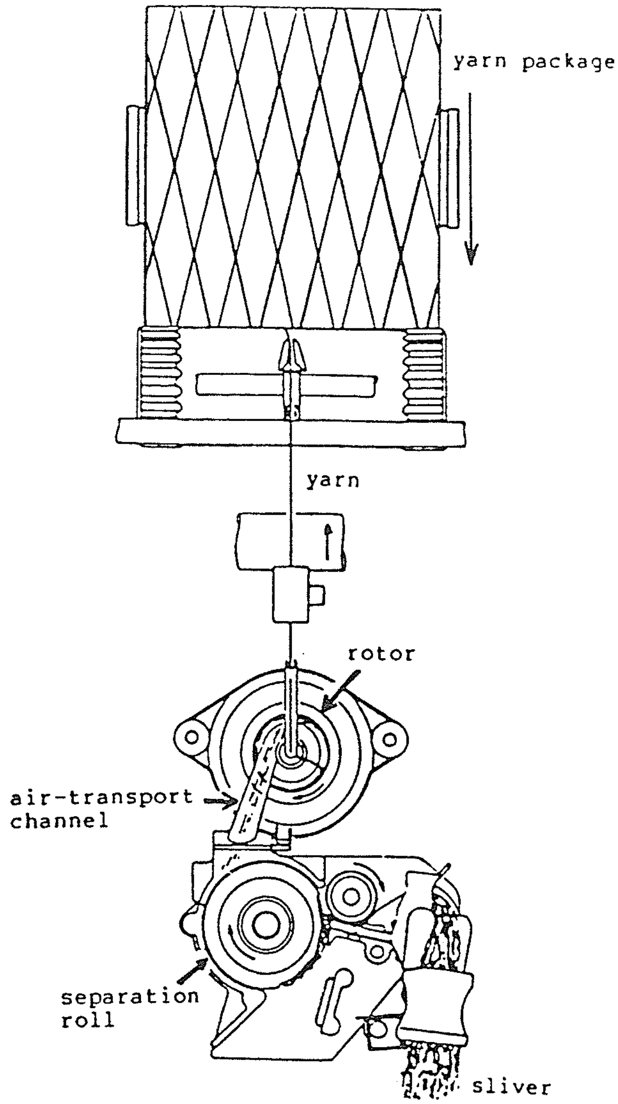

Figure 1. Yarn formation in rotor yarn spinning [38]

STATEMENT OF THE PROBLEM

The principal role of the fiber transport process is to continuously supply fibers to the collecting surface of the rotor twisting device. To achieve this, the fibers have to be in the form of individual elements capable of being independently controlled. As part of the fiber transport system, the purpose of the separation section is to progressively remove the fibers from the fiber sliver and transport them uniformly to the air-transport channel.

The requirements of the separation process are to (a) remove individual fibers from the sliver, (b) facilitate removal of the fibers at the separation roll/air-transport channel interface, and (c) provide a clean and continuous assembly of fibers. Since the action of the separation section is to transform a fiber sliver into individual fibers, frictional interaction plays a major role in controlling the movement of fibers in the separation section. In general, differences in the processability of fibers may be regarded as being due to differences in the physical surface attributes of the fibers. The physical surface attributes of the fibers which determine frictional interaction include: the geometry, or roughness of the fiber surface, the condition of the surface, the proportion of surface in contact with neighboring surfaces, and the static and/or dynamic coefficients of friction between a fiber and other surfaces [3,5,14,23,32,39,40]. Differences in these surface attributes are responsible for the variable frictional interaction of the fiber with neighboring surfaces. The magnitude of frictional interactions is affected by certain independent parameters of the separation system. A number of these are discussed in the following paragraphs.

The dynamic states of surfaces have been found to influence interaction of surfaces [5,29,31,32]. The momentum of an object is directly proportional to the velocity and mass of the object. Since frictional forces created between surfaces affect changes in momentum [29,36], a fiber surrounded by other surfaces will have a change in momentum depending on the change in the velocity of the fiber relative to the velocities of the other surfaces. The change in velocity can be either in magnitude or direction. Changes in the momentum of a fiber indicate the position of the fiber in the system at a given moment.

Machine designs also influence interaction of surfaces during the separation process [12,25]. Differences in machine designs include differences in the separation roll diameter, roll teeth space, shape, and angle, and the separation edge dimensions. The diameter of a roll determines the surface or tangential speed of the roll [29]. Teeth space, shape, or angle influence the proportion of contact points and the ability to penetrate the fibers [12].

Other important forces which exist in the separation section are aerodynamic forces. Aerodynamic forces are created due to the motion of the separation roll. These forces act on a free fiber body during transportation and affect its movement [36]. Aerodynamic forces from an external suction system are responsible for the removal of a fiber from the surface of a separation roll [12,33,34,36].

This study concerned the factors involved in influencing frictional interaction in the transportation of fibers by the separation section. To date, there has been lack of investigations on the importance of frictional interaction in the movement of fibers in the separation process of open-end rotor spinning.

The physical form of frictional interaction is complicated and difficult to measure. Fibers are presented to the separation section in the form of a sliver. The fibers in a sliver are in a random arrangement [22]. Hence, the movement of fibers in fiber processing machines has been treated as a random process by researchers [2,18,28,42]. Transfer probability values have been used to explain the likelihood of a fiber being located at particular sections of the processing machine in a unit of time. The magnitude of these values is influenced by frictional interaction which is a function of process parameters discussed previously. This influence is reflected in a frictional interaction factor. Probability values can be determined from experimental measurements of the average mass of fiber material reaching a particular point during a process and the mass reaching a subsequent point in a unit of time [2].

The response variable for this study was the interaction factor. Of the number of factors discussed before, the inter-fiber static coefficient of friction, the feeding speed, and the separation roll speed were considered to be critical to the response and were selected to be the independent variables of the study. The inter-fiber static coefficient of friction was regarded to be important since it characterizes a material. The feeding and separation roll speeds are significant to dynamic influences on the fiber and neighboring surfaces. The physical form of influence of these factors in fiber separation is discussed in Chapter 2. Other factors not selected either remained fixed or were assumed to be dependent on the selected factors.

Regression methods of analysis were chosen to develop a prediction model from the variables. Such a model expresses the effect of the independent variables on the response variable in terms of parameters obtained from a statistical analysis of experimental data. The parameters reflect the change in the response as an independent variable is moved from one level to another while the levels of the other variables remain fixed.

GOALS OF THE STUDY

The purpose of this research was to develop an empirical model to predict an interaction factor of the fiber separation process of open-end rotor spinning, taking into account factors influencing frictional movement of the fiber in the system. The factors included in this model were the inter-fiber static coefficient of friction, the fiber feeding speed, and the separation roll speed.

As a result of previous investigations, described above that were concerned in upgrading the product of rotor technology and examining the role of frictional interaction in fiber processing, the researcher prepared a study to investigate solutions to problems related to frictional interaction. The most widely used fiber in spinning technologies is cotton, hence, it was regarded an important material to use in the study.

This research is regarded as being unique since it concentrates on an isolated section of the open-end spinning process. This is important because conclusions may be made based on changes in the section, without involving influences of transformations in other sections of the process, as might be the case when the product of the overall process is considered.

Previous models have been developed purely for exploratory purposes by relating behaviors of different variables in a theoretical form [3,6,7,26,35,42]. Since the proposed model will be developed from experimental measurements, it is of importance for direct application to real life situations.

Other models have been previously developed in open-end spinning studies to optimize the parameters of the final product and machine designs [11,34,37]. These models provide information of the conditions which maximize desirable or minimize undesirable aspects of a process. A prediction model such as the one in this report is important for decision making purposes by establishing a means to explore the problem through manipulation of the variables in the model. It can also offer means of assessing differences in machine designs or types of fibers.

It is believed that this type of research provides information vital to a broader scope from which to study the role of the interaction of both machine and fibers in the separation of fibers during open-end rotor yarn spinning. Most processing conditions are a trade-off of various parameters of the process. A modelled interaction factor can be helpful to explain such trade-offs.

OBJECTIVES

The objectives of the research were: (1) to measure and calculate the data expressing the interaction factor at different values of the independent variables, (2) to evaluate the nature of frictional influence on the data, and (3) to develop a suitable prediction equation of the interaction factor based on the observed data.

LIMITATIONS

This research did not take into account variations in parameters such as fiber fineness, length, component blend and other machine conditions which are important to rotor yarn spinning [10]. In such cases the model could be used as a general indication of the behavior of the process. The model will not provide actual measurements of the physical interaction reflected by the behavior of the response. Rather, it will express results based only on changes in the independent variables. It will not be possible to isolate individual contributions of the variables in the model. Therefore the model should be considered in its entire form.

The model is not applicable to extrapolation of values outside the range of variables used in the research. Therefore the model will only be applicable under the set of conditions described in the report.

Some of the words in this report require definition to facilitate understanding of their use in the context. The definitions of these are discussed in the Glossary.

Chapter II

LITERATURE REVIEW

This chapter contains a discussion of the nature of frictional interactions, and published research investigating the importance of factors such as static coefficient of inter-fiber friction, fiber feeding speed, and separation roll speed. The fiber separation process and modelling techniques related to this study are also discussed.

Additionally, some research of the carding process is reported since it may be considered as an analogous process in terms of the action of teeth. The information provided by Rholena et. al. [36] is a theoretical-physical interpretation of the technology of open-end spinning.

THEORY OF FIBER SEPARATION PROCESS

A fiber sliver is an untwisted assembly of fibers arranged at random along the axis of the sliver so as to exhibit a preferential orientation [22]. It described in terms of its physical properties including the linear density and coherence of the sliver. These properties of the sliver are dependent on the physical properties of the fibers and the conditions governing the preparation of the fiber sliver [22,32]. Man-made staple fibers are produced with less variable properties than natural fibers [17,22]. Inter-fiber friction is important to the coherence of the sliver. In spinning practices, coherence of the sliver is altered by condensing the sliver, addition of adhesive or lubricating chemicals to fibers, and insertion of crimp to fibers (applicable to man-made fibers) [22,32].

The fiber separation section is the first process in open-end rotor spinning. The section consists of the feed roll and attachments, and the separation roll [25,36] (See Figure 2). The separation roll surface is covered by a metallic "clothing" of pins or saw teeth.

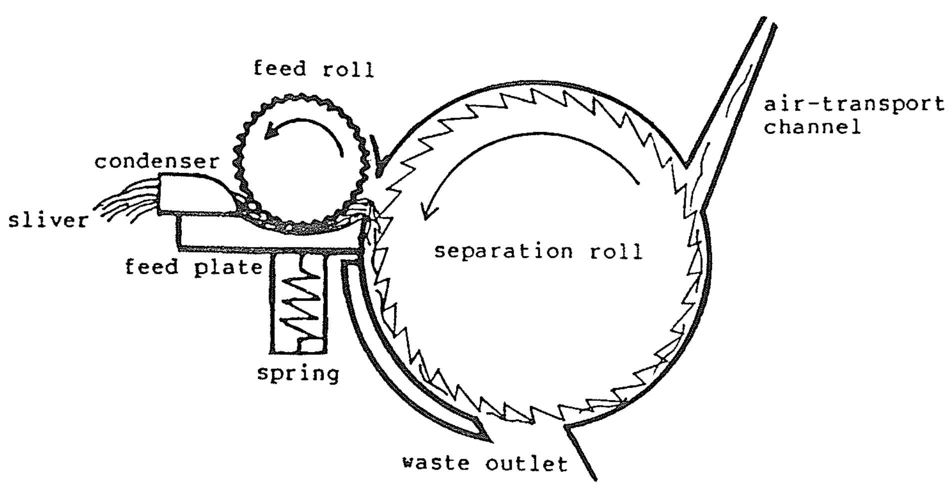

Figure 2. Fiber separation section of rotor yarn spinning

The fiber sliver is fed to the spinning unit at a determined rate through a condenser. The rate may be varied depending on the linear density or draft ratio required of the final product [25,36]. The size of the condenser depends on the linear density of the fiber sliver. A nip point is formed between the feed plate and the feed roll so as to exert high pressure on the sliver. The pressure is regulated by a spring situated under the feed plate. The slanted fluting design on the feed roll maximizes traction between the feed roll and fibers and increase the needed force to move the sliver. The part of the sliver leaving the high pressure zone increases in cross-sectional area and cohesion is reduced.

The fibers contact the teeth of the separation roll in the region in front of the separation edge. The separation roll acts on the fibers that are within reach and removes those fibers whose inter-fiber frictional force is lower than the force from the action of teeth. Separated fibers are transported by the teeth and are stripped from the roll by air currents in the air-transport channel depending on the magnitude of opposing forces contributed by frictional forces with the roll teeth and the inertia force acting on the fiber. Otherwise the fibers remain attached to the separation roll [36]. Some fibers are not acted upon by the teeth since there is space between the teeth and a gap between the separation roll and the feed plate edge. Some of these fibers are carried by the ambient force due to the motion of the roll.

A metallic housing prevents fibers from being thrown off due to centrifugal force of the roll. Dirt and a percentage of fibers escape through an opening in the housing and are deposited as waste. The action of the separation roll is carried out at speeds of 6000 to 11000 revolutions per minute [12,25,27,41].

A number of variables are discussed in the following section of this chapter. These variables have been denoted by the symbols defined in Table 10, in the Glossary of this report.

MECHANICS OF INTERACTION

When surfaces are in close contact, the load (normal force) at the contact points causes deformation of the contact points (Figure 3) [32]. Heat is produced causing the contact points to stick together. When the surfaces are moved against one another, frictional interaction is created between them.

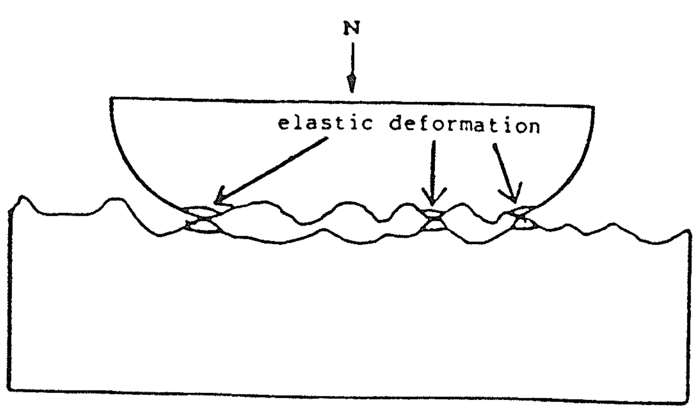

Figure 3. Deformation of surfaces at points of contact [32]

The classical equation of the maximum frictional force acting on the surfaces is[1] [29,32]:

$$F = \mu N \qquad (1)$$

This equation shows that inter-surface friction is directly related to the coefficient of friction (μ) and the load or normal force acting on the surface (N). The importance of the nature of the material is indicated in the form [32]:

$$F = \frac{S}{P}N$$

where,

S denotes the shear strength of the weaker surface
P denotes the yield pressure

The presence of natural or other contaminants on the surface of the material alters the coefficient of friction [14,23,32]. Results of studies in carding [14] showed that when a lubricant such as oil is applied to the fibers or machine parts, frictional resistance decreases. However, the change was believed to be more significant in fiber-to-metal friction rather than inter-fiber friction. The friction increases with lubricant content due to increase in the viscous resistance to flow [32]. Friction was also affected by changes in oil viscosity. Other studies [32,39,40] have indicated that surface geometry also plays a major role in the frictional resistance of fibers.

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[1] Nonlinear relationships for fiber material are discussed in some of the literature [32], however, the classical relation is widely applied, including standard tests for friction of fiber material.

The position of the fibers in the nip of the feed roll and the feed plate is illustrated in Figure 4. The frictional force created on the sliver surface is of the form [36]:

$$F_3 = \mu_0 F_1$$

This relation means that the magnitude of frictional resistance to movement of the sliver is directly dependent on the static coefficient of friction (μ_0) between the sliver fibers and the feed plate and the normal force (F_1) exerted on the roll.

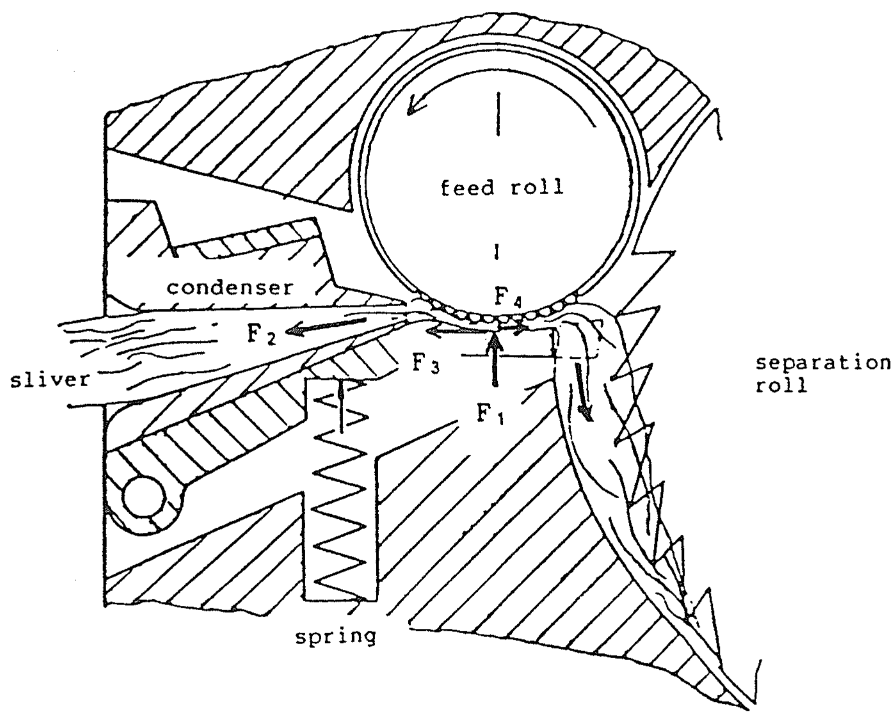

Figure 4. Sliver feeding section of the separation process [36]

The reduction in the cross-section of the sliver due to the condenser introduces radial stress on the sliver [36]. This increases inter-fiber frictional forces and increases cohesion of the sliver when the sliver is pulled from the action of the feed roll. Cohesion depends on the magnitude of the distance between the feed roll and the condenser.

When the resistance force from the action of the separation roll on the fibers is considered negligible, the force acting on the feed roll is approximately determined from the following [36]:

$$F_4 = F_2 + F_3 < \mu_1 F_1$$

When the sliver leaves the nip region of the feed roll the frictional forces on the elements of the fiber are reduced due to reduction in normal pressure. The fibers leaving the high pressure region come into contact with the separation roll. The depth of penetration of the roll teeth into the fiber bundle is dependent on factors such as the fiber feeding rate, dimensions of the separation edge, teeth angle, space, and shape, the striking force (speed) of the roll, and the coefficient of friction [12,36].

Dynamic and static frictional forces created in the region of separation and transportation contribute to the magnitude of distance moved by fibers and the direction of movement during the separation process. This influence determines the presence of fibers in the waste or other sections of the separation process.

Fibers in the separation zone may be classified according to their positions in the sliver (Figure 5). Separation of the fiber may be due to interaction with either the roll or the faster moving neighboring fibers. The action of the separation roll creates a dynamic frictional force between the roll surface and a layer of fibers. When a fiber is engaged by the separation roll it is subjected to a velocity change from ν_0 to ν_1. Constraining forces are created with the stationary surface and slower moving fibers in the separation zone. Fibers in the layer in direct contact with the moving surface have a higher priority of being separated. An increase in the fiber feeding speed will increase the proportion of fiber-to-roll contact area leading to more interaction between the fibers and the moving surface of the roll. Fiber feeding speed also influences the speed of the fiber before separation relative to the speed of the separation roll surface.

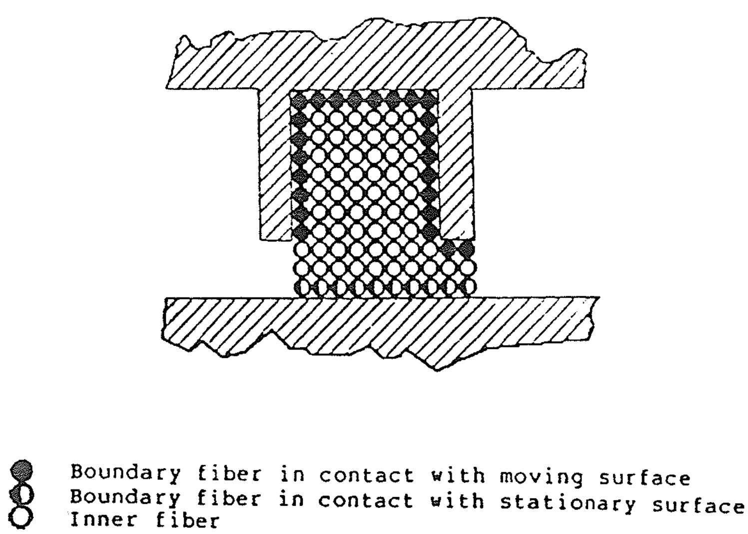

Figure 5. Classification of fibers in the separation zone

The condition of a fiber being engaged by the roll depends on the dynamic frictional force with the roll surface and the static frictional forces with the stationary or slow moving surfaces. From the law of change of momentum, the fiber is accelerated by the dynamic force F_7 in the equation [36]:

$$F_7 \Delta t = m(\nu_1 - \nu_0) \qquad (2)$$

This relation expresses the force that must overcome the constraining forces of the fiber assembly in a time, Δt.

The role of the dynamic frictional forces in acceleration of a fiber was examined by Belov [5] in drafting during conventional spinning. A fiber is separated from other surfaces when the ratio of mean dynamic frictional force at each fiber contact element to the static frictional force is smaller than unity, that is when:

$$F_{01} </= F_0 \ , \quad \text{or} \ \mu_{01} </= \mu_0$$

Belov analyzed the role of of friction in the determination of the transition of a "floating fiber" from a velocity ν_0 to a velocity ν_1. A floating fiber is in contact with other fibers at a elements per centimeter of its length. Of these elements ϵ are in contact with fast moving fibers, and $a-\epsilon$ are in contact with slow moving fibers. The fiber is constrained to velocity, ν_0, by the static frictional force, $a-\epsilon F_0$, from the slow moving surface. Dynamic frictional force, ϵF_{01}, is created between the fast moving surface and the fiber. Upon transition to velocity, ν_1, the fiber is kept moving by the static frictional force, ϵF_0, with the fast moving surface. The slow moving surface restrains the fiber by a dynamic frictional force $a-\epsilon F_{01}$. The change in velocity from ν_0 to ν_1 will occur when the following condition is satisfied [5]:

$$\epsilon' F_{01} > (a-\epsilon') F_0 \qquad (3)$$

In order to maintain this fiber at ν_1, the following condition must also be satisfied [5]:

$$\epsilon'' F_0 > (a-\epsilon'') F_{01} \qquad (4)$$

Belov conducted tests on the effect of the speed of the surfaces on the static and dynamic frictional forces between them. Results showed that the static and dynamic coefficients of friction between surfaces increase with the relative speed of the surfaces. Belov indicated that when the ratio of the coefficient of dynamic friction to the coefficient of static friction is less than one, the change of the fiber speed from ν_0 to ν_1 is instantaneous, and when the ratio is much greater than one the change is "accelerated or jerky". The transition time and the distance moved increases with the difference between the ratio and unity.

Studies conducted by Fujino and colleagues [16] on apron drafting indicated that the influence of withdrawal force of a single fiber from a sliver increases with the normal force on the fibers and the the speed of withdrawal force. The ratio of the limiting dynamic withdrawal force to the maximum static withdrawal force was found to be constant, at the varying speeds of withdrawal. An equation developed from these studies expressed the maximum static withdrawal force in the following relationship [16]:

$$F_6 = f_0 + cp$$

where,

F_6 denotes the maximum static withdrawal force
f_0 is a coefficient for interaction between fibers
c is an experimental coefficient
p denotes pressure

The major dynamic forces in fiber transportation are to the separation roll/air-transport channel associated with the curvilinear motion of the roll (Figure 6). The fiber must change in momentum in accordance with the angular momentum of the roll. The fiber is acted upon by centrifugal forces F_8 and F_9 [36]. The frictional forces opposing the centrifugal force create a centripetal force which acts to constrain the fiber on the roll. In order for the fiber to remain on the roll, the centripetal force must be equal to the centrifugal force.

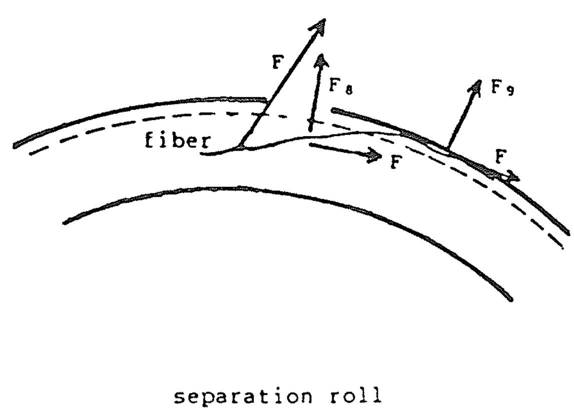

Figure 6. Forces acting on the fiber during transport [36]

The change in centrifugal force acting on an object is directly proportional to the mass of the particle and the square of the tangential speed, and indirectly proportional to the radius of motion [29]. This was regarded as the reason for the results obtained by Miller and colleagues [31] in studies of the carding process. They found that when the speed of a licker-in was high (650 revolutions per minute), the waste produced at the licker-in section of carding was higher than at lower (450 revolutions per minute) speeds. Also, a licker-in with a smaller radius (3.6 inches in diameter), generated more air current and considerable loss of fiber, when run at the same surface speed as the normal size (9 inches in diameter). When the card cylinder was run at 3 revolutions per minute, the size and density of the material on the licker-in were observed to be the same as those at 650 revolutions per minute, however, the licker-in waste at the slower speed consisted mostly of "pepper trash" and shorter fibers. The quantity was observed to be three times more than that at the higher speed. The lower speed created lower centrifugal forces, therefore, resulting in less heavier material such as "motes" being thrown off.

Results of open-end spinning studies have been discussed by Hunter [25]. The amount of waste removed during the separation process depends on the speed of the separation roll. The faster the separation roll speed, the smaller the amount of fibers removed at the separation zone. The amount of fibers on the separation roll decreases exponentially as the roll speed increases and increases as the amount of fibers supplied increases. The resistance to the separation roll force increases with an increase in fiber sliver linear density, the staple length of the fibers, the type of fiber, and the type of separation roll. Increase in the separation roll speed can increase the air currents to such an extent that trash particles are thrown into the system and fine dust is generated due to the action of the separation roll.

Stripping forces are created by the air current in the air-transport channel. The resistance to stripping at the separation roll/air-transport channel has been found to be influenced by the speed of the separation roll [12,33]. It has been reported that the stripping force increases as the square of the difference between the air speed in the channel and the separation roll surface speed [12]. Photographic studies [33] have been conducted to investigate the influence of the air flow rate in the air-transport channel on the configuration of fibers in the channel. These studies indicated that the higher the ratio of the speed of the air current generated at the inlet of the air transport channel to that of the surface speed of the separation roll, the lower the average number of fibers observed in the cross-section of the air transport channel.

MODELLING TECHNIQUES

Researchers have applied a variety of techniques to investigate the phenomenon of fiber transport in yarn spinning technologies.

In yarn preparation processes, computer simulation models have been used to study the relative positions of fibers during the carding processes. Harakawa, Kinoshita, and Tanaka [18] simulated the transfer mechanisms of fibers between carding rolls taking into account the probability of transfer (roll collecting power) of a fiber from the teeth of one roll to another. The collecting power was assumed to be due to gripping of the fiber by the roll teeth and fiber distribution. The model involved geometrical definition of fiber gripping. Statistical expressions were developed to simulate the relation between the collecting power and experimental parameters such as fiber length and mechanical settings. They were able to establish that the effectiveness of the carding region of the roll in fiber transfer between rolls was closely related to the fiber density around the region. Johnson [28] conducted a computer simulation study of roll-drafting of fibers. In this study, it was assumed that the distribution of fiber ends along the length of the sliver were in the form of a Poisson statistical distribution. The ends were advanced as they were encountered in a short interval of the sliver. The simulation model also took into account the sliver-elasticity theory of drafting: the influence of restraining forces due to fiber end density on the irregularity of the product.

Computer simulation offers the advantage of controlled study of a complicated process. The simulation model is characterized by a set of variables which are manipulated by computer coded expressions to simulate changes in the real system. The technique takes into account the movement of individual fibers rather than average values as obtained from experimental techniques. Hence, this technique is complicated and requires a number of assumptions. The model obtained does not provide the actual values of the real system, however it is useful for comparison purposes.

Photometeric techniques have been applied in carding process studies in order to measure the transfer efficiency of wool fibers from the card cylinder to the doffer roll [19]. The efficiencies were determined from the following relation:

$$E = \frac{\rho'}{\rho}$$

where,

ρ' denotes the average fiber density removed by the doffer
ρ denotes the average fiber density on top of the cylinder

The signal level from photometeric measurements was regarded as proportional to ρ.

Because of the small size of open-end sections, and the enclosed nature of the process, it has been difficult to access the interior of the open-end machine for experimental purposes. Lawrence and Chen [33] applied three dimensional photographic techniques to study the configuration of fibers in the air-transport channel of the open-end rotor spinning unit. The technique required construction of a transparent channel and setting up imaging devises around the channel. The data from the study were used to develop a mathematical model [34] to optimize the design of the air-transport channel of the rotor spinning machine.

Stochastic statistical models have been used to account for the randomness of the movement of fibers. Abhiraman and Waller [2] applied stochastic theory to account for the changes in the transfer probabilities at carding points upon collection of the fiber by the worker. Transfer probabilities reflected the collecting powers of the worker rolls. The probability of transfer to the doffer was regarded as the absorption probability. The theory was used to express the transfer of two types of fibers expressed in the following relation [2]:

$$p(a\nu) = \sum_{i=1}^{N} f_i p^{(i)}$$

where,

$p(a\nu)$ is the average collecting power
f_i is the number fraction of the i-th blend component
$p^{(i)}$ is the probability of transfer of the i-th component

The mathematical expressions in the stochastic models enabled application of the model to empirical studies of the process to define the phenomenon of fiber movement. Abhiraman and Waller verified their theory with experimental measurements on the card machine at varying speeds and set-ups of the workers.

A similar relation developed for the carding process [2] was found to be useful reference in studying the probable form of the relation:

$$\xi = \frac{V_1K_1K_2K_3}{V_0K_4+V_1K_1K_2K_3}$$

where,

x is the percentage of fiber transfered from card cylinder to doffer
V_0 and V_1 denote the speeds of the carding cylinder and doffer, respectively
K_1 denotes the doffer to cylinder teeth ratio
K_2 is a coefficient due to entrapment power of cylinder and doffer
K_3 is a coefficient due to interaction of surfaces
K_4 is a coefficient due to the centrifugal force

Theoretical expressions have also been used to model the movement of fibers [3,6,7,26,42]. Buturovich [7] developed a theoretical statistical model to examine the equalizing power of carding machines. The method was based on statistical distributions of probabilities of fiber transfer in a time domain.

The real nature of fiber separation in open-end rotor spinning is still to be determined, unlike carding and conventional drafting processes which have had extensive theories developed to describe the phenomenon of fiber movement. It is the intent of this study to develop a model that will predict a frictional interaction factor from parameters of the fier separation section of the rotor spinning. This model will be based on techniques to measure transfer probabilities and statistical methods of regression.

THEORY OF THE PROPOSED MODEL

A summary of the fiber separation process is as follows: A sliver of fibers is input into the machine unit (See Figure 7). The separation roll removes the fibers from the sliver and transports them to the output at the air-transport channel entrance. A percentage of the fiber material is removed as waste. The remaining material is either removed by suction at the output, or retained in the roll. The retained material joins the new fibers at the input section.

Frictional interaction is created during the process. The interaction facilitates the movement of fibers to locations of the separation section.

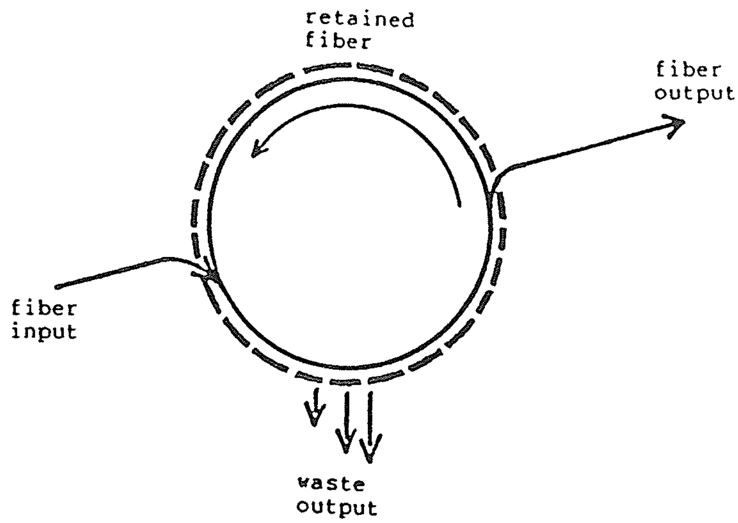

Figure 7. Flow of fibers through the separation section

The presence of fiber material at the separated fiber output on the roll and at the waste output are regarded as the critical occurrences of the process. The random nature of each occurrence is explained by the theories of stochastic processes [8,15].

A suitable model for the system is regarded as a three state Markov process [8,15], where,

State 1 is the fiber present on the roll,

State 2 the fiber in waste, and

State 3 the fiber in separation output.

In order to apply this model it is assumed that the process basically satisfies the following assumptions [8,15]:

(i) The presence of a fiber at a point in the system depends entirely on the most recent state.

(ii) The separation process does reach steady-state.

(iii) All elements of the fiber material going into the system are treated the same way.

The first two assumptions are made from an understanding of the process of separation. The third assumption is made in order to simplify the mathematical equations needed to describe the process. This treatment is illustrated in Figure 8.

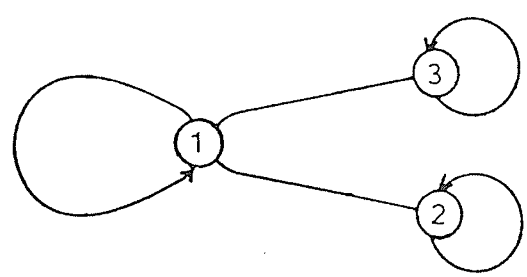

Figure 8. Transition diagram of the separation process

For each individual fiber the system will be in state 1 for a period of time, until it ultimately transfers to states 2 and 3 [8,15]. States 2 and 3 are regarded as absorbing states since the system will remain in these states. The system will enter one or the other of these final states. The movement of a fiber in the system is described by the following [8,15]:

$$a_{12} = p_{12} + p_{11}a_{12}$$

$$a_{13} = p_{13} + p_{11}a_{13}$$

where,

a_{12} and a_{13} are the absorption probabilities
p_{11}, p_{12}, and p_{13} are transition probabilities

In order to determine the values of the transfer probabilities ratios are calculated from experimental measurements of the mass (M_i) of fiber arriving at a point of the system and the mass (m_i) reaching the next point, in a unit time [2]:

$$p_i = \frac{m_i}{M_i}$$

where,

p_i is the transfer probability to point i.

At large values of time the system attains steady-state and the probability values converge [8,15]. The sum of the probability values approaches unity. Based on discussions in previous sections, values are a function of frictional interaction which in turn is dependent on certain parameters of the process. The hypothesis from this evaluation is that the value of the final probability is dependent on the parameters:

$$\alpha^* = \xi \qquad (5)$$

where,

> α^* denotes the final probability
> ξ is a function of parameters

An interaction factor of the system is reflected by the final probability values. Therefore the interaction factors may be represented as:

$$k = \frac{\text{average mass of separated fibers collected in a unit time}}{\text{average mass of material entering the unit in a unit time}}$$

$$l = \frac{\text{average mass of waste collected in a unit time}}{\text{average mass of material entering the unit in a unit time}}$$

where,

> k and l are factors associated with states (3) and (2), respectively.

The sum of these factors is one.

Analytical representations of the interaction factors and the parameters in this study are given by the functional relations:

$$k = f(\chi,\phi,\psi) \qquad (6)$$

$$l = f(\chi,\phi,\psi) \qquad (7)$$

where,

> χ denotes the inter-fiber static coefficient of friction
> ϕ denotes the fiber feeding speed
> ψ denotes the separation speed

The general form of a statistical equation used to represent the above relation is of the form [11,30].

$$Y = \beta_0 + \beta_1 X_1 + \ldots. + \beta_K X_K + \epsilon$$

where,

Y is the value of the response
$\beta_0, \beta_1, \ldots., \beta_K$ are parameters
X_K are the values of the independent variables
ϵ is the random error associated with the relationship

Chapter III

EXPERIMENTAL METHODOLOGY

This chapter contains a description of the parameters and variables studied, the data collected, the test methods implemented, and the data analyses performed in the research study.

The response variable of this study was previously defined as the frictional interaction factor. This factor was in two forms: one form was associated with the stripped fiber output and the other was associated with the waste output. The independent variables were the inter-fiber static coefficient of friction, the fiber feeding speed, and the separation roll speed. The interaction factors were expressed in the form of probability values of the separation system. The objectives of the research were to obtain data expressing the interaction factor at different values of the independent variables, to evaluate the nature of frictional influence on the data, and to develop a suitable prediction equation of the interaction factor based on the data.

The major assumptions from the analysis of the process in Chapter 2 were that the data was taken under steady-state conditions and that all the material going into the separation section was treated the same way. The objective of the experimental part was to obtain measurements of the mass of stripped and waste fiber material in order to determine the interaction factor values of the separation.

Testing was conducted at three levels of the independent variables (parameters) to enable analysis of higher order effects (joint and quadratic) for the development of the statistical model [4]. At least one replication per combination was needed to enable analysis of interaction of the variable [4,30]. Data were collected at all the combinations. The levels of the parameters used in the tests are shown in Table 1. Tests were also conducted to determine the inter-fiber static coefficients of friction.

Table 1. Levels of the independent variables

	Level		
Parameter	1	2	3
Inter-fiber coefficient of friction	0.28	0.31	0.33
Fiber feeding speed (m/min)	0.16	0.39	0.60
Separation roll speed (rpm)	6000	7000	8000

PREPARATION OF FIBERS

The fiber used in the study was 100% cotton of staple length 1 1/16 inches and fineness of 4.2 micronaire. The fibers were in the form of second draw sliver of 3.97 Kilotex in size.

In order to reduce the coefficient of friction, the fibers were sprayed with a lubricant, Lubritol C, to yield .01% and .02% of weight of fibers. The sliver was carefully spread open and one half the side of the sliver was sprayed once on both sides with a very fine film of the lubricant to yield the .01% sample. The sliver was eased back with the treated fibers on the inside. The .02% sample was prepared by spraying both sides of the sliver.

In order to increase the coefficient of fiber friction a fat solvent carbon tetrachloride was run through the sliver at a retention of 20 minutes. Three samples were prepared by extraction with 1, 5, and 10 passes, respectively. Preliminary tests were conducted to examine the levels of parameters suitable for the study. Samples which caused a build up of pressure in the twisting chamber during tests were disregarded. Feeding rate levels were studied to establish a visible difference in outputs.

The technique to reduce the coefficient of friction was suitable since the fibers were already in sliver form. Similar techniques have been used by researchers. The method used to reduce the coefficient of friction was designed from standard methods for removing fatty substances from fibers [43].

OUTPUT COLLECTION

The tests were conducted on a modified Auto-coro model yarn spinning unit. The unit was modified so as to permit collection of the fiber directly from the separation section by eliminating the yarn twisting device. A collection tank for fibers was placed at the rotor mount opening. The modified unit is illustrated in Figure 9.

The major components of the apparatus were the spinning unit, a high pressure glass collection tank (diameter - 100 mm and length - 350 mm) with a vacuum outlet of 1.25 mm and a high pressure aluminum lid, a glass suction funnel (funnel diameter - 48 mm, funnel depth - 25 mm, tube diameter - 8 mm, and tube length - 60 mm), a nylon bag (width - 90 mm, length - 250 mm, and mesh - 5/mm) for collection of stripped fibers, a polyethylene bag for waste collection, a vacuum pump, a feed roll drive, and a separation roll drive. The feed roll and the separation roll were driven by V belts from a 1/2 h.p. motor. The feed roll drive consisted of a variable speed reducer box , and a set of timing pulleys and belts. The separation roll drive consisted of flat pulleys and an endless belt.

Three flat pulleys provided separation roll speeds of 6000, 7000, and 8000 revolutions per minute. The variable speed reducer box was used to select the feeding roll speeds. Tests were conducted with a type OB 20 separation roll for 100% cotton [41]. Red code condenser size and pressure setting position 1 were used, as recommended for the size of sliver used in the study [41].

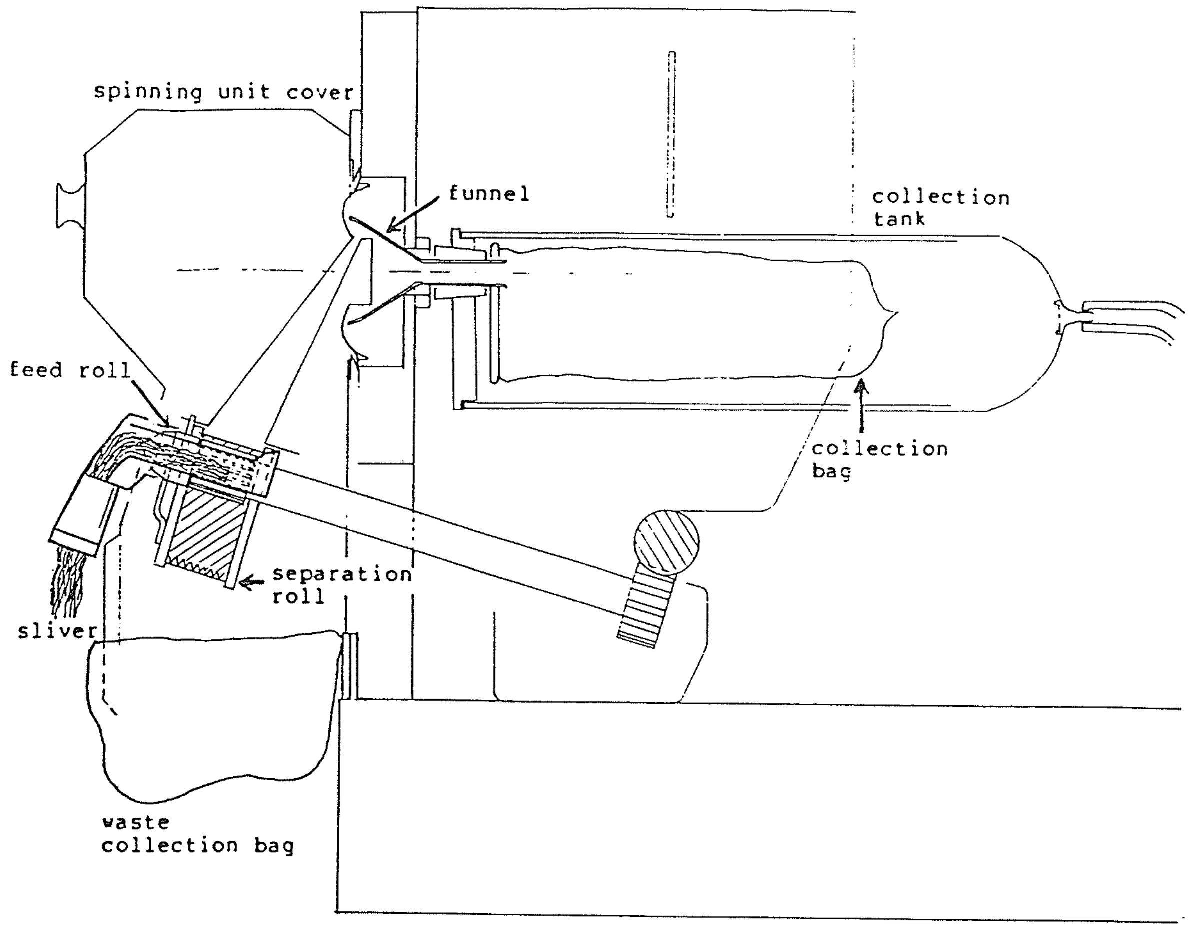

Figure 9. Cross-sectional diagram of modified fiber collection equipment

Tests for the collection of fibers were run in a controlled environment of 23°C and 50% relative humidity. The conditions were made to resemble spinning mill conditions as closely as possible (28°C and 52% relative humidity respectively [44]). The pressure gauge was set to generate a vacuum pressure of 2 inches of mercury (Hg) which was more than the pressure required in the operation of a rotor yarn spinning machine technical manual (50 - 65 millibars [41]). A higher setting was necessary because the pressure could not be stabilized below the 2 inch Hg setting. These parameters for testing are shown in Table 1, page 33. The feeding speed parameter levels were within the ranges stated in the open-end machine technical manual (.16 - 5.0 meters per minute [41]).

A cut and weigh method was used to collect the fibers. The method has been used in carding studies [19,24,31] although some researchers have criticized it [19]. The criticism is due to the decay period following the stopping of the machine. Since the problem is largely due to the heavy parts of the machine, it was assumed not to be significant in this study since the open-end machine parts are much smaller and lighter. There was no evidence of decay during the tests.

Ten replications entailed each combination of the parameters, placed in random order. It was important to randomize testing in order to minimize the effect of time dependent factors, such as machine fatigue. The following procedure was used to collect fibers at the outputs:

1. Insert the fiber sliver into the condenser and under the feed roll.
2. Set initial system conditions by conducting a 60 second run as in 4 to 8.
3. Mark a one meter length on the sliver such that one mark is on the condenser.
4. Place the collection bags and tank in position and close the unit.
5. Switch on the vacuum pump, and after 2 minutes adjust the pressure to a setting of 2.
6. Start the motor to begin the test.
7. Turn off the motor and pump when the lower meter mark reaches the condenser mark.
8. Remove the collection bags and check inside machine for fibers and waste.
9. Repeat 1 to 8.

The weight of the separated fiber output and waste were determined using a Sartorius digital balance. The bags and fibers were kept in controlled environment with relative humidity of 65% +/- 2% and temperature 21°C +/- 1°C for 24 hours prior to weighing. The bags were weighed before their use. After testing, the bags and fiber were weighed and the difference of the two weights determined. The bags were cleaned with an industrial vacuum cleaner and weighed again in preparation for the next test.

STATIC COEFFICIENT OF FRICTION

The method for determining the inter-fiber static coefficients of friction was that developed by E. Lord, as described by Hearle and Husain [23]. The method has been widely applied to determine the coefficient of friction of staple fibers [39]. The method was found most suitable because it takes into account the contribution of neighboring fibers to the static friction. The procedure is known as the fringe method.

The apparatus used to measure the static frictional force is illustrated in Figure 10. The equipment consists of an Instron tensile testing machine with a load cell of maximum 100 grams, an aluminum platform (350mm x 150 mm) with a low friction pulley mounted on one end, a metal sled (55 x 55 mm) and a weight, and a continuous nylon thread attached to one end of the sled. The measurements recorded by the machine were in the form of load (force) of strain.

Measurements were made under standard environment of humidity 65% +/- 2% relative humidity, and temperature 21^0 +/- 1^0C. Samples were conditioned for 24 hours prior to testing.

A representative sample was picked from each of the three types of slivers involved in the study. The fibers were combed to make them parallel and of equal length. A uniform thin layer 20 mm wide was prepared from the samples. Adhesive tape was placed on one end of the layer and folded to cover 5-mm length of the fibers. Four pairs of such fiber fringes were prepared from representative samples of each of the three types of slivers.

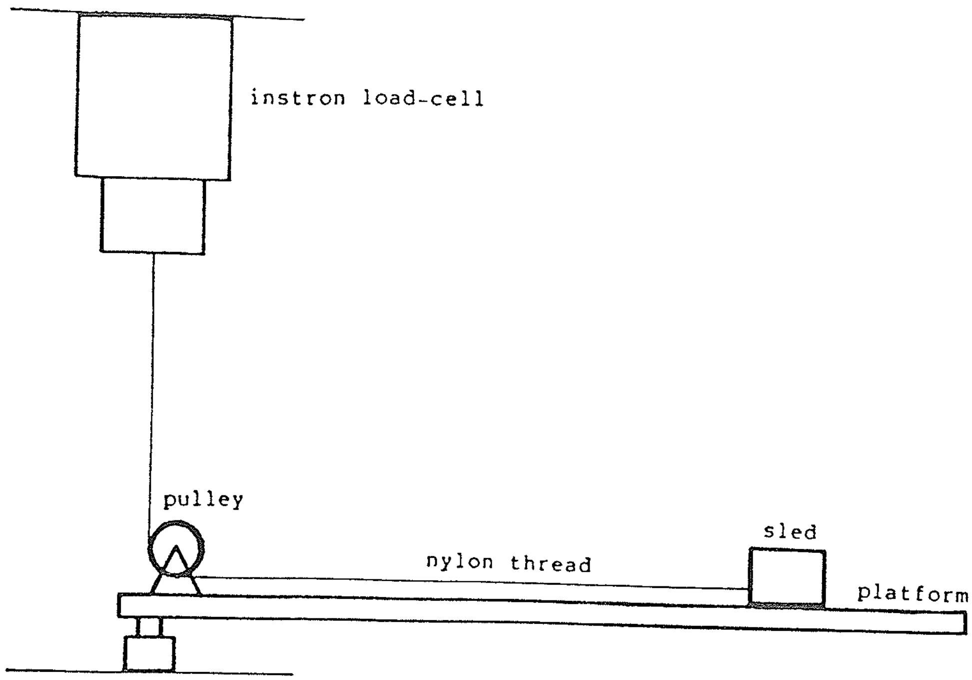

Figure 10. Schematic diagram of friction testing equipment

The pulley end of the platform was mounted on the Instron machine. The following routine was followed in conducting the tests:

1. Clamp one fringe of the pair at one end of the platform.
2. Clamp the other fringe to the sled.
3. Position the nylon thread under the pulley and attach to the Instron load-cell.
4. Place a load (~200 grams) on the sled.
5. Comb the fringes and place the sled over the platform such that the top fringe is lying over the bottom fringe with the free ends pointing in opposite directions.
6. Run the Instron at a rate of 20 mm per minute.
7. Stop the machine when the sled reaches the free end of the bottom fringe.
8. Reset the machine.
9. Repeat steps 5 to 8 ten times and remove the fiber fringes.

The method required that the fibers were straight and parallel before each test.

STATISTICAL ANALYSES

The 10 replications for each condition of test were based on a selected level of precision (.002 grams) and confidence level .05 [20]. The standard deviation statistic was determined after each weighing.

The values of the interaction factors were calculated from the separated fiber and waste output data:

$$k = \frac{\text{mass of stripped fiber}}{\text{average weight of fiber input}}$$

$$l = \frac{\text{mass of waste fiber}}{\text{average weight of fiber input}}$$

Calculation of the static coefficient of friction was determined from a representative curve of the pulling force selected to give the closest fit to the mean curves of each sample. A straight line was drawn so that it either touched peaks, or divided them so that they fell equally on either side of the line, when the heights of the peaks were not equal. The average of the mean forces at the beginning and end of the peak lines for each sample was taken as the average force due to static friction. The coefficient of friction was calculated as follows:

$$\mu = \frac{\text{average force of static friction}}{\text{normal weight of load}}$$

The observed values from the output measurements were expected to satisfy the hypothesis that transfer probability values of the separation system are dependent on the parameters used in the process, as discussed in the previous chapter:

$$a^* = \xi$$

The values of the variables k and l were analyzed by statistical regression methods in order to develop a prediction model of the general form:

$$Y = \beta_0 + \beta_1 X_1 + \ldots + \beta_K X_K + \epsilon$$

where,

Y is the value of the response
$\beta_0, \beta_1, \ldots, \beta_K$ are parameters of the equation
X_K are the values of the independent variables
ϵ is the random error associated with the relationship

Chapter IV

ANALYSIS OF DATA AND DEVELOPMENT OF THE MODEL

This chapter contains a summary of the statistics calculated from the data. It also includes analyses of the statistics and development of the model for predicting the interaction factor from the inter-fiber static coefficient of friction, fiber feeding speed, and separation roll speed variables.

Statistics and graphical representations in this chapter were developed with the assistance of a Statistical Analysis System computer package prepared by SAS Institute Inc.

SUMMARY OF STATISTICS

Statistics were developed from observed measurements of the mass of fiber material deposited in the stripped fiber and waste outputs of the fiber separation section of the rotor yarn spinning machine and the average mass input into the section. Frictional interaction factors k and l were associated with the flow of fibers to the stripped and waste locations, respectively.

The means of the calculated values of the interaction factors are shown in Tables 2 and 3. The pattern of the values indicated that the independent variables, namely, inter-fiber static coefficient of friction, fiber feeding speed and separation roll speed, influenced the values of the response variables k and l.

Table 2. Summary of statistics of values of interaction factor k

Inter-fiber coefficient of friction	Fiber feeding speed	Separation roll speed	k mean	t-test* mean group	CV	Variance
0.28	0.18	6000	0.9900	B	4.76	0.00002722
		7000	0.9849	C	6.41	0.00004491
		8000	0.9663	I	3.72	0.00001789
	0.39	6000	0.9959	A	3.98	0.00001382
		7000	0.9893	B	6.87	0.00001262
		8000	0.9745	H	4.41	0.00002345
	0.60	6000	0.9966	A	3.70	0.00001861
		7000	0.9898	B	4.56	0.00002536
		8000	0.9750	H	3.99	0.00002017
0.31	0.18	6000	0.9810	E C D	5.44	0.00003350
		7000	0.9762	G H	4.66	0.00002568
		8000	0.9612	K	6.34	0.00004202
	0.39	6000	0.9833	E C D	6.65	0.00004778
		7000	0.9803	E G F D	3.90	0.00001958
		8000	0.9689	I	5.19	0.00003025
	0.60	6000	0.9841	C D	3.95	0.00002009
		7000	0.9810	E C F D	6.89	0.00005068
		8000	0.9696	I J	3.66	0.00001756
0.33	0.18	6000	0.9749	H	5.42	0.00003294
		7000	0.9700	I	3.42	0.00001500
		8000	0.9594	K	4.31	0.00001508
	0.39	6000	0.9798	E G F	5.27	0.00003169
		7000	0.9730	H	3.45	0.00001632
		8000	0.9654	J	5.24	0.00003057
	0.60	6000	0.9815	E C D	5.51	0.00003428
		7000	0.9767	G H	3.81	0.00001885
		8000	0.9700	I	5.59	0.00003443

*Means with the same letter are not significantly different at .01 level of significance

Table 3. Summary of statistics of values of interaction factor l

Inter-fiber coefficient of friction	Fiber feeding speed	Separation roll speed	l mean	t-test* mean group	CV	Variance
0.28	0.18	6000	0.0020	S	4.43	0.00000061
		7000	0.0105	N	3.55	0.00000067
		8000	0.0194	H	3.43	0.00000065
	0.39	6000	0.0019	S	7.27	0.00000062
		7000	0.0085	O	3.57	0.00000065
		8000	0.0177	I	3.24	0.00000093
	0.60	6000	0.0009	T	8.95	0.00000071
		7000	0.0054	R	4.93	0.00000077
		8000	0.0168	J	3.66	0.00000096
0.31	0.18	6000	0.0083	P	7.21	0.00000073
		7000	0.0182	I	4.24	0.00000107
		8000	0.0280	A B	3.45	0.00000118
	0.39	6000	0.0081	Q	3.18	0.00000061
		7000	0.0163	K	6.11	0.00000099
		8000	0.0242	D	5.62	0.00000140
	0.60	6000	0.0079	Q	4.62	0.00000061
		7000	0.0123	M	6.98	0.00000079
		8000	0.0235	E	4.24	0.00000095
0.33	0.18	6000	0.0160	L	5.21	0.00000062
		7000	0.0214	F	5.67	0.00000081
		8000	0.0281	A	5.51	0.00000108
	0.39	6000	0.0159	L	5.58	0.00000063
		7000	0.0204	G	6.51	0.00000085
		8000	0.0278	B	5.54	0.00000106
	0.60	6000	0.0156	L	5.54	0.00000062
		7000	0.0189	H	5.12	0.00000068
		8000	0.0250	C	3.57	0.00000072

*Means with the same letter are not significantly different at .01 level of significance

Examination of the correlation figures of the response and independent variables (Table 4) indicated that: (1) the coefficient of friction had a negative effect on the factor k and a positive effect on the factor l, (2) the feeding speed had a positive effect on the factor k and a negative effect on the factor l, and (3) the separation roll speed had a negative effect on the factor k and a positive effect on the factor l. The correlation between the factors (k and l) was negatively high at -.75. The correlation coefficients were determined at the .0001 level of significance.

Table 4. Correlation coefficients of variables*

	Inter-fiber coefficient of friction	Fiber feeding speed	Separation roll speed	k	l
Inter-fiber coefficient of friction	1.00000	0.00000	0.00000	-0.47890	0.00365
Fiber feeding speed		1.00000	0.00000	0.25987	-0.05455
Separation roll speed			1.00000	-0.67058	0.82664
k				1.00000	-0.74595
l					1.00000

*Significance level=0.0001

The significance of the differences in the means of the values was tested by using the t - test at a significance level of .01 (Table 2 and 3). The coefficients of variation were reasonably stable for variable k, and varied from 3.175 to 8.949 for variable l. The variances of the observed values were unequal (Table 5).

Table 5. Variances of k and l at values of the independent variables

Independent variable	Level	Variance k	Variance l
Inter-fiber coefficient of friction	0.28	0.0001657	0.0000200
	0.31	0.0001304	0.0000381
	0.33	0.0001160	0.0000513
Fiber feeding speed (m/min)	0.18	0.0001500	0.0000276
	0.39	0.0001734	0.0000320
	0.60	0.0001426	0.0000380
Separation roll speed (rpm)	6000	0.0001482	0.0000064
	7000	0.0001053	0.0000112
	8000	0.0000832	0.0000189

The dispersions of the mean values of the variable k as illustrated in scatter plots in Figures 11, 12, and 13 illustrate possible heterogeneity in the variance. The dispersion of the means appeared unequal at the values of the independent variables. The dispersion was more at lower values of the coefficient of friction and separation roll speed variables. There was a tendency of the response variable to have lower changes at higher values of the coefficient of friction and larger changes at higher values of the separation roll speed.

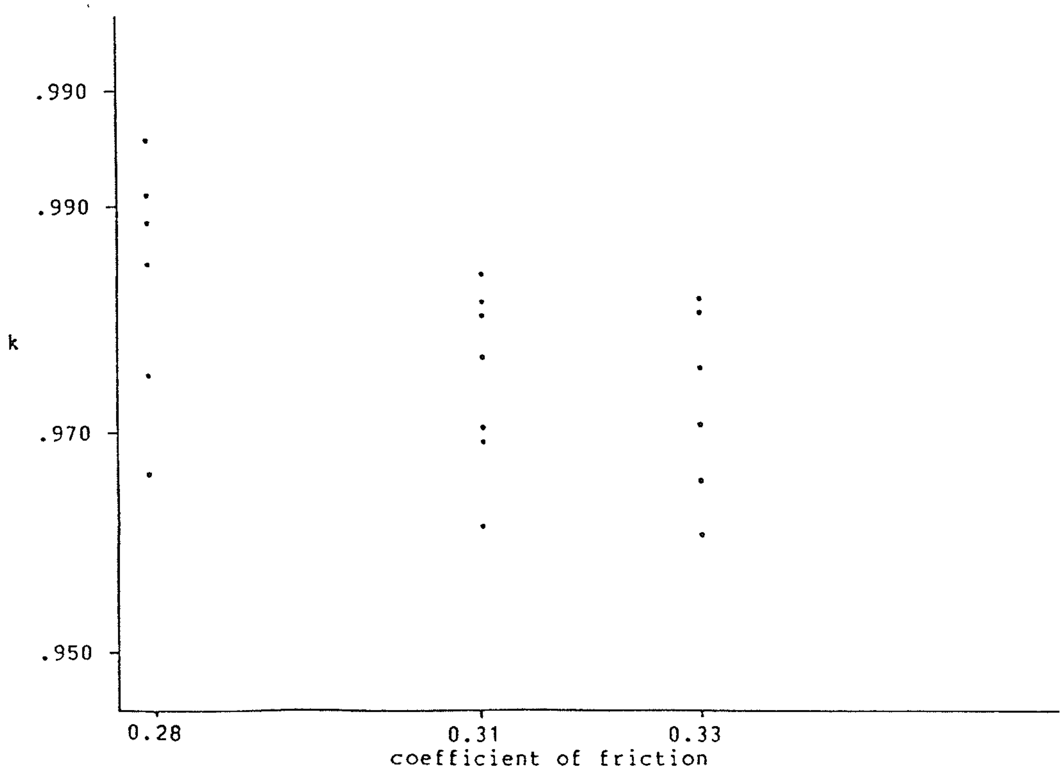

Figure 11. Scatter plots of the mean values of the response variable k versus the coefficient of friction variable

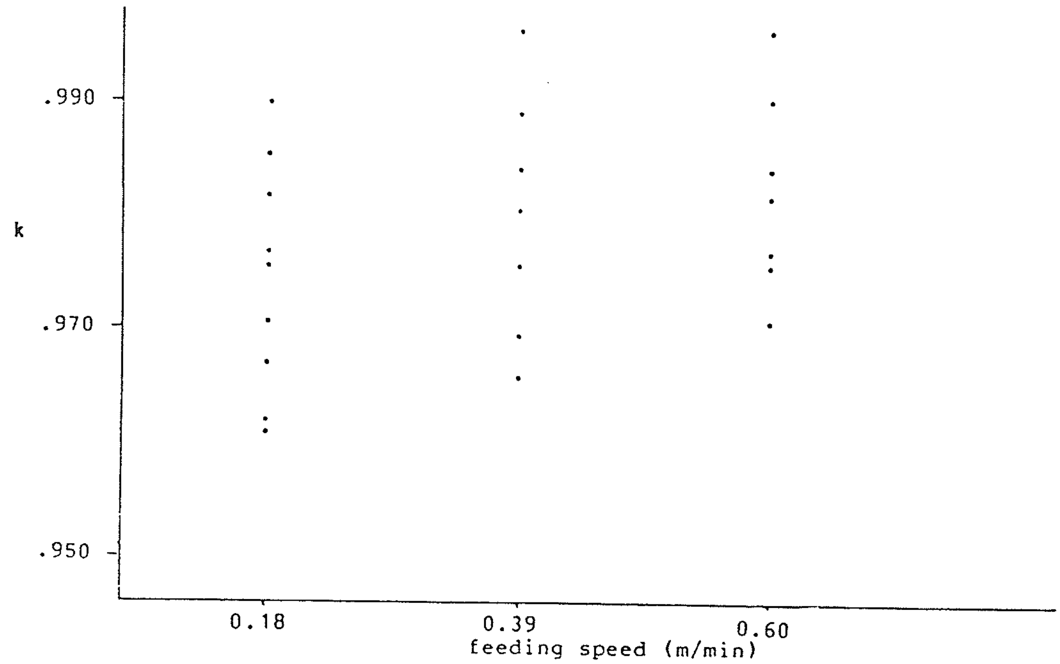

Figure 12. Scatter plots of the mean values of the response variable k versus the feeding speed variable

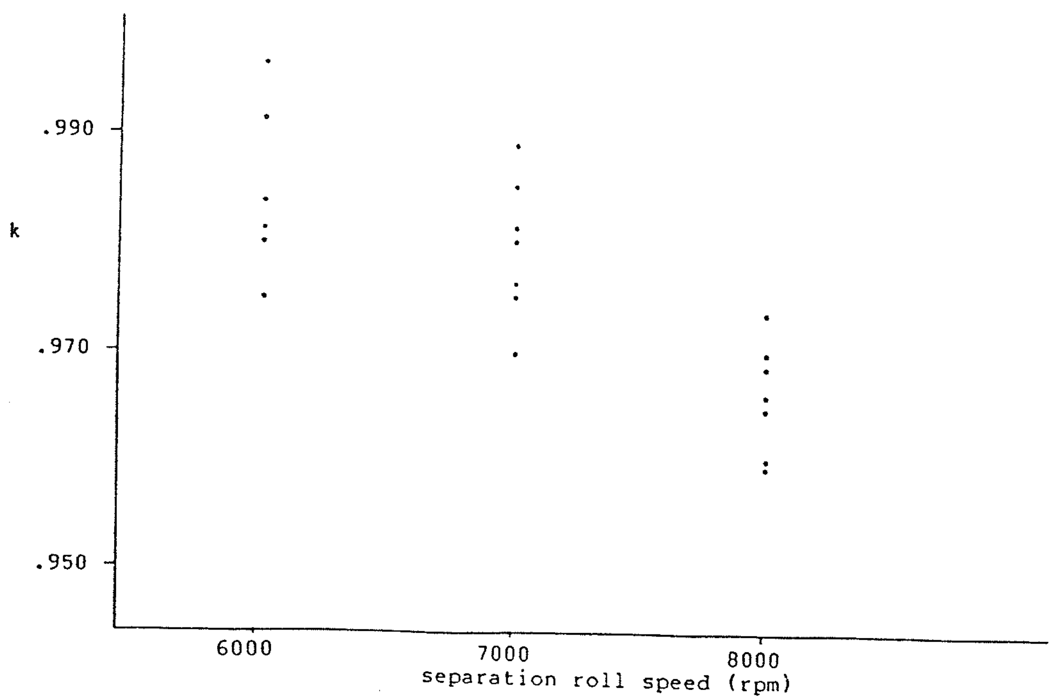

Figure 13. Scatter plots of the mean values of the response variable k versus values of separation roll speed variable

DISCUSSION OF STATISTICS

The above behavior of the response data was reasonable since it appeared to follow some of the expected behavior expressed in the literature as described in Chapter 2.

Conclusions were drawn as to the possible role of frictional forces in the behavior of the response variable, taking into account the information discussed in Chapter 2. However, based on the results from the research, it was not possible to determine the physical magnitude of these influences or the presence of other factors other than those attributed to the parameters of the study. Since the separation process was assumed to be at steady-state it was therefore assumed that all the material engaged and carried to the separation roll/air-transport channel interface was expressed in the response variable k, and the rest of the material was expressed in the response variable l. A noted observation from measurements of waste was that in small measurements, the waste material had a larger proportion of fine wood and cotton seed particles than fibers, while in higher measurements, the waste material had more fibers.

Previous discussions indicated that the static coefficient of friction directly influences frictional force between surfaces (equation 1). Since the condition of a fiber being engaged by the roll depends on the magnitude of the dynamic frictional force created by the action of the roll and the constraining frictional forces in the fiber separation region, an increase in the inter-fiber static coefficient of friction leads to less fibers being engaged by the separation roll, if the striking force of the roll is considered negligible in comparison to restraining forces. Frictional resistance to centrifugal forces during transportation of the fiber by the roll is also increased due to increase in the coefficient of friction which results in less fibers being thrown off the separation roll during transportation. These factors contributed to reductions in the variable k with increase in the coefficient of friction variable and also to a tendency of less reductions in k at larger values of the coefficient of friction. It was noticed by the researcher during preliminary tests that values higher than 0.33 coefficient of friction resulted in high resistance to stripping and hence led to a build up of material on the separation roll and eventually in waste. Increase in the coefficient of friction has been reported to have led to similar results in carding by reducing production [14,31].

Increase in the fiber speed increases the proportion of a fiber in close contact with the moving surface of the separation roll [5,12,36] and also reduces the dynamic force necessary to remove a fiber from the sliver due to the increase in the speed of the fed fibers relative to the speed of the separation roll (equation 2). The frictional force constraining the fiber to the feeding speed is proportional to the proportion of the fiber surface in contact with the slower surfaces. The transition of the fiber to a faster speed depends on the proportions of the fiber in contact with the slower moving or stationary surfaces and the faster moving surface (equations 3 and 4). These factors probably increased the chance of the fiber material being engaged by the roll and led to higher values of the variable k. The influence of the feed speed was almost negligible due to the magnitude of the separation roll speed in relation to the feeding speed. Therefore the changes were observed to be small and tended to diminish as the feeding speed values increased.

An increase in the separation roll speed leads to an increase in the magnitude of constraining frictional forces created due to the withdrawal action of fibers from the sliver [36]. It also leads to an increase in centrifugal forces acting on a fiber body during transportation to the interface. Consequently, fewer fibers are separated and more fibers are thrown off by the action of the roll resulting in a large increase in the variable l. Similar results have been observed in studies of the licker-in in the carding process [24]. The capacity of the separation roll to engage fibers is also dependent on the dimensions of the roll's teeth [12,36]. Hence, the increase in the amount of fiber engaged by the roll, as the roll speed is increased, has a limit.

Results from open-end studies [25] have indicated that, in general, the amount of material removed during the separation process depends on the speed of the separation roll, the amount of fiber supplied and the type of fiber processed. The faster the separation roll speed the smaller the amount of fibers removed at the separation zone. The amount of fibers engaged by the separation roll decreases exponentially as the roll speed increases and increases as the amount of fibers supplied increases. Resistance to the separation roll force changes with the type of fiber (such as fibers exhibiting different magnitudes of coefficients of friction).

It was suspected from examination of the scatter plots of mean values (Figures 11, 12, and 13) that the values of the variable k converged at higher values of the independent variables. The unequal dispersion observed in the plots signified unequal variances in the data. The dispersions also indicated possible interaction of the variables.

Tests on significance of differences in means revealed that there was no significant difference in some of the means. Some tests [12] have shown statistically insignificant differences in linear densities of yarn (regarded as a good indicator of changes in k) when the separation roll speed is varied. However, data from this study indicated a trend in the means and a significant difference in most of them. The trend basically satisfied the hypothesis on the relationship between final transfer probability and certain process parameters (equation 5). This meant that a mathematical equation could be developed from the data to express the relationship.

THE MODEL

The functional relation in the response variables, k and l, and the the independent variables of inter-fiber static coefficient of friction, fiber feeding speed, and separation roll speed, was previously expressed as:

$$k = f(\chi, \phi, \psi)$$

$$l = f(\chi, \phi, \psi)$$

The physical form of this relationship may be expressed by a mathematical equation. This section contains a discussion of the development of such a relationship. Since the response variables k and l were highly correlated, the values of the variable k were chosen to develop the relationship. However, this does not mean that two separate models may be developed from the data if both variables are of interest. In such a case the variables k and l will have to be analyzed simultaneously.

The relationship between the k and the coefficient of inter-fiber friction, the fiber feeding speed, and the separation roll speed variables was developed by assuming a linear relationship in the unknown parameters of the equation relating the independent variables, and then estimating the parameters by using the observed data to generate a set of equations expressing this relationship. The common method of developing this relationship is the method of least squares to solve the set of equations [13,30]. Such an analysis takes into account slight errors in the data and produces a regression surface from the locus of the means of the values.

Regression Model

The simple form of a regression equation is,

$$Y = \beta_0 + \beta_1 X_1 + \ldots \ldots + \beta_K X_K + \epsilon$$

where,

Y is the value of the response
β_0, β_1, ..., β_K are parameters
X_1, X_2, and X_K are values of the independent variables
ϵ is the random error term in the model

The parameters indicate to what degree the independent variables change the response variable. The variables alone do not account for all the variation in the response, so an error term ϵ is included to account for the undetermined source of variation. The regression equation is estimated by the prediction model:

$$\hat{Y} = b_0 + b_1X_1 + \ldots + b_KX_K$$

where,

$\hat{Y}$ is the predicted value of Y
$b_0, b_1, .., b_K$ are estimates of $\beta_0, \beta_1, .., \beta_K$

The value of ϵ in the equation is unknown since it changes with each observation.

The method of least squares solves the set of equations from the observations of the response variable:

$$Y_i = \beta_0 + \beta_1X_1i + \ldots + \beta_KX_Ki + \epsilon i$$

where,

Y_i is the value of the response in the i-th observation
X_K are the values of the independent variables in the i-th observation
ϵi is the random error in the i-th observation

The sum of squares from such a line would be:

$$\sum_{i=1}^{n}(Y_i-Y_i)^2$$

The least squares solution is the surface for which the sum of squares is a minimum.

In order to apply the methods of linear regression to develop the prediction model, certain assumptions on the errors are required. The necessary assumptions concerning the errors, ϵi, are [13,30]:

1. The expected value of ϵi, $E(\epsilon i)$, is zero. This indicates that the model is appropriate for the data.
2. The variance of ϵi, $V(\epsilon i)$, is equal to σ^2. This means that the variance is constant.
3. The covariance of ϵi, and ϵi, $cov(\epsilon i, \epsilon i)$, is equal to zero, i/=j. This means that the values ϵi and ϵ are uncorrelated.
4. Measurement errors relative to the independent variables are small with respect to σ.
5. ϵi is normally distributed, $\epsilon i \sim N(0,\sigma^2)$.

An importance of the second assumption is that the error mean square statistic obtained in the development of the model may be used as an estimate of the variance, σ^2, of the relationship of the response variable k and the independent variables [13,30]. Previous examination of the data of this study indicated that the variances were unequal. Bartlett's test technique was used to test for homogeneity in the variance. The test is on the null hypothesis:

$$H_0: \ \sigma^2{}_{111}=\sigma^2{}_{112}=\sigma^2{}_{113}=\sigma^2{}_{121}=\sigma^2{}_{122}=\ldots.\sigma^2{}_{333}$$

where, σ^2 is estimated by s^2.

Development of the Empirical Model

The initial assumption in the development of the empirical model was that the dependence of the variable $\bar{k}$ could be presented from the linear, joint, and quadratic terms of the independent variables. Joint terms were regarded as being important in order to account for the lack additivity of the errors at the values of the independent variables [9]. A source of lack additivity is the interaction of the variables as the levels are changed. This was observed from the unequal dispersion of the plots of the means of the variable k (Figures 11, 12, and 13). Quadratic terms were necessary to account for the departure of the response values from linearity which was indicated by the convergence of the means at higher values of the independent variables.

The complete model was of the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1X_2 + b_5X_1X_3 + b_6X_2X_3 + b_7X_1^2 + b_8X_2^2 + b_9X_3^2 + e$$

where,

$X_1, \ldots, X_3$ are the linear terms
X_1X_2, X_1X_3, and X_2X_3 are the joint terms
X_1^2, X_2^2, and X_3^2 are the quadratic terms

In order to determine the appropriateness of the model, the assumptions made in the previous section on the errors were examined for any violations. Since the value of the error ϵ_i is not measurable, the examination was conducted indirectly by using the residuals e_i [9,13,30]. Residuals are the calculated differences between the observed value (Y_i) and the predicted value ($\hat{Y}_i$), where i is the observation. The residuals were examined graphically for peculiar and systematic patterns indicating violations of the assumptions on errors. The graphical methods used were plots of the weighted residuals against the observed, predicted, and independent variables and histogram plots of the standardized residuals. The residual plots were also used to detect potential outliers due to unusually high or low values of the data or inadequacy of the prediction model. Detection of outliers is important because it helps determine how the data should be analyzed. The residuals were plotted against the variables in the weighted form:

$$t_i = \frac{e_i}{s_i}$$

where, s_i^2 is the estimate variance of the i-th observation.

The plots of the residuals against the variables were expected to show an even and random distribution of points [9,13,30].

The histogram was expected to show a normal distribution of the standardized residuals. The standardized residuals were of the form:

$$r_i = \frac{e_i}{s}$$

where, s^2 is the estimate of the variance of the errors σ^2.

Normality was tested by using the Kolmogorov test on the null hypothesis for normal distribution.

Analysis of outliers was performed quantitatively by conducting tests on the standardized residuals [9,13,30]. This was done by evaluation of the histogram statistics for the quantity of values outside +/-1.96 ($\pm 2\sigma$).

The relationship of the residuals with the errors is clearly shown in the equation [9,13,30]:

$$e_i = \epsilon_i - \sum_{j=1}^{n} s_{ij}^2 \epsilon_i$$

The above relationship also shows the dependence of the residuals on the influence of variances. If the variances s_{ij}^2 are sufficiently small, e_i is a reasonable estimate of ϵ_i, as implied by assumption 2. If the value of s_{ij}^2 is large, the predicted value of Y_{ij} will be large relative to the remaining values. If the observed variance is not constant the variance in the prediction model will be large. The test for homogeneity of variance was conducted by using the Bartlett's test on the null hypothesis at the values of the independent variables, at a .05 level of significance. The results indicated lack of homogeneity at the values of the coefficient of friction and separation roll speed. It was necessary to use the method of weighted least squares in developing the prediction model in order to minimize the effect of the residual sum of squares in the model.

The method of weighted least squares is used to analyze data for which the variance is not homogeneous. The method helps to obtain estimated parameters with no bias and with small variance. Weights were applied in the form [13]:

$$w_i = \frac{1}{s_i^2}$$

Regression analysis of the data provided important statistics such as the following [13]:

1. The standard errors of the estimated parameters are an indication of how close to the parametric value the estimater is. A small value is more desirable.
2. The F - test indicates how well the independent variables accounted for the variability in the dependent variable. Accompanying the F value is the probability value or the observed level of significance, P. The smaller P>F is, the more significant the result.
3. The square of the correlation coefficient, R^2, is a measure of variation about the mean of the observed values expressed by the model. A large R^2 statistic is more desirable.
4. The sequential and partial sum of squares explain the significance of terms in the model. The sequential sum of squares gives the importance of the variable entered at that stage of the

regression, while the partial sum of squares gives the importance of a variable in the model, given that all the variables, excluding the variable, are present in the model.

5. The residual or error mean square value is a measure of the precision of the prediction. A small statistic is more desirable.

6. The T - test statistic is equivalent to the partial sum of squares F - test statistic. The F statistic is the square of the T statistic. The T - test is the Student t - test of the null hypothesis on the parameters:

$$H_0: \beta_1=0, \ldots, \beta_K=0.$$

The result of the test indicates whether there is significant relation between the parameters of the independent variables and the response. The T statistic is accompanied by a probability value, P. The smaller the $P>|T|$ value the more the parameters differ from 0.

The model was built by first considering regressions by the linear terms of the independent variables individually. Table 6 contains the statistics from the univariate regressions of each of the independent variables on the response variable k.

Table 6. Regressions of the variable k by the independent variables

Variable*	Error mean square	F(P>F)	R^2	b_1	T(P>|T|)	Estimate std.error
χ	5.14269	101.59 (0.0001)	0.27488	-0.27982	-10.08 (0.0001)	0.0277613
ϕ	6.25107	36.06 (0.0001)	0.11860	0.02283	6.01 (0.0001)	0.0038022
ψ	3.19022	327.79 (0.0001)	0.55018	-0.00001	-18.10 (0.0001)	0.0000006

*χ = inter-fiber coefficient of static friction, ϕ = fiber feeding speed, and ψ = separation roll speed.

The linear dependence on the individual variables was significant as indicated by the T - test statistics. The squares of the correlation coefficient indicated that .27, .12, and .55 of the variation in the data was accounted for by the models due to regression by the coefficient of friction, feeding speed, and separation roll speed variables, respectively. All the F - test statistics indicated significant accountability of error by the models. The T - test and F - test statistics were equivalent, as indicated in the previous discussion. The T - test statistics indicate high significance. This implies high accountability of the response variable by the estimated parameters and high importance of the linear terms. The values of the residual sum of squares appeared inflated which indicated the need for improvement of the prediction model in order to reduce the high errors associated with the univariate regressions.

A model was developed from the combination of the independent variables using their linear terms. The variables were combined by starting with the independent variable of highest influence on the response variable and adding the remaining variables in order of their influence as indicated in the univariate regressions. Table 7(a) contains the statistics of the regression model.

The statistics indicated more dependence by the response variable on the combined independent variables than on the individual variables. The square of the multiple correlation coefficient, indicated that .81 of the variation in the data was accounted for by the model. The overall F - test statistic was high and indicated significant accountability of the variation. The sequential sum of squares statistics indicated that the addition of the coefficient of friction and feeding speed terms to the separation roll speed (which had the highest dependence in the univariate model) contributed significantly. The information given by the the partial sum of squares statistics indicated that the importance of each variable in the model was similar to that indicated in the univariate regressions.

Table 7(a). Regression of the variable k by the linear terms of the combined independent variables (weighted least squares method)

Model	Source of variation	Error mean square	F(P>F)	R^2	Sequential sum of squares	F(P>F)	Partial sum of squares	F(P>F)	Parameter estimate	T(P>T)	Estimate std. error
linear		1.34481	382.45 (0.0001)	0.81180							
	b_0								1.1083485	218.75 (0.0001)	0.00506681
	b_1				1045.7249	777.60 (0.0001)	864.0521	642.51 (0.0001)	-0.0000095	-25.35 (0.0001)	0.00000037
	b_2				391.9344	290.99 (0.0001)	345.3273	256.78 (0.0001)	-0.2298789	-16.02 (0.0001)	0.01434547
	b_3				105.9344	78.77 (0.0001)	105.9344	78.77 (0.0001)	0.0157967	8.88 (0.0001)	0.00177984

*b_1 = separation roll speed, b_2 = inter-fiber coefficient of static friction, and b_3 = fiber feeding speed.

The partial sum of squares statistics indicated that the separation roll speed was the most important variable in the model and the feeding speed was the least important. The estimated parameters were highly significant as indicated by the T - test statistics. Figures 14, 15, and 16 show the scatter plots of the residuals against the coefficient of friction, the feeding speed, and the separation roll speed variables, respectively. Due to the vertical scatter of the plots the dependence of the residuals on the variables was not obvious.

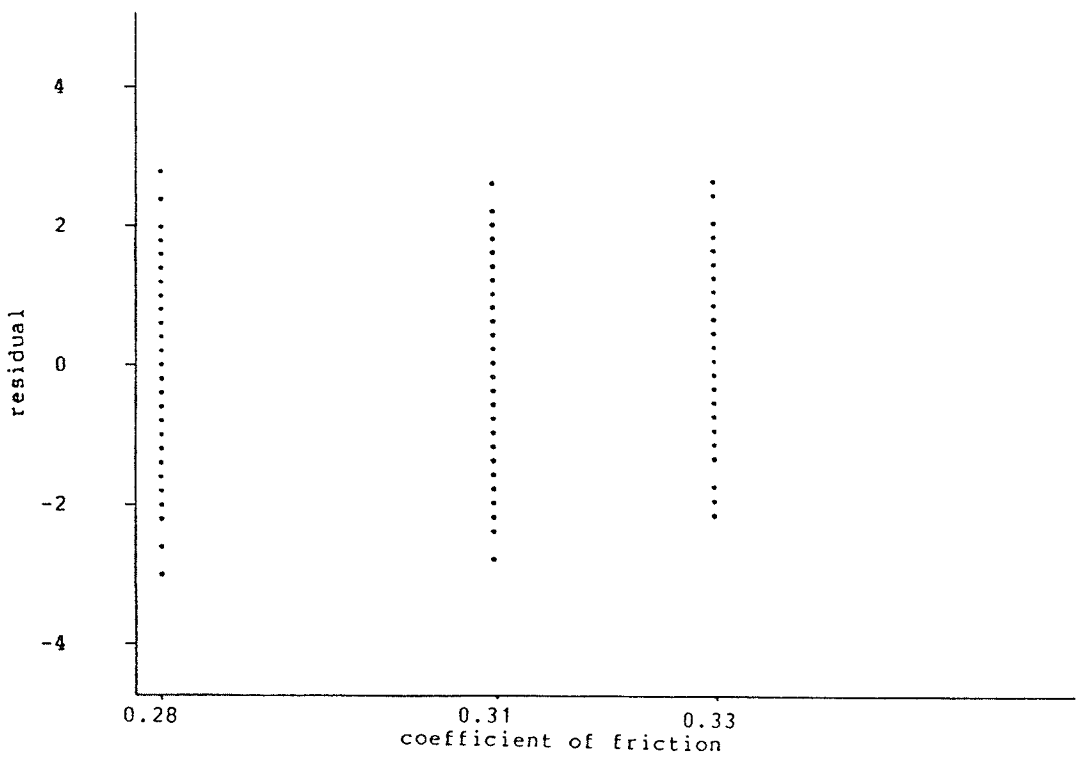

Figure 14. Scatter plot of residuals versus coefficient of friction of the combined variables model of linear terms

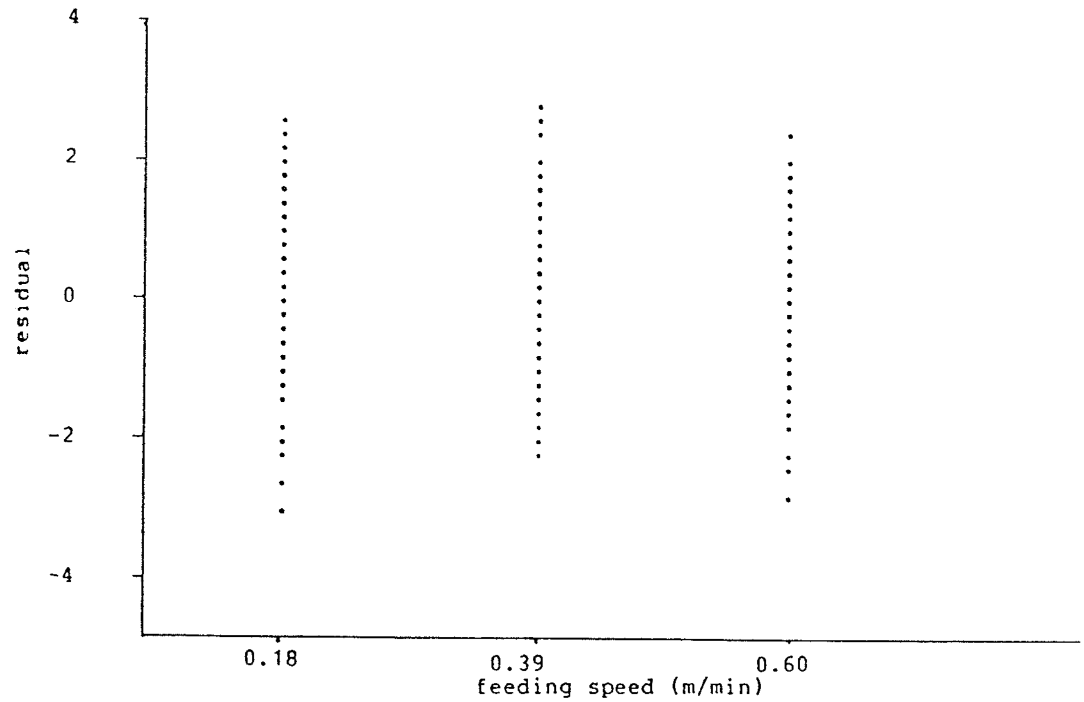

Figure 15. Scatter plot of residuals versus feeding speed of the combined variables model of linear terms

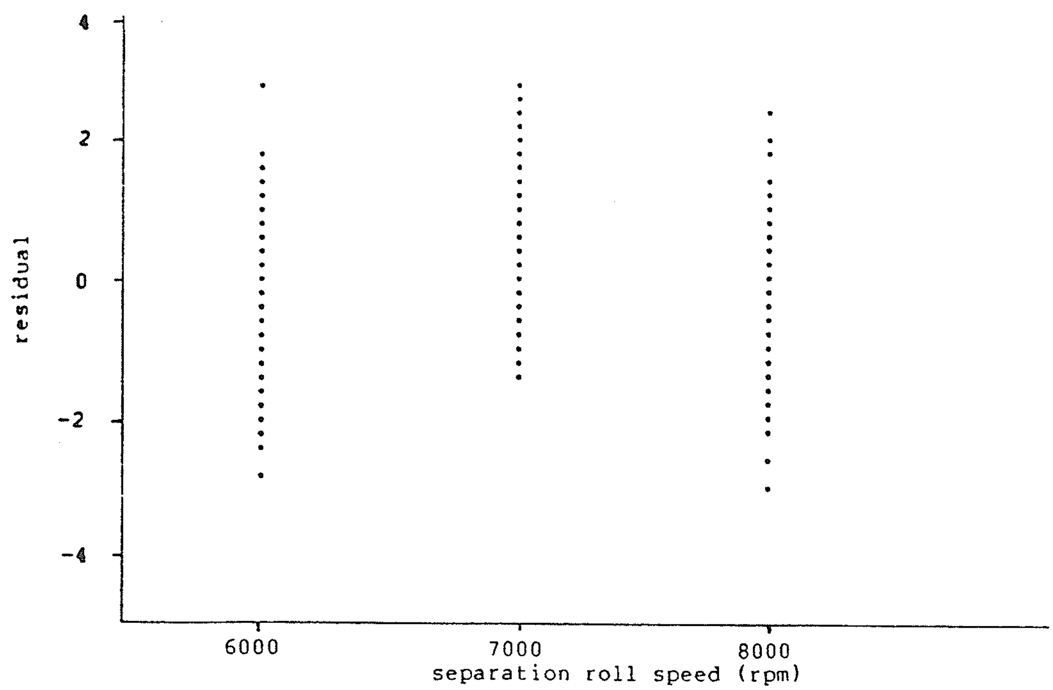

Figure 16. Scatter plot of residuals versus separation roll speed of the combined variables model of linear terms

Weighted residuals were plotted against the predicted data (Figure 17). The plots indicated no violation of the assumptions made regarding errors. There was also no indication of potential outliers.

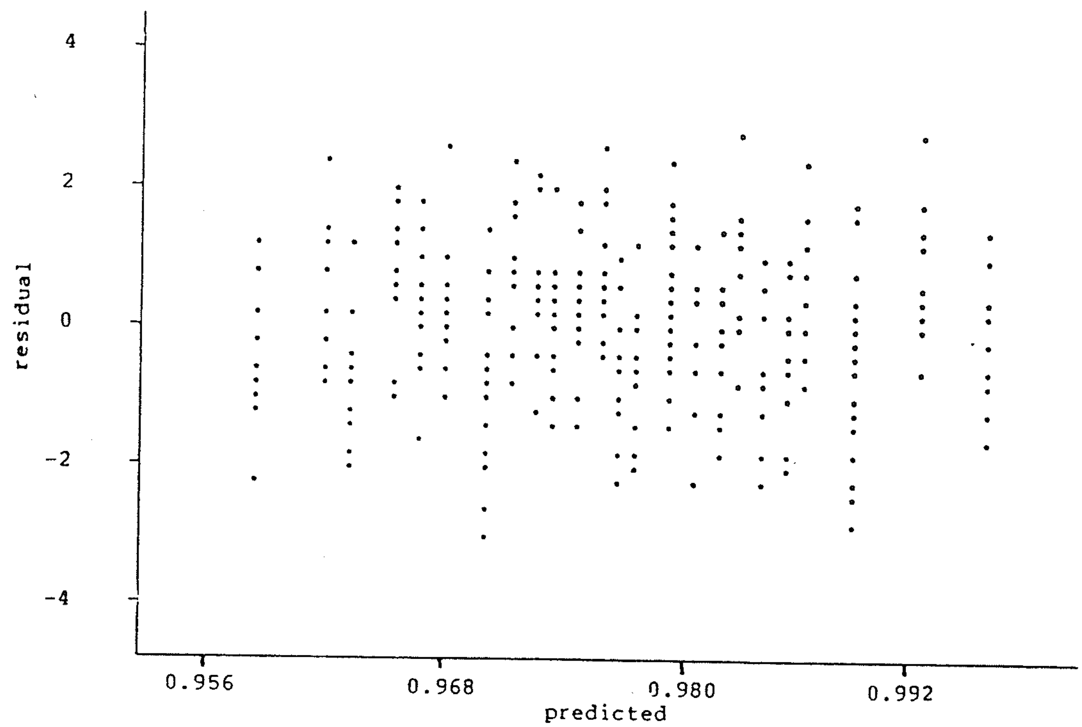

Figure 17. Scatter plot of residuals versus predicted values of the combined variables model of linear terms

Table 7(b) contains statistics from a regression of the response by the linear terms using the method of ordinary least squares. The improvement achieved by using weighted least squares (Table 7(a)) indicates the adverse effect of variance heterogeneity in prediction and the need for weights in the analysis of the data.

Table 7(b). Regression of the variable k by linear terms of combined independent variables (ordinary least squares method)

Model	Source of variation	Error mean square	F(P>F)	R^2	Parameter estimate	T(P>T)	Estimate std.error
linear		0.00004	261.18 (0.0001)	0.74656			
	b_0				1.1098997	192.53 (0.0001)	0.00576477
	b_1				-0.0000088	-21.72 (0.0001)	0.00000041
	b_2				-0.2502974	-15.51 (0.0001)	0.01613292
	b_3				0.0162770	8.42 (0.0001)	0.00193335

*b_1 = separation roll speed, b_2 = inter-fiber coefficient of static friction, and b_3 = fiber feeding speed.

The method of weighted least squares improved the value of the estimated parameters, and reduced their standard errors. The square of the multiple correlation coefficient improved from .75 to .81, indicating more accountability of the variation in the data by the weighted least squares model. The weighted least squares method produced a better fitting prediction model. However, high dependence on linear terms did not mean that other terms were not required.

The next stage in the development of the model was the addition of joint terms (page 16) to the model. The terms were analyzed for the significance of their contributions (Table 9). The square of the multiple correlation coefficient statistic was .83. The improvement was not regarded large since the addition of more terms will always lead to more variation response being accounted for by the model. The overall regression F - test statistic was significant as in the previous model. The importance of the addition of the joint terms was evaluated by examining the sequential sum of squares statistics. The statistics indicated that the contributions of the terms to the model were not significant, except for the separation roll/coefficient of friction term. The T - test statistic for the feeding speed linear term parameter estimate was adversely affected by the addition of joint terms. The estimated parameters of the separation roll speed/feeding speed and coefficient of friction/feeding speed joint terms were not significant, and therefore not necessary.

Table 8. Regression of the variable k by the linear and joint terms of the independent variables

Source of variation*	Sequential sum of squares	F(P>F)	Parameter estimate	T(P>|T|)	Estimate std. error
b_0 |			1.3054740	33.25 (0.0001)	0.03926679
b_1 |	1045.7249	862.44 (0.0001)	-0.0000368	-7.04 (0.0001)	0.00000523
b_2 |	391.9344	322.73 (0.0001)	-0.8189125	- 6.45 (0.0001)	0.12690867
b_3 |	105.9344	87.37 (0.0001)	-0.0444998	-1.57 (0.1176)	0.02834068
b_4 |	25.3190	20.88 (0.0011)	0.0000816	4.84 (0.0001)	0.00001684
b_5 |	13.1846	10.87 (0.0001)	0.0000067	3.28 (0.0012)	0.00000205
b_6 |	0.32265	0.27 (0.6064)	0.0413883	0.52 (0.6064)	0.08023336
Error mean square					1.21253
F					217.43
P>F					0.0001
R^2					0.83222

*b_4 = separation roll speed/inter-fiber coefficient of static friction, b_5 = separation roll/feeding speed, and b_6 = inter-fiber coefficient of static friction/feeding speed.

There was no peculiarity in the plot of the residuals against the predicted data (Figure 18). This was expected since the plot from the linear terms model did not show any problems with data.

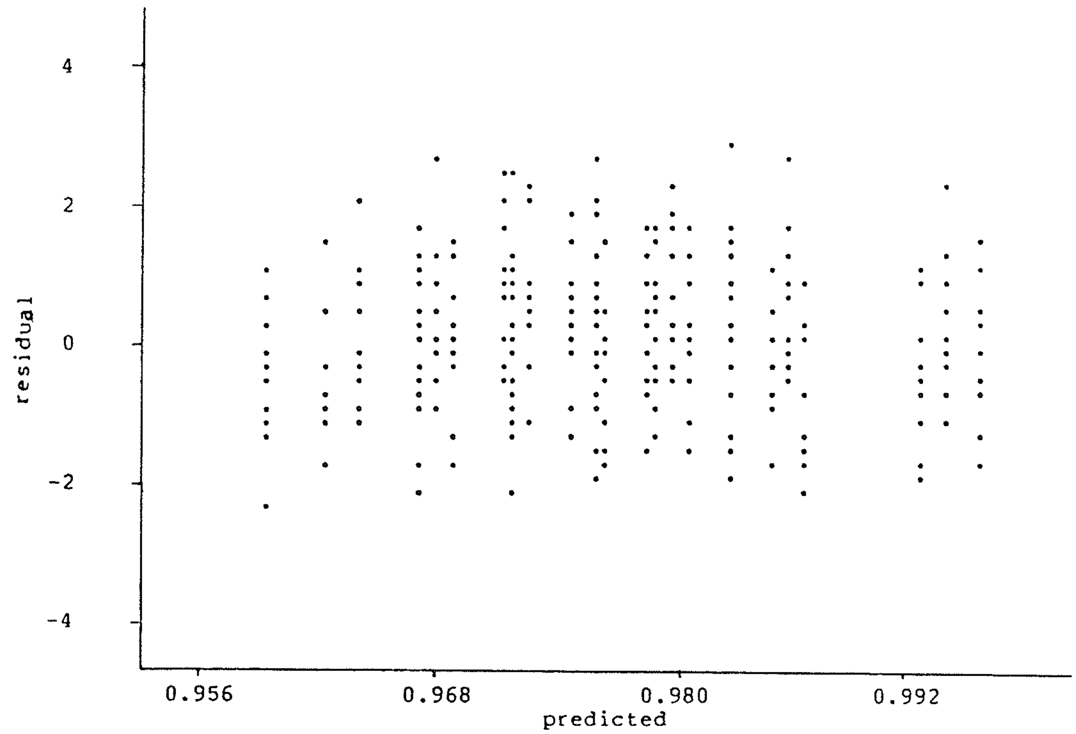

Figure 18. Scatter plot of residuals versus predicted values of the model of linear and joint terms

The last stage in the development of the model was the addition of quadratic terms (Table 9). The square of the multiple correlation coefficient improved to .87. The sequential sum of squares statistics indicated that the contributions of the separation roll speed and feeding speed quadratic terms were significant. However, since the estimated parameter of the separation roll speed term was close or equal to zero, this term appeared to be unnecessary in the prediction model. A separate analysis of the feeding speed quadratic term indicated that the term could not be used as an alternative to the linear term since this did not lead to an improvement of the overall statistics of the regression. The importance of the estimated parameters of all the linear terms were adversely affected by the addition of quadratic terms. This meant that the use of linear and quadratic terms together was not an advantage. The scatter plot of the weighted residuals against the observed and the predicted values (Figure 19) showed an improved overall appearance in the distribution of the residuals.

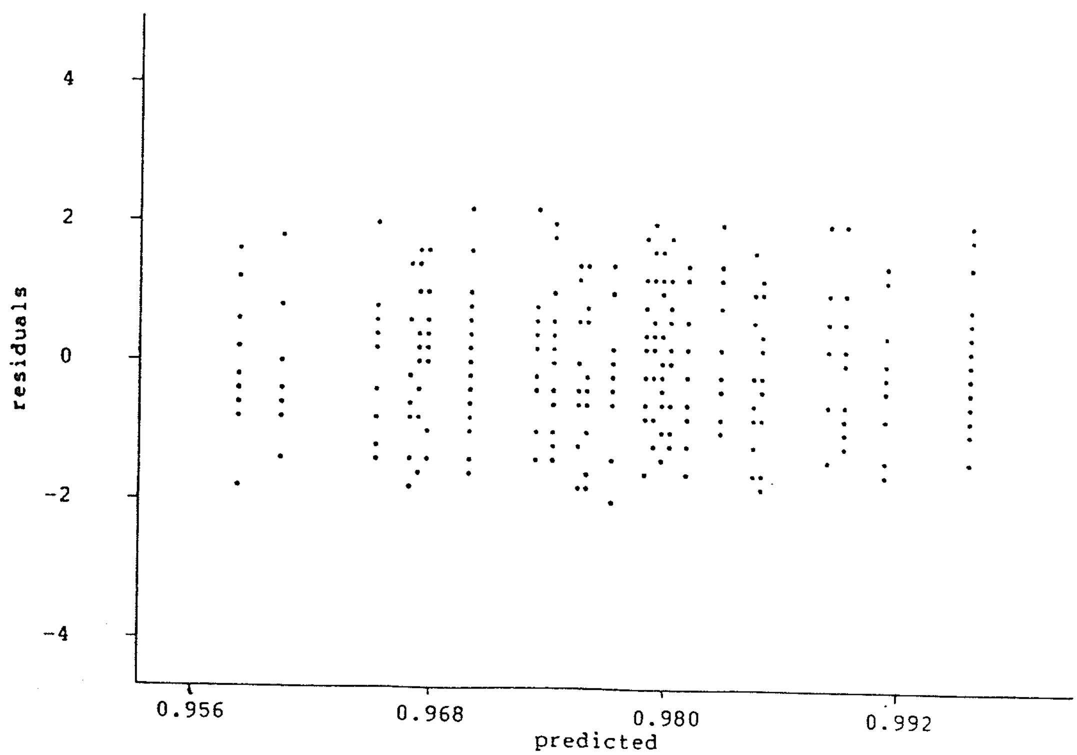

Figure 19. Scatter plot of residuals versus predicted values of the model of linear, joint, and quadratic terms

Table 9. Regression of the variable k by the linear, joint, and quadratic terms of the independent variables

Source of variation*	Sequential sum of squares	F(P>F)	Parameter estimate	T(P>|T|)	Estimate std. error
b_0|			1.2781612	-12.74 (0.0001)	0.10028904
b_1|	1045.7249	1071.08 (0.0001)	0.0000153	-1.70 (0.0910)	0.00000900
b_2|	391.9344	108.50 (0.0001)	-1.8668049	-3.09 (0.0022)	0.60476486
b_3|	105.9344	25.93 (0.0001)	0.0048707	0.17 (0.8647)	0.02855953
b_4|	25.3190	25.93 (0.0001)	0.0000852	5.60 (0.0001)	0.00001522
b_5|	13.1846	13.50 (0.0003)	0.0000057	3.07 (0.0024)	0.00000186
b_6|	0.32265	0.33 (0.5659)	0.0372216	0.51 (0.6083)	0.07253665
b_7|	45.8969	47.01 (0.0001)	-0.0000000	-6.53 (0.0001)	0.00000000
b_8|	2.98532	3.06 (0.0815)	1.6500427	1.69 (0.0929)	0.97840618
b_9|	16.16741	16.56 (0.0001)	-0.0514069	-4.07 (0.0001)	0.01263276

Error Mean Square	0.97632
F	187.41
P>F	0.0001
R^2	0.86645

*b_7 = separation roll speed, b_8 = feeding speed, and b_9 = inter-fiber coefficient of static friction.

Selected Model

The nature of separation technology made it necessary to consider it important to include all the linear terms of the independent variables in the model. Since the contributions of the joint and quadratic terms did not add significant information to the linear model, the conclusion was that within the limits used for the variables values, the response was adequately accounted for by the linear parameter estimates. The selected model was of the form:

$$k = 1.10835 - 2.2988\text{x}10\chi + 1.5797\text{x}10^2\phi - 9.5\text{x}10^6\psi$$

Table 7(a), page 63, contains the statistics of the selected model. The model's accountability of variation in the data is high at 81%. The overall regression F - test is highly significant at a .0001 propability value, and so are the sequential and partial statistics. The residual mean square, or variance of the data, is low. The estimated parameters are highly significant as indicated by the T statistics.

The parameters and the statistics of the model are reasonable in their reflection of the trends in the observed data. The inter-fiber static coefficient of friction and the separation roll speed terms lower the value of the interaction factor and the feeding speed term raises it. It was expected that the importance of the separation roll speed term would dominate because of the magnitude of the operation mode of the separation device. Each term of the separation roll speed variable had the largest contribution to the model in the linear, joint, and quadratic terms. It was also expected that the coefficient of friction term would contribute the most to the error value because of the varying nature of cotton fiber properties.

ADEQUACY OF MODEL

It is important that the selected model shows high agreement with the observed data.

A final graphical assessment of the residuals was made to examine the adequacy of the model. Examination of the plot of means of weighted residuals against the observed values (Figure 20) indicated an even distribution of the high and low values of the residuals [13]. This is a desired indication that the model is appropriate. The plot also indicated that the model is appropriate over all observed values. Figure 21 shows the histogram distribution of the standardized residuals and the results of the normal distribution tests. The Kolmogorov test (D statistic) indicated a highly significant normal distribution. The normal probability plot illustrated good agreement between the model residuals and the normal distribution. The tests and the plots indicated that the residuals were random with distribution $N(0,\sigma^2)$ (See assumption 5). 98% of the residuals are within -1.73 and +1.73, which are within the acceptable limits of the 2σ value of the normal distribution [13].

Figure 22 shows a plot of the predicted mean values against observed mean values. The plots were close to the diagonal line described at 45^0 from each axis. This information is an indication of good fit of the prediction model.

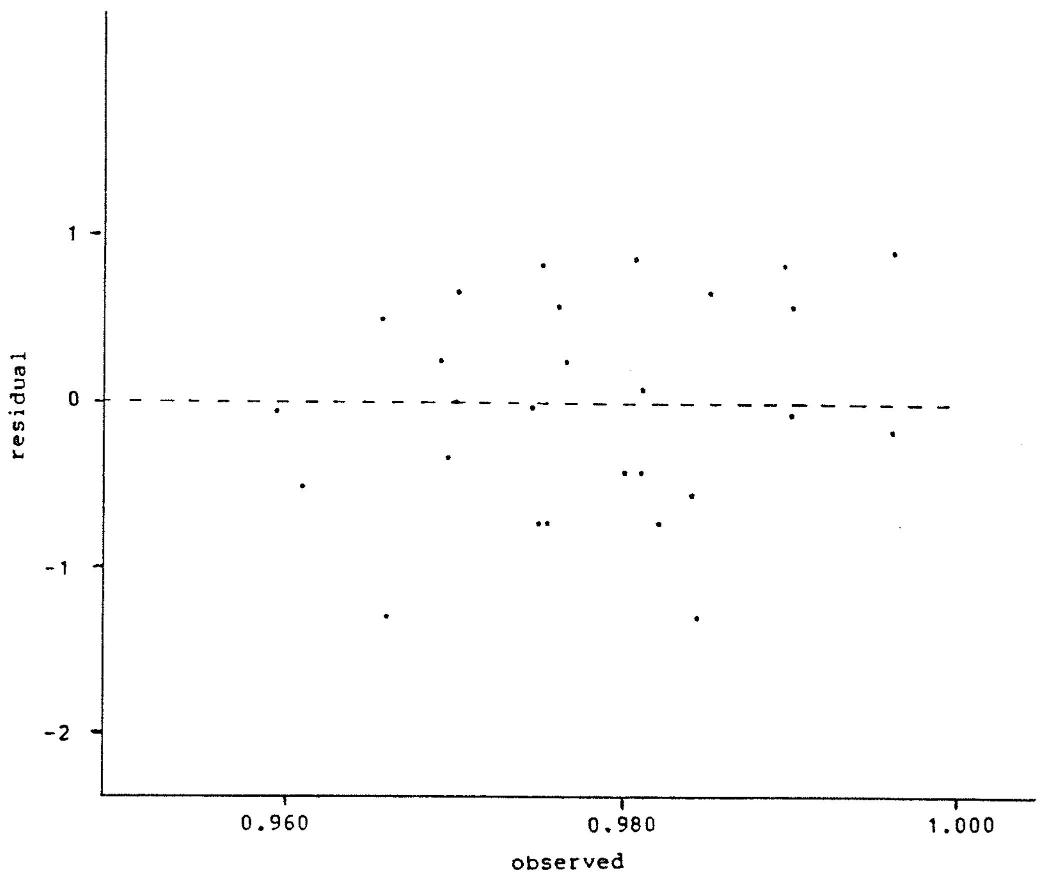

Figure 20. Scatter plot of residual means versus observed data of the model of linear terms

```
D:NORMAL     0.028033   PROB>D          >.15

                    HISTOGRAM                      #
  3.25+*
      .*                                           1
      .***                                         1
      .********                                    5
      .***********                                15
      .*******************                        19
      .*********************************          36
      .**********************                     62
      .*********************                      44
      .**************                             42
      .*****                                      28
 -2.25+****                                       10
       ----+----+----+----+----+----+-             7
```

QUANTILES

99%	2.40741
95%	1.67747
90%	1.29587
10%	-1.25089
5%	-1.73053
1%	-2.18345

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                    NORMAL PROBABILITY PLOT
  3.25+
       |                                                   *
       |                                                   *
       |                                              ****+
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       +----+----+----+----+----+----+----+----+----+----+
           -2        -1         0        +1        +2
```

Figure 21. Plots of normality of the residuals of the model of linear terms

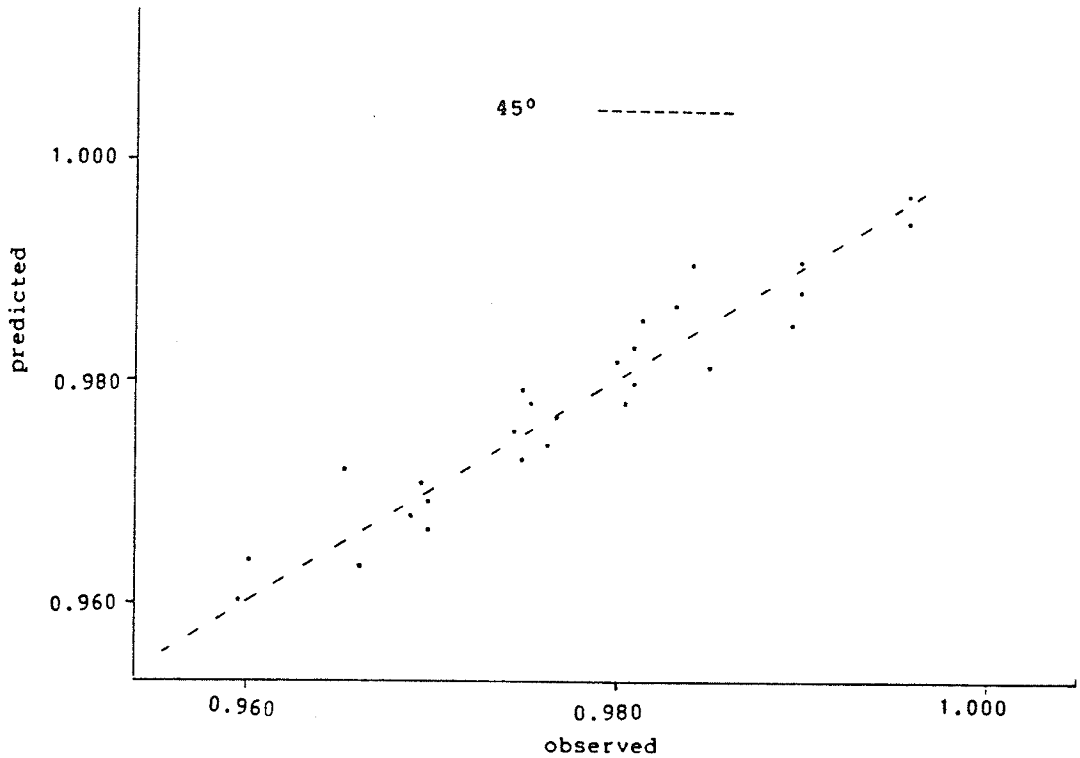

Figure 22. Scatter plot of mean values of predicted versus observed data of the model of linear terms

Figures 23, 24, and 25 show comparisons of the means of the predicted and observed values of the variable k against the coefficient of friction, feeding speed, and separation roll speed, respectively. The plots indicated good prediction of the variable k by the model. Therefore the terms in the model were considered adequate in expressing the behaviour of the data.

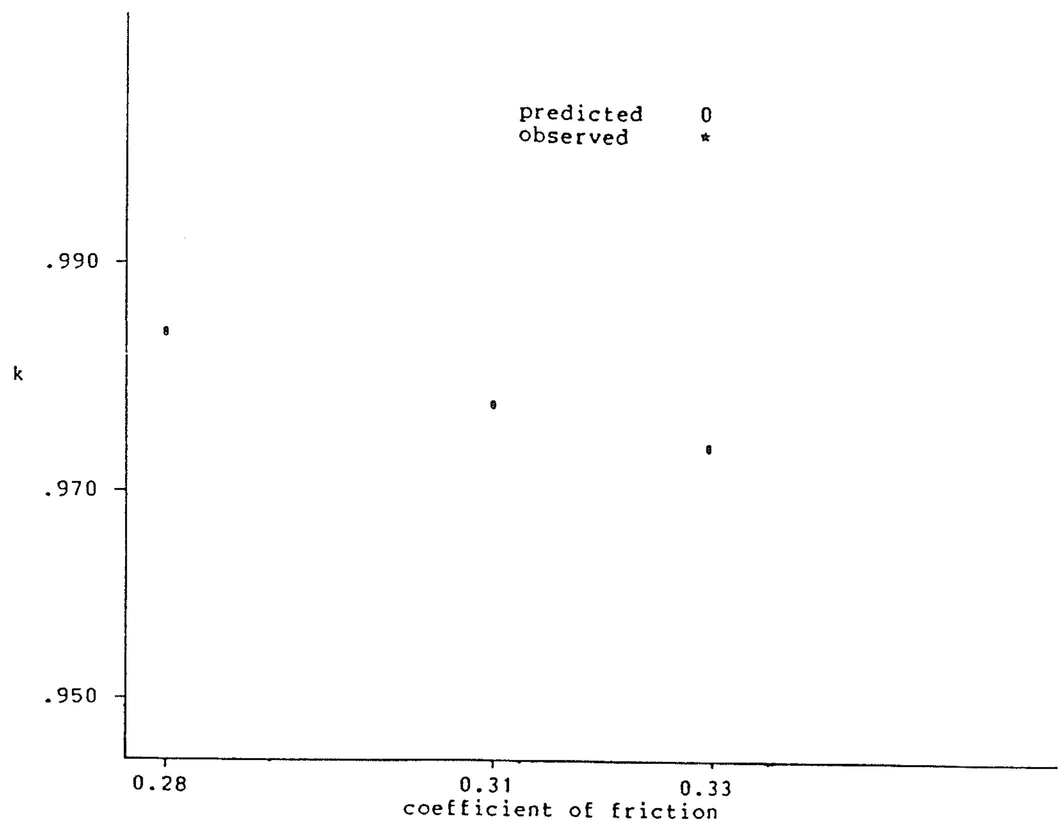

Figure 23. Scatter plots of mean values of predicted and observed versus coefficient of friction values of the model of linear terms

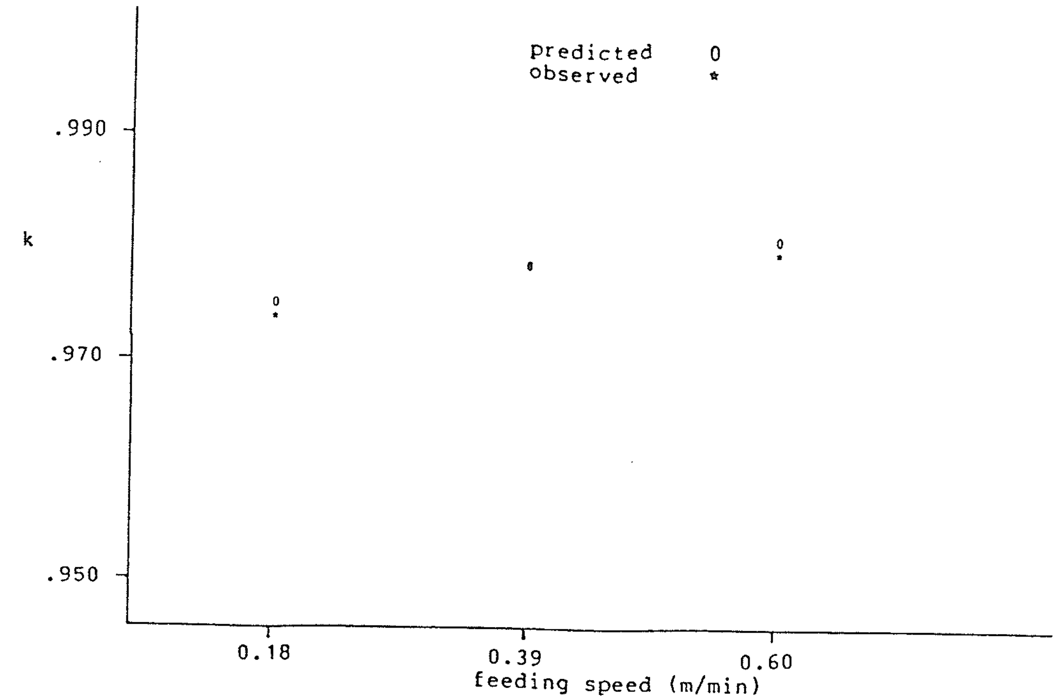

Figure 24. Scatter plots of mean values of predicted and observed versus feeding speed values of the model of linear terms

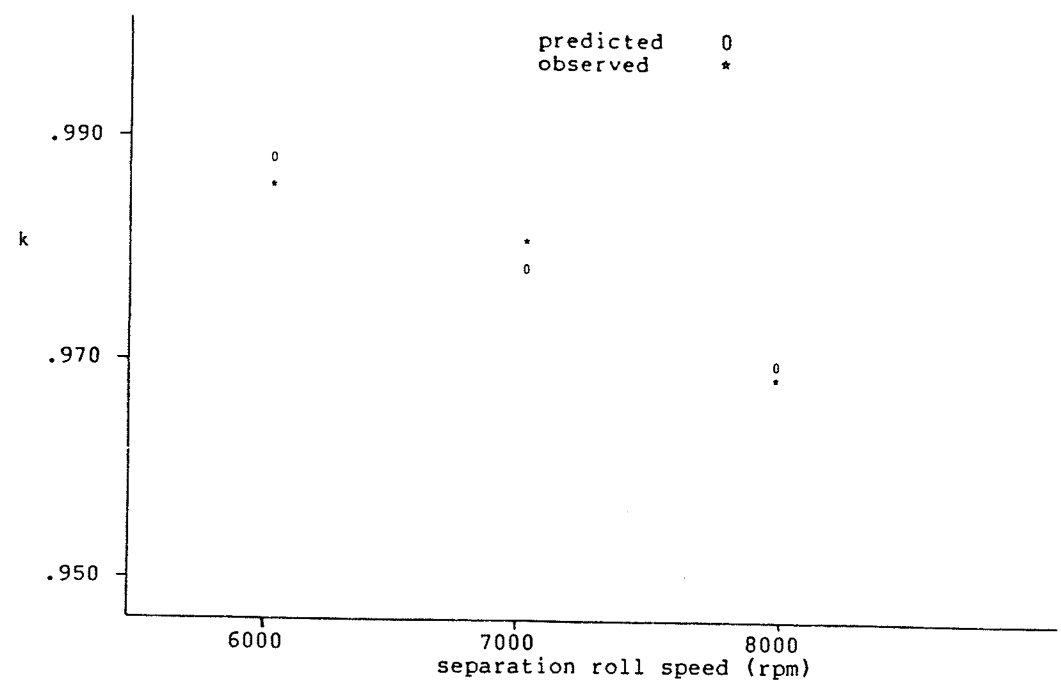

Figure 25. Scatter plots of mean values of predicted and observed versus separation roll speed values of the model of linear terms

The model obtained is an empirical one for predicting the frictional interaction factor from inter-fiber static coefficient of friction, fiber feeding speed, and separation roll speed variables in the separation process of open-end yarn spinning. The model is made up of parameters of the linear terms of the variables.

Chapter V

CONCLUSIONS

SUMMARY

It has been demonstrated through information from literature and experimental investigations of this study that frictional interaction is important to the processing of fibers.

The review of past studies provided theoretical and experimental information on the nature and influence of three major parameters of the fiber separation process of open-end rotor yarn spinning. The investigated parameters were: the inter-fiber coefficient of static friction, fiber feeding speed, and separation roll speed. Literature by Hearle [32], Belov [5], Rholena et. al. [36] and other researchers indicated that inter-fiber coefficient of friction and dynamic and static conditions of the fiber influence the movement of fibers in yarn spinning processes, including that of rotor spinning. In rotor spinning, inter-fiber coefficient of static friction influences the restraining forces at fiber separation, transportation and stripping while the fiber feeding speed influences frictional interaction forces at fiber separation, and the proportion of a fiber acted on by the separation roll. Separation roll speed influences forces created due to the force of separating fibers, and due to forces created from the motion of the separation roll. Since these influences affect interaction between the fiber and neighboring surfaces, the flow of the fibers is affected. The concept of an interaction factor was developed to express changes in fiber flow in the separation section of the rotor yarn spinning unit.

Experimental tests were conducted on cotton fiber slivers. The inter-fiber coefficient of static friction was altered in order to provide three values of the coefficient. The fibers were passed through the separation section of an open-end rotor unit at three levels of the feeding and separation roll speeds. The mass of fiber entering the unit and the mass of fiber deposited in the output were used to determine values of the frictional interaction factor. The data indicated that the value of the interaction factor is reduced by increases in the coefficient of friction and separation roll speed and is increased by increase in the feeding speed. The variances at the values of the independent variables were not constant. The lack of homogeneity in the variance of the data was determined using Bartlett's test.

The investigations led to the development of an empirical model to predict the interaction factor from the process parameters. The model was developed by statistical methods of regression of the data. The method of weighted least squares was used because of heterogeneity in the variance of the data. The method reduced the error of the prediction model and improved the square of multiple correlation by 6%. The most important parts of a prediction model are the parameter estimates which express the extent of influence on the dependent variable. Estimates for the linear, joint, and quadratic terms of the independent variables were evaluated for the importance of terms. The most important variable was the separation roll speed and the least was the fiber feeding speed.

The model was found to be significantly linear. Its accountability of the variation in the data was high and significant at 81%. The separation roll/inter-fiber coefficient of friction was the only joint term with significant parameter estimates; however the contribution was of little importance. The coefficient of friction had an insignificant quadratic term. The rest of the quadratic terms contributed little information to the model. The linear model was adequate over the whole range of data. The model was of the form:

$$k = 1.10835 - 2.2988x10\chi + 1.5797x10^{2}\phi - 9.5x10^{6}\psi$$

APPLICATION OF MODEL

The model was developed from data obtained from tests on cotton fibers. There is no evidence that the model is applicable to other types of fibers, however, since the differences in the response values are due to the interaction of surfaces, all fibers are expected to behave similarly when these conditions are affected. The model does not provide information on the source of the variability in the interaction factor, however, possible sources were discussed in the report. There is no evidence to indicate that the model will be applicable outside the range space of the independent variables used in the study. It is equally important that conditions of application of the model resemble those used in the study.

A significant application of the model is in process and quality control decision making. The model offers an opportunity to evaluate changes in the final product when changes in process conditions are realized, without the involvement of costly production stoppages. Since the conditions in the development of the model were made to resemble manufacturing conditions as much as possible the model may be used for problem solving purposes in the manufacture of yarn. The model is also considered important for research work in fiber and rotor technology development.

IMPLICATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

This research is regarded to provide important information for further research in the area of frictional interaction in fiber processes. Other variables which affect surface interaction of fibers are necessary for the complete development of the model, such as fiber length and fineness.

A number of researchers have investigated changes in the parameters of spinning products. Since the study did not involve processing of fibers into yarn, it is desirable to investigate the correlation of the behavior of the model to the parameters of the final product.

A useful study would be to investigate the periodic and nonperiodic variations of the interaction factors from inhomogeneous and homogeneous mixtures of fibers. Since frictional changes have been found to affect the flow of fibers it is expected that the information of the interaction factor does reflect changes in the flow. It is also important to investigate steady-state conditions of the process since these are crucial to information concerning machine stoppages and/or product consistency.

Most processing conditions are a trade-off of setting conditions. It is useful to investigate the relation of frictional interaction factors on the life of the product and processing equipment, in order to get information of the benefit of such conditions.

Most of the proposed studies would be complicated to investigate. Computer simulation is useful in the investigation of such cases. The technique provides a model of the real system which is a useful as indicator of the behavior of the real system under a combination of conditions. Simulated dynamic changes can be correlated with real data to provide a more realistic model of the system. The model, however, is not capable of predicting the response values, but is useful for comparison purposes.

GLOSSARY

DEFINITION OF TERMS

The following is a discussion of words and symbols used in the context of this report.

Sliver is an oriented untwisted continuous assembly of fibers arranged at random along an axis.

Separation is the process of removing a fiber or fiber tuft from an assembly of fibers. The separation roll is also known as the combing roll or opening roll.

Stripping is the removal of fibers from the separation roll by the air currents of the air-transport channel.

Drafting is the process of sliding fibers of a sliver past each other so as to elongate the sliver.

Floating fiber is a fiber shorter than the distance set between guiding rolls in roller drafting.

Steady-state is the condition of a process after a long period of time.

Contact element is the specific unit area of a material.

Table 10. Definition of variable notation

a	=	total number of contact elements per centimeter of the floating fiber length
ϵ	=	number of elements in contact with moving surface
ϵ'	=	number of contact elements necessary for its transfer to speed ν_1
ϵ''	=	number of contact elements necessary to maintain ν_1
c	=	factor of the dependence of F_6 on pressure
F	=	frictional force of resistance to sliding
F_0	=	static frictional force between surfaces
F_{01}	=	dynamic frictional force between sliding surfaces
F_1	=	force compressing the sliver in the nip
F_2	=	resultant frictional force in the condenser
F_3	=	frictional force between sliver and feed plate
F_4	=	circumferential force on the feed roll
F_6	=	maximum static withdrawal force
F_7	=	dynamic force acting on fibers at a speed change
f_0	=	force constant representing interaction between fibers
μ	=	coefficient of friction between surfaces
m	=	mass of fiber
μ_0	=	static coefficient of friction
μ_{01}	=	dynamic coefficient of friction
μ_2	=	coefficient of friction between sliver and feed plate
μ_3	=	coefficient of friction between sliver and feed roll
p	=	pressure in the drafting zone
N	=	normal force (load) acting on surface

BIBLIOGRAPHY

1 Abadeer, E. F., "The Effect of Opening roller Speed on the Properties of Open-end Spun Yarns". M.S. thesis. The Victoria University Manchester, Faculty of Technology, 1976.

2 Abhiraman, A.S. and George Waller, "A New Aspect of the Stochastic Nature of Carding". Textile Research Journal, V.43, 452-467, 1973.

3 Anbinder, S.U., "Analysis of the Extension of a Filament Moving along a Surface with Friction". Technology of Textile Industry. USSR, No.1, 63-67, 1969.

4 Bartee, Edwin M., Engineering Experimental Design Fundamentals. London: Prentice-Hall, Inc., 1968.

5 Belov, M.F., "Analysis of the Movement of the Floating Fibres in the Drafting Process on the Basis of Static and Dynamic Friction". Technology of Textile Industry. USSR, No.1, 47-51, 1968.

6 Buturovich, I.KH, "The Dynamics of the Fibre Flow in the Flat Card". Technology of Textile Industry. USSR, No.6, 52-56, 1967.

7 Buturovich, I.KH, "Analysis of the Equalizing Action of the Flat Card from the Frequency Characteristics". Technology of Textile Industry. USSR, No.1, 38-42, 1968.

8 Clarke, A.B., and R. Disney, Probability and Random Processes for Engineers and Scientists. New York: John Wiley and Sons, Inc., 1970.

9 Cook, Dennis R.,and Sanford Weisberg, Residuals and Influence in Regression. New York: 1982.

10 Deussen, Helmut, "Engineering Rotor Yarns for End Products: A Guide to Selecting Fiber Properties and Machine Components". A paper presented at the Textile Conference, Queen's University, Ontario.

11 Doria, G., Sala, G.G., and Trevison, E., "Development of Statistical Modelling in the Optimization of Leacril Open-End Spinning". Lenzinger Berichte, No.63, 48-55, 1987.

12 Dyson, E., "A study of Openend Spinning by Circumferential Assembly with Especial Reference to the Spinning of Modified Rayon: Part I". Journal of Textile Institute, V.69, 588-594, 1974.

13 Draper, N.R. and H. Smith, Applied Regression Analysis. New York: John Wiley and Sons, Inc., 1966.

14 Eley, J.R. and B.V. Harrowfield, "The Effect of Cylinder Loading on Fiber Breakage in Worsted Carding". Journal of Textile Institute, V.77, 267-273, 1986.

15 Feiring, E. Personal notes. Department of Industrial and Mechanical Engineering, University of Manitoba, Winnipeg, R3T 2N2.

16 Fujino, K. Y., Shimotsuma, and T. Fujii, "A Study of Apron Drafting; Part I: Experimental Studies". Journal of Textile Institute, V.68, 50-59, 1977.

17 Ganesh, K., "The Variability of Cotton-Fibre Properties". Journal of Textile Institute, V.68, 74-83, 1977.

18 Harakawa, Kazuhisa, Shuichi Kinoshita, and Kenji Tanaka, "Simulation of Fiber Transfer between Carding rollers Running near the Critical Velocity". Journal of the Textile Machinery of Japan, V.23, 1-7, 1977.

19 Harrowfield, B.V. and D. Gravolin, "Dynamic Transfer Efficiency of Wool Fibres from Swift to Doffer in a Miniature Card". Journal of Textile Institute, V.77, 9-18, 1986.

20 Hambey, Dannes, "Fiber Testing and Physical Properties", The American Cotton Handbook, 3rd Edition, 1075-1167. New York: Interscience Publishers, 1960.

21 Happey, F., Contemporary Textile Engineering, London: Academic Press, 1982.

22 Hearle, J.W.S., P. Grosberg, and S Backer, Structural Mechanics of Fibers, Yarns, and Fabrics, V.1. New York: John Wiley and Sons, Inc., 1969.

23 Hearle, J.W.S. and A.K.M.M. Husain, "Studies in needled Fabrics, Part VIII: The Effect of friction on the Processing and Properties of Needle-Bonded Fabrics". Journal of Textile Institute, V.62, 83-107, 1971.

24 Hewitt, A. and P.P. Townend, "The Effect of Fibre Length on Droppings during Carding". Journal of Textile Institute, V.62, 95-113, 1971.

25 Hunter, L., "The Production and Properties of Staple-Fibre Yarns Made by Recently Developed Techniques". Textile Progress, V.10, 1978.

26 Ihara, Motozo and Tooru Nogai, "Study on Transfer Function of Drafting Process, Part I: Equilibrium and Time-Dependent States". Journal of the Textile Machinery of Japan, V.22, 430-441, 1985.

27 Jakoubek, Alois and Premysl Vorisek, "New Conception of Czechoslovak Open End Spinning Machines". Strojimport, V.3, 45-47, 1987.

28 Johnson, E., "Simulation of the Drafting Process". Journal of Textile Institute, V.68, 115-120, 1977.

29 Joseph, Alexander, Kalman Pomeranz, Jack Prince, and David Sacher, Physics for Engineering Technology. New York: John Wiley and Sons, Inc., 1968.

30 Kleinbaum, David G., Lawrence L.Kupper, and Keith E. Muller, Applied Regression Analysis and Other Multivariate Methods. Boston: PWS-Kent Publishing Company, 1987.

31 Miller, August L., Roger S. Brown, Charles L. Shepard, and Heber W. Willer, Jr., "Observations on the Effect of Slow Speeds, and Electrostatic, Aerodynamic, and Mechanical Forces on Carding". Journal of Textile Institute, V.36, 222-232, 1966.

32 Morton, W.E., J.W.S. Hearle, Physical Properties of Textile Fibers. New York: John Wiley and Sons, Inc., 1975.

33 Lawrence, C.A., and K.Z. Chen, "High-Speed Photographic Studies if the Fibre Configuration During Transfer from Opening roller of Rotor- Spinning Unit". Journal of Textile Institute, V.77, 201-211, 1986.

34 Lawrence, C.A., and K.Z. Chen, "A Study of the Fiber Transfer-Channel Design in Rotor Spinning". Journal of Textile Institute, V.79, 71-90, 1988.

35 Protasova V.A., "The Dynamics of the Drafting Process". Technology of Textile Industry. USSR, No.6, 70-72, 1972.

36 Rholena, Vaclav, et al, Open-End Spinning. Amsterdam: Elsevier Scientific Publishing Company, 1975.

37 Salhotra, K.R. and P. Balasubramanian, "An Approach to the Optimization of Rotor-Spinning-Machine Parameters". Textile Research Journal, V.77, 128-135, 1986.

38 Salhotra, K.R. and R. Chahopadhyay, "Loss in Fiber Tenacity During Separation in Rotor Spinning". Textile Research Journal, V.54, 194-197, 1984.

39 Scardino, Francis L. and W. James Lyons, "Fiber Surface Properties in Relation to Linear Assemblies During Processing; Part I: General Considerations; Results on the Worsted System". Textile Research Journal, V.37, 874-880, 1967.

40 Scheier, Stanley C. and W. James Lyons, "Measurement of the Surface Friction of Fibers by an Electro-Mechanical Method". Textile Research Journal, V.35, 385-394, 1965.

41 Schlafhorst Inc., Auto-coro Technical Manual. Charlotte, North Carolina.

42 Sevostyanov, A.G. and Stogov S.S., "The Probability Characteristics of a Discrete Fibre Flow in the Sliver". Technology of Textile Industry. USSR, No.1, 42-45, 1972.

43 Trotman, E.R., Dyeing and Chemical Technology of Textile Fibres, 6th Edition. Worcester: Charles Griffin and Company, Ltd., 1984.

44 Yarn Mill (Long Sault), Division of Dominion Textiles, Quality Control Standards. Long Sault, Ontario.

45 Vigo, J.P. and A. Barella, "Influence of Opening roller Type on Properties of Open-End Polyester-Viscose Yarns". Textile Research Journal, V.51, 34-39, 1981.