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Effects of Material Parameters and Process Conditions on the Roll-Drafting Dynamics

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Abstract: Roll drafting, a mechanical operation attenuating fiber bundles to an appropriate thickness, is an important operation unit for manufacturing staple yarns. It influences not only the linear density regularity of the slivers or staple yarns that are produced, but also the quality of the textile product and the efficiency of the thereafter processes. In this research, the dynamic states of the fiber bundle in the roll drafting zone were analyzed by simulation, based on the mathematical model that describes the dynamic behavior of the flowing bundle. The state variables are the linear density and velocity of the fiber bundles and we simulated the dynamics states of the bundle flow, e.g., the profiles of the linear density and velocity in the draft zone for various values of the model parameters and boundary conditions, including the initial conditions to obtain their influence on the dynamic state. Results showed that the mean velocity profile of the fiber bundle was strongly influenced by draft ratio and process speed, while the input sliver linear density has hardly affected the process dynamics. Velocity variance of individual fibers that could be supposed to be a disturbing factor in drafting was also influenced by the process speed. But the major disturbance occurred due to the velocity slope discontinuity at the front roll, which was strongly influenced by the process speed. Thickness of input sliver didn't play any important role in the process dynamics.

Keywords: Fundamental equations system, Steady state, Velocity variance, Flowing bundle, Model parameter, Material parameters, Process parameters, Bundle coherence, Velocity slope, Discontinuity, Disturbance

Introduction

Drafting is one of the mechanical process operations used in manufacturing staple yarns. It is being performed repeatedly along with or without doubling in every process where fiber bundles have to be attenuated to get the thickness appropriate to the next processes. Due to lack of the complete control on the motion of each fibers or fiber groups, however, the fiber bundles after this operation have more or less irregular linear density. As the irregularities influence to a serious extent the product quality and the process efficiency, there have been many questions since long, for example, about the generation mechanism of linear density variation, about the parameters and their extent of influencing the linear density variation, about characteristics of the irregularities, etc..

The first consideration on the cause of the draft irregularity was made by Ball, who suggested the existence of "draft wave" [1]. Thereafter, there have been many researches to dig out the mechanism how the irregularity of fiber bundle appears [2-7], to set up the exact relationship between the irregularity and process conditions [8-11], and to develop a new device to measure the irregularity exactly and affordably [12-14]. Many researches not mentioned here also were devoted to analyzing irregularity theoretically or experimentally. All the efforts are not yet sufficient to describe the dynamic states of the fiber bundles in a roll draft zone, because numerous factors are affecting the roll drafting, separately, or in coupled ways with each other. In order to establish the process conditions even not exactly optimal, but ever in a best acceptable way for the bundle drafting, it is required to describe the relations of process variables and material parameters with the dynamic states of the roll drafting.

Fiber bundles in drafting must behave differently according to the material properties and process conditions. Material properties, for examples, are species of the fiber material, thickness of the bundle, coherence of fibers that is influenced again by the fiber length distribution, waviness of the fiber, surface feature, entanglement of fibers, etc.. Process conditions are delivery speed, draft ratio, draft gauge length, and roll diameter, etc.. This study is treating of the mathematical model suggested by Huh *et al.* [15] that describes the dynamic behavior of fiber bundles during drafting, i.e., velocity and linear density of the staple strand as a whole in a draft zone. The influence of the material factors and process conditions on the dynamic state variables under the steady-state condition is analyzed by simulating the profiles of the mean velocity and linear density of the fiber bundle in roll drafting for various process conditions and model parameters, including the resultant velocity variance profiles of the individual fibers.

Fundamental Equations System

With the assumptions such as

1) the fibers are arrayed in a paralleled and more or less stretched way,
2) all the fibers have the same linear density,
3) the fibers flow parallel in the flow direction, and
4) flow occurs only by the drag force from the both nipping lines,

and along with the legends as followings, referring to Figure 1:

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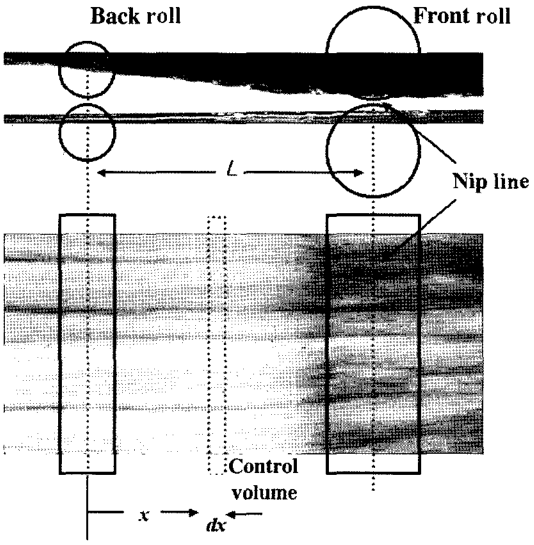

Figure 1. Photograph of the drafted fiber bundle in a draft zone.

$v(t, x)$: mean velocity of the fiber bundle at position x and time t
$vi(t, x)$: velocity of the i-th fiber in the bundle at (t, x)
$lb(t, x)$: linear density of the fiber bundle at (t, x)
L: draft gauge length
the governing equations system that describes the bundle behavior consists of the continuity equation and the equation of motion, along with the constitutive model that the surface force is proportional to the strain rate, while the linear density specific viscosity is constant as:

$$f(t,x) = \mu\cdot lb(t,x)\cdot\left\{\frac{\partial v(t,x)}{\partial x}\right\},\ \mu=\text{constant} \tag{1}$$

and a velocity variance model in a steady state as:

$$Var[vi(t,x)] = a_0\cdot v(t,x)\cdot\left(1-\cos\frac{2\pi}{L}x\right),\ a_0=\text{constant} \tag{2}$$

Then, the fundamental equations system in a steady state ends up to equations (3) and (4) [15,16]:

$$\mu\cdot\left\{\frac{dv(x)}{dx}\right\} = v(t,x)^2 + a_0\cdot v(x)\cdot\left(1-\cos\frac{2\pi}{L}x\right) \tag{3}$$

$$\frac{d\{lb(x)\}}{dx}+\frac{a_0}{\mu}\cdot\left(1-\cos\frac{2\pi}{L}x\right)\cdot lb(x) = -\frac{m_0}{\mu} \tag{4}$$

where, m_0 stands for the fiber mass flow rate that is assumed constant over the draft zone, which is acceptable, if the draft resonance does not take place in a steady state.

Simulation

The fundamental equations system, consisting of equation (3) and (4), shows that the problem is still nonlinear, but the equations are decoupled, which causes the problem to be handled in a much simpler way. To solve the problem and analyze the influence of the material parameter and the process conditions on the dynamic state of the roll drafting, we used the numerical method based on a software package Maple 7. The dynamic state variables of the roll drafting are the linear density and the velocity of the fiber bundle in the draft zone. Model parameters are μ and a_0, while input thickness, draft ratio, process speed or delivery speed are process conditions that are given in forms of initial or boundary conditions in simulation. The model parameters are adjusted to the experimental results and used for simulating the dynamic states at positions in the draft zone.

Experiments

The drawing frame in which the linear density distribution at position is measured is equipped with a 3/3 draft device which mainly processes cotton slivers. When the drawing frame was supposed to run in a steady state after a while having been fed with fiber bundles, the machine was stopped deliberately by an operator, who lifted the pendulum arm open, releasing the roll pressure on the fibers, and took out the fiber bundle. By weighing the specimens cut by the length of 40 mm (full length of the draft rauge), 20 mm (half length of the draft gauge), 10 mm (quarter length of the draft length) and 5 mm (one eighth of the draft gauge) respectively in each experiment (the sample size reduction method [15,16]), the linear density profiles of the fiber bundle could be approximately obtained. The experiments were repeated 6 times for a specimen under the same processing conditions, which resulted, thus, in the average profiles of the linear density.

Experiments were performed for various conditions. But the process speed was controlled relatively low in order to realize the running condition as near the steady state as possible. The material was combed cotton slivers that had the mean fiber length of 27.5 mm. The linear density of the sliver used was 4,000 Tex. Experimental conditions are given in Table 1.

Results and Discussion

Dynamic behavior of fibers in a draft zone may change

Table 1. Experimental process conditions of the drafting system

Draft gauge length (mm)	Main	40	
	Break	45	
Draft ratio	Main	3	4.67, 5.7, 6.2
	Break	1.21, 1.27, 1.32	1.32
	Total	3.6, 3.8, 4.0	6.2, 7.5, 8.2
Delivery speed (m/min)		68.1	68.1, 107.6
No. of doublings		4	7

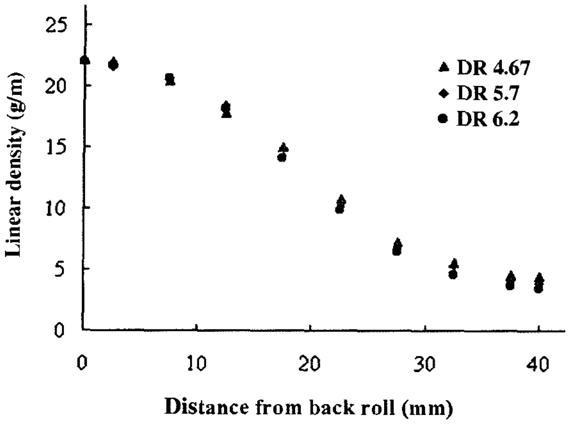

Figure 2. Experimental results of the linear density profiles for various draft ratios.

according to the process conditions, which can be identified by the state variables such as the linear density and velocity of the in-process fiber bundle. The profiles of the linear density obtained from experiments can, thus, provide with information on the state of the velocity. In this study, we measured the linear density profiles, while the process variables such as draft ratio, delivery speed, and input sliver thickness were considered.

Draft Ratio

Draft ratio is a process variable that can have a direct access to the dynamic behavior of fibers in a draft zone. Therefore the effect of the draft ratio on the linear density profile in the draft zone was experimented, where 3 main draft ratios were chosen of 4.67, 5.7, and 6.2 for a constant break draft 1.32 and a constant delivery speed 68.1 m/min. Figure 2 shows the results of the linear density profile obtained from experiments in the main draft zone for 3 different main draft ratios. At the beginning the fiber bundle is attenuated very slowly, but nearing the front roll makes the fiber band so fast thinner that it already seems to reach almost the output thickness some distance before the front roll.

Simulation of the linear density profile with the parameters μ and a_0, showing a fairly good approximation to experimental results, can assure the effectiveness of the model. Adjusting μ and a_0 is done in the following sequences; at first the velocity profile is calculated from equation (3), satisfying the initial and boundary conditions; then, the linear density profile is obtained from equation (4) with those parameters that bring least deviation of the linear density profile from the experimental data.

Figure 3 shows the fitted curves that result from the simulation based on the theoretical model, where the dots denote the data from the experiments and the curves simulation results. The theoretical model given in equations (3) and (4) seems to describe very good the dynamics of the roll drafting in a steady state condition. For the constant parameter μ, the value of a_0 increases as draft ratio increases.

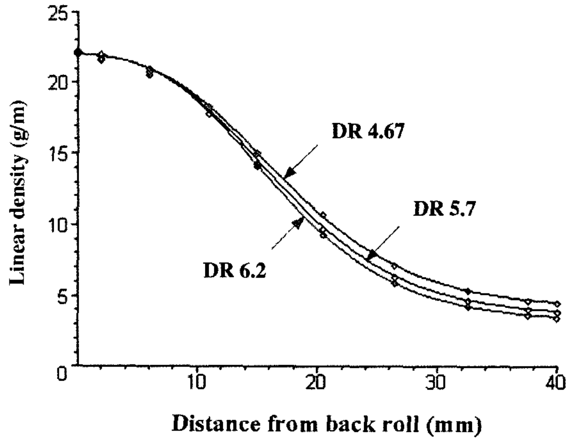

Figure 3. Adjusted profiles of the linear density of the fiber bundle to the experiments for various draft ratios; L=40 mm, μ= 3700 m^2/min, $v(0)$= 14.0 m/min, a_0= 112.3 for DR=4.67, $v(0)$= 12.2 m/min, a_0= 126.0 for DR=5.70, $v(0)$= 11.0 m/min, a_0= 137.5 for DR= 6.20.

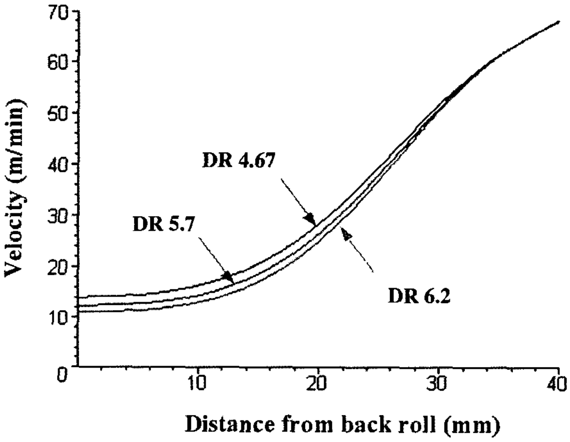

Figure 4. Theoretical velocity profiles of the fiber bundle estimated from the model with the measured profiles of the linear density for various draft ratios; L=40 mm, μ=3700 m^2/min, $v(0)$ = 14.0 m/min, a_0= 112.3 for DR=4.67, $v(0)$= 12.2 m/min, a_0= 126.0 for DR=5.70, $v(0)$= 11.0 m/min, a_0= 137.5 for DR=6.20.

Figure 4 shows the profiles of the mean velocity of fiber bundle in the draft zone that are estimated on the basis of the theoretical model by using the same values of the parameters in Figure 3. As expected, the fibers are accelerated in average continuously in the draft zone and the velocity slope increases fast as draft ratio increases. But as nearing the front roll, the bundle acceleration reduces, however, not to the extent that the fibers might pass through the nip line of the front roll smoothly. A discontinuity of the slope of the velocity profile takes place at the nip point of the front roll.

Process Speed

The behavior of fiber bundle in the draft zone may be influenced not only by draft ratio but also by delivery speed, because the speed determines the rate of the bundle deformation and the time in which the surface forces act on constituent fibers. Therefore the linear density profiles of the bundle are measured under the condition that main draft ratio is kept constant as 5.7 and different delivery speeds are applied to investigate the effect of the process speed on the fiber bundle dynamics in the draft zone. To this end two levels of the delivery speed are used; 68.1 m/min and 107.6 m/min, while the bundle feeding speeds are 12.2 m/min and 18.85 m/min respectively.

Figure 5 shows the linear density profiles of fiber bundle obtained from experiments and the curves with the adjusted parameters according to the model. The linear density profile seems not to be influenced significantly by the process speed.

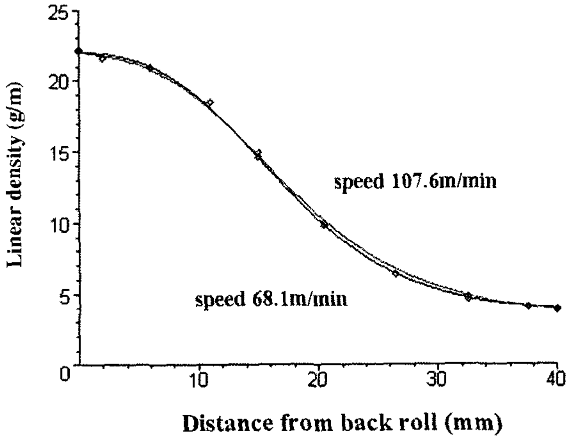

Figure 5. Adjusted profiles of the linear density to the experiments with the change of process speed; $L=40$ mm, $DR=5.7$, $\mu=3700$ m^2/min, $a_0=126.0$ for $v(L)=68.10$ m/min, $\mu=3700$ m^2/min, $a_0=110.5$ for $v(L)=107.6$ m/min.

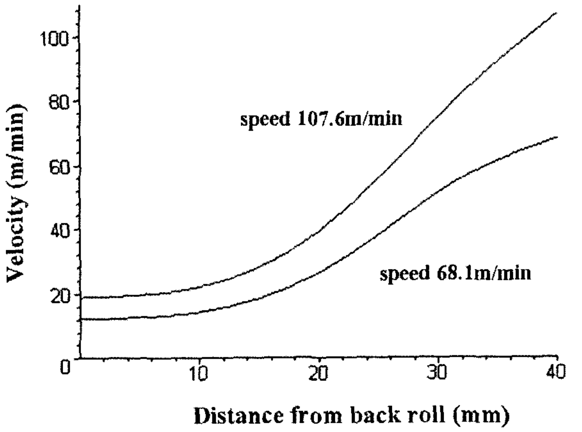

Figure 6. Theoretical profiles of the mean velocity of the fiber bundle for different delivery speeds; $L=40$ mm, $DR=5.7$, $\mu=3700$ m^2/min, $a_0=126.0$ for $v(L)=68.10$ m/min, $\mu=3700$ m^2/min, $a_0=110.5$ for $v(L)=107.6$ m/min.

But the velocity profile (Figure 6) shows that the curves have different shapes in a great extent. Nevertheless the discontinuity of the slope of the velocity profile at the nip point of the front roll becomes bigger, as the delivery speed increases. Therefore it can be expected that the fiber bundle can be exposed to a greater possibility of the behavior disturbance near the front roll, when a high performance drafting is conducted.

And the process speed can have more influence on the velocity profiles of the fiber bundle in the draft zone than on the linear density profiles. This result indicates that problems in controlling the irregularity of fiber bundle in a roll drafting process, when the delivery speed gets high, can be attributed to the change of the dynamics of the fiber bundle around the front nip point.

Sliver Thickness

To investigate the effect of input thickness on the fiber bundle dynamics, linear density profiles of the in-process bundle are measured under the conditions that main draft ratio is kept constant as 3.0 and three different levels of the thickness of the input slivers, flowing into the main draft zone, are selected as 12.0 g/m, 12.6 g/m and 13.2 g/m, which was realized by changing slightly the break draft ratio mechanically. It is well known that the break draft ratio can influence the dynamics of fiber bundle in main draft zone. But if the drafting is done with a relatively low speed, we can take the bundle dynamics almost independent of the break draft ratio.

The linear density profiles from experiments along with those from simulation are given in Figure 7.

Even though the experimental results are deviating more or less from the estimated curves from the simulation, they can be accepted to be in a good agreement with each other. The slight discrepancy of the experimental points from the

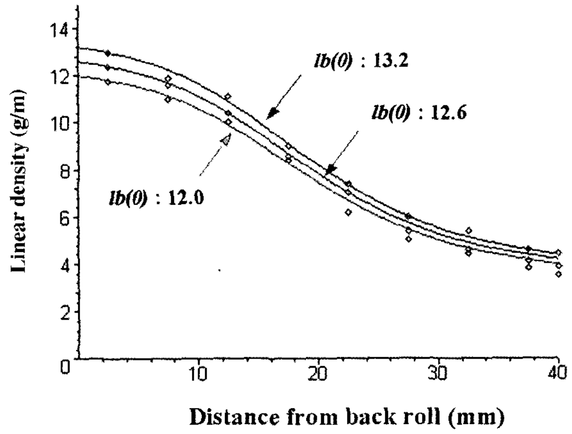

Figure 7. Adjusted profiles of the linear density of the fiber bundle to the experiments for various thicknesses of input sliver; $L=40$ mm, $v(0)=22.7$ m/min, $DR=3.0$, $\mu=3700$ m^2/min, $a_0=61.35$, linear density of input sliver $lb(0)=13.2$ g/m, 12.6 g/m, 12.0 g/m.

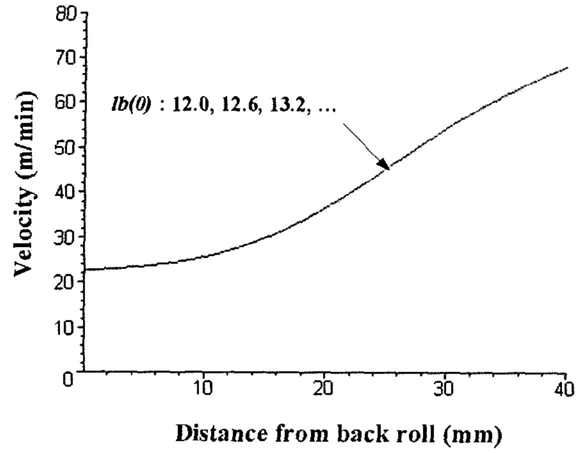

Figure 8. Theoretical profiles of the mean velocity of the fiber bundle with various thickness of input sliver; L=40 mm, $v(0)$= 22.7 m/min, DR=3.0, μ=3700 m^2/min, a_0= 61.35, linear density of input sliver $lb(0)$ = 13.2 g/m, 12.6 g/m, 12.0 g/m.

simulation curves might be due to the change of the bundle properties and dynamics in the main draft zone by different break draft ratios.

Figure 8 shows the profiles of the mean velocity that is given by simulation with the same parameters as used in Figure 7. The velocity profiles in the main draft zone for different input thicknesses fall down to a single curve, exactly overlapping each other, which means that the input thickness doesn't play an major role in the bundle dynamics, as long as the draft ratio remains constant.

Further Considerations by Simulation

Effect of Model Parameters

As confirmed experimentally just before, various conditions resulted in different dynamics of fiber bundle in a draft zone, which required different values of the model parameters that stand for the material properties and the process conditions. Based on the experimental results so far, we tried to find out the effect of the parameters on the bundle dynamics by expanding the ranges of their values.

From the definitions of the parameters a_0 and μ, a constant of velocity variance and a constitutive constant, they could be in a physical sense closely related with the properties of the constituent fibers such as surface friction, waviness, fiber orientation and entanglement, fiber length and fineness, etc.. And simulations can provide with the information on the effects of the parameters on the fiber bundle dynamics during drafting, that is, the profiles of velocity and linear density for various values of the parameters. The parameters a_0 and μ have such values satisfying the boundary conditions at the two ends of the draft zone and the initial conditions.

Simulation results in a unified draft gauge are given in Figure 9. Figure 9(a) shows that the fibers are early accelerated, if the parameter μ has a high value. At the same time the parameter a_0 becomes great, too. Fibers start moving with a relatively steady velocity almost equal to the feeding speed and then get accelerated at some position in the middle of the draft zone, while moving forwards.

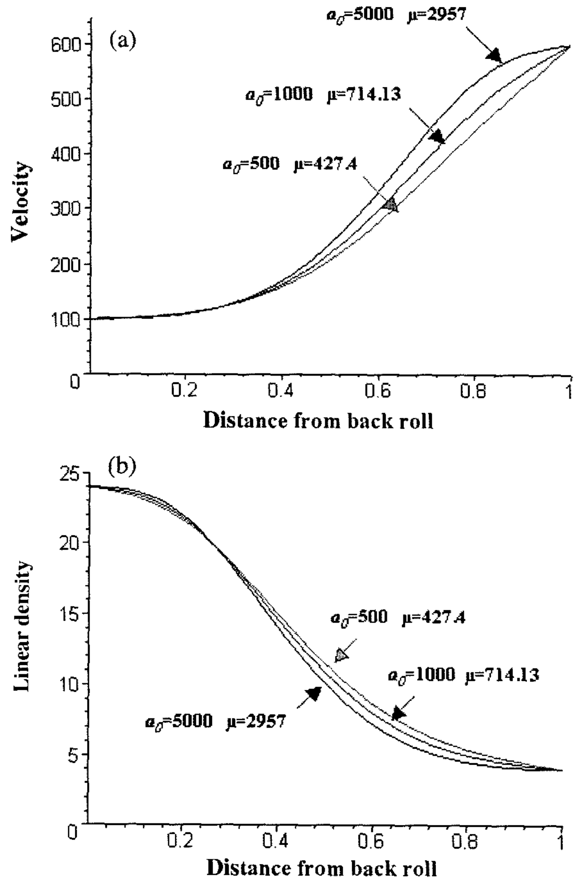

Figure 9. Profiles of (a) the mean velocity and (b) the linear density in the draft zone for various parameters; L=1, DR=6.0, $v(0)$=100, $lb(0)$=24.

A high value of μ, that means a high viscous bundle, requires a high value of a_0. In other words, the velocities of the individual fibers should be scattered with a broad variance as a result. Thus, the fibers are accelerated early and reach almost the delivery speed already near the front roll. In the case of low viscous bundles they are accelerated throughout in the draft zone. Even near the front roll a continuous acceleration appears, whereby the velocity variance seems to reduce. Therefore the movement of the fiber bundle must be restrained mechanically by the front roll, which causes more disturbances to occur. As for the linear density profiles of the fiber bundles, Figure 9(b) shows that the bundle of high viscosity remains thick at the beginning, and then gets attenuated fast to reach the output linear density. Linear density profiles come cross each other for different parameter values.

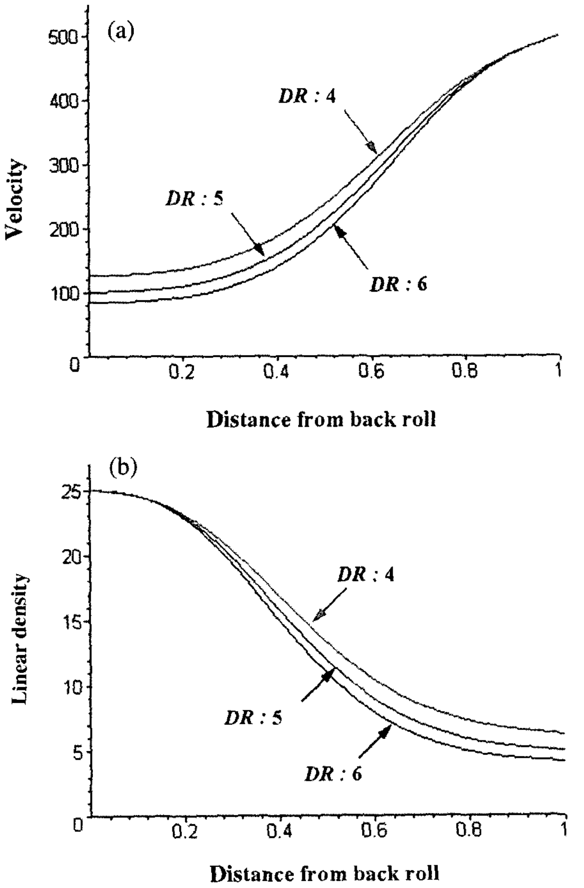

Figure 10. Profiles of (a) the mean velocity and (b) the linear density in the draft zone with various draft ratios under the same delivery speed; m=1000, L=1, $lb(0)$=25, $v(L)$=500, $v(0)$=125.00, DR=4.0, a_0=1114.0, $v(0)$=100.00, DR=5.0, a_0=1355.4, $v(0)$=83.333, DR=6.0, a_0=1550.7.

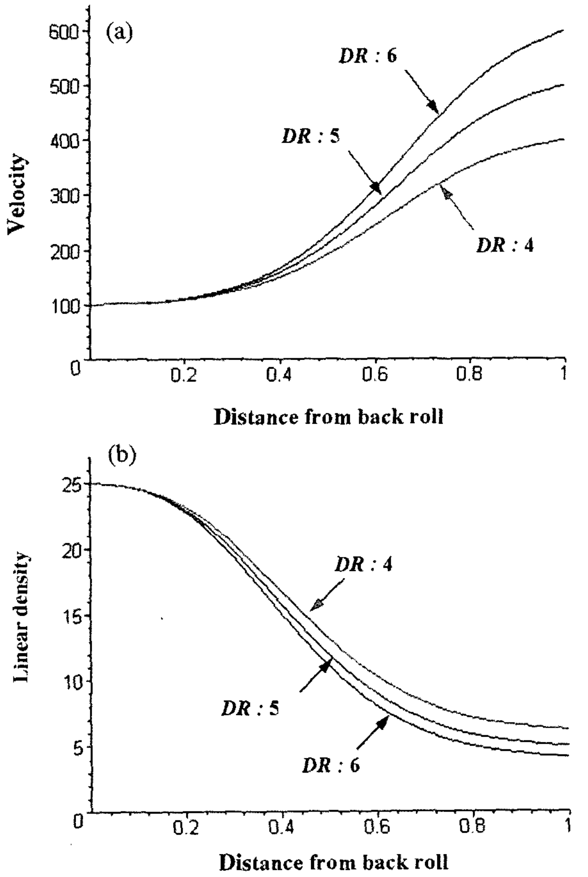

Figure 11. Profiles of (a) the mean velocity and (b) the linear density in the draft zone with various draft ratios under the same feeding speed; m=1000, L=1, $lb(0)$=25, $v(0)$=100, $v(L)$=400, DR=4, a_0=1166,.4, $v(L)$=500, DR=5, a_0=1355.4, $v(L)$=600, DR=6, a_0=1505.0.

Effect of Draft Ratios

Draft ratio is one of the process parameters, influencing the drafting dynamics, as suggested from experiments. Thus, we investigated the effect of draft ratio in a more detailed way by realizing various draft ratios under the same delivery speed or feeding speed. Figure 10 shows the simulation results for the cases in which the draft ratio is changed by the feeding speed, while the delivery speed is maintained constant. Results under the same feeding speed and various delivery speeds are given in Figure 11. The (a)'s of the both Figure 10 and 11 are about the velocity profiles, the (b)'s about the linear density profiles.

Velocity profiles show that the fibers are moving with the initial velocity, i.e., the speed of back roll and then accelerated in the middle of the draft zone. Around the delivery roll the bundle moves almost with the delivery speed. And the fibers get accelerated more and at the same time the velocity variance parameter a_0 increases, as the draft ratio increases. This indicates that if the input sliver material is the same, individual fibers move with broad velocity differences as draft ratio increases. From the point of view of the dynamic perturbation, the delivery speed plays a more important role than the draft ratio does, because the velocity slope at the delivery roll is more dependent on the delivery speed than on the draft ratio, as seen from Figure 10 and 11.

Linear density profiles, however, seems to be determined only by the draft ratio and not to be influenced by the boundary conditions. The way how the draft ratio change is realized, i.e., whether the delivery speed is changed or the feeding speed under the same draft ratio yields no difference in the linear density profiles.

Effect of Process Speed

Modern drawing frames can be characterized by high speed, wide process flexibility, easy maintenance, and good quality of the sliver products. Especially the process speed can have a direct influence on the dynamic state of the bundle. In the case of very low coherent bundles, i.e., a low

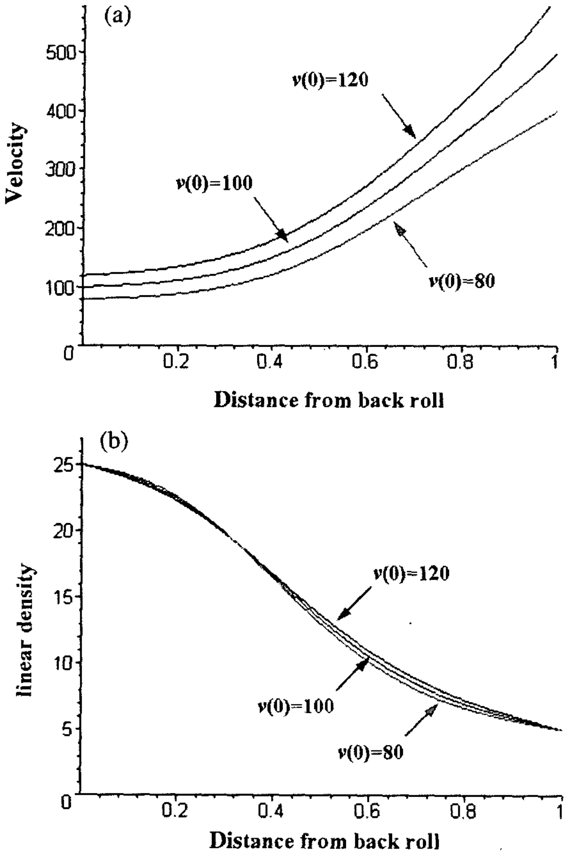

Figure 12. Profiles of (a) the mean velocity and (b) the linear density in the draft zone for various process speeds; $m=300$, $DR=5.0$, $L=1.0$, $lb(0)=25.0$, $v(0)=80$, $a_0=294.2$, $v(0)=100$, $a_0=253.0$, $v(0)=120$, $a_0=213.5$.

value of the parameter μ, the dynamic state of the bundle can be influenced easily by the boundary conditions, even though the draft ratio remains constant. We simulated the profiles of the velocity and linear density, while keeping the draft ratio constant, but changing the process speed. Figure 12 shows the simulation results. The bundle driven with a higher speed shows a steeper slope for the both profiles of the velocity and the linear density around the delivery roll. Bundles can more be exposed to the chances that the dynamic perturbation occurs, as the process speed is higher. It is to note that the velocity variance parameter a_0 becomes small, as the process speed increases.

Effect of Input Thickness

Many engineers have been occupied in finding the optimal conditions in drawing process and there are still discussions which strategy can bring a better result, comparing the case of thick inputs drawn with a high draft ratio with that of thin inputs with a low draft ratio. To get closer to finding the solution, we simulated the dynamic state distribution for various input thickness. The profiles of the mean velocity and the linear density are given in Figure 13. Under a constant draft ratio, the velocity profiles (Figure 13(a)) show that they are not influenced by the input thickness. They have the same profile independently to the input thickness. The linear density profiles (Figure 12(b)), however, look as they have almost the same shape and just the magnitude depends on the input linear density.

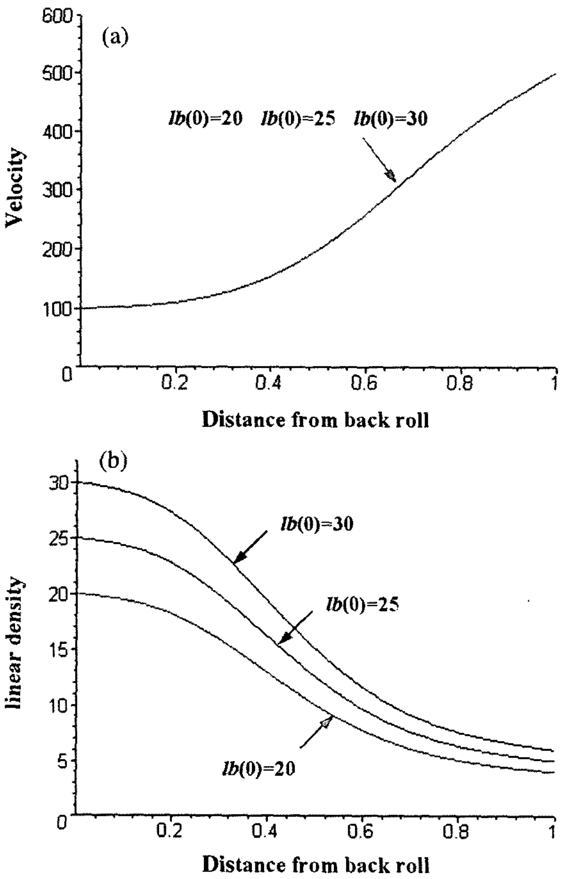

Figure 13. Profiles of (a) the mean velocity and (b) the linear density in the draft zone with various thickness of input sliver; $v(0)=100$, $m=500$, $L=1$, $DR=5.0$, $lb(0)=20$, $a_0=562.3$, $lb(0)=25$, $a_0=562.3$, $lb(0)=30$, $a_0=562.3$.

Velocity Variances

The velocity variance of the constituent fibers in the draft zone was given in forms of a model in equation (2):

$$Var[vi(t,x)] = a_0 \cdot v(t,x) \cdot \left(1-\cos\frac{2\pi}{L}x\right),\ a_0 = \text{constant} \qquad (2)$$

Based on the velocity profiles obtained from the adjusted model parameters, the profiles of the velocity variance for various draft ratios showed a shift of the maximum variance position toward front roll as the draft ratio increased [15]. And a high draft ratio yielded a big velocity variance and a low placed velocity profile.

In this simulation the profiles of the mean velocity and

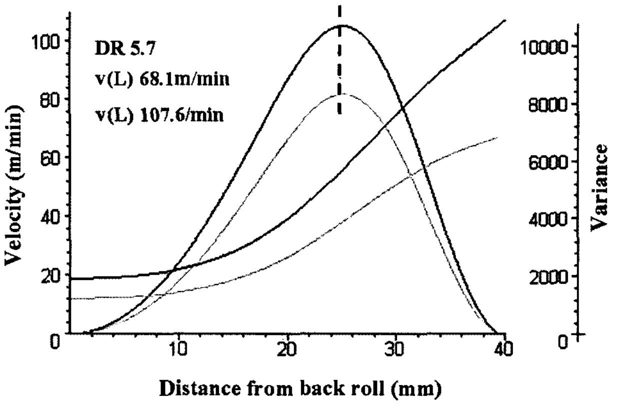

Figure 14. Theoretical profiles of the mean velocity of the fiber bundle and of the velocity variance of fibers for different process speeds; $L=40$ mm, $DR=5.7$, $\mu=3700$ m^2/min, $a_0=126.0$ for $v(L)=68.1$ m/min, $a_0=110.5$ for $v(L)=107.6$ m/min.

velocity variance for two levels of the process speed were estimated, while the draft ratio was kept constant. The results are given in Figure 14. The shape of the curve seems unchanged by the process speed, but the magnitude of the curve is influenced by the process speed; that is, the velocity variance becomes bigger as the process speed increases. It is to note that the parameter a_0 takes a low value for a high process speed; thus, the velocity variance doesn't increase in such a rate as the process speed increases.

Considering the results obtained so far, it turns out as a whole that the mean velocity of fiber bundle in the draft zone is influenced by the draft ratio and the delivery speed, while the linear density by the draft ratio and the input sliver thickness. The draft process is apt to be thrown under disturbances as the process speed increases. Even though the velocity variance of individual fiber that may be a disturbing factor in drafting increases for a high process speed, the model parameter a_0 becomes small. Therefore, the major dynamic disturbance can occur due to the velocity slope discontinuity near the front roll.

Conclusion

In this research the dynamic behavior of fiber bundle in a steady state was analyzed by simulation on the basis of the theoretical model. The model included the parameters that represented the material properties and process conditions. Process variables such as draft ratio, feeding speed, thickness of the fiber bundle, process speed were considered as initial and/or boundary conditions.

This research revealed that the model used was in a good agreement with the experimental results in a steady state, if the parameters were adequately adjusted. Fiber bundles were continuously accelerated in the draft zone as the bundles moved forwards, but at the front roll a discontinuity of the slope of the velocity profile took place, which could disturb the dynamic state of the fiber bundle at the exit. Process speed and draft ratio showed a strong influence on the dynamic states of the fiber bundle in the draft zone. Thickness of input sliver didn't play any important role in the process dynamics.

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