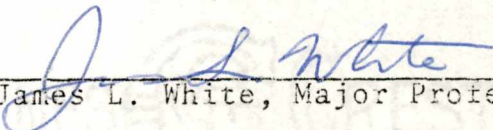
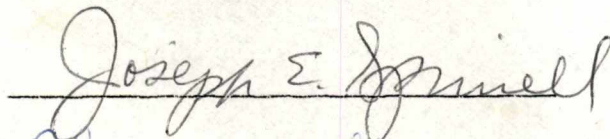


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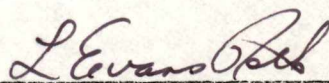
I am submitting herewith a thesis written by Chih-Hung Chen entitled "A Basic Study of Spunbonding Polypropylene." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Polymer Engineering.


James L. White, Major Professor

We have read this thesis
and recommend its acceptance:




Accepted for the Council:


Vice Chancellor
Graduate Studies and Research

A

A BASIC STUDY OF SPUNBONDING POLYPROPYLENE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Chih-Hung Chen

December 1981

3055416

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the many people who have contributed to the completion of this thesis.

First, sincere appreciation is extended to Professors James L. White, Joseph E. Spruiell and Bhuvnesh C. Goswami, the author's advisors throughout his graduate study at The University of Tennessee, for their comments, suggestions, and encouragement in all aspects of this work.

Thanks are extended to Mr. H. B. Thompson and his co-workers for their kind help in building the equipment used in this research. Thanks are also extended to all the faculty members and student colleagues who have given useful suggestions and discussions in this study.

Financial support was provided by the Polymer Consortium, National Science Foundation, and a Teaching Assistantship. This support is gratefully acknowledged.

Finally, the author wishes to express his deepest appreciation to his parents, Mr. and Mrs. Liang-Ann Chen. Without their help and encouragement, he would not have realized his childhood dream.

ABSTRACT

Spunbonded fabrics have been challenging woven fabrics and paper. Almost no technical papers have been published in this field. In this thesis, a fundamental study of the spunbonding process is reported. A model spunbonding apparatus was designed and built based on considerations of the patent literature. This involved extruding molten polymer filaments through a spinneret and into an aspirator from which they were blown onto a moving conveyer belt.

The force balance for a filament in the spunbonding process was developed. The air drag coefficient for air flow past a fiber in an aspirator was measured in a specially designed experiment. The values are expressed as a function of the Reynolds number based on relative velocities, fiber diameter and kinematic viscosity of the air. The dependence of the drag coefficient on the Reynolds number is the same as a correlation of air drag in melt but the magnitudes are larger. This could be caused by the vibration of the filament while it is in the aspirator.

Wide-angle X-ray diffraction and birefringence were used to characterize the orientation of spunbonded or better air drag attenuated polypropylene filaments. Hermans-Stein orientation factors were determined for the crystalline phase. Comparing the orientation factors of these filaments

with those of melt spun fibers taken-up on a winder, we find that these correspond to the same measured spinline stress. Birefringence measurements confirm that the structure developed in the filament is a unique function of the spinline stress.

A solid filament or a melt spinning filament drawn down by an aspirator was used to investigate the formation of the spunbonded fabric on the surface of the conveyer belt. An empirical equation was developed to predict the number of loops on the surface of the conveyer belt for a spunbonding process.

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CHAPTER I

INTRODUCTION

Nonwoven fabrics generally are defined as sheet or web structures made by bonding and/or interlocking fibers, yarns or filaments by mechanical, thermal, chemical or solvent means. They have been found useful in a wide array of products including electrical insulation, diapers, carpets, blankets, disposable hospital supplies, leather replacement materials, industrial wipers, and household textiles. In these fields, they are on the threshold of seriously challenging wovens and knit fabrics and certain to get a greater share of the market in the near future. New applications and processes for manufacture are continually being developed. Many researchers (18, 19, 20, 23, 89) are centered on means of improving strength, "hand" and abrasion resistance through new techniques in web formation, mechanical bonding process, and in the use of binders.

The major routes to nonwovens are dry laid webs, wet processing (modified paper-making techniques), spunbonding, and laminations. These are reviewed by Casper (12). Spunbonded products are defined as continuous filament, fibrous structures which can be made in the form of sheets, webs, and tapes and are prepared from synthetic polymers in a process integrated with fiber manufacture (80).

In this thesis, a basic study of spunbonding is reported. The air drag and dynamics of the spunbonding process are investigated. The relationship between spunbonding conditions and filament structure is studied. Investigations are also done on the formation of the fabric from the descending fibers on conveyer belts.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 SPUNBONDED TECHNOLOGY

Slayer and Thomas (83) invented a method of forming glass fibers and causing them simultaneously to entangle and "interfelt" with each other in such a manner that they form a mat which has been called "glass wool." Molten glass was extruded through a series of capillaries of diameters from 0.02 to 0.15 inches. Two air blowers were spaced a short distance below the spinneret. The direction of these air stream nozzles was about 12° with the vertical, this angle being great enough to seize the glass streams and cause their attenuation to 0.001 ~ 0.01 inches in diameter. Suction may be applied to assist in the formation of the mat. Some binders were sprayed later.

Till and Smallman (91) described in their patent how to make a sheet of synthetic organic fibers using a high potential static electricity generator to collect the fibers. They surrounded the orifice, from which a polymer or its solution was supplied, with a gas nozzle like a spray gun. At the same time, the fibers were supplied with high potential static electricity. Then, the discontinuously attenuated and charged fibers were blown into a tower open at its upper end. A conveyer with opposite charge was

located at the upper end of the tower to collect the fibers to form a reticulated web. A suction chest was positioned on the opposite side of the porous collecting surface (the conveyer belt). If a fiber-forming spray solution, i.e., a dispersion of polymer in a suitable solvent, is used, the suction chest may also serve as an aid to the recovery of vaporized solvent. The reticulated web may be passed through a heating chamber, which may be used to activate the fibers to provide a greater bond between them before being removed from the conveyer belt by a doffer.

Guandique and Katz (30) and Kinney (53) of Du Pont described an apparatus (Fig. 2.1) in which extruded filaments issuing from a spinneret passed through an aspirator jet to which air is supplied under pressure. The filaments were drawn and oriented by the concurrent air stream supplied by the aspirator. The descending filaments were also subjected to the effects of a high static electrical potential charge between the jet and a collecting device upon which the filaments impinge. Under the influence of the electrical charge, the filaments separated and lay down in a completely random configuration upon the collecting device. A process suggested by them was to supply the aspirator jet with 40 psig air and charge it to a high positive potential using an 8,000-volt source.

The patent of Guandique and Katz (30) was for the nonwoven fabric structure. A fabric containing continuous

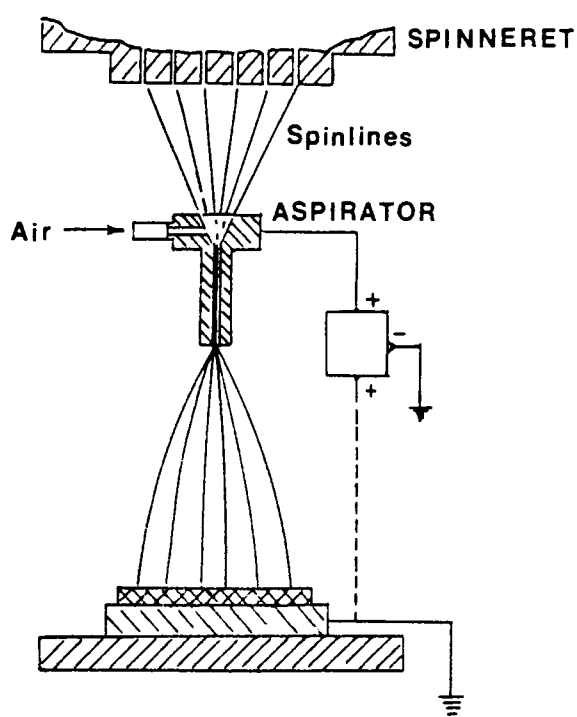


Figure 2.1 Spunbonding process patented by Guandique and Katz (30) and Kinney (53).

filaments of a very highly crimped and convoluted configuration was prepared by the technique described above. Kinney (53) in his patent, which was based on this process, claimed a moving multifilament bundle of at least 20 continuous synthetic organic filaments capable of holding an electrostatic charge which was charged to a potential (at least 30,000 e.s.u) sufficient to separate them. The charging had to be accomplished while the filaments were under tension, so that they did not separate until such tension was released. He also noted that in order to obtain a web in which the filaments are randomly disposed, V_f/V_b must be larger than 5 and 15 is preferable. (V_f is the velocity of the filament and V_b is the velocity of the conveyer belt.)

The charging methods described in the aforementioned patents are not generally useful with unmodified fibers other than polyamides, since these do not normally have a high enough electrical conductivity in the molten state. Talbert (89) of Du Pont invented a process in which small amounts of alkali metal salt added to a polymer melt (about 0.044 gram-moles of the alkali metal component of the salt per 100 kg of polymer) greatly enhanced the positive charge level. Equipment slightly modified from Kinney's patent (53) was applied in this method.

Edwards (20) noted that carpet backing, which is made by the former patents, may lengthen in the "machine

direction," by exhibiting a narrowing or "necking down." Since such dimensional changes are not desirable, he invented a method to overcome this defect. He let the filaments spray from the jet in line by using two additional slits at the end of the jet. The aligned filaments were lying along the machine and cross-machine direction.

Hartmann (33, 34, 35, 36) of Carl Freudenberg of West Germany patented spunbonding processes based on the apparatus in Fig. 2.2 (in which the gases drawing down the filaments issued from the spinneret). The gas velocity was so adjusted that the filaments were carried away from the spinneret without breaking off, and the filament diameter decreased within a distance of 5 mm from the spinneret by a ratio at least 30:1 but preferably higher. The air channel or passageway for the purpose of keeping the filaments at a distance of 5 cm to 6 cm were chilled from 300°C to 60-100°C. The fabric produced thereby can be calendered at, for example, room temperature or steam treated to bond the filaments together. They can also be bonded with synthetic resin, especially if a soft hand is desired. The air leaving the slots was heated. The temperature of the air depended on the polymer which was used. For example, the air was heated to 220°C for nylon-6 (m.p. 210°C, relative viscosity 2.28) and traveled at a velocity of 12,000 m/min. Such filaments were thereby accelerated from a velocity of 1 m/min within the nozzle holes to about 1,200 m/min at a distance of 3 mm from the nozzle exit.

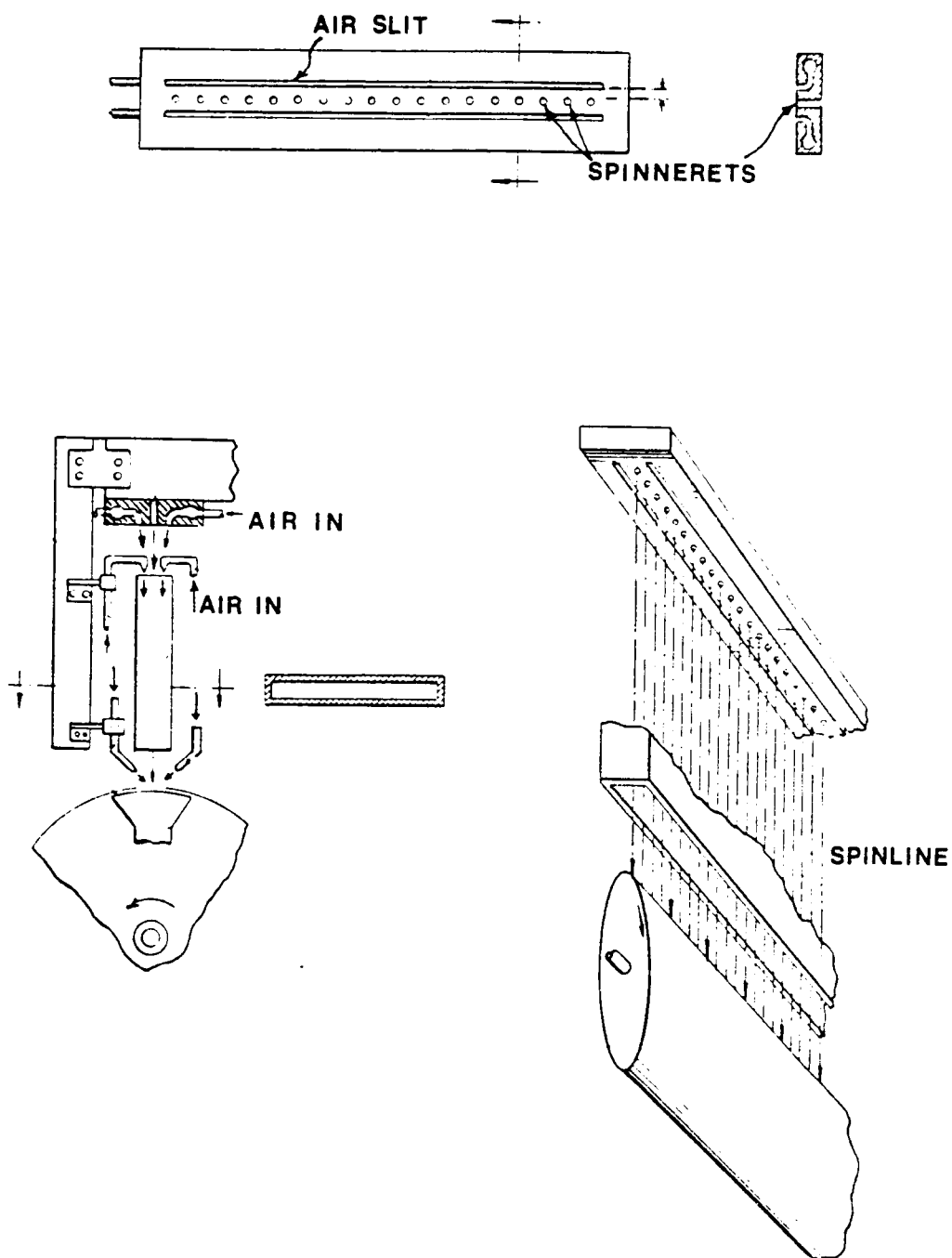


Figure 2.2 Spunbonding process patented by Hartmann (33-36).

Dobo, Cary, Kim, and Mallonee (19) of Monsanto described a process and apparatus by which they can produce a soft bonded nonwoven fabric from a polymer melt in a single continuous operation. Continuous filaments were spun through a spinneret and attenuated by an aspirator, which was mechanically traversed in a horizontal direction by a reciprocating mechanism. The filaments were deposited upon a belt, underneath which a suction box was provided. After being sprayed by a solvent, the web left the forwarding belt and passed through a pair of press rolls for calendering to improve web density.

The web then entered a chamber which was filled with activating gas. Two hot rolls were used to evaporate the solvent and to establish the desired number of filament contacts for bonding. At the end a wash bath was used to remove the activating gas.

Hydrogen chloride was used as an activating gas in nylon (18). The hydrogen chloride in the nylon causes the interchain hydrogen bond to break, and upon removal of hydrogen chloride from the nylon in the next step, the interchain hydrogen bonds reform. Some bonds form between amide groups of different filaments at the cross-over point. These bonds, which act as binding agents, stick the filaments together at the cross-over points.

2.2 DYNAMICS AND AIR DRAG COEFFICIENT OF MELT SPINNING

2.2.1 Dynamics

Force balances on a spinline were first treated by Ziabicki (97, 98) a generation ago. The forces acting on a descending spinline include the take-up tension, F_L ; gravity, F_{grav} ; frictional drag, F_{drag} ; and momentum fluxes. If we make a balance between position " X_1 " and " L " on X direction, the tension F_{X_1} or F_{rheo} at a position X_1 in the spinline is (shown in Fig. 2.3):

$$F_{\text{rheo}} = \frac{\pi d^2}{4} \sigma_{xx}(X_1) = F_L + F_{\text{grav}} - F_{\text{drag}} - \rho Q(V_L - V_{X_1}) \quad [2.1]$$

where

$$F_{\text{grav}} = \int_{X_1}^L \frac{\pi d^2}{4} \rho g dx \quad [2.2]$$

$$F_{\text{drag}} = \int_{X_1}^L \pi d \sigma_f dx \quad [2.3]$$

$$\sigma_f = C_f \frac{\rho_a V_x^2}{2} \quad [2.4]$$

ρ_a is density of air

C_f is the air drag coefficient

d is the diameter of the filament

$\sigma_{xx}(X_1)$ is the spinline stress at position X_1

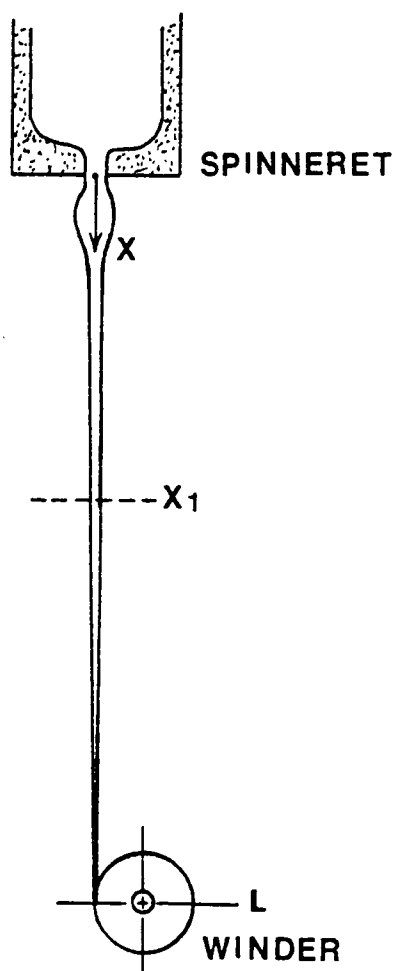


Figure 2.3 Force balance on a melt spinline.

2.2.2 Air Drag

2.2.2.1 Theoretical. Glauert and Lighthill in 1955 (27) considered the axisymmetric laminar flow of constant velocity, U , over a long thin cylinder of radius, a , by boundary layer theory. The Pohlhausen method with a velocity profile proportional to $\ln(1 + \frac{Y}{a})$ was followed by them (Fig. 2.4). They predicted that the air drag coefficient was a function of $(Re_a)(\frac{X}{D})$, where

$$Re_a = \frac{U\rho_a a}{\eta_a} \quad [2.5]$$

and

ρ_a is the density of the air

η_a is the viscosity of the air

a is the radius of the cylinder

Sakiadis (78) has dealt with air drag on a continuous moving cylinder with a constant velocity, U . He used the Pohlhausen method with a velocity profile proportional to $[1 - \frac{1}{\beta} \ln(1 + \frac{Y}{a})]$, where β is a function of X . His theory also predicted the air drag coefficient is a function of $(Re_a)(\frac{X}{D})$. Matsui (59) has noted that existing experiments (32, 79) indicated that the drag coefficient was not influenced by filament length. He argued that C_f is only a function of Re_D , and assumed that the momentum flow along the Z -axis is constant (Fig. 2.5). A theoretical analysis of air drag has been carried out, considering momentum

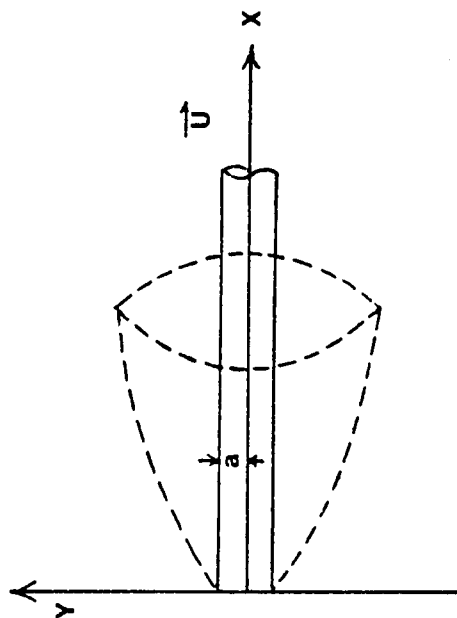


Figure 2.4 Boundary layer near a moving filament.

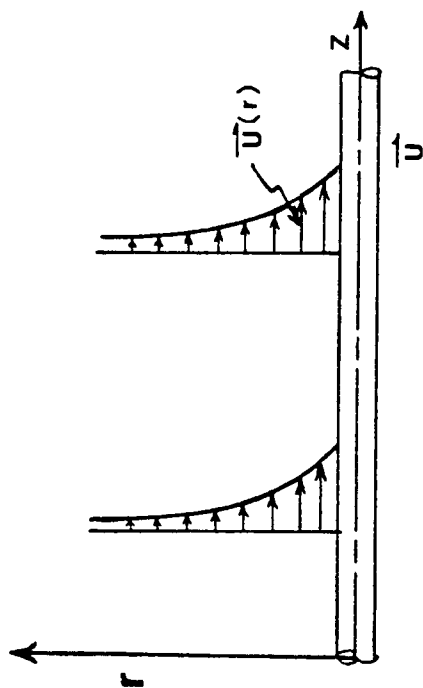


Figure 2.5 Velocity distribution around a filament moving with velocity U .

transfer and Prandtl's mixing length theory of turbulent air flow on a moving filament. The air drag coefficient is approximated as

$$C_f = 1.22 K^{0.78} Re_D^{-0.61} \quad [2.6]$$

in the range of $0.5 < K^2 Re_D < 15$. The K value should be determined from experimental data.

2.2.2.2 Experimental measurement of air drag. Anderson and Stubbs in 1958 (5) put solidified fibers of diameters varying from 2×10^{-3} cm to 5×10^{-3} cm into a suction tube to measure tensions of the fibers. By varying the length of the fiber in the suction tube and changing the air velocities from 210 m/min to 1,062 m/min, they obtained a plot of tensions versus fiber lengths in the tube. After calculations, the air drag coefficients can be expressed as:

$$C_f = 0.9 Re_D^{-0.61} \quad [2.7]$$

Shortly thereafter, Andrew and Cansfield (6) measured the air drag forces on filaments in a wind tunnel. Their results were recalculated and expressed as:

$$C_f = 1.32 Re_D^{-0.61} \text{ for } 20 < Re_D < 300 \quad [2.8]$$

Selwood (84) pulled a solidified nylon fiber vertically in stationary air at speeds varying from 300 m/min to 1,200 m/min. The tensiometer was first placed only a foot

above a cone to measure the fiber take-off tensions. Before the fiber was wound up about 20 meters above the cone, the fiber tensions were measured again by the same tensiometer. The difference between tensions measured at these two positions gave the air drag acting on the fiber. His results can be plotted and expressed by:

$$C_f = 0.58 \text{ Re}_D^{-0.61} \text{ for } 8 < \text{Re}_D < 108 \quad [2.9]$$

Fukuda (25) also used a solidified filament to do the experiment at air velocity below 300 m/min, and got the air drag coefficients, which can be expressed as:

$$C_f = 2.2 \text{ Re}_D^{-0.61} \text{ for } 6 < \text{Re}_D < 14 \quad [2.10]$$

Sano and Orii (79) of Mitsubishi Rayon made drag measurements on a continuous polypropylene spinning line at spinning speeds varying from 200 m/min to 800 m/min in a stationary or flowing air. They measured tensions at two positions: one was about 1.6 meters below the spinneret, the other was about 5 meters below the spinneret (above the winder). The drag force was calculated from the difference in tension between those two positions. They found that:

$$C_f = 0.68 \text{ Re}_D^{-0.8} \text{ for } 10 < \text{Re}_D < 50 \quad [2.11]$$

Hamana, Kato, and Matsui (32) and Matsui (59) measured the air drag in the melt spinning of polyester fibers. Tensions were measured at different positions along the

spinline with a Rothshield Tensiometer below the solidification point. Hamana et al. spun the fiber at spinning speeds varying from 300 m/min to 1,000 m/min. Later, Matsui increased the spinning speed to 6,000 m/min. They all got the following relationship:

$$C_f = 0.37 \text{ Re}_D^{-0.61} \text{ for } 10 < \text{Re}_D < 260 \quad [2.12]$$

Kwon and Prevorsek (56) of Allied Chemical carried out experiments similar to those of Selwood and measured tensions at two positions at the same time. They also measured the air velocity by using a thermoanemometer to find that the air velocity profile is larger than the theories predicted by Glauert and Lighthill (27), and Sakiadis (78). The measured air drag forces on the moving filaments are significantly larger than the drag values estimated from these theories.

Gould and Smith (29) used a glass tube wind tunnel of 25 mm diameter to measure the tensions on tensioned filaments passing through the wind tunnel. The filament diameters varied from 1.7×10^{-3} to 30.0×10^{-3} cm. Under high air velocities (1,200 m/min ~ 6,000 m/min), they got:

$$C_f = 0.43 \text{ Re}_D^{-0.61} \text{ for } 40 < \text{Re}_D < 400 \quad [2.13]$$

This value seems smaller than the results of Andrew and Cansfield. Gould and Smith argued that Andrew and Cansfield's work was done with fairly thick ($5.0 \sim 40.0 \times 10^{-3}$

cm) untensioned filaments, which could flap in the air flow. This would lead to larger drag forces.

A comparison of all the theories and experimental results is presented in Fig. 2.6.

2.2.3 Rheological Response

Theories of diameter variation in melt spinning were first considered by Ziabicki and Kedzierska (99), and by Kase and Matsuo (49) of Toyobo in Japan. They presumed that the melt could be represented as a Newtonian fluid, and F_{rheo} was approximately equal to F_L . It follows that

$$F_L = \frac{\pi d^2}{4} \chi \frac{dV_1}{dX_1} \quad [2.14]$$

where χ is the elongational viscosity which depends on temperature only. More recent studies (2, 17, 24, 60, 63) have considered the visco-elastic properties of the molten filaments.

2.3 HEAT TRANSFER DURING MELT SPINNING

2.3.1 Theoretical

Heat transfer from a fiber spinline to ambient medium involves radiation and forced convection. Kase and Matsuo (49) derived a heat balance which has the form

$$C_p \rho \pi R^2 \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial X} \right) - 2\pi R [h(T-T^*) + \sigma \epsilon (T^4 - T^{*4})] = 0 \quad [2.15]$$

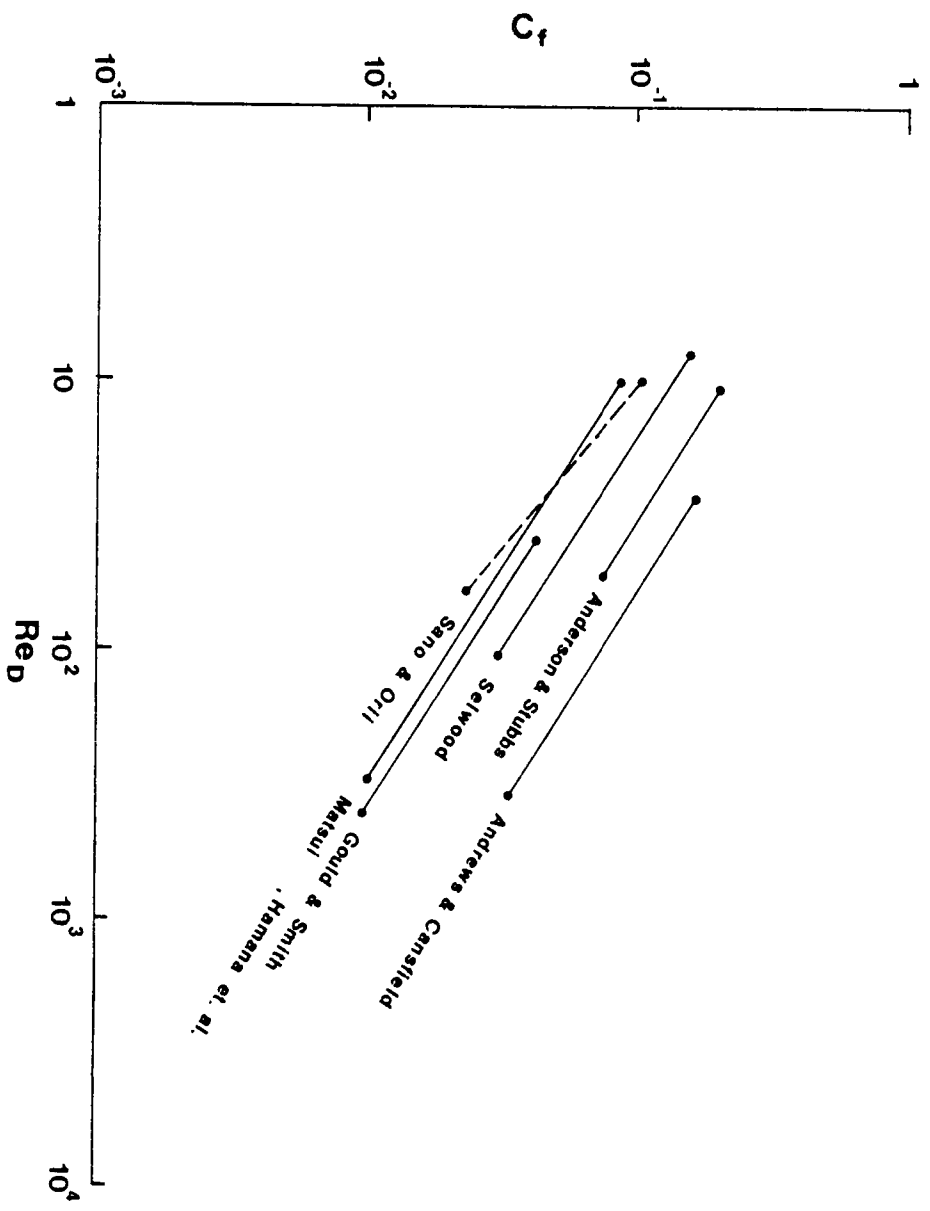


Figure 2.6 Comparison of air drag coefficients from the literature.

where R is the local radius of the filament

h is the coefficient of heat transfer at filament surface

T is local temperature of the filament

T^* is the temperature of ambient air

t is time

σ is the Stefan-Boltzmann constant

ϵ is the emissivity

ρ is the density of the filament

C_p is the isobaric specific heat.

They considered the term for radiant heat loss to be small in comparison to the first term for convective loss, and got:

$$v \frac{\partial T}{\partial X} + \frac{\partial T}{\partial t} = - \frac{2\sqrt{\pi}h}{C_p A \rho} (T^* - T) \quad [2.16]$$

On steady state, the derivatives with respect to time drop out. Using $G = \rho v A = \text{constant}$, they obtained:

$$\frac{dT}{dX} = \frac{2h\sqrt{\pi A}}{C_p G} (T^* - T) \quad [2.17]$$

In most industrial melt spinning operations, cooling air is blown at right angles to the filaments. Kase and Matsuo (50) also numerically computed the temperature profile in the melt spinning filament without assuming axisymmetry. They considered the equation of continuity

$$\frac{1}{r} \frac{\partial}{\partial r}(rv_r) + \frac{\partial v}{\partial X} = 0 \quad [2.18]$$

and the energy equation

$$\rho C_p [v_r \frac{\partial T}{\partial r} + v \frac{\partial T}{\partial X}] = k [\frac{1}{r} \frac{\partial}{\partial r} (r \frac{\partial T}{\partial r}) + \frac{1}{r^2} \frac{\partial^2 T}{\partial t^2}] \quad [2.19]$$

in cylindrical coordinates, where v_r is the velocity in radial direction, v is the velocity in the X-direction, and k is the thermal conductivity. This led them to the two-dimensional heat conduction equation:

$$\frac{\partial T}{\partial \Sigma} = \frac{1}{\xi} \frac{\partial T}{\partial \xi} + \frac{\partial^2 T}{\partial \xi^2} + \frac{1}{\xi^2} \frac{\partial^2 T}{\partial t^2} \quad [2.20]$$

$$\text{where } \Sigma = \frac{\pi k}{G C_p} x \quad \xi = \frac{r}{R(x)}$$

They solved the above equation with boundary conditions,

$$k \frac{\partial T}{\partial r} = (T^* - T)h \quad \text{at } r = R \quad [2.21]$$

and computed constant-temperature contours. These were approximately concentric circles with their center shifted from the filament center in the downstream direction of cooling air flow.

The spinline temperature during crystallization is governed by the competition between heat generated by crystallization and heat loss as a result of continuous cooling. The effect of crystallization was first considered by Nakamura, Watanable, Amano, and Katayama (67, 68, 69). For the steady state, they derived:

$$\alpha \nabla^2 T = \underline{V} \nabla T - \frac{\Delta H}{C_p} \underline{V} \nabla X_c \quad [2.22]$$

where $\alpha = \frac{k}{\rho C_p}$, the thermal diffusivity

$\underline{V}$ is the velocity

ΔH is the heat of crystallization

X_c is the crystallinity.

They argued that according to the kinetics of crystallization,

$$X_c = 1 - \exp [-(\int_0^t k(T) dt)^n] \quad [2.23]$$

where n is the Avrami index and $k(T)$ is a crystallization rate constant. Simultaneous solution of equations [2.22] and [2.23] under given initial and boundary conditions gives the crystallinity and temperature at any point within the filament.

2.3.2 Heat Transfer Coefficient

Ziabicki (100) noted that free convection, associated with the motion of ambient medium in the temperature field around the cooling body, is the typical heat transfer mechanism for a stationary system. The Nuselt number, $Nu = h \cdot D / \lambda^\circ$, characterizing the heat transfer coefficient, is then a function of Grashof and Prandtl numbers. When the spinline moves in a stationary medium with a velocity of the order of $10^2 \sim 10^3$ m/min and/or a parallel or transverse air stream is applied, heat transfer is due to forced

convection. The Nuselt number is

$$Nu = Nu(Pr, Re_D, X/D) \quad [2.24]$$

where X is the exposed length of the filament. Glicksman (28) considered the laminar and turbulent boundary layers in axial air flow over a stationary cylinder and got:

$$Nu = 0.325 Re_D^{0.5} \quad [2.25]$$

The Nuselt number was independent of the exposed slender ratio (X/D).

Several theories have been proposed for the prediction of heat transfer coefficients in fiber spinning and related processes. Vasudevan and Middleman (93), and Acierno, Dalton, Rodriguez, and White (2) considered the laminar boundary layer over a continuous cylinder, and found that the Nuselt number in both these theories resulted as a function of a single variable β , where

$$\beta = \beta[Re (D/X)^2, Pr] \quad [2.26]$$

Turning to experimental studies, Kase and Matsuo (48) measured $\rho A(X)$ by trapping the molten filament in a booklike apparatus. The temperature was measured by means of a contact thermocouple similar to the one used by Culpin, Madoc and Jones (15). From $\rho A(X)$ and temperature $T(X)$, Kase and Matsuo compared their experimental results with theoretical results. From experiments, they give

$$Nu = 0.42 Re_D^{0.334} (1 + k) \quad [2.27]$$

for air flowing parallel to the cylinder, where $(1 + k)$ is the corrective coefficient. For air flowing perpendicular to the cylinder, they give

$$(1 + k) = [1 + (\frac{8V_y}{V})^2]^{0.167} \quad [2.28]$$

where V_y is the air speed to the fiber axis

V is the filament velocity.

Several apparatuses used for measuring the running filament temperature are based on the principle of a contact thermocouple. A typical apparatus of this type is one developed by Cupin et al. (15), in which the thermocouple is mounted on an electrically heated head. However, contact type thermocouples are difficult to use on the melt surface just below the spinneret. Wilhelm (96) used a contactless temperature measuring apparatus, in which he measured I. R. radiation emitted by the filament. Evaporograph (22) also developed an apparatus, which used a thermal imaging device that converts I. R. radiation into a visible color image.

2.4 STRUCTURE CHARACTERIZATION

Spruiell and White (86) pointed out that the most useful methods of investigating the morphology of fibers are the classical techniques of optical and electron microscopy and wide angle X-ray diffraction (WAXS). The latter

yields information in the range of $10\text{\AA}$ giving crystallographic structure and orientation, while small angle X-ray diffraction (SAXS) gives information on the order of a scale of $100\text{\AA}$. Scattering and retardation of polarized light can be used on fibers to determine information about structural features on the order of $10,000\text{\AA}$. Structural characteristics of fibers can also be studied by optical microscopy (50 to 1,000 times) and by scanning electron microscopy (up to $\sim 50,000$ times). Transmission electron microscopy allows magnification of the order 10^6 times.

The quantitative characterization of orientation is of considerable importance. Hermans and his coworkers (46) have proposed using the anisotropy of polarizability as a measure of the average orientation of polymer chain relative to the axis of fiber. The Herman orientation factor is

$$f_H = \frac{\alpha_{//} - \alpha_{\perp}}{\alpha_1 - \alpha_2} \quad [2.29]$$

where $\alpha_{//}$ and $\alpha_{\perp}$ are the average polarizabilities parallel and perpendicular to the fiber axis, and α_1 and α_2 are the polarizabilities parallel and perpendicular to the polymer chain. This they show is equivalent to

$$f_H = \frac{1}{2} [3 \overline{\cos^2 \phi_{c,z}} - 1] \quad [2.30]$$

where $\overline{\cos^2 \phi_{c,z}}$ is the average value of the cosine square of the angle between the fiber axis z and the chain axis c .

For an amorphous polymer, it is readily shown that this is equivalent to

$$f_H = \frac{\Delta n}{\Delta^\circ} \quad [2.31]$$

where Δn is the birefringence which is the difference between the principle refractive index parallel to the stretch direction, $n_{\parallel}$, and the principle refractive index perpendicular to it, $n_{\perp}$, for an oriented specimen, i.e., $\Delta n = n_{\parallel} - n_{\perp}$. Δ° is the maximum or intrinsic birefringence of the system at full orientation.

For crystalline filaments, Stein (88) has argued that Equation [2.30] may be extended to all three crystallographic axes. These are called Herman-Stein uniaxial orientation factors given by

$$f_j = \frac{1}{2}(3 \overline{\cos^2 \phi_{j,z}} - 1) \quad [2.32]$$

where $\overline{\cos^2 \phi_{j,z}}$ is the average value of the cosine square of the angle between the fiber axis z and the j - crystallographic axis ($j = a, b, c$). For orthogonal crystal axes,

$$\overline{\cos^2 \phi_{a,z}} + \overline{\cos^2 \phi_{b,z}} + \overline{\cos^2 \phi_{c,z}} = 1.0 \quad [2.33]$$

and

$$f_a + f_b + f_c = 0 \quad [2.34]$$

The measurement of orientation functions requires evaluation of the $\overline{\cos^2 \phi_{j,z}}$ term in Equation [2.32].

Assuming rotational symmetry about the fiber axis, $\overline{\cos^2\phi_{j,z}}$ can be determined from Equation [2.35] for crystalline orientation.

$$\overline{\cos^2\phi_{j,z}} = \frac{\int_0^{\pi/2} I_{hkl}(\phi_{j,z}) \cos^2\phi_{j,z} \sin\phi_{j,z} d\phi_{j,z}}{\int_0^{\pi/2} I_{hkl}(\phi_{j,z}) \sin\phi_{j,z} d\phi_{j,z}} \quad [2.35]$$

where $I_{hkl}(\phi_{j,z})$ is the intensity diffracted from the (hkl) planes, which are normal to the j - crystallographic axis.

The Hermans-Stein orientation factors refer only to the crystalline phase and we need also to be concerned about the amorphous regions in polymers, as crystallinities are generally considerably less than 100 percent. The total birefringence Δn is related to both the crystalline and amorphous birefringence through

$$\Delta n = f_c X \Delta_c^\circ + (1 - X) \Delta_{am}^\circ f_{am} + \Delta n_{form} \quad [2.36]$$

where X is crystallinity. The Hermans orientation factors of crystalline and amorphous regions are f_c and f_{am} . The intrinsic birefringences of crystalline and amorphous regions are Δ_c° and Δ_{am}° . Δn_{form} is the so-called "form birefringence" (9) and is neglected in most of the calculations for homopolymers.

2.5 ORIENTATION DEVELOPMENT IN MELT SPUN FIBERS

In the following sections, the orientation of three fundamental glassy and crystalline polymers are discussed.

2.5.1 Polystyrene

Andrews (7) and Oda, White and Clark (72) found the birefringence of polystyrene spun fibers is negative and its magnitude increases with draw down and take-up velocity. The negative value of birefringence suggests that the birefringence was developed in molten state, where the stress optical coefficient is negative, and is frozen in. Oda et al. (72) noted that the plot of birefringence versus spinline stress is a single nearly straight line with a slope equivalent to the melt phase stress optical constant. It is

$$\Delta n = C\sigma_{11} = C\left(\frac{F}{\pi R^2}\right) \quad [2.37]$$

where "1" is the spinline direction, and C is an apparent stress optical constant and corresponds to a value of -4,500 Brewster (B) (1 B = 10^{-13} cm²/dyne). From Equations [2.31] and [2.37], it follows that:

$$f = \frac{C}{\Delta^{\circ}} \sigma_{11} \quad [2.38]$$

The Hermans orientation factor of the fibers varies linearly with spinline stress. The value of Δ° for polystyrene has

been reported as -0.3 by Gurnee (31), -0.012 by Milagin et al. (62), and -0.01246 by Matsumoto and Hirohiko (61).

2.5.2 Polyethylene

Polyethylene has long been known to readily and rapidly crystallize from the melt (86). As first shown by Bunn (11), it crystallizes into an orthorhombic unit cell with a diameter $a = 7.40$, $b = 4.94$, $c = 2.54 \text{ \AA}$. The idea of bulk-crystallized polyethylene consisting of a folded chain lamellae is consistent with numerous observations, such as the SAXS pattern, showing a repeat distance of the order $100 \text{ \AA}$ (3, 26), and the birefringence of spherulites (10, 94), which indicates that the polymer chain axes are perpendicular to the spherulite radius.

The variation in level of crystallinity in melt spun fibers as a function of take-up velocity has been studied by Kitao et al. (54), Abbott and White (1), Dees and Spruiell (16), and White, Dharod, and Clark (94). For low density polyethylene (LDPE), the level of crystallinity is of the order of 30 percent and constant. For high density polyethylene (HDPE), crystallinities are of the order of 65 percent at low take-up velocity and decrease to about 60 percent with increasing take-up velocities.

From WAXS measurements, many authors (1, 16, 51, 54, 96) have noted the orientation factors of HDPE. At sufficiently low take-up velocity, the sample is random and $f_a = f_b$ and f_c . As take-up velocity increases, f_b becomes

negative, f_a and f_c becomes positive and approximately equal, i.e., $f_b \sim -0.45$, $f_a \approx f_b \approx 0.22$. These are nearly the exact value of the type of orientation, called a "row structure" by Keller and Machin (52) in which the b axes are perpendicular to the fiber axis and randomly disposed within a plane perpendicular to the fiber axis. The a and c axes tend to rotate randomly about the b axes. At the higher take-up velocity,

$$f_b \approx -0.45, f_c \rightarrow 0.65, f_a \rightarrow -0.20$$

the a axes as well as the b crystallographic axes tend to become perpendicular to the fiber axis.

The variation of orientation functions with take-up velocity has been described by Abott and White (1), and Dees and Spruiell (16). The latter authors measured spinline stress and found that the orientation factors are a unique function of spinline stress, i.e.,

$$f_j = f_j(\sigma_{11}) \quad [2.39]$$

where $j = a, b, c$.

SAXS patterns have been studied by Dees and Spruiell (16). The patterns show that there is a strong intensity maximum on the meridian for a take-up velocity as low as 50 m/min (low stress). However, the intensity spreads around the incident beam at low stress. This effect disappears as stress increases. Quantitative SAXS results

show that there seems to be a trend toward smaller long periods with increasing spinline stress, although the changes are not large.

Birefringence measurements of Dees and Spruiell (16) show that the birefringence increases steadily as the spinline stress increases. It follows that:

$$\Delta n = \Delta n(\sigma_{11}) \quad [2.40]$$

2.5.3 Polypropylene

The most common crystal form of isotactic propylene (PP) is monoclinic. The unit cell of monoclinic PP has been determined by Natta and Corradini (70). The dimensions are $a = 6.65$, $b = 20.96$, $c = 6.50 \text{ \AA}$, and $\beta = 99^\circ 22'$. The PP chain has a helical conformation and the c-axis parallel to the axis of the helix. Sheehan and Cole (82) show that monoclinic PP is produced under normal air quenching conditions, but quenching in cold water produced a paracrystalline smectic structure.

We now turn to crystalline orientation. It is convenient to define an a' -axis which is not a true crystallographic axis, but perpendicular to both the b and c axes. In monoclinic PP, Wilchinsky (95) has shown that the $\overline{\cos^2 \phi_{c,z}}$ for a crystalline region may be represented as:

$$\overline{\cos^2 \phi_{c,z}} = 1 - 1.099 \overline{\cos^2 \phi_{110,z}} - 0.901 \overline{\cos^2 \phi_{040,z}} \quad [2.41]$$

Kitao, Ohya, Furakawa, and Yamashita (54) and Nadella, Henson, Spruiell and White (66) studied the WAXS patterns and reported the c-axis orientation of PP filament (spun into ambient air) increases with take-up velocity. Nadella et al. (66) reported that higher take-up velocity, low extrusion rate, low spinning temperature, and higher molecular weight, gives higher orientation. They found that crystalline orientation is a unique function of spinline stress independent of polymer molecular weight and probably molecular weight distribution. This further emphasizes the significance of the spinline stress. The value of f_c increases with spinline stress, leaving off at 0.91, which indicates that the c-axes are tending to become more aligned with the fiber axis with increasing stress. The f_b decreases rapidly reaching a value of -0.48 indicating a near perpendicular alignment of the b-axes with the fiber axis. The value of $f_{a'}$ decreases slowly at first, but it then decreases rapidly and finally approaches -0.43. However, Henson's results introduced by Spruiell and White (86) show that $f_{a'}$ is positive at very low spinline stress and increases slowly as spinline stress increases. After approaching a small value 0.05, it decreases rapidly to a value of -0.23 as spinline stress increases. Nadella et al. (66) indicated that careful examination of the WAXS patterns shows that a distinctive bimodal orientation of the unit cells occurs in melt-spun filaments. This bimodal

orientation was also pointed out by several other investigators (4, 13, 14), when PP is crystallized from the melt under the condition of extentional flow.

The variation in the SAXS pattern from a ring pattern at low spinline stresses to a "two-point" pattern at high spinline stresses is reported by Nadella et al.(66), Noether and Whitney (71), and Spruiell and White (87). This is similar to those reported for high-density polyethylene (1, 54, 86, 96).

Nadella et al. (66) also indicated that the measured birefringence is a function of spinline stress.

2.6 FORMATION OF SPUNBONDED FABRICS

An apparatus, made to study the form taken by thread laid on a moving belt under different conditions, is described by Hearle, Sultan and Govender (44). It is shown that the form of the laid-down thread can vary according to the type of thread, the height of the feed point, and the feed and belt speeds.

A cotton roving of linear density 175 tex. was found to be the most suitable for this investigation owing to its low snarling tendency and its high uniformity.

If a loop is formed as in Fig. 2.7, we can have:

$$\begin{aligned} X &= R \cos \omega t + V_b t \\ Y &= R \sin \omega t \end{aligned} \quad [2.41]$$

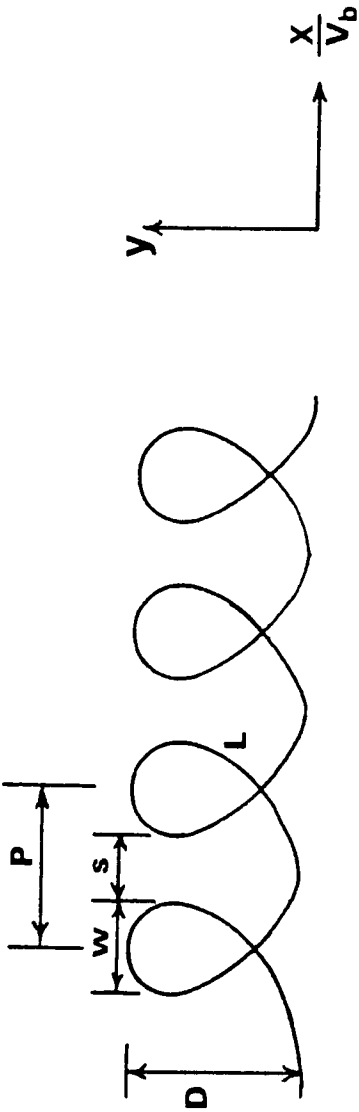


Figure 2.7 Looping form of mono-filament cycloid.

We also have

$$\frac{\lambda}{P} = \frac{V_f t}{V_b t} = \frac{V_f}{V_b} \quad [2.42]$$

where $\omega = \frac{d\theta}{dt}$ is an angular frequency

λ = length in one cycle

s = loop separation

ω = loop width

P = pitch

t = time

$V_f = \omega R$ is the velocity of feed thread

V_b = velocity of belt

D = transverse amplitude.

If V_f/V_b decreases, the loops become smaller. When $V_f/V_b \rightarrow 2$ or less, D/D_0 changes very rapidly. At $V_f/V_b \ll 1.5$, the loop disappears.

Theoretically, if the pattern is a modified cycloid, its shape should depend only on the speed ratio, V_f/V_b , and not on the feed height or thread properties. However, the evidence of the authors' experiments is inconclusive as to whether or not the height and bending and torsional rigidities affect the speed ratio at which the pattern changes.

They argued that all dimensions increase with feed height. The loop height and wave amplitude increase, and the loop pitch and wavelength decrease as the speed ratio

V_f/V_b increased. When the threads are falling under the effect of their own weight, the effect of rigidity on dimensions is consistent. Dimensions increase with the bending and torsional rigidities. When the threads are being compressed, the relationship is inconsistent.

Euler (23) in 1744 first considered the problem of buckling of columns or bars, which were restrained at the bottom and loaded axially at the top. A critical load F is defined as the axial load, which is sufficient to keep the bar in a slightly bent form. If the axial load is less than its critical value, the bar remains straight and undergoes only axial compression. Taking the coordinate axes as indicated in Fig. 2.8, the bending moment at any cross section m-n is $F(\delta - y)$ and the differential equation of the deflection curve becomes

$$EI \frac{d^2y}{dx^2} = F(\delta - y) \quad [2.43]$$

where E = Young's Modulus

I = moment of inertia

The equation can be solved and the critical load F_{cr} is given by

$$F_{cr} = \frac{\pi^2 EI}{4L^2} \quad [2.45]$$

In the case of a bar with hinged ends (92), Fig. 28-d, it is evident from symmetry that each half of the bar is in

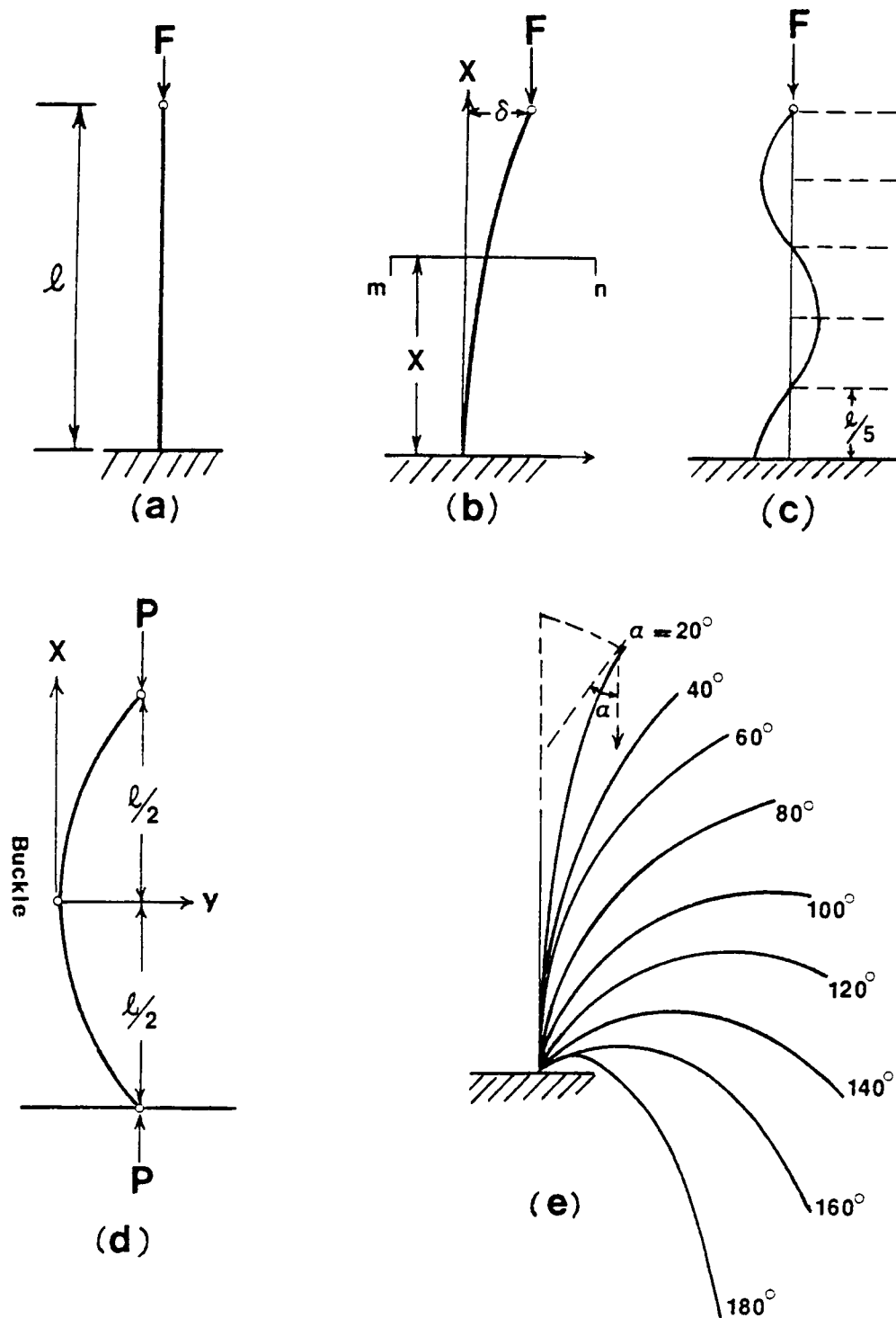


Figure 2.8 Buckling columns under different boundary conditions.

the same condition as the entire bar of Fig. 2.8-b. Hence, the critical load is:

$$F_{cr} = \frac{\pi^2 EI}{l^2} \quad [2.46]$$

Dividing the above formula by the cross-sectioned area A of the bar, and letting $r = \sqrt{\frac{I}{A}}$ be the smallest radius of gyration, the critical load is:

$$\sigma_{cr} = \frac{F_{cr}}{A} = \pi^2 E \left(\frac{r}{l}\right)^2 \quad [2.47]$$

If the load F is taken somewhat larger than the critical value F_{cr} , a large deflection of a bar will be produced (8, 77) (Fig. 2.8-e). Let α be the initial angular displacement of the pendulum from the vertical. With the increase of load F , the angle α increases also. The relationships between α and F/F_{cr} were given in a table (92). The results of large deflections discussed above can be used also in the case of a bar with hinged ends. In this case the curves of Fig. 2.8-e represent only half of the length of the bar. The curves shown in Fig. 2.9, representing forms of equilibrium of a thin wire, can all be obtained by combining curves of Fig. 2.8-e. Thus, the forces necessary to produce such bending can be found from the table mentioned above.

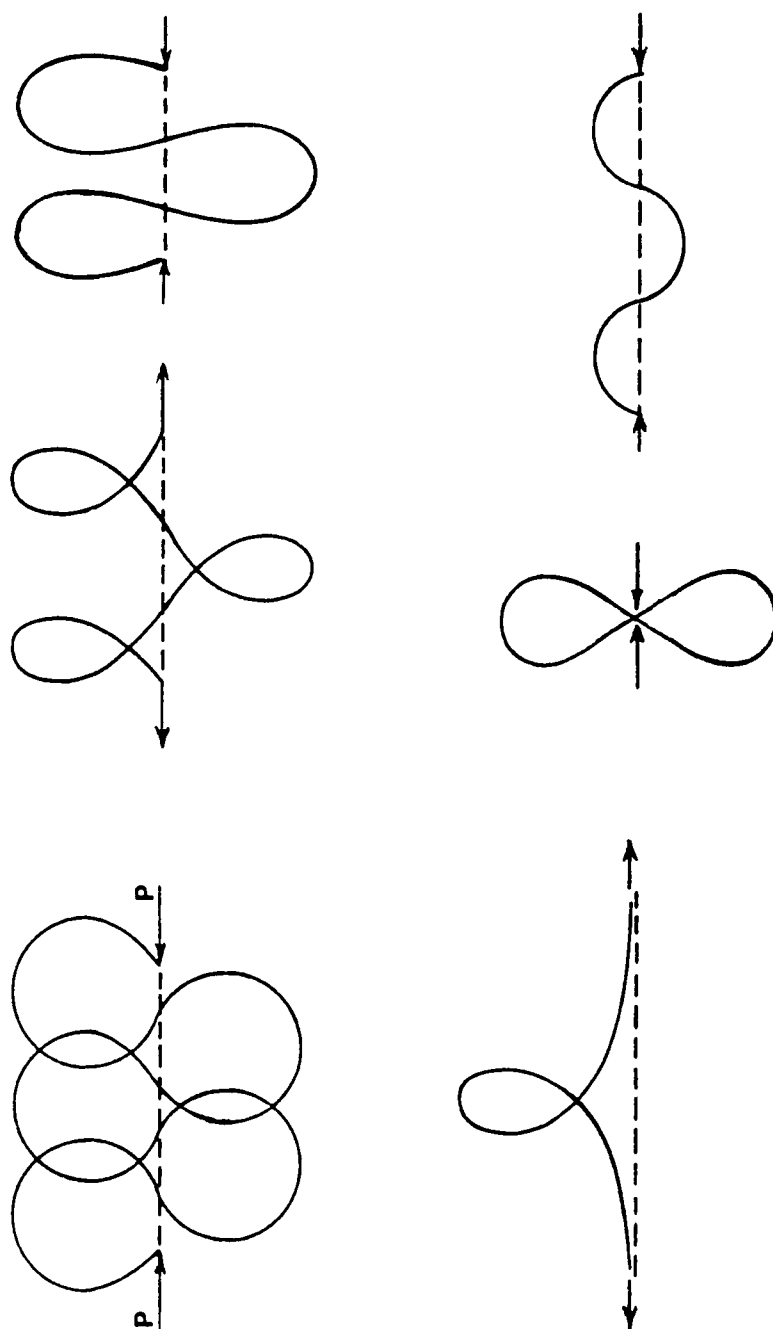


Figure 2.9 Equilibrium curves of large deformation bars.

Konopasek and Hearle (55) considered large bending deformation of thin rods or fibers, and developed a mathematical model of the three-dimensional curve in vector and scalar form. The mathematical model is so arranged to provide easy programming and efficient computation. Two subroutines for solution of the three dimensional bending curve were set up. By using these subroutines, the shape of the bending curve can be predicted under some boundary conditions.

2.7 ARRANGEMENT OF FILAMENTS IN FABRICS

Ericson and Baxter (21) proposed that the arrangement of filaments in nonwoven fabrics could be characterized by three measurements:

- (1) Fabric Weight Uniformity
- (2) Filament Separation
- (3) Geometrical Filament Orientation.

While all three categories are to some extent interdependent, the effects each has on fabric properties can be considered independently.

2.7.1 Fabric Weight Uniformity

This can be determined directly by weighing a statistically significant number of samples of some fixed size and expressing the result statistically, e.g., as a coefficient of variation ($cv = \delta/\bar{X}$). A less laborious approach

is to use a beta-ray device. A number of commercial beta-ray devices are available for this purpose.

2.7.2 Fabric Separation

2.7.2.1 Bunching coefficient. The concept of bunching coefficient was first introduced by Petterson (73) and is defined by

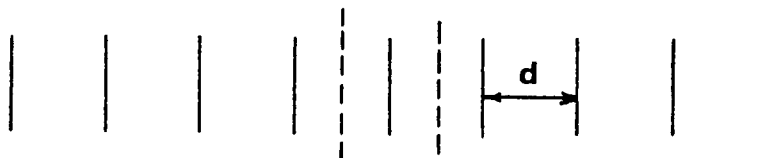
$$B.C. = FS_o/FS_a \quad [2.48]$$

where FS_o is the number of fiber spaces occupied

FS_a is the number of fiber spaces available.

The fiber space in a web is defined by the average distance between parallel fibers measured along a line which lies perpendicular to the fibers (Fig. 2.10). To determine the bunching coefficient, a nonwoven web is photographed at a magnification sufficient to allow resolution of the individual filaments. The fiber space is calculated by dividing the length of the line by the numbers perpendicular to the line.

2.7.2.2 Coefficient of variation of filament separation. Two distinctly different levels of filament separation may have the same bunching coefficient. It is desirable to have a second way of analyzing filament separation. The Coefficient of Variation of Filament Separation, defined by Ericson and Baxter (21) is calculated by



d = Distance between fibers
Dotted lines define the boundaries
of a fiber space

Figure 2.10 Fiber separation in an "ideal" web.

$$\% C V_{fs} = \frac{100\delta}{\bar{d}} \quad [2.49]$$

where δ = standard deviation in units of d

$\bar{d}$ = average distance between filaments.

2.7.3 Geometrical Filament Orientation

2.7.3.1 Filament directionality. The problem of determining filament directionality in a nonwoven product was first considered by Hearle and Stevensen (40). In their method, a web is viewed by using a projection microscope. At a convenient magnification, a circle of arbitrary size is fixed either on the microscope screen or on a transparent overlay. Filaments in the field of view are traced out. The angle which the filaments, passing through the circle, make with an axis of interest is determined. This method is particularly tedious when the filaments are highly curved or crimped. Levy (57) described randomness as a measure of isotropic nature of the arrangement of the individual filaments in the web. The measure of randomness, randomness ratio, is calculated as follows:

A/B = randomness ratio, or degree of isotropy, or
edge count ratio

where A = total number of filaments on side having the
largest count

B = total number of filaments on side having the
smallest count.

Ericson and Baxter (21) noted that the other way used was a randometer, which is an optical device, to determine the proportionate length of filament segments oriented at some direction in a sheet to the length oriented in any other direction.

2.8 MECHANICAL PROPERTIES AND STRUCTURE OF NONWOVENS

Theories of mechanical properties and structure of nonwovens have been developed and numerous experiments have been reported (37, 38, 39, 41, 42, 43, 74, 75).

Anisotropic mechanical behavior formulations are well developed in the literature of classical linear elasticity (58). This was used by Petterson and Backer (74, 75) with an orthotropic formulation. They obtained the result:

$$S_{yyyy} = \frac{\epsilon_{yy}}{\sigma_{yy}} = \frac{1}{E_{yy}} = \frac{\cos^4 \theta}{E_L} + \frac{\sin^4 \theta}{E_T} + \left[\frac{1}{G_{LT}} - \frac{2\mu_{LT}}{E_L} \right] \sin^2 \theta \cos^2 \theta \quad [2.50]$$

$$S_{xxyy} = \frac{\epsilon_{xx}}{\sigma_{yy}} = \frac{\mu_{yx}}{E_{yy}} = -\frac{\mu_{LT}}{E_L} + \left[\frac{1}{E_L} + \frac{1}{E_T} + \frac{2\mu_{LT}}{E_{LT}} - \frac{1}{G_{LT}} \right] \sin^2 \theta \cos^2 \theta \quad [2.51]$$

$$S_{yxyy} = \frac{\epsilon_{xy}}{\sigma_{yy}} = \left[\frac{1}{G_{LT}} - \frac{2\mu_{LT}}{E_L} - \frac{2}{E_L} \right] \sin \theta \cos^3 \theta - \left[\frac{1}{G_{LT}} - \frac{2\mu_{LT}}{E_L} - \frac{2}{E_T} \right] \sin^3 \theta \cos \theta \quad [2.52]$$

$$\frac{1}{G_{LT}} = \frac{4}{E_{45^\circ}} - \frac{2\mu_{LT}}{E_L} - \frac{1}{E_L} - \frac{1}{E_T} \quad [2.53]$$

where L and T are axes of symmetry of the rectangular orthotropic material, whose length lies parallel to the direction y which makes an angle θ to the L direction. E_L and E_T are elastic moduli in the L and T directions. μ_{LT} is the contraction ratio between contractive strain in the T direction and a positive strain in the tensioned L direction. G_{LT} is the shear modulus in the LT direction.

Hearle and Stevenson (41) described an improved theory of anisotropy of nonwoven fabrics for both small strains and large strains. Hearle and Newton (42) showed that the stress f_L in a nonwoven fabric can be calculated at any given strain ϵ_L , assuming that the fabric is composed of fiber elements, each one bonded at its extremities to two or more other elements.

In their experiments, Backer and Petterson (75) used an Instron Tensile Tester at constant crosshead speed to measure tensile behavior over a range of angles to the principle direction. From their experimental results, the orthotropic theory developed for rigid materials appears to predict well the behavior of selected flexible textile fiber nonwoven structures.

Hearle and Stevenson (43) attempted to develop a correlation of nonwoven fabric properties, particularly those associated with fabric drape, with the properties of

component fiber and binder. They found that the initial modulus of fabric is less sensitive to change in the binder. The drape coefficient also varies markedly with fiber modulus and to a small extent with binder modulus.

Shealy (80) stated that the continuous filament structure of spunbonded material gave a different balance of physical and aesthetic properties from that normally found in staple nonwovens. Typically spunbonded products show higher strength at low binder concentration than the staple nonwoven products. This is believed to arise from the fact that fewer bonds are needed in a spunbonded structure to set up a continuous stress-bearing network. Shealy and Hentschel (81) also stated that spunbonded polyethylene fibers are oriented and crystalline; X-ray diffraction film patterns typically show an orientation angle of about 20° with high crystallinity. Optical measurements give a birefringence of about 0.022. Precise measurements of the tenacity of individual fibers is difficult, because of the variable and irregular cross section and small size of the fibers. Fiber tenacity is estimated to be in the range of 5 g/den.

CHAPTER III

EXPERIMENTAL

3.1 MATERIAL

Polypropylene (PP) has been frequently studied, and characterized in our laboratories (64, 65, 66, 86, 87). Its nature and properties are well established by previous researchers. For this first study, which extends our efforts to the spunbonding process, PP was considered the best choice because of our experience with it. Hercules Profax [®]6323 of melt index 12 was used in all experiments. Nadella et al. (65, 66), in our laboratories, measured the intrinsic viscosity in decalin of this polymer at 137°C and obtained a value of 1.99. This corresponds to a weight average molecular weight of 2.36×10^5 in grams/mole. They also found that an 18 percent decrease occurred due to thermal degradation during melt spinning of fibers at a melt temperature of 230°C.

3.2 MELT SPINNING WITH ASPIRATOR JET

A one-inch Modern Plastics Screw Extruder connected to a Zenith Metering Pump (HPB type) was used to spin filaments. A one-hole spinneret with a capillary diameter of 0.787 mm and L/D ratio 25.5 was used. In the investigations of filament formation, a three-hole spinneret ($D = 0.787$ mm

and $L/D = 3.23$) and an eight-hole spinneret ($D = 0.660$ mm and $L/D = 3.85$) were also used to decrease the mass flow rate per hole.

The spun fibers were drawn down by an aspirator jet (Fig. 3.1). Air pressure was applied at the air intake to produce a suction force at the filament entrance of the aspirator (Fig. 3.2 and 3.3). The aspirator shown in Fig. 3.1 has diameters of 5 mm in the first section and 11.6 mm in the second section. Eight small holes are regularly distributed around an annular ring to provide and distribute the supplied air to the second section.

The conveyer belt, Fig. 3.2, was made from Globe Albany Belting's Style [®]940, loosely woven polyester. The conveyer is 1.5 feet wide and 7 feet long. A 1.5 foot square suction box is attached beneath the porous belt to help stabilize and hold the filaments on the conveyer belt. The suction box is connected to a large blower.

All the experiments were performed at a constant extrusion temperature of 215°C. The air intake pressure to the aspirator was varied from 20 psig to 70 psig. A volumetric flow rate of 2.56 cm³/min or a mass flow rate of 1.91 g/min was kept approximately constant for the one-hole spinneret. The final filament velocities V_f ranged from 45 m/min to 348 m/min under the air pressure supplies (20 ~ 70 psig). The distance from the spinneret to the aspirator was maintained at 185 cm. If the distance was smaller than

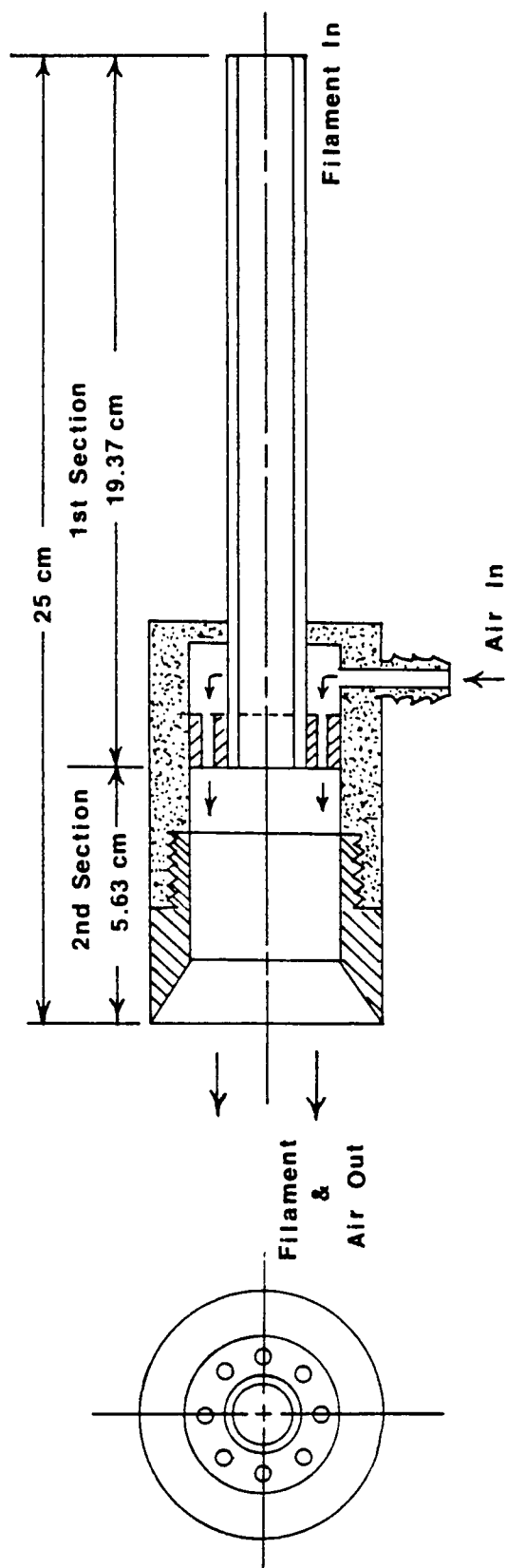


Figure 3.1 Schematic of aspirator.

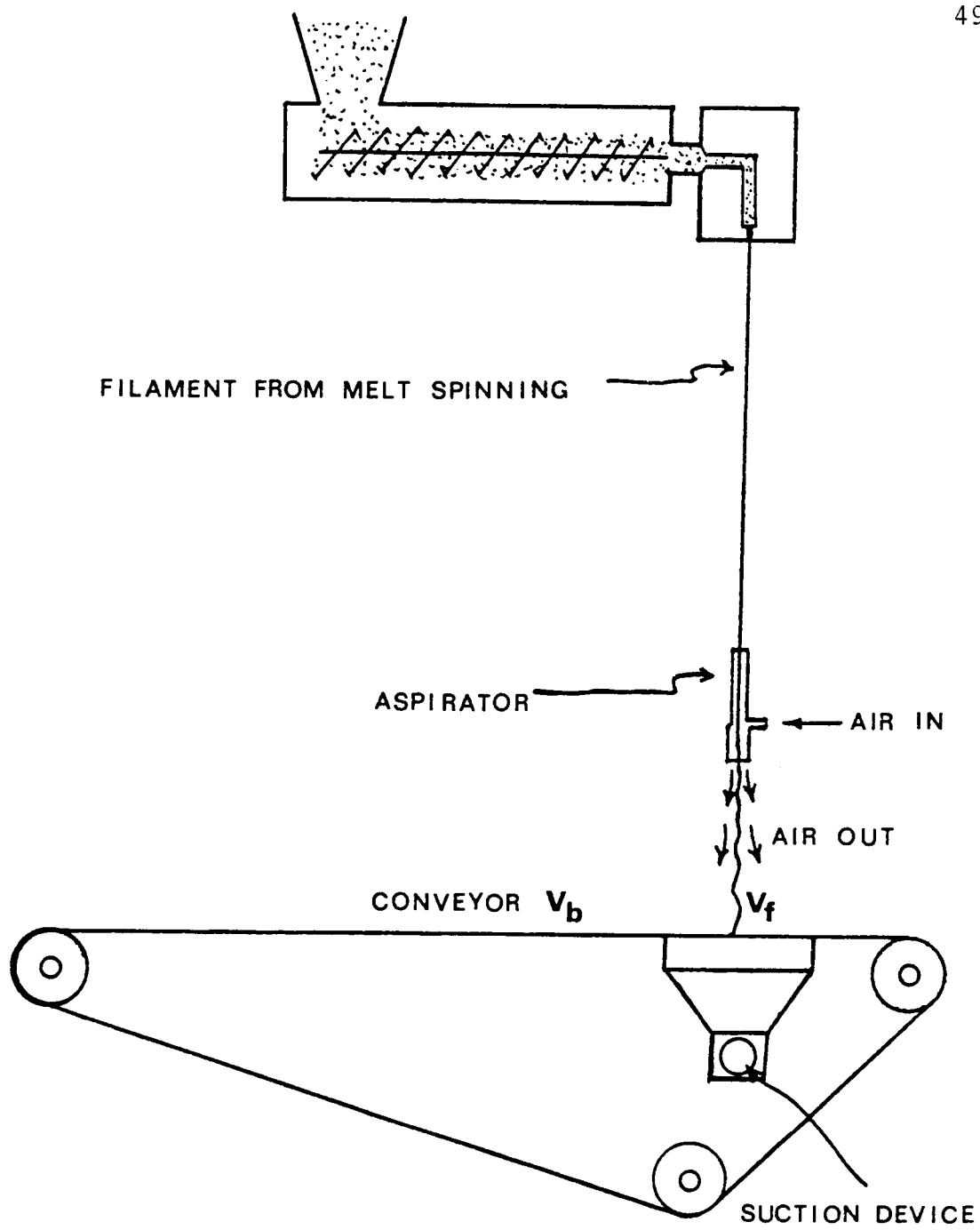


Figure 3.2 Schematic of spunbonding process.

Figure 3.3 Photograph showing aspirator and conveyer belt.

150 cm under the constant mass flow rate mentioned above, the filament stuck on the inside wall of the aspirator at a low spinning speed. Distances greater than 185 cm were simply inconvenient.

Diameters of filaments were measured with an Optical Microscope provided with a Bausch & Lomb filar micrometer eyepiece. They varied from 222 μm to 80 μm .

3.3 CHARACTERIZATION OF FIBER SAMPLES

3.3.1 Birefringence Measurement

An Olympus Microscope equipped with mutually perpendicular polarizer and analyzer was used. A Berek Compensator was inserted into the microscope. A ($\lambda = 530 \text{ m}\mu$) wavelength plate was used to determine the optical constant for the compensator ($\frac{C}{1000} = 0.895$). The retardation R was obtained by adjusting the compensator with crossed polars. The birefringence was calculated from

$$\Delta n = \frac{R}{d} \quad [3.1]$$

where d is the diameter of the filament.

3.3.2 Measurement of Orientation Factors from

Wide Angle X-Ray Scattering

In order to compute the orientation factors of filaments, WAXS patterns were made using a General Electric X-ray Diffractometer equipped with a single crystal orienter. The radiation used was crystal-monochromated

Cu - α of wavelength 1,542 Angstroms. The X-ray unit was operated at 40 kV and 15 mA. A scintillation counter was used to measure the intensities of reflections. The 110 and 040 reflections were observed at about $2\theta = 14^\circ$ and 17° . The variation of intensity was measured as a function of the azimuthal angle ϕ by the following procedure. Fixing the sample on one of the 2θ angles for diffraction from a chosen set of diffraction planes, the sample can be rotated through ϕ by the single crystal orienter as shown in Fig.

3.4. The intensities $I(\phi_{hkl,z})$ measured are related to

$\overline{\cos^2 \phi_{hkl,z}}$ which is the average value of the square of the cosine of the angle between the fiber axis and the normal to (hkl) plane, by

$$\overline{\cos^2 \phi_{hkl,z}} = \frac{\sum_{\phi=0}^{\phi=\frac{\pi}{2}} I(\phi_{hkl,z}) \cos^2 \phi_{hkl,z} \sin \phi_{hkl,z}}{\sum_{\phi=0}^{\phi=\frac{\pi}{2}} I(\phi_{hkl,z}) \sin \phi_{hkl,z}} \quad [3.2]$$

The equipment was connected with a PDP - 15 computer by an interface. All the values of intensity I were measured for a 5-second counting time and at 2.5° interval in ϕ . Sub-program XRAY - 2 and Revised XRAY - 7, which were developed in our laboratories by J. E. Spruiell (85), were used to compute $\overline{\cos^2 \phi_{hkl,z}}$ and print out the result on a teletype.

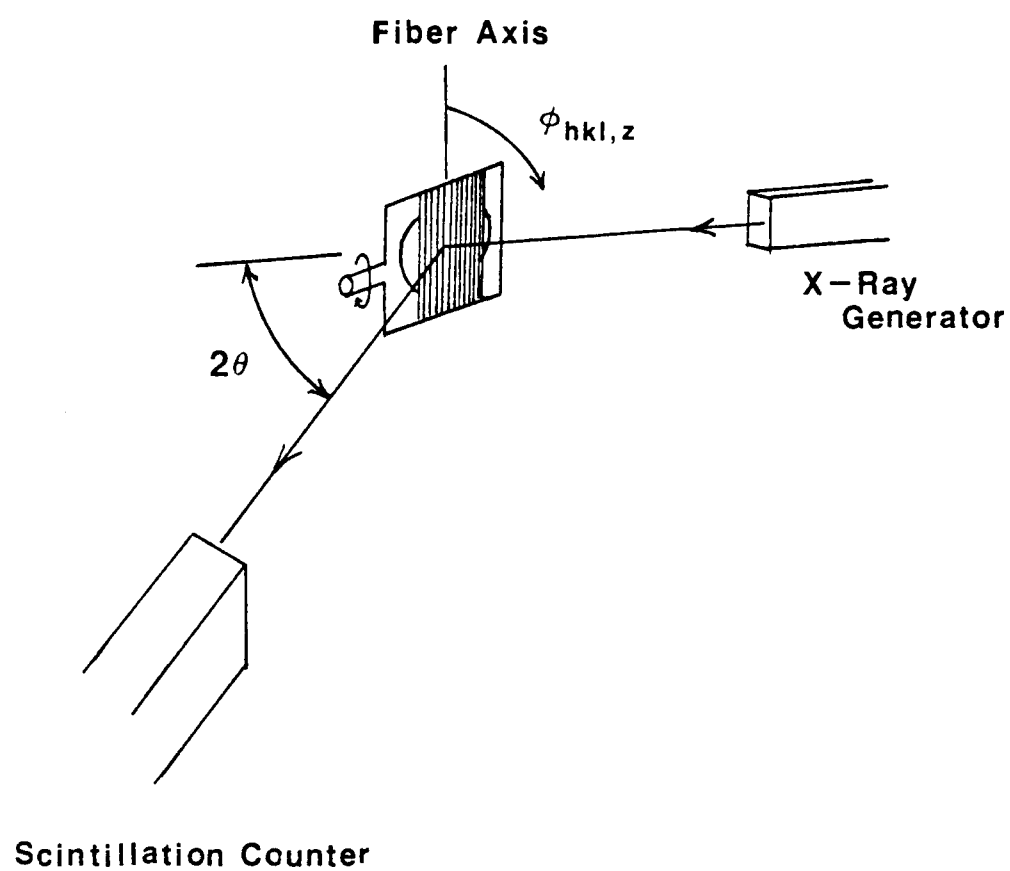


Figure 3.4 Schematic illustrating method of making orientation measurements using WAXS.

At low spinline stress, the contrast between the intensities of background and the intensities of (hkl) plane reflections are small. The background intensities turn out to be important terms which must be carefully determined. Because of the influence of (hkl) plane reflections, it is very difficult to determine the intensities of background at $\chi = 90^\circ$ (Fig. 3.5-a). In this study, we set the χ angle equal to 0° , and measured the background as shown in Fig. 3.5-b.

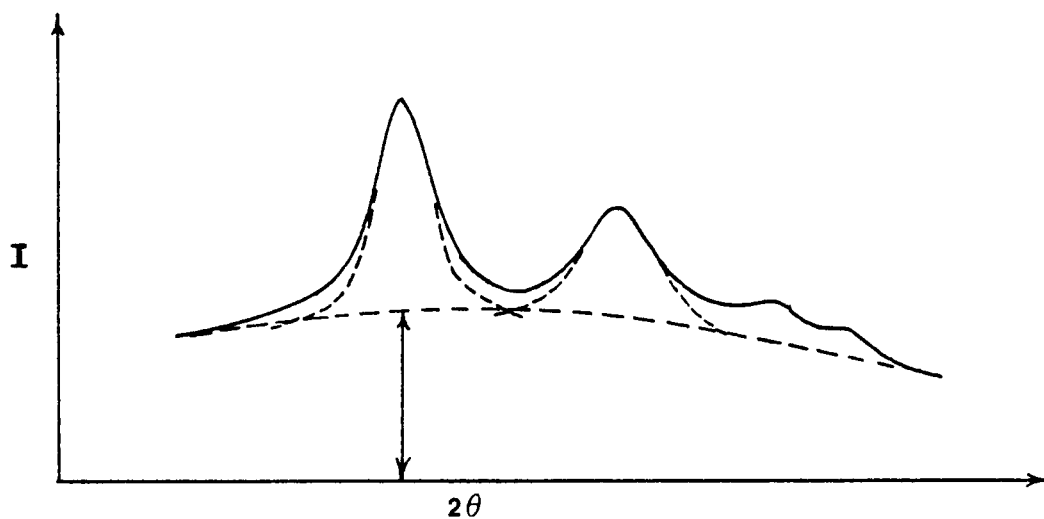
Following Wilchinsky (95), considering the monoclinic unit cell of polypropylene, $\overline{\cos^2\phi_{c,z}}$ was calculated by Equation [3.3] from values of $\cos^2\phi_{hkl,z}$ measured on the 110 and 040 reflections:

$$\overline{\cos^2\phi_{c,z}} = 1 - 1.099 \overline{\cos^2\phi_{110,z}} - 0.901 \overline{\cos^2\phi_{040,z}} \quad [3.3]$$

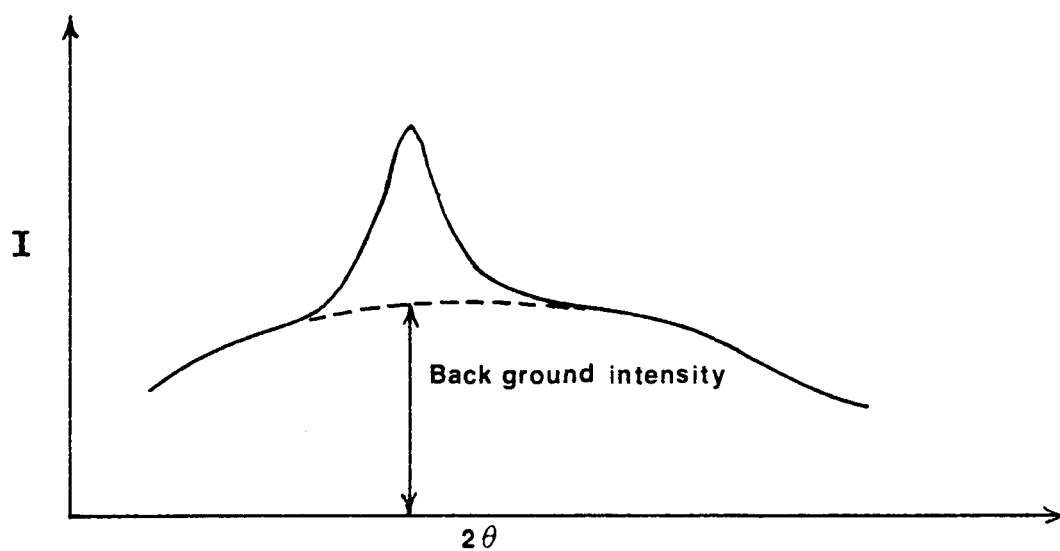
$$\text{Also,} \quad \overline{\cos^2\phi_{b,z}} = \overline{\cos^2\phi_{040,z}} \quad [3.4]$$

The orientation factors were calculated from Equation [2.32] for b and c axes. An a' - axis perpendicular to b and c axes was introduced, and its orientation factor was calculated by Equation [3.5]

$$f_{a'} + f_b + f_c = 0 \quad [3.5]$$



(a)



(b)

Figure 3.5 Variation of intensities with 2θ for WAXS at different χ angles.
 (a) Illustration of peak overlap which makes background determination difficult at $\chi=90^\circ$.
 (b) Determination of background intensity in this study ($\chi=0^\circ$). Peak overlap is negligible due to sample orientation.

3.4 AIR DRAG

3.4.1 Air Velocity Measurements

The air velocity measurements are very important in the determination of air drag. In our experiments, the air velocities in the first section and the second section are quite different. Due to the large air pressure drop and short distance in section 2, the air velocities inside this section are very unstable and change from one position to another. In order to measure air velocities within section 2 of the aspirator, a pitot tube was inserted. The pitot tube was connected with a scanning type pressure sampling valve (made by Scanivalve Inc.), a transducer, a Datel Digital Panel Meter, a 8008 microprocessor, and a teletype (Fig. 3.6). From the pressure drop reading, velocities were calculated. The pitot tube could not be used to measure the velocities of section 1. Fortunately, the air velocities in section 1 are very stable and flow is well developed. A Cochrane 12 ft³ Rotameter (Type 610 R-60) was used to measure the volume flow rate (Fig. 3.7). A Merian LEF Laminar Flow Element (Model 50 MC2) was used to calibrate the Rotameter (Fig. 3.8). Assuming continuity, the air velocities of section 1 were calculated by

$$\bar{V} = AV \quad [3.6]$$

where $\bar{V}$ is Volume flow rate of section 1

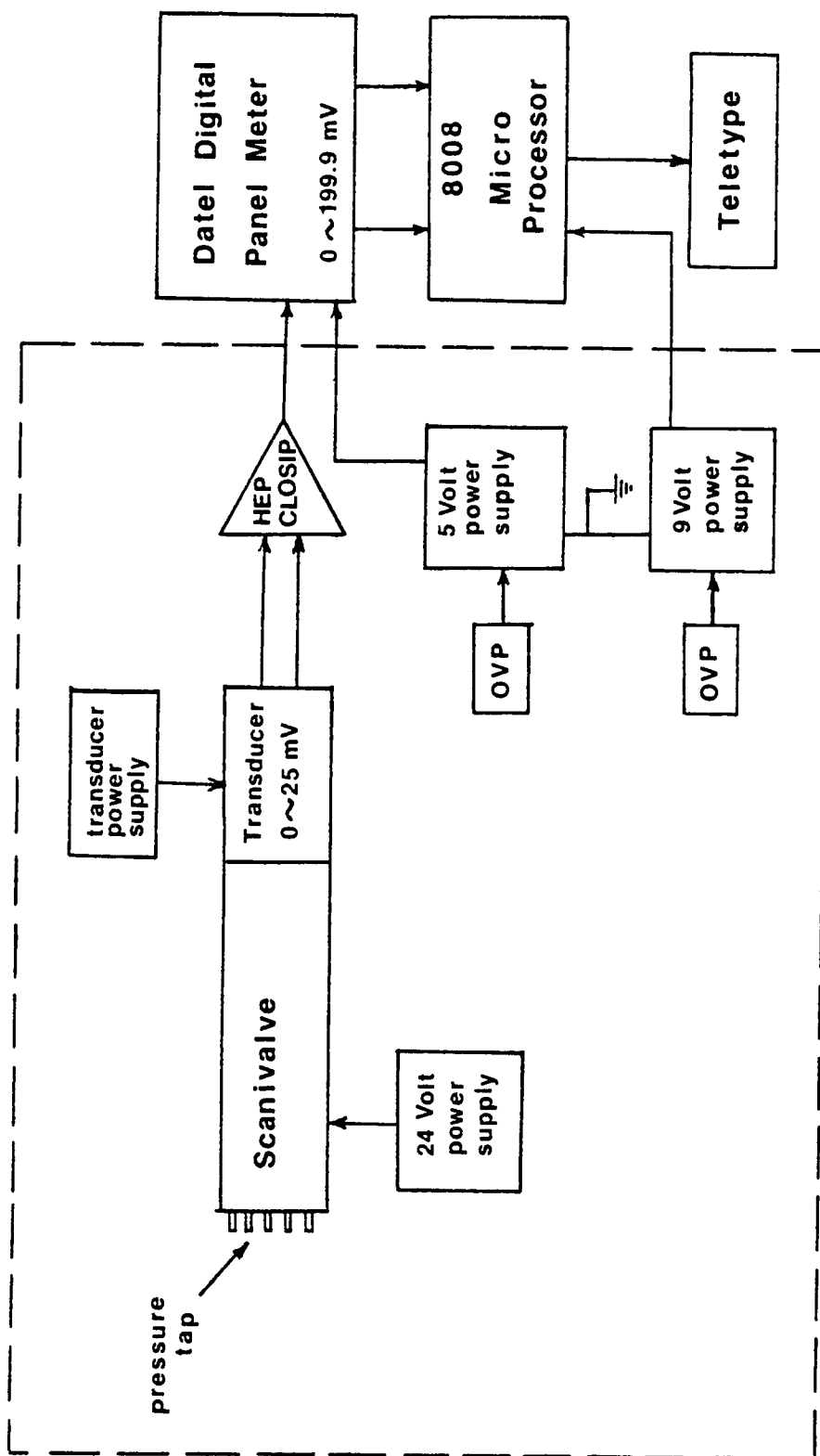


Figure 3.6 Block diagram of apparatus used to make air velocity measurement.
This was connected directly to a pitot tube.

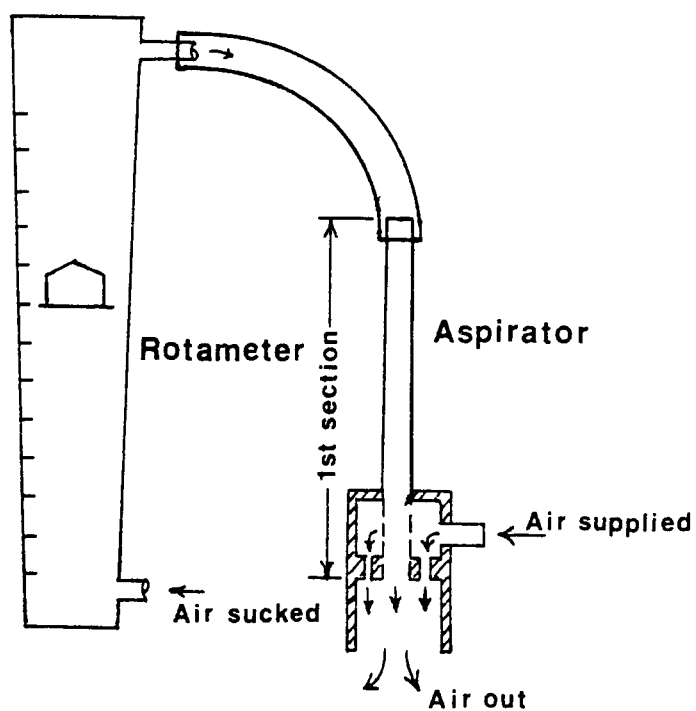


Figure 3.7 Schematic of air velocity measurement by a Rotameter.

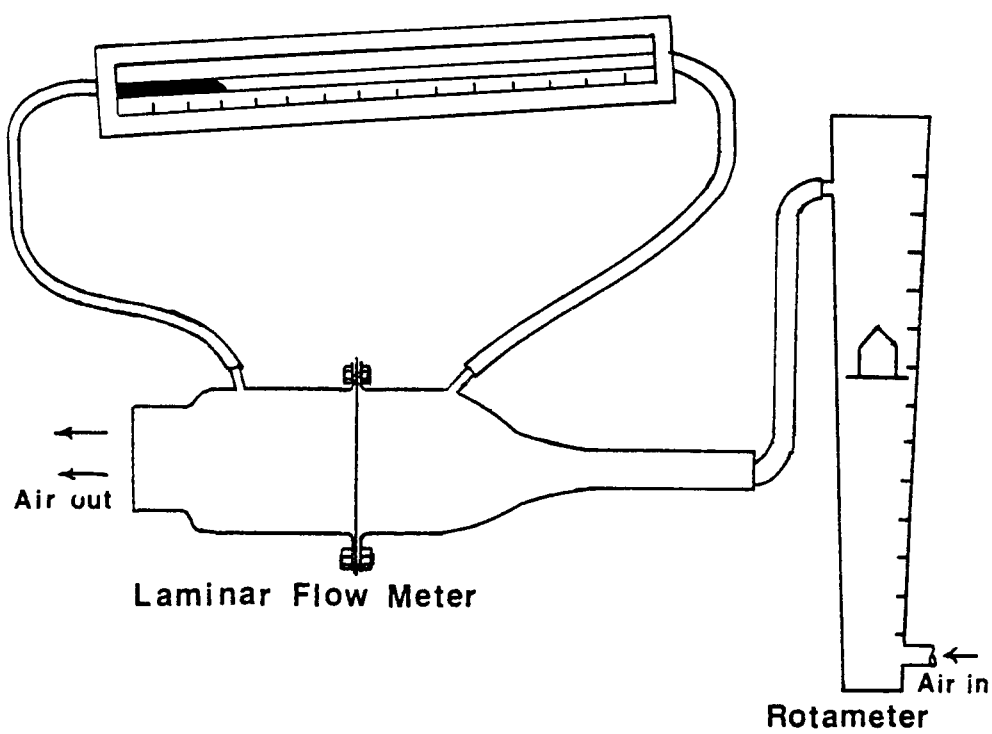


Figure 3.8 Schematic of Rotameter calibration by a laminar flow meter.

A is cross section area of section 1

V is velocity of section 1

3.4.2 Air Drag Force Measurements

A Rothschild Tensiometer with a ten-gram measuring head was employed to measure the tension of the spinning filament. The tensiometer was located 3 cm above the aspirator as shown in Fig. 3.9. Due to the large friction force of the inserted tensiometer's measuring head, the rheological force above this point was greatly decreased. This rheological force reduction causes greater die swell near the spinneret, and eventually ductile failure at a position a little below the swelling region of spinline (Fig. 3.10). We believe this happens due to a combination of the reduced force and still molten polymer just below the swelling region. The breaking problem may be solved by increasing the air drag force given by the aspirator (increasing the supplied air pressure to 60 psig). Under this high pressure, the friction force introduced by the tensiometer's measuring head is reduced by the thinner spinline, and the difference between the rheological force and the friction force is larger due to the increase of the air drag force. When the tensiometer's measuring head was inserted in the spinline, which was drawn down by higher air pressure (about 60 psig), the only change was that the spinline's diameter increased slightly. However, this high

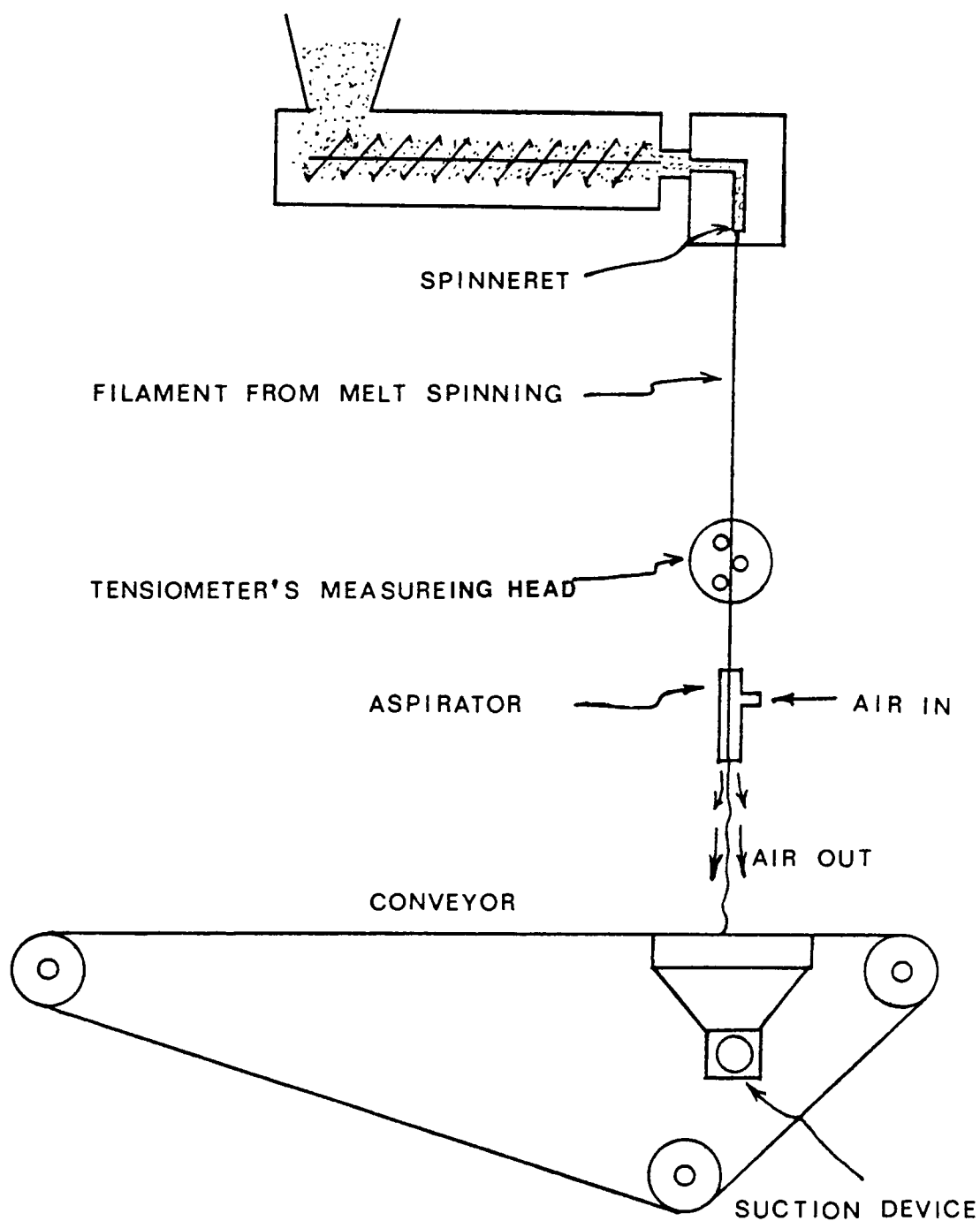


Figure 3.9 Schematic of intended method of measuring tension by inserting tensiometer into the spinline.

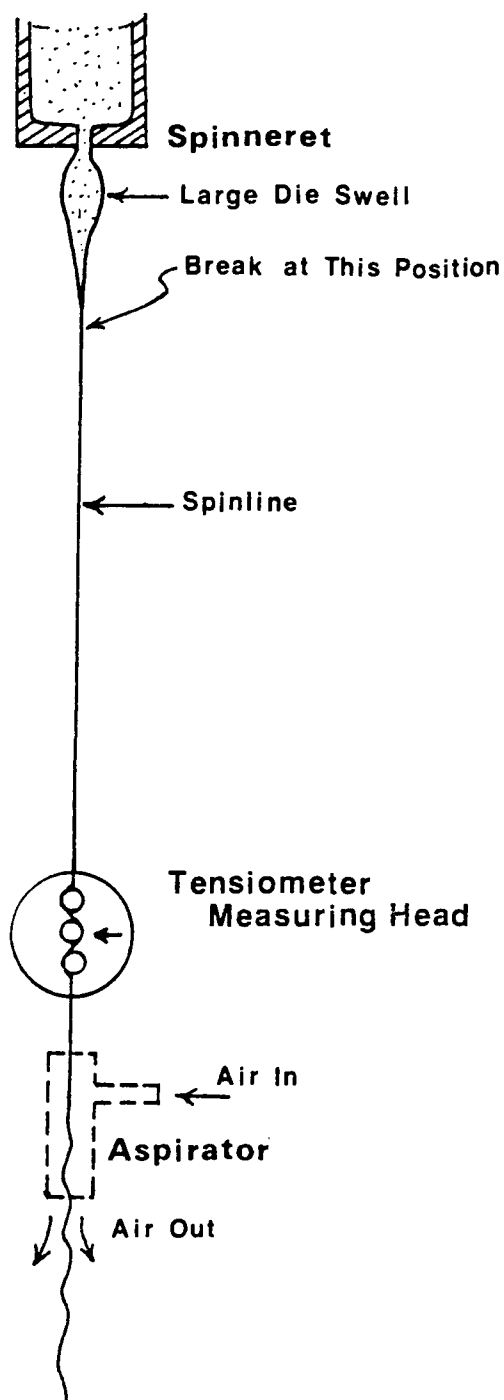


Figure 3.10 Schematic of ductile failure of a spinline under the influence of tensiometer measuring head.

pressure is near the upper limit of the apparatus. The results cannot be analyzed with such limited data.

Because of the difficulties of tension measurement during melt spinning with an aspirator, a solidified filament was used to measure the air drag force. The equipment was arranged as shown in Fig. 3.11. A Rothschild Tensiometer with a 4-gram measuring head, calibrated with a 2-gram weight, was used to measure the tensile force on the filament. A 1-meter filament of 86 μm diameter was placed as shown and successively cut from the lower end in increments of ~ 1 cm. The drag force was measured at each length (see diagram). In this manner, the force on the spinline versus the length of the filament could be obtained. At different air velocities, the above measurements were repeated.

3.5 FORMATION OF THE FABRIC

A pigmented polymer melt was spun and drawn down by an aspirator. The filament was blown onto a conveyer belt, which moved at the desired speed. The pattern formed by the filaments on top of the conveyer belt was photographed by a camera. The photographs were enlarged with a slide projector and the fiber configurations analyzed. The above experiments were repeated with different air velocities and belt speeds.

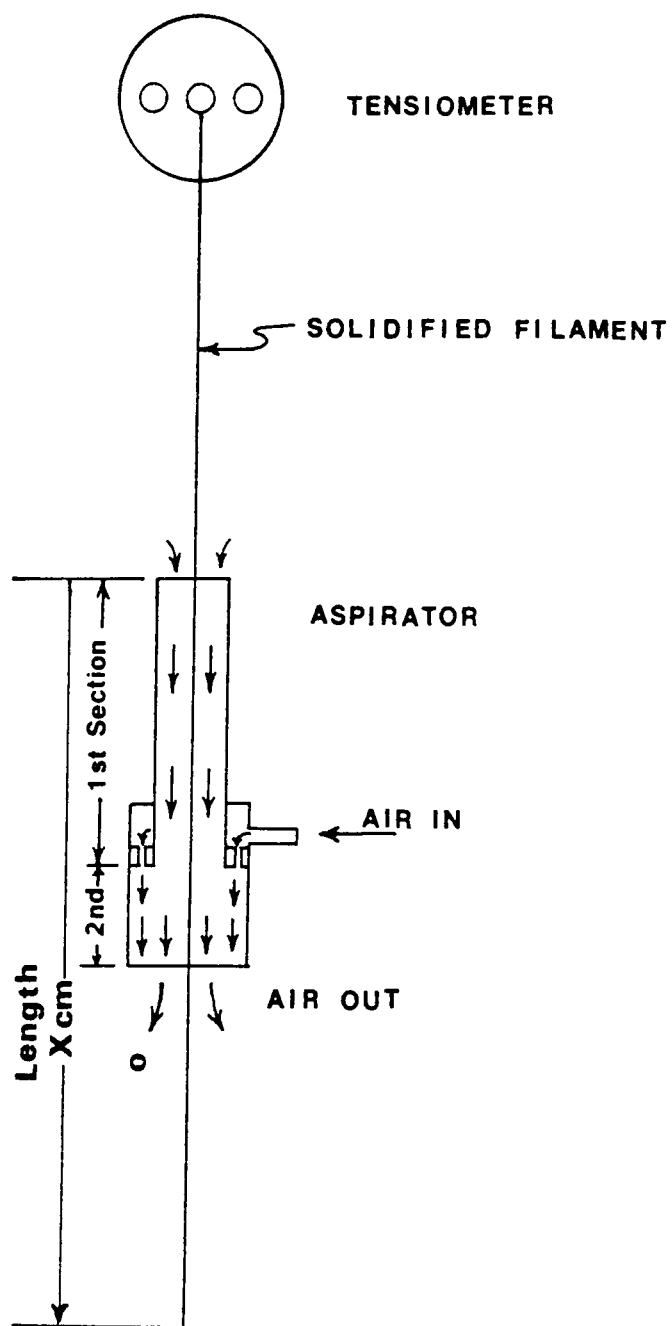


Figure 3.11 Schematic of tension measurement for a solid PP filament drawn by an aspirator.

Due to the high filament speed during melt spinning and the small filament size, it is very difficult to take photographs in order to analyze the correlation between the buckles in the descending filament and the loops on the surface of the stationary conveyer belt. For this reason, a solidified filament was used to study this problem. The filament was supplied by a bobbin at a lower speed of 21.4 m/min, and it was drawn down by the aspirator (Fig. 3.12). The filament configuration was determined after the filament was laid down. This experiment was repeated with different filament diameters and different air velocities.

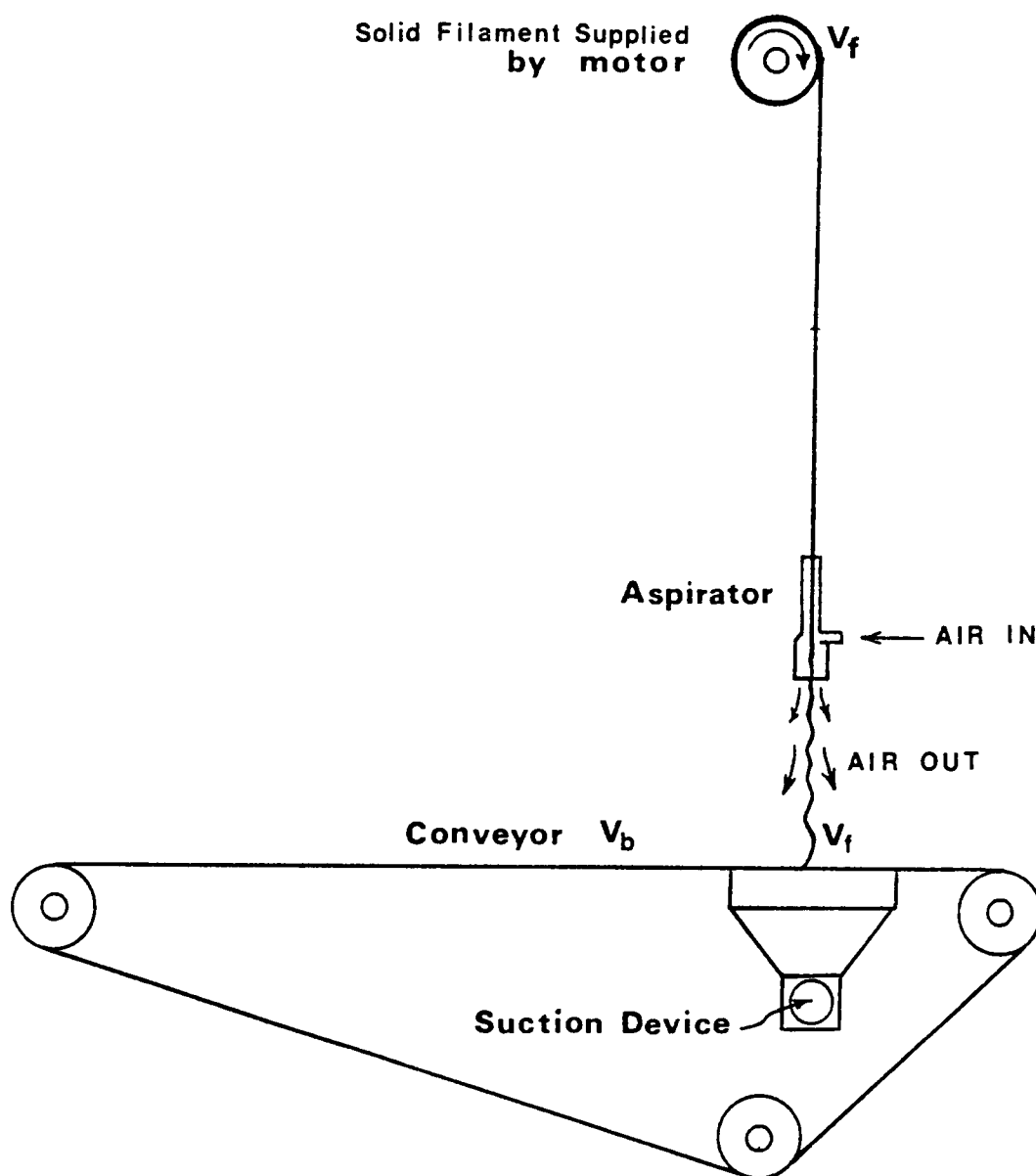


Figure 3.12 Schematic of arrangement used to analyze the correlation between buckles in the descending filament and loops on the surface of the stationary conveyor belt.

CHAPTER IV

DYNAMICS OF SPUNBONDING

4.1 FORCE BALANCE

The forces acting on a descending spinline being drawn down by an aspirator include the gravity force F_{grav} , the air drag force F_{drag} acting on the moving filament above the aspirator, the air drag force due to the aspirator $(F_{\text{drag}})_{\text{asp}}$, and momentum fluxes. If we make a force balance between position X_1 and L in the spinline as shown in Fig. 4.1, we obtain

$$(F_{\text{drag}})_{\text{asp}} - F_{\text{rheo}} + F_{\text{grav}} - F_{\text{drag}} = \rho Q V_L - \rho Q V_{X_1} \quad [4.1]$$

Here F_{rheo} is the force in the spinline at position X_1 and F_{drag} and F_{grav} are considered terms acting on intermediate spinline positions. Equation [4.1] may be rewritten in terms of F_{rheo} as

$$F_{\text{rheo}} = \frac{\pi d^2(X_1)}{4} \sigma_{xx}(X_1) = (F_{\text{drag}})_{\text{asp}} + F_{\text{grav}} - F_{\text{drag}} - \rho Q (V_L - V_{X_1}) \quad [4.2]$$

where $d(X_1)$ is the diameter of the filament at position X_1

ρ is the fiber density

$\sigma_{xx}(X_1)$ is the spinline stress at position X_1 ,

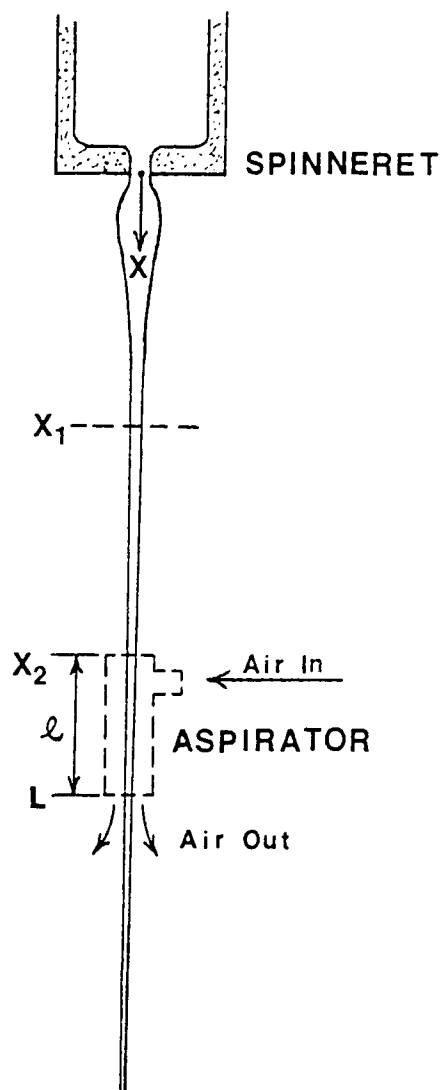


Figure 4.1 Force balance on a spunbonding filament.

the terms F_{grav} , F_{drag} , and $(F_{\text{drag}})_{\text{asp}}$ have the forms

$$F_{\text{grav}} = \int_{X_1}^L \frac{\pi d^2}{4} \rho g \, dX \quad [4.3]$$

$$F_{\text{drag}} = \int_{X_1}^{X_2} \pi \sigma_f \, dX \quad [4.4]$$

$$(F_{\text{drag}})_{\text{asp}} = \int_{X_2}^L \pi d(\sigma_f)_{\text{asp}} \, dX \quad [4.5]$$

where X_1 is any position above the aspirator in the spin-line, X_2 is the upper boundary of the aspirator, L is the lower boundary of the aspirator. Traditionally from engineering fluid mechanics, the terms (σ_f) and $(\sigma_f)_{\text{asp}}$ are expressed in terms of the air drag coefficients C_f and $(C_f)_{\text{asp}}$ as

$$\sigma_f = \frac{C_f \rho_a V_f^2}{2} \quad [4.6]$$

$$(\sigma_f)_{\text{asp}} = \frac{(C_f)_{\text{asp}} \rho_a (V_g - V_f)^2}{2} \quad [4.7]$$

where V_f is the velocity of filament

V_g is the air velocity in the aspirator

ρ_a is the density of air.

When the air velocity is much larger than the filament velocity, Equation [4.7] can be simplified to

$$(\sigma_f)_{asp} = \frac{(C_f)_{asp} \rho_a V_g^2}{2} \quad [4.8]$$

The air drag coefficient will be discussed in sections 4.2 and 4.3.

Comparing Equation [4.1] with Equation [2.1], which describes the force balance on a melt spinning filament drawn down by a take-up machine, the take-up force F_L is replaced by the air drag force exerted in the aspirator $(F_{drag})_{asp}$. Ziabicki and Kedzierska (99) pointed out that F_{rheo} was approximately F_L for a spinline with a take-up machine, because F_{drag} and F_{grav} tend to cancel each other out over a wide range of conditions. For melt spinning with an aspirator, this is equivalent to the $(F_{drag})_{asp}$ being approximately equal to F_{rheo} . The values of F_{grav} , F_{drag} and $(F_{drag})_{asp}$ for the experiments carried out in this thesis are given by the results presented in Table 4.1. It follows that

$$F_{rheo} = \frac{\pi d^2}{4} \sigma_{11} \cong (F_{drag})_{asp} \quad [4.9]$$

Under all experimental conditions $(F_{drag})_{asp}$ represents the largest contribution to F_{rheo} . The sum of F_{grav} and F_{drag} are less than 10 percent of $(F_{drag})_{asp}$ under all conditions except for the lowest air pressures and speeds where F_{grav} is important. At lower air pressures F_{grav} is quite significant while F_{drag} is small; at higher air pressure F_{drag} is significant while F_{grav} is small.

TABLE 4.1 Individual forces acting on the spinline of a spunbonding process.

air pressure (psig)	V_f (cm/s)	V_g (cm/s)	F_{grav} (dyne)	$F_{drag}^{\dagger}$ (dyne)	$(F_{drag})_{asp}^{\S}$ (dyne)
20	76	5,001	70.2	- 3.8	387
30	130	6,860	40.7	- 7.3	493
40	248	8,722	21.2	-19.2	877
60	581	11,374	9.1	-43.4	930

† Air drag coefficients are calculated as $C_f = 0.37 Re_D^{-0.61}$ (59).

§ Air drag coefficients given by the aspirator are calculated as $C_f = 0.91 Re_D^{-0.61}$ (our experiments).

Distance from spinneret to aspirator is 185 cm; length of the aspirator is 25 cm.

4.2 AIR DRAG COEFFICIENT

4.2.1 Interpretation

For the experimental arrangement shown in section 3.4.2, the solidified filament does not move. Consequently the momentum flux and the air drag force associated with the moving filament F_{drag} are zero for this experimental arrangement. The gravity force F_{grav} is constant and is removed by the calibration procedure for the tensiometer. Only the air drag force produced by the aspirator $(F_{\text{drag}})_{\text{asp}}$ acting on the filament is measured. So, the tension T measured by the tensiometer is equal to $(F_{\text{drag}})_{\text{asp}}$. Replacing $(F_{\text{drag}})_{\text{asp}}$ by Equations [4.5] and [4.8], it follows that

$$T(X_1) = \int_0^{X_1} \pi d \frac{(C_f)_{\text{asp}} \rho_a V_g^2}{2} \quad [4.10]$$

where 0 is the upper limit of the aspirator

X_1 is any position below 0 position on the filament.

After integration, we have

$$T(X_1) = \frac{\pi d (C_f)_{\text{asp}} \rho_a V_g^2 X_1}{2} \quad [4.11]$$

4.2.2 Results

Tension measurements are plotted as a function of filament length (this length is the distance from the top end of the aspirator to any position X ; the data are plotted

in Fig. 4.2. These tension measurements were made on a solid PP filament using the experimental procedures outlined in section 3.4.2 and the arrangement shown in Fig. 3.11. A more detailed diagram of the tension data of section 1 and section 2 is presented in Fig. 4.3. The slopes $(\Delta T/\Delta X)$ of section 1 and section 2 were computed. The air drag coefficient of the aspirator $[(C_f)_{asp}]_{\text{experiment}}$ can be calculated by the rearrangement of Equation [4.11] as

$$[(C_f)_{asp}]_{\text{exp}} = \frac{2(\Delta T/\Delta X)}{\pi d \rho_a V_g^2} \quad [4.12]$$

A logarithmic plot of $[(C_f)_{asp}]_{\text{exp}}$ and Re_D was made for section 1 and section 2, and is shown in Fig. 4.4. The Reynolds number Re_D is

$$Re_D = \frac{d V_g \rho_a}{\eta_a} \quad [4.13]$$

where V_g is the velocity of air.

From the plots of Fig. 4.4, the air drag coefficients of the aspirator, $(C_f)_{asp}$, are computed. For the first section, we obtain

$$[(C_f)_{asp1}]_{\text{calculated}} = 0.91 Re_D^{-0.61} \quad [4.14]$$

For the second section, we obtain

$$[(C_f)_{asp2}]_{\text{calculated}} = 0.33 Re^{-0.63} \quad [4.15]$$

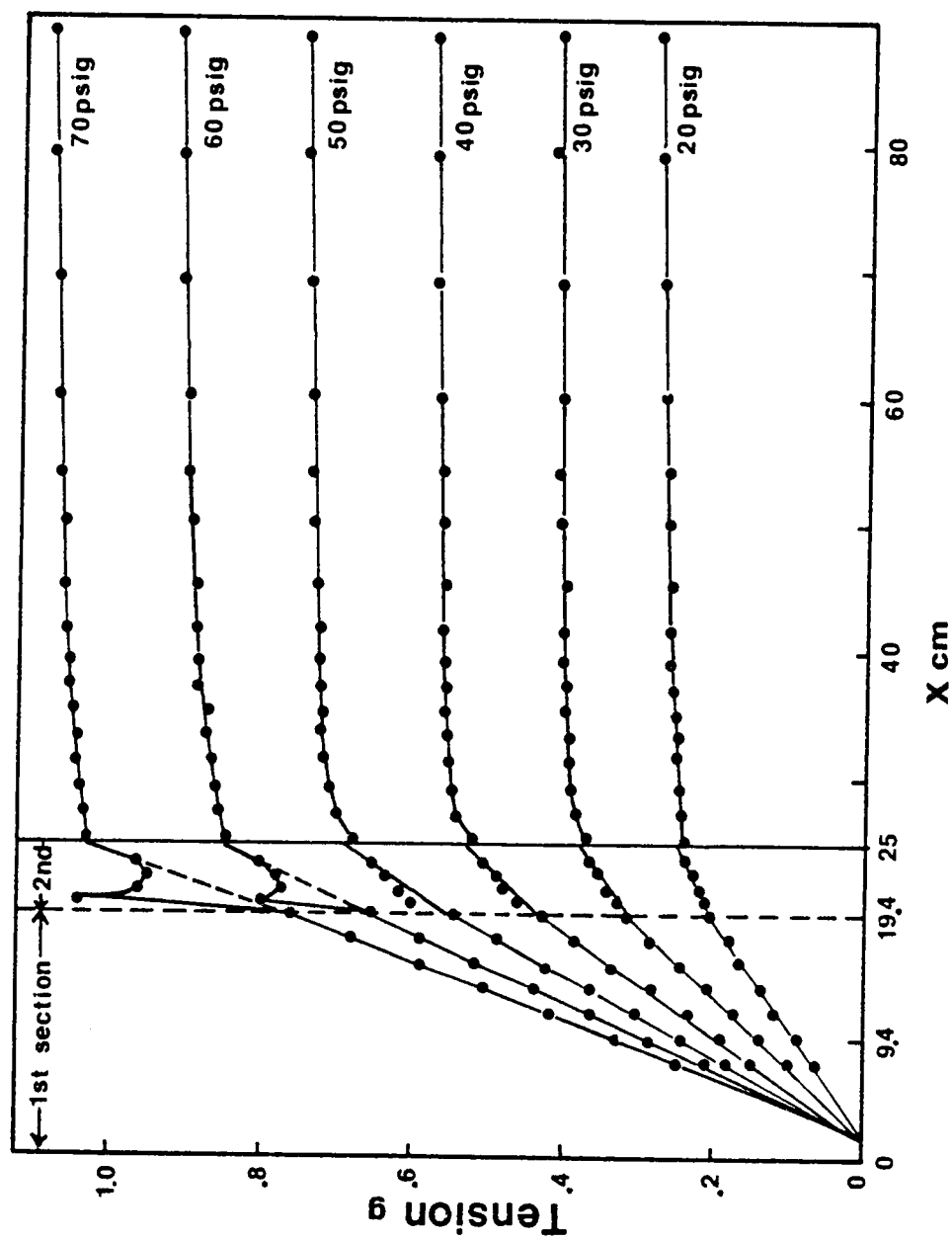


Figure 4.2 Variation of tension with fiber length (from the top end of the aspirator to any position X below it).

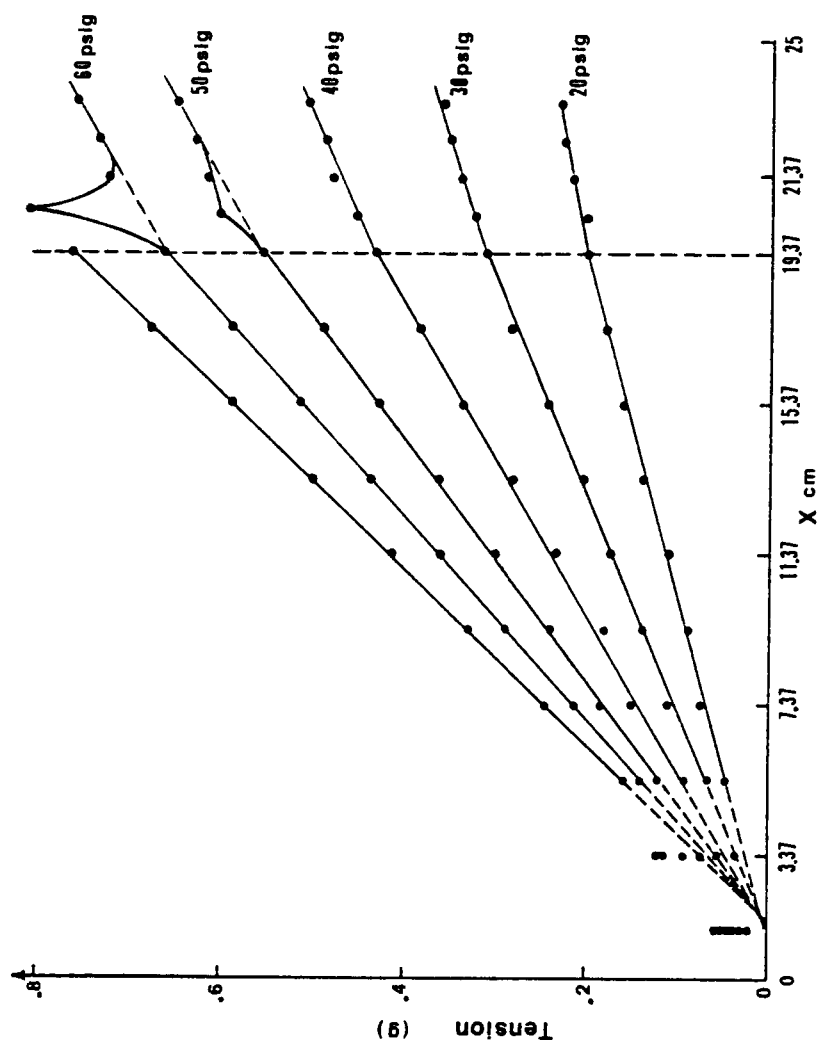


Figure 4.3 Variation of tension with fiber length inside the aspirator.

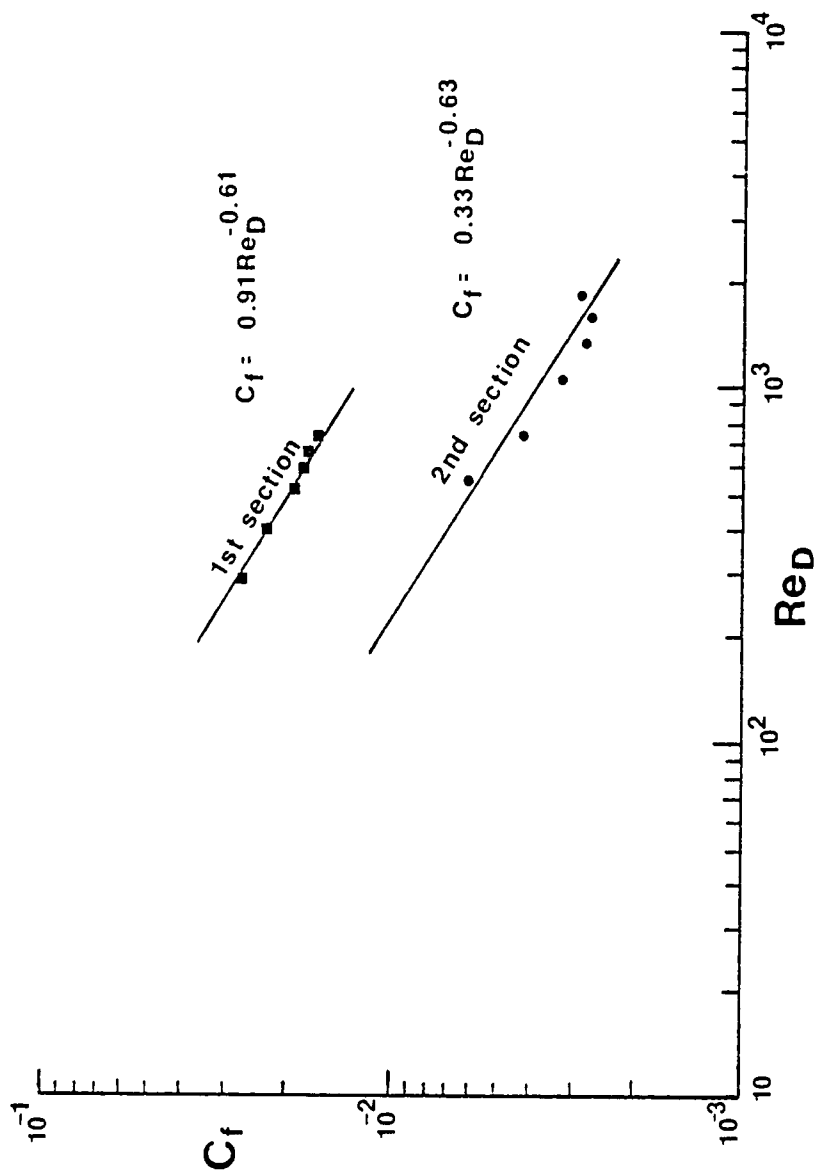


Figure 4.4 Correlation between drag coefficient and diameter Reynolds number for axial flow.

4.3 DISCUSSION

4.3.1 Air Drag Coefficients of the Aspirator

The velocities were carefully measured by a pitot tube in the second section of the aspirator. However, the air flow itself was highly turbulent in this section. The air velocity may change from point to point. In this study, the air velocities were calculated as the average of the measurements made at four points which are shown in Fig. 4.5 as solid black points. At these points, the air velocities are presumed to have large effects on the filament.

When the filament vibrates in this section, the air velocities near the filament are difficult to determine. In Equation [4.12], $[(C_f)_{asp}]_{exp}$ is dominated by the square of the air velocity. In Equation [4.13], Re_D is also a function of the air velocity. These two approximate values, which are used to develop the air drag coefficient of the second section, induce the smaller value of $[(C_f)_{asp2}]_{exp}$ in Equation [4.12].

Fortunately, the air velocity of section 1 is very stable. The air drag coefficient of the first section in Equation [4.14] is more acceptable than the value of the second section in Equation [4.15]. From Fig. 4.2, we still have a little air drag force below the aspirator. Due to the small values, we can neglect this effect and presume

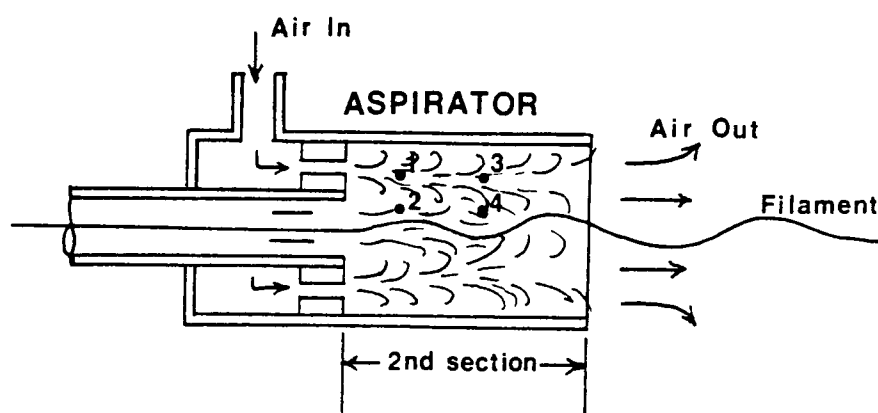


Figure 4.5 Schematic showing positions at which air velocities were measured.

that all the air drag forces are those determined inside the aspirator. In addition, the slopes of sections 1 and 2, shown in Fig. 4.3, are so close and the length of the second section is so short that it can be presumed that the air coefficient of section 1, $[(C_f)_{asp1}]_{cal}$, can be applied to the whole aspirator. Using this assumption, we can use $[(C_f)_{asp1}]_{cal}$ and the tension T , measured by the tensiometer on the 1-meter filament, to calculate an apparant aspirator length $(\Delta X)_{calculated}$ by the rearrangement of Equation [4.11] as

$$(\Delta X)_{cal} = \frac{2T}{\pi d [(C_f)_{asp1}]_{cal} \rho_a V_g^2} \quad [4.16]$$

where V_g is the air velocity of the first section. The results are shown in Table 4.2. The average value of $(\Delta X)_{cal}$ is very close to the full length of the aspirator ($\Delta X = 25$ cm). So, it can be presumed that the velocities measured in section 1 and the air drag coefficient developed in section 1 can be used the aspirator shown in Fig. 3.1 without introducing large errors.

The above assumptions were also used to calculate the spinline stress for the melt spinning filament drawn down by the aspirator. These assumptions may not be used in different aspirators. However, the air drag coefficient of the first section points out the approach to the spun-bonding process. This will be discussed in the next section.

TABLE 4.2 Tensions, air drag coefficients, and ΔX predicted by this study

air pressure psig	Tensions T $\times 10^3$ dyne	V_g cm/s	$[(C_f)_{asp}]_{cal.}$ $\times 10^{-2}$	$[\Delta X]_{cal.}$ cm
20	0.27	5,001	2.86	23.64
30	0.42	6,860	2.36	23.48
40	0.59	8,722	2.04	23.49
50	0.80	10,190	1.85	24.38
60	0.92	11,374	1.73	25.35
70	1.09	12,314	1.64	26.13

$$[(C_f)_{asp}]_{cal.} = 0.91 \text{ Re}_D^{-0.61}$$

$$\text{av. } (\Delta X)_{cal.} = 24.41 \text{ cm; act. } \Delta X = 25 \text{ cm}$$

4.3.2 Comparison of the Air Drag Coefficients

Developed by Former Workers

The constant 0.91 of the air drag coefficient, developed in the first section, is larger than the values of the former workers (5, 6, 25, 29, 32, 79, 84). However, the exponential value -0.61 is the same as many former workers' experimental results (5, 6, 25, 29, 32, 84) except Sano and Orii (79). This value was also predicted by the theory of Matsui (59).

Gould and Smith (29) analyzed Andrew and Cansfield's results (6), and noted that their work was done with fairly thick (50 ~ 400 μm diameter) untensioned filaments, which could flap in the air flow; this would lead to larger drag forces.

The aspirator itself is very similar to a wind tunnel except for its smaller diameter. No other former researchers except Gould and Smith (29) did experiments at high Reynolds number ($40 < \text{Re}_D < 400$) in a wind tunnel. The filaments used by Gould and Smith were tensioned by a weight. A filament in an aspirator can freely vibrate. According to Gould and Smith's assumptions, the untensioned filament would cause larger drag forces. This is also found in the air drag coefficient obtained from our experiments. It is believed, however, that the results for untensioned filaments are more representative of the actual conditions during the spunbonding process.

Different aspirators may have different amplitudes and frequencies of vibration, and may possess different constants of the air drag coefficient. However, the exponential value will be the same. For a spunbonding filament undergoing high amplitude vibrations, the constant will be larger than the constant of many former workers. A very simple arrangement, shown in Fig. 3.11 (p. 64), is suggested to measure the constant value of the air drag coefficient by the author.

CHAPTER V

STRUCTURE DEVELOPMENT IN SPUN FILAMENTS

5.1 BIREFRINGENCE

5.1.1 Results

The birefringence of filaments drawn down by the aspirator were measured by the technique described in Chapter III. Table 5.1 shows the birefringence and the spinline stress calculated in the manner described in section 4.3. These results are plotted on semi-log coordinates and compared to the results of Nadella et al. (66) for conventional spinning in Fig. 5.1. Results are also shown for conventional spinning with a take-up device for Hercules Profax [®]6323. These results were measured in the present study by the techniques used by Nadella et al.

5.1.2 Discussion

The average of the prior results of Nadella et al. (66), obtained for a series of polypropylene melt spun with a Leesona winder, are shown by the solid curve in Fig. 5.1. Comparing the results from the spunbonding process--shown by a dotted line--with the results of Nadella et al., the deviations between the two are well within the scatter band of Nadella et al. This implies that the spinline

TABLE 5.1 Birefringence varies with
spinline stress calculated
by this study

$\Delta n \times 10^{-3}$	$\sigma \times 10^6 \text{ dyne/cm}^2$
13.13	14.0
9.61	5.5
7.38	2.2
6.08	0.96

Using Δn of spunbonded fiber,
find stress by the stress-birefringence
relationship.

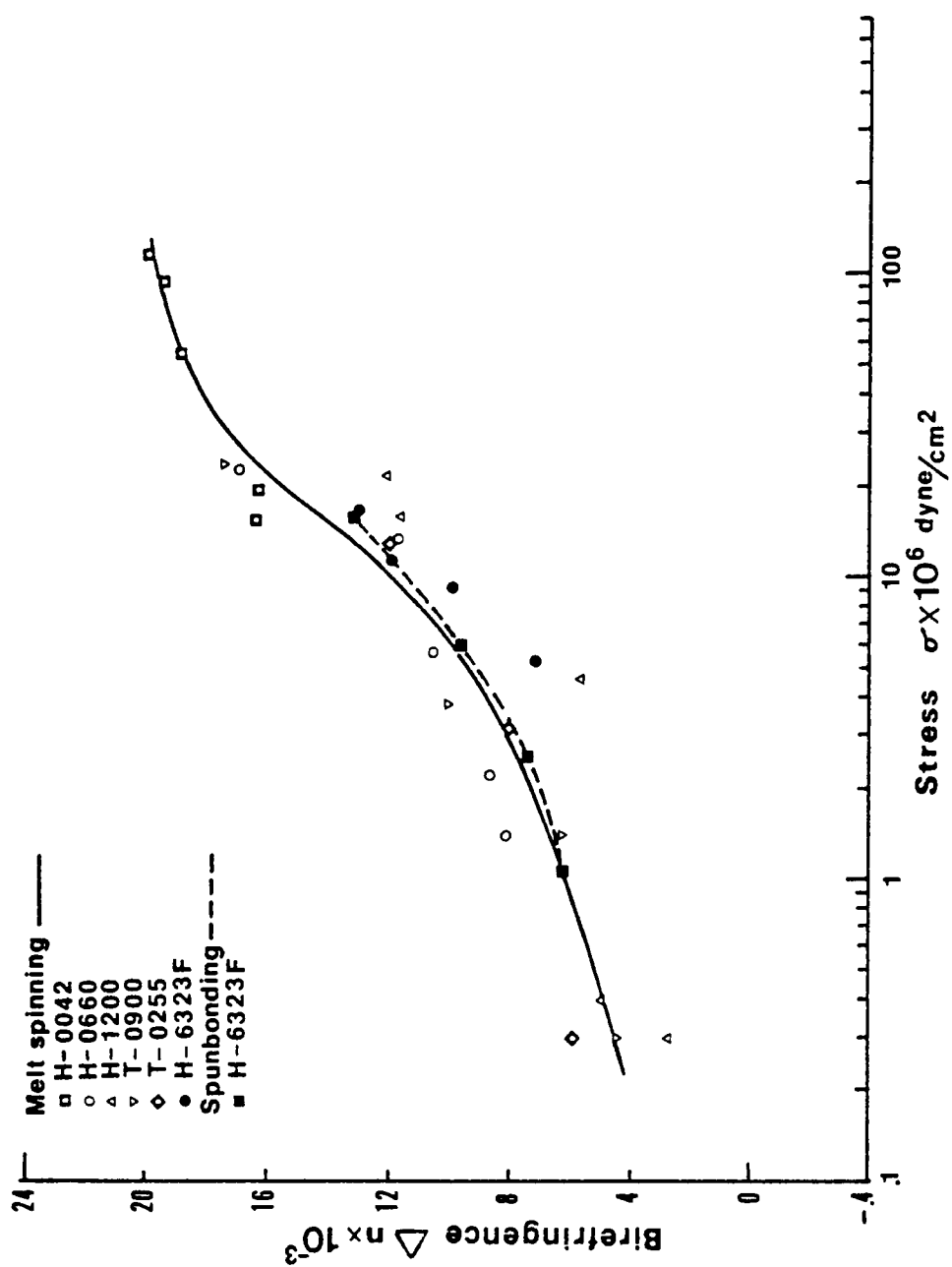


Figure 5.1 Comparison of birefringence-stress relationship for melt spinning with a winder and with an aspirator.

stresses calculated for the spunbonding process are very close to the real stresses on the spinline. In other words, the assumptions and calculations described previously for the spunbonding process are acceptable. It further confirms that the structure developed in the filaments are unique functions of the spinline stress.

5.2 X-RAY DIFFRACTION

5.2.1 Results

Orientation factors, calculated from wide angle X-ray diffraction measurements, are plotted against spinline stresses, calculated for the spunbonding process, and are shown as a dotted line in Fig. 5.2.

5.2.2 Discussion

Nadella et al. (66) and Henson (45) have measured crystalline orientation factors as a function of spinline stress in the melt spinning of polypropylene. The results of Nadella et al. differ somewhat from Henson's at low spinline stresses (Fig. 5.3). These differences probably occur from two sources. First, stress measurements in the low stress range are difficult using a tensiometer. Second, and probably more important, the background intensity determinations which are very important in establishing the actual value of the orientation factors at low spinline stress (as was noted in section 3.3.2 in this thesis), are

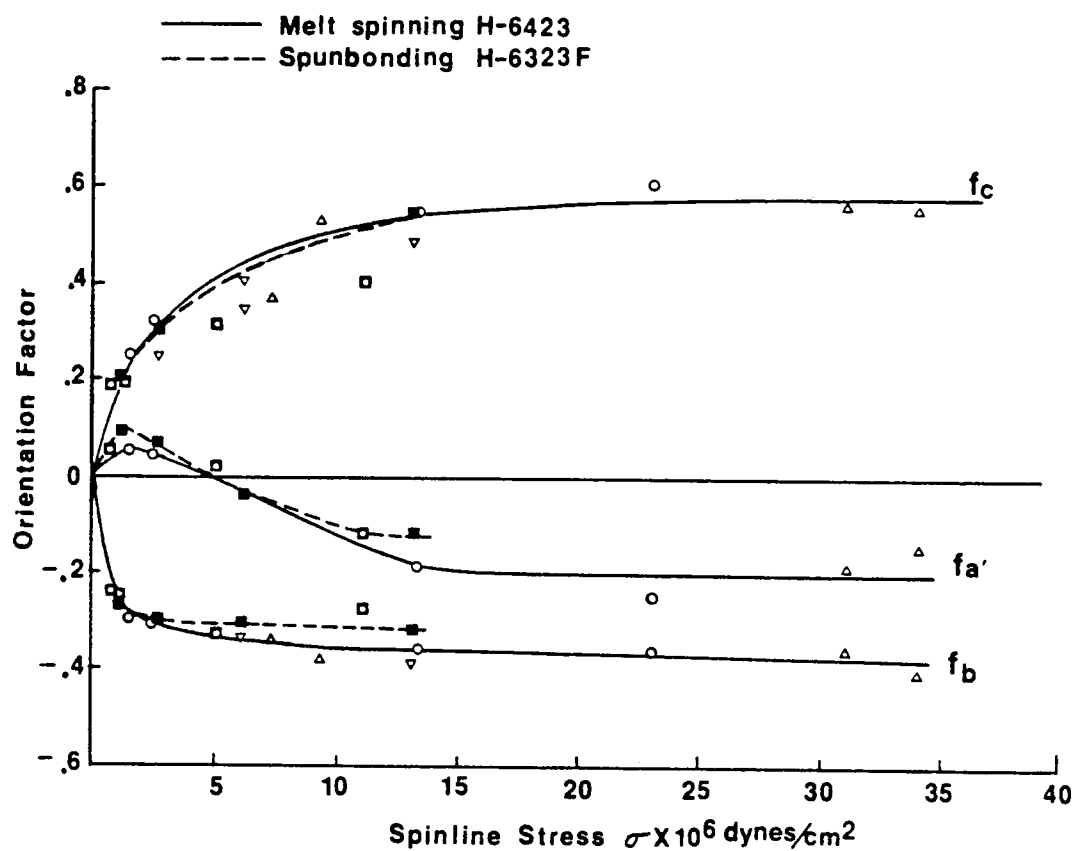


Figure 5.2 Comparison of orientation factor versus spinline stress relationship between melt spinning with a take-up device (Henson's data) and spunbonding process using the aspirator for draw down.

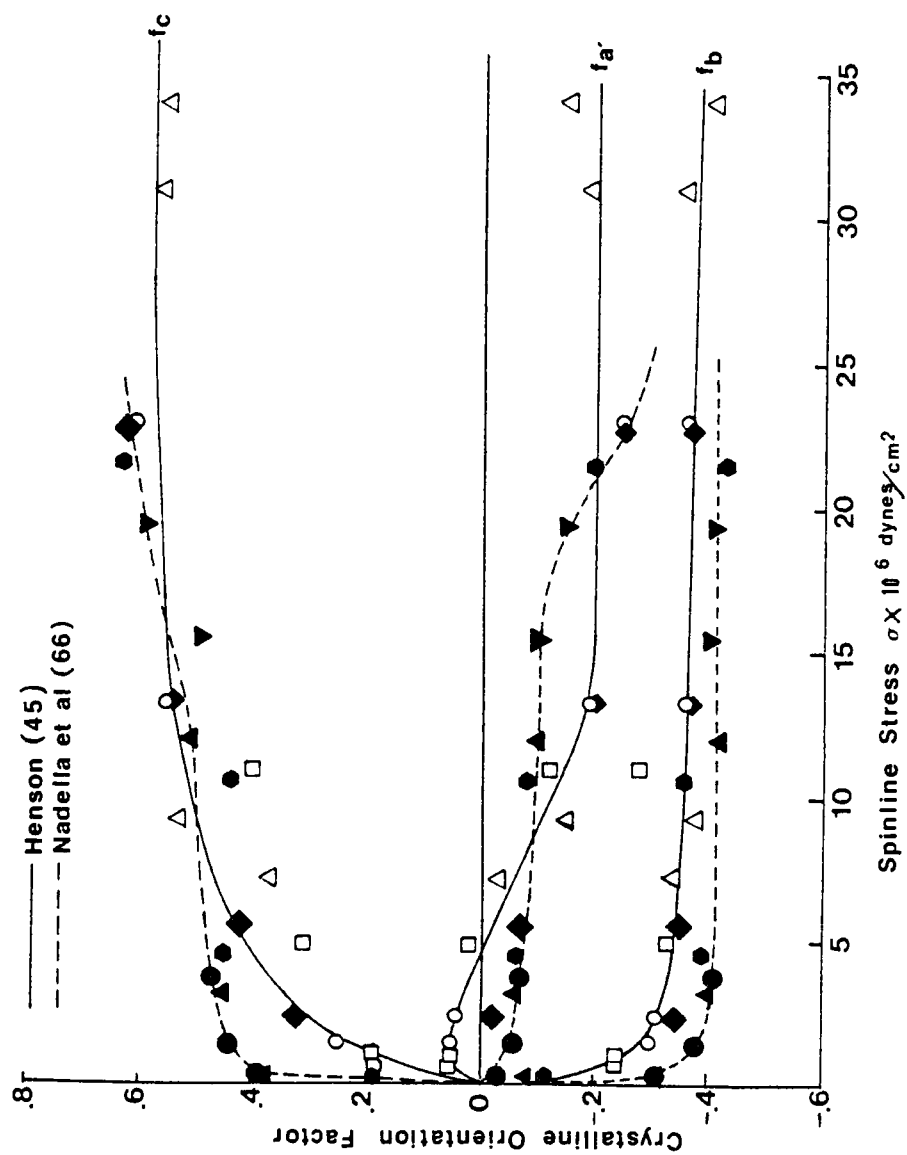


Figure 5.3 Comparison of crystalline orientation factor versus spinline stress relationship between Henson (45) and Nadella et al. (66) in the melt spinning of polypropylene.

made differently. It is believed that the difference on the f_a curve at low spinline stresses may result from these different techniques used to determine the background intensities.

Henson's results (45) are also plotted in Fig. 5.2 and represented by a solid line. The results for spun-bonded filament coincide with Henson's, because the same techniques were used for background correction. This also leads to two conclusions. These are: (1) the structure of filaments taken up by an aspirator have a similar structure to the filaments drawn down by a winder under the same spinline stress; (2) the spinline stresses which have been computed from the analysis of air drag in the aspirator are very close to the real stresses on the spinline.

CHAPTER VI

FABRIC FORMATION

6.1 BUCKLING OF A COTTON THREAD

A cotton thread (323 tex., 5 turn S/inch, 13 turn Z/inch) was used to investigate the buckling of a filament on a moving conveyer belt. The apparatus is shown in Fig. 3.12 (p. 66). The results are summarized in Fig. 6.1. When the belt is not moving ($V_f/V_b = \infty$), two buckles (Fig. 2.8-d, p. 36) formed during the lay-down process form a loop on the surface of the conveyer belt. When the belt moves, the buckles formed during the laying down are deformed, due to the frictional force between the conveyer belt and the cotton thread. As V_f/V_b approaches 1, all the buckles are deformed to a nearly straight line.

6.2 BUCKLING OF A SOLIDIFIED POLYPROPYLENE FILAMENT ON A STATIONARY CONVEYER BELT

Due to the irregular shape of the cross sectional area of the cotton thread, and the built-in stress contributed by the yarn twist, a series of solidified melt spun polypropylene filaments were used. The shape of the buckled polypropylene filament is characterized in Table 6.1 in terms of average length of buckles. This term was

$$\frac{V_f}{V_b}$$

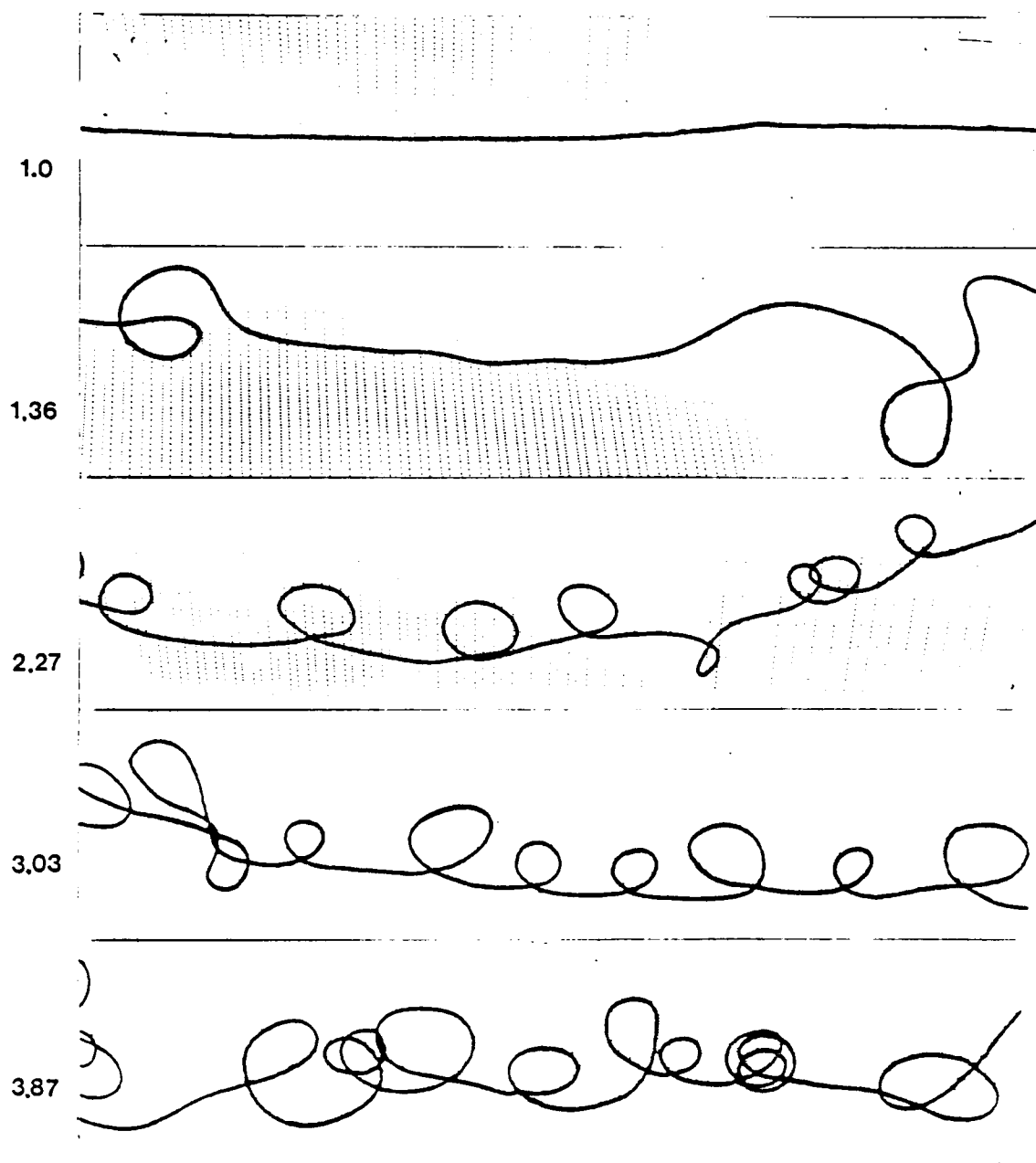


Figure 6.1 Conveyor belt movement effect on lay-down of cotton thread.

TABLE 6.1 Influence of stress and filament diameter on the buckling length formed in a solid PP filament

V_g (cm/s)	r $\times 10^{-3}$ cm	σ_{11} $\times 10^6$ dyne/cm ²	F (dyne)	av. Le (cm)	$(Le)^2$ F $\times 10^4$ dyne-cm ²	C
5001	2.121	5.12	289.4	6.89	1.37	10.32
5925	2.121	6.48	366.2	6.13	1.38	10.40
6860	2.121	7.97	450.2	5.5	1.36	10.24
5001	3.07	2.83	334.6	11.1	av.	av.
5925	3.07	3.55	419.8	9.8	4.12	9.76
6860	3.07	4.38	517.7	8.9	4.07	9.64
5001	4.03	1.83	372.6	16.0	4.10	9.68
5925	4.03	2.31	470.3	14.2	av.	av.
6860	4.03	2.83	576.1	13.0	9.54	9.64
5001	5.13	1.23	405.0	21.9	9.42	9.52
5925	5.13	1.56	514.9	19.5	9.74	9.84
6860	5.13	1.92	633.7	17.5	av.	av.
5001	5.85	1.0	430.0	24.7	9.57	9.68
5925	5.85	1.26	541.8	22.6	19.47	9.24
6860	5.85	1.55	666.5	20.7	19.58	9.28
					19.45	9.24
					av.	av.
					19.50	9.24
					26.2	8.24
					27.7	8.72
					28.6	9.0
					av.	av.
					27.5	8.54
					total	9.52

$$E = 1 \times 10^{10} \text{ dyne/cm}^2$$

$$C = \frac{(Le)^2 F}{\pi^3 Er^3}$$

measured by determining one-half the average length of loops on the stationary conveyor belt.

6.3 CORRELATION OF BUCKLED FILAMENT SHAPE WITH ASPIRATOR FORCE ON A STATIONARY BELT

In these experiments a solidified PP filament was supplied by a D. C. motor at constant speed ($V_f = 33.5$ m/min) and passed through the aspirator. The compressive force exerted by the aspirator was calculated using the correlation of Chapter IV. A plot was made for the compressive stress on the buckling filament, σ_{11} , as a function of the average buckle length, Le . This is shown in Fig. 6.2. A linear plot was observed for each filament on logarithmic coordinates. Different correlations were obtained for each filament diameter. All of the σ_{11} versus Le lines have slopes close to a value of -2. This means the stress σ_{11} is proportional to $(Le)^{-2}$, and the stress is also a function of the diameter of the filament d or the radius of gyration of the filament r . A log-log plot of the product of force on the filament F and the square of the average buckle length Le versus radius of gyration r is shown in Fig. 6.3. The slope of this straight line is about 3.13. This indicates

$$F \propto (Le)^{-2} (r)^{3.13} \quad [6.1]$$

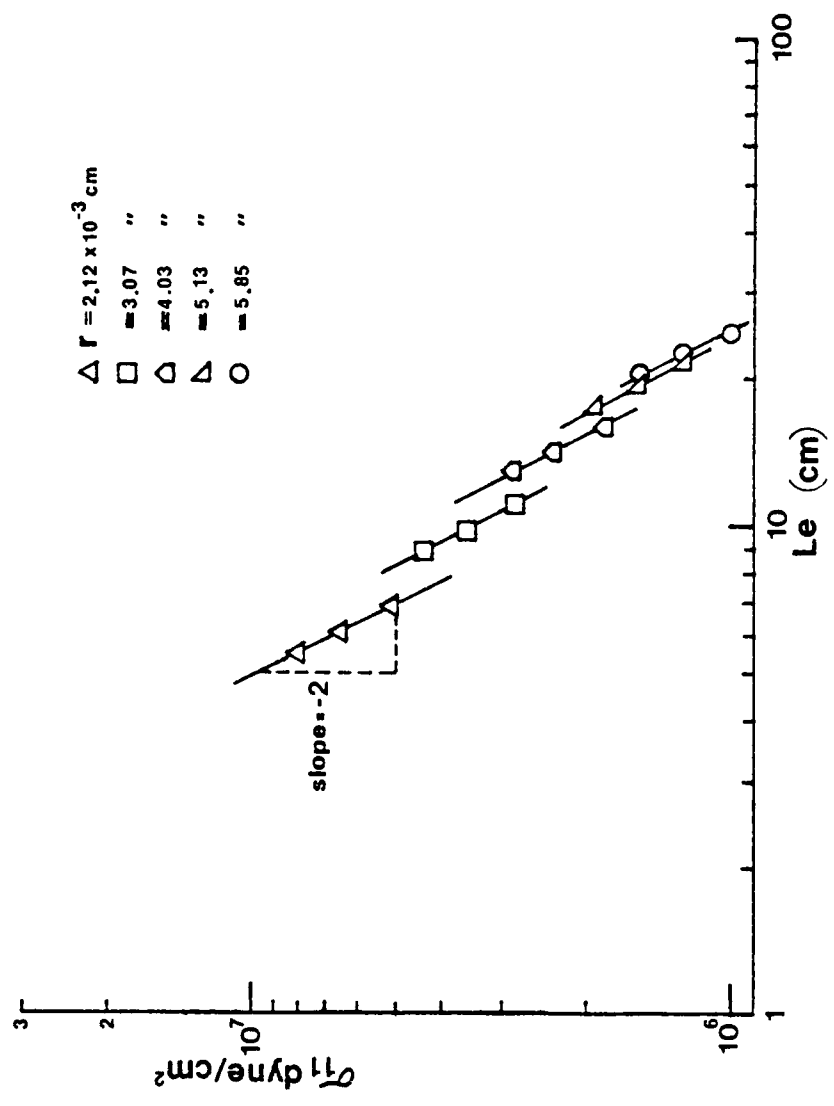


Figure 6.2 Stress-average buckling length relationship under different diameters of filaments.

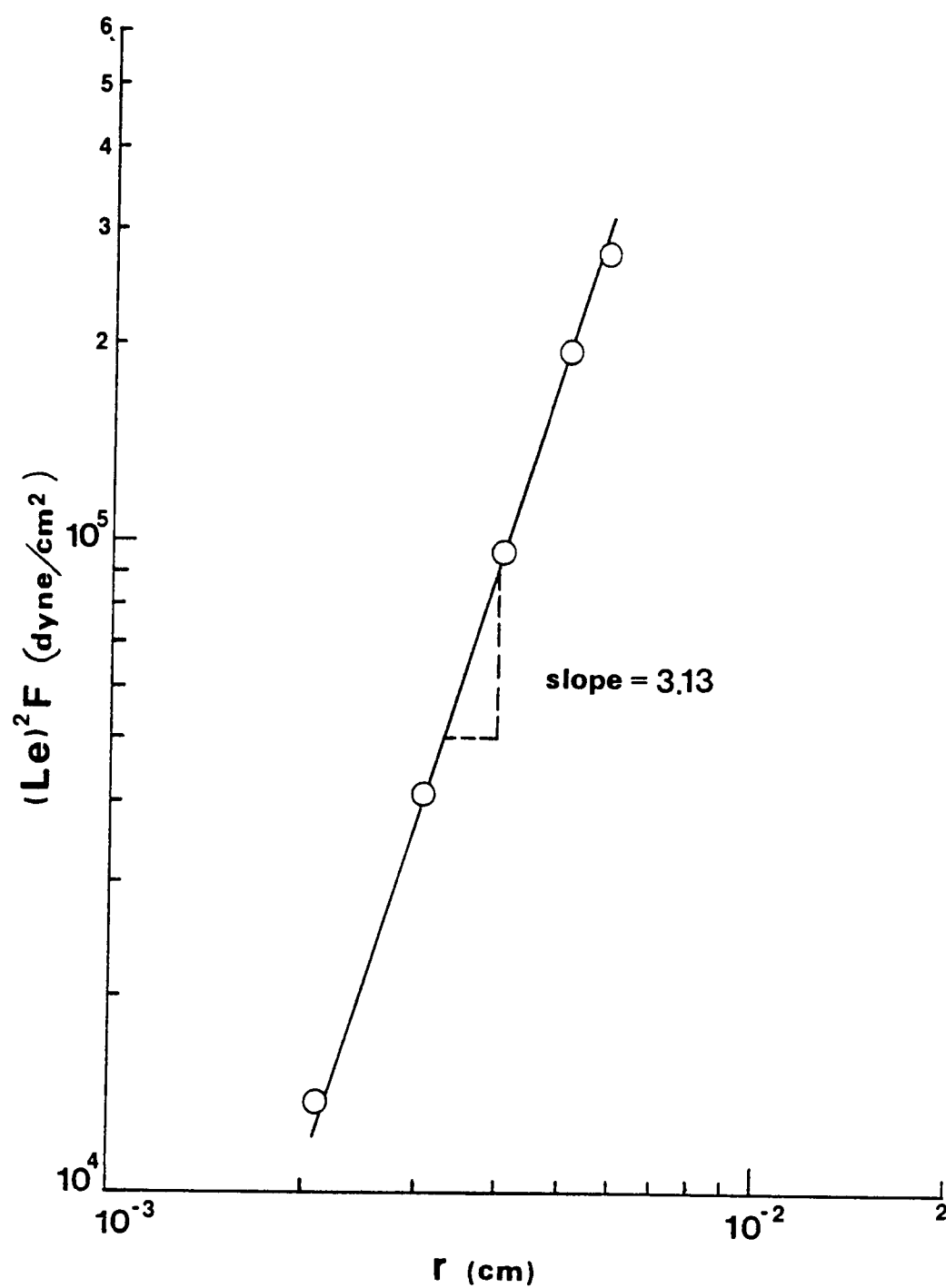


Figure 6.3 $(Le)^2 F$ and radius of gyration relationships for a series of solid PP filaments.

There are other factors which may influence the shape of the filament on a stationary belt. One factor is gravity force of the filament. For a fine filament, it appears that the gravity force can be neglected. The motion of air near the filament is another factor that influences the formation of the loops on the surface of the stationary belt. The motion of the air can cause the filament to move on the surface of the conveyor belt. According to the author's observations, this motion will deform the buckles in the descending filament, and decrease the number of loops on the surface of the stationary belt. However, the contribution of this effect is very difficult to estimate at any moment. As filament velocities went higher than $V_f = 30 \text{ m/min}$, the influence of the filament velocities was small in our experimental range ($V_g = 5001 \text{ m/s} \sim 6860 \text{ m/s}$).

6.4 INTERPRETATIONS USING EULER'S BUCKLING FORMULA

About 200 years ago, Euler (23) solved the problem of lateral buckling of a compressed column, which can be expressed as Equation [6.2] for a circular cross section:

$$F = CE(Le)^{-2} (r)^4 \quad [6.2]$$

where C is equal to $4\pi^3$.

Euler's buckling formula had been proven by experiments on

steel, aluminum, and other construction materials by various investigators (47, 76, 90). The results for steel of von Kármán and Tetmajer are shown in Fig. 6.4, where we plot σ/E versus Le/r on a linear graph. The experimental results for the spunbonded PP filaments are also plotted in Fig. 6.4. They are randomly distributed in the range from 10^{-3} to 10^{-4} . In Fig. 6.5, a clearer logarithmic plot of the steel and PP filaments is presented. σ/E is not a function of Le/r for PP filaments in this plot.

If we substitute the values of the compressive force F , and the radius of gyration r of PP filaments used in this study into Euler's buckling formula (Equation [6.2]), the smallest buckling length Le is predicted to have a value of 0.20 cm for filaments of diameter 85 μm with an air flow of velocity 5000 cm/s in the aspirator. The value is about 23 times smaller than the experimental measured value (4.55 cm). We may correlate our experimental results for non-zero V_f with

$$F = C\pi^3 E (Le)^{-2} (r)^{5.13} \quad [6.3]$$

where C is about 9.5.

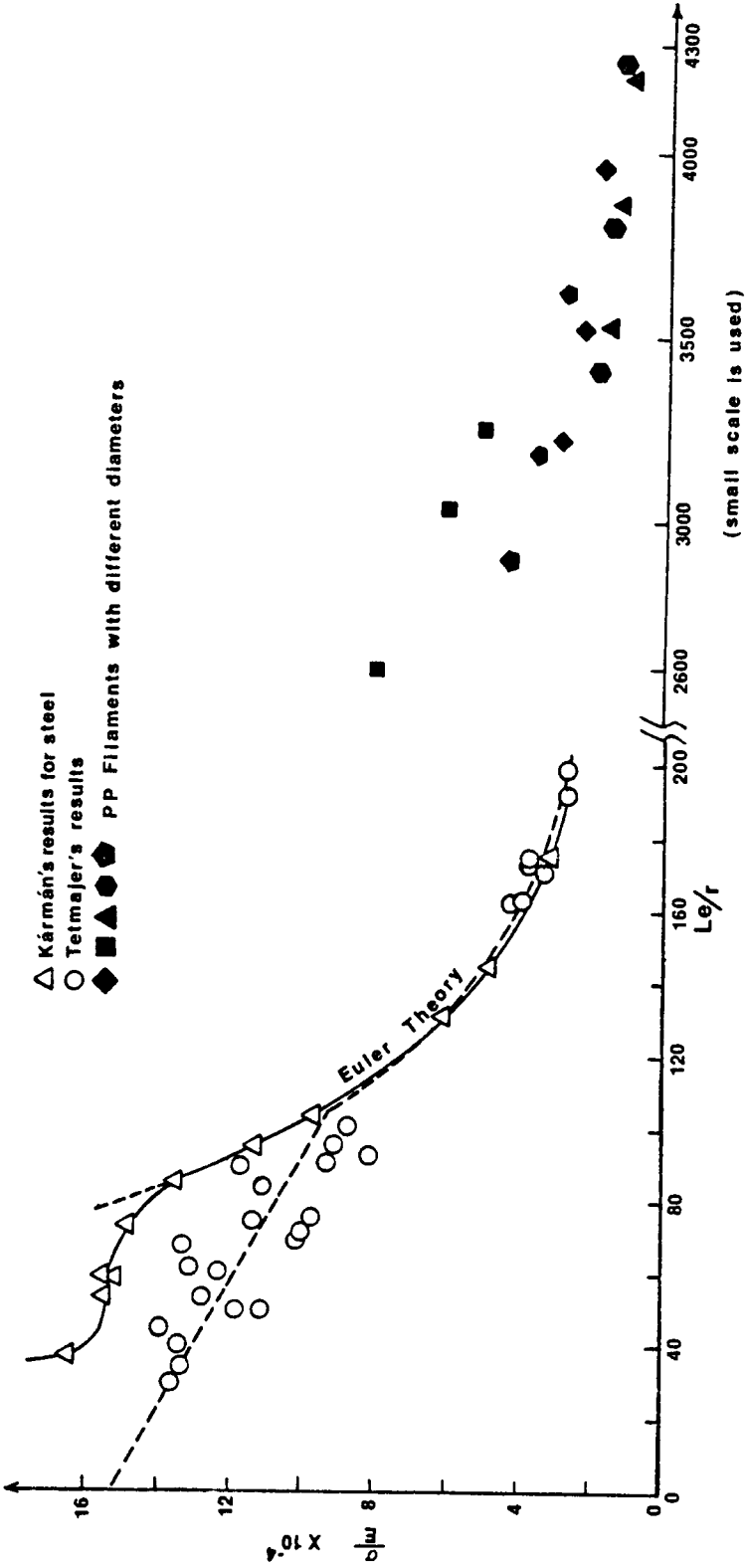


Figure 6.4 $\sigma/E - Le/r$ curves for experimental results of steel and solid pp filaments.

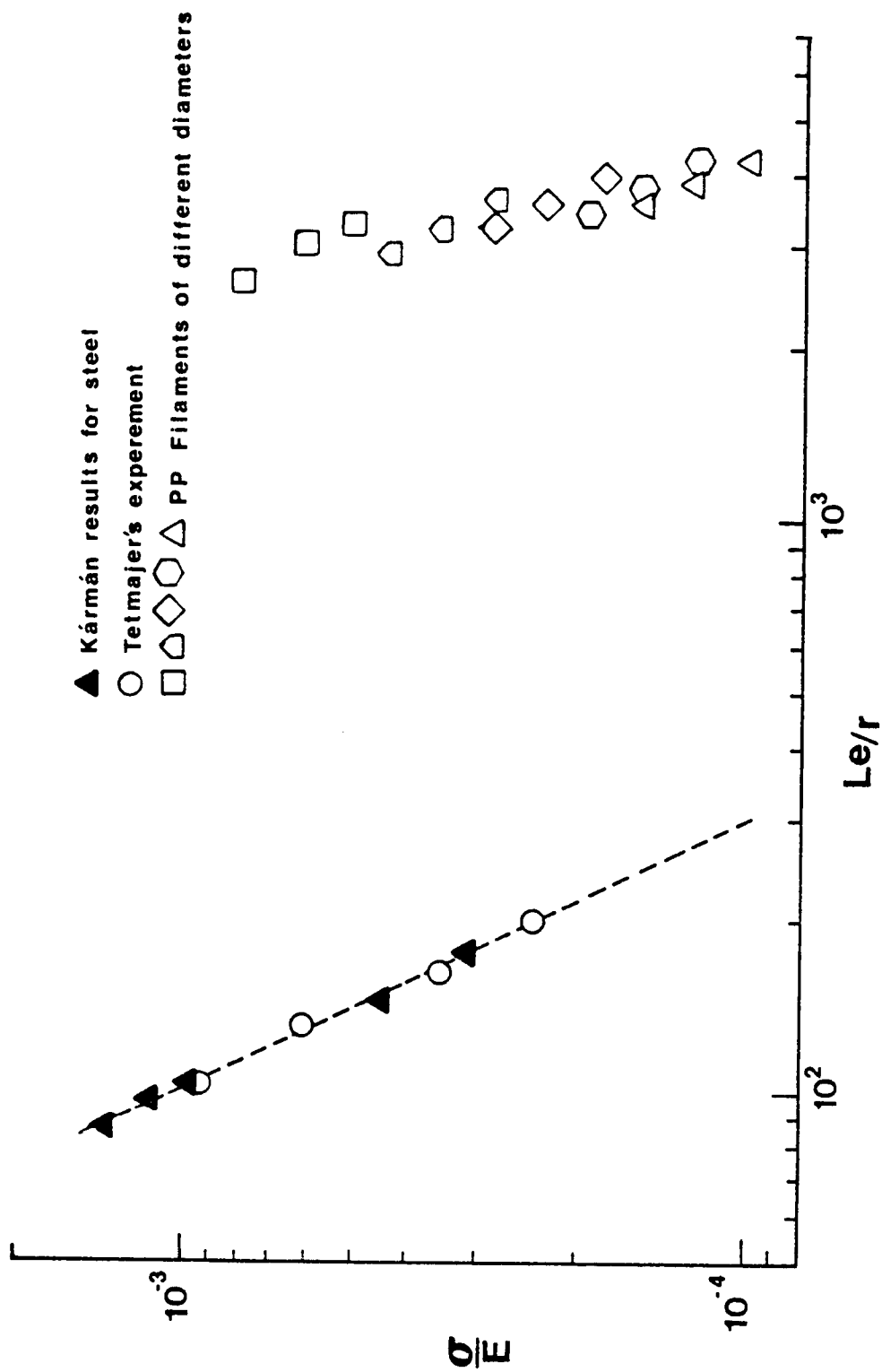


Figure 6.5 A log-log plot of σ/E versus Le/r for experimental results of steel and solid PP filaments.

6.5 THE STRUCTURE OF A MONOFILAMENT FABRIC ON A STATIONARY CONVEYER BELT FROM A CONTINUOUSLY EXTRUDED FILAMENT

In this section, the descending solidified PP filament, supplied by a D. C. motor, was replaced by a descending filament extruded from a spinneret and drawn down by an aspirator. The experimental results on buckled filament shape are shown in Table 6.2. The average length of buckles was measured from half value of the average length of each loop on the surface of the stationary belt. The compressive force F was calculated according to the assumptions described in Chapter IV. The L_e (predicted) was calculated according to the interpretations in section 6.4 and Equation [6.3]. The L_e^* (predicted by Euler's buckling formula) was calculated through Equation [6.2]. L_e^* (predicted) is too small to compare with L_e (measured). It follows that Euler's buckling formula cannot be applied. The errors between L_e (predicted) and L_e (measured) decrease with increasing air velocity of the aspirator V_g . In other words, the number of loops measured is larger than the number of loops predicted at lower aspirator air velocities. Further interpretation will be discussed in section 6.7.

TABLE 6.2 Differences of the buckling length measured and predicted on a stationary belt

V_g (cm/s)	V_f (m/min)	V_f/V_b	av. L_e (cm)	b (cm)	σ_{11} $\times 10^6$ dyne/cm ²	F (dyne)	$L_e(\text{predict})$ (cm)	Error (%)	$L_e^*(\text{predict})$ (cm)
5,001	72.4	∞	8.95	.0117	3.03	325.8	10.3	15.1	0.53
6,860	130.8	∞	6.05	.0101	6.0	480.7	6.74	11.4	0.32
8,722	187.6	∞	4.55	.0085	11.1	629.9	4.49	- 1.3	0.20

Note: $E = 1 \times 10^{10}$ dyne/cm²

L_e^* (predict) - predicted by Euler's Buckling Formula, Equation [6.2]

L_e (predict) - predicted by Equation [6.3]

Error (%) is calculated by $\frac{L_e(\text{predict}) - L_e(\text{measured})}{L_e(\text{measured})} \times 100\%$

6.6 THE FORMATION OF A MONOFILAMENT FABRIC ON A MOVING CONVEYER BELT FROM A CONTINUOUSLY EXTRUDED FILAMENT

If the belt moves at different speeds, a series of results is observed as shown in Table 6.3. A plot of V_f/V_b versus Le/Le_0 is shown in Fig. 6.6, where Le_0 is the average length of buckles on a stationary conveyer belt ($V_b = 0$).

The moving belt introduced a frictional force between the buckling filament and the moving conveyer belt. This frictional force will influence the formation of loops on the surface of the conveyer belt, and let the ratio between the number of buckles on the descending filament and the number of loops formed on the moving conveyer belt become larger than 0.5. However, this influence is not so large. If $V_f/V_b = 6$, only 23 percent of the buckles formed in the descending filament are removed by the moving belt. The larger the value of V_f/V_b , the smaller the effect of the conveyer belt motion. When V_f/V_b is equal to ∞ , there is no effect of the conveyer belt motion and Le/Le_0 reduces to a value of 1. When V_f/V_b is equal to 1, the effect of conveyer belt motion is a maximum and the radius of a loop becomes infinite (a straight line).

TABLE 6.3 Le/Le_0 changes under different V_f/V_b

V_g (cm/s)	V_b (m/min)	V_f (m/min)	V_f/V_b	av. Le (cm)	Le/Le_0
6860	0	130.8	∞	10.8	1
"	7.8	"	16.77	11.1	1.03
"	11.5	"	11.37	12.0	1.11
"	15.3	"	8.55	12.3	1.14
"	17.7	"	7.39	12.8	1.19
"	21.3	"	6.14	13.3	1.23

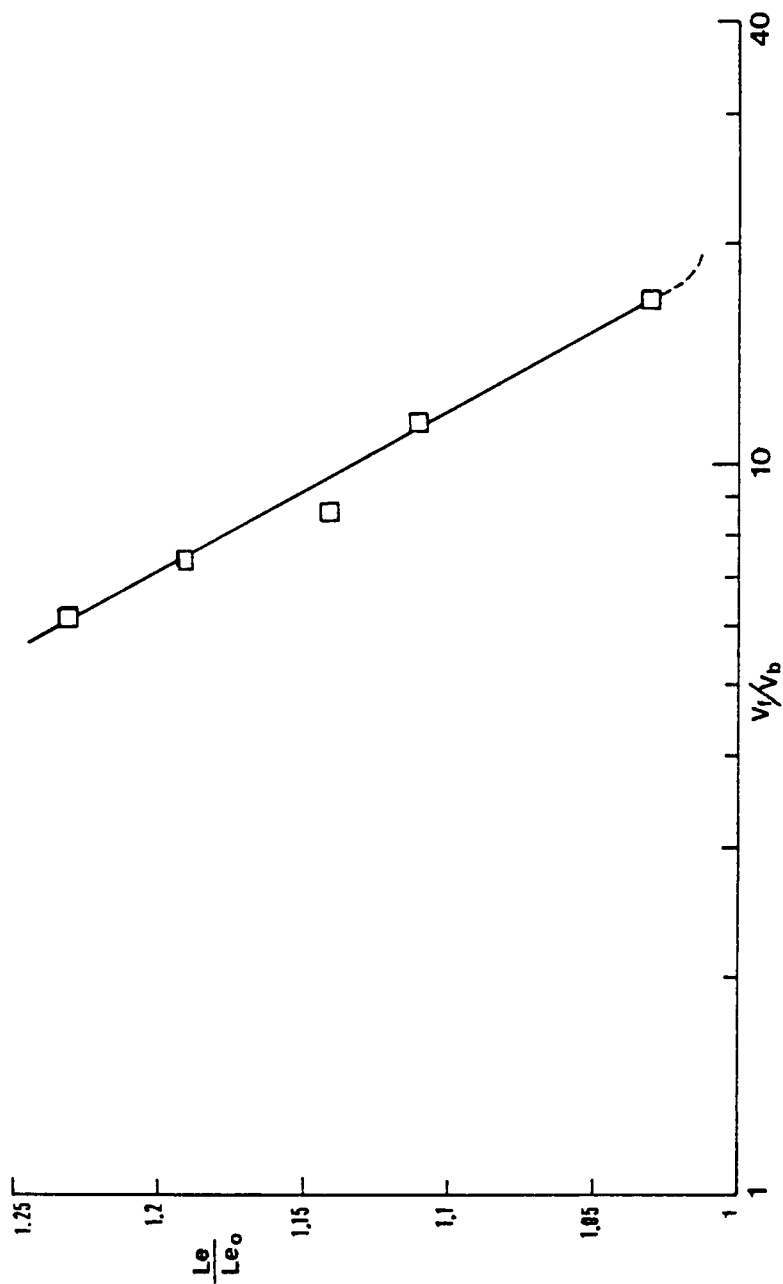


Figure 6.6 A log-log plot of L_e/L_{e0} versus V_f/V_b for a descending melt spinning filament, which was drawn by an aspirator with different belt velocities.

6.7 INTERPRETATIONS OF THE FORMATION OF A MONOFILAMENT FABRIC ON THE SURFACE OF THE CONVEYER BELT FROM A CONTINUOUSLY EXTRUDED FILAMENT

6.7.1 Stationary Belt Case

In Table 6.2, the differences between the measured values of Le and those predicted from Equation [6.3] are not so large, the assumptions of section 6.3 and interpretations of section 6.4 can be accepted especially for continuously extruded thin filaments. It follows that Equation [6.3] can be used to predict the number of loops on the surface of a stationary conveyer belt during melt spinning with draw down by an aspirator under the assumption of section 6.3. In other words, the number of loops mentioned above can be predicted from the compressive force on a descending filament exerted by the aspirator as predicted from the relations in Chapter IV, and the diameter and modulus of the filament.

6.7.2 Moving Conveyer Belt Case

Fig. 6.6 gives the relationship between loop formation with a stationary conveyer belt and a moving conveyer belt during melt spinning under the draw down force exerted by the aspirator. The following relationship results:

$$\frac{Le}{Le_0} = -0.47 \log \frac{V_f}{V_b} + 1.60 \quad [6.4]$$

Substituting Equation [6.3] (p. 97) into Equation [6.4], it follows that:

$$(Le) = [-0.47 \log \frac{V_f}{V_b} + 1.60] \left[\frac{9.5 \pi^3 E_r^{3.13}}{F} \right]^{1/2} \quad [6.5]$$

This empirical equation can be used to predict the average length of loops $2Le$ formed on the surface of the conveyer belt under a spunbonding process. The compressive force F was calculated by using the correlation of Chapter IV.

V_f/V_b can be measured during experiments. Above or below the experimental range, from $V_f/V_b = 6.14$ to 16.77 , this equation may or may not be valid. Due to the limitation in the apparatus used in this study, a larger range of experimental conditions could not be studied.

CHAPTER VII

SUMMARY AND CONCLUSIONS

This thesis is the first fundamental study of the spunbonding process. No open technical literature has been published. A laboratory spunbonding apparatus based on a screw extruder, aspirator and conveyer belt has been designed and built.

The air drag in the aspirator was obtained with a special arrangement of the tensiometer measuring head and a solid filament which passed vertically downward through the aspirator. Larger values were obtained than those reported in most studies in the literature. These results coincide with those of Gould and Smith, who argued that a highly vibrating filament lead to higher air drag coefficients.

Birefringences of the filaments formed in the spunbonding process were plotted against the spinline stresses predicted by this study. Comparing the above results with those of Nadella et al. in which the melt spun filament was drawn down by a winder confirms that the structure developed in the spunbonding filaments are unique functions of the spinline stress.

Orientation factors, computed from wide angle X-ray diffraction measurements were plotted versus spinline

stress. The results are very close to those previously determined by Henson (45) for the melt spinning process. This comparison leads to the conclusion that the structure of filaments from the spunbonding process has a structure similar to that of filaments melt spun and drawn by a winder.

A cotton thread was used to investigate the relationship between the buckles formed in the descending filaments and loops on the surface of the conveyer belt. It was found that two buckles formed in the descending cotton thread form a loop on the surface of the conveyer belt. A solid PP filament supplied by a bobbin at low speed was also used to study the relationship between the compressive force given by the aspirator and the buckles formed in the descending filament. An empirical equation was obtained relating compressive force and fiber cross section.

The formation of a monofilament fabric on the surface of the conveyer belt from a continuously extruded filament was studied. For the case of a stationary belt, the results coincide with the empirical equation mentioned above. In the case of a moving belt, some of the buckles formed in the descending filament were removed by the belt as a result of friction between the filament and the belt. An empirical equation was developed in this study. This equation can be used to predict the number of loops formed on the surface of the conveyer belt in the range from $V_f/V_b = 6.14$ to 16.77 .

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