

To the Graduate Council:

I am submitting herewith a thesis written by Edmund Gerald Spencer entitled "AN EXPERIMENTAL INVESTIGATION OF PROCESSING PARAMETERS FOR THE PRODUCTION OF MICRO FIBERS USING THE MELT BLOWING PROCESS." 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 Aerospace Engineering.


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AN EXPERIMENTAL INVESTIGATION OF
PROCESSING PARAMETERS FOR THE PRODUCTION
OF MICRO FIBERS USING THE MELT BLOWING PROCESS

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ABSTRACT

A comprehensive experimental investigation was conducted to determine the effect that the processing parameters have on the fiber diameter of micro fibers produced in the melt blowing process. The UTK single hole die melt blowing facility was used during this research and only 650 MFR polypropylene was utilized. Among the processing parameters that were investigated were the die geometry (air gap, setback, and air jet injection angle), polymer throughput, air jet exit velocity, and collection distance. Also, data was collected to establish the independent effect that both the air jet temperature and polymer temperature have on the diameter of the fibers.

Increasing the air jet momentum decreased the average fiber diameter. This increase in air jet momentum was attained by: increasing the air jet exit velocity, increasing the air gap, reducing the setback, or by decreasing the air jet injection angle. Also, a decrease in the polymer flow rate produced smaller fibers. The variation in the average fiber diameter for samples collected from 10 to 40 inches from the die tip was within the uncertainty of the fiber diameter measuring technique. Polymer temperature showed a strong effect on the average fiber diameter; an increase in polymer temperature produced smaller fiber for a

constant air jet temperature. The air jet temperature however, showed a negligible effect on the diameter of the fibers.

Single fibers were collected to determine the effect that the air jet temperature had on fiber strength. A trend of producing stronger fibers at lower air jet temperatures was found. The difference in the strength of these fibers however, was very small even for large differences in air jet temperatures.

Several empirical models were developed using the experimental data collected during this research. The dimensionless variables used in developing these models accounted for the most important parameters that describe the melt blowing process: die geometry, air jet and polymer temperature, air flow rate, and polymer throughput and viscosity. These models successfully predicted the average fiber diameter within 2 microns not only for samples processed at the UTK single hole die, but also for samples processed at the UTK 20 inch multiple hole die.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADS	Air Delivery System
ASME	American Society of Mechanical Engineers
A_e	air jet exit area
A_{die}	die orifice area
C	coefficient of discharge
DCD	Drum Collecting Distance (distance from die exit to where samples are collected)
$\bar{d}$	average fiber diameter
d_{die}	die orifice diameter, 356 microns
d_g	air gap
d_{ori}	diameter of air delivery system measuring orifice
d_{pipe}	ADS pipe diameter
d_s	die setback
F	velocity approach factor
F_e	thermal expansion factor
h	air jet exit height
h_{ref}	air jet exit height reference value
h_m	pressure differential across ADS orifice
MFR	Melt Flow Rate (an indirect measure of polymer viscosity)
$\dot{m}_a$	air flow rate
$\dot{m}_p$	polymer flow rate (throughput)

$\dot{m}_{\text{ref}}$	reference polymer throughput
p	static pressure at exit plane
p_o	stagnation pressure at exit plane
p^*	critical static pressure at exit plane
R	specific gas constant
SAS	Statistical Analysis System
SCFM	standard cubic feet per minute
T_a	static temperature of air jet at exit plane
T_{ao}	stagnation temperature of air jet at exit plane
T_a^{ref}	air jet temperature reference value
T_p	polymer temperature at die tip
T_p^{ref}	polymer temperature reference value
T_{pipe}	temperature of the air at delivery system orifice
UTK	University of Tennessee, Knoxville
V_e	air jet exit velocity
w	single hole die width
x_i	auxiliary variables

Greek Symbols

α	die included angle
β	dimensionless polymer throughput ratio
γ	specific heat ratio
γ^2	coefficient of multiple determination

Γ	dimensionless polymer to air mass flux ratio
δ	dimensionless fiber diameter ratio
Δ	modified dependent variable for empirical models
θ	air jet injection angle
Θ	dimensionless polymer temperature ratio [$^{\circ}\text{R}$]
λ	phase difference (interference microscope)
Λ	dimensionless polymer temperature ratio [$^{\circ}\text{F}$]
μ_a	air jet momentum
μ_p	polymer momentum
ξ	dimensionless air jet temperature ratio [$^{\circ}\text{R}$]
Π	dimensionless nose piece angle ratio
ρ_a	density of air
τ	dimensionless air jet temperature ratio [$^{\circ}\text{F}$]
Σ	dimensionless temperature difference ratio
Φ	dimensionless exit width ratio
Ψ	dimensionless air to polymer momentum flux ratio
Ω	dimensionless polymer MFR ratio

CHAPTER I

INTRODUCTION

The origin of the melt blowing process dates back to the early 1950's when the Naval Research Laboratory initiated a research project to investigate the production of small fibers. This research was driven by the understanding of the excellent filtration capabilities of filters made of very small fibers. The melt blowing process consists of extruding the molten polymer through a die where two converging air jets attenuate the molten material into fibers of small diameter. High performance filters, diapers, medical garments, battery separators, and absorbent media are just a few of the many commercial applications of melt blown products. For the interested reader, Malkan [1] presents a detailed discussion on the history of the melt blowing process.

Wente [2] was one of the pioneer investigators in the production of small fibers. The commercialized melt blowing systems developed by the Exxon Corporation [3] in the early 1970's based on Wente's research are widely used in industry today. The hardware used in the production of melt blowing fibers has not changed significantly over the years as compared to the polymers used in this process [4].

The melt blowing industry is constantly striving to

produce fibers that are small in diameter, strong, and inexpensive to produce. Several experimental investigations have been conducted to better understand the mechanisms that dominate the attenuation of the fibers and how the processing conditions affect the physical and mechanical properties of the fibers.

Milligan and Haynes [5] investigated the behavior of a flexible cylinder flapping in an axial flow field resulting from a free jet identical to the melt blown flow field. They showed that the flapping motion enhanced the fiber drawing force (drag). Other experimental investigations [1,4,6,7,8,9] have explored web characteristics such as bursting strength and tenacity. Straeffer and Goswami [6] determined that increasing the air velocity resulted in smaller and more uniform fibers. Malkan [1] studied the qualitative effect that air temperature, polymer temperature and throughput, and die orifice diameter had on the diameter of the fibers. Malkan's results indicated that polymer throughput had the strongest effect on the size of the fibers: an increase in polymer throughput resulted in larger fiber diameters. Lee and Wadsworth [10] investigated the effect that air flow rate and processing temperature had on the filtration capabilities of a melt blown web. An increase in the processing temperature resulted in webs of smaller average fiber diameters which in turn resulted in webs with greater filtration efficiencies. Milligan and Haynes [11]

determined using still photography of a single fiber in "flight" that the fiber is a continuous filament which varies in diameter along the length of the fiber. It was previously believed that multiple fibers were formed due to breaking or splitting of the fibers.

Kayser and Shambaugh [12] developed an empirical model based on the mass flux ratio using data collected from a single hole die . This model did not successfully correlate all of their data. Haynes [13] also developed several empirical models using the mass flux ratio and correlated the experimental data with some success.

There have not been studies conducted which explore the independent effect that the air and the polymer temperature have on fiber diameter primarily due to the inability of the production facilities to independently control these processing variables.

Attempts to develop analytical models that describe the melt blowing process is another area of interest that has been addressed by only a few investigators. Uyttendeale and Shambaugh [14] developed a one dimensional analytical model of the melt blowing process. Haynes [13] further refined this model with some success. His model predicted general trends for different processing conditions but consistently predicted larger fiber diameters.

Objectives

The following is a list of the objectives that were addressed in this investigation:

- determine the effect of exit air velocity (V_{exit}) on average fiber diameter ($\bar{d}$).
- determine the effect that air gap (d_g) and die setback (d_s) have on average fiber diameter.
- determine the effect of air jet injection angle (θ) on average fiber diameter.
- determine the effect that air jet temperature (T_a) has on average fiber diameter while keeping a constant polymer temperature (T_p).
- determine the effect of polymer throughput ($\dot{m}_p$) on average fiber diameter.
- determine the effect that polymer temperature has on average fiber diameter while keeping a constant primary air temperature.
- determine the effect that air jet temperature has on the strength of single fibers.
- develop a comprehensive empirical correlation model.

- For the dimensionless temperature ratio variables, use degrees Fahrenheit and absolute temperature to establish the effect in the predicted average fiber diameter.
- Develop empirical models using both mass flux ratio and momentum flux ratio.
- compare experimental data from other melt blowing facilities and/or investigators with the newly developed empirical models.

CHAPTER II

EXPERIMENTAL APPARATUS AND PROCEDURES

This Chapter describes the equipment used to produce the melt blown fibers, and how the samples were collected and tested to determine their mechanical and physical properties. It begins by describing the apparatus and instrumentation used in collecting the melt blown fiber samples. A brief overview follows of how the desired processing conditions were achieved. The next section describes the types of samples that were processed, how they were collected, and the equipment used to measure their physical and mechanical properties. To conclude, the reproducibility of experimental results is presented. It should be mentioned that only one type of polymer, 650 MFR white polypropylene, was used throughout this research.

Single Hole Melt Blowing Facility

The single hole melt blowing facility located in the Dougherty Engineering Building at The University of Tennessee was used to produce the melt blown fibers used in this research. The unit consists of three major components: the extruder, the air delivery system, and the test section.

Figure 2.1 shows the arrangement of the single hole melt blowing facility components located at the research lab.

Extruder

The function of the extruder is to melt the polymer to a given temperature and to deliver this molten material to the die at a given flow rate. A Killion extruder was used to accomplish this task. Figure 2.2 shows a schematic of the extruder configuration. The polymer is fed to the extruder through the hopper. The motor-driven screw pushes the material through the extruder while five independently controlled heaters melt the polymer to the desired temperatures. The controller for each heater is located in the extruder control panel. The speed of the motor which turns the screw is controlled by a dial located on the control panel. A digital read out of the motor speed is displayed on the control panel. The desired flow rate of polymer exiting through the die was achieved by controlling the motor speed and by monitoring the read out of the melt pressure sensor. A Dynisco pressure sensor measured the pressure that the polymer was exerting on the tube walls (melt pressure) between zones 4 and 5 and the read out from the sensor was used to monitor and ensure that a constant polymer flow rate (throughput) was being supplied to the die while the samples were being collected. The actual polymer

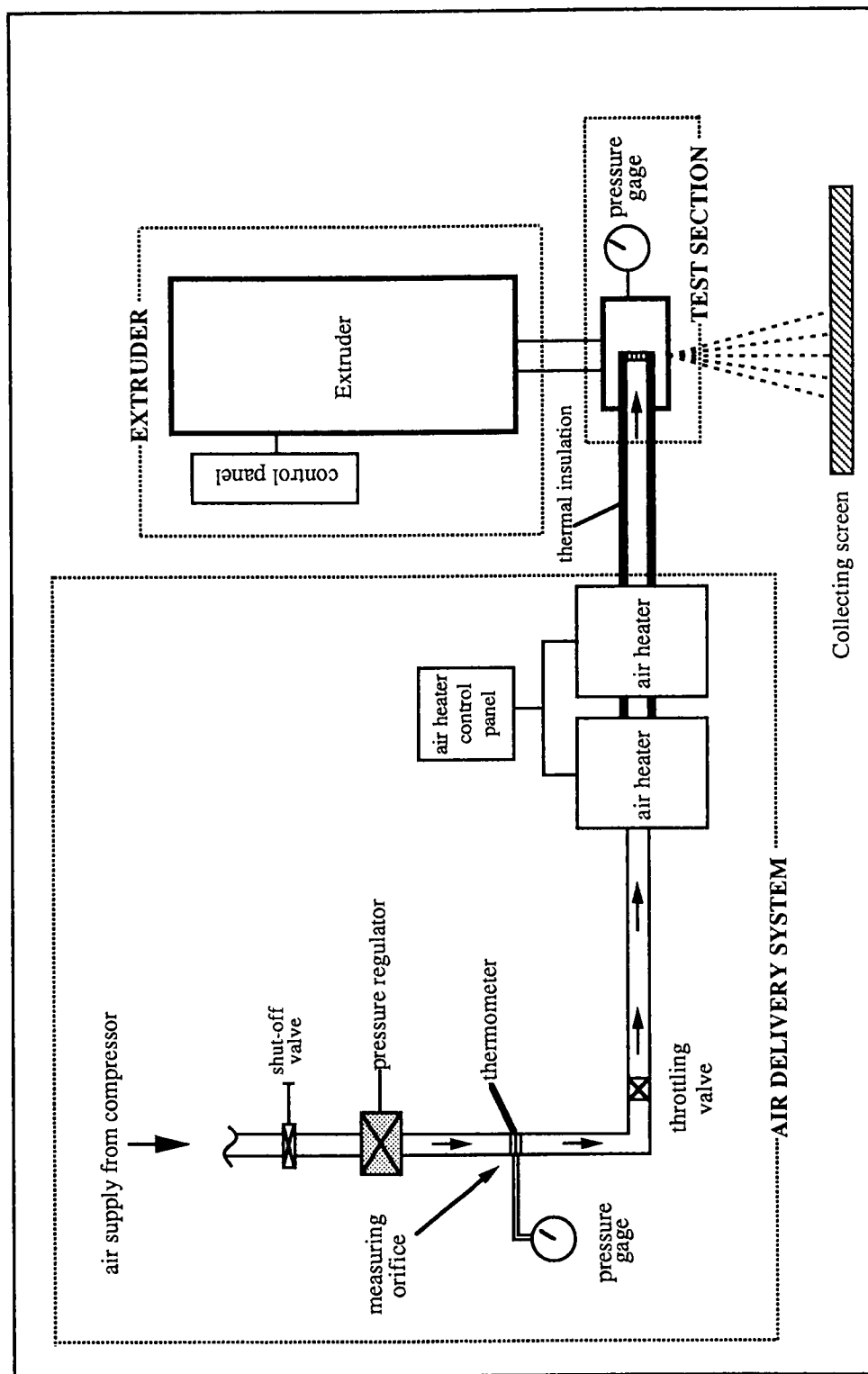


Figure 2.1: Arrangement of the single hole melt blowing facility components at the UTK research lab

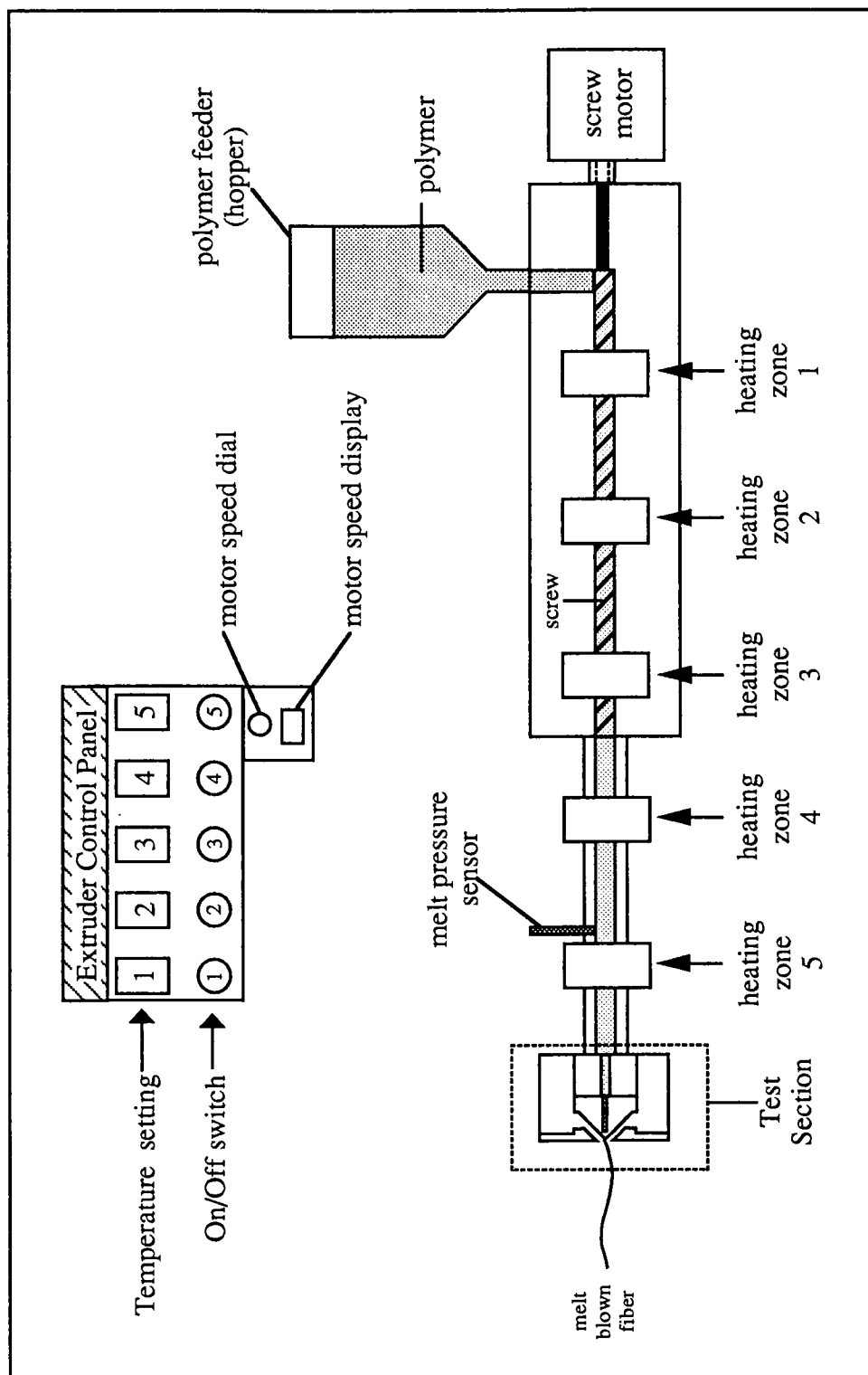


Figure 2.2: Schematic of the extruder

throughput was determined by collecting the material coming out of the die (in flight) for a known period of time, usually 30 seconds. The material collected was then weighed on an Ainsworth digital balance. The throughput in grams per minute was then readily calculated.

Air Delivery System

The Air Delivery System (ADS) provides a continuous supply of air at a given temperature and pressure into the test section. A diagram of the ADS configuration is included in Figure 2.1. The pressurized air was provided to the research lab by either one of the two compressors located in the building. Both of these compressor were capable of delivering 250 standard cubic feet per minute (SCFM) of air at a pressure of 110 psig. A pressure regulator located downstream from the shut-off valve maintained a constant supply pressure of 50 psia. A flow measuring orifice constructed according to the American Society of Mechanical Engineers (ASME) Flow Measurement Code [15] is located downstream of the pressure regulator in order to determine the flow rate of air being delivered to the test section. The pressure drop across this standard measuring orifice was read by a pressure gauge in inches of water. A Fisher thermometer adjacent to the orifice was used to measure the temperature of the pipe. A manual valve (throttling valve)

was used to regulate the air flow rate through the system. Two Accutherm heaters were used to heat the air before entering the test section. The two heaters were arranged in series (Figure 2.1). The portion of the steel pipe running from the air heaters to the test section was thermally insulated to reduce the heat losses from the pipes.

A simplified expression for the air flow rate passing through the ADS in terms of the pipe temperature (T_{pipe}) and the pressure drop across the orifice (h_m) is given by Equation 1.1:

$$\dot{m}_a = 2.45 * 10^4 \sqrt{\frac{h_m}{1.8T_{\text{pipe}} + 492}} \quad 1.1$$

where: $\dot{m}_a$ air flow rate in grams per minute
 h_m pressure drop in inches of water
 T_{pipe} temperature in degrees Celsius

Equation 1.1 assumes a constant atmospheric (room) pressure of 14.7 psia. A detailed derivation of Equation 1.1 is presented in Appendix A.

Test Section

The test section consists of four major components: the die, a spacer block, two adjustable face plates, and two cartridge heaters. Figure 2.3 shows a cross sectional view of the test section. The spacer block is an aluminum block with several holes in the vertical plane. It is used as an adapter and a spacer between the die and the test section back wall. Air from the air delivery system enters the test section from the top and the bottom through a 2 inch thermally insulated stainless steel pipe. The holes in the spacer block allow for pressure equalization and air mixing between the top and bottom regions of the test section before the air reaches the exit plane. A type K thermocouple and a pressure gauge mounted on the side wall of the test section (Figure 2.4) were used to measure air stagnation temperature and air stagnation pressure, respectively. The die is a four inch wide aluminum block with a single hole drilled from the back to the tip. At the tip of the die the hole has an L/D (length to diameter ratio) equal to 8.5 and is 356 microns in diameter. Figure 2.3 shows how the hole tapers down from the back of the die to the tip. The molten polymer coming from the extruder enters the test section through the back wall. A screen pack is placed at the interface area between the extruder and the test section back wall to remove foreign particles and impurities.

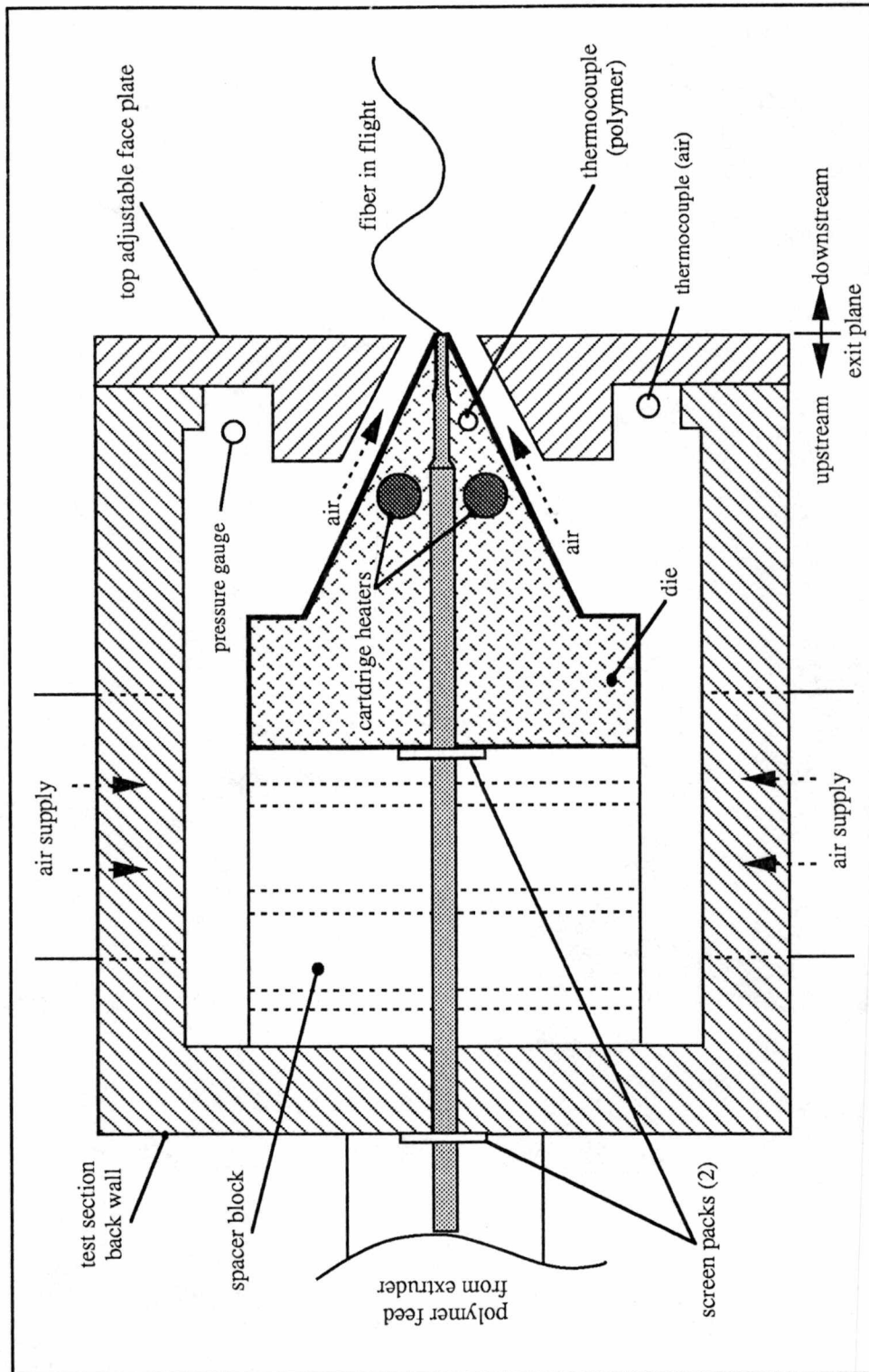


Figure 2.3: Cross sectional view of the test section

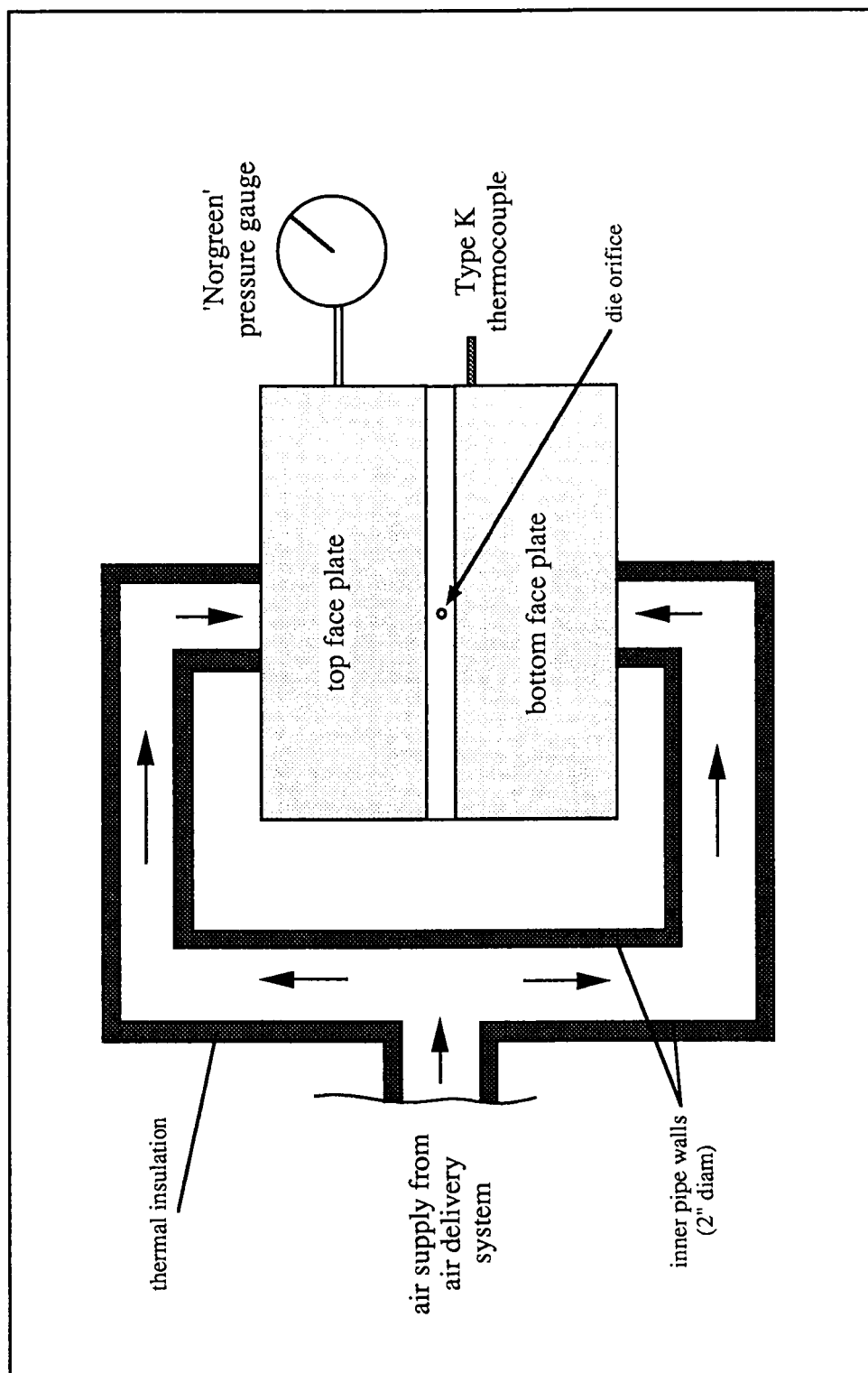


Figure 2.4: Front view of the test section

Another screen pack is located at the interface between the spacer block and the die to further reduce the possibility of foreign particles reaching the die orifice. Two cartridge heaters each rated at 280 watts were used to maintain a specific polymer temperature at the tip of the die. As the polymer reaches the die tip forced by pressure from the extruder screw, the air draws the single fiber and sets it into a flapping motion. Samples having fiber diameters ranging from 3 to 40 microns were collected during this research.

Experimental Procedures

"Operating Procedures" for the single hole melt blowing facility were documented by the author and can be found in Appendix B. A brief discussion on how the equipment was maintained at a given set of processing conditions will be presented.

A test plan specifying the processing conditions at which the experiment would be conducted was first prepared. The ADS throttling valve was then opened to a "home setting" position which produced a pressure drop across the ADS measuring orifice of 2 inches of water. The ADS air heaters were then set to a temperature which would supply air to the test section at the temperature specified in the test plan. The heaters (5 independent sets) located in the extruder and

the two cartridge heaters located on the die were set to deliver the molten material to the tip of the die at the temperature specified in the test plan. The extruder motor was then turned on to a nominal speed of 2 rpm. Once the temperature of the air at the test section and the polymer temperature at the die tip reached steady state conditions (approximately 1 hour from the time the screw motor was turned on), then the polymer throughput would be established. This task was accomplished by collecting the molten material flying out of the die over a known period of time. During this iterative process, the polymer melt pressure and the screw motor speed were recorded. The sample was immediately weighed and the throughput (in grams per minute) was readily determined. The screw motor speed was adjusted until the polymer throughput specified in the test plan was achieved. The final step before a specimen was collected was to set the ADS throttling valve to the position specified in the test plan. The throttling valve position controlled the velocity of the air exiting the test section. Once the specimen was collected using one of the techniques described in the next section, the valve was returned to the "home setting" position.

The UTK single hole melt blowing facility differs from production lines in that the latter have a multiple hole die. The UTK 20 inch die melt blowing facility located at the UTK Textiles Department, for instance, has an overall width of

26 inches, where 20 inches of the die have 25 holes per inch (501 holes total). Because of this difference, the webs made in production lines are formed by the fibers entangling with each other a few centimeters downstream from the die exit. The webs from the single hole die, on the other hand, are created by holding the sample collector in the air stream containing the fibers in flight long enough to capture sufficient single fibers to form a web.

Two types of specimens were collected from the single hole die: webs and single fibers. The technique developed by Haynes [13] for collecting a web was adopted in this investigation. Since this single hole die unit is unique, no techniques for collecting single fiber specimens had been developed. Several methods for collecting single fiber specimens were attempted but only one was adopted throughout this research. A comprehensive description of the process for collecting single fiber specimens will follow the brief explanation on how web samples were collected.

Collection of Webs

The web specimens were collected by placing a piece of constructing paper in the flow field containing the fiber for 5 to 8 seconds. During the early stages of this research, the constructing paper was placed over two different collecting surfaces: a 24 by 24 inch flat plate,

and a 6 inch diameter drum. The objective of this study was to determine the effect these two different collecting body shapes had on the final diameter of the webs being collected. Figure 2.5 shows a comparison between the average fiber diameter of the webs collected using the drum and the flat plate bodies. All specimens were collected under the same processing conditions. The maximum difference in average fiber diameter was 6% (0.5 microns). These results suggest that the shape of the bodies used to collect the webs had no significant effect on the average fiber diameter since the uncertainty of the process for measuring fiber diameter (microscope) is 1.25 microns. Therefore, the flat plate collector was chosen over the drum collector to maintain consistency with other researcher specimen collecting techniques [13].

Another aspect of the technique for collecting web specimens that was studied before the bulk of the data for this project was collected involved determining the effect that collecting distance (or Drum Collection Distance, DCD) had on fiber diameter. Specimens were collected at four different DCD's: 10, 20, 30, and 40 inches. At each of these DCD's, three polymer throughputs were processed: 0.8, 1.6, and 3.0 g/min. Samples were collected at these three polymer throughputs to ensure that the conclusions from this study would be valid for a wide range of polymer throughputs.

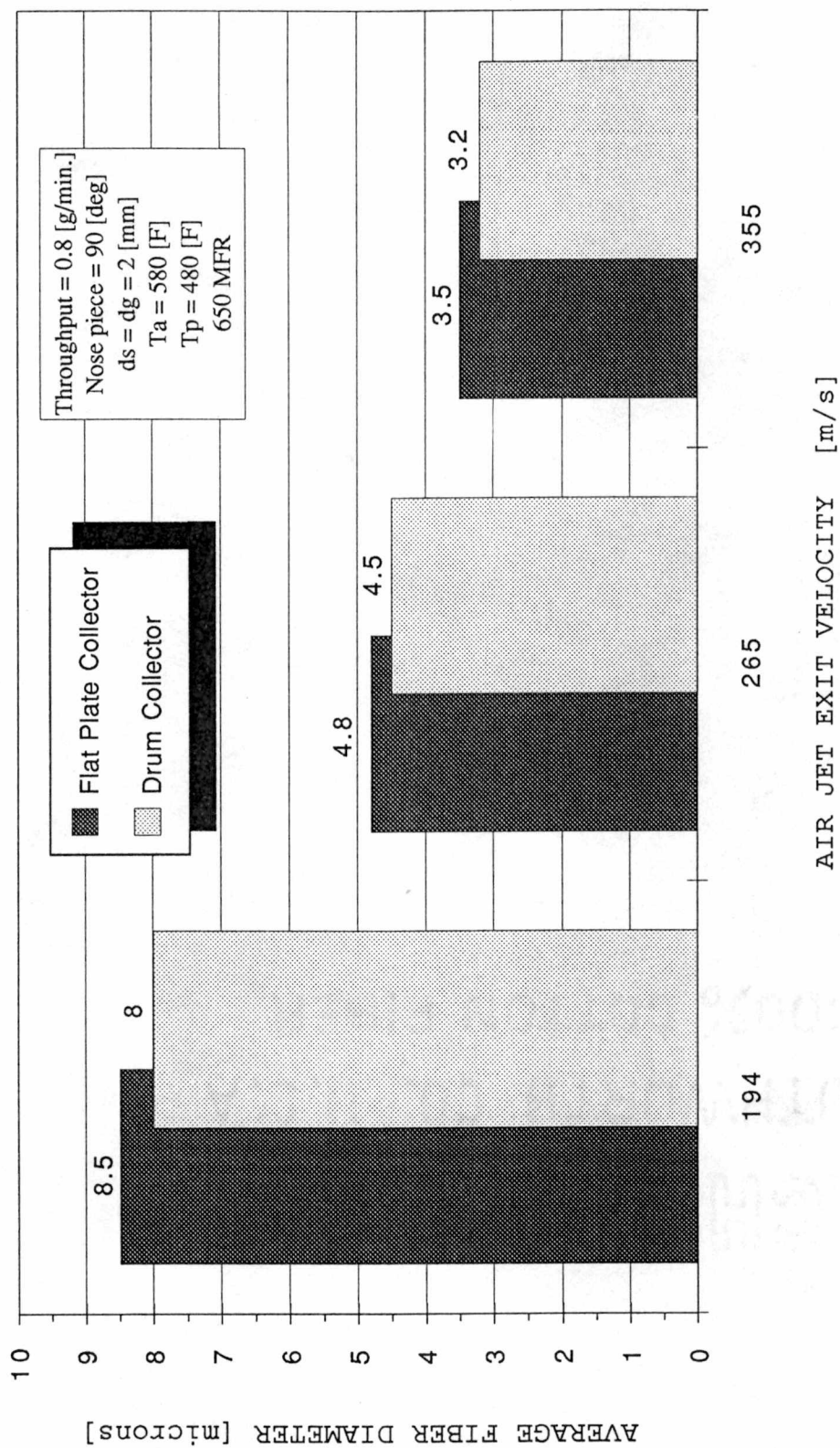


Figure 2.5: Comparison between the average fiber diameter of webs collected with a flat plate and a drum type collector

Figure 2.6 shows a comparison between the average fiber diameter of webs collected at 10, 20, 30, and 40 inches from the die tip. The maximum difference in fiber diameter is 1.9 microns, and it occurs at the lowest exit air velocity (193 m/sec). Figure 2.7 shows similar results, but at a higher polymer throughput of 1.6 g/min. The maximum difference in fiber diameter is 3.3 microns, and it also occurs at the lowest exit air velocity. Finally, Figure 2.8 shows that the maximum difference in average fiber diameter is 5.4 microns, which also occurs at the lowest exit air velocity. The overall maximum difference in fiber diameter (for a wide range of exit air velocities and polymer throughputs) is 5.4 microns. The uncertainty of the process for measuring the average fiber diameter (optical microscope) is 1.25 microns. Therefore, it can be concluded that DCD has no significant effect on the average fiber diameter based on two observations. First, the absolute difference in average fiber diameter is small compared to the uncertainty in measuring fiber diameter. And second, the data does not show a consistent trend that clearly indicates that an increase in DCD would produce larger or smaller fiber diameters.

It should be mentioned that all specimens were collected at 40 inches downstream from the die tip in order to maintain consistency in the collection technique. Also, all web specimens were collected using the constructing paper attached to the 24 by 24 inch flat plate collector.

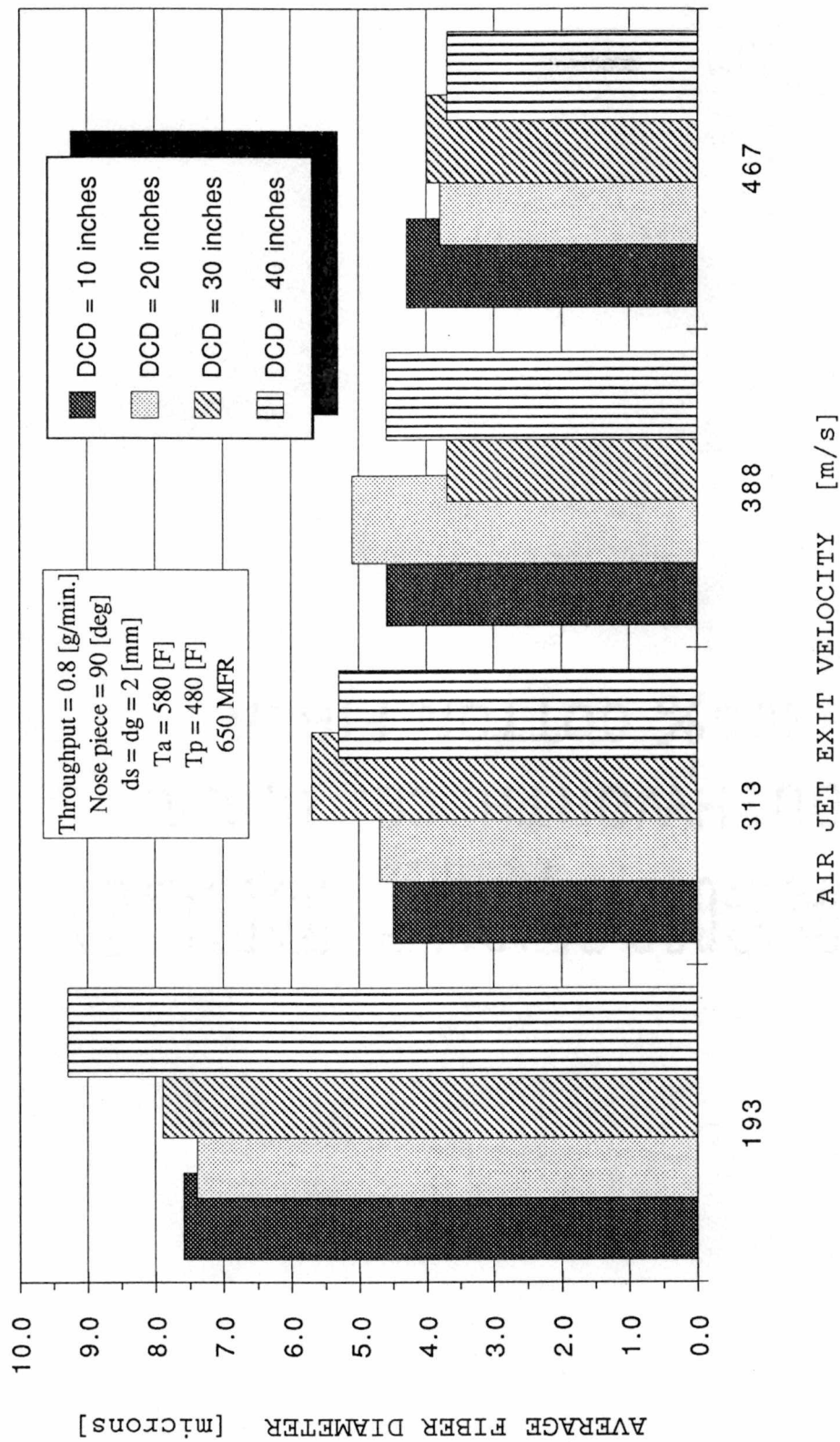


Figure 2.6: Comparison between the average fiber diameter of webs collected at several DCD's (0.8 g/min.)

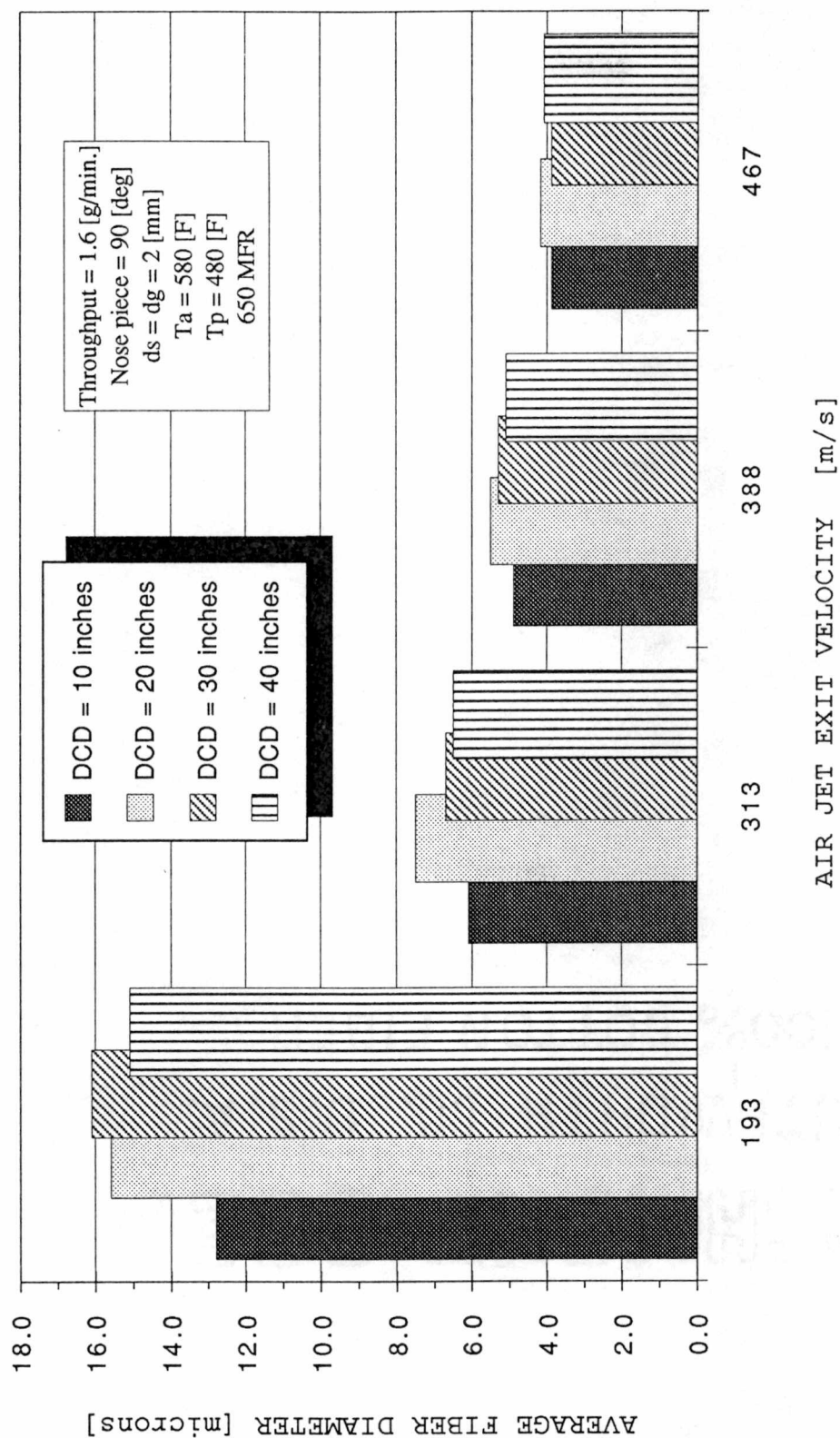


Figure 2.7: Comparison between the average fiber diameter of webs collected at several DCD's (1.6 g/min.)

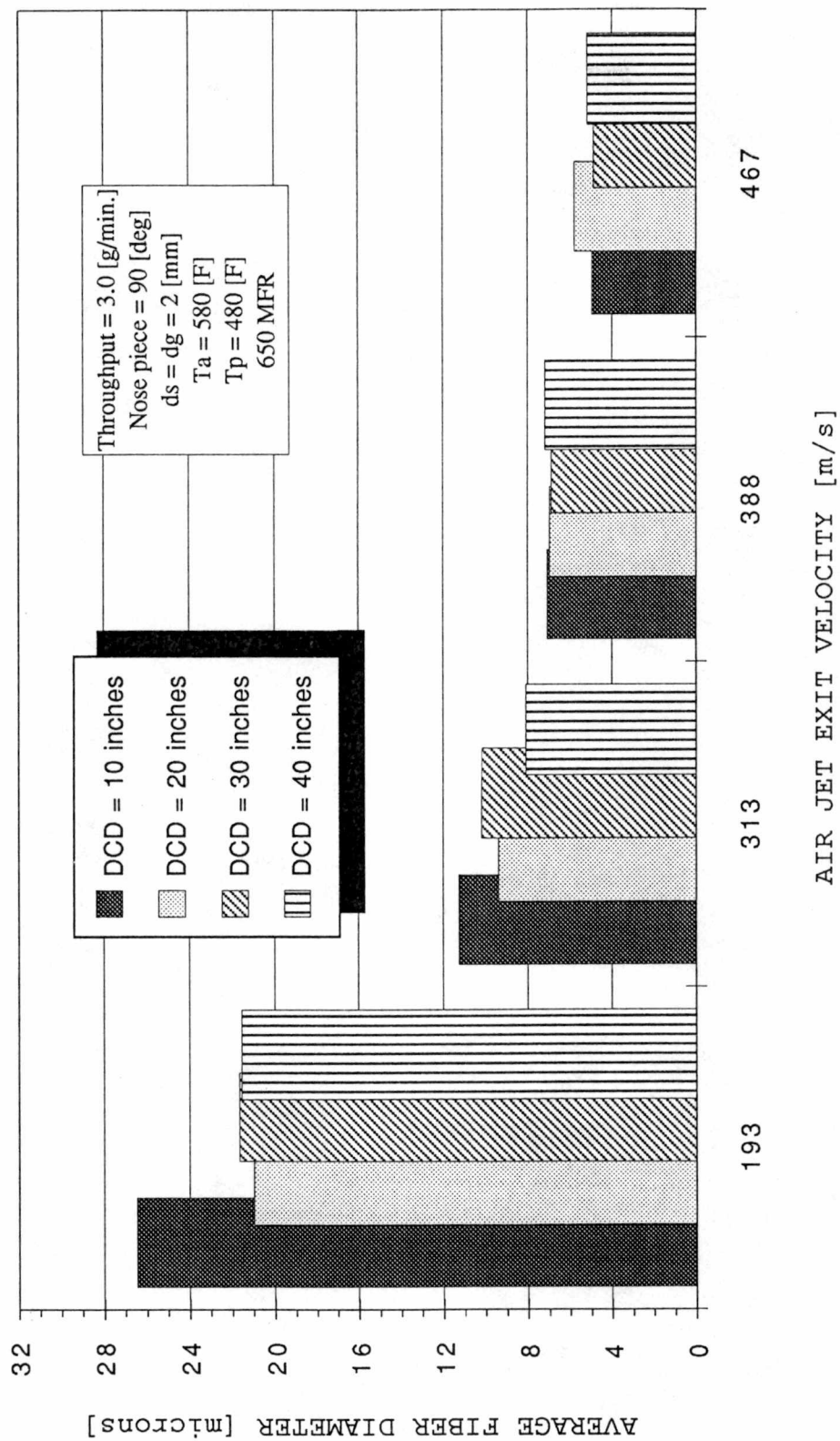


Figure 2.8: Comparison between the average fiber diameter of webs collected at several DCD's (3.0 g/min.)

Collection of Single Fibers

Figure 2.9 shows the apparatus (fork) used to collect single fiber specimens. Figure 2.10 shows the sequence of events adopted for collecting single fiber specimens. Once the desired processing conditions were established, the fork would be placed 40 inches downstream from the die face plate and just below the lower boundary of the flow field containing the fibers in flight (Figure 2.10.a). A 13 inch long single fiber specimen was collected by passing the fork in a rapid upward motion through the flow field (Figure 2.10.b). The fork was lifted until it was just above the upper flow field boundary. The upstream end of the specimen was cut first (Figure 2.10.c), and then the downstream end of the specimen was cut next (Figure 2.10.d). The risk of stretching the fiber during this step was reduced significantly by cutting the specimen in this particular order.

The specimen was then carefully transferred into a transparent film as shown in Figure 2.11. The single fiber specimen was placed over the transparent film and the extremes of the specimen were taped to the film (Figure 2.11.a). The outboard extremes of the specimen were then cut to free it from the fork (Figure 2.11.b). The film containing the specimen was placed over a scaled piece of paper which had a grid of 1 inch markings. The specimen was

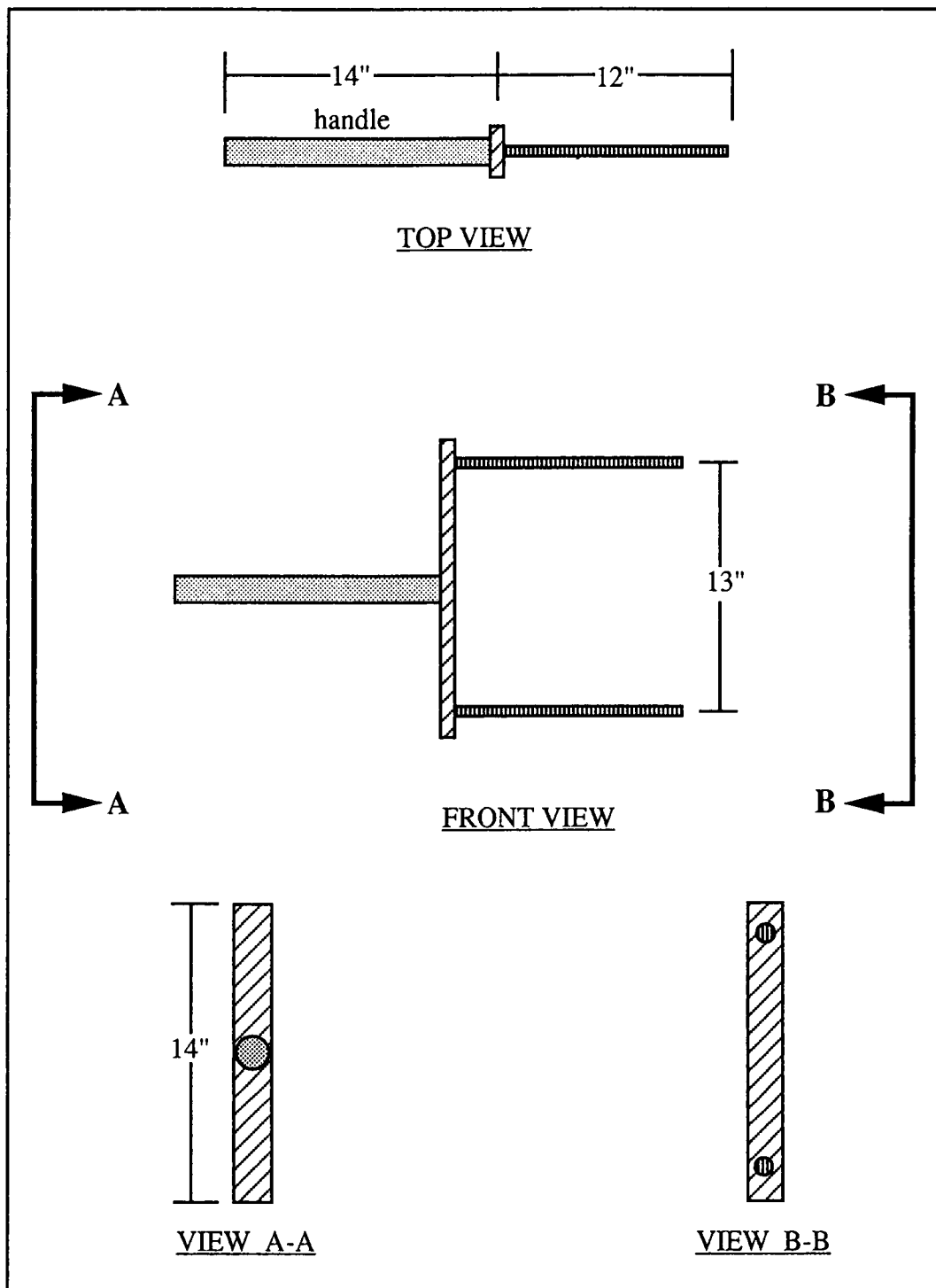


Figure 2.9: Apparatus (fork) used to collect single fiber specimens

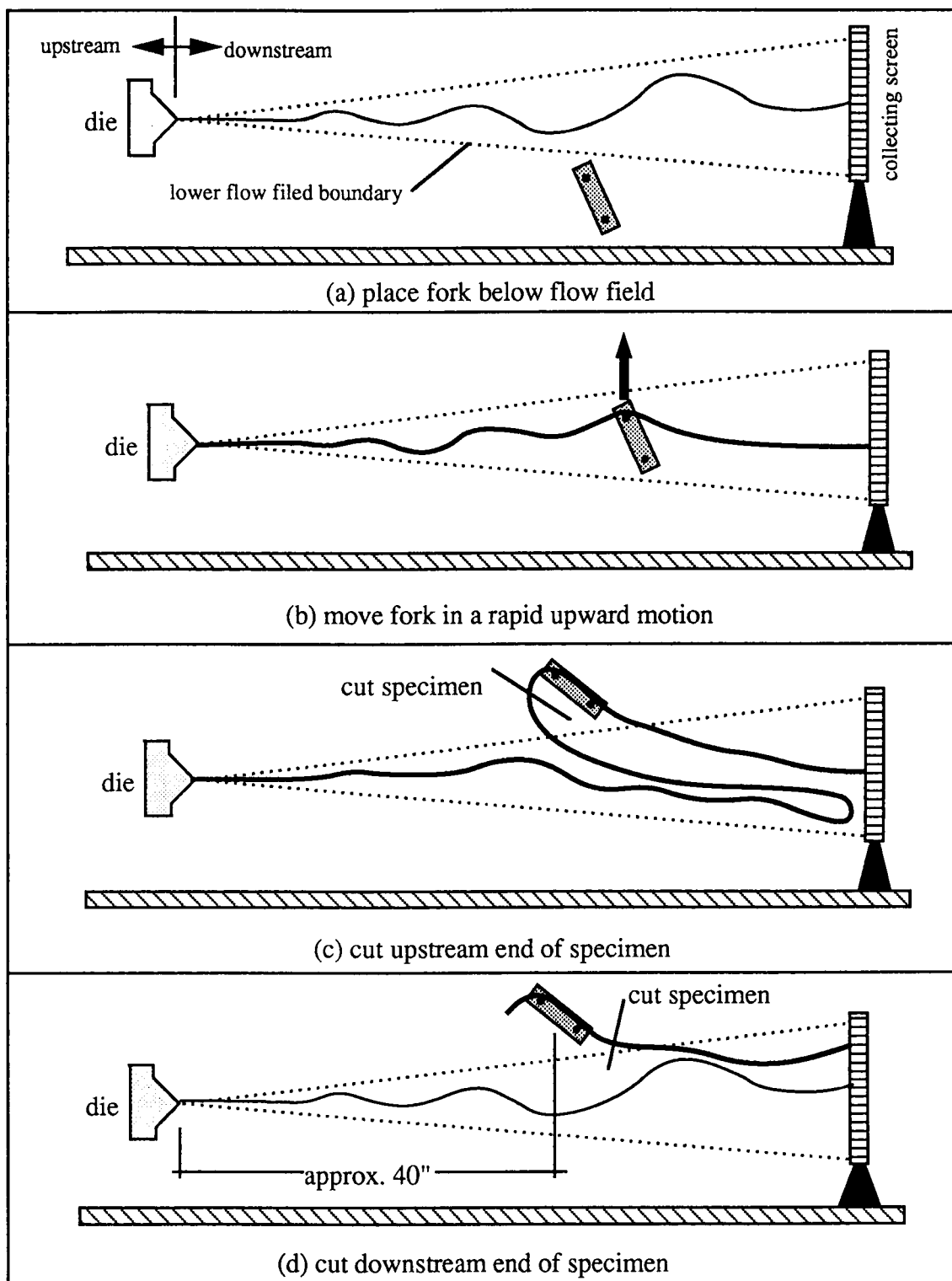


Figure 2.10: Sequence of events adopted for collecting single fiber specimens

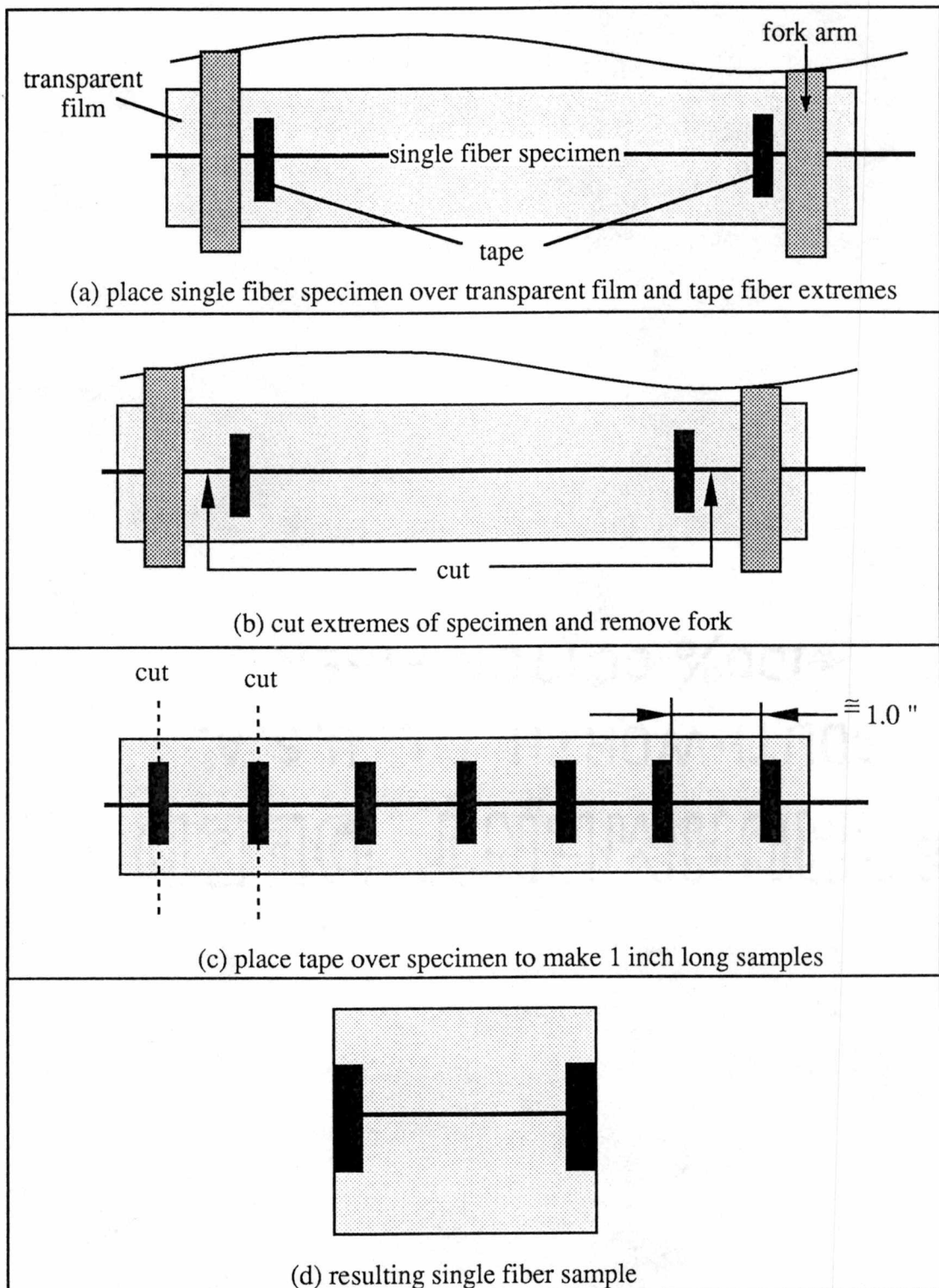


Figure 2.11: Transfer of single fiber specimens from fork to transparent film

taped to the film at several locations thus producing 6 to 7 single fiber samples (Figure 2.11.c). The transparent film was then cut through the taped areas resulting in 6 to 7 samples similar to the one shown in Figure 2.11.d.

Each one of the 6 to 7 samples were then placed under the optical microscope and the diameter at three locations were measured and recorded. Furthermore, each sample was scanned under the microscope throughout its length to ensure it was an acceptable sample with no multiple fibers, no 'bubbles', and no other defects. Samples not meeting any of these criteria were discarded. The 'good' samples were labeled and carefully stored for further analysis.

Data Reduction

After the specimens were collected as described in the previous sections, they were tested to determine their physical and mechanical properties. The physical properties tests were limited to the measurement of the diameter of the fiber, which is one the most important properties of the specimens. The process and equipment used in conducting these measurements is presented in the next section. Two other instruments, an Interference Microscope and an Instron Tensile Tester, were used to determine specific physical properties of single fiber samples. The subsequent sections

describe the procedures used in conducting these tests and the equipment used.

Optical Microscope

A one square inch section of the web was cut and placed under the microscope. An Olympus optical microscope which had a scaled eye piece was used to measure the diameter of several individual fibers. Three arbitrary locations of the sample were chosen as reference points to perform these measurements. At each location, 8 to 15 individual fibers were identified and the diameter of each fiber was recorded in a data sheet like the one shown in Figure 2.12. A sketch of each fiber was drawn and labeled in the data sheet so that the same fiber would not be measured twice. A computer program developed by Haynes [13] was used to perform the statistical analysis of the data. Average fiber diameter, standard deviation, and diameter count (histogram) were the statistical parameters determined by the program. An output of this program is shown in Figure 2.13.

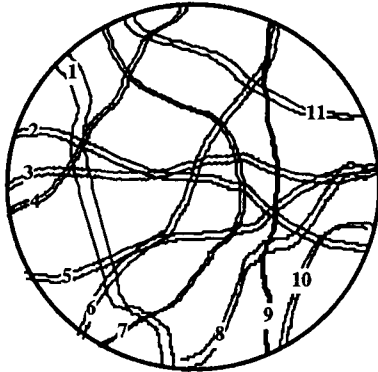
Interference Microscope

The measured birefringence is an indicator of molecular orientation in the fiber. It is a dimensionless parameter that is related to the strength of the fiber. The

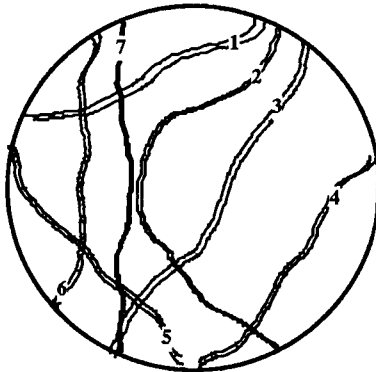
INITIALS: EGS
 DATE: 07-29-91

Sample Number

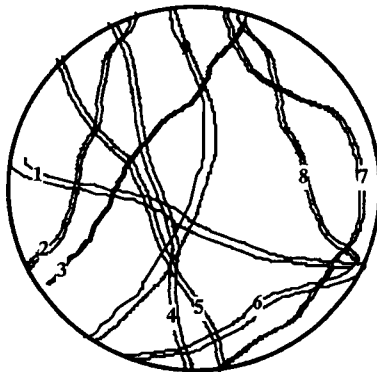
072391-01



1: 4.0
 2: 3.0
 3: 1.75
 4: 2.0
 5: 3.0
 6: 1.0
 7: 1.5
 8: 1.5
 9: 1.0
 10: 1.0
 11: 2.0



1: 2.25
 2: 1.0
 3: 1.75
 4: 2.0
 5: 3.25
 6: 1.0
 7: 2.5
 8:
 9:
 10:
 11:



1: 1.75
 2: 3.0
 3: 3.0
 4: 1.75
 5: 2.75
 6: 2.75
 7: 2.0
 8: 2.75
 9: 2.25
 10:
 11:

Edmund G. Spencer 7-29-91

Figure 2.12: Data sheet used to keep records of fiber diameter measurements

DATE : 11/19/91
 SAMPLE : 09279113
 PERFORMED BY : SPH
 OPTICAL CORRECTION FACTOR : 2.5

MEASUREMENT [divisions]	DIAMETER [microns]
3.50	8.750
2.25	5.625
2.25	5.625
1.75	4.375
2.75	6.875
2.50	6.250
2.50	6.250
2.25	5.625
2.50	6.250
3.75	9.375
2.50	6.250
2.25	5.625
2.50	6.250
2.25	5.625
1.50	3.750
2.75	6.875
2.25	5.625
2.25	5.625
2.00	5.000
2.50	6.250
2.75	6.875
2.50	6.250
3.25	8.125
2.00	5.000
2.25	5.625
2.50	6.250
1.75	4.375
1.75	4.375
1.75	4.375
2.25	5.625
4.00	10.000
6.00	15.000
7.75	19.375

NUMBER OF POINTS = 33
 NUMERICAL AVERAGE = 6.761
 WEIGHTED AVERAGE = 8.114
 STANDARD DEVIATION = 3.072

DIVISION	FREQUENCY
0.00 - 2.00	0
2.00 - 4.00	1
4.00 - 6.00	15
6.00 - 8.00	11
8.00 - 10.00	4
10.00 - 12.00	1
12.00 - 14.00	0
14.00 - 16.00	1
16.00 - 18.00	0
18.00 - 20.00	1
20.00 - 22.00	0
22.00 - 24.00	0
24.00 - 26.00	0
26.00 - 28.00	0

Figure 2.13: Output from computer program used to perform statistical analyses of optical microscope data

birefringence of approximately 80 single fiber samples were measured using a Zeiss polarizing microscope equipped with a Berek Compensator. The Compensator was used to determine the phase difference between two perpendicular polarized-light waves emerging from the sample. The phase difference (λ) was determined by first rotating the Compensator knob clockwise until the fiber was seen through the eye piece as a dark spot. The knob reading was recorded. The knob was then rotated counter-clockwise, past the zero point, until the fiber again was seen as a dark spot. This knob reading was also recorded. The sum of these two numbers (knob readings) was used to find the corresponding phase difference from tabulated results provided by the Compensator manufacturer. The birefringence was then calculated using the following expression:

$$\text{birefringence} = \frac{\lambda}{d} \qquad 1.2$$

where: λ is the phase difference in microns
 d is the single fiber diameter in microns

Instron Tensile Tester

The Instron Tensile Tester measures the force required to break a single fiber sample and the elongation of the fiber before it breaks. This information is recorded in a running-pen plotter.

Both ends of the single fiber are clipped to the tester. One end of the fiber is clipped to a stationary clip which is attached to a load cell. The other end of the fiber is clipped to a moving clip which is moved by the machine. The load cell measures the pulling force being exerted on the fiber until the fiber breaks. The rate at which the fibers are pulled is controlled by the operator. This is obviously a destructive test, and after the fibers were pulled and torn they were thrown away.

Figure 2.14 shows the process involved in preparing the single fiber samples for the tensile strength test. After the samples were collected and examined under the microscope, a window was cut around the sample (Figure 2.14.a). The sides of the transparent film that run parallel to the single fiber serve as a structural frame which prevents the researcher from stretching the fiber before the sample is mounted. The samples were then carefully mounted on the clips (Figure 2.14.b), ensuring that the fiber was in a straight line. The sides of the transparent film were then

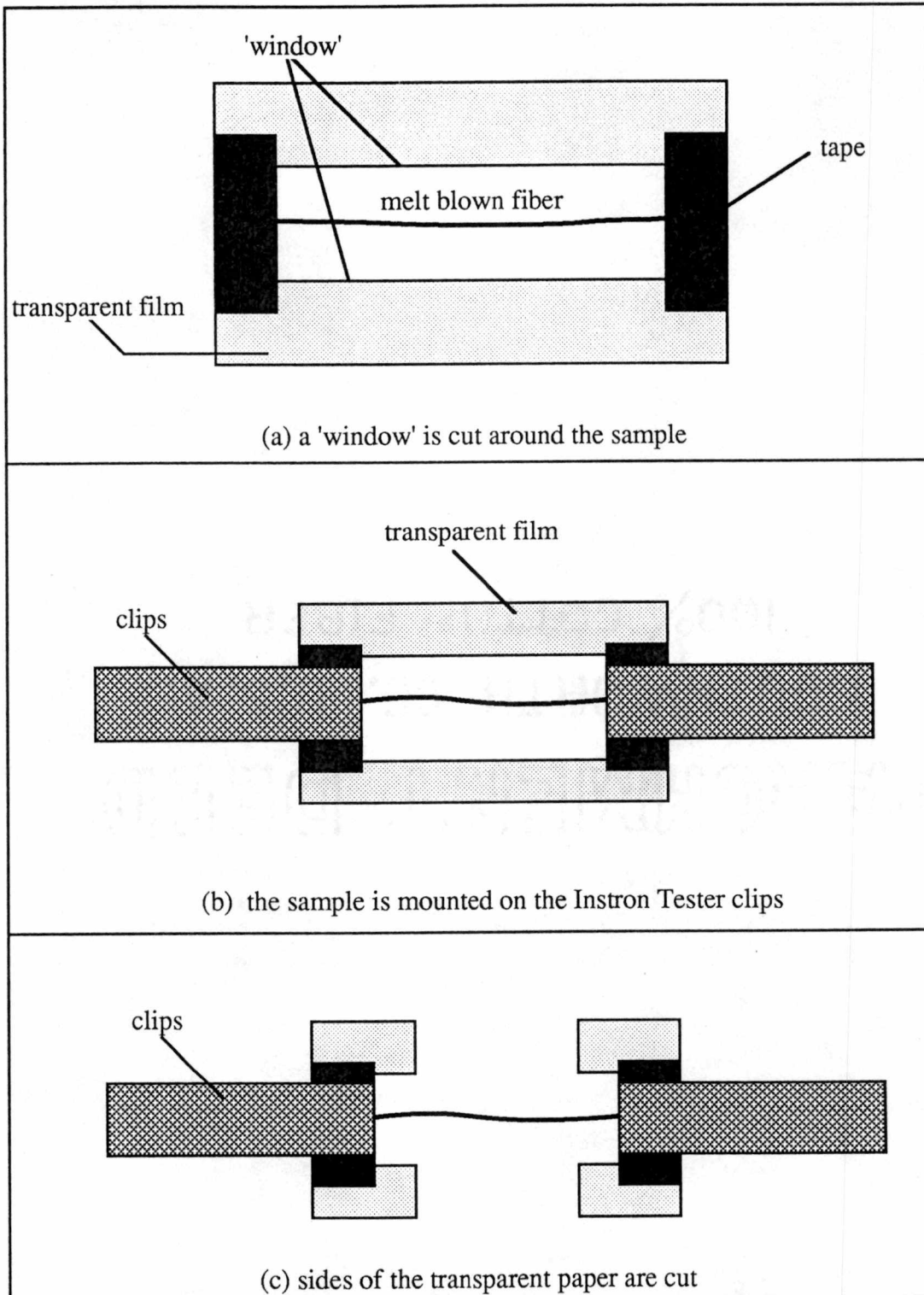


Figure 2.14: Process for preparing the single fiber samples for the tensile strength test

cut (Figure 2.14.c), leaving the single fiber free from the frame and ready to be pulled.

Care was taken at all times to prevent pulling the samples before the test was started, specially while cutting around the windows on the transparent paper and while mounting the samples into the clips.

Reproducibility of Experimental Results

A study was performed in order to determine if the same average fiber diameter could be reproduced under the same processing conditions, but on different occasions. Two experiments, each a few days apart, were conducted at the same processing conditions: primary air temperature (580 F), polymer temperature (470 F), polymer throughput (0.8 g/min.), and die geometry ($d_s = d_g = 2 \text{ mm}$). Samples were collected at these processing conditions for three exit air velocities. Figure 2.15 shows the average fiber diameter of the samples collected at different dates versus exit air velocity. The maximum difference in average fiber diameter is only 0.7 microns. Thus, the results of this study show that the average fiber diameter of a sample can be reproduced if the same processing conditions exist.

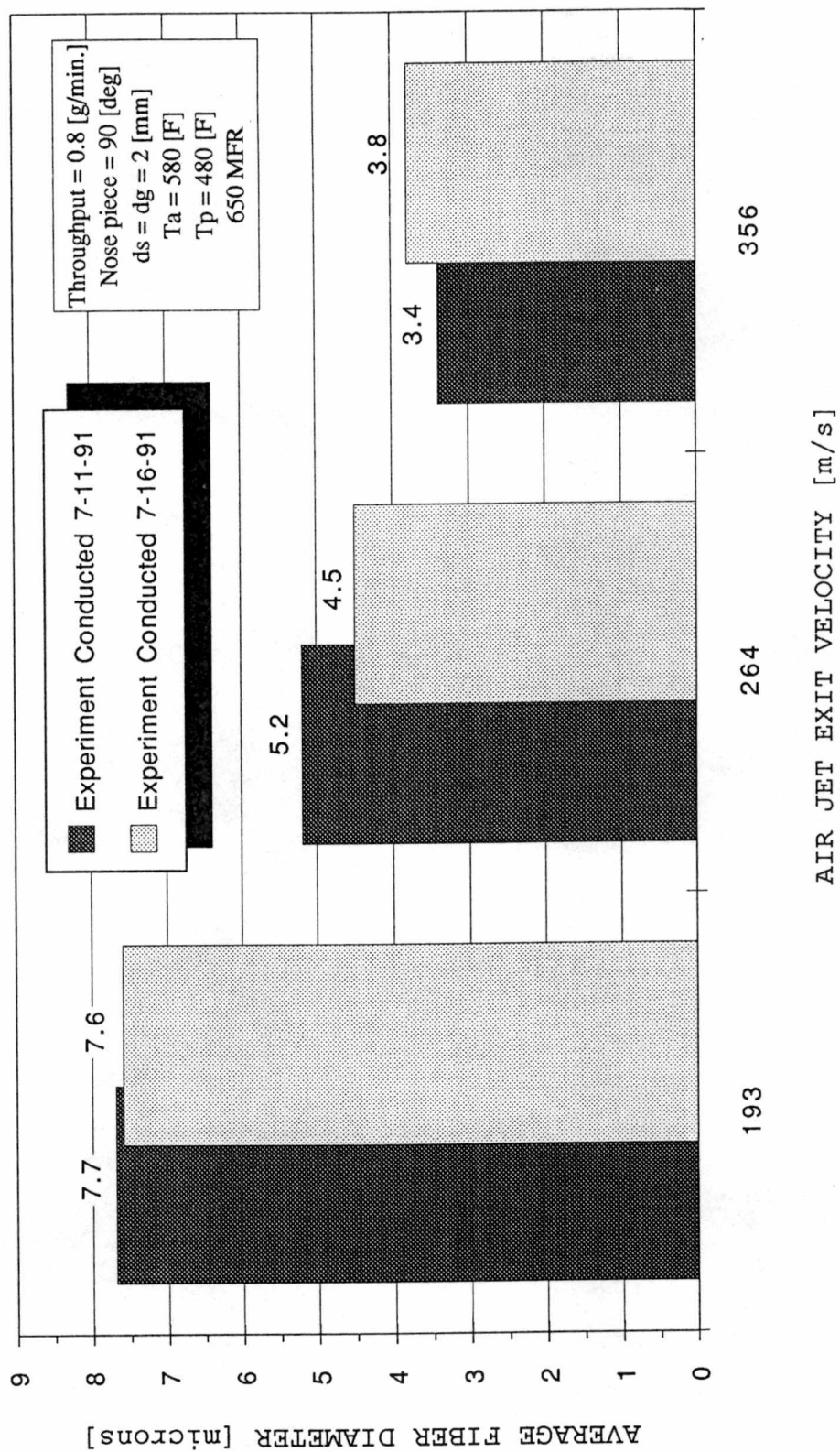


Figure 2.15: Average fiber diameter of samples collected at different dates

CHAPTER III

EXPERIMENTAL RESULTS AND DISCUSSION

This chapter presents and discusses the experimental results obtained during this research. The first sections present the effect that the processing conditions have on the diameter of the web specimens collected. Air jet exit velocity, die geometry (air gap, setback, and air jet injection angle), polymer throughput, polymer temperature, and air temperature are the processing conditions (independent variables) that were investigated. Results from the study of the effect that processing conditions have on the mechanical and physical properties of single fibers are presented in the last section.

A large number of samples were collected throughout this investigation. A total of 359 web samples and 131 single fiber specimens were collected. All of these samples were produced using a 650 MFR white polypropylene. The majority of the samples were collected at different processing conditions, while a few samples were collected at the same processing conditions to establish the reproducibility of these experiments (see Chapter II).

Figure 3.1 shows a test matrix of the different processing conditions at which the web samples were

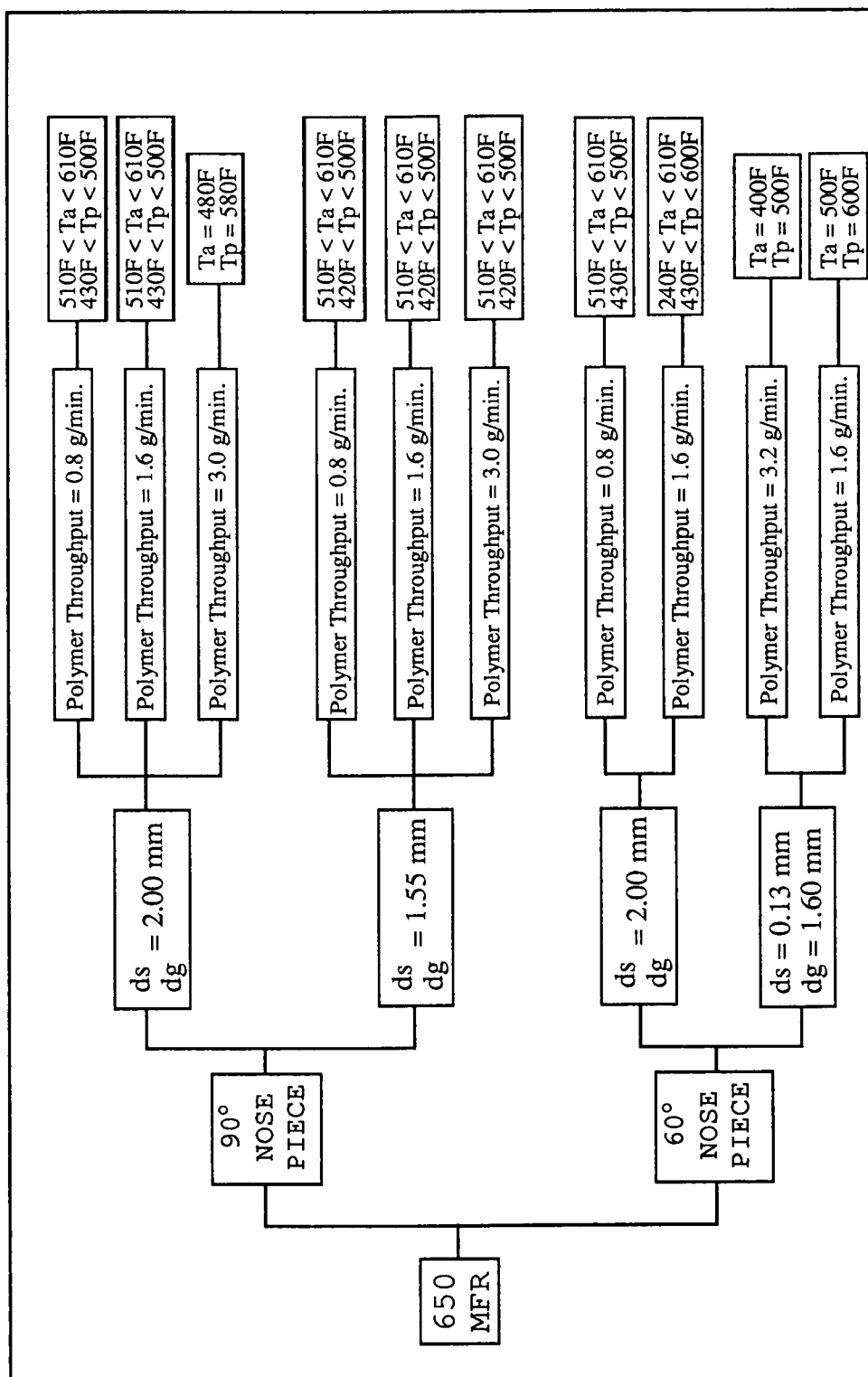


Figure 3.1: Test matrix of the processing conditions at which the web samples were collected

collected. Table 3.1 shows a full description of the processing conditions at which the experiments were conducted. Each experiment is identified by a "Case ID" number which will be referenced to throughout this chapter. All of the experimental variables that were measured during each experiment are listed in Appendix C. These measured experimental variables are used throughout this and the next chapter to determine other important parameters that characterize the melt blowing process.

Figure 3.2 shows a test matrix of the different processing conditions at which the single fiber specimens were collected. Each single fiber specimen was collected at a different exit air velocity during the same experiment. The "Number of Samples" shown in Figure 3.2 indicates the total number of samples that were made out of all of the specimens collected in that experiment (see Collection of Single Fibers, Chapter II).

The derivation of the equations used to calculate the air jet exit area and the air jet exit velocity can be found in Appendices D and E, respectively.

Air Jet Exit Velocity

The velocity at which the air jet exits the test section is considered to be the processing variable that has the strongest effect on the average fiber diameter of the

Table 3.1: Description of the processing conditions
at which the experiments were conducted.

CASE ID	Nose Piece [degrees]	Air gap (dg) Setback (ds) [mm]	Throughput [g/min.]	Tpolymer [F]	Tair [F]	Air Jet Exit Velocity [m/s]	Number of data points
2	90	2.00	1.6	430	510	178 < Ve < 437	8
3			0.8	430	510	177 < Ve < 440	8
4			0.8	430	510	244 < Ve < 363	6
5			0.5	430	510	179 < Ve < 443	8
6			0.8	480	580	192 < Ve < 447	4
7			1.6	480	580	192 < Ve < 445	4
8			0.8	480	580	162 < Ve < 389	6
9			1.6	500	610	199 < Ve < 459	4
10			0.8	500	610	199 < Ve < 460	4
11			0.8	500	610	272 < Ve < 402	6
12			0.8	466	580	Ve = 191	4
13			0.8	480	580	Ve = 260	4
14			0.8	480	580	Ve = 350	4
15			0.8	470	580	Ve = 191	6
16			0.8	480	580	Ve = 261	6
17			0.8	480	580	Ve=350	6
18			0.8	485	580	190 < Ve < 464	16
19			1.6	475	580	191 < Ve < 467	16
20			3.0	480	580	191 < Ve < 463	16
21		1.55	0.8	420	510	160 < Ve < 409	6
22			1.6	420	510	161 < Ve < 407	6
23			3.0	420	510	161 < Ve < 409	6
24			0.8	470	580	172 < Ve < 410	5
25			1.6	470	580	173 < Ve < 421	6
26			3.0	470	580	169 < Ve < 417	6
27			0.8	500	610	175 < Ve < 413	5
28			1.6	500	610	177 < Ve < 429	6
29			3.0	500	610	177 < Ve < 425	6
30	60	2.00	0.8	430	510	98 < Ve < 381	7
31			1.6	430	510	98 < Ve < 408	7
32			0.8	470	570	103 < Ve < 400	7
33			1.6	470	570	103 < Ve < 402	7
34			0.8	500	610	107 < Ve < 313	6
35			1.6	500	610	107 < Ve < 381	7
36			1.6	500	330	112 < Ve < 319	7
37			1.6	500	400	122 < Ve < 345	7
38			1.6	500	510	136 < Ve < 382	7
39			1.6	550	400	87 < Ve < 312	9
40			1.6	550	510	98 < Ve < 347	9
41			1.6	600	510	98 < Ve < 348	9
42			1.6	550	320	80 < Ve < 288	9
43			1.6	500	240	71 < Ve < 258	9
44			1.6	600	370	84 < Ve < 303	9
45			1.6	600	400	87 < Ve < 313	9
46			1.6	500	460	92 < Ve < 329	9
47			1.6	550	460	93 < Ve < 331	9
48			1.6	600	460	93 < Ve < 333	9
49		ds=0.13	3.2	500	400	193 < Ve < 378	10
50		dg=0.25	1.6	600	500	215 < Ve < 389	9

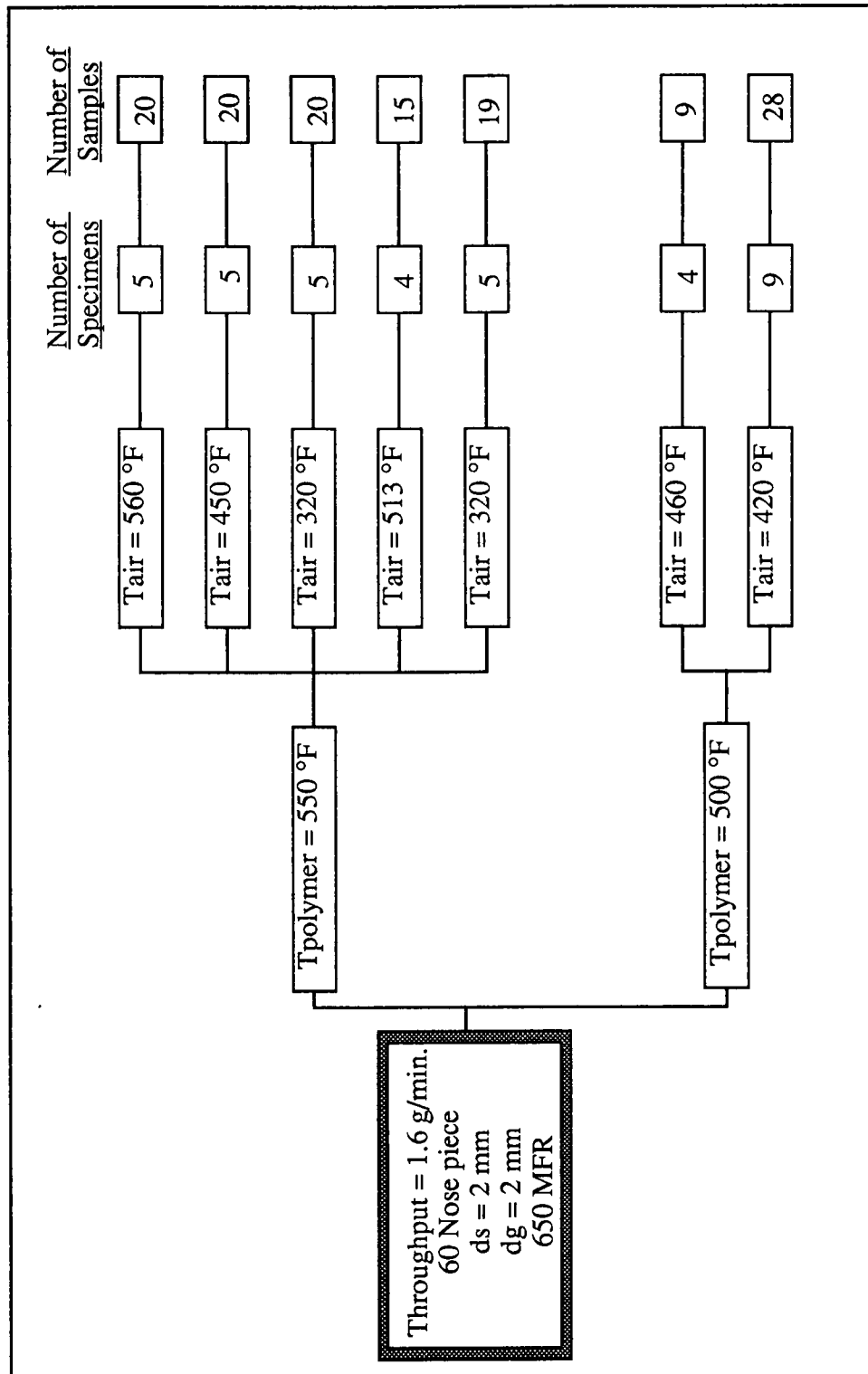


Figure 3.2: Test matrix of the processing conditions at which the single fiber specimens were collected

webs produced in the melt blowing process [11,13]. The average fiber diameter of a web varies significantly for a given range of exit air velocities. To verify this effect, web samples were collected at exit air velocities as low as 71 m/sec and as high as 467 m/sec while keeping all other processing conditions constant. This approach was repeated at several combinations of processing conditions (see Table 3.1). The expression used to determine the air exit velocity, which is derived in Appendix E (Equation E.8), is given by:

$$V_e = \frac{\dot{m}_a R T_{ao}}{A_e p} \left[\frac{p}{p_o} \right]^{\left(\frac{\gamma-1}{\gamma} \right)} \quad 3.1$$

where:

$\dot{m}_a$ air flow rate (Appendix A)

R specific gas constant

T_{ao} ... air jet stagnation temperature at exit plane

A_e air jet exit area (Appendix D)

p static pressure at exit plane

p_o stagnation pressure at exit plane

γ specific heat ratio

Figure 3.3 shows how the average fiber diameter of a web is influenced by the air jet exit velocity for a fixed set of processing conditions (Case ID 31). Increasing the air velocity decreases the average fiber diameter in a

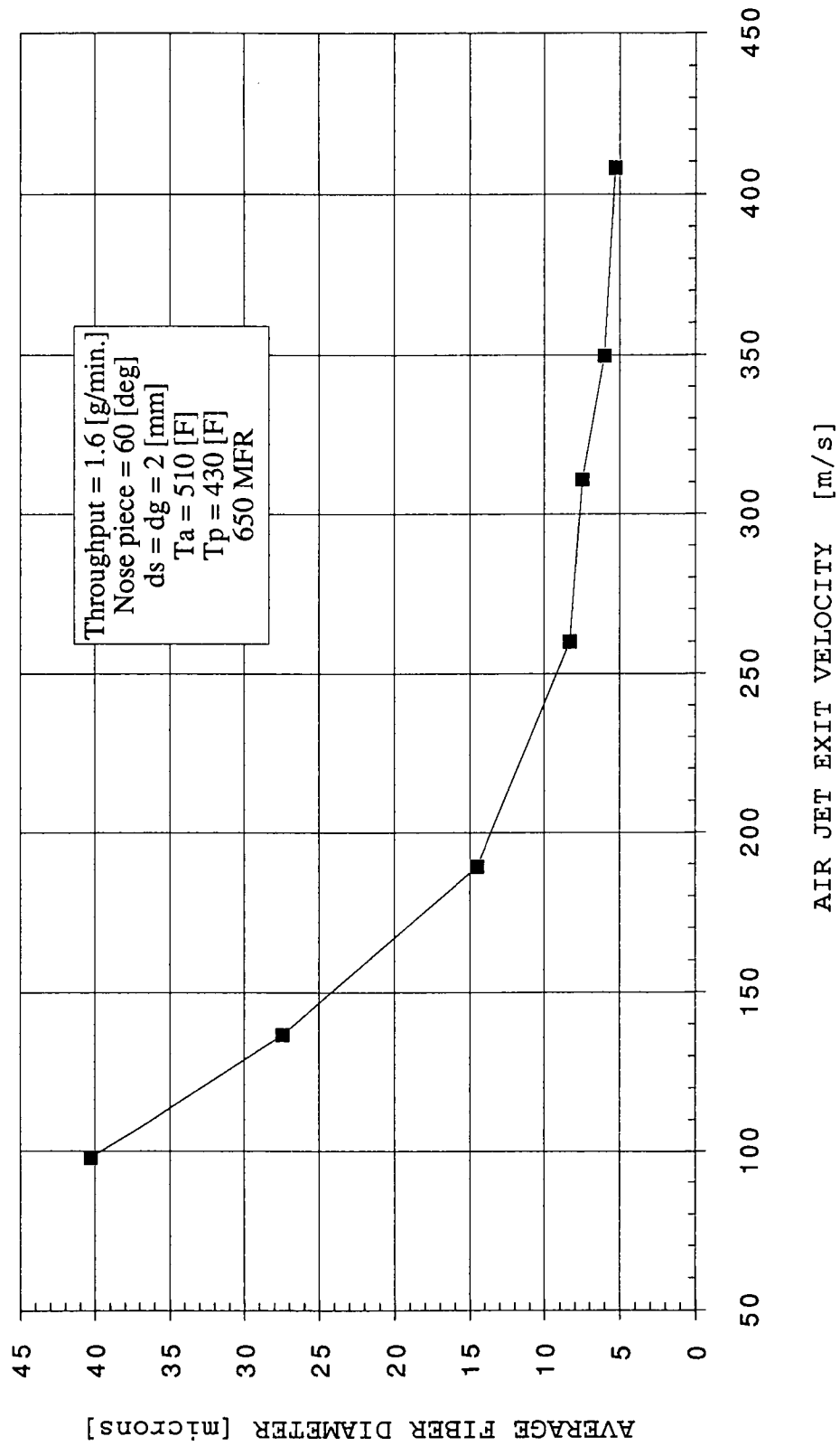


Figure 3.3: Effect of air jet exit velocity on average fiber diameter (ID 31)

nonlinear behavior. Figure 3.4 shows a comparison between the fiber diameter histograms for the samples that were collected at 98 and 408 m/sec. The distribution of the fiber diameters at the higher exit air velocities is narrower, thus making the web more uniform.

This trend of producing webs with smaller and more uniform fiber diameters at higher air jet velocities is present for all combination of processing conditions. Figures 3.5 through 3.8. show how the average fiber diameter decreases with an increase in air jet velocity, regardless of the processing conditions. The data shown in Figure 3.5 (Case ID 2) was generated under the same processing conditions that the data from Figure 3.3 (Case ID 31) was generated, with the exception that the former was processed with a 90° nose piece die. Similarly, the data from Figure 3.6 (Case ID 30) and Figure 3.3 differ only on the polymer throughput at which they were processed; 0.8 and 1.6 g/min., respectively. Also, the data from Figure 3.7 (Case ID 41) and Figure 3.3 differ only on the processing temperature of the polymer; 600°F and 430°F, respectively. Finally, none of the processing conditions at which the data from Figure 3.8 (Case ID 29) and Figure 3.3 were collected are the same.

A comparison between the fiber diameter histograms of the samples that were collected at the lowest and highest exit air velocities which are plotted in Figures 3.5, 3.6, 3.7, and 3.8 are shown in Figures 3.9, 3.10, 3.11, and 3.12,

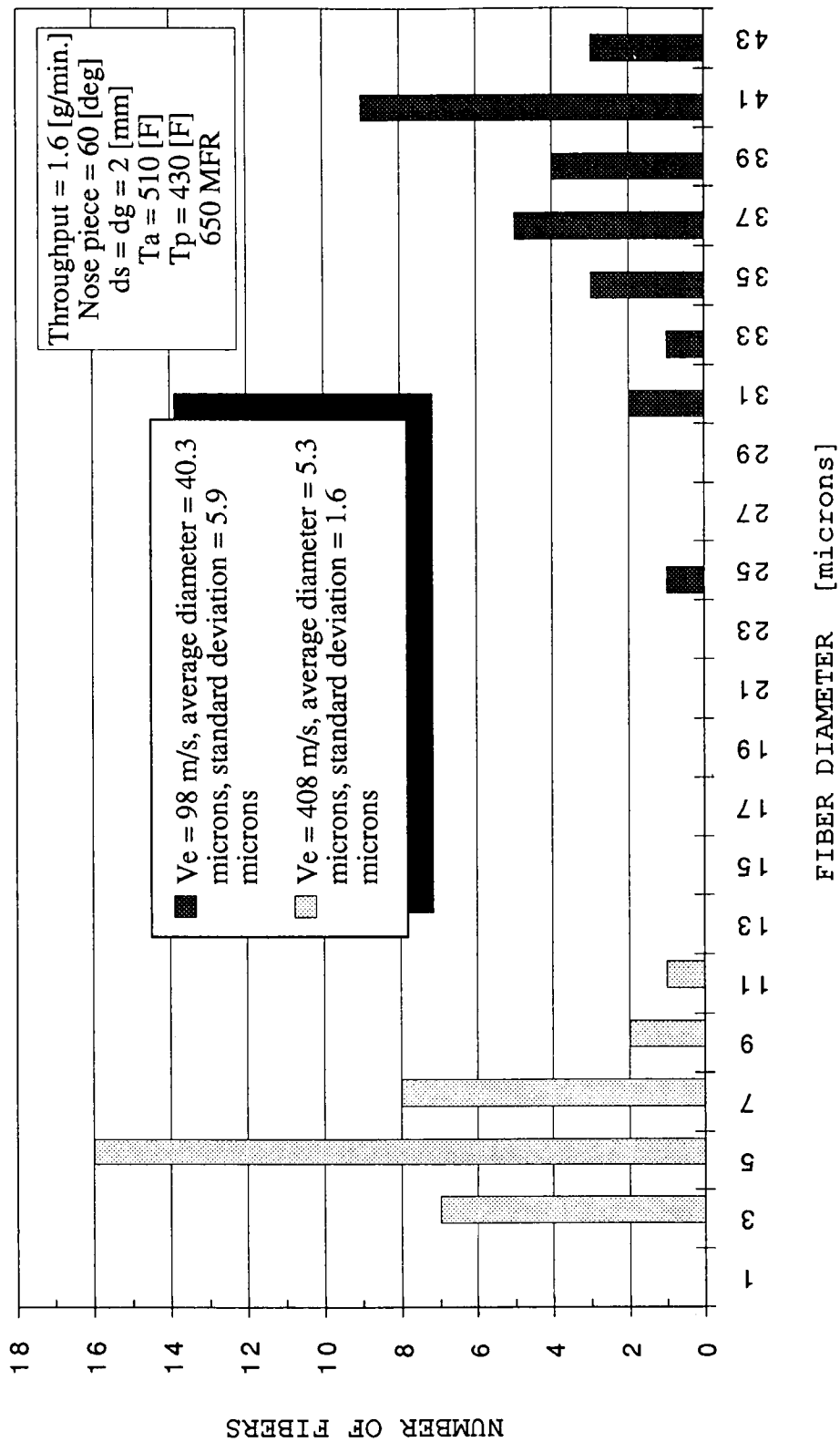


Figure 3.4: Comparison between fiber diameter histograms for samples collected at 98 and 408 m/s (ID 31)

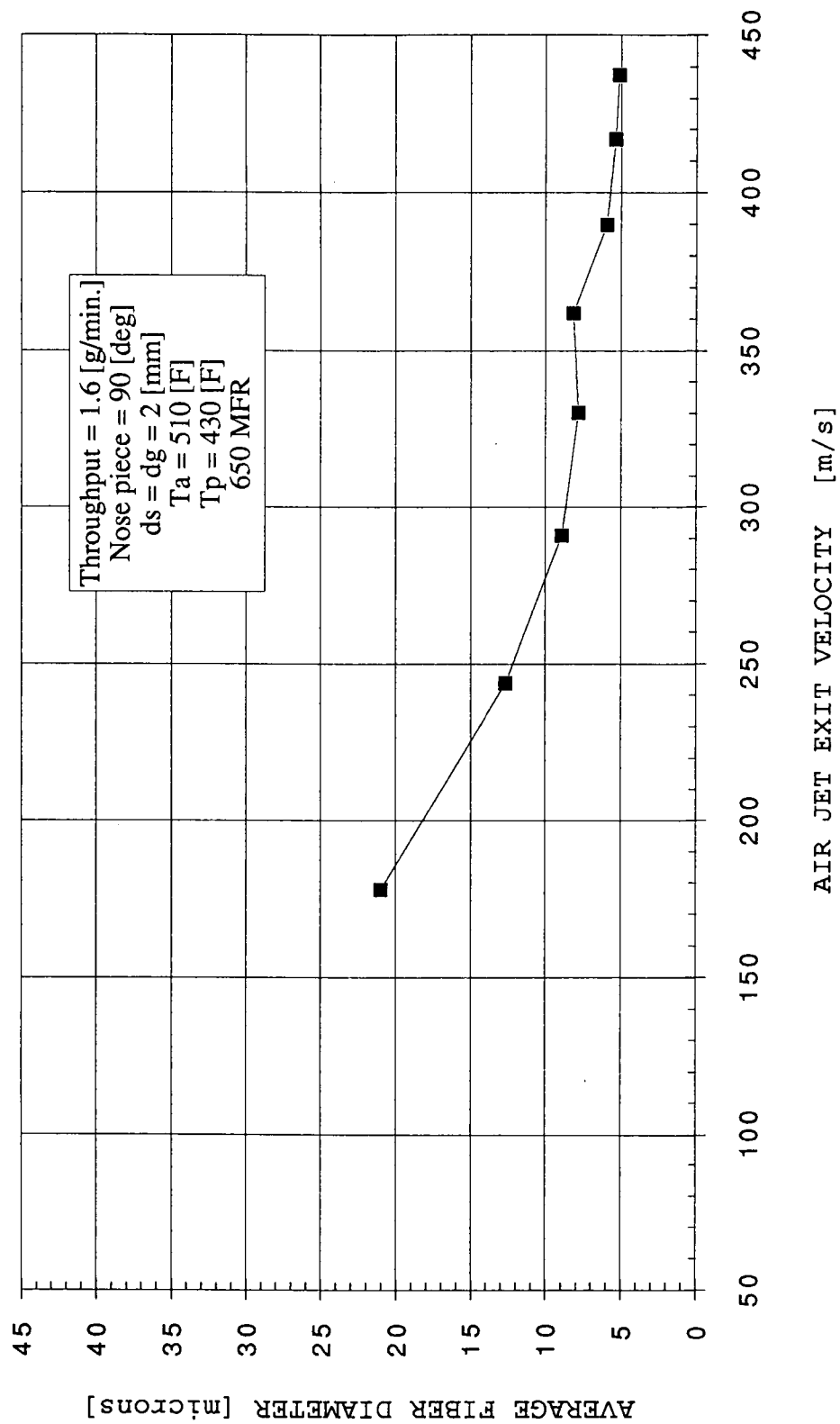


Figure 3.5: Effect of air jet exit velocity on average fiber diameter (ID 2)

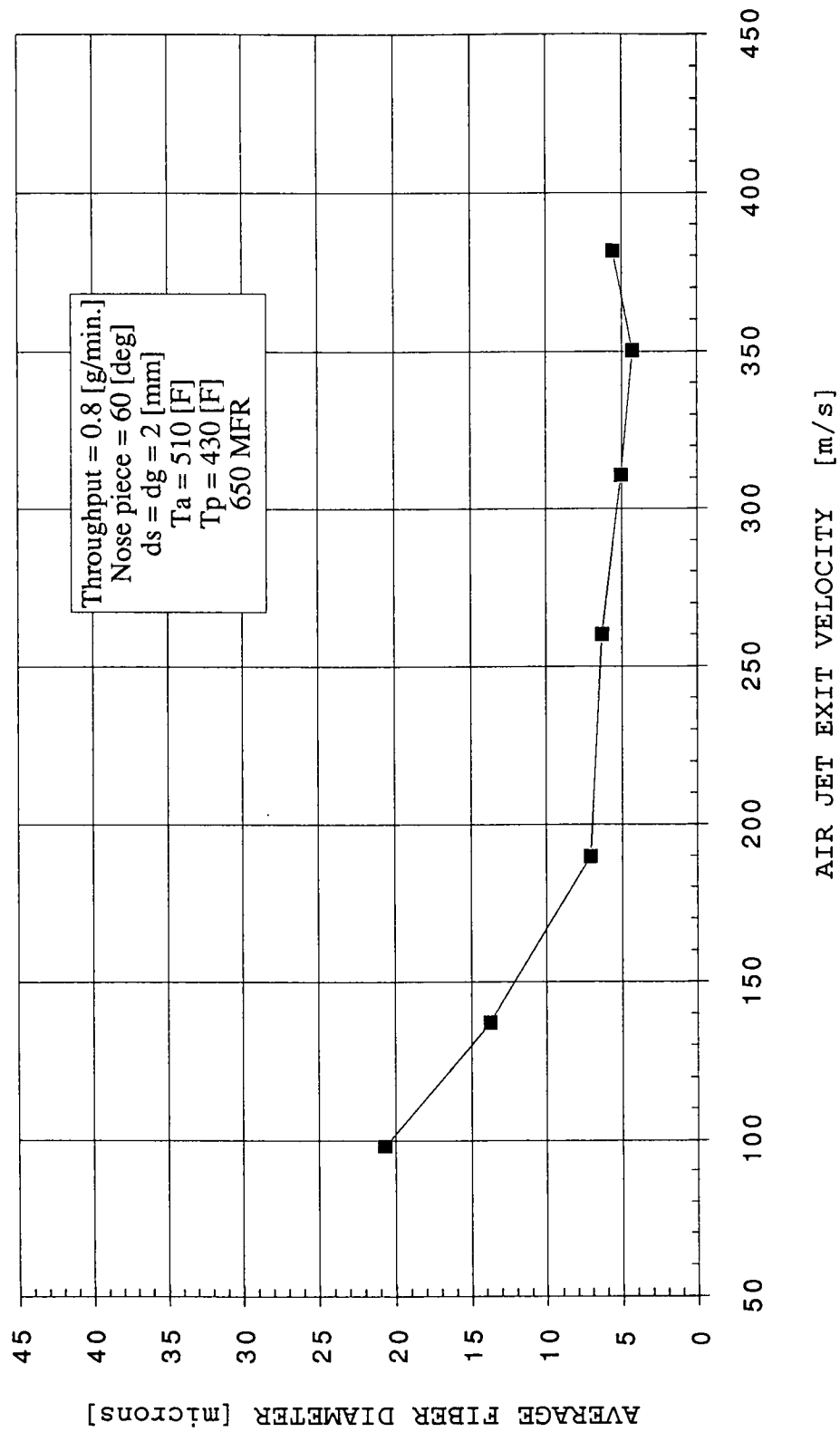


Figure 3.6: Effect of air jet exit velocity on average fiber diameter (ID 30)

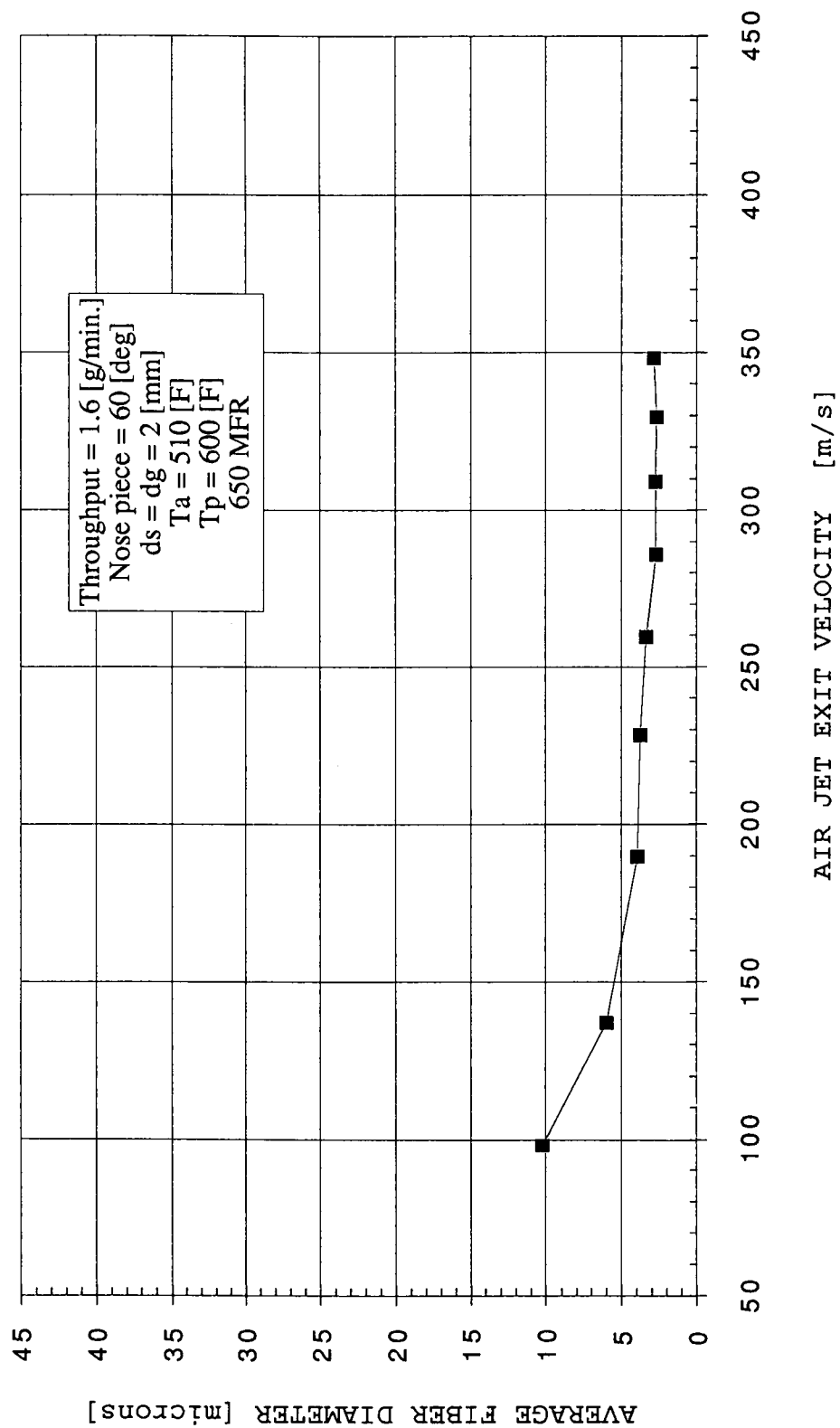


Figure 3.7: Effect of air jet exit velocity on average fiber diameter (ID 41)

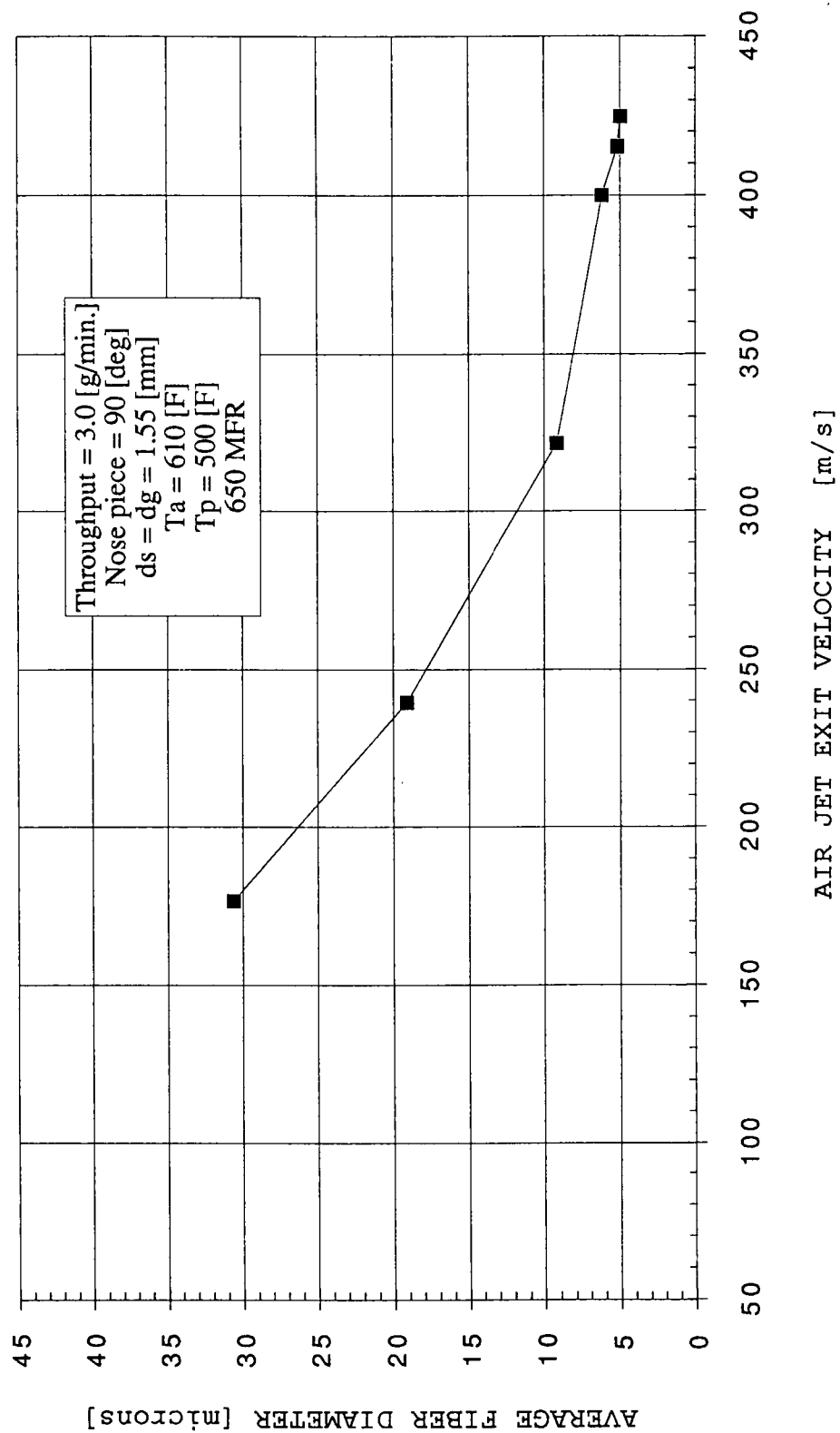


Figure 3.8: Effect of air jet exit velocity on average fiber diameter (ID 29)

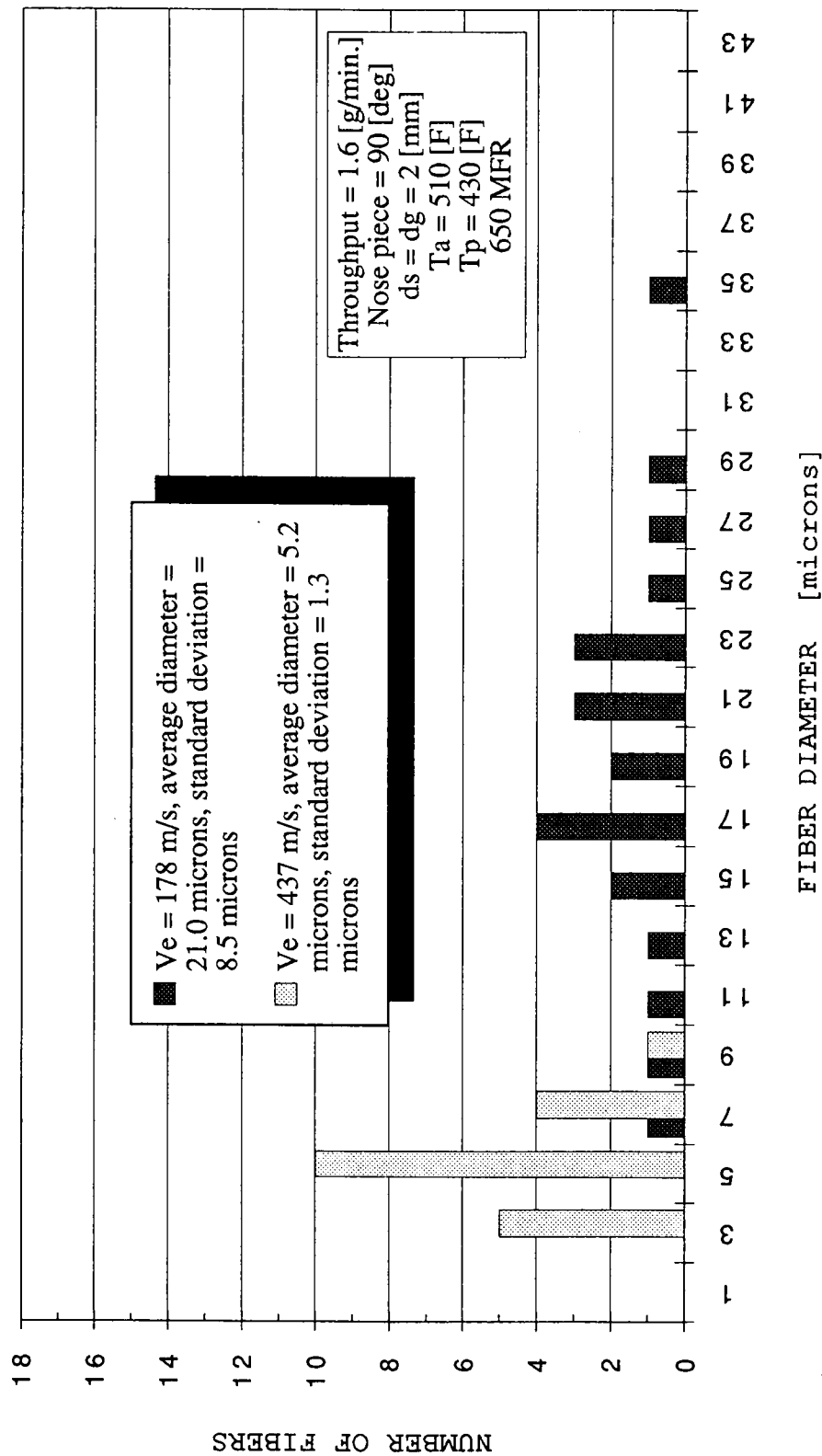


Figure 3.9: Comparison between fiber diameter histograms; samples collected at 178 and 437 m/s (ID 2)

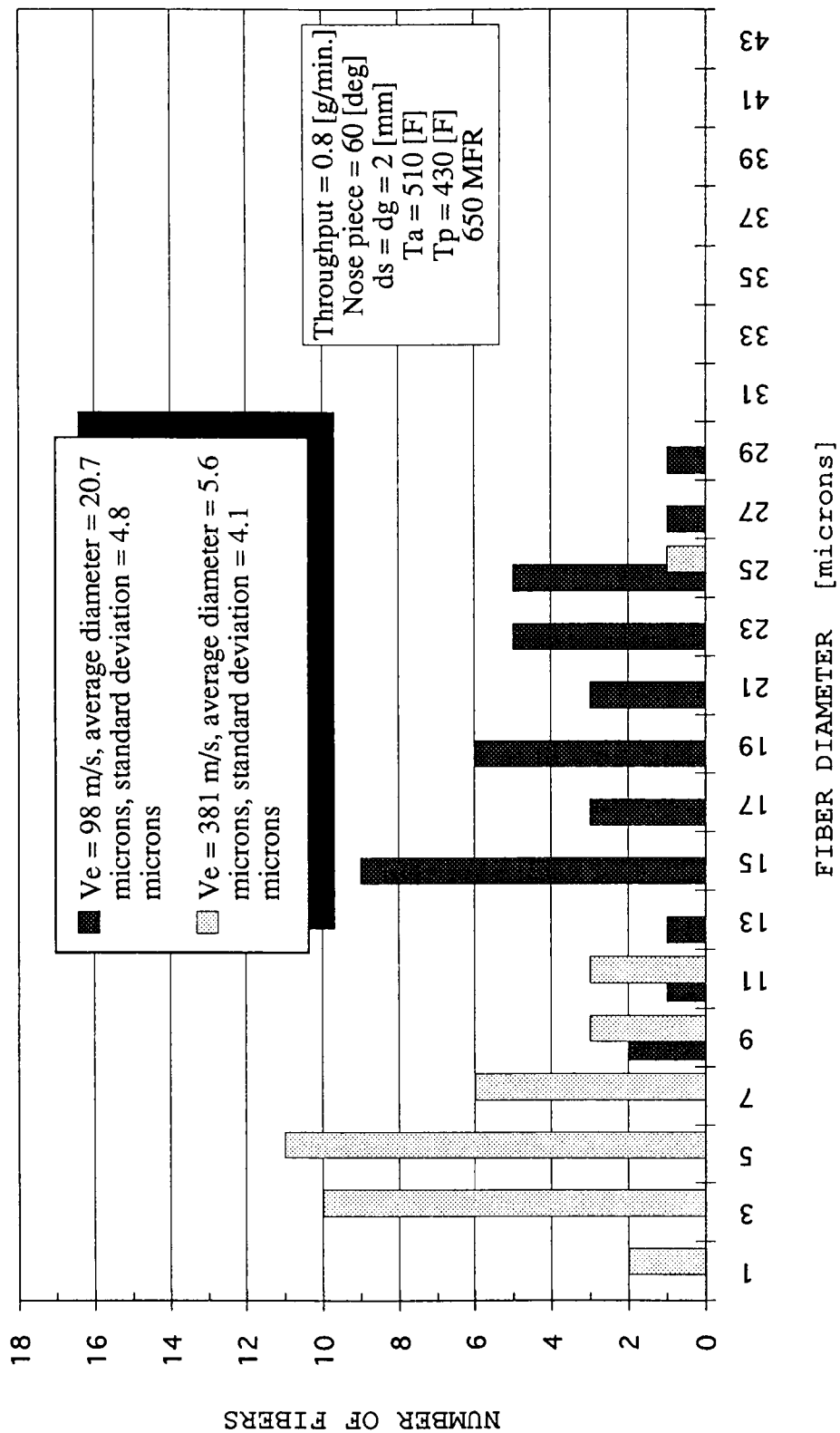


Figure 3.10: Comparison between fiber diameter histograms; samples collected at 98 and 381 m/s (ID 30)

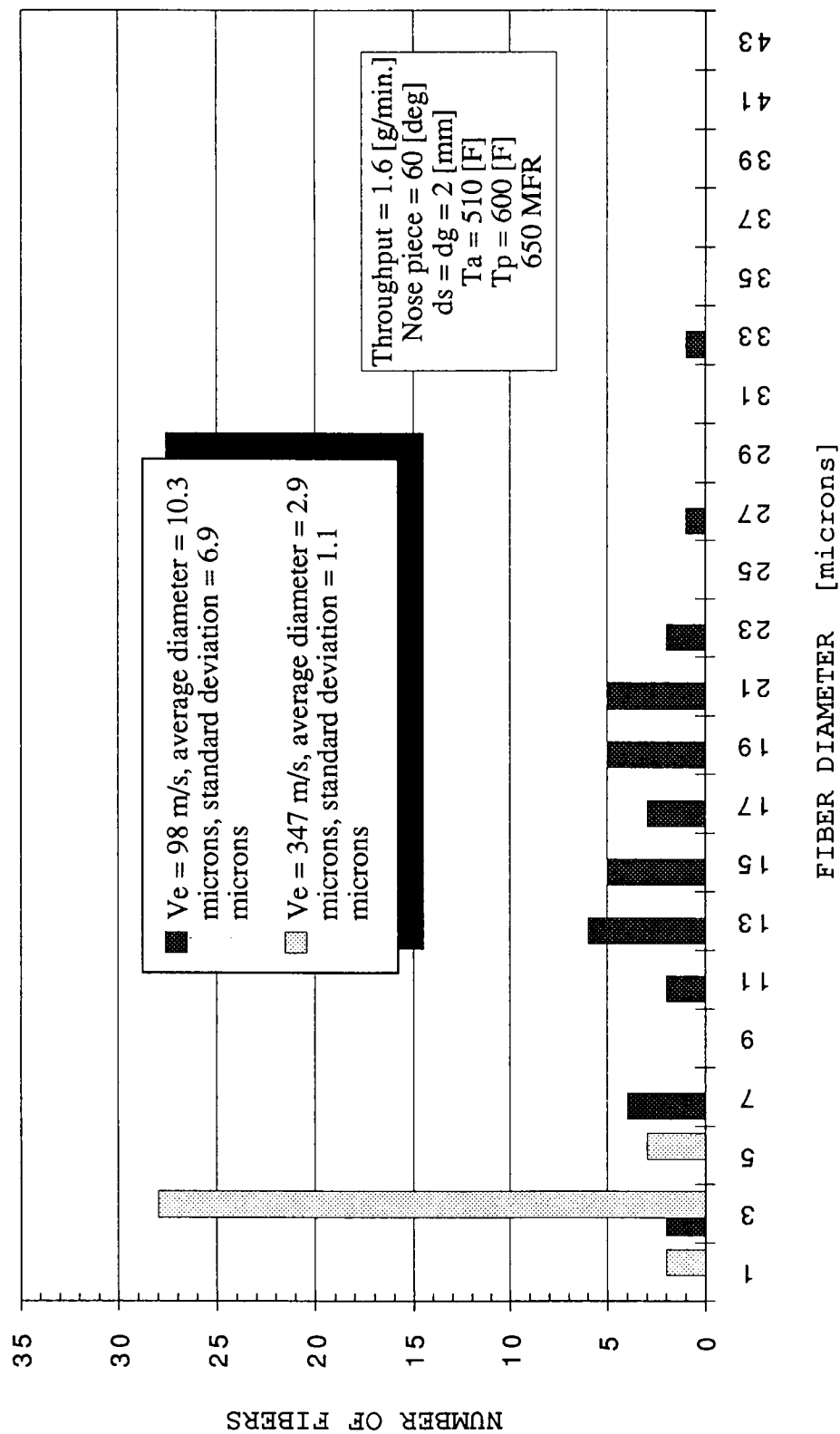


Figure 3.11: Comparison between fiber diameter histograms; samples collected at 98 and 347 m/s (ID 41)

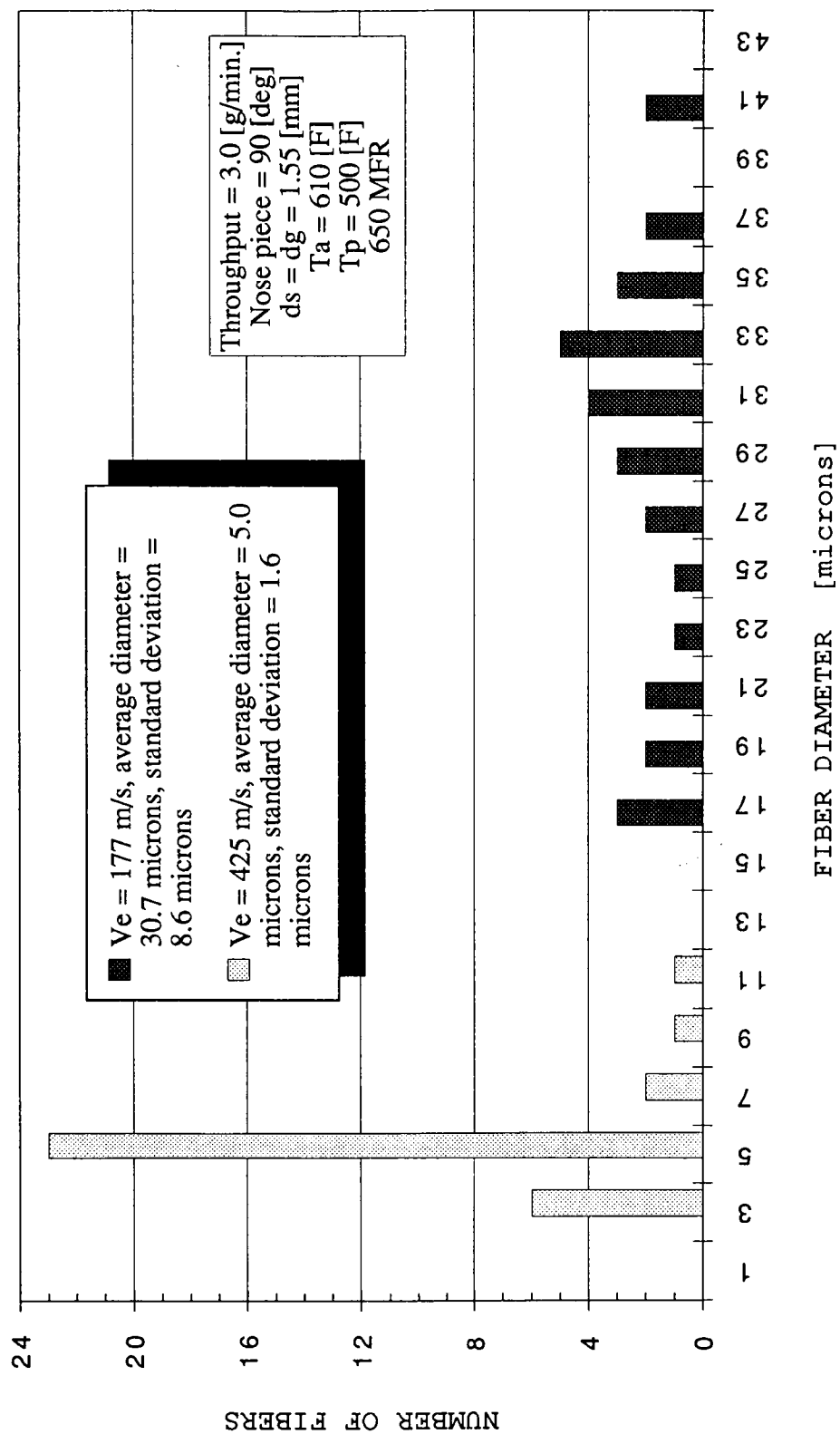


Figure 3.12: Comparison between fiber diameter histograms; samples collected at 177 and 425 m/s (ID 29)

respectively. It can be seen from these Figures that the webs have a more uniform fiber diameter distribution at the higher air jet exit velocities. Also larger average fiber diameters are consistently associated with larger standard deviations (less uniform webs) regardless of the air velocity.

These trends are consistent with the findings made by Haynes [13] who showed that by increasing the air jet exit velocity, webs with smaller and more uniform fibers are produced. Furthermore, Haynes [5] demonstrated that the drag force exerted on a flexible fiber in a melt blown flow field was a linear function the air jet momentum ($\mu_a = \rho_a V_e^2 A_e$). Therefore, reducing the air jet exit velocity (V_e) decreases the air jet momentum for a given air jet exit area (A_e) and density (ρ_e). This reduction in air jet momentum then reduces the attenuation force (drag) exerted on the fiber, thus producing webs with larger and less uniform fibers. The results presented in this section are consistent with the findings made by Haynes [13] in that for a fixed die geometry (A_e) an increase in air jet velocity (air jet momentum) decreases the average fiber diameter.

It should be noted that there appears to be no further significant reduction in average fiber diameter beyond a certain air velocity (critical velocity). This asymptotic behavior is clearly seen in Figure 3.3 and in Figures 3.5 through 3.8. This behavior could be attributed to the fact

that the cooling rate of the fibers increases with an increase in air velocity (due to convection) up to a point where the fiber will solidify and a further reduction in diameter is no longer possible. It can also be seen from these Figures (3.3, and 3.5 through 3.8) that this critical velocity varies for different processing conditions. The dependence of this critical exit velocity on the different processing conditions will be addressed in upcoming sections of this Chapter.

Die Geometry

The effect that the air gap, setback, and air jet injection angle have on the average fiber diameter will be presented in this section. The definition of the die geometry parameters are illustrated in Figure 3.13. The expression used to determine the air jet exit area, which is derived in Appendix D (Equation D.12), is given by:

$$A_e = 2.03 * 10^{-4} [d_g (\cos \theta + \sin \theta \tan \theta) - d_s \tan \theta] + d_{die} \quad 3.2$$

where:

A_e air jet exit area (m^2)

d_s setback (mm)

d_g air gap (mm)

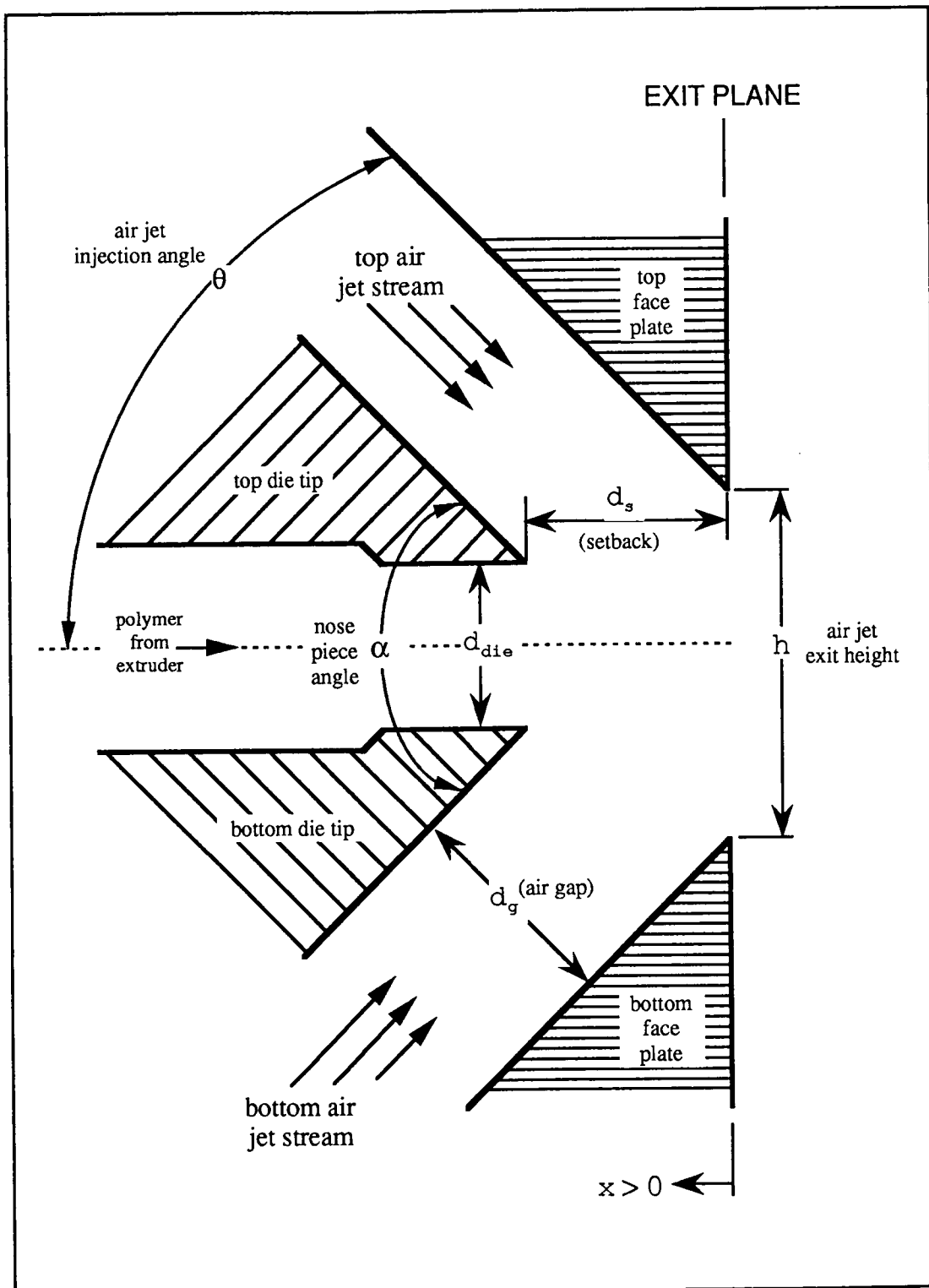


Figure 3.13: Definition of die geometry parameters

θ air jet injection angle (radians)

d_{die} ... die orifice diameter (mm)

Air gap and Setback

The data available to support this study is limited and restricted to just two different air gap and setback settings. Samples were processed by setting both the air gap and the setback to the same values: 2.00 and 1.55 mm. Haynes [13] however, conducted a more detailed study in this area by varying one of these parameters while keeping the other one constant. He concluded that for any set of processing conditions, given a constant air velocity, an increase in air gap for a constant setback produces fibers of smaller diameter. He also concluded that for a constant air velocity, a decrease in setback for a constant air gap produces fibers of smaller diameter.

By looking at Equation 3.2 it can be seen that an increase in air gap results in an increase in the air jet exit area for a constant setback and air jet injection angle. Also, a decrease in setback increases the air jet exit area for a constant air gap and injection angle. It is not apparent just by looking at Equation 3.2 whether the air jet exit area will increase if both the air gap and the setback are increased simultaneously. Using Equation 3.2, the air jet exit area for an air gap/setback of 2.0 and 1.55

mm. are calculated to be 205.1 and 161.4 mm², respectively. The air jet injection angle for both cases is 45 degrees. Therefore, an increase in both air gap and setback increases the air jet exit area.

Figure 3.14 shows the coupled effect that air gap and setback have on the average fiber diameter for samples processed with air gaps/setbacks of 2.00 and 1.55 mm. (Case ID 3 and 21, respectively). The samples processed with the larger air jet exit area ($d_s = d_g = 2.00$ mm) are consistently smaller in diameter than the fibers processed at the smaller air jet exit area ($d_s = d_g = 1.55$ mm). Figures 3.15 and 3.16 show the fiber diameter histograms for the samples collected at 165 and 295 m/s, respectively, which are shown in Figure 3.14. It is not apparent that the air gap and setback have a significant effect on the fiber diameter distribution for a given air jet exit velocity. However, larger average fiber diameters are consistently associated with larger standard deviations (less uniform webs). Figures 3.17 and 3.18 present more results showing the effect that air gap and setback have on fiber diameter for samples collected at the same processing conditions but different throughputs; 1.6 and 3.0 g/min., respectively. It is clear by looking at Figures 3.17 and 3.18 that the samples processed with the larger air jet exit area are consistently smaller in diameter than the fibers processed at the smaller air jet exit area at a given air velocity.

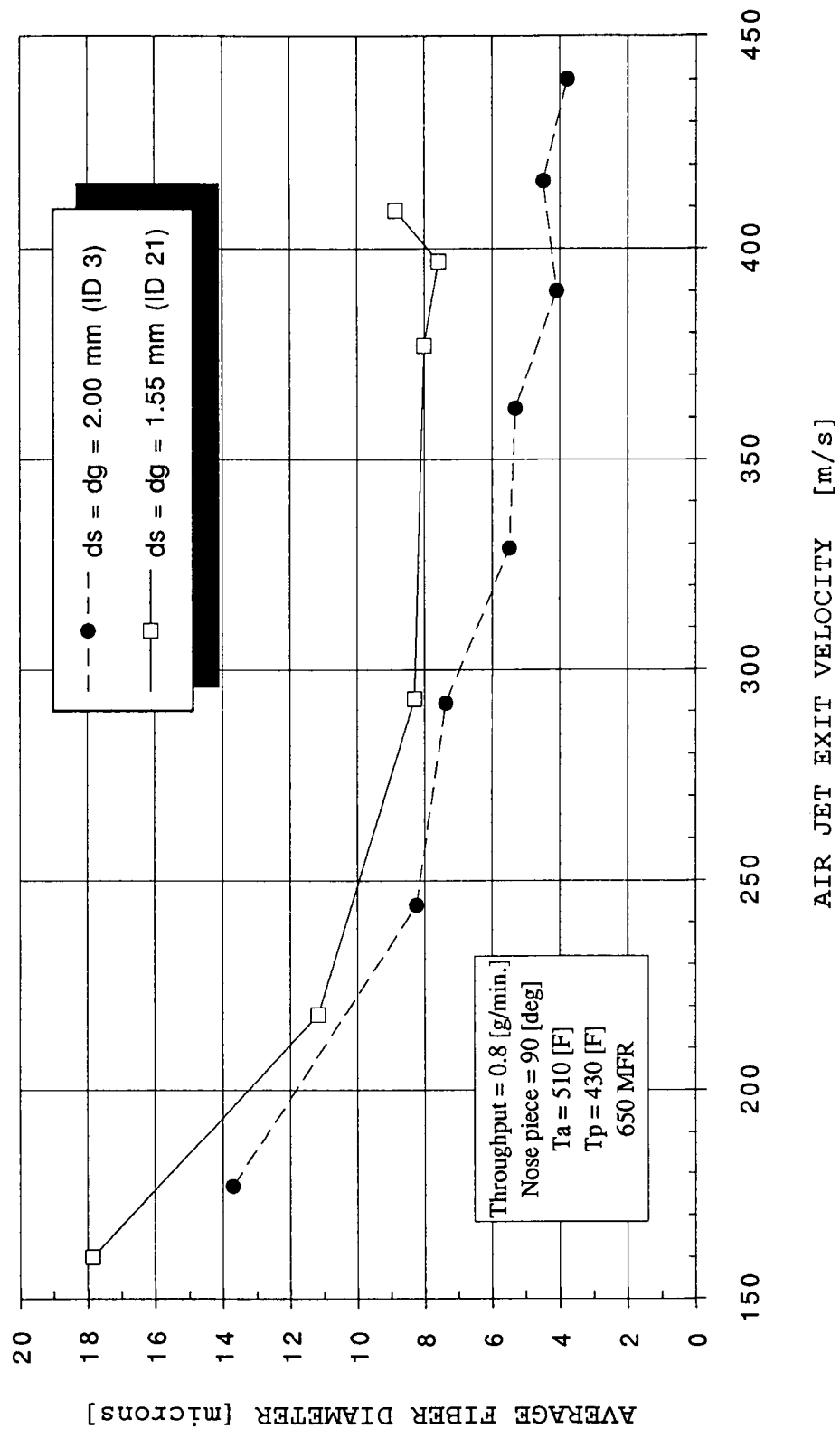


Figure 3.14: Effect of air gap and setback on average fiber diameter (ID 3 vs. 21)

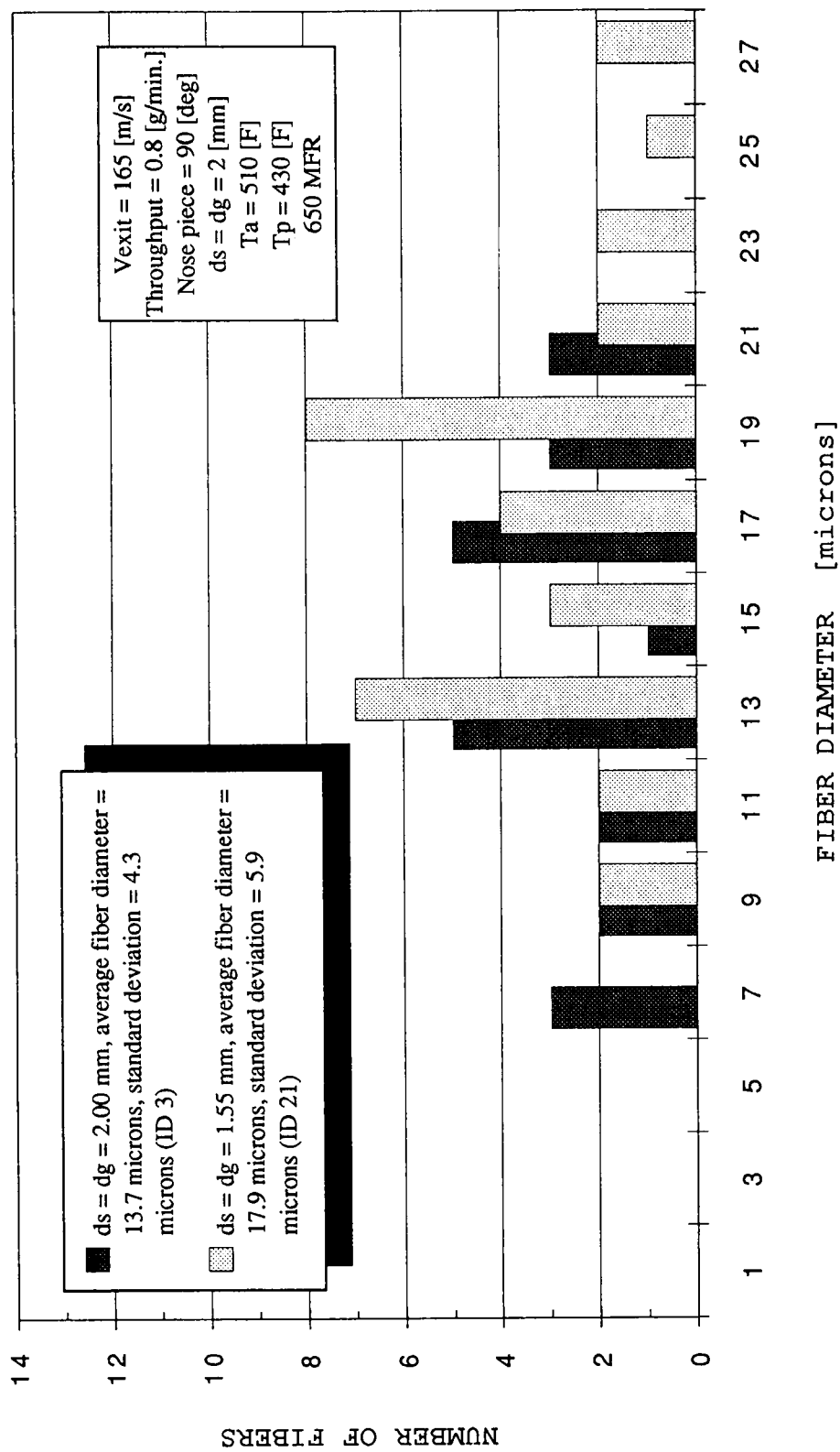


Figure 3.15: Effect that air gap and setback have on fiber diameter histograms; 165 m/s (ID 3 vs. 21)

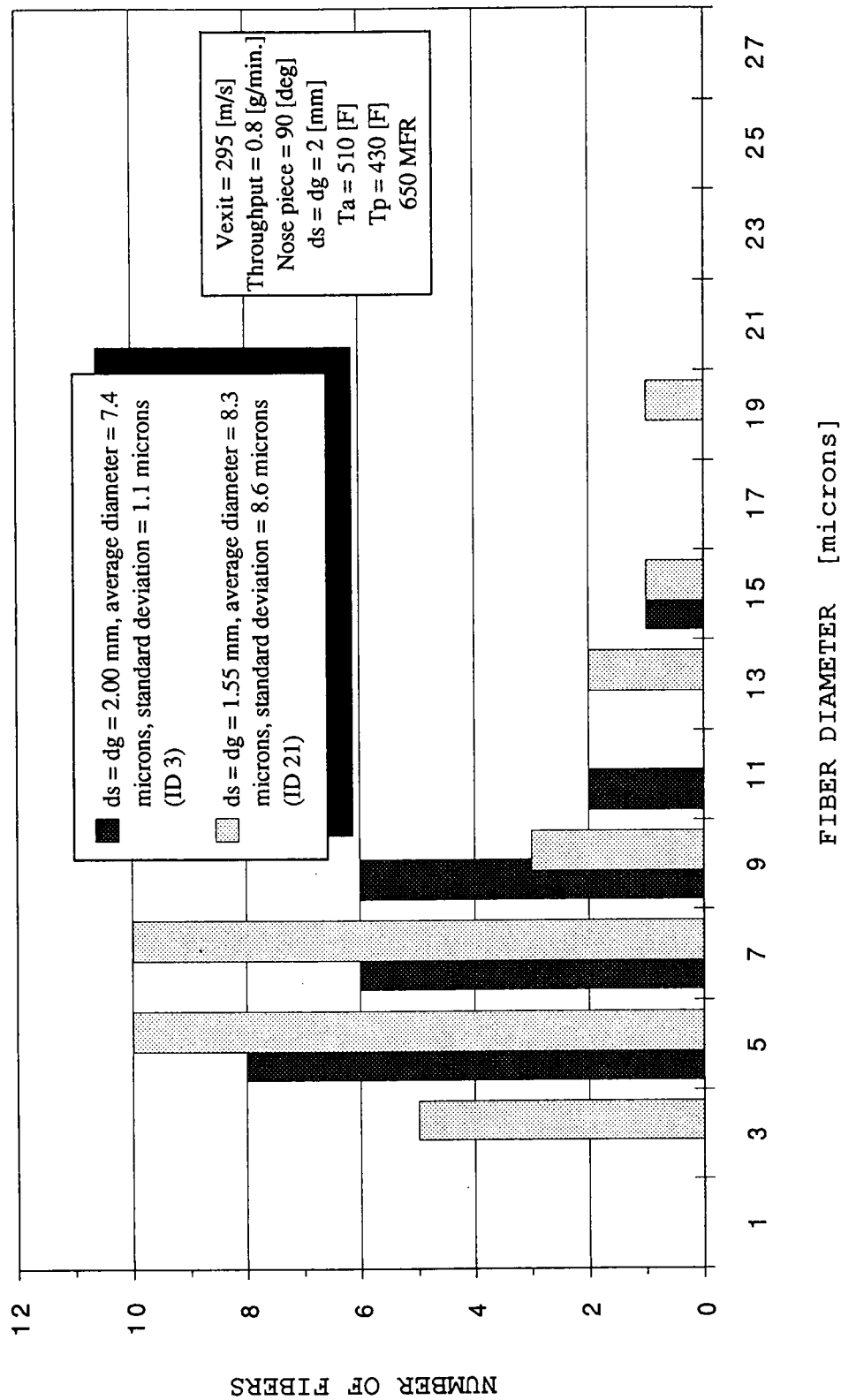


Figure 3.16: Effect that air gap and setback have on fiber diameter histograms; 295 m/s (ID 3 vs. 21)

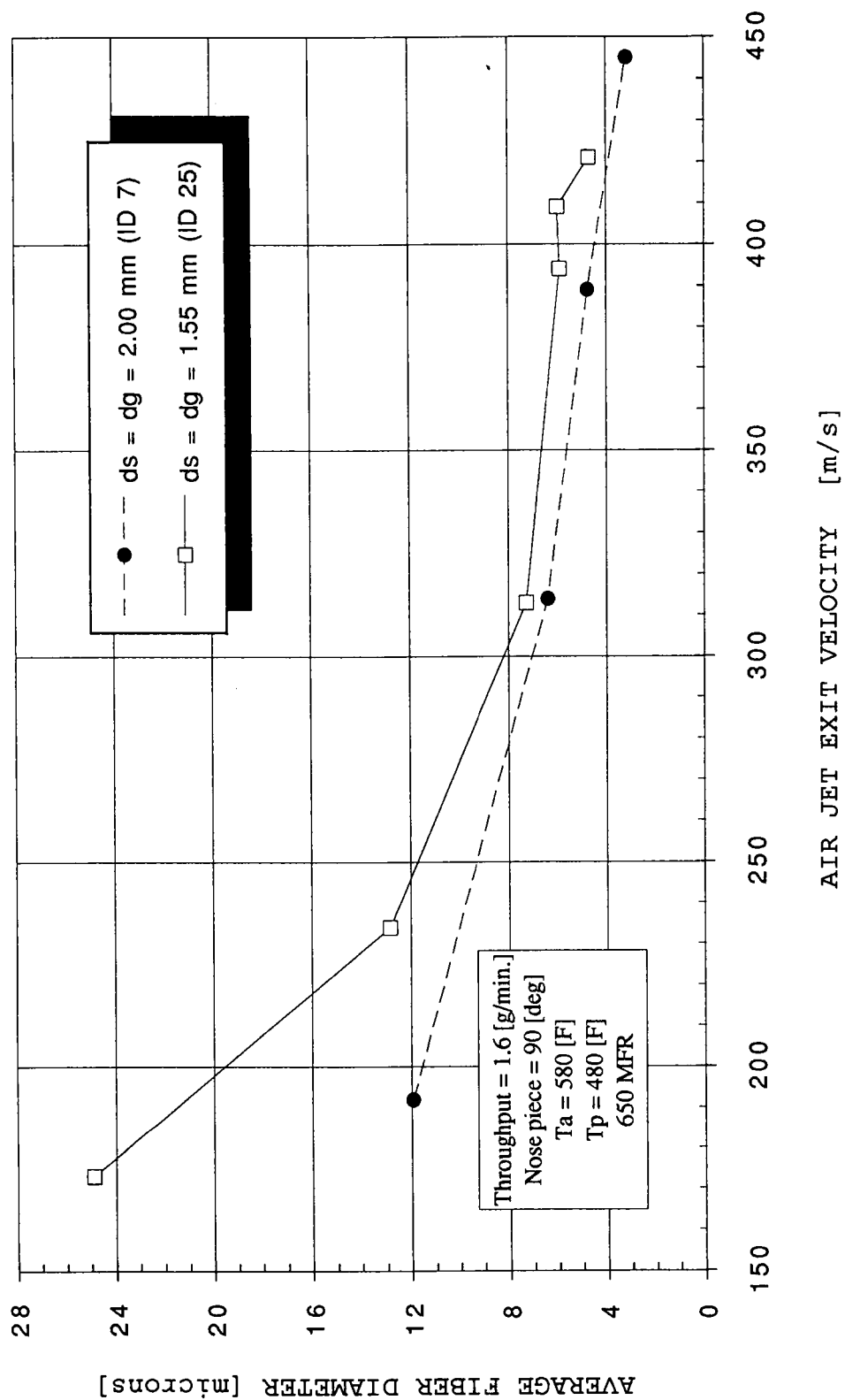


Figure 3.17: Effect of air gap and setback on average fiber diameter (ID 7 vs. 25)

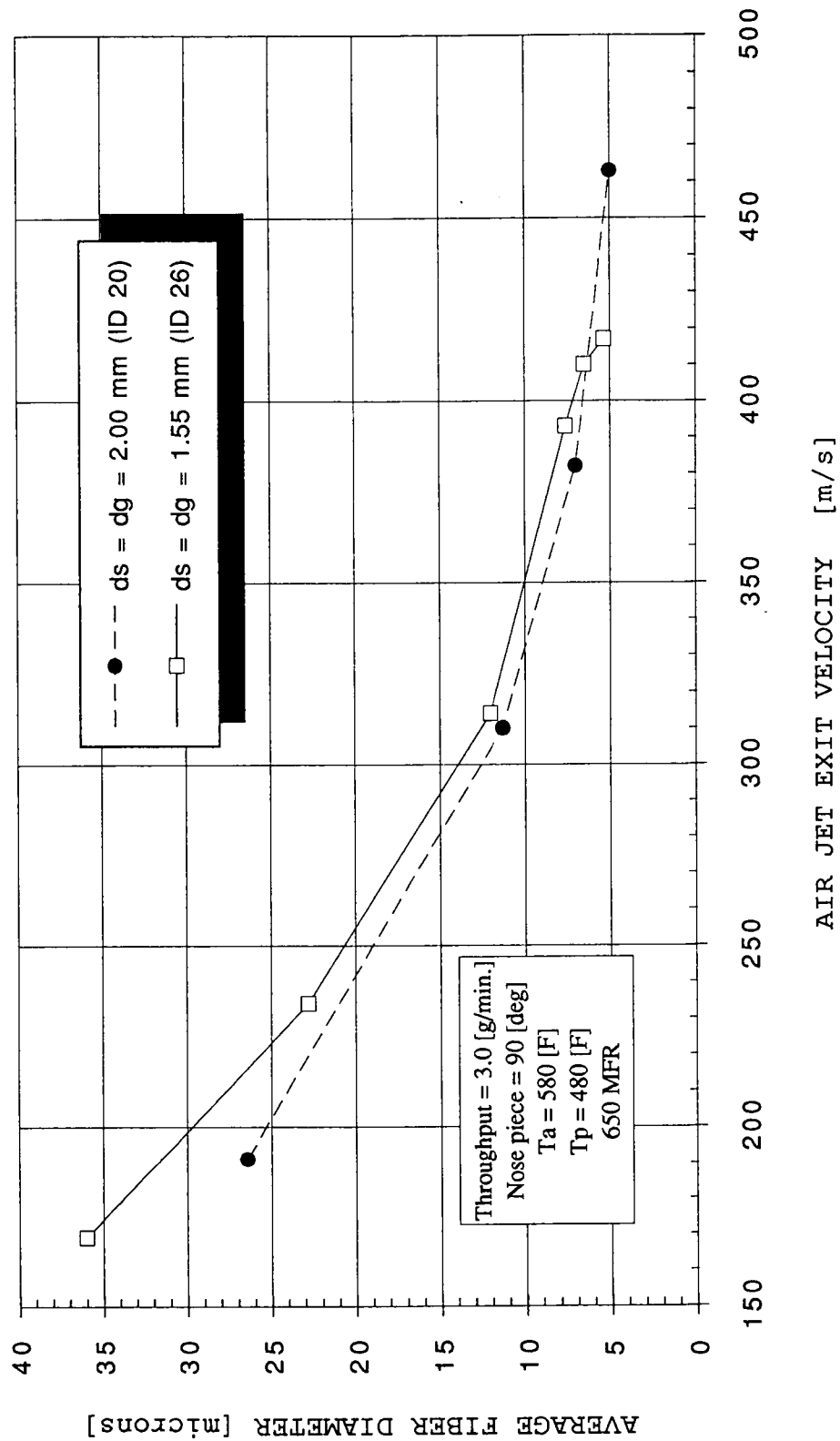


Figure 3.18: Effect of air gap and setback on average fiber diameter (ID 20 vs. 26)

Air Jet Injection Angle

It is not apparent just by looking at Equation 3.2 whether the air jet exit area would increase or decrease if only the air jet injection angle was to be increased (constant air gap and setback). Thus, it is not apparent what would happen to the air jet momentum with this increase in air injection angle. However, by intuition, the axial component of the air jet momentum at the die tip would be expected to be smaller if the air injection angle was to be increased. The objective of the present study is to experimentally establish the effect that the air jet injection angle has on the fiber diameter.

A new die (90° nose piece = 45° air jet injection angle) and the corresponding face plates had to be manufactured for this study. It should be noted that the surfaces of the die tip and the face plate are parallel (see Figure 3.13) in both the upper and lower air flow regions. Both 90° and 60° nose piece dies were used to study the effect that air jet injection angle (45° and 30° , respectively) has on fiber diameter.

The air jet exit area for the 90° and the 60° nose pieces were calculated (Equation 3.2) to be 205.1 and 271.6 mm^2 , respectively. Thus the 90° nose piece has a smaller air jet exit area than the 60° nose piece, for a constant air gap and setback (2.00 mm). Consequently, the 90° nose

piece has a smaller air jet momentum than the 60° nose piece at a given exit air velocity. Figures 3.19 and 3.20 show the effect that air jet injection angle has on average fiber diameter for a polymer throughput of 0.8 and 1.6 g/min., respectively (other processing conditions are constant). In both cases, an increase in air jet injection angle produces fibers of larger diameter. The experimental results shown in Figures 3.19 and 3.20 are consistent with the findings from the previous section in that for a given air velocity, increasing the air jet exit area (thus the air jet momentum) produces fibers of smaller diameter. Figures 3.21 and 3.22 show the fiber diameter histograms for the samples collected at 200 and 320 m/s, respectively, which are shown in Figure 3.19. Similarly, Figures 3.23 and 3.24 show the fiber diameter histograms for the samples collected at 200 and 390 m/s, respectively, which are shown in Figure 3.20. Two conclusions can be drawn from the results shown in Figures 3.21 through 3.24. First, larger average fiber diameters are produced at the larger air jet injection angles for a given air velocity. Second, larger average fiber diameters are associated with larger standard deviations (less uniform webs). There is no indication from these results that the air jet injection angle has a direct effect on how uniform the webs are. It seems that the uniformity of the webs is strictly dependent on the average fiber diameter rather than in the air jet injection angle in

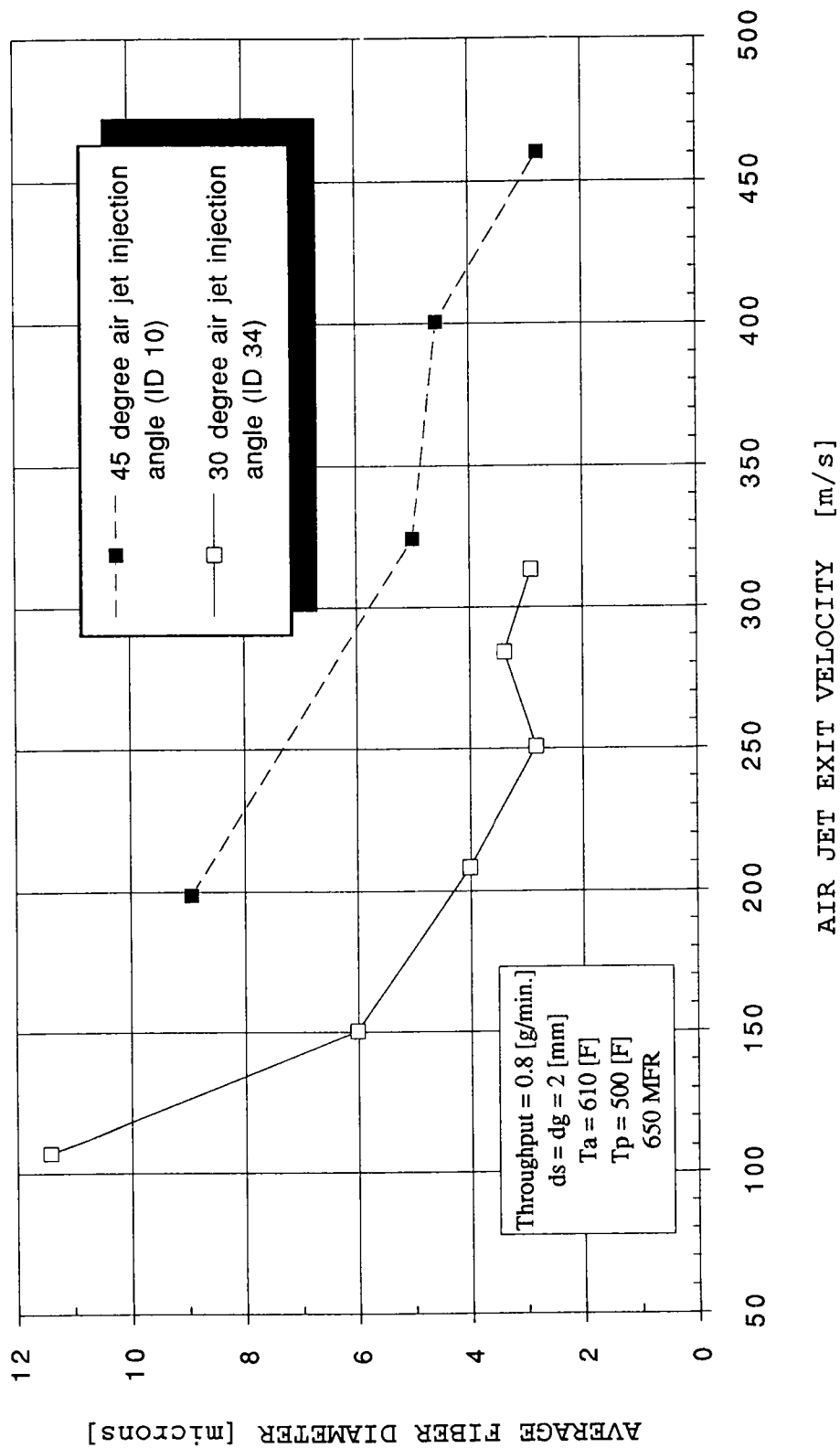


Figure 3.19: Effect of air jet injection angle on average fiber diameter (ID 10 vs. 34)

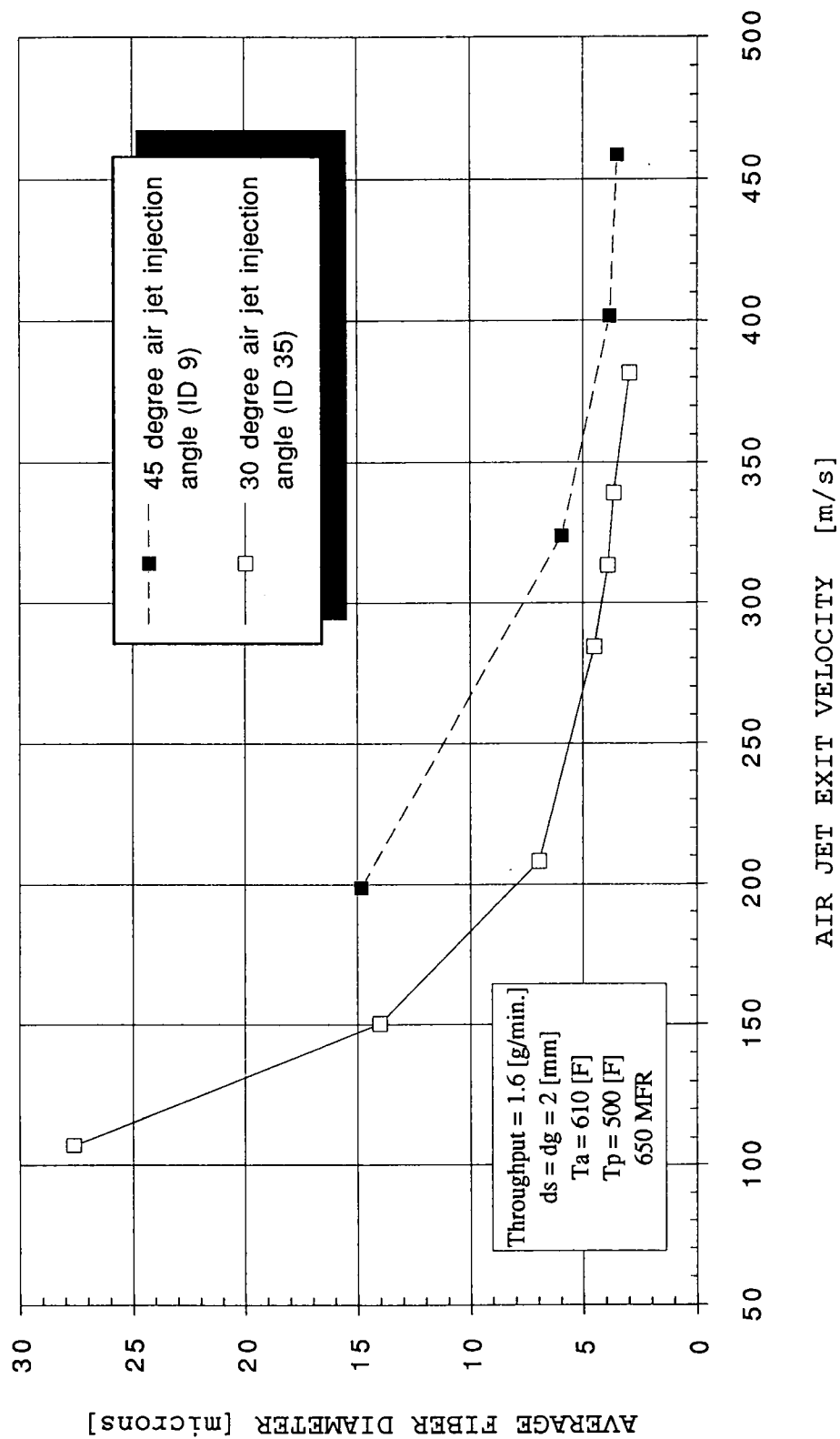


Figure 3.20: Effect of air jet injection angle on average fiber diameter (ID 9 vs. 35)

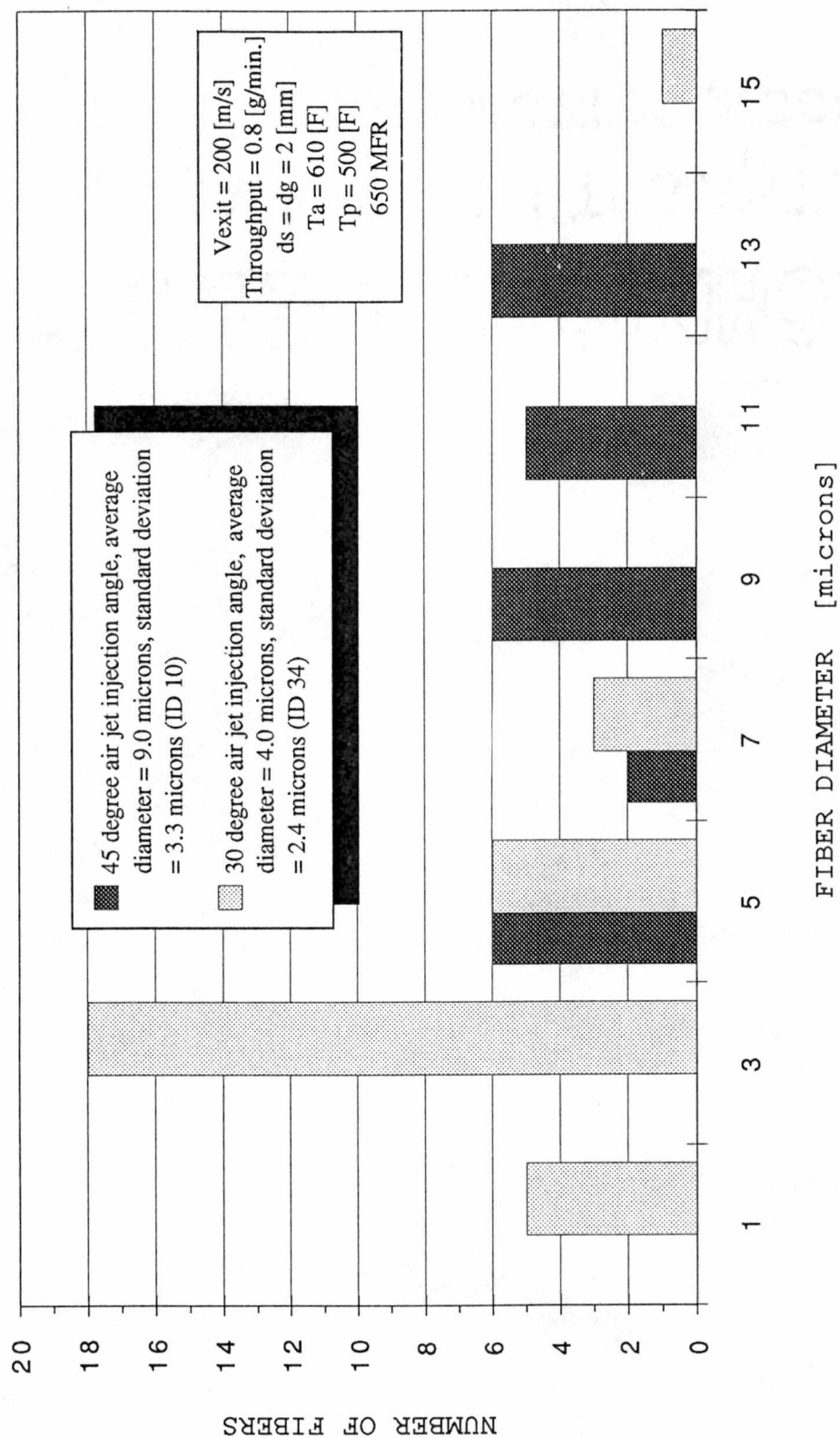


Figure 3.21: Effect that air jet injection angle has on fiber diameter histograms; 200 m/s (ID 10 vs. 34)

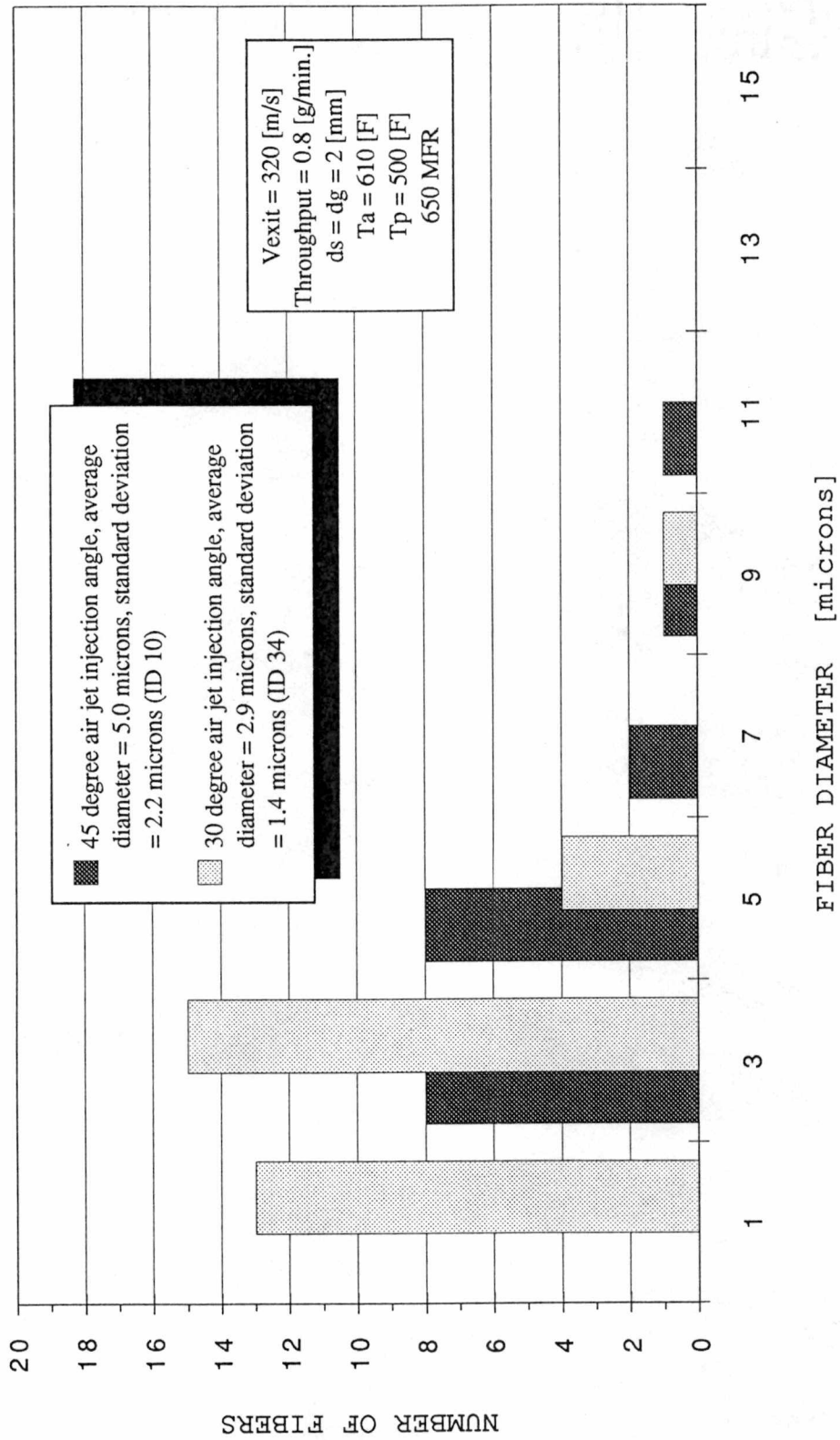


Figure 3.22: Effect that air jet injection angle has on fiber diameter histograms; 320 m/s (ID 10 vs. 34)

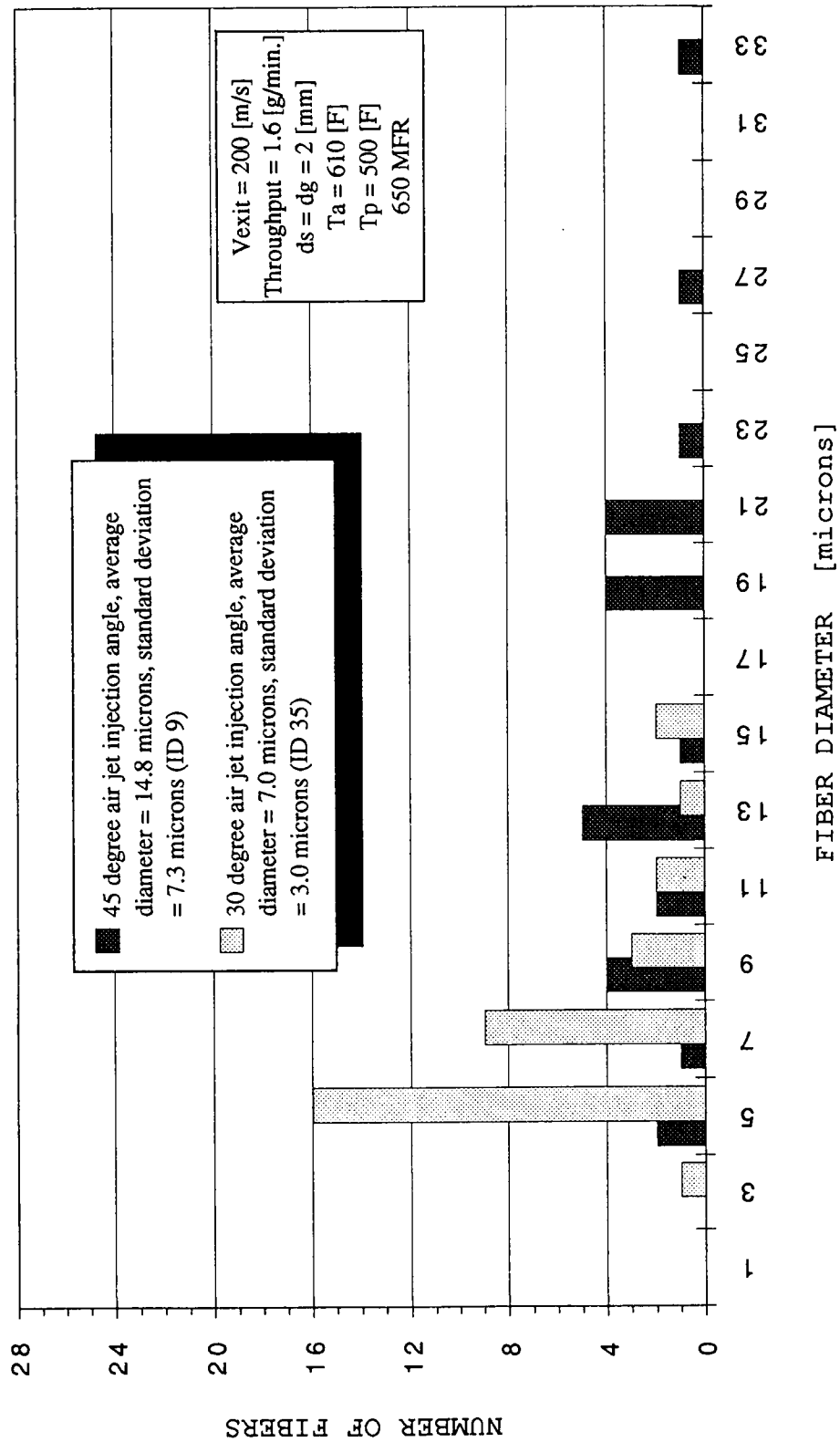


Figure 3.23: Effect that air jet injection angle has on fiber diameter histograms; 200 m/s (ID 9 vs. 35)

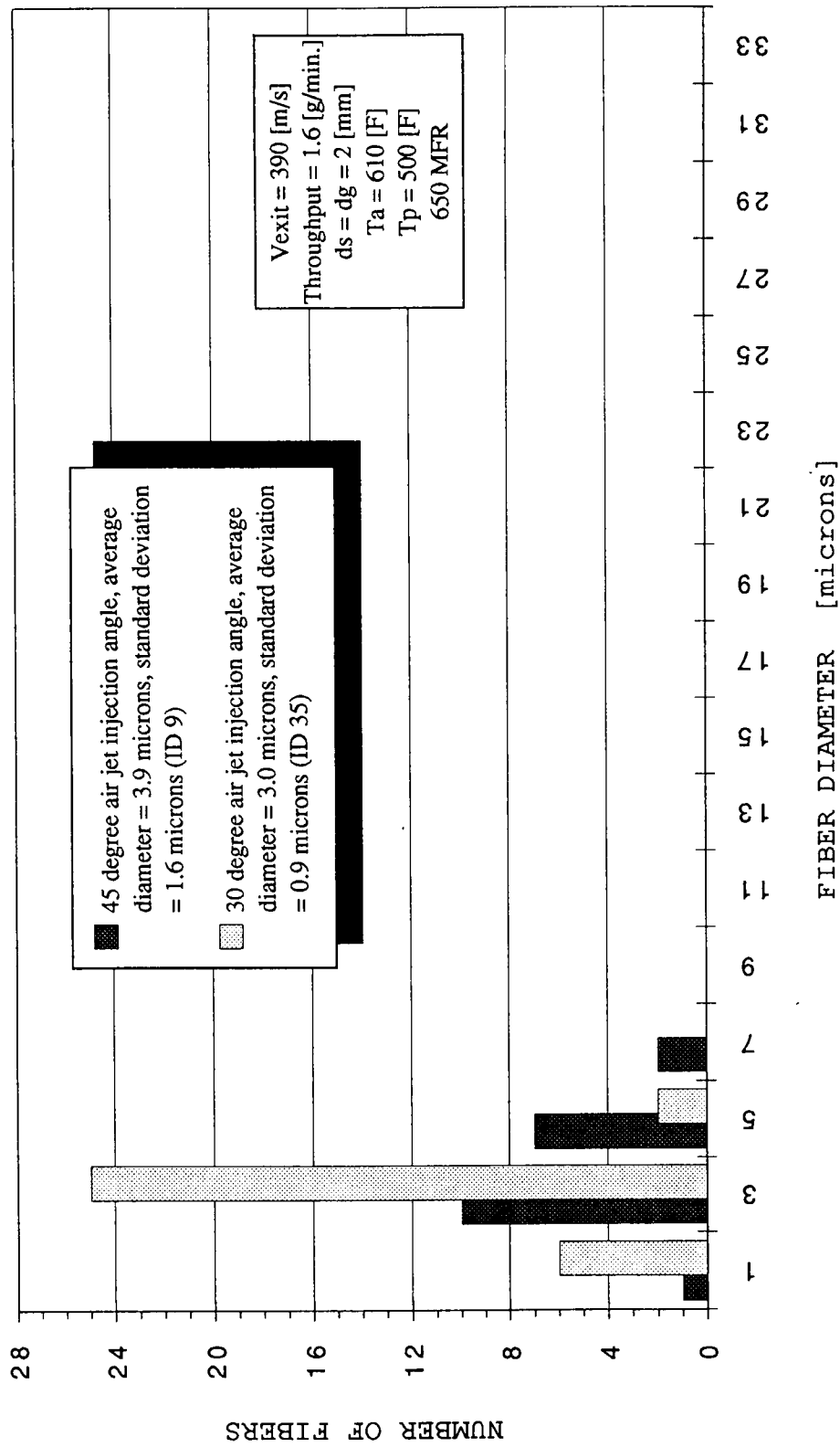


Figure 3.24: Effect that air jet injection angle has on fiber diameter histograms; 390 m/s (ID 9 vs. 35)

this case. Figures 3.25 and 3.26 show similar results for samples collected at higher polymer and air temperatures. It should be noted that Figures 3.20, 3.25, and 3.26 clearly show how the average fiber diameter tends to reach an asymptotic value, which is in the order of 3 to 5 microns, as the air jet exit velocity is increased.

It can be concluded then that it is the axial component of the air jet momentum at the die tip that dominates the attenuation of the fibers. Larger air jet injection angles results in larger fiber diameters. In the limiting case, if the air jets were placed normal to the direction of flow of the polymer, one would expect little or no attenuation of the fibers at all. These three die geometry parameters, air gap, setback, and air jet injection angle can could be effectively arranged to produce fibers with small average diameter. Also, it is the average fiber diameter of a web that has a direct effect on the distribution of the fiber diameter; webs with smaller average fiber diameter have a narrower fiber diameter distribution (small standard deviation) than webs with a higher average fiber diameter.

Polymer Throughput

Three sets of experiments were conducted to study the effect that polymer throughput has on fiber diameter. Three

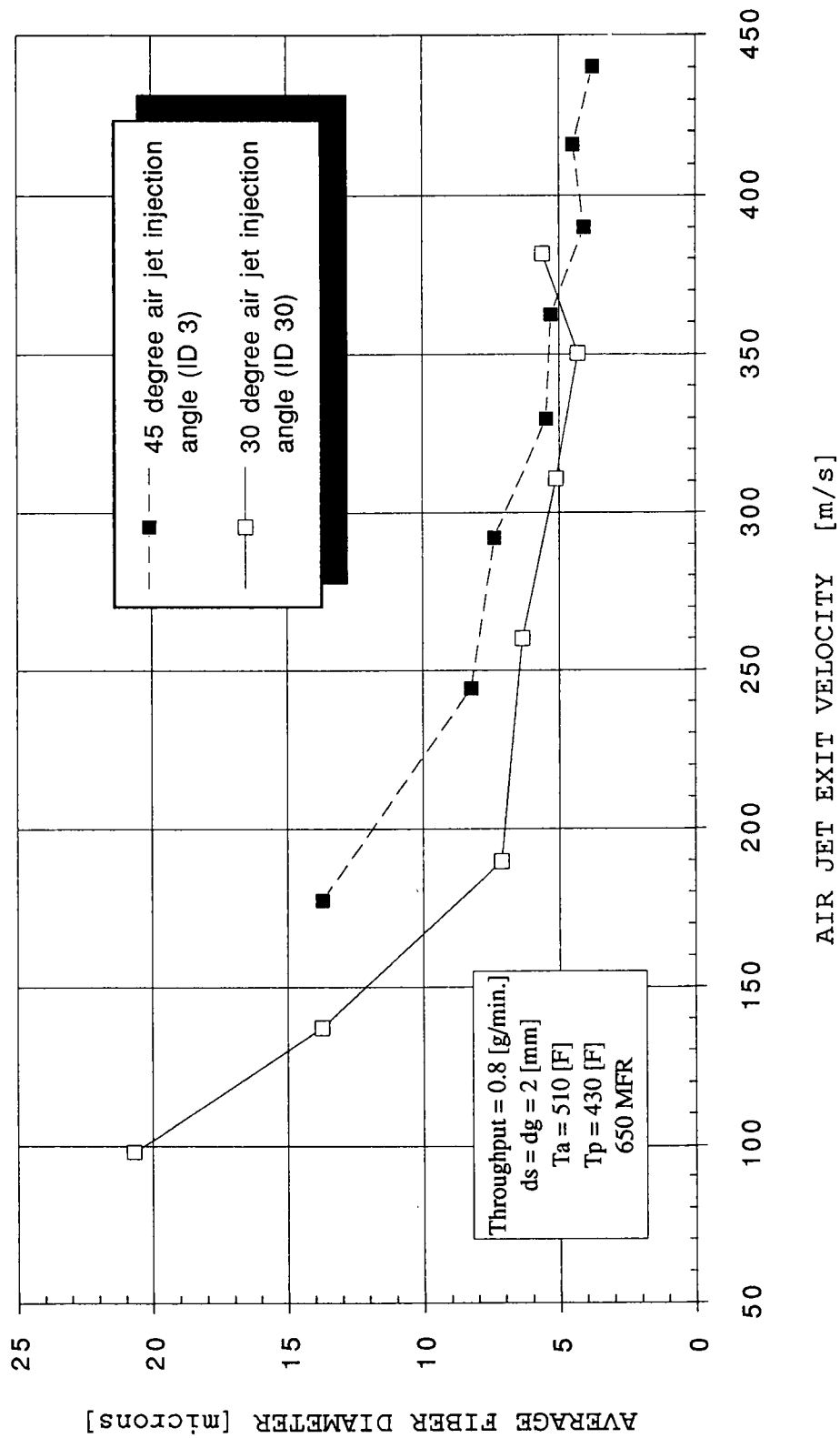


Figure 3.25: Effect of air jet injection angle on average fiber diameter (ID 3 vs. 30)

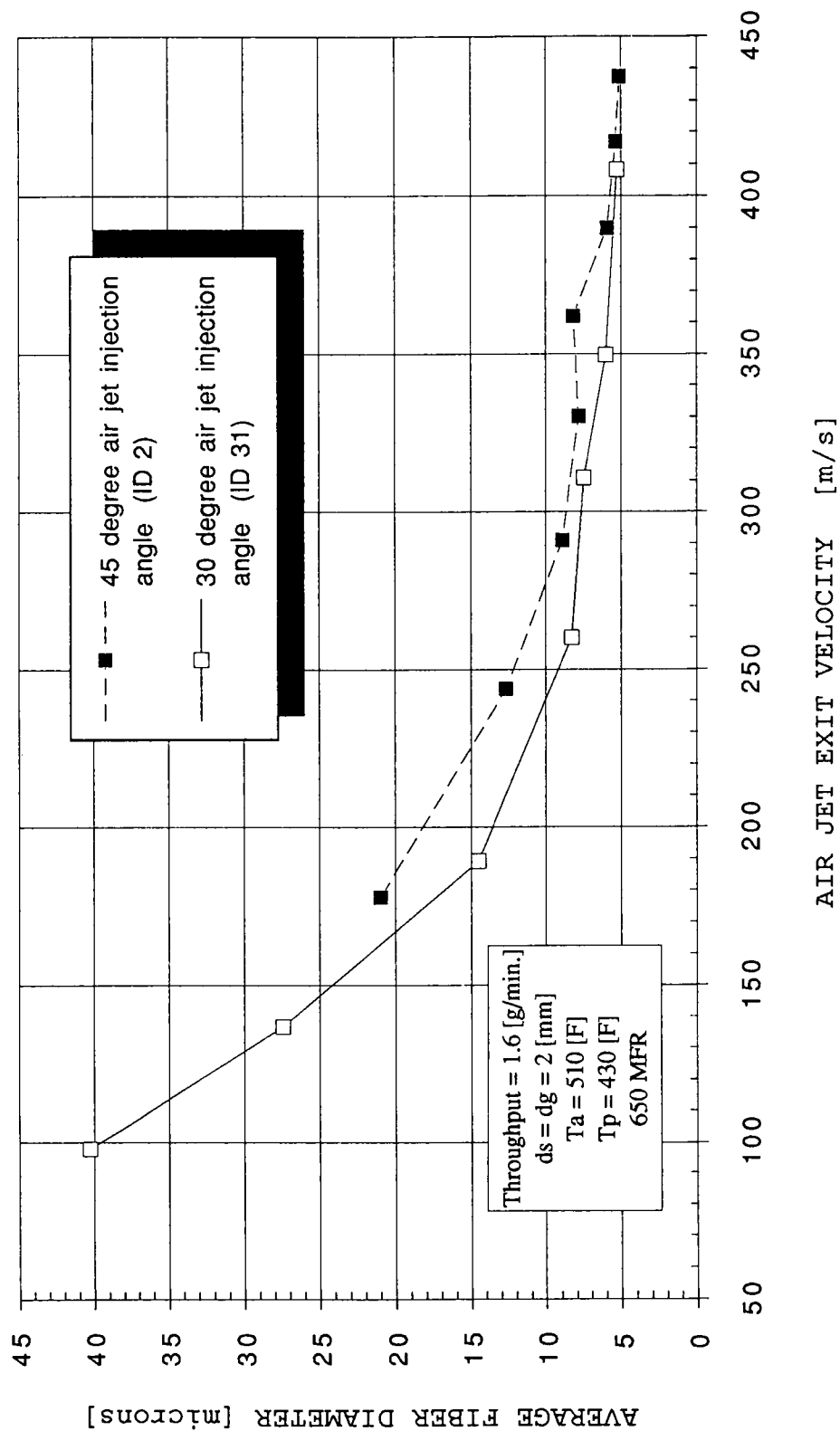


Figure 3.26: Effect of air jet injection angle on average fiber diameter (ID 2 vs. 31)

polymer throughputs (3.0, 1.6, and 0.8 g/min.) were processed at each experiment.

Figure 3.27 shows the results for the first experiment ($T_a = 510$ F, $T_p = 420$ F). It can be seen that lower polymer throughputs are associated with smaller fiber diameters at any given exit air velocity. Figures 3.28 and 3.29 show the fiber diameter histograms for the samples collected at 160 and 380 m/s, respectively, which are shown in Figure 3.27. By looking at Figure 3.28 it can be observed that as the average fiber diameter decreases so does the standard deviation. The same general trends are seen in Figure 3.29. Figure 3.30 shows the effect that polymer throughput has on average fiber diameter at higher polymer and air temperatures ($T_a = 580$ F, $T_p = 470$ F). It can be seen again that for a given exit air velocity, as polymer throughput is decreased, average fiber diameter also decreases. Figure 3.31 shows the effect of polymer throughput on fiber diameter at even higher polymer and air temperatures. Once again, smaller polymer throughputs produce smaller fibers. This effect is more pronounced at low air velocities, whereas at high air velocities this effect becomes less pronounced. Figures 3.32 and 3.33 show the fiber diameter histograms for the samples collected at 170 and 400 m/s, respectively, which are shown in Figure 3.31. In both Figures there appears to be a general trend indicating that

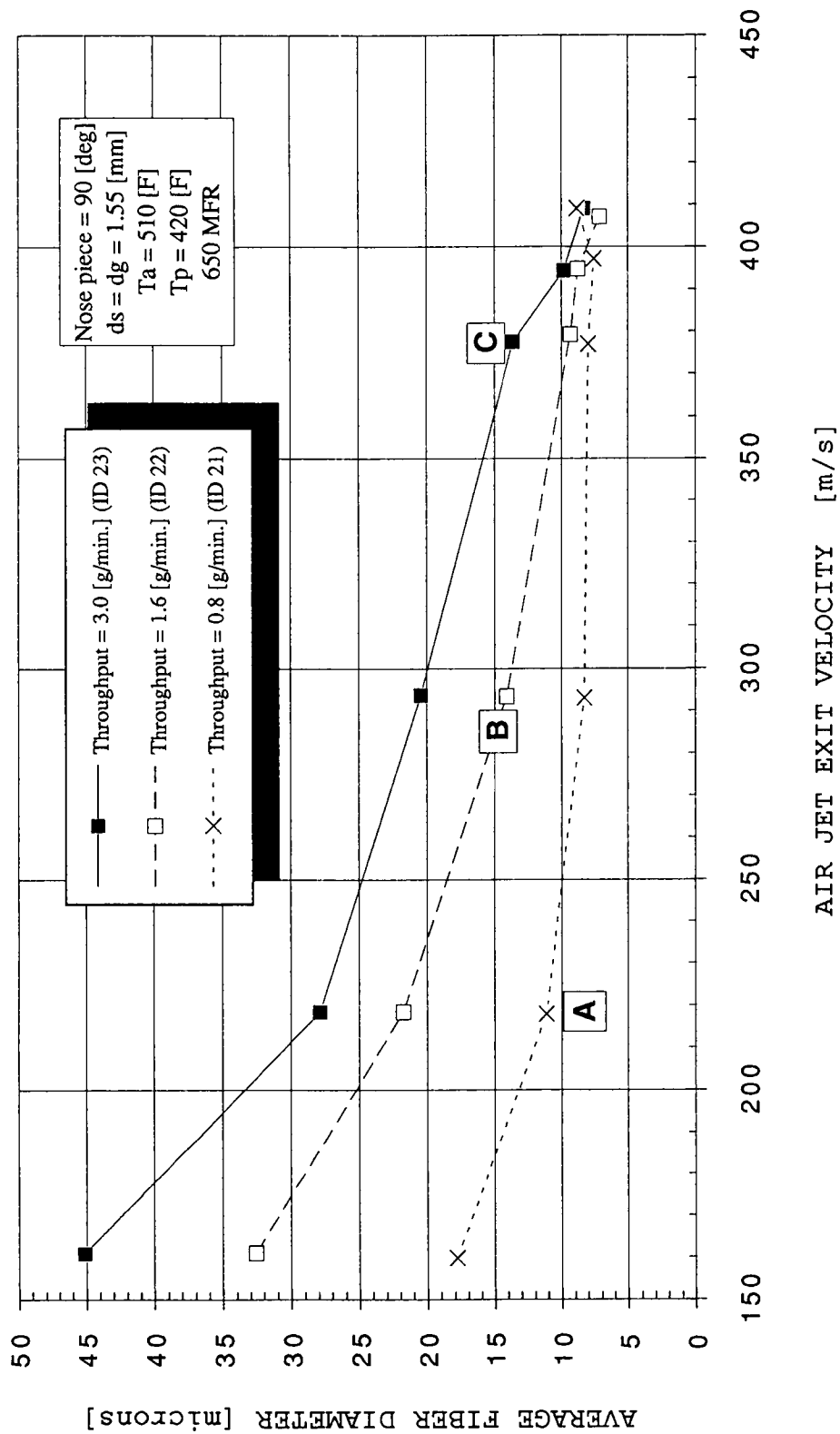


Figure 3.27: Effect of polymer throughput on average fiber diameter; (Ta = 510 F, Tp = 420 F)

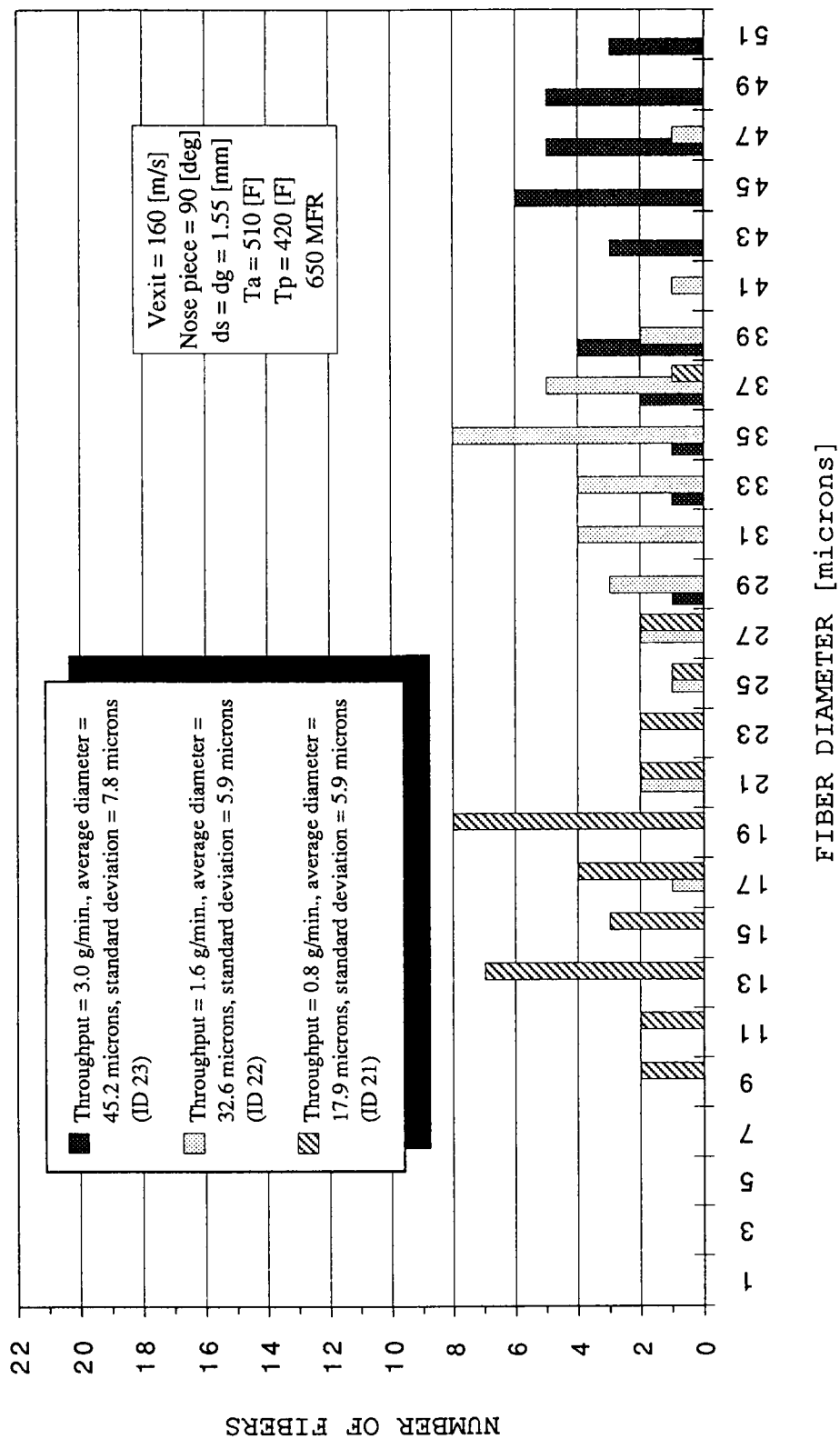


Figure 3.28: Effect of polymer throughput on fiber diameter histograms; 160 m/s (ID 21, 22, 23)

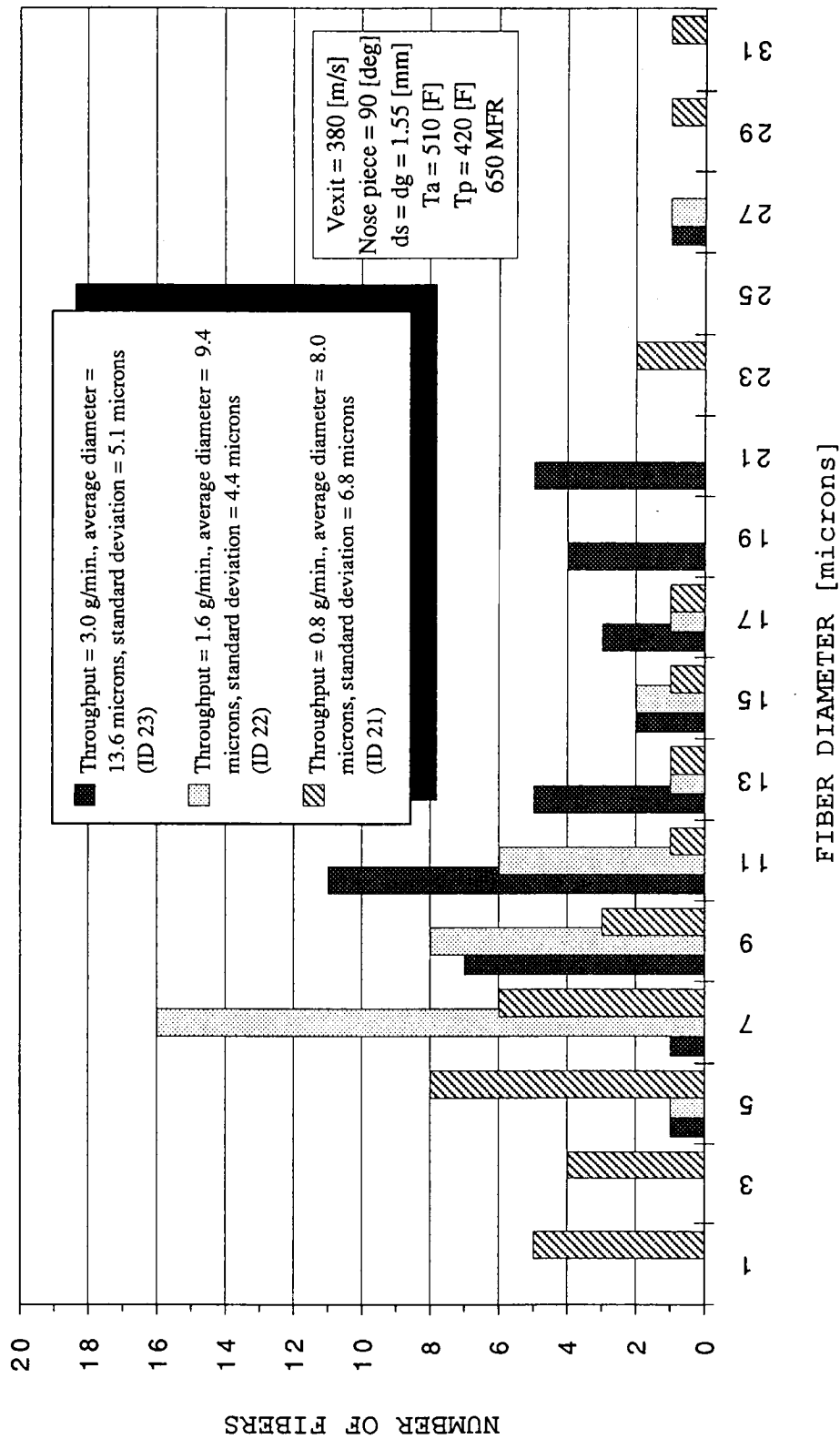


Figure 3.29: Effect of polymer throughput on fiber diameter histograms; 380 m/s (ID 21, 22, 23)

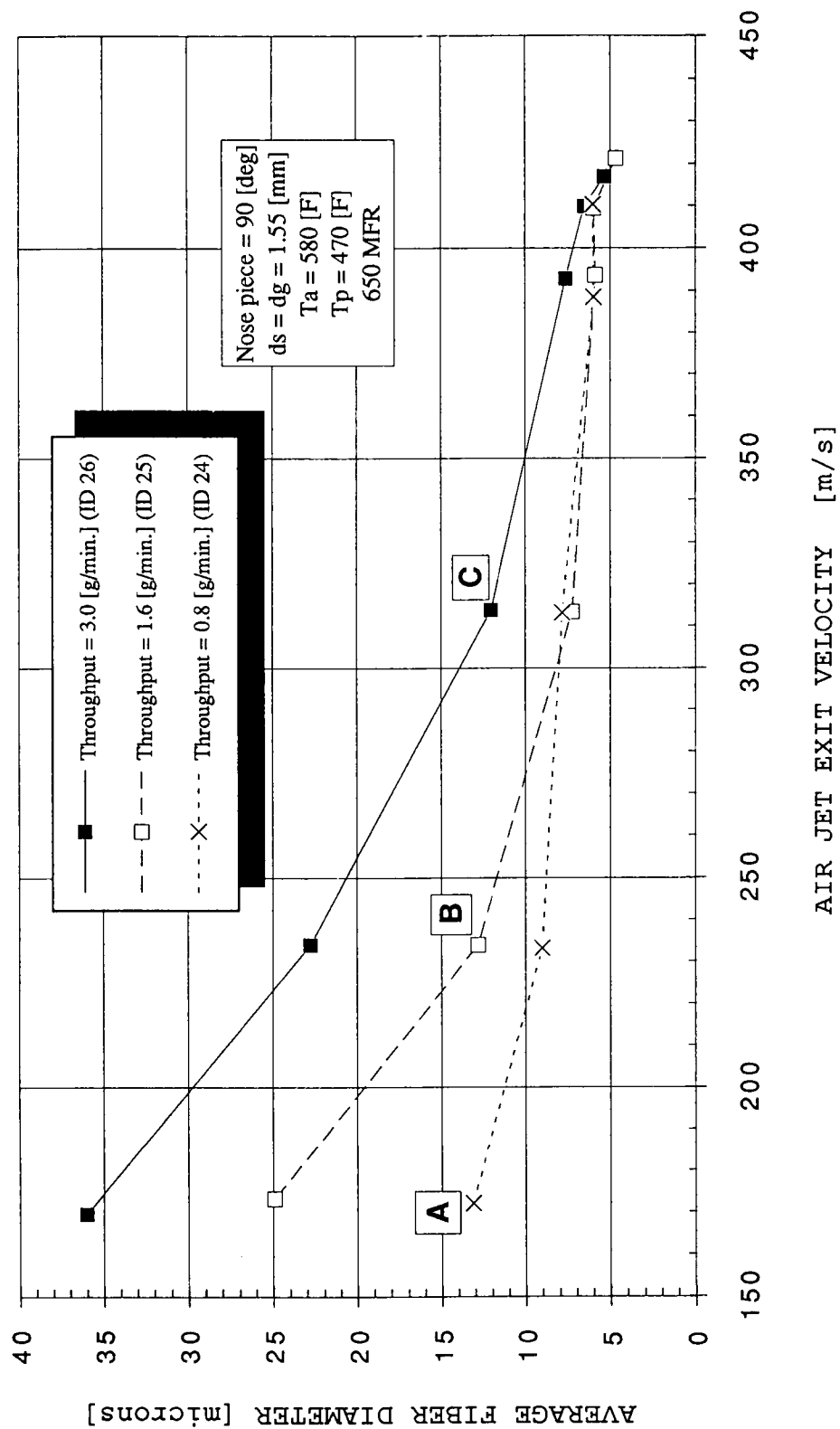


Figure 3.30: Effect of polymer throughput on average fiber diameter; (Ta = 580 F, Tp = 470 F)

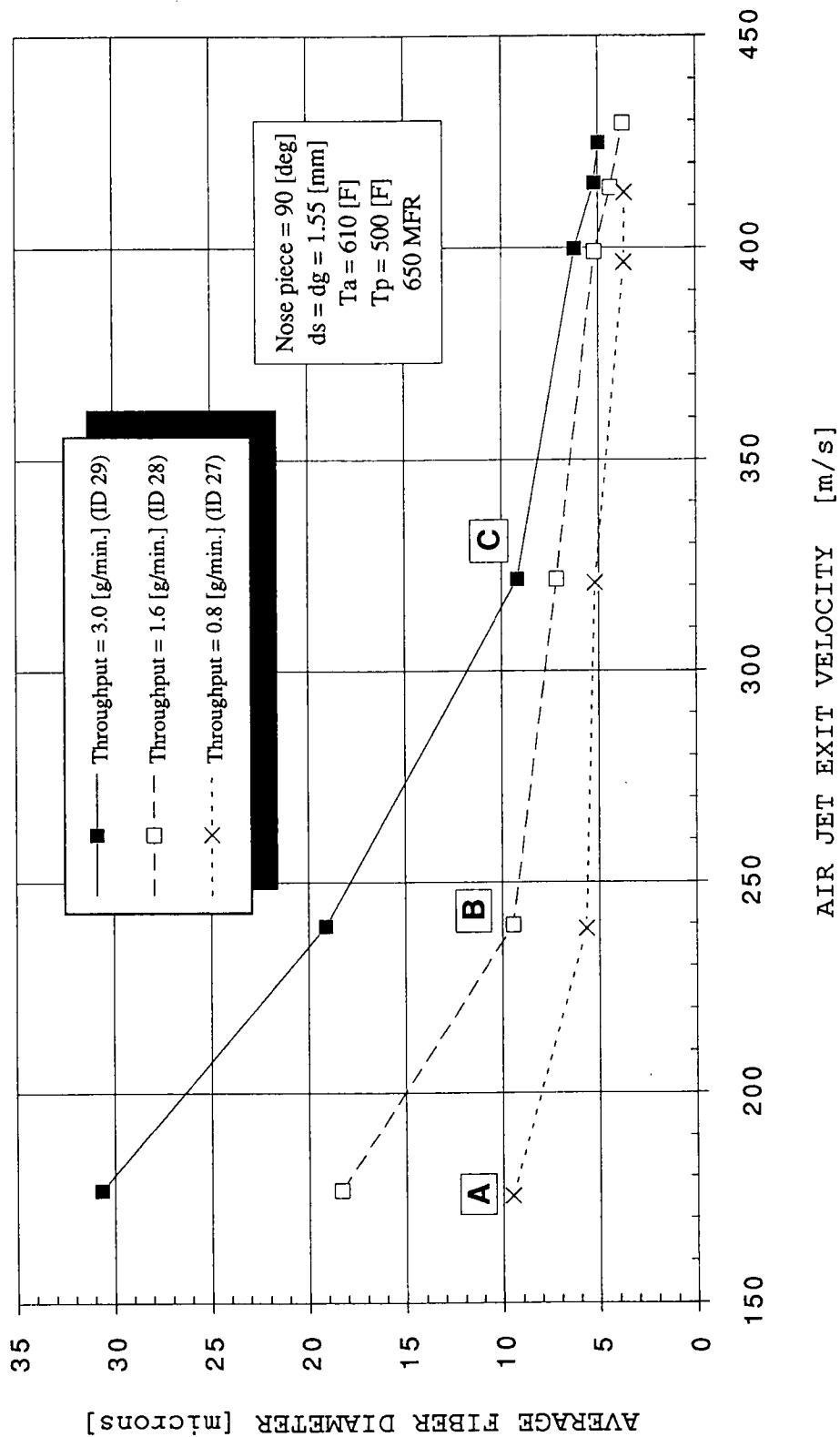


Figure 3.31: Effect of polymer throughput on average fiber diameter; (Ta = 610 F, Tp = 500 F)

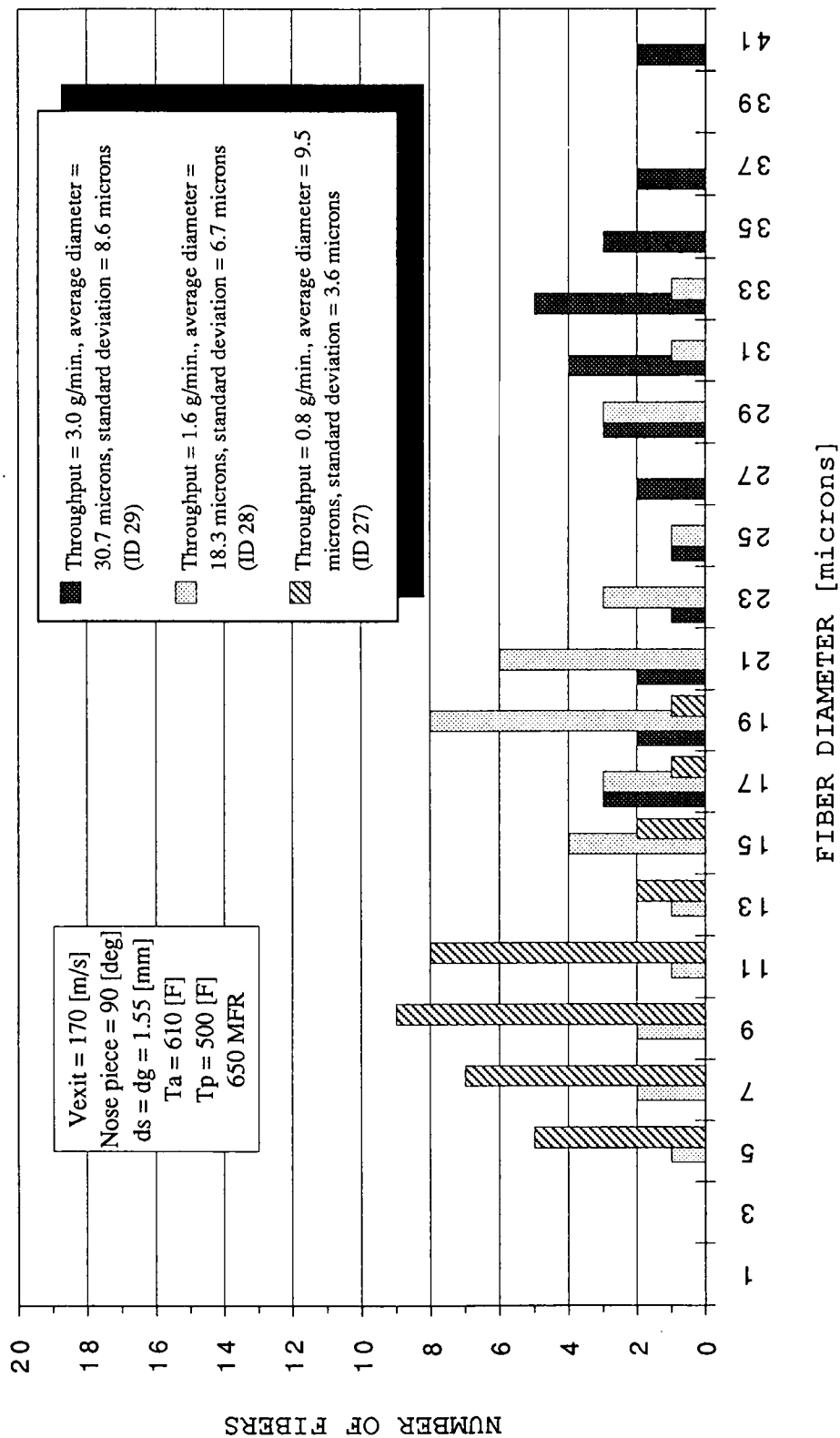


Figure 3.32: Effect of polymer throughput on fiber diameter histograms; 170 m/s (ID 27, 28, 29)

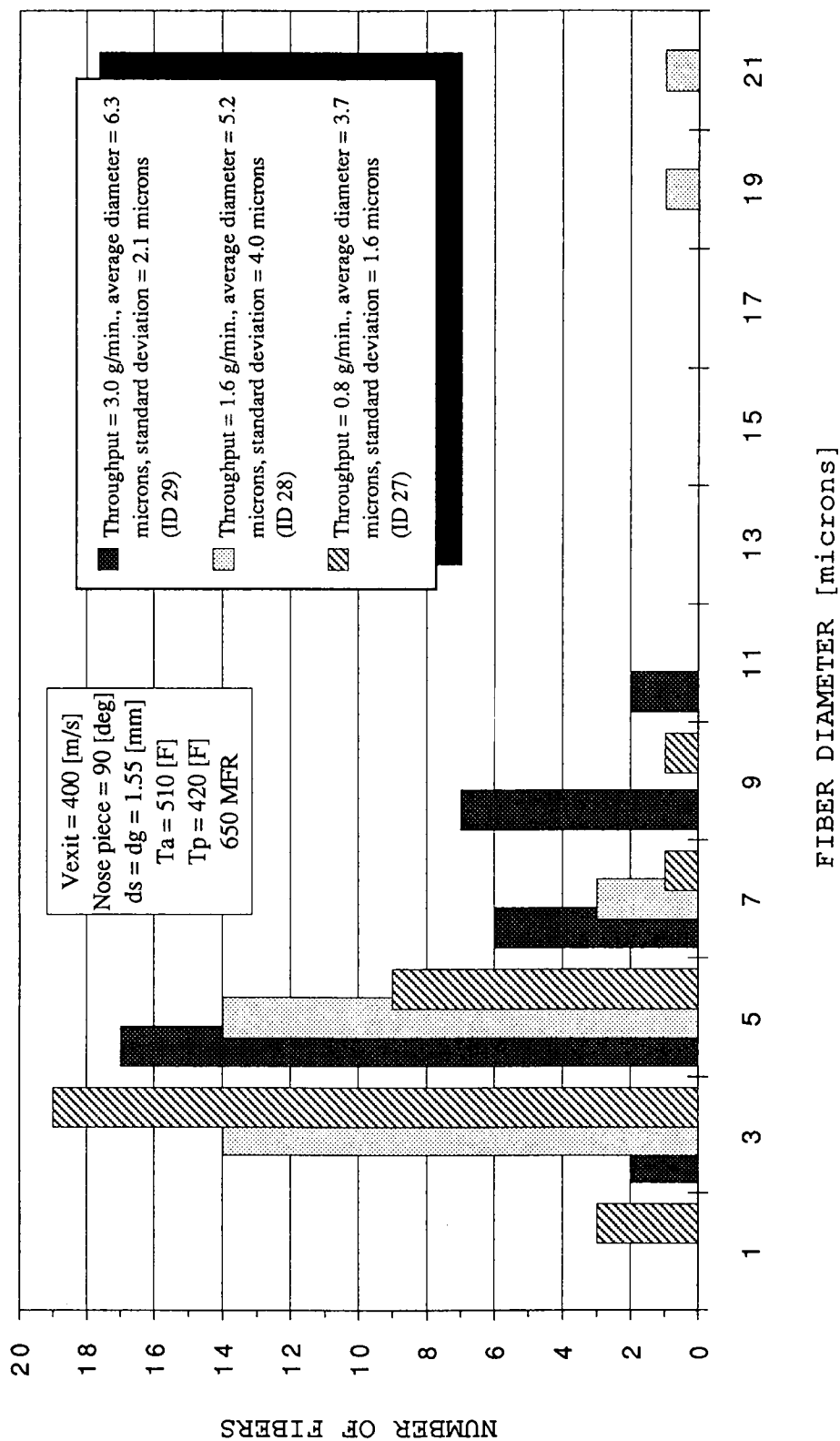


Figure 3.33: Effect of polymer throughput on fiber diameter histograms; 400 m/s (ID 27, 28, 29)

smaller average fiber diameters are associated with smaller standard deviations at a given exit air velocity.

Figure 3.34 shows the fiber diameter histograms for three samples (each at a different polymer throughput) with similar average fiber diameters (Samples A, B, and C from Figure 3.27). It can be seen that their distributions are very similar. Figure 3.35 shows the fiber diameter histograms for the three more samples (Samples A, B, and C from Figure 3.30) which also have similar average fiber diameter but which were collected at different polymer throughputs. It can be seen from this Figure that samples having the same average fiber diameter tend to have similar standard deviations. Finally, Figure 3.36 shows another set of data (Samples A, B, and C from Figure 3.31) which supports the fact that fibers of similar average fiber diameter tend to have the same standard deviation, regardless of the throughput at which they were processed.

These results support the findings made by Haynes [13] in that for a given exit air velocity a decrease in polymer throughput yields smaller fiber diameters for a given set of processing conditions. It can also be stated that this dependence is the strongest at low exit air velocities and the least at high exit air velocities. The uniformity of a web in terms of their fiber diameter distribution seems to be dependent upon the average diameter of the web rather

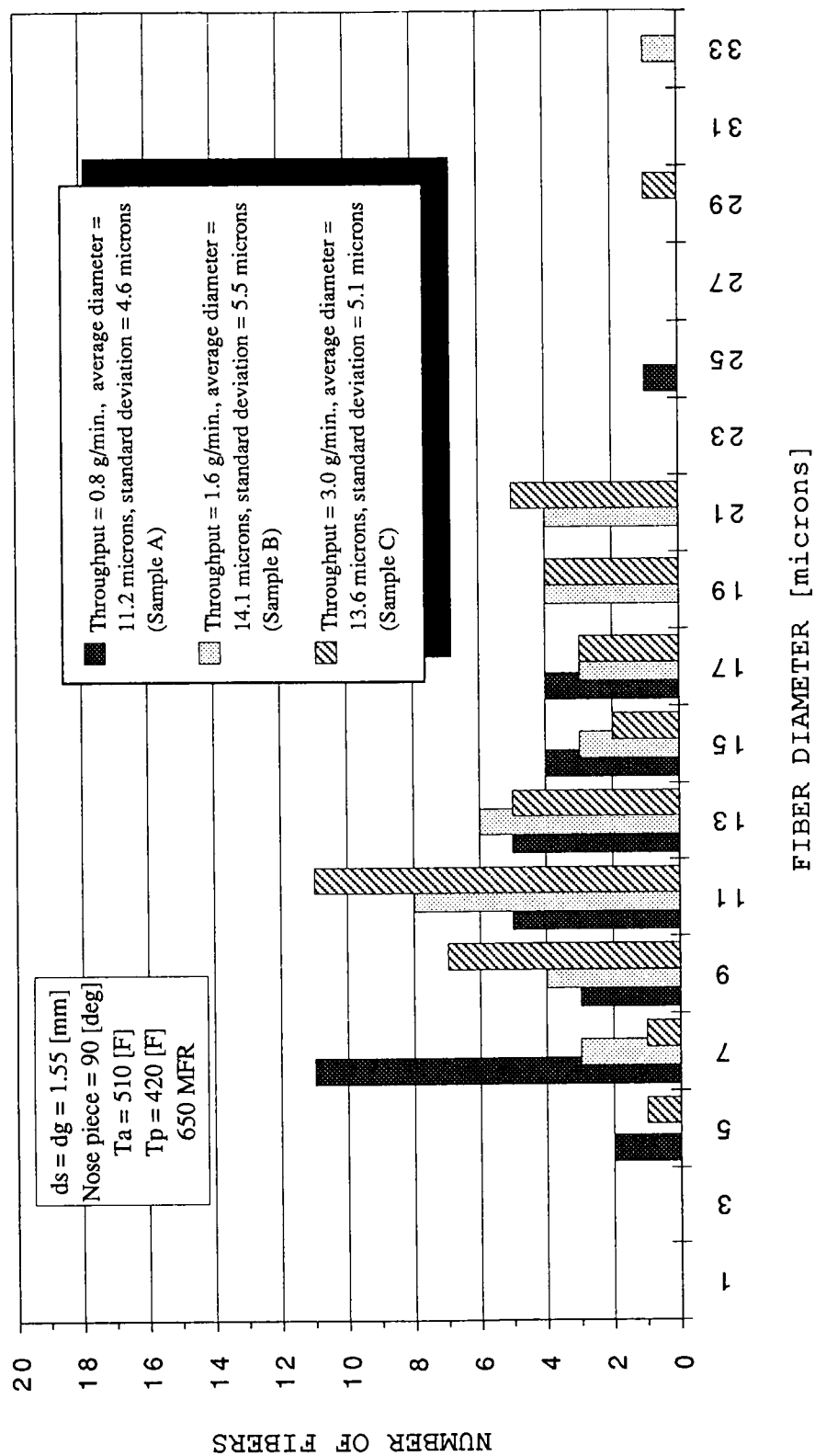


Figure 3.34: Effect of polymer throughput on fiber diameter histograms for samples of similar average diameter (Ta=510 F, Tp = 420F)

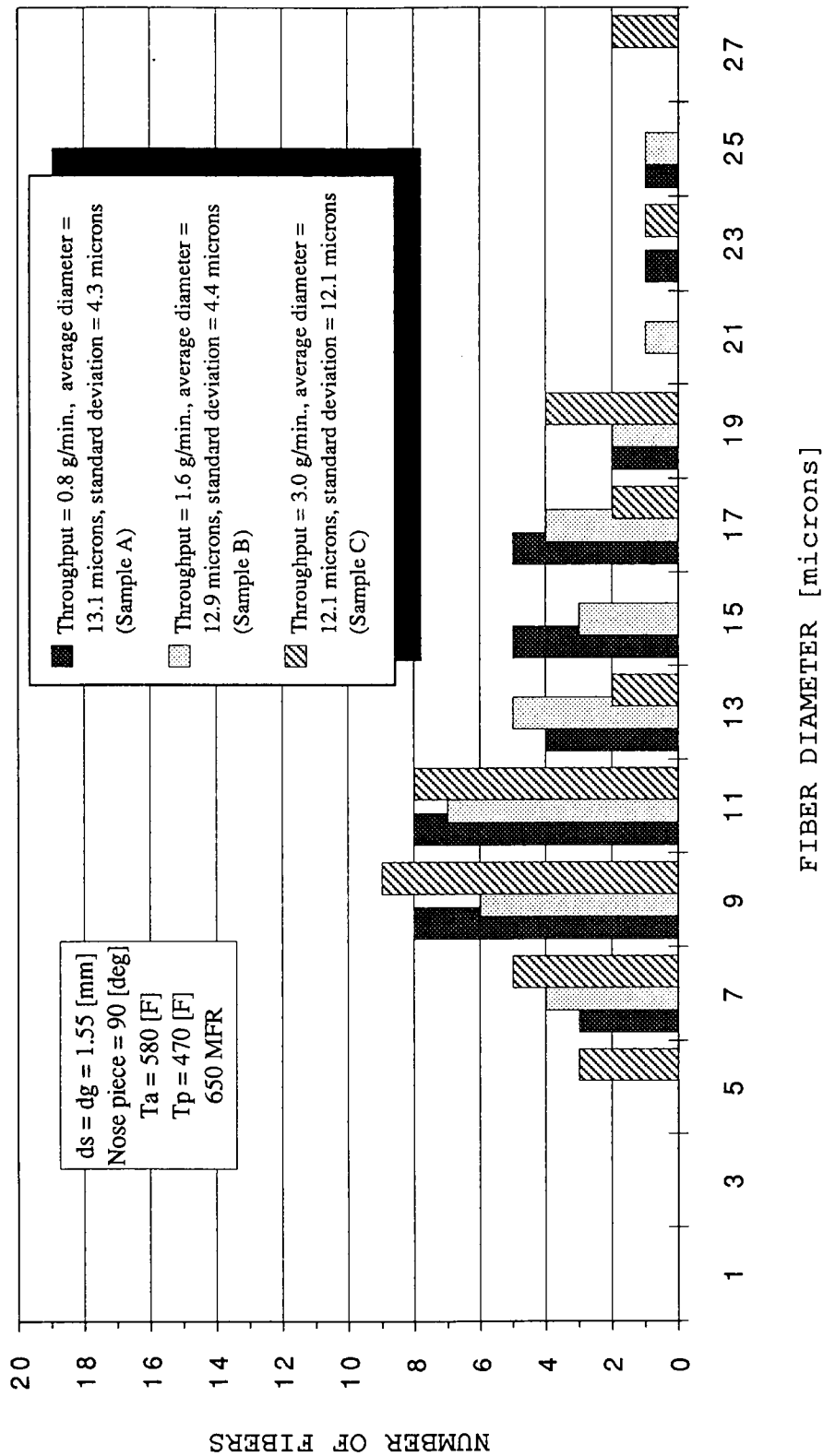


Figure 3.35: Effect of polymer throughput on fiber diameter histograms for samples of similar average diameter (Ta = 580 F, Tp = 470 F)

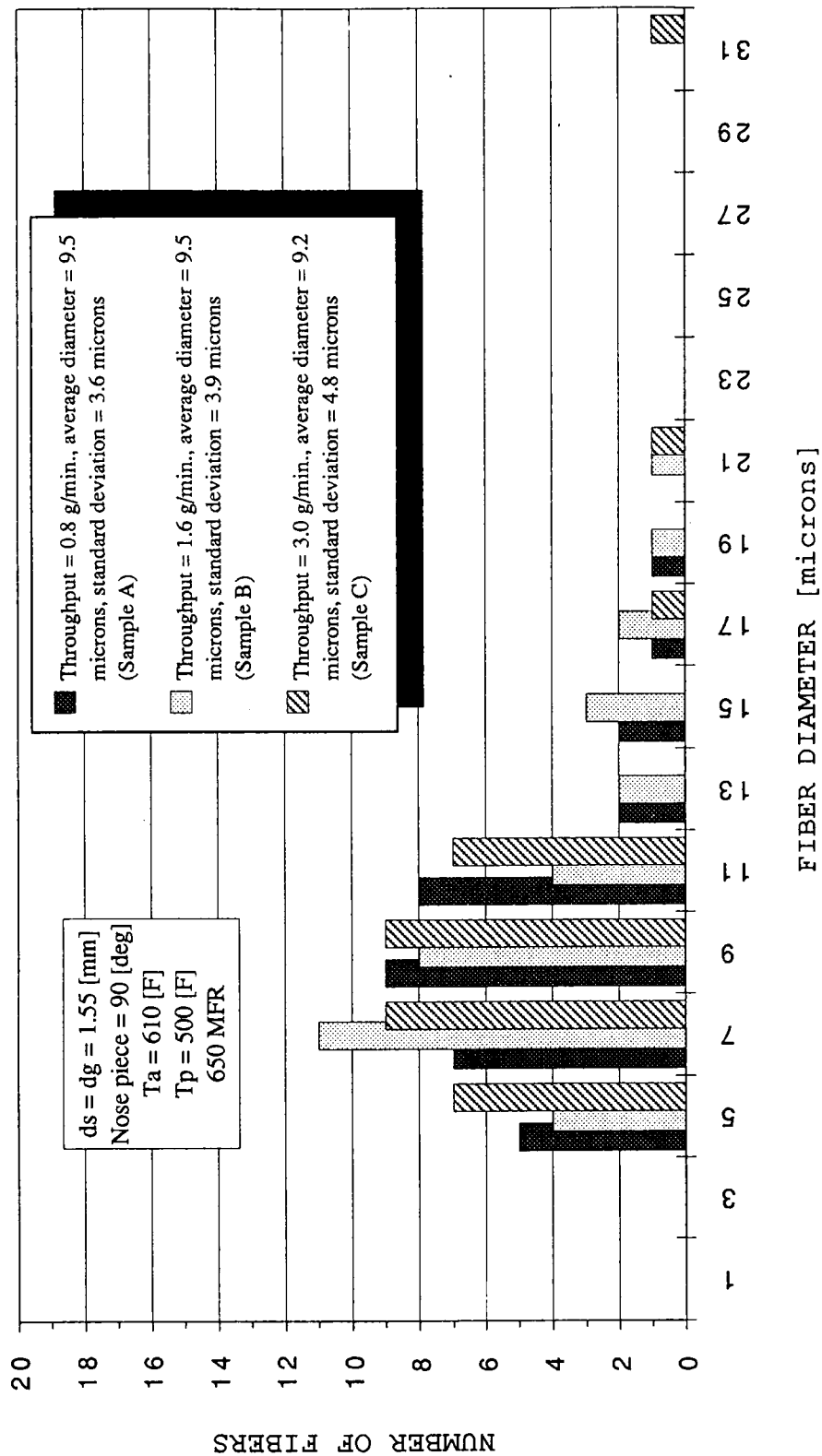


Figure 3.36: Effect of polymer throughput on fiber diameter histograms for samples of similar average diameter (Ta = 610 F, Tp = 500 F)

than in the processing conditions at which they are processed.

Polymer and Air Jet Temperature

Some modifications to the UTK single hole melt blowing facility had to be made in order to perform the following two studies: effect of polymer and air jet temperature on fiber diameter. The modification was required to decouple one temperature from the other since previously, in order to achieve a given polymer temperature, the air jet temperature had to be adjusted until the desired die tip temperature was achieved. Haynes studies [13] in this area are limited by this coupled effect. Two cartridge heaters were installed at the die tip. These heaters could maintain a given die tip temperature independent of the air jet temperature. With this new set up, a range of polymer temperatures could be processed at a constant air jet temperature, and vice versa.

Polymer Temperature

Several polymer temperatures were processed at three air jet temperatures (510, 460, and 400 F). Figure 3.37 shows the effect that polymer temperature has on average fiber diameter for an air jet temperature of 510 F. It can be seen that an increase the polymer temperature results in

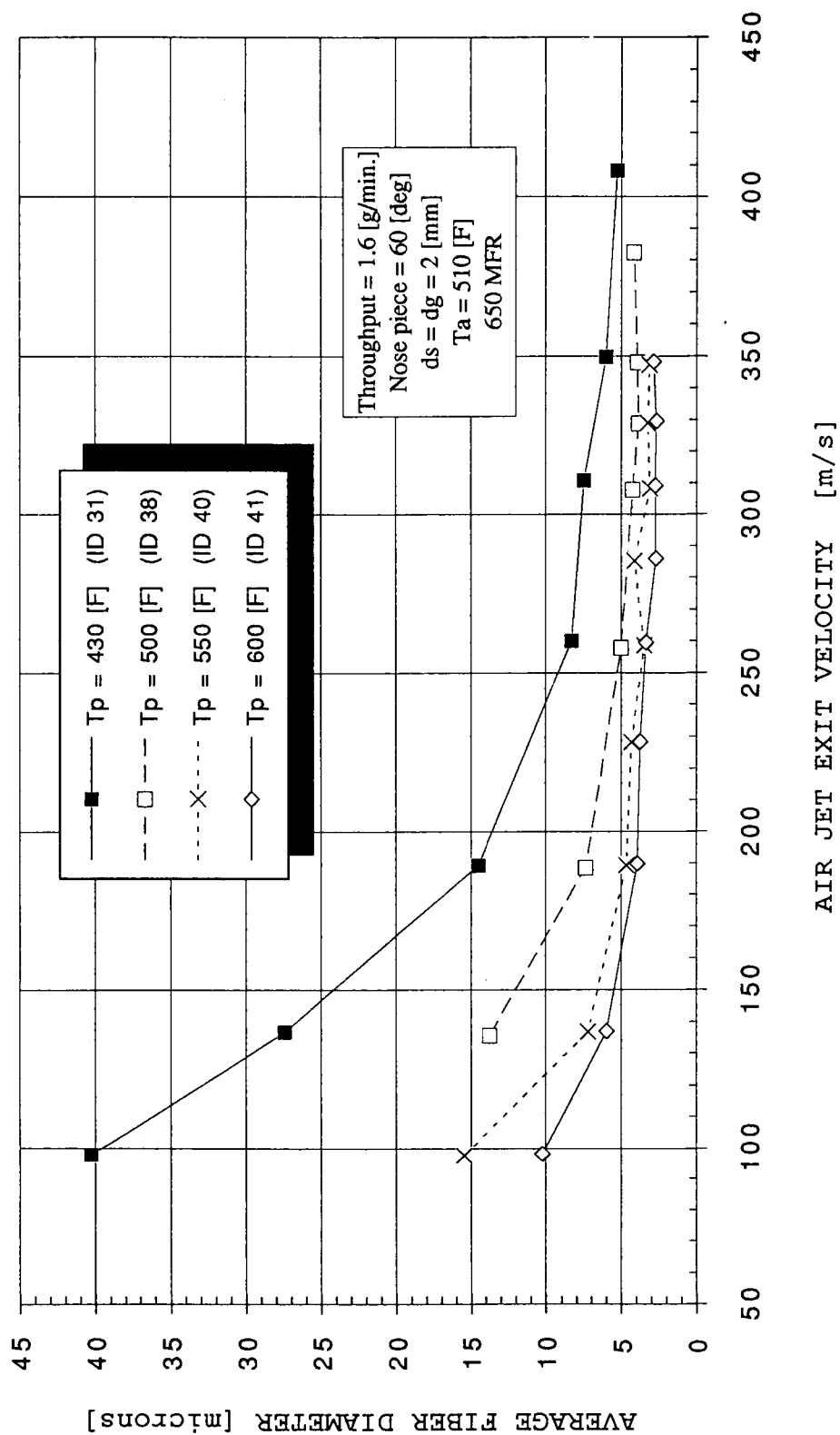


Figure 3.37: Effect of polymer temperature on average fiber diameter (Ta = 510 F)

smaller fiber diameters. This effect is most significant at low air velocities. Figures 3.38 and 3.39 show the fiber diameter histograms for the samples collected at 140 and 350 m/s, respectively, which are shown in Figure 3.37. Increasing the polymer temperature reduces the average fiber diameter for a given exit air velocity. Also, more uniform fibers are produced at higher polymer temperatures for a given exit air velocity. Figures 3.40 and 3.41 present more data showing the effect that polymer temperature has on average fiber diameter for air jet temperatures of 460 and 400 F, respectively. It can be seen from these Figures that as the air velocity increases the fiber diameter dependence on polymer temperature is asymptotically reduced. As it has been shown in previous sections, the average fiber diameter seems to approach an asymptotic value as the exit air velocity is increased. The dependence of these asymptotic values on air jet temperature seems to be negligible since in all three cases, the fiber diameters converge to values between 4 to 6 microns. Figures 3.42 and 3.43 show the fiber diameter histograms for the samples collected at 125 and 320 m/s, respectively, which are shown in Figure 3.41. It can be seen that increasing the polymer temperature reduces the average fiber diameter. Also, as it has been seen in the previous sections, smaller average fiber diameters are associated with more uniform fibers (smaller standard deviation).

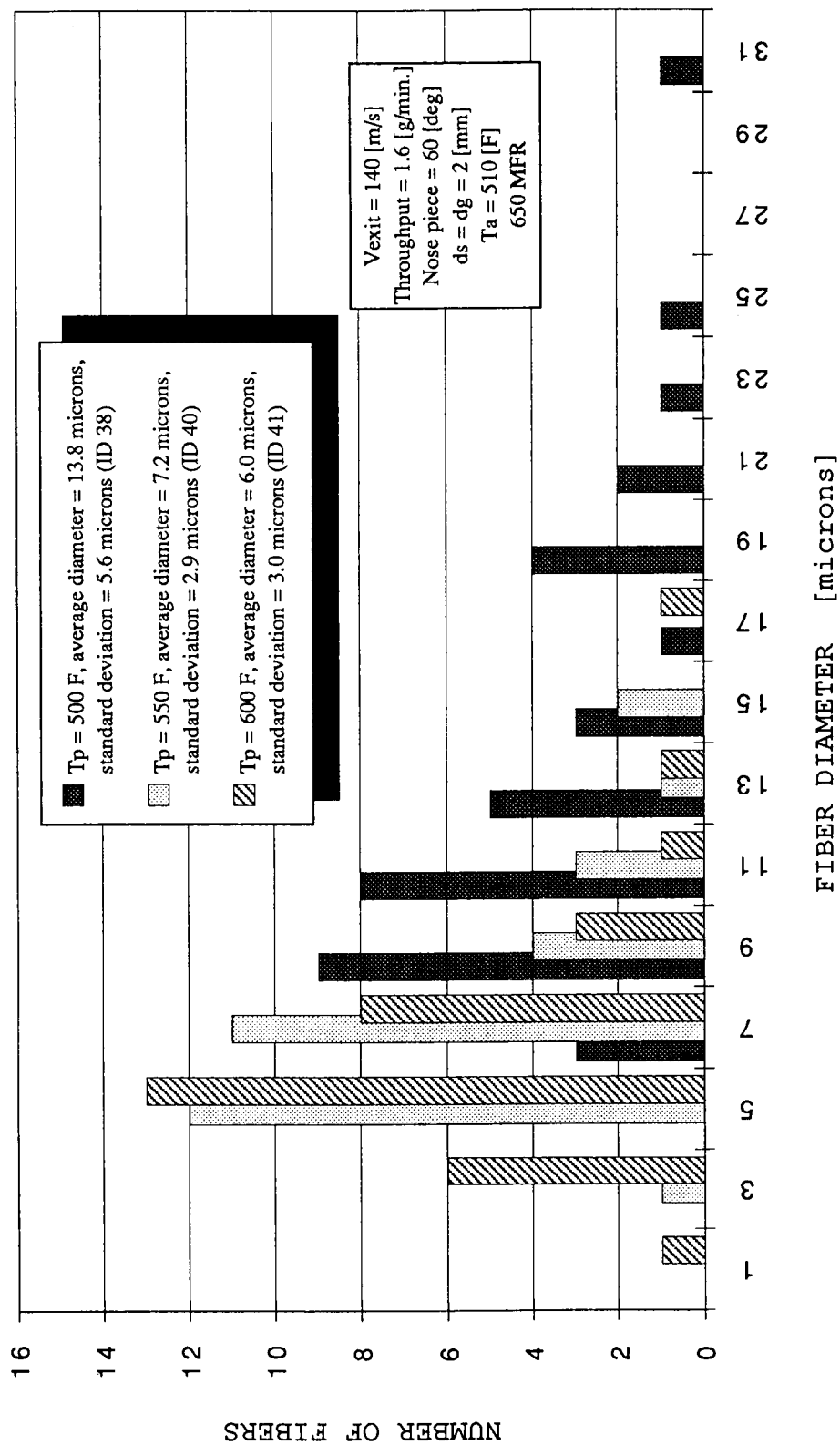


Figure 3.38: Effect of polymer temperature on fiber diameter histograms; 140 m/s (ID 38, 40, 41)

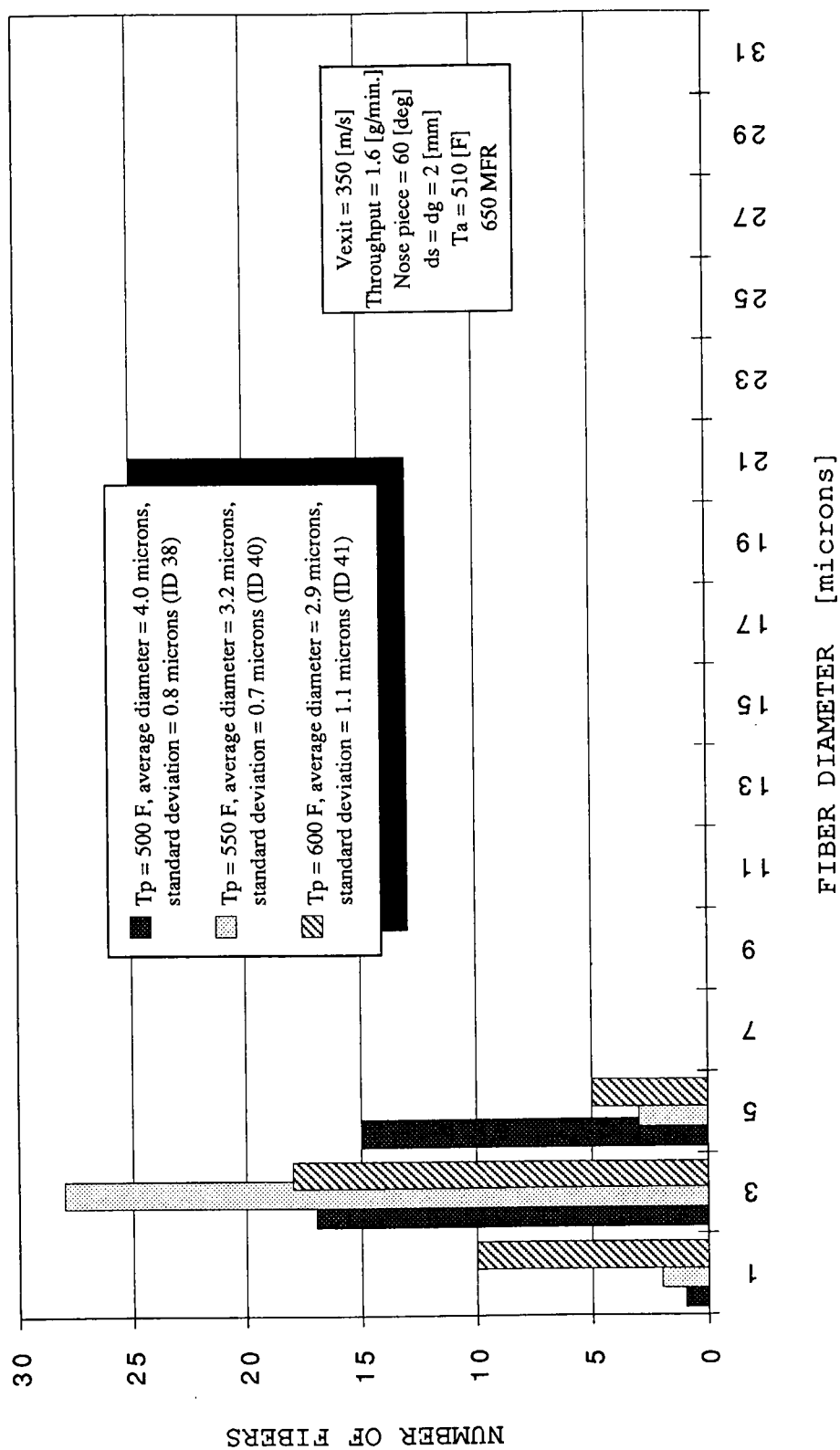


Figure 3.39: Effect of polymer temperature on fiber diameter histograms; 350 m/s (ID 38, 40, 41)

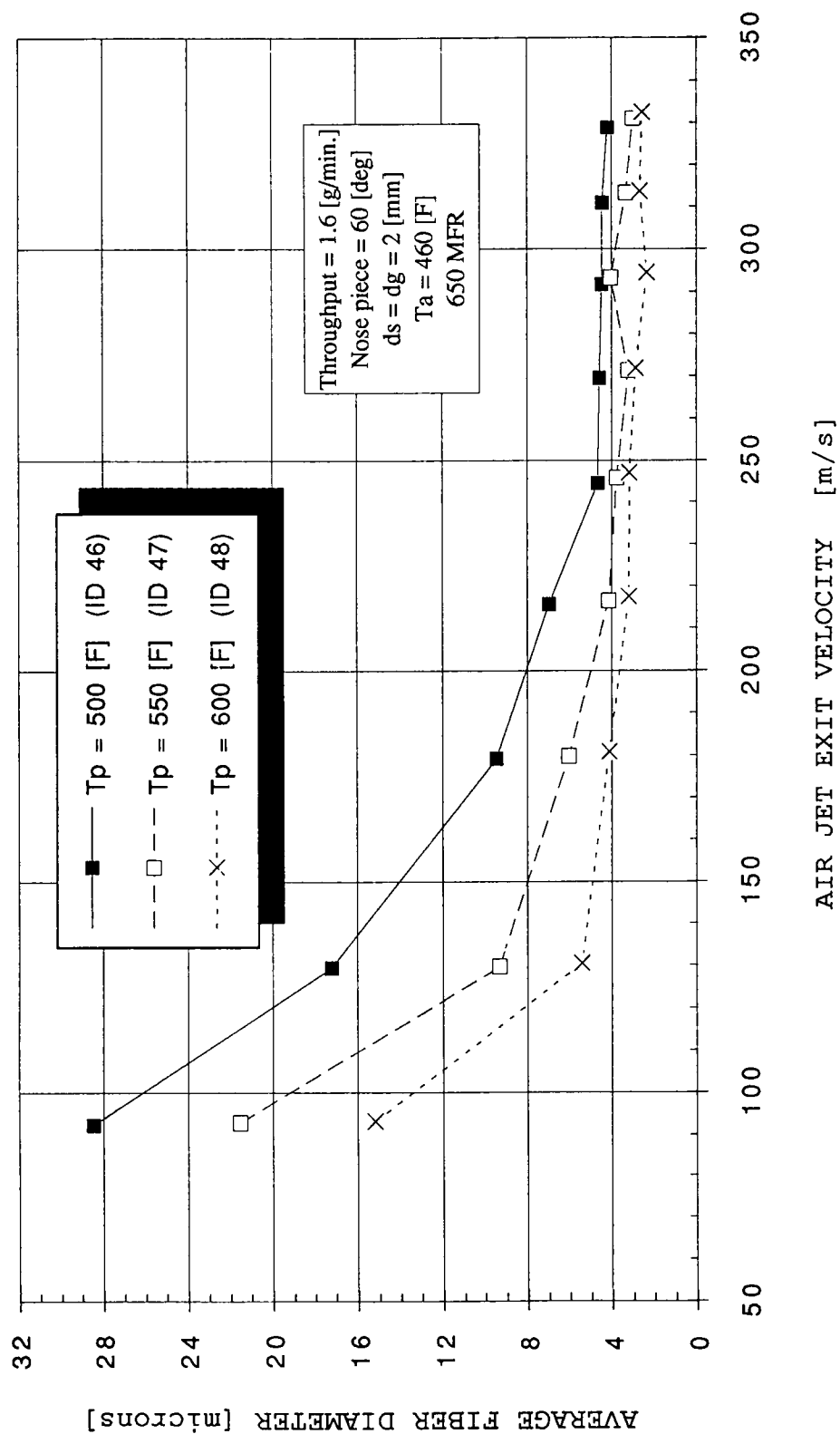


Figure 3.40: Effect of polymer temperature on average fiber diameter (Ta = 460 F)

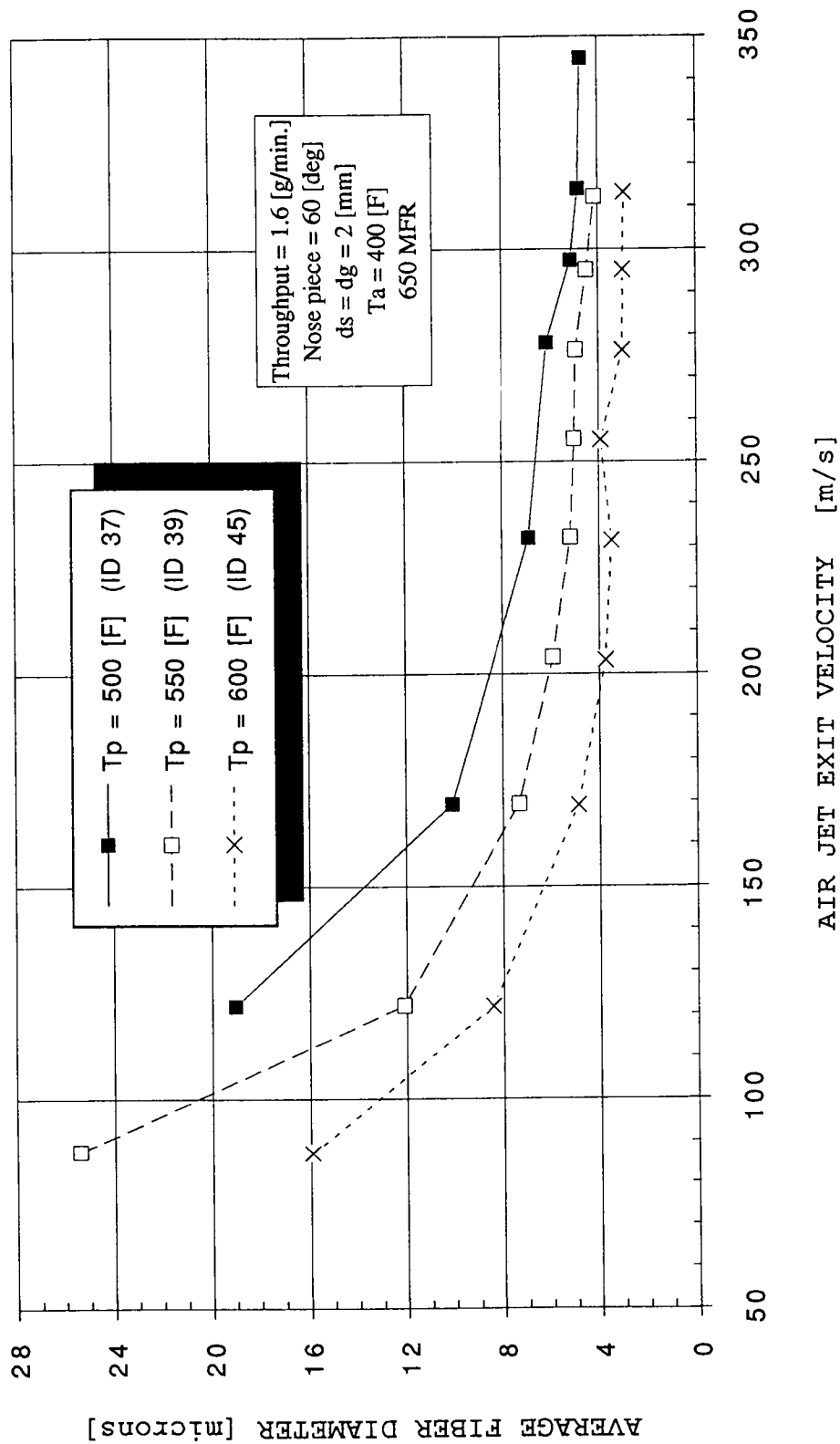


Figure 3.41: Effect of polymer temperature on average fiber diameter (Ta = 400 F)

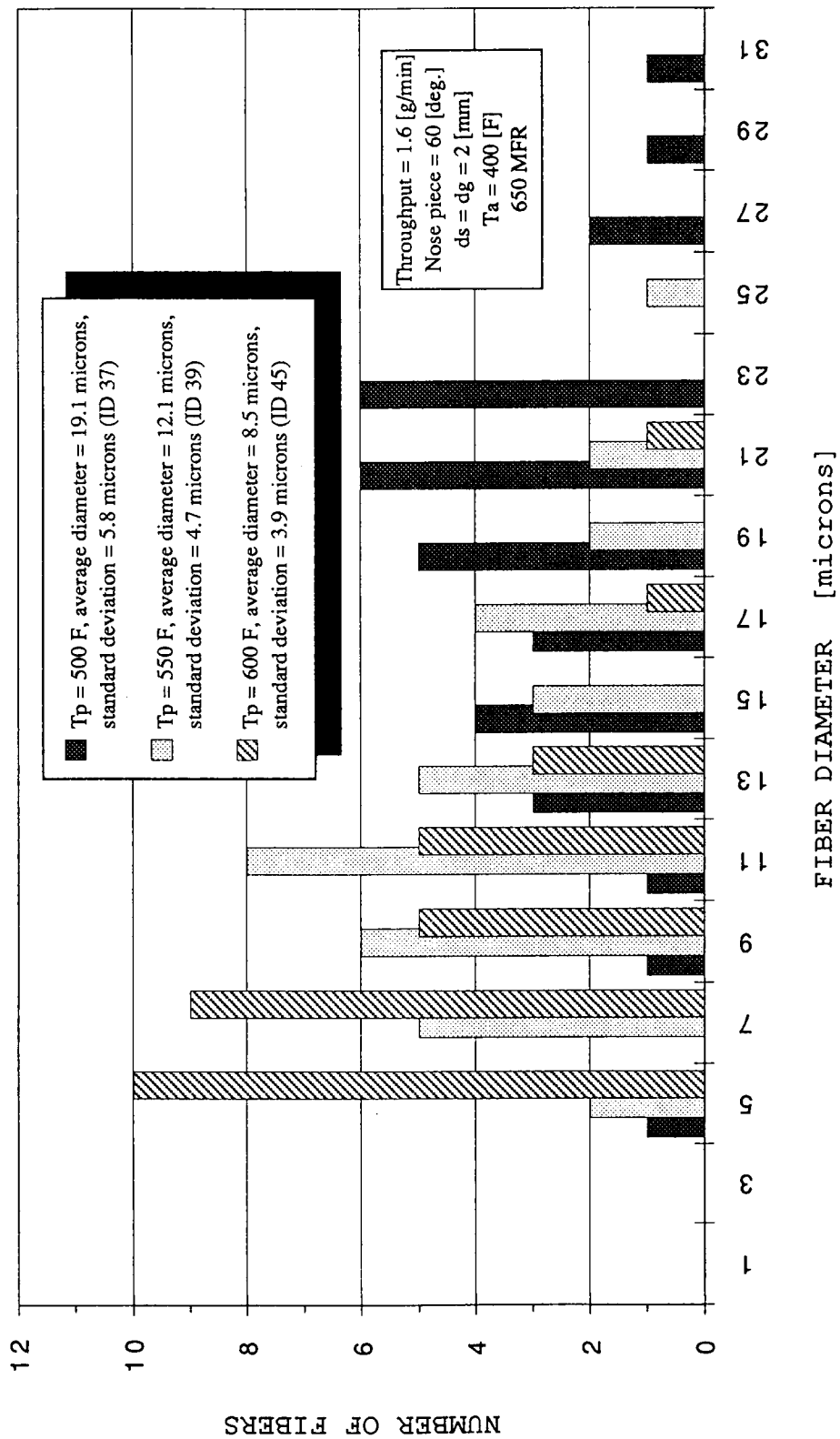


Figure 3.42: Effect of polymer temperature on fiber diameter histograms; 125 m/s (ID 37, 39, 45)

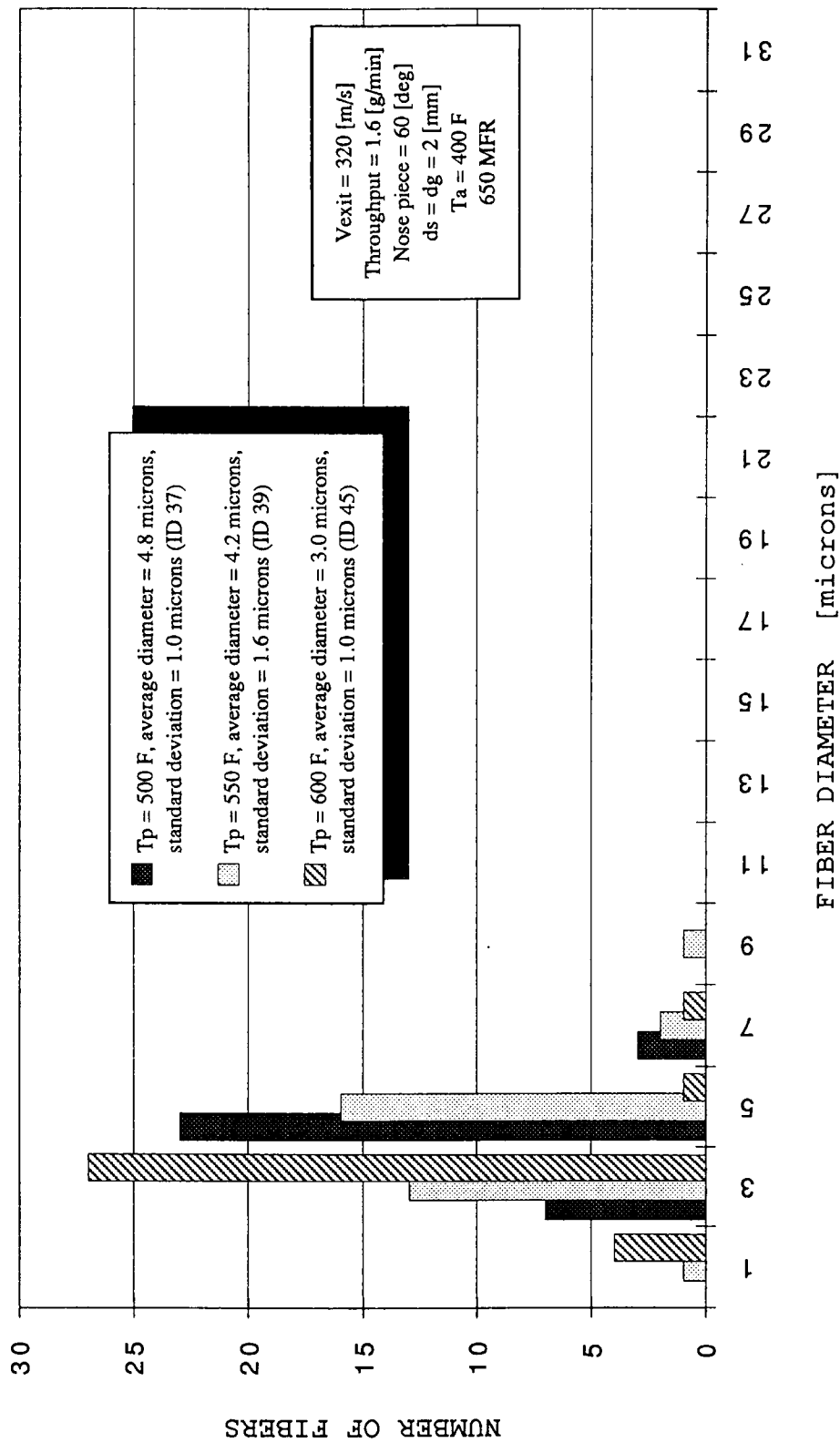


Figure 3.43: Effect of polymer temperature on fiber diameter histograms; 320 m/s (ID 37, 39, 45)

The reason why the fiber diameter is smaller at higher polymer temperatures for a given exit air velocity could be attributed to the fact that at higher polymer temperatures, the fibers in flight can be attenuated for a longer period of time before they reach their solidification temperature. After the fibers solidify they can no longer be further reduced in diameter. Also, as it has been shown in previous sections for other processing variables, there is no clear indication that this increase in polymer temperature is directly responsible for the fibers being more or less uniform.

Air jet Temperature

Several air jet temperatures were processed at three polymer temperatures (500, 550, and 600 F). Figure 3.44 shows the effect that air jet temperature has on average fiber diameter for a polymer temperature of 600 F. It can be seen that increasing the air jet temperature from 370 to 510 F has a small effect on fiber diameter for a given air velocity except at air velocities below 100 m/s where there seems to be a trend of producing larger fibers at lower air jet temperatures. Figures 3.45 and 3.46 show the fiber diameter histograms for the samples collected at air velocities of 300 and 125 m/s, respectively, which are shown in Figure 3.44. All of the webs collected at 300 m/s (Figure

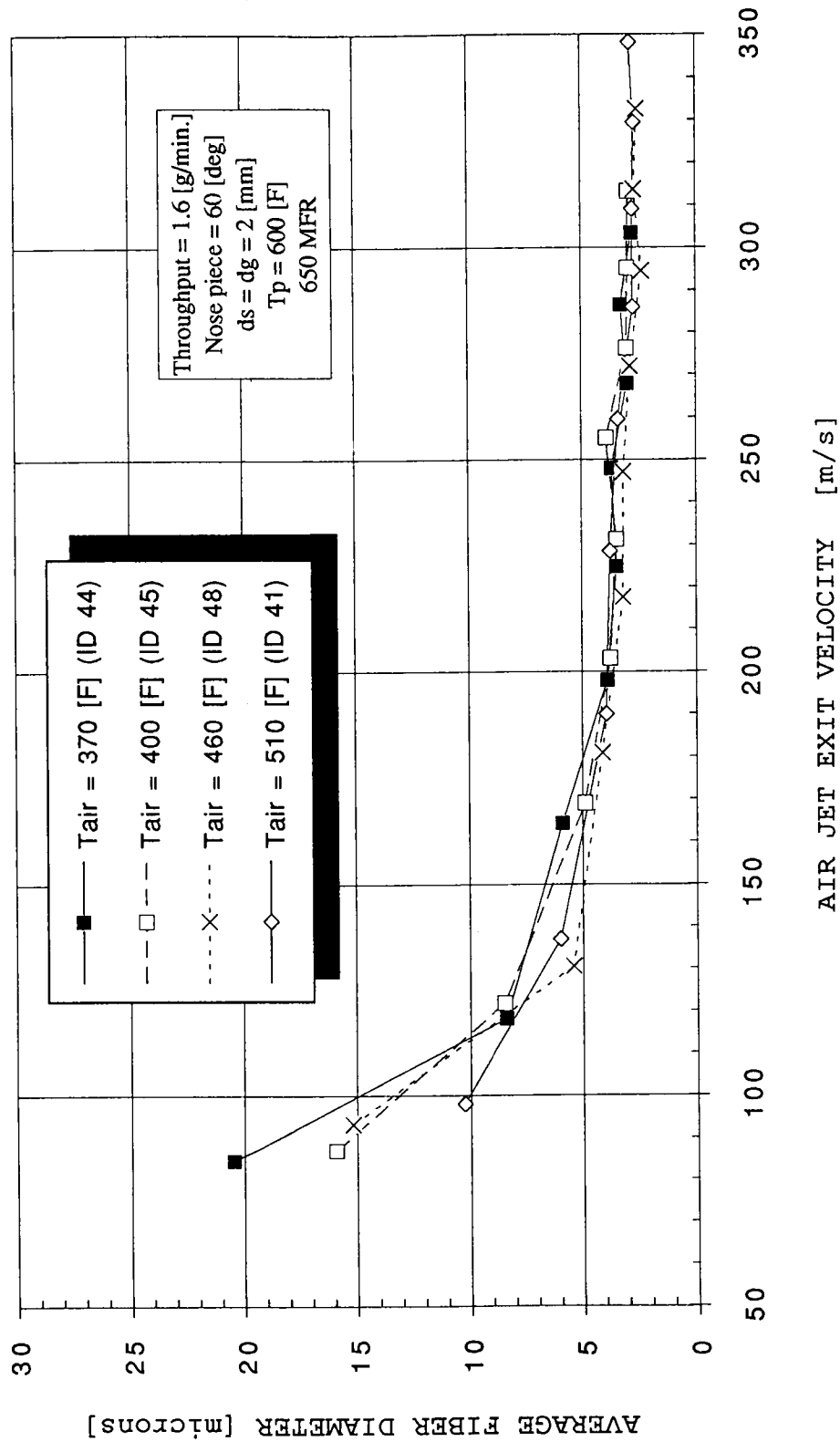


Figure 3.44: Effect of air jet temperature on average fiber diameter; (Tp = 600 F)

3.45) have approximately the same small average fiber diameter value (2.9 microns) and approximately the same small standard deviation (0.8 microns). These results suggest that the air jet temperature has a negligible effect on the size of the fibers and in the uniformity of the fibers at high air jet velocities. At low air jet velocities (see Figure 3.46) the fibers are less uniform and larger in diameter. Also, there appears to be a trend of making larger fibers at lower air jet temperatures. Figures 3.47 and 3.48 show the effect that air jet temperature has on average fiber diameter at lower polymer temperatures: 550 and 500 F, respectively. It can be seen that as the air jet velocity increases, the effect that air jet temperature has on fiber diameter becomes negligible. However, as the polymer temperature is decreased from 600 to 500 F (see Figures 3.44 and 3.48, respectively) there appears to be a trend of producing larger fibers at lower air jet temperatures. Figure 3.49 shows the fiber diameter histograms for the samples collected at an exit air velocities of 290 m/s which are shown in Figure 3.47. As it should be expected, small sized fibers are produced at high exit air velocities with a small standard deviation.

There is no evidence that indicates that the air jet temperature has an effect on the size and on how uniform a fiber is. Also, up to this point, all the results indicate that it is the size of the fibers and not the processing

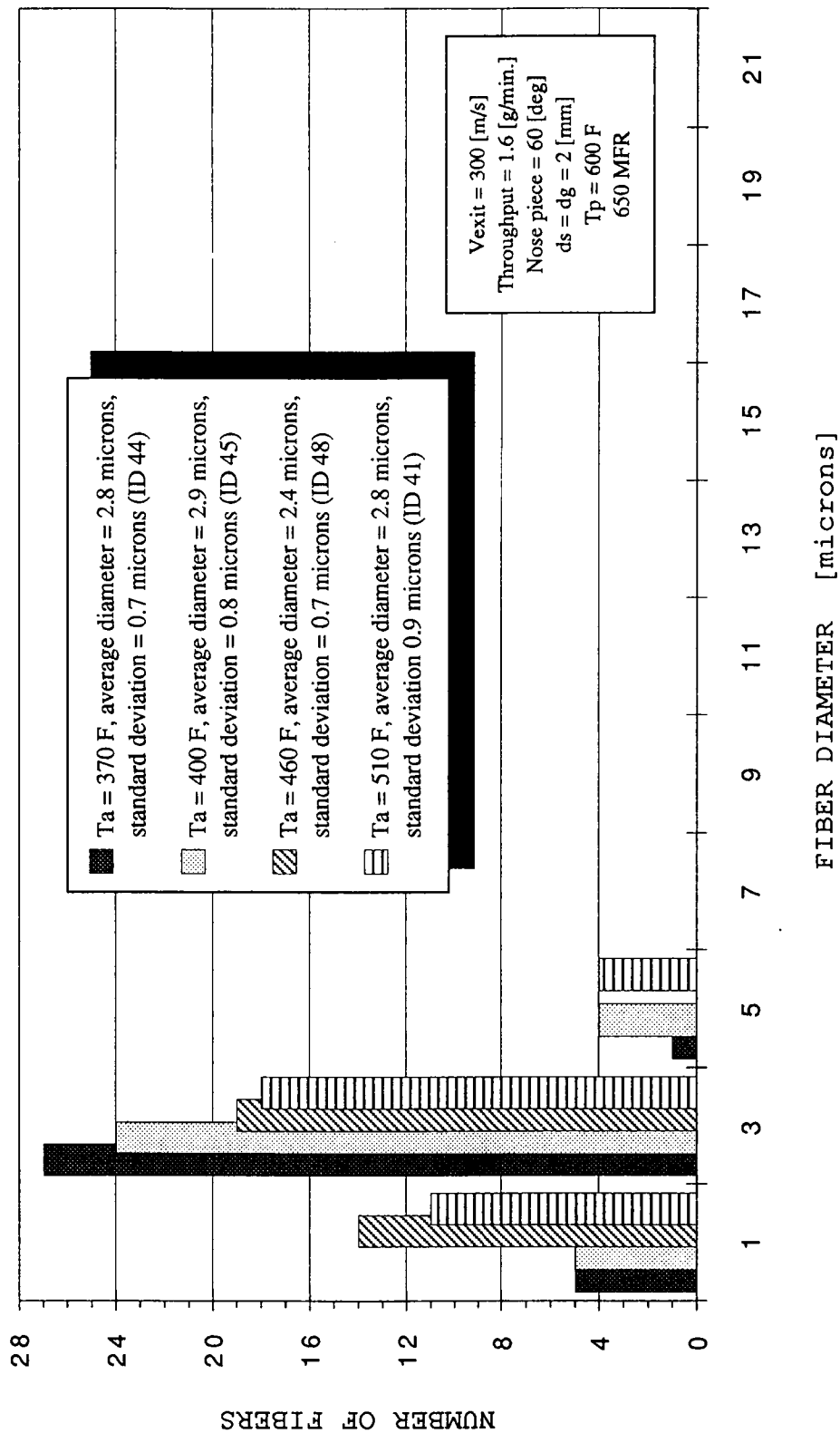


Figure 3.45: Effect of air jet temperature on fiber diameter histograms; 300 m/s (ID 44, 45, 48, 41)

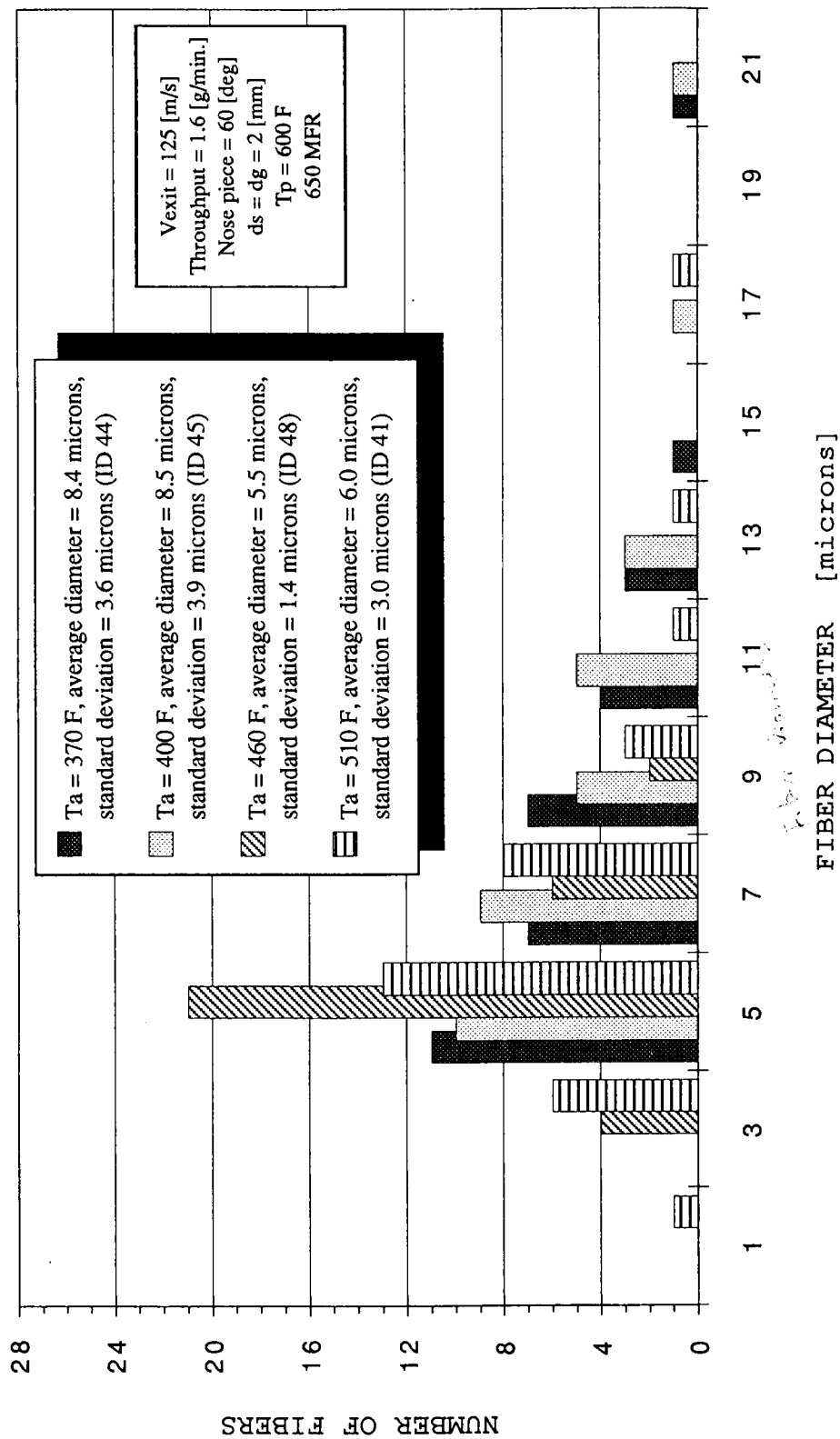


Figure 3.46: Effect of air jet temperature on fiber diameter histograms; 125 m/s (ID 44, 45, 48, 41)

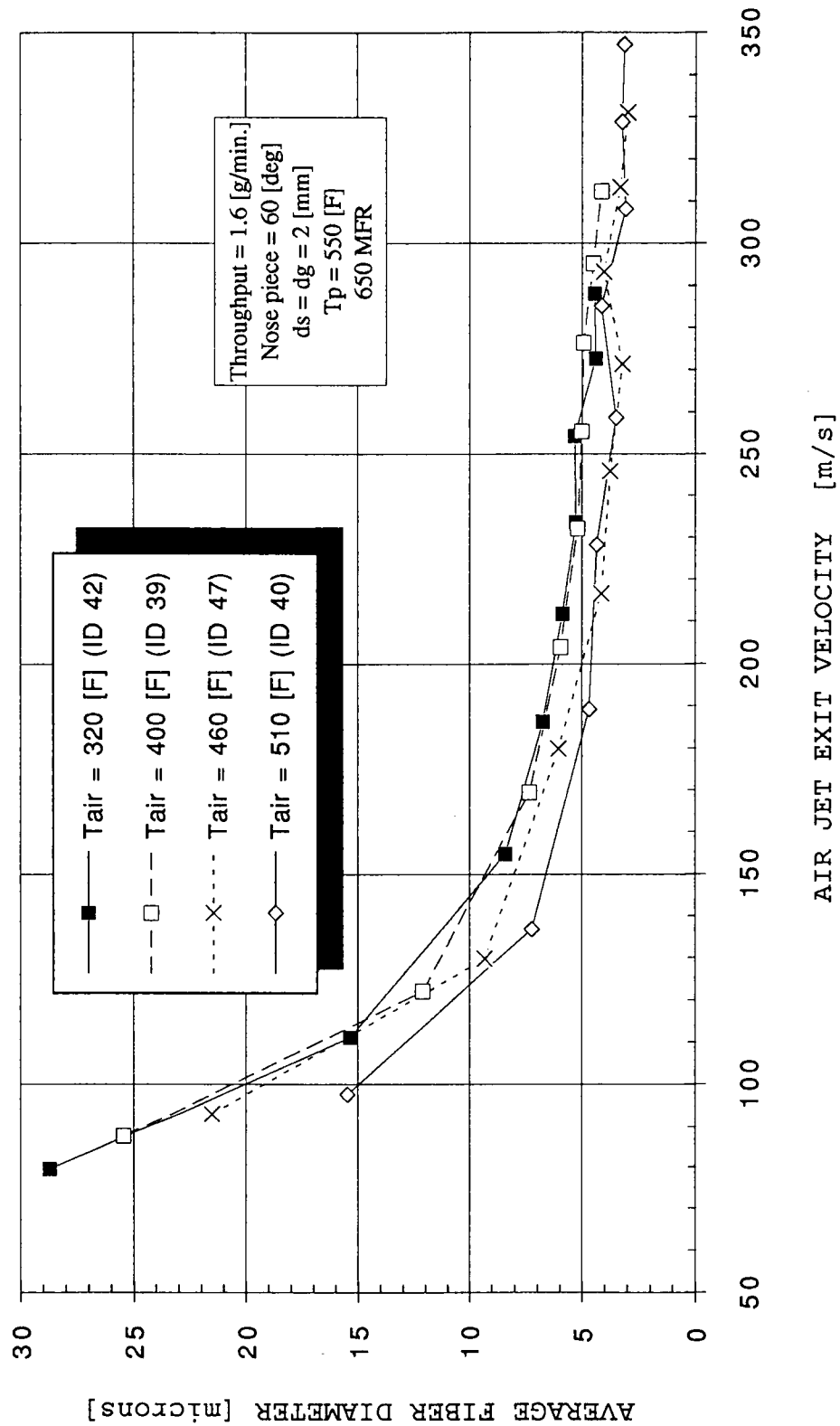


Figure 3.47: Effect of air jet temperature on average fiber diameter; (Tp = 550 F)

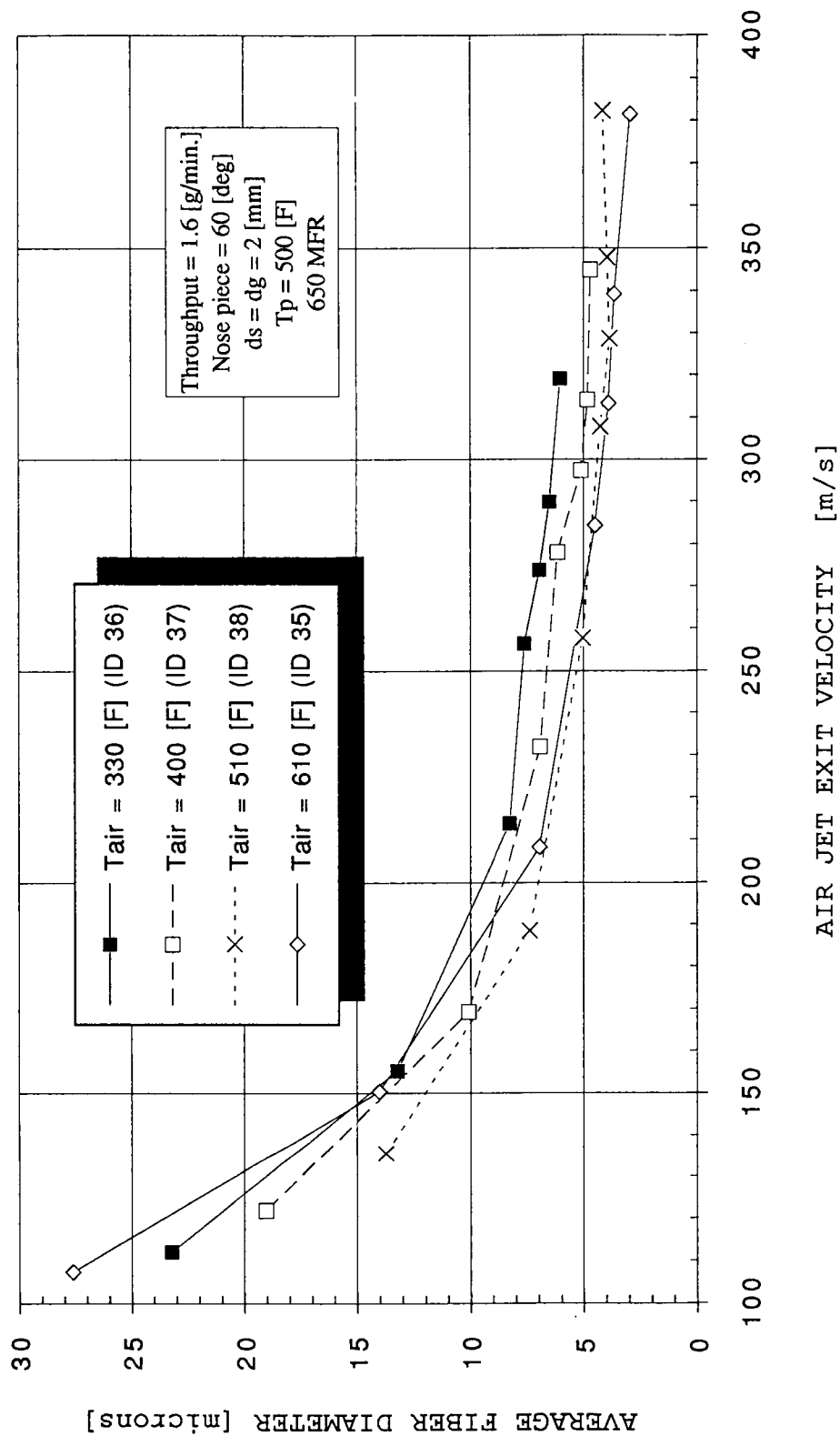


Figure 3.48: Effect of air jet temperature on average fiber diameter; (Tp = 500 F)

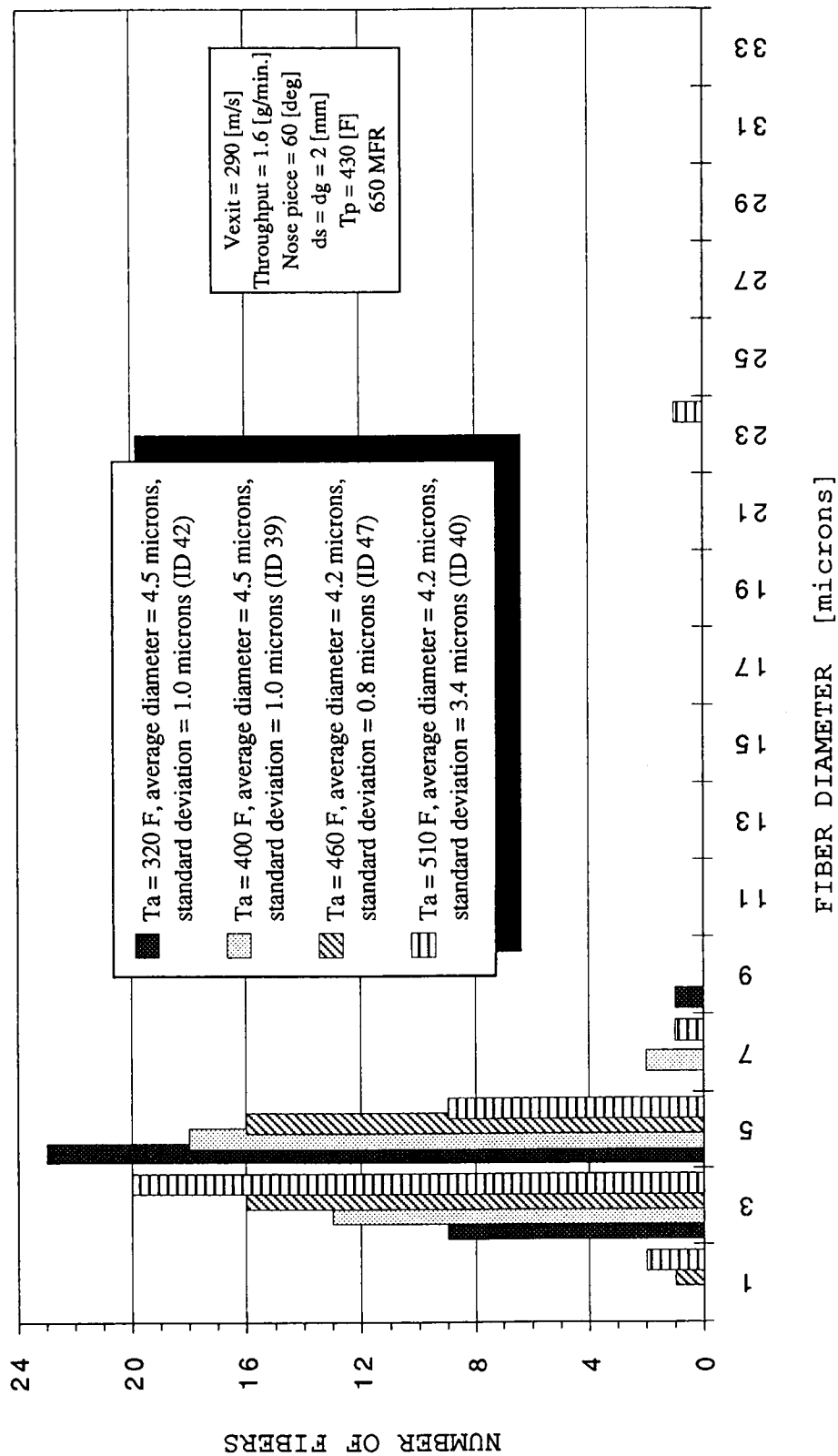


Figure 3.49: Effect of air jet temperature on fiber diameter histograms; 290 m/s (ID 42, 39, 47, 40)

conditions that determines how uniform a fiber is. All other processing conditions except air jet temperature have shown to have a direct effect on the size of the fibers being produced: increasing exit air velocity ,increasing the air gap, reducing setback, decreasing air jet injection angle, decreasing polymer throughput, and increasing polymer temperature, each one independently reduces the average fiber diameter of a web. It is valid then to postulate at this time that air jet temperature might have an effect on the mechanical properties rather than the size of the fibers. The next section addresses this specific question: Does the air jet temperature have an effect on the strength of the fibers?

Mechanical Properties of Single Fibers

This section presents the results of the efforts made to determine what effect, if any, air jet temperature has on the strength of single fibers. Two independent sets of data were used to support this study: one set of data was generated by the author using 650 MFR polypropylene material while the other set was generated by Sherwood [16] using 35 MFR polypropylene. The results for each set of data are presented separately.

As mentioned in Chapter II, birefringence is an indicator of the strength of a single fiber and it is

measured in a non-destructive test (interference microscope). Breaking force and breaking stress, on the other hand, are two parameters which also provide an indication of how strong a single fiber is. These last two parameters, however, are obtained from a destructive test (tensile strength test). All three of these single fiber strength indicators are used in the next subsections to determine if there is any correlation between the strength of a single fiber and the air jet temperature. An experiment was conducted to determine the reproducibility of the tensile strength test results before the actual samples were analyzed. A total of 14 samples were cut from a spool of polypropylene material of constant diameter. Each one of these samples was subjected to the tensile strength test described in Chapter II. The breaking force and breaking elongation was recorded and the results are shown in Table 3.2. The data is distributed in a narrow band as is indicated by the low standard deviations for both the breaking force (0.03 N) and breaking elongation (17%) which have average values of 0.35 N and 127%, respectively. The least count for the breaking force and the breaking stress are 0.001 N and 2.5%, respectively.

It should also be remembered that a single fiber specimen is a single fiber approximately 13 inches long which is cut into up to six single fiber samples. Thus, there are up to six data points for each specimen at a given

Table 3.2: Reproduction of tensile strength test.

SAMPLE	ELONGATION [%]	BREAKING FORCE [N]
1	288	0.33
2	268	0.30
3	315	0.36
4	275	0.35
5	310	0.39
6	345	0.39
7	228	0.31
8	373	0.31
9	313	0.32
10	313	0.36
11	375	0.34
12	375	0.40
13	320	0.36
14	355	0.39
Average	318	0.351
Standard Deviation	42	0.032
Least Count	3	0.001

set of processing conditions. It is the average of these six data points that is presented in all of the results to follow in this section.

650 MFR Data

Two sets of data at a different polymer temperature (550 and 500 F) were collected to support this study. The first set of single fiber specimens were collected at a polymer temperature of 550 F (see Figure 3.2). Figure 3.50 shows the average birefringence at three air jet temperatures (560, 450, and 320 F) as a function of the specimen average diameter. It can be seen that as the air jet temperature is decreased the fibers tend to be stronger for diameters smaller than 8 microns. No clear trends are seen beyond this point. Figure 3.51 shows the average breaking force (force required to break the samples under tension) as a function of the specimen average diameter. It can be seen that specimens with larger average diameters are stronger (larger average breaking forces). However, there doesn't appear to be a clear trend showing the dependence of average breaking force on air jet temperature. In order to remove the dependence that the strength of the fibers has on the size (area) of the fibers, a new parameter is introduced: breaking stress (breaking force per unit area). Figure 3.52 shows the average breaking stress as a function

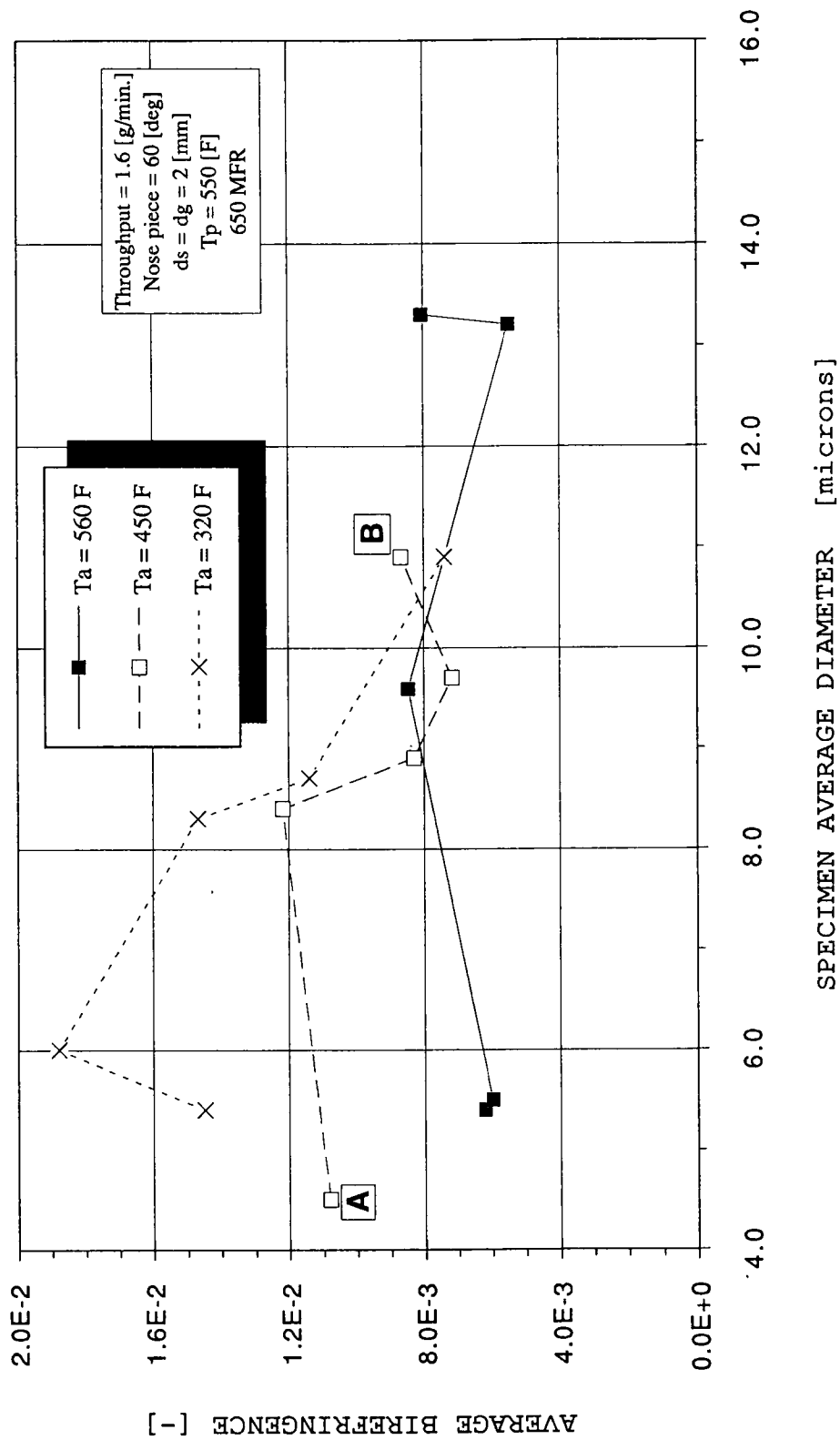


Figure 3.50: Average birefringence versus average diameter of single fiber specimens; (Tp = 550 F)

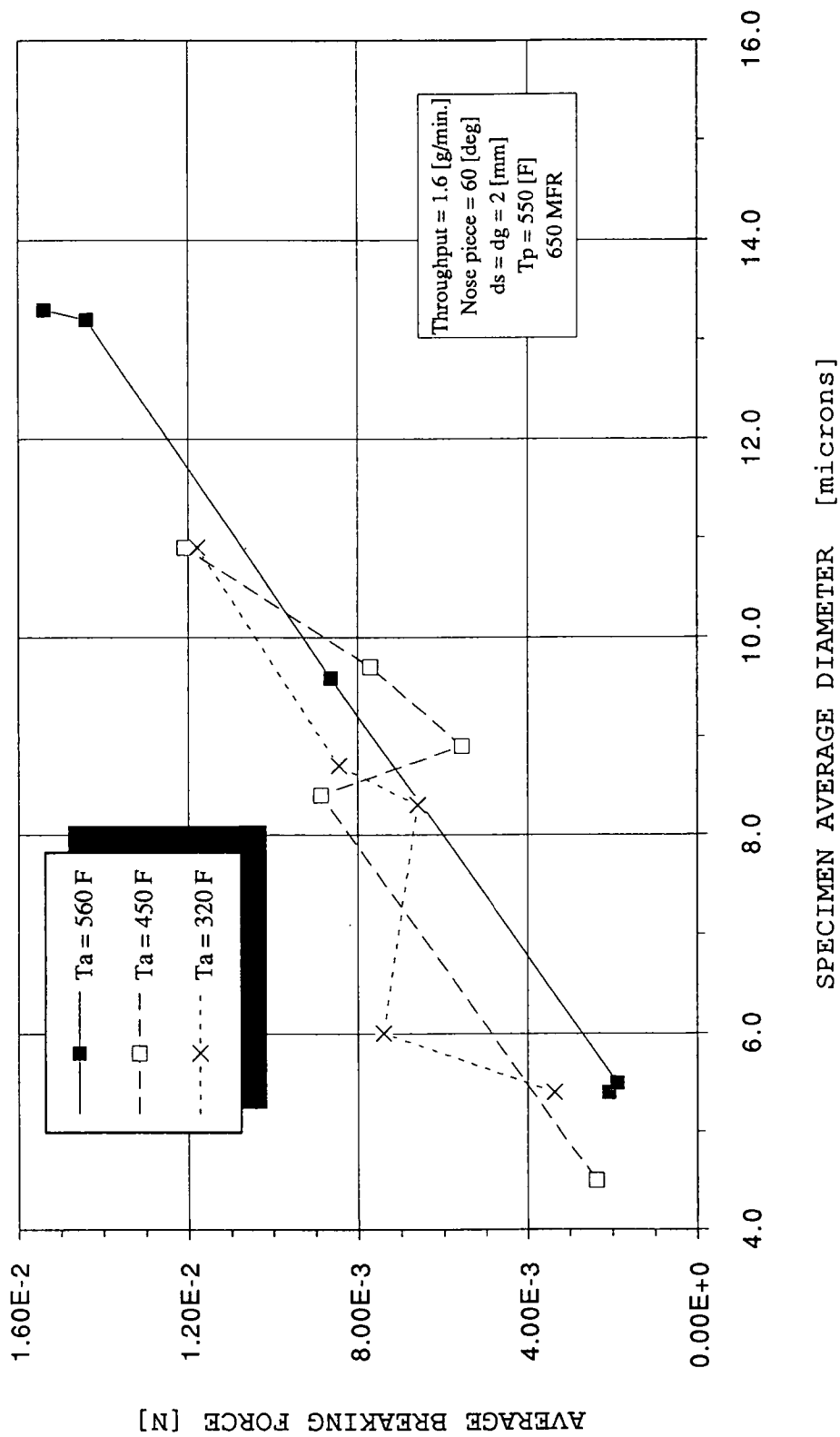


Figure 3.51: Average breaking force versus average diameter of single fiber specimens; (Tp = 550 F)

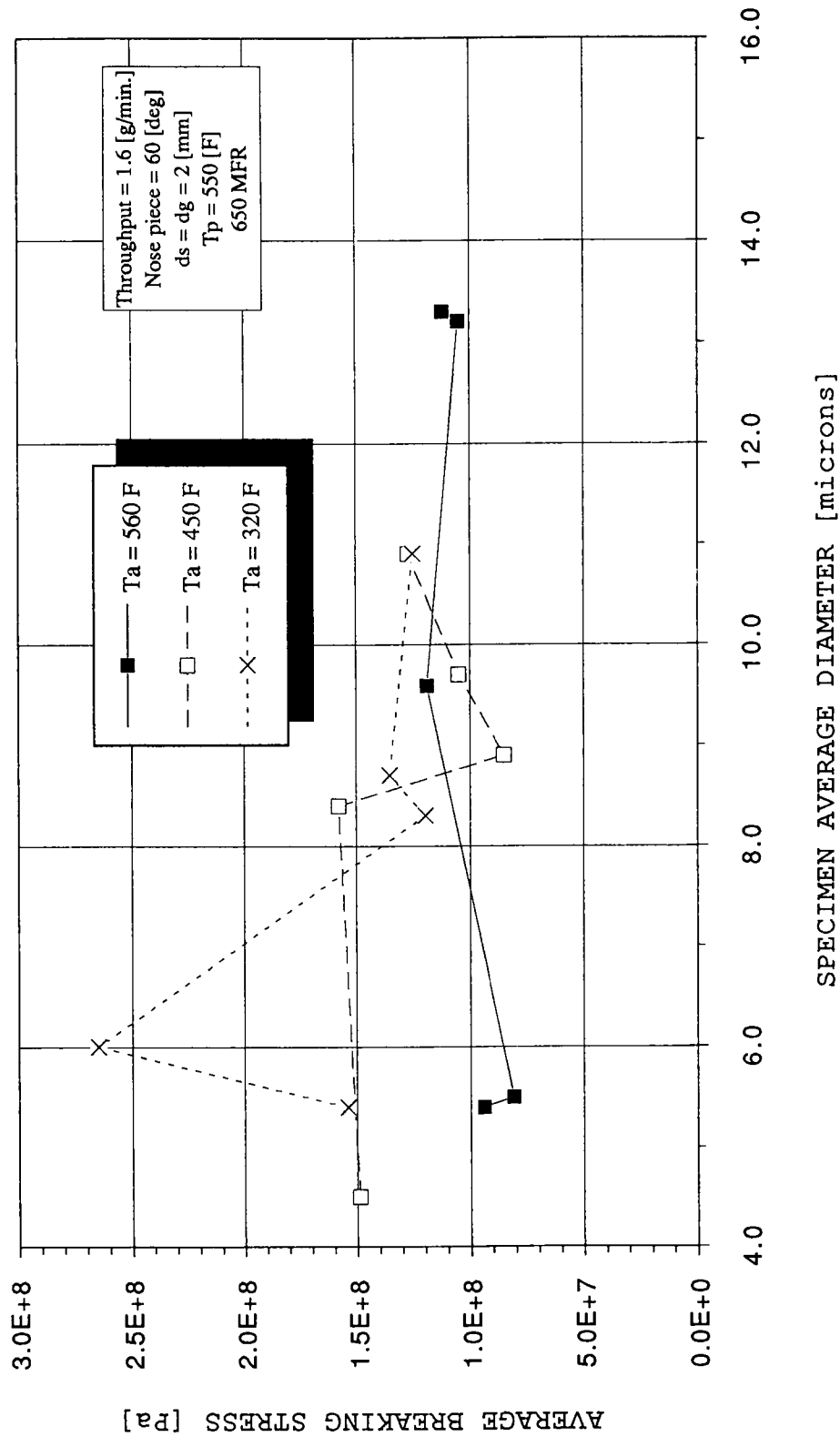


Figure 3.52: Average breaking stress versus average diameter of single fiber specimens (Tp = 550 F)

of the specimen average diameter. As with the results shown in Figure 3.50, it can be seen that the fibers are stronger when processed at lower air temperatures but only up to a given specimen average diameter (8 microns). Figure 3.53 shows the average breaking elongation (on a percent basis from the original length of the sample) as a function of the specimen average diameter. It can be seen that the fibers have a longer average breaking elongation as the specimen average diameter increases. However, there is no evidence showing that air jet temperature has a consistent effect on the breaking elongation of these specimens.

The second set of single fiber samples were collected at a lower polymer temperature (500 F) in order to further pursue the objective of determining if air jet temperature does have an effect on the strength of single fibers. Figure 3.54 shows the average breaking force as a function of the specimen average diameter. Contrary to what was shown in Figure 3.51, now there is a consistent trend of having stronger fibers associated with lower air jet temperatures for a given specimen average diameter. Figure 3.55 shows the average breaking stress as a function of the specimen average diameter. These results are also consistent with previous results in that stronger fibers (larger breaking stresses) are associated with lower air jet temperatures.

One major point should be made at this time. The birefringence and tensile strength tests results indicate

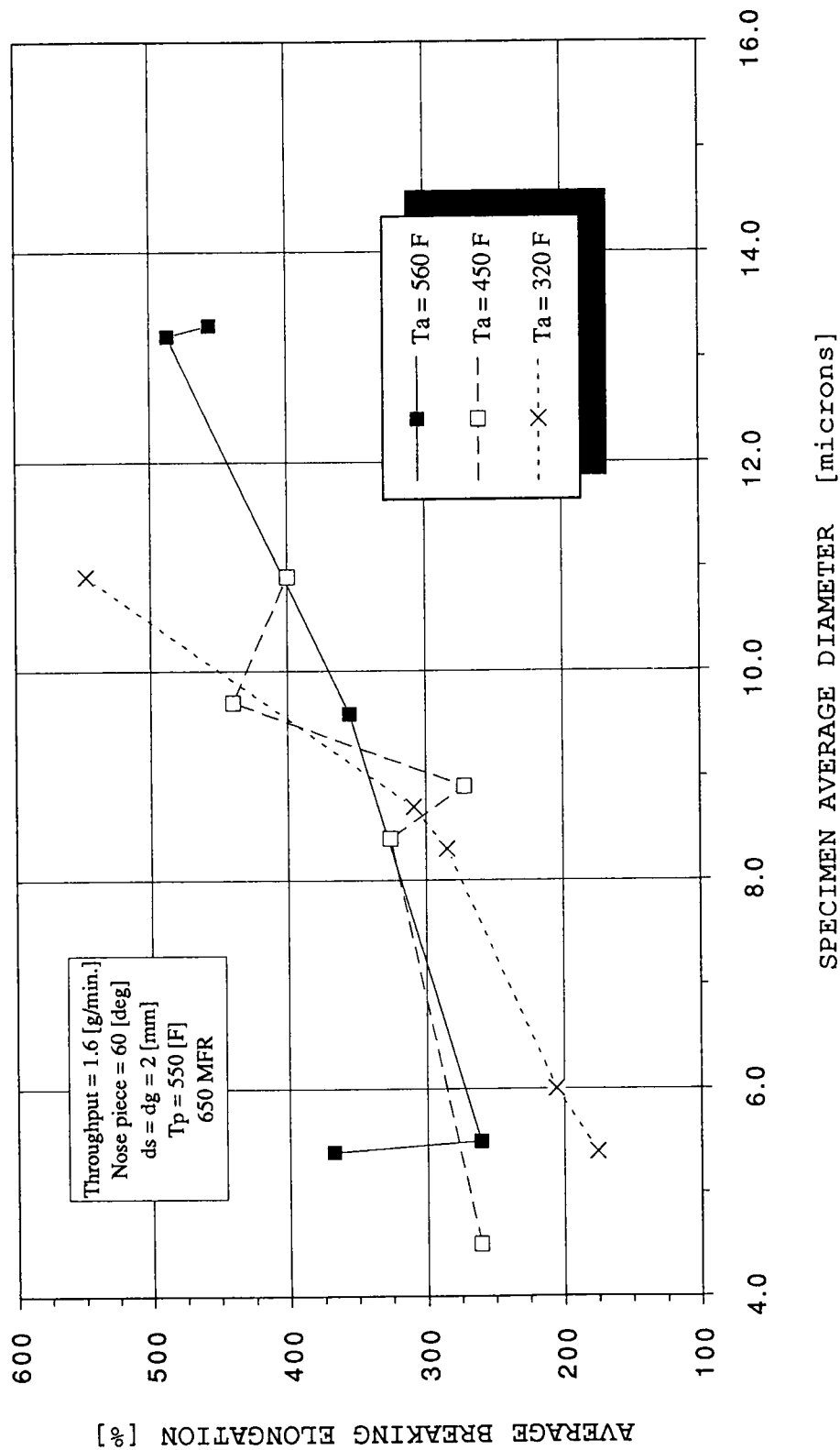


Figure 3.53: Average breaking elongation versus average diameter of single fiber specimens; (Tp = 550 F)

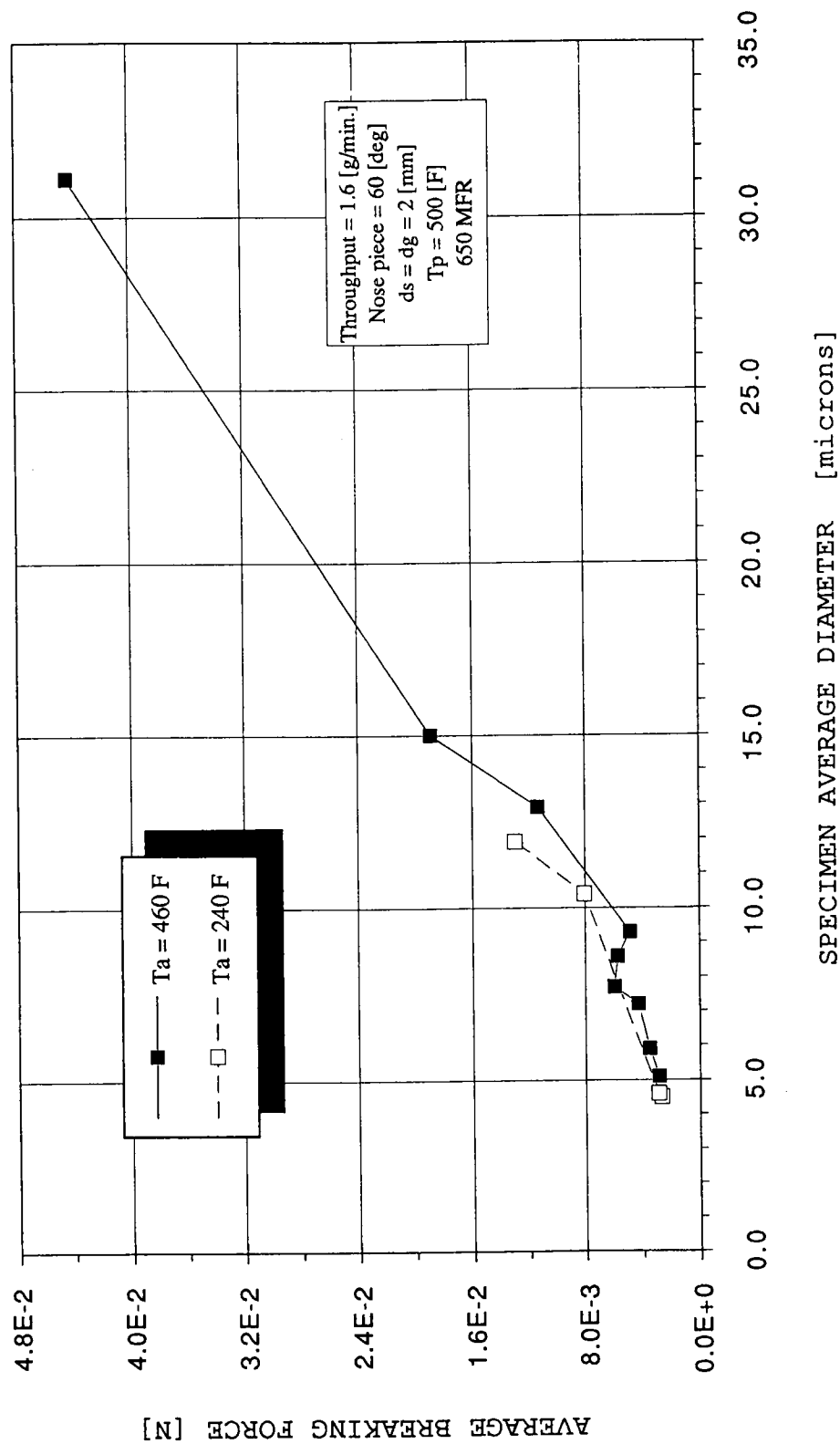


Figure 3.54: Average breaking force versus average diameter of single fiber specimens; (Tp = 500 F)

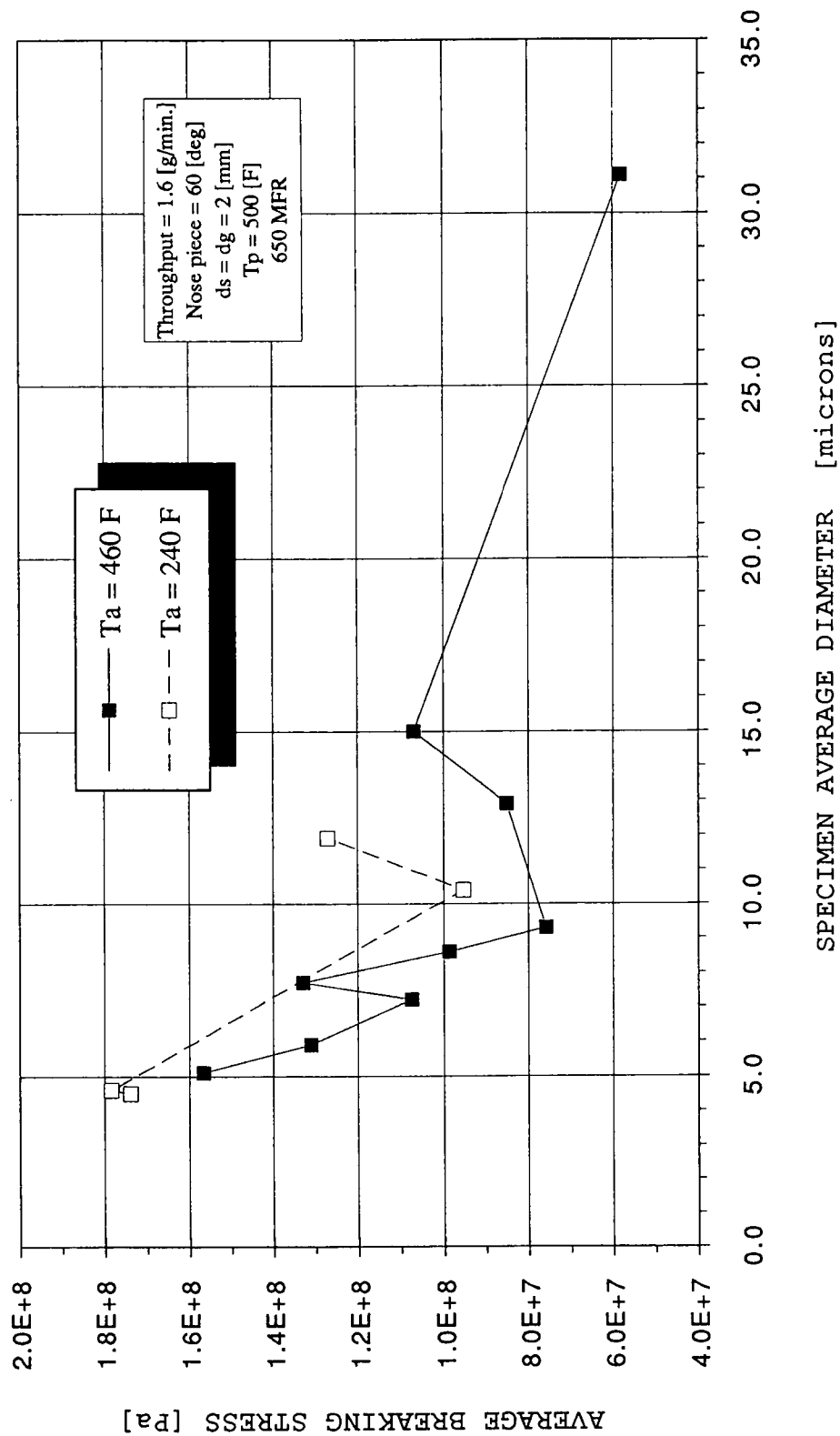


Figure 3.55: Average breaking stress versus average diameter of single fiber specimens; (Tp = 500 F)

that there seems to be a relationship between air jet temperature and fiber strength for specimens of small diameter (less than 8 microns): stronger fibers seem to be associated with lower air jet temperatures.

35 MFR Data

Figure 3.56 shows the average birefringence as a function of the specimen average diameter for the 35 MFR data [16]. Contrary to the birefringence results shown for the 650 MFR data, these results indicate an opposite trend; stronger fibers are associated with higher air jet temperatures for a given specimen average diameter. Figure 3.57 however, presents results that agree with the findings made with the 650 MFR data; larger average breaking stresses (stronger fibers) are associated with lower air jet temperatures.

When comparing the results between the 35 and 650 MFR data, two conclusions can be made. First, both sets of data show that there is a certain relationship between air jet temperature and breaking stress: stronger fibers seem to be associated with lower air jet temperatures. Secondly, birefringence results show opposite trends between each set of data. Therefore, nothing can be concluded about the relationship between air jet temperature and single fiber strength when using results from birefringence tests.

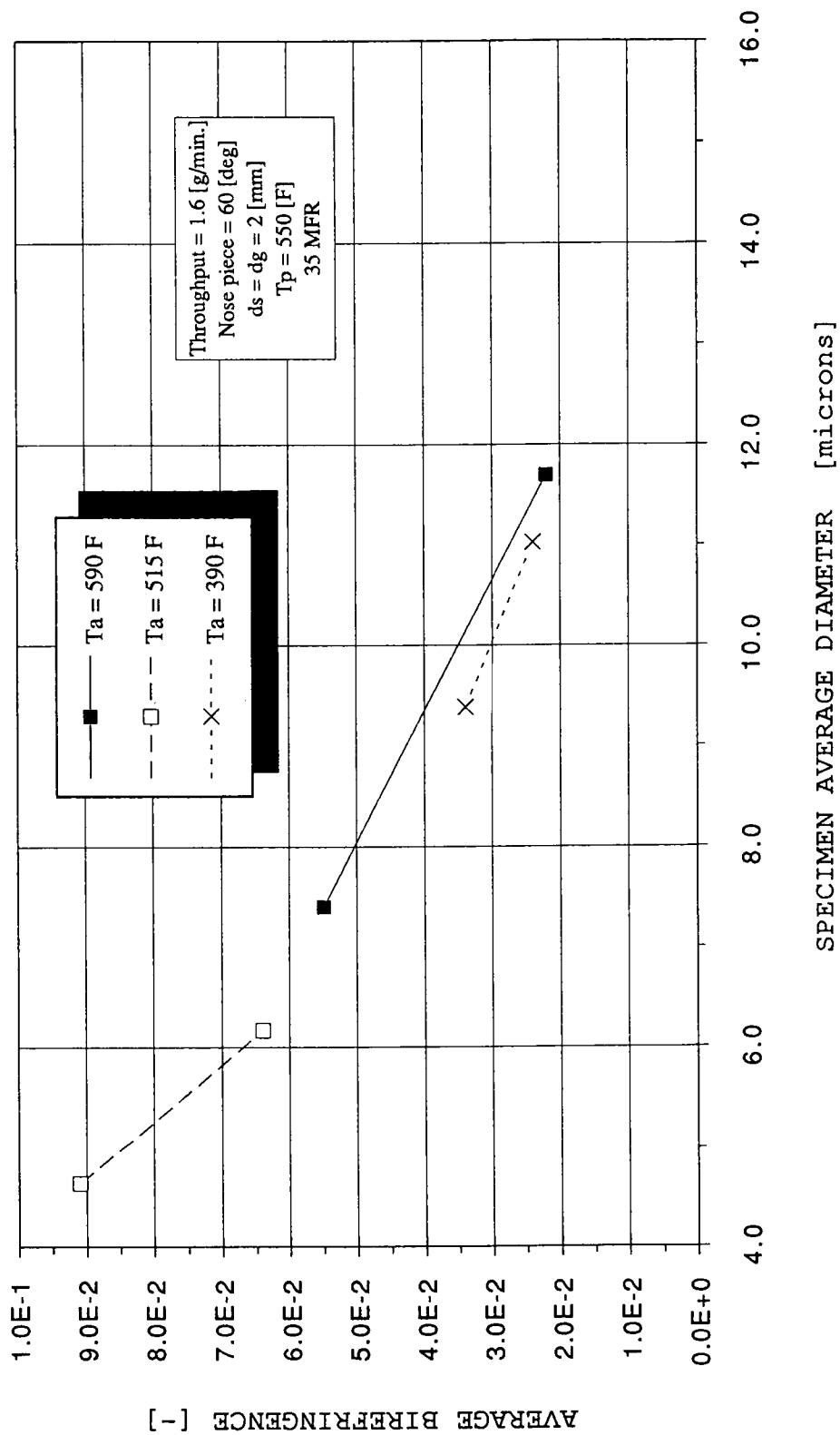


Figure 3.56: Average birefringence versus average diameter of single fiber specimens; (35 MFR)

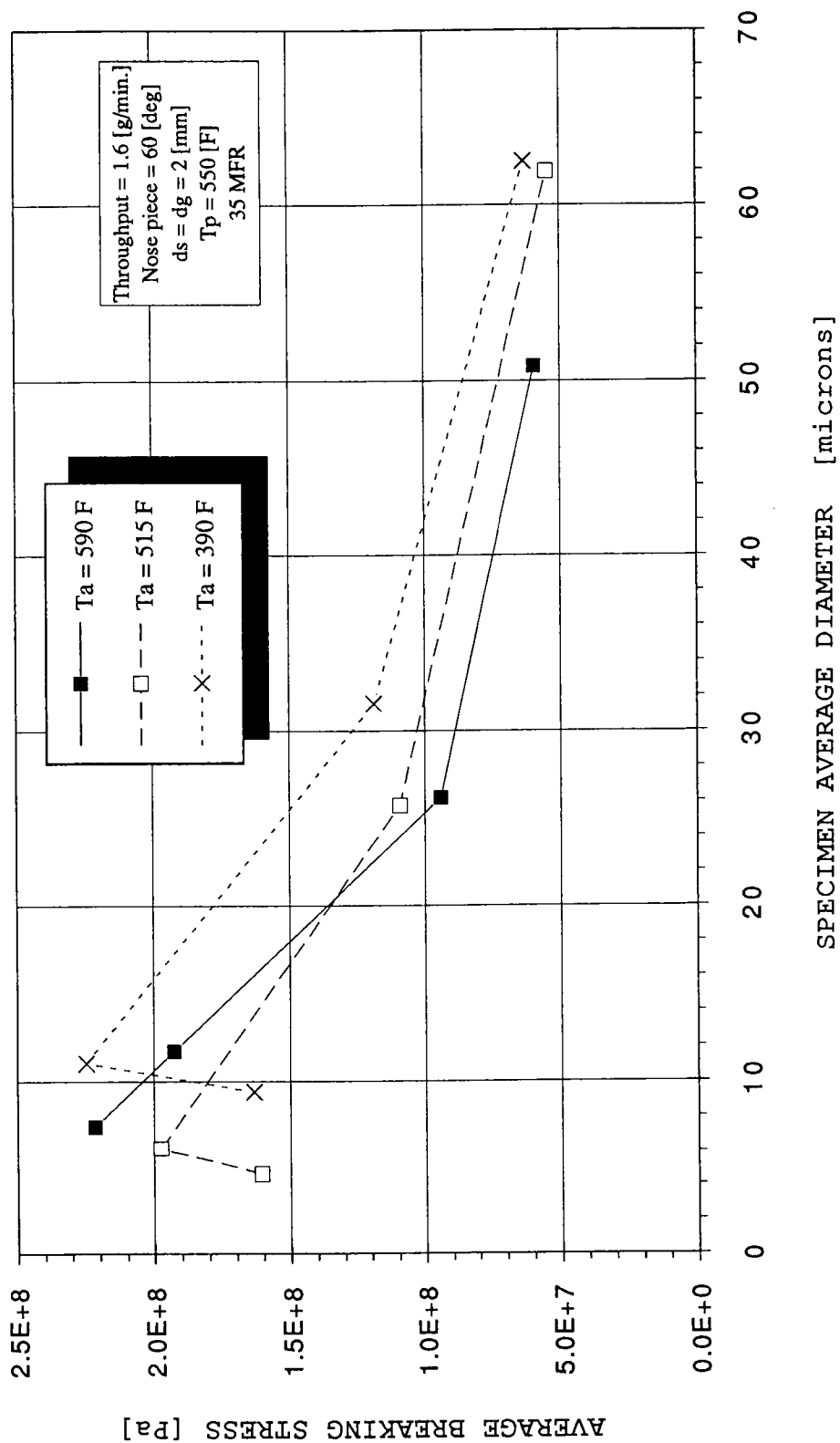


Figure 3.57: Average breaking stress versus average diameter of single fiber specimens; (35 MFR)

CHAPTER IV

CORRELATION OF EXPERIMENTAL DATA

This chapter presents the efforts made to correlate the experimental data collected during this research into mathematical expressions that can predict the average diameter of a melt blown fiber for any set of processing conditions. Two main models are derived each using a different principal dimensionless variable: one uses the air to polymer mass flux ratio (Γ) term as the principal variable while the other uses the air to polymer momentum flux ratio (Ψ) term as the principal variable. The mathematical expressions (models) developed are nonlinear in nature and are of the general form:

$$\delta = A + B C_1^{e_1} C_2^{e_2} C_3^{e_3} \dots C_i^{e_i} \quad 4.1$$

where

- δ dimensionless average fiber diameter ratio
- A constant
- B multiplying constant
- C_i dimensionless variables
- e_i exponent of the dimensionless variables

This first section introduces the dimensionless variables and describes how they are determined from the experimental data. A brief discussion on the procedures and the software that was used to develop the models is presented next. A systematic approach is then used to develop the first general model; starting only with one main describing dimensionless variable (mass flux ratio, Γ), other dimensionless variables are introduced into the model one by one. It will be shown that a clear improvement in the accuracy with which the average fiber diameter can be predicted is observed with this systematic approach. The second series of models are then developed using the momentum flux dimensionless variable (Ψ) as the main parameter. The more general models from each series are then compared with each other to determine their effectiveness in predicting the average fiber diameter of a melt blown fiber. It should be mentioned that these models are valid for a wide range of different processing conditions and are only restricted to 650 polymer Melt Flow Rates (MFR). Consequently, the following section presents the efforts made to expand these models to polymer MFRs other than just 650. These expanded models, which are now valid for any polymer MFR, are then used to predict the average fiber diameter of samples collected by another researcher using the same single hole melt blowing facility. The following section shows the results obtained when the models are used

to predict the average fiber diameter of samples collected at the UTK 20 inch multiple hole die facility. The last section of this Chapter presents the results of two studies conducted to determine the behavior of these models. The first study determines whether the use of absolute temperature ($^{\circ}\text{R}$) or degrees Fahrenheit when calculating the polymer and air temperature dimensionless variables had any influence in either the exponent of these variables or in the accuracy of the models to predict average fiber diameters. The second study determined what happens to the exponents of the model when the reference values used to calculate some of the dimensionless variables are changed.

Description of Dimensionless Variables

All of the dimensionless variables used to develop the empirical models are evaluated with measured experimental values. Table 4.1 lists the dimensionless variables with their appropriate mathematical expressions. Appendix C lists all of the experimental variables that were measured during each experiment. The following are some of the experimental variables that were measured during each experiment:

$\dot{m}_p$ polymer throughput

Table 4.1: List of dimensionless variables.

Variable	Expression	Reference Value
β polymer throughput ratio	$\frac{\dot{m}_p}{(\dot{m}_p)_{ref}}$	0.8 [g/min]
Γ air to polymer mass flux ratio	$\frac{\dot{m}_a / A_e}{\dot{m}_p / A_{die}}$	N/A
δ average fiber diameter ratio	$\frac{\bar{d}}{d_{die}}$	N/A
Θ polymer temperature ratio	$\frac{T_p}{(T_p)_{ref}}$	960 [°R]
Λ polymer temperature ratio	$\frac{T_p}{(T_p)_{ref}}$	500 [°F]
ξ air jet temperature ratio	$\frac{T_a}{(T_a)_{ref}}$	835 [°R]
Π air jet injection angle ratio	$\frac{\theta}{(\theta)_{ref}}$	45 deg.
τ air jet temperature ratio	$\frac{T_a}{(T_a)_{ref}}$	375 [°F]
Σ air-polymer temp. difference	$\frac{ T_p - T_a }{T_{ref}}$	50 [°F]
Φ air jet exit height ratio	$\frac{h}{(h)_{ref}}$	2.00 [mm]
Ψ air-polymer momentum flux ratio	$\frac{\dot{m}_a V_a / A_e}{\dot{m}_p V_p / A_{die}}$	N/A
Ω polymer MFR ratio	$\frac{MFR}{(MFR)_{ref}}$	650 [MFR]

..... polymer temperature
 air jet temperature
 air jet injection angle
 average fiber diameter
 A_{die} die orifice area (0.0995 mm^2)
 d_{die} die orifice diameter (0.356 mm)
 MFR polymer Melt Flow Rate

The air flow rate ($\dot{m}_a$), the air jet exit area (A_e), and the air jet exit velocity (V_e) expressions are derived in Appendices A, D, and E, respectively. The principle of conservation of mass, applied to the polymer that is extruded out of the die, is used to determine the polymer exit velocity (V_p) at the die tip. This conservation principle is given by Equation 4.2.

$$\dot{m}_p = \rho_p V_p A_{\text{die}} \quad 4.2$$

Solving for the polymer exit velocity:

$$V_p = \frac{\dot{m}_p}{\rho_p A_{\text{die}}} \quad 4.3$$

The only unknown in Equation 4.3 is the polymer density (ρ_p). Zieminski [17] derived an expression which determines

the polymer density as a function of the polymer temperature. This expression is given by Equation 4.4.

$$\rho_p = \frac{1,000}{1.129 + (5.017 * 10^{-4}) T_p} \quad [\text{Kg/m}^3] \quad 4.4$$

where T_p is in degrees Fahrenheit.

It should be noted that an attempt was made to use the polymer to air jet temperature difference dimensionless variable (Σ) in developing the empirical models. The reason for introducing this parameter was to account for the radiation/conduction effects between the air jet and the polymer. This effort proved to be unsuccessful. Some of the data was generated at similar air jet and polymer temperatures. These data points resulted in Σ values equal to zero. The exponents of the dimensionless variables then could not be determined due to a divergence problem introduced by these zero valued variables.

Computational Method for Developing the Empirical Models

The non-linear regression analysis procedure of the Statistical Analysis System (SAS) software package [18] was used to develop the empirical models. This procedure

predicts the values of the exponents of the dimensionless variables ($e_1, e_2, \dots, e_i$) and the two constants (A and B).

The input program consists of two parts. An expression similar to the one shown in Equation 4.1, and a set of initial guess values for the two constants and the exponents are supplied to SAS in the first part of the input program. The second part is a data file which contains a list of the dimensionless variables ($C_1, C_2, \dots, C_i$) for each one of the experimental data points. Figure 4.1 shows an input program for the SAS non-linear regression procedure. The output from the regression procedure includes the predicted values for the exponents of the dimensionless variables as well as the two constants. Figure 4.2 shows a portion of a non-linear regression procedure output file. The coefficient of multiple regression (γ^2) is also obtained from this output file. This coefficient gives an indication whether the variation in the fit is due to the regression procedure or due to the possibility that important predictor variables have not been considered in the describing equation or due to chance. For instance, $\gamma^2 = 0.75$ means that 75% of the variation is explained by the variation in the independent variables in the model and the reminder 25% is due to chance or due to important predictor variables missing in the describing equation [13].

```

*****
*
*      SAS NON-LINEAR REGRESSION CODE
*      (Input program)
*
*****
*
*      This program supplies the SAS software package with
*      the form of the empirical equation and with initial guess
*      values for the exponents of the coefficients. Also, this
*      program provides to SAS the name and location of the input
*      data file.
*
*****
*
*      OPTIONS LS=72;
*      DATA; INFILE' [SPENCER]DATA.DAT';
*      INPUT ID DE PS GA BE PH SI TH XI OM PI;
*      PROC NLIN;
*      PARMS A=0.005 B=2.1 C=-1.5 D=-6.3 E=-1.9 F=-0.8 G=-0.5 H=0.6;
*      MODEL DE = A + B*(GA**C)*(TH**D)*(XI**E)*(BE**F)*(PH**G)*(PI**H)
*      RUN;
*
*****

```

Figure 4.1: SAS input program for the non-linear regression procedure

1 The SAS System 1
04:46 Thursday, December 9, 1993

Non-Linear Least Squares DUD Initialization			Dependent Variable DE	
DUD	A	B	C	Sum of Squares
-4	0.010400	0.004000	-1.900000	0.044451
-3	0.011440	0.004000	-1.900000	0.043226
-2	0.010400	0.004400	-1.900000	0.043463
-1	0.010400	0.004000	-2.090000	0.049016
0	0.011440	0.004000	-1.900000	0.043226
1	0.012183	0.004152	-1.897645	0.042686
2	0.012205	0.004131	-1.900789	0.042686
3	0.012205	0.004131	-1.900773	0.042686

NOTE: Convergence criterion met.

Non-Linear Least Squares Summary Statistics			Dependent Variable DE
Source	DF	Sum of Squares	Mean Square
Regression	3	0.27538201944	0.09179400648
Residual	356	0.04268613056	0.00011990486
Uncorrected Total	359	0.31806815000	
(Corrected Total)	358	0.12610463398	

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval	
			Lower	Upper
A	0.012205281	0.00124146138	0.0097637261	0.0146468365
B	0.004131446	0.00096497758	0.0022336451	0.0060292461
C	-1.900773073	0.15918616116	-2.2138410476	-1.5877050980

Asymptotic Correlation Matrix			
Corr	A	B	C
A	1	-0.862562289	-0.82461011
B	-0.862562289	1	0.9883159985
C	-0.82461011	0.9883159985	1

Figure 4.2: Portion of a non-linear regression procedure output file

Models with Mass Flux Ratio Term as Main Variable

Results obtained from the efforts made by other investigators in this field will be used as a starting point to determine the form of the mathematical expression that will better correlate the experimental data. Shambaugh [19] introduced the mass flow ratio dimensionless variable, which is the ratio of the air flow rate to the polymer throughput (flow rate). He correlated his data with some success. Haynes [13] took this idea one step further by introducing the air jet and the polymer exit areas to this term, thus forming the mass flux ratio term (Γ). Haynes' data correlated better using this mass flux ratio term as compared to the mass flow ratio term. Thus, the mass flux dimensionless variable is used in this study as the starting point for developing the first set of empirical models.

The form of the first empirical model developed is given by Equation 4.5.

$$\delta_1 = A_1 + B_1 \Gamma^{e_1} \quad 4.5$$

It should be mentioned that all of the experimental data (359 data points) collected throughout this research are used in developing the model described by Equation 4.5 and all of the models presented in this and the next section.

The solution to Equation 4.5 is given by Equation 4.6:

$$\begin{aligned}\delta_1 &= 0.012 + 0.004 \Gamma^{-1.90} & 4.6 \\ (\gamma^2 &= 0.8658)\end{aligned}$$

Figure 4.3 shows a comparison between Equation 4.6 and the experimental data. This model, although simple in form, does a good job in correlating the experimental data to the model. The next step in improving this model would be to add another dimensionless variable to the model. All of the other dimensionless variables (β , Φ , ξ , Θ , Π) are individually added to the model in order to determine which variable produces the best improvement. Equations 4.7 through 4.11 show the results.

$$\begin{aligned}\delta_2 &= 0.012 + 0.004 \Gamma^{-1.90} \beta^{0.01} & 4.7 \\ (\gamma^2 &= 0.8658)\end{aligned}$$

$$\begin{aligned}\delta_3 &= 0.011 + 0.005 \Gamma^{-1.80} \Phi^{-0.42} & 4.8 \\ (\gamma^2 &= 0.8734)\end{aligned}$$

$$\begin{aligned}\delta_4 &= 0.012 + 0.004 \Gamma^{-1.93} \xi^{-0.38} & 4.9 \\ (\gamma^2 &= 0.8663)\end{aligned}$$

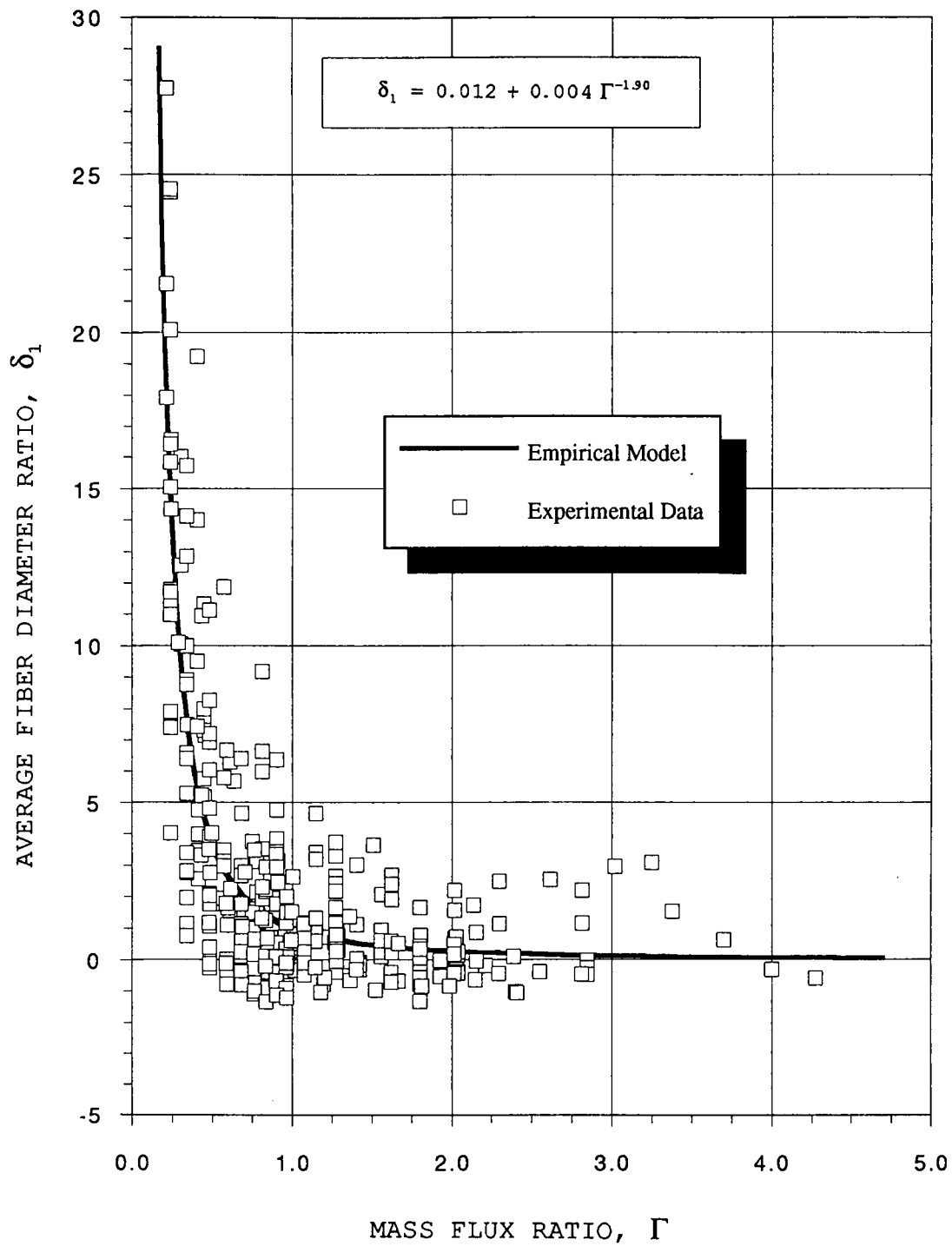


Figure 4.3: Comparison between mass flux empirical model and experimental data (Equation 4.6)

$$\delta_5 = 0.005 + 0.010 \Gamma^{-1.25} \Theta^{-6.35} \quad 4.10$$

$$(\gamma^2 = 0.9336)$$

$$\delta_6 = 0.010 + 0.008 \Gamma^{-1.61} \Pi^{0.76} \quad 4.11$$

$$(\gamma^2 = 0.8750)$$

Equation 4.10 has the largest coefficient of multiple correlation. This result indicates that the polymer temperature is the second most important parameter for properly correlating the given set of experimental data. It should also be mentioned that Equation 4.7, which includes the polymer throughput ratio term (β), showed no improvement at all.

If Equation 4.10 was to be compared with the experimental data like it was done for Equation 4.6 (Figure 4.3), then a series of curves would have to be generated; one curve for each value of the polymer temperature ratio variable (Θ). For instance, if there are 7 different values for the polymer temperature ratio variable (which is the case with the given set of experimental data), then 7 different curves would have to be generated in order to fit every data point. This task would be both cumbersome and ineffective. A family of curves, however, which represents all of the different possible values for the polymer temperature ratio can be generated by formulating Equation 4.10 into an alternate

form to plot a modified average fiber diameter ratio term (δ), namely Δ , as a function on one independent variable, Γ . The following expressions result:

$$\Delta_5 = \Gamma^{-1.25} \quad 4.12a$$

$$\Delta_5 = \frac{\delta_5 - 0.005}{0.010 \Theta^{-6.35}} \quad 4.12b$$

Equations 4.12a and 4.12b can be seen plotted in Figure 4.4. Equation 4.12a represents the predicted values from the empirical model, whereas Equation 4.12b is used to calculate the modified diameter ratio term for the experimental data. Further improvements to the model given by Equation 4.10 can be achieved by adding a third variable to this model. Equations 4.13 through 4.16 show the results.

$$\delta_7 = 0.005 + 0.013 \Gamma^{-1.43} \Theta^{-6.71} \beta^{-0.44} \quad 4.13$$

$$(\gamma^2 = 0.9484)$$

$$\delta_8 = 0.006 + 0.010 \Gamma^{-1.25} \Theta^{-6.36} \Phi^{0.01} \quad 4.14$$

$$(\gamma^2 = 0.9336)$$

$$\delta_9 = 0.006 + 0.012 \Gamma^{-1.30} \Theta^{-7.41} \xi^{-1.71} \quad 4.15$$

$$(\gamma^2 = 0.9508)$$

$$\delta_{10} = 0.006 + 0.010 \Gamma^{-1.29} \Theta^{-6.81} \Pi^{-0.26} \quad 4.16$$

$$(\gamma^2 = 0.9350)$$

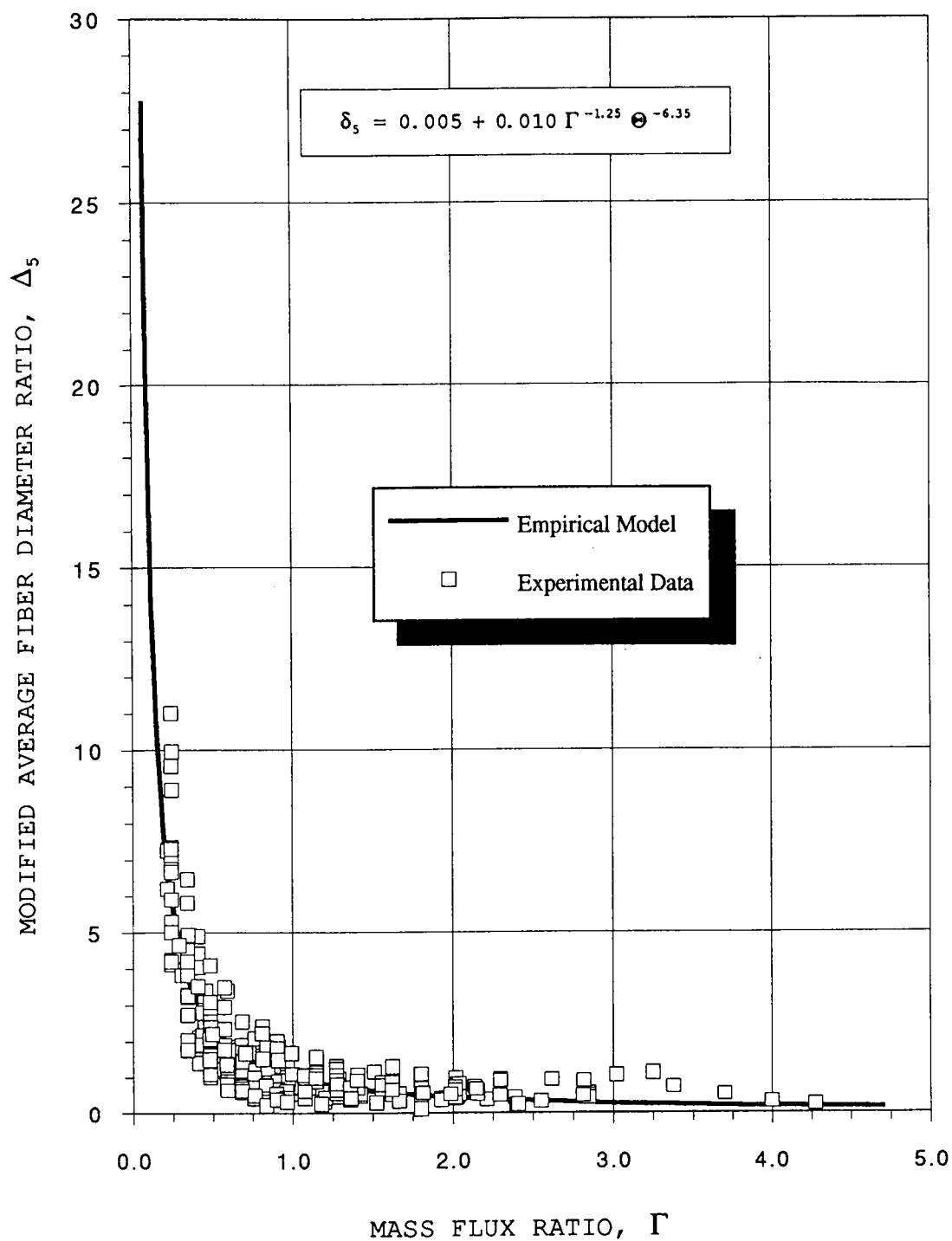


Figure 4.4: Comparison between mass flux empirical model and experimental data (Equation 4.10)

Equation 4.15, which incorporates the air jet temperature ratio term (ξ), shows the best improvement over the other models based on the coefficient of multiple correlation. This equation is formulated in terms of the modified diameter ratio as it was previously done.

$$\Delta_g = \Gamma^{-1.30} \quad 4.17a$$

$$\Delta_g = \frac{\delta_g - 0.006}{0.012 \Theta^{-7.41} \xi^{-1.71}} \quad 4.17b$$

Figure 4.5 shows Equation 4.17a (empirical model) compared with the experimental data determined by Equation 4.17b. It can be seen that the data tends to collapse to the line defined by the model as terms are added to the empirical model. The remaining variables are now individually added to Equation 4.15.

$$\delta_{11} = 0.005 + 0.015 \Gamma^{-1.38} \Theta^{-7.55} \xi^{-1.45} \beta^{-0.38} \quad 4.18$$

$$(\gamma^2 = 0.9616)$$

$$\delta_{12} = 0.006 + 0.012 \Gamma^{-1.29} \Theta^{-7.35} \xi^{-1.72} \Phi^{-0.03} \quad 4.19$$

$$(\gamma^2 = 0.9509)$$

$$\delta_{13} = 0.006 + 0.013 \Gamma^{-1.27} \Theta^{-7.18} \xi^{-1.80} \Pi^{0.15} \quad 4.20$$

$$(\gamma^2 = 0.9511)$$

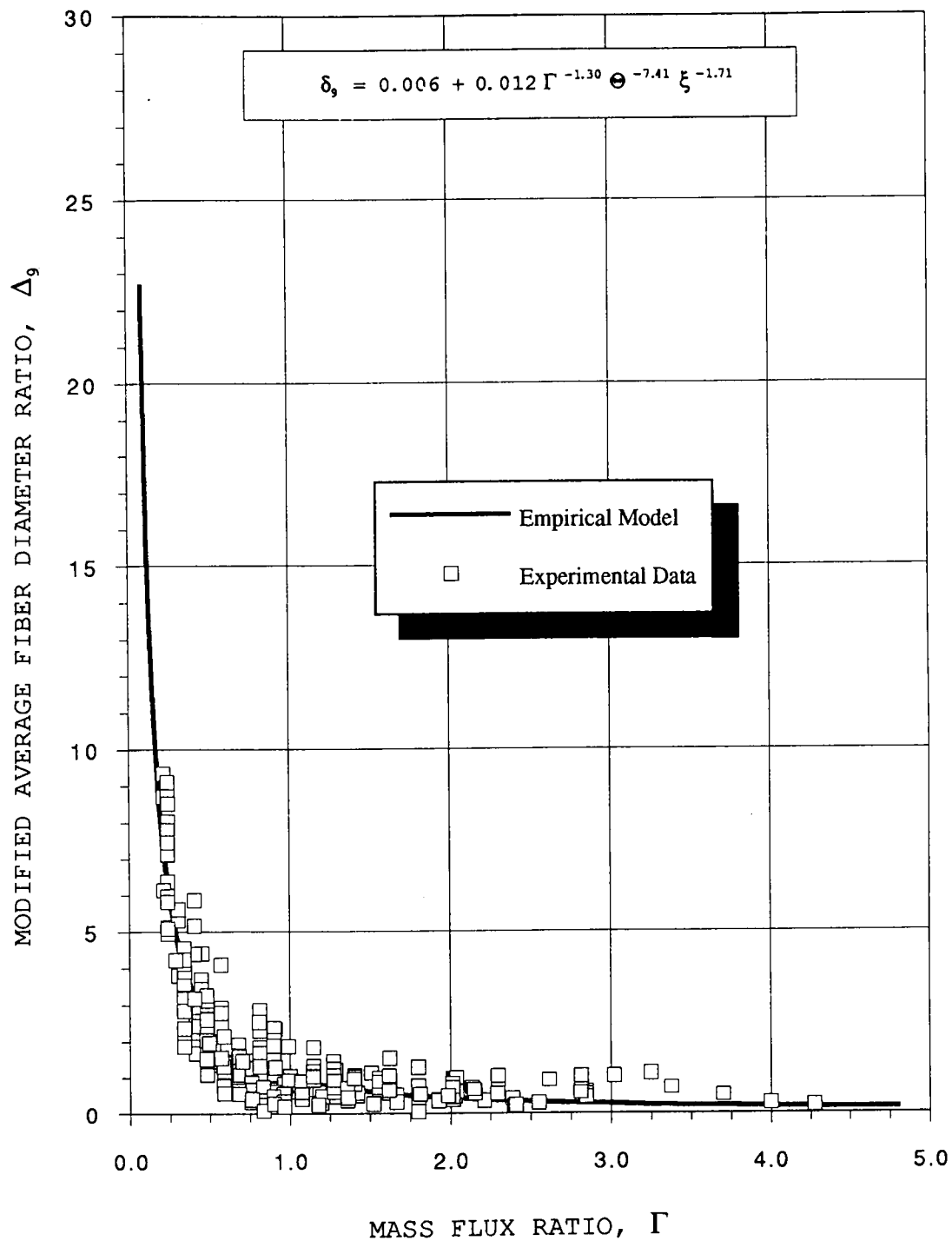


Figure 4.5: Comparison between mass flux empirical model and experimental data (Equation 4.15)

Equation 4.18, which added the polymer throughput ratio term (β), shows the best improvement ($\gamma^2 = 0.9616$) among the three latest Equations. Rearranging Equation 4.18 into the modified diameter ratio form:

$$\Delta_{11} = \Gamma^{-1.38} \quad 4.21a$$

$$\Delta_{11} = \frac{\delta_{11} - 0.005}{0.015 \Theta^{-7.55} \xi^{-1.45} \beta^{-0.38}} \quad 4.21b$$

Figure 4.6 shows the comparison between the empirical equation (Equation 4.21a) and the experimental data (Equation 4.21b). The two remaining variables are now added to Equation 4.18.

$$\delta_{14} = 0.005 + 0.019 \Gamma^{-1.48} \Theta^{-6.86} \xi^{-1.49} \beta^{-0.68} \Phi^{-0.56} \quad 4.22$$

$$(\gamma^2 = 0.9722)$$

$$\delta_{15} = 0.005 + 0.022 \Gamma^{-1.53} \Theta^{-6.62} \xi^{-1.93} \beta^{-0.66} \Pi^{0.92} \quad 4.23$$

$$(\gamma^2 = 0.9718)$$

Equation 4.22, which added the air jet exit width ratio term (Φ), has a slightly larger coefficient of multiple correlation over Equation 4.23, which added the air jet injection angle ratio term (Π). Therefore, Equation 4.22 will be used to continue with the process of adding terms to

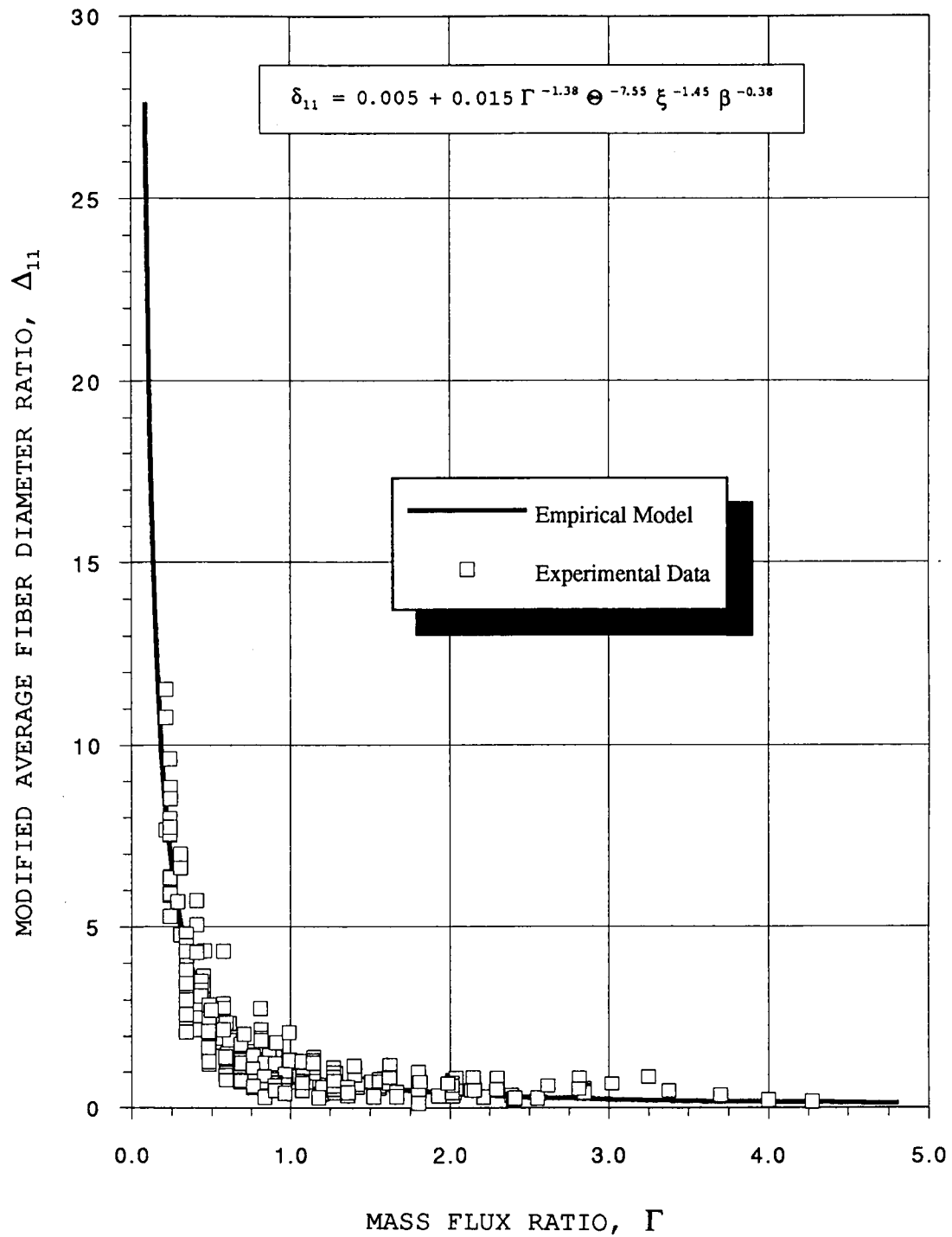


Figure 4.6: Comparison between mass flux empirical model and experimental data (Equation 4.18)

the empirical model. Equations 4.24a and 4.24b show the modified version of Equation 4.22:

$$\Delta_{14} = \Gamma^{-1.48} \quad 4.24a$$

$$\Delta_{14} = \frac{\delta_{11} - 0.005}{0.019 \Theta^{-6.86} \xi^{-1.49} \beta^{-0.68} \Phi^{-0.56}} \quad 4.24b$$

Figure 4.7 shows the comparison between the empirical model (Equation 4.24a) and the experimental data (Equation 4.24b). The final step of this systematic method of building the general empirical model is to add the air jet injection angle ratio term (Π) to Equation 4.22. Equation 4.25 shows the resulting empirical model.

$$\delta_{16} = 0.005 + 0.023 \Gamma^{-1.56} \Theta^{-6.26} \xi^{-1.87} \beta^{-0.78} \Phi^{-0.48} \Pi^{0.61} \quad 4.25$$

($\gamma^2 = 0.9771$)

Equation 4.25 represents the most general empirical model developed using the mass flux ratio term as the main parameter. Equations 4.26a and 4.26b show the modified version of Equation 4.25:

$$\Delta_{16} = \Gamma^{-1.56} \quad 4.26a$$

$$\Delta_{16} = \frac{\delta_{16} - 0.005}{0.023 \Theta^{-6.26} \xi^{-1.87} \beta^{-0.78} \Phi^{-0.48} \Pi^{0.61}} \quad 4.26b$$

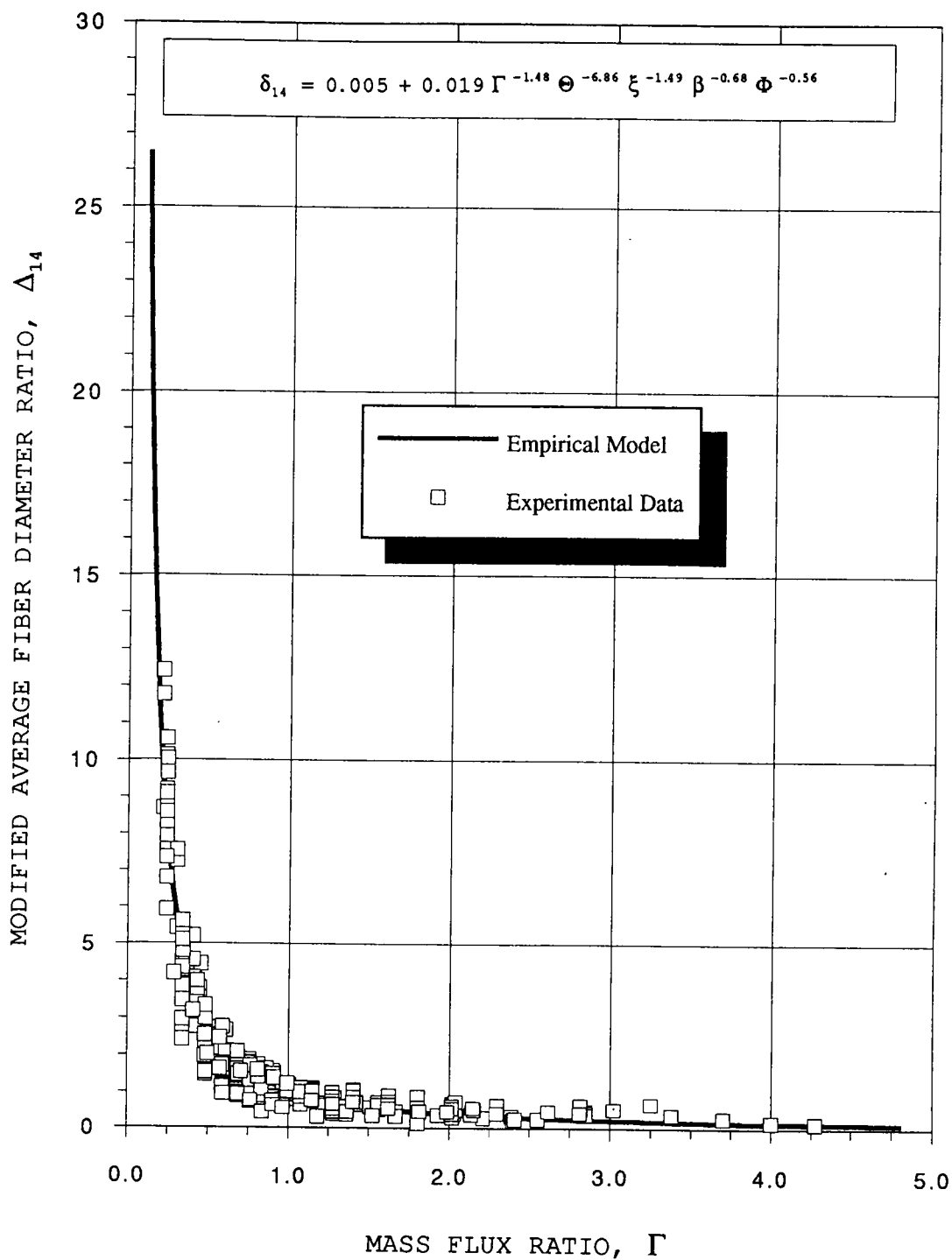


Figure 4.7: Comparison between mass flux empirical model and experimental data (Equation 4.22)

Figure 4.8 shows the comparison between the empirical equation (Equation 4.26a) and the experimental data (Equation 4.26b). It can be seen that this model (Equation 4.25) does a good job in correlating the experimental data. Table 4.2 summarizes all of the models that have been developed so far.

In conclusion, Equation 4.25 provides an excellent fit to all of the experimental data. Further evaluations of how well this model can predict the average diameter of a melt blown fiber will be presented in subsequent sections of this Chapter.

Models with Momentum Flux Ratio Term as Main Variable

Kayser and Shambaugh [12] reported that the mass flux ratio term was the dominant independent group based on a dimensional analysis performed by Shambaugh [19]. The results from the previous section indicates that the mass flux ratio term indeed correlates the experimental data very well. However, in the previous Chapter it was shown that the average fiber diameter was strongly dependent on the air jet momentum rather than just the air flow rate. This section develops a series of models using the momentum flux ratio term (Ψ) as the main variable. The momentum flux ratio term is the ratio of air momentum per unit area to the polymer momentum per unit area (see Table 4.1). The same

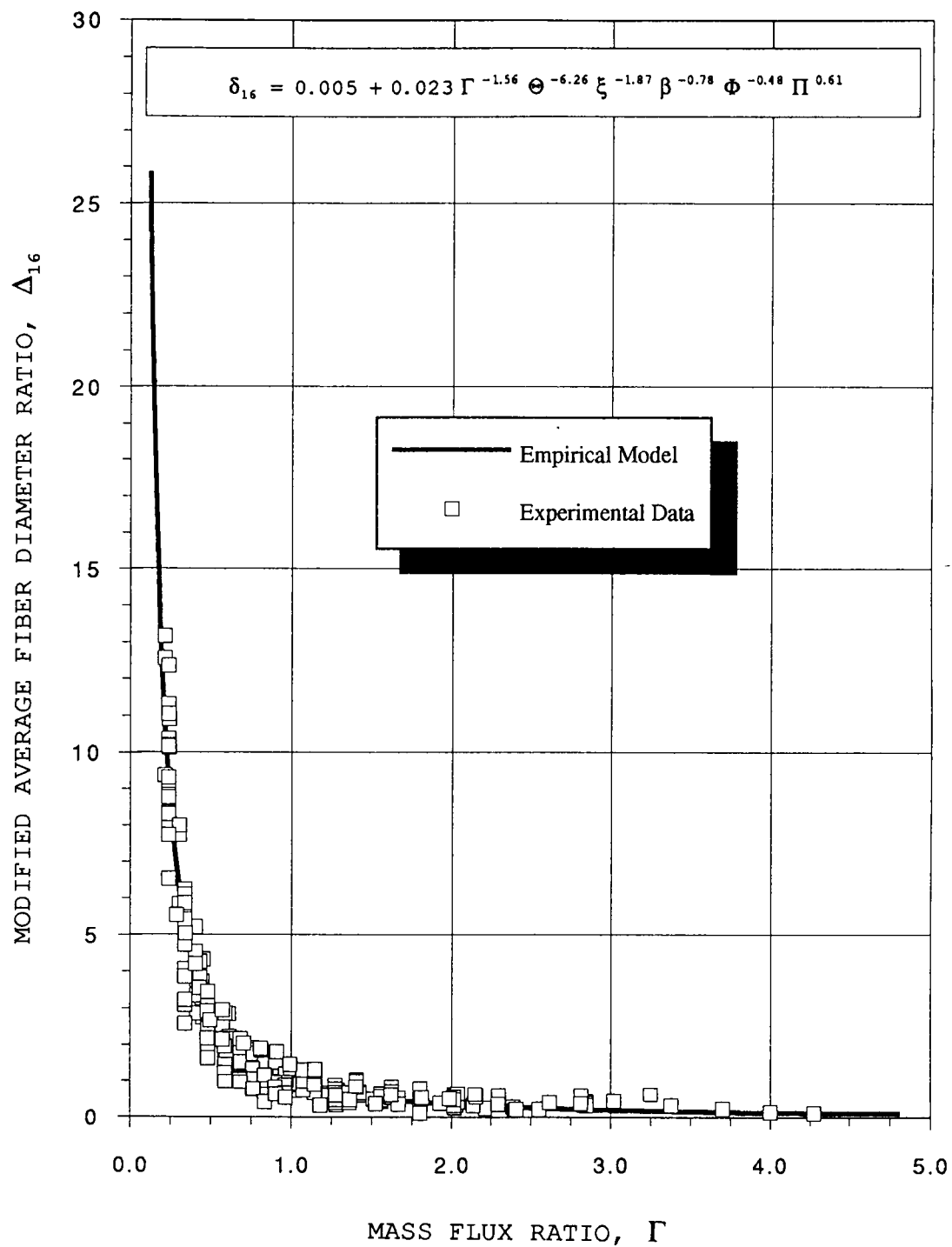


Figure 4.8: Comparison between mass flux empirical model and experimental data (Equation 4.25)

Table 4.2: Summary of empirical models developed with the mass flux ratio term.

Empirical Model	Coefficient of Multiple Correlation	Equation
$\delta_1 = 0.012 + 0.004 \Gamma^{-1.90}$	$\gamma^2 = 0.8658$	4.6
$\delta_2 = 0.012 + 0.004 \Gamma^{-1.90} \beta^{0.01}$	$\gamma^2 = 0.8658$	4.7
$\delta_3 = 0.011 + 0.005 \Gamma^{-1.80} \Phi^{-0.42}$	$\gamma^2 = 0.8734$	4.8
$\delta_4 = 0.012 + 0.004 \Gamma^{-1.93} \xi^{-0.38}$	$\gamma^2 = 0.8663$	4.9
$\delta_5 = 0.005 + 0.010 \Gamma^{-1.25} \Theta^{-6.35}$	$\gamma^2 = 0.9336$	4.10
$\delta_6 = 0.010 + 0.008 \Gamma^{-1.61} \Pi^{0.76}$	$\gamma^2 = 0.8750$	4.11
$\delta_7 = 0.005 + 0.013 \Gamma^{-1.43} \Theta^{-6.71} \beta^{-0.44}$	$\gamma^2 = 0.9484$	4.13
$\delta_8 = 0.006 + 0.010 \Gamma^{-1.25} \Theta^{-6.36} \Phi^{0.01}$	$\gamma^2 = 0.9336$	4.14
$\delta_9 = 0.006 + 0.012 \Gamma^{-1.30} \Theta^{-7.41} \xi^{-1.71}$	$\gamma^2 = 0.9508$	4.15
$\delta_{10} = 0.006 + 0.010 \Gamma^{-1.29} \Theta^{-6.81} \Pi^{-0.26}$	$\gamma^2 = 0.9350$	4.16
$\delta_{11} = 0.005 + 0.015 \Gamma^{-1.38} \Theta^{-7.55} \xi^{-1.45} \beta^{-0.38}$	$\gamma^2 = 0.9616$	4.18
$\delta_{12} = 0.006 + 0.012 \Gamma^{-1.29} \Theta^{-7.35} \xi^{-1.72} \Phi^{-0.03}$	$\gamma^2 = 0.9509$	4.19
$\delta_{13} = 0.006 + 0.013 \Gamma^{-1.27} \Theta^{-7.18} \xi^{-1.80} \Pi^{0.15}$	$\gamma^2 = 0.9511$	4.20
$\delta_{14} = 0.005 + 0.019 \Gamma^{-1.48} \Theta^{-6.86} \xi^{-1.49} \beta^{-0.68} \Phi^{-0.56}$	$\gamma^2 = 0.9722$	4.22
$\delta_{15} = 0.005 + 0.022 \Gamma^{-1.53} \Theta^{-6.62} \xi^{-1.93} \beta^{-0.66} \Pi^{0.92}$	$\gamma^2 = 0.9718$	4.23
$\delta_{16} = 0.005 + 0.023 \Gamma^{-1.56} \Theta^{-6.26} \xi^{-1.87} \beta^{-0.78} \Phi^{-0.48} \Pi^{0.61}$	$\gamma^2 = 0.9771$	4.25

approach used for developing the models in the previous section is used in this section.

The first empirical model developed is of the form

$$\delta_{17} = A_{17} + B_{17} \Psi^{e_{17}} \quad 4.27$$

The solution to Equation 4.27 is given by Equation 4.28:

$$\begin{aligned} \delta_{17} &= 0.013 + 3.57 \Psi^{-0.99} \quad 4.28 \\ (\gamma^2 &= 0.8584) \end{aligned}$$

Figure 4.9 shows a comparison between Equation 4.28 and the experimental data. All of the other dimensionless variables are individually added to the model given by Equation 4.28. Equations 4.29 through 4.33 show the results.

$$\begin{aligned} \delta_{18} &= 0.013 + 3.49 \Psi^{-1.04} \beta^{0.22} \quad 4.29 \\ (\gamma^2 &= 0.8598) \end{aligned}$$

$$\begin{aligned} \delta_{19} &= 0.012 + 3.71 \Psi^{-0.99} \Phi^{-0.40} \quad 4.30 \\ (\gamma^2 &= 0.8659) \end{aligned}$$

$$\begin{aligned} \delta_{20} &= 0.012 + 3.42 \Psi^{-1.00} \xi^{0.61} \quad 4.31 \\ (\gamma^2 &= 0.8599) \end{aligned}$$

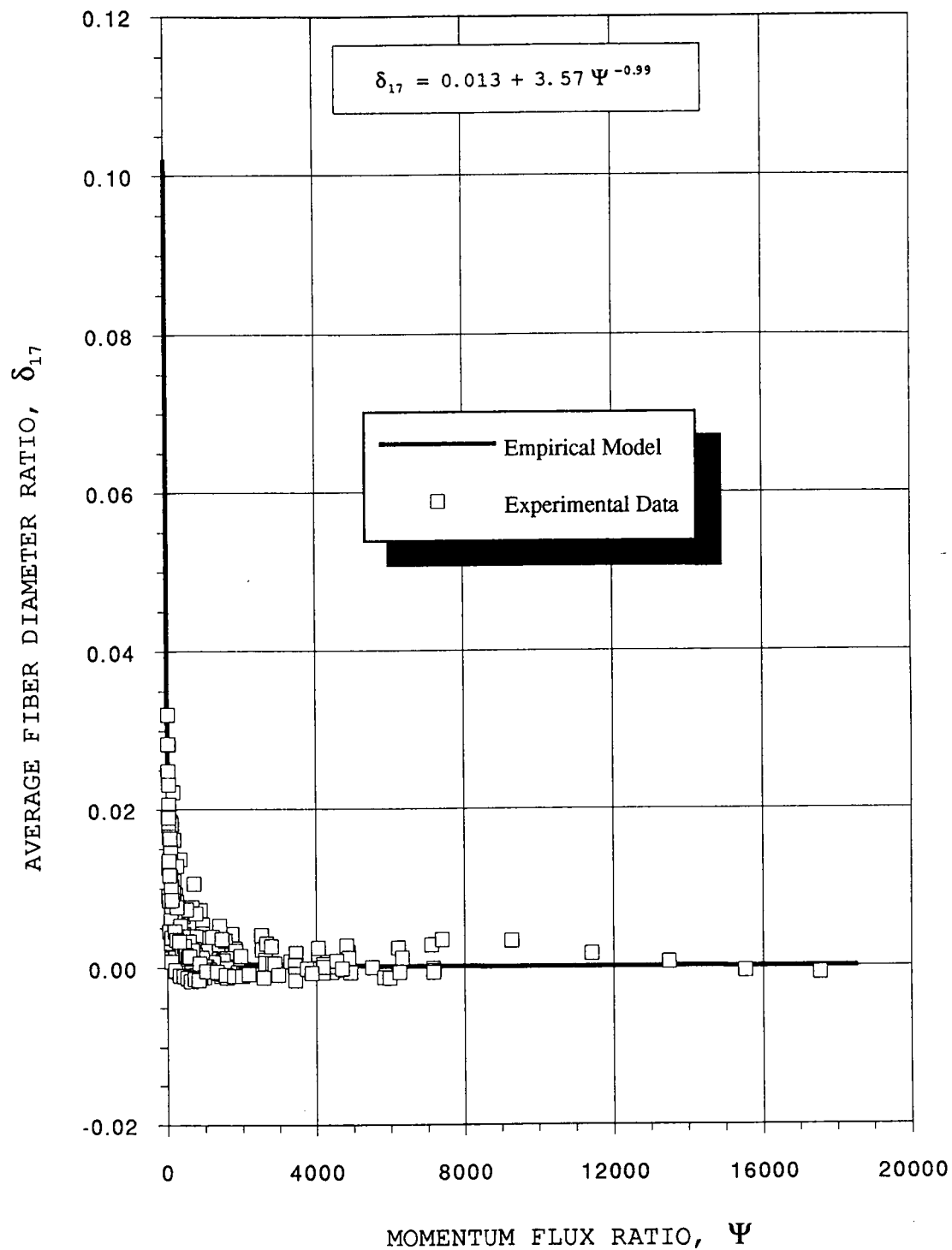


Figure 4.9: Comparison between momentum flux empirical model and experimental data (Equation 4.28)

$$\delta_{21} = 0.006 + 1.05 \Psi^{-0.69} \Theta^{-6.84} \quad 4.32$$

$$(\gamma^2 = 0.9397)$$

$$\delta_{22} = 0.010 + 2.77 \Psi^{-0.86} \Pi^{1.02} \quad 4.33$$

$$(\gamma^2 = 0.8757)$$

Equation 4.32 has the largest coefficient of multiple correlation. As was the case for the mass flux ratio model (Equation 4.10), the polymer temperature is the second most important parameter for properly correlating the given set of experimental data. Rearranging Equation 4.32 into the modified diameter ratio form:

$$\Delta_{21} = \Psi^{-0.69} \quad 4.34a$$

$$\Delta_{21} = \frac{\delta_{21} - 0.006}{1.05 \Theta^{-6.84}} \quad 4.34b$$

Figure 4.10 shows Equation 4.34a (empirical model) compared with the experimental data determined by Equation 4.34b. The data clearly fits the model better when the polymer temperature term is added. Further improvements to the model given by Equation 4.32 can be achieved by adding a second variable to this model. Equations 4.35 through 4.38 show the results.

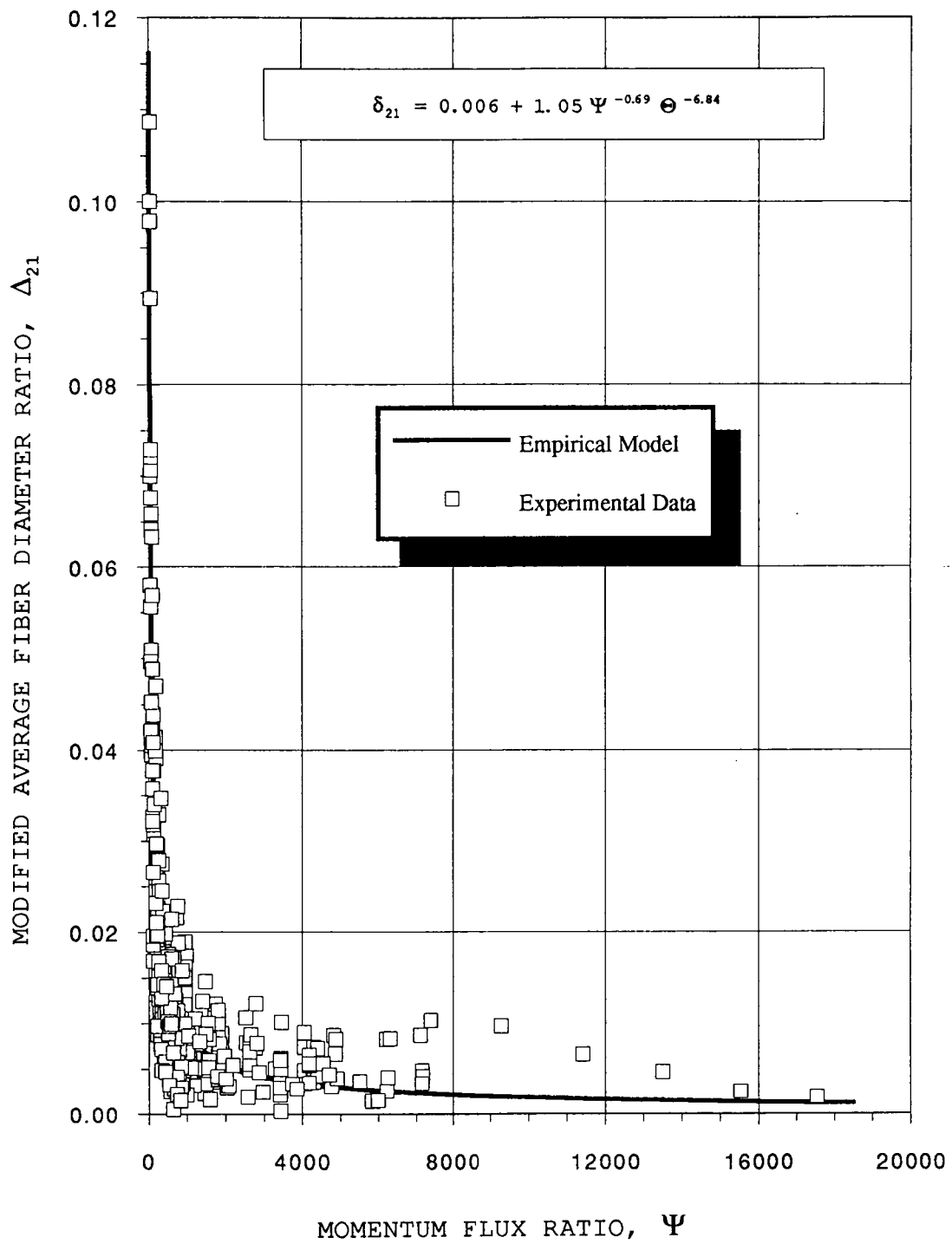


Figure 4.10: Comparison between momentum flux empirical model and experimental data (Equation 4.32)

$$\delta_{23} = 0.005 + 2.14 \Psi^{-0.73} \Theta^{-7.26} \beta^{-0.50} \quad 4.35$$

$$(\gamma^2 = 0.9598)$$

$$\delta_{24} = 0.007 + 1.07 \Psi^{-0.69} \Theta^{-7.05} \Phi^{0.10} \quad 4.36$$

$$(\gamma^2 = 0.9402)$$

$$\delta_{25} = 0.007 + 1.16 \Psi^{-0.68} \Theta^{-7.64} \xi^{-1.09} \quad 4.37$$

$$(\gamma^2 = 0.9472)$$

$$\delta_{26} = 0.007 + 1.07 \Psi^{-0.71} \Theta^{-7.29} \Pi^{-0.23} \quad 4.38$$

$$(\gamma^2 = 0.9407)$$

Equation 4.35, which incorporates the polymer throughput ratio term (β), shows the best improvement over the other models based on the coefficient of multiple correlation. This equation is formulated in terms of the modified diameter ratio term.

$$\Delta_{23} = \Psi^{-0.73} \quad 4.39a$$

$$\Delta_{23} = \frac{\delta_{23} - 0.005}{2.14 \Theta^{-7.26} \beta^{-0.50}} \quad 4.39b$$

Figure 4.11 shows Equation 4.39a compared to the experimental data expressed in the form of Equation 4.39b. It can be seen that the data tends to collapse to the line defined by the model as terms are added to the

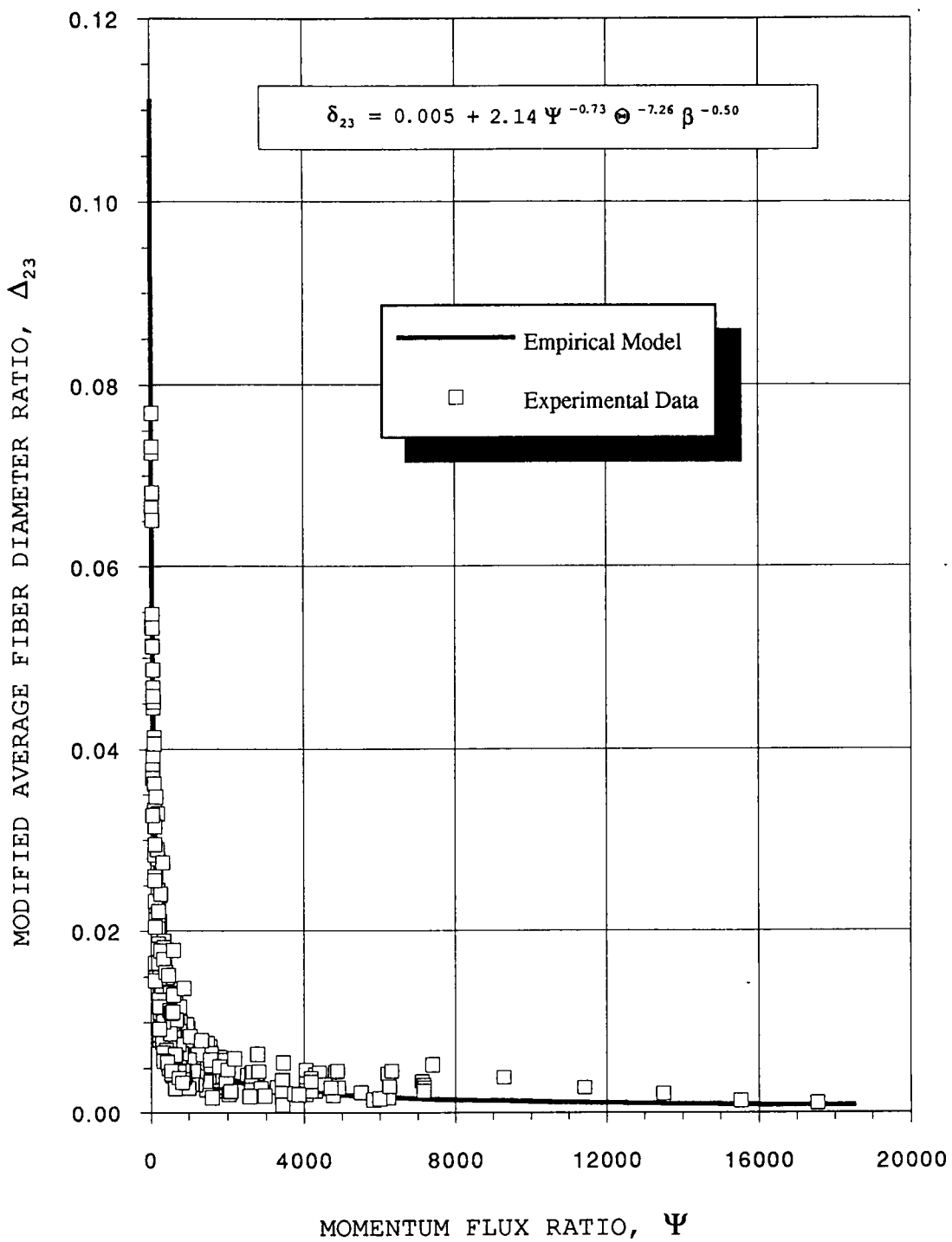


Figure 4.11: Comparison between momentum flux empirical model and experimental data (Equation 4.35)

empirical model. The remaining variables are now individually added to Equation 4.35.

$$\delta_{27} = 0.005 + 4.20 \Psi^{-0.81} \Theta^{-6.78} \beta^{-0.80} \Phi^{-0.56} \quad 4.40$$

$$(\gamma^2 = 0.9700)$$

$$\delta_{28} = 0.005 + 1.99 \Psi^{-0.71} \Theta^{-7.70} \beta^{-0.46} \xi^{-0.71} \quad 4.41$$

$$(\gamma^2 = 0.9632)$$

$$\delta_{29} = 0.006 + 5.41 \Psi^{-0.85} \Theta^{-6.63} \beta^{-0.78} \Pi^{0.74} \quad 4.42$$

$$(\gamma^2 = 0.9667)$$

Equation 4.40 which added the air jet exit width ratio term (Φ) shows the best improvement ($\gamma^2 = 0.9700$) among the three latest Equations. Rearranging Equation 4.40 into the modified diameter ratio:

$$\Delta_{27} = \Psi^{-0.81} \quad 4.43a$$

$$\Delta_{27} = \frac{\delta_{27} - 0.005}{4.20 \Theta^{-6.78} \beta^{-0.80} \Phi^{-0.56}} \quad 4.43b$$

Figure 4.12 shows Equation 4.43a compared to the experimental data expressed in the form of Equation 4.43b. An improvement in the ability of the model to correlate the data can be seen in Figure 4.12. The remaining two variables are now added to Equation 4.40.

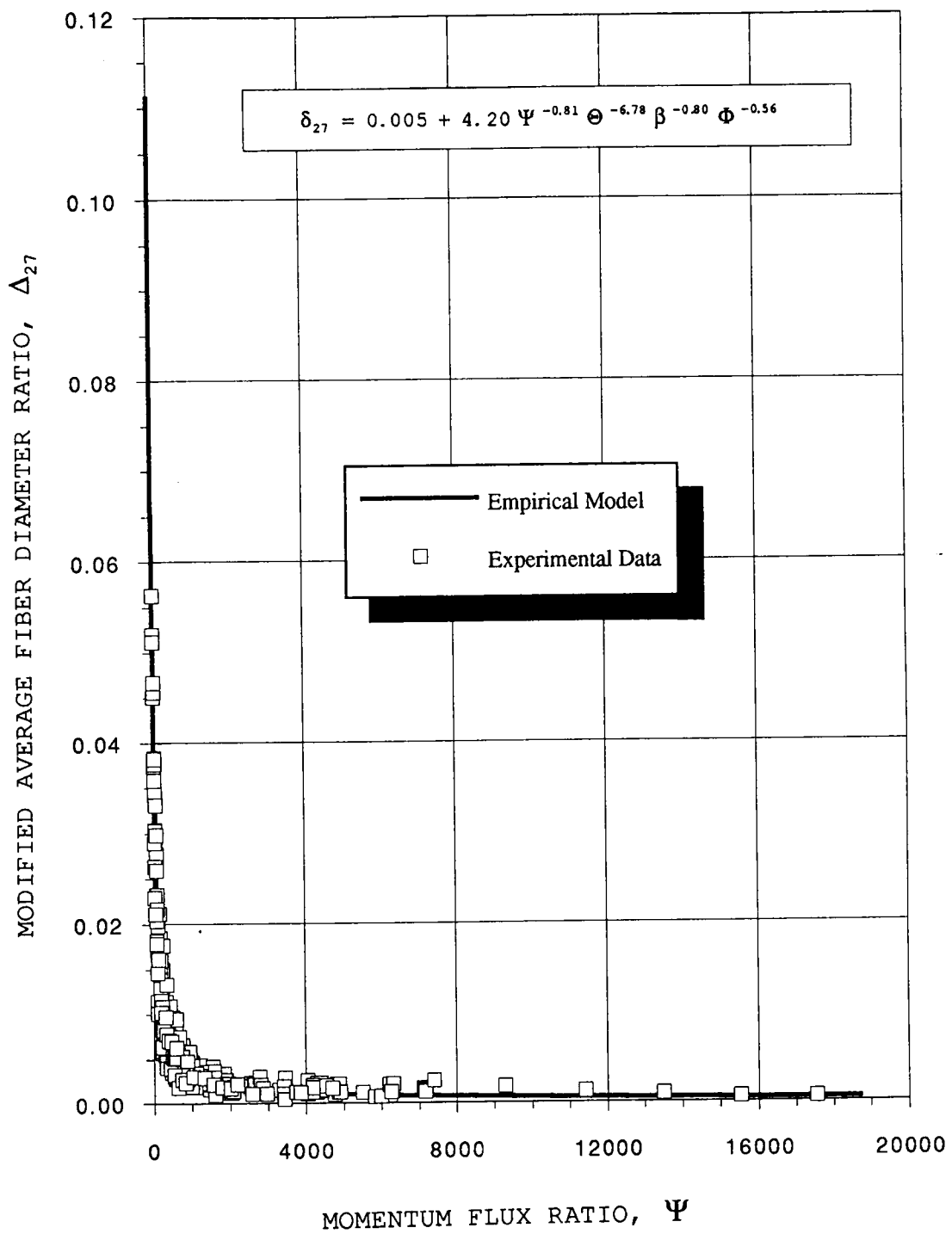


Figure 4.12: Comparison between momentum flux empirical model and experimental data (Equation 4.40)

$$\delta_{30} = 0.004 + 3.57 \Psi^{-0.77} \Theta^{-7.12} \beta^{-0.75} \Phi^{-0.52} \xi^{-0.67} \quad 4.44$$

$$(\gamma^2 = 0.9730)$$

$$\delta_{31} = 0.006 + 6.86 \Psi^{-0.87} \Theta^{-6.34} \beta^{-0.93} \Phi^{-0.53} \Pi^{0.44} \quad 4.45$$

$$(\gamma^2 = 0.9728)$$

Equation 4.44, which added the air jet temperature ratio term (ξ), has a slightly larger coefficient of multiple correlation over Equation 4.45, which added the air jet injection angle ratio term (Π). Equations 4.46a and 4.46b show the modified version of Equation 4.44:

$$\Delta_{30} = \Psi^{-0.77} \quad 4.46a$$

$$\Delta_{30} = \frac{\delta_{30} - 0.004}{3.57 \Theta^{-7.12} \beta^{-0.75} \Phi^{-0.52} \xi^{-0.67}} \quad 4.46b$$

Figure 4.13 shows the comparison between the empirical equation and the experimental data. The final step is to add the air jet injection angle ratio term (Π) to Equation 4.44. Equation 4.47 shows the resulting empirical model.

$$\delta_{32} = 0.004 + 5.80 \Psi^{-0.81} \Theta^{-6.46} \beta^{-0.85} \Phi^{-0.44} \xi^{-1.05} \Pi^{0.66} \quad 4.47$$

$$(\gamma^2 = 0.9791)$$

Equation 4.47 represents the most general empirical model developed using the momentum flux ratio term as the

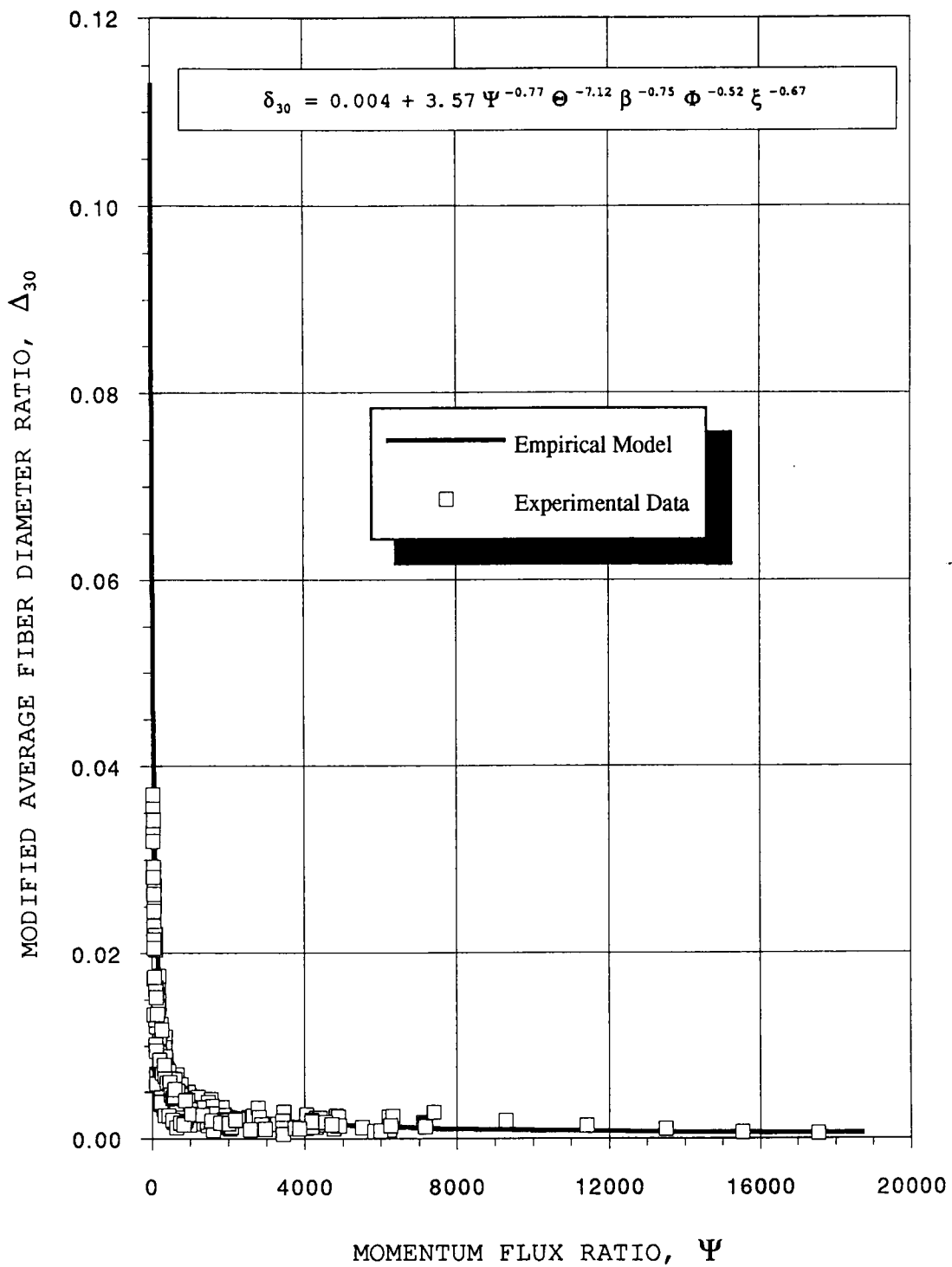


Figure 4.13: Comparison between momentum flux empirical model and experimental data (Equation 4.44)

main parameter. Equations 4.48a and 4.48b show the modified version of Equation 4.47:

$$\Delta_{32} = \Psi^{-0.81} \quad 4.48a$$

$$\Delta_{32} = \frac{\delta_{32} - 0.004}{5.80 \Theta^{-6.46} \beta^{-0.85} \Phi^{-0.44} \xi^{-1.04} \Pi^{0.66}} \quad 4.48b$$

Figure 4.14 shows Equation 4.48a compared to the experimental data expressed in the form of Equation 4.48b. It can be seen that this model (Equation 4.48) does a good job in correlating the experimental data. Table 4.3 summarizes all of the models that were developed using the momentum flux term as the main variable.

Comparison Between Empirical Models

A comparison between the most general empirical models developed using the mass flux ratio term (Equation 4.25) and the momentum flux ratio term (Equation 4.47) will be presented in this section. The objective of this comparison is to establish how well these models can predict the average diameter of a melt blown fiber.

Table 4.4 shows the distribution of the average fiber diameters for the 359 samples as measured from the optical microscope. It can be seen that most of the samples have an average diameter smaller than 10 microns; 51% are smaller

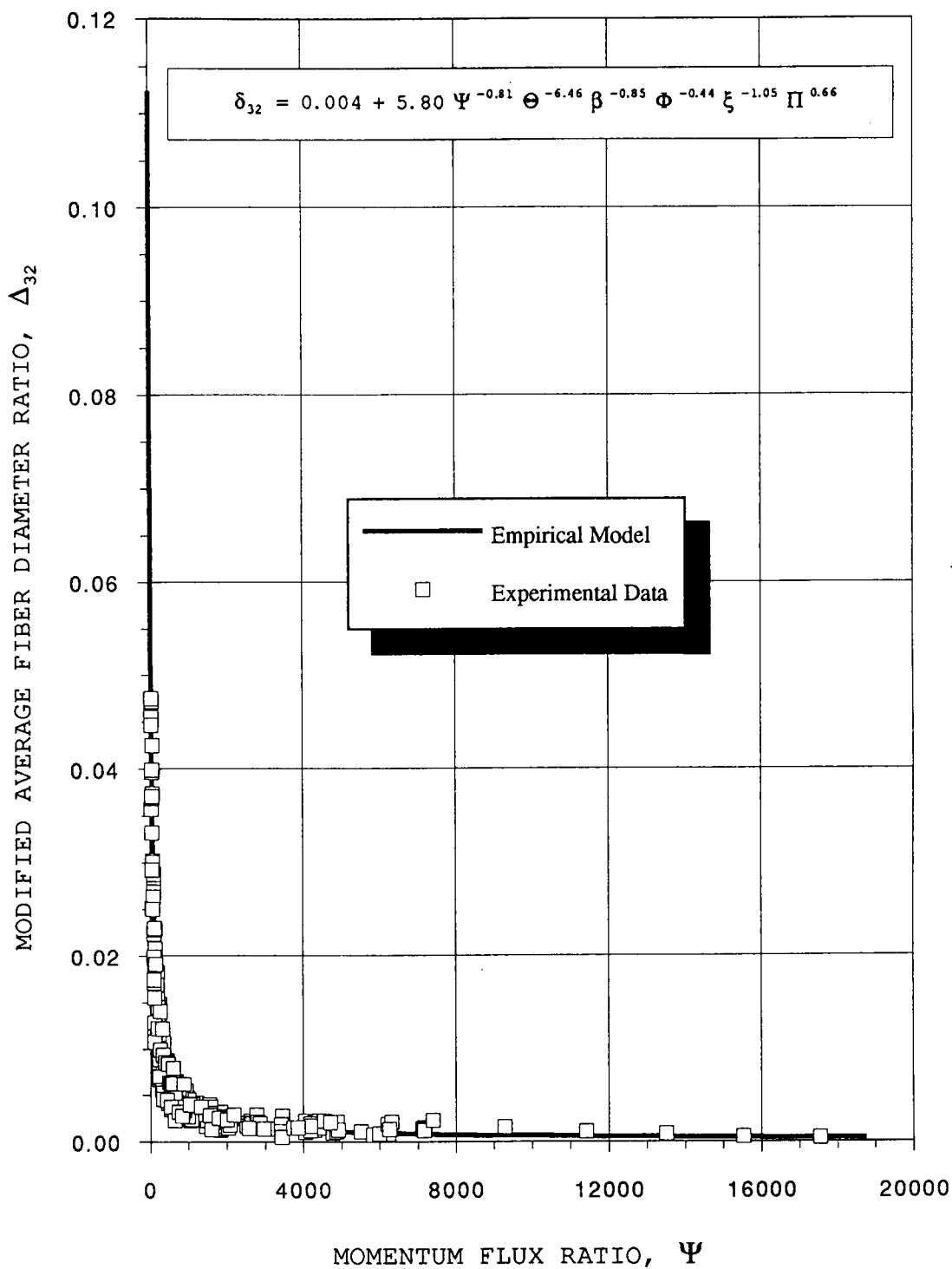


Figure 4.14: Comparison between momentum flux empirical model and experimental data (Equation 4.47)

Table 4.3: Summary of empirical models developed with the momentum flux ratio term.

Empirical Model	Coefficient of Multiple Correlation	Equation
$\delta_{17} = 0.013 + 3.57 \Psi^{-0.99}$	$\gamma^2 = 0.8584$	4.28
$\delta_{18} = 0.013 + 3.49 \Psi^{-1.04} \beta^{0.22}$	$\gamma^2 = 0.8598$	4.29
$\delta_{19} = 0.012 + 3.71 \Psi^{-0.99} \Phi^{-0.40}$	$\gamma^2 = 0.8659$	4.30
$\delta_{20} = 0.012 + 3.42 \Psi^{-1.00} \xi^{0.61}$	$\gamma^2 = 0.8599$	4.31
$\delta_{21} = 0.006 + 1.05 \Psi^{-0.69} \Theta^{-6.84}$	$\gamma^2 = 0.9397$	4.32
$\delta_{22} = 0.010 + 2.77 \Psi^{-0.86} \Pi^{1.02}$	$\gamma^2 = 0.8757$	4.33
$\delta_{23} = 0.005 + 2.14 \Psi^{-0.73} \Theta^{-7.26} \beta^{-0.50}$	$\gamma^2 = 0.9598$	4.35
$\delta_{24} = 0.007 + 1.07 \Psi^{-0.69} \Theta^{-7.05} \Phi^{0.10}$	$\gamma^2 = 0.9402$	4.36
$\delta_{25} = 0.007 + 1.16 \Psi^{-0.68} \Theta^{-7.64} \xi^{-1.09}$	$\gamma^2 = 0.9472$	4.37
$\delta_{26} = 0.007 + 1.07 \Psi^{-0.71} \Theta^{-7.29} \Pi^{-0.23}$	$\gamma^2 = 0.9407$	4.38
$\delta_{27} = 0.005 + 4.20 \Psi^{-0.81} \Theta^{-6.78} \beta^{-0.80} \Phi^{-0.56}$	$\gamma^2 = 0.9700$	4.40
$\delta_{28} = 0.005 + 1.99 \Psi^{-0.71} \Theta^{-7.70} \beta^{-0.46} \xi^{-0.71}$	$\gamma^2 = 0.9632$	4.41
$\delta_{29} = 0.006 + 5.41 \Psi^{-0.85} \Theta^{-6.63} \beta^{-0.78} \Pi^{0.74}$	$\gamma^2 = 0.9667$	4.42
$\delta_{30} = 0.004 + 3.57 \Psi^{-0.77} \Theta^{-7.12} \beta^{-0.75} \Phi^{-0.52} \xi^{-0.67}$	$\gamma^2 = 0.9730$	4.44
$\delta_{31} = 0.006 + 6.86 \Psi^{-0.87} \Theta^{-6.34} \beta^{-0.93} \Phi^{-0.53} \Pi^{0.44}$	$\gamma^2 = 0.9728$	4.45
$\delta_{32} = 0.004 + 5.80 \Psi^{-0.81} \Theta^{-6.46} \beta^{-0.85} \Phi^{-0.44} \xi^{-1.05} \Pi^{0.66}$	$\gamma^2 = 0.9791$	4.47

Table 4.4: Distribution of average fiber diameter as measured from the optical microscope.

Measured Average Fiber Diameter [microns]	Number of Samples [-]	Percent of Total Population [%]	Partial Percentage [%]
less than 2	0	0.0	51.0
between 2 and 4	78	21.7	
between 4 and 6	105	29.2	
between 6 and 8	61	17.0	29.5
between 8 and 10	45	12.5	
between 10 and 12	10	2.8	
between 12 and 14	11	3.1	19.5
between 14 and 16	13	3.6	
between 16 and 18	5	1.4	
between 18 and 20	4	1.1	
between 20 and 22	9	2.5	
between 22 and 24	2	0.6	
greater than 24	16	4.5	
Total	359		

than 6 microns, 29.5% have average diameters between 6 and 10 microns, and 19.5% are greater than 10 microns. Figure 4.15 shows a graphical presentation of the data shown in Table 4.4. The predicted average fiber diameter for each one of the samples were determined using both models. The absolute difference between the measured and predicted average fiber diameter for each model was then calculated for each sample. Table 4.5 summarizes the results obtained. The majority of the average diameters are predicted within 2 microns of the measured value with either model. For instance, 84.4% of the samples were predicted within 2 microns of the experimental value using the momentum flux model, and 83.3% of the samples were predicted within 2 microns using the mass flux model. Furthermore, 97.5% of the samples are predicted within 4 microns of the experimental value using either model. Thus, the momentum flux empirical model seems to be just slightly better than the mass flux model in predicting the average diameter of a melt blown fiber.

The following effort focuses on answering the following question: given a set of samples having a specific range of measured average diameter, how many of these samples are predicted within a certain absolute difference band? A specific case would be to determine how many of the samples having a measured average diameter less than 4 microns are predicted within 2 microns? within 4 microns? Table 4.6

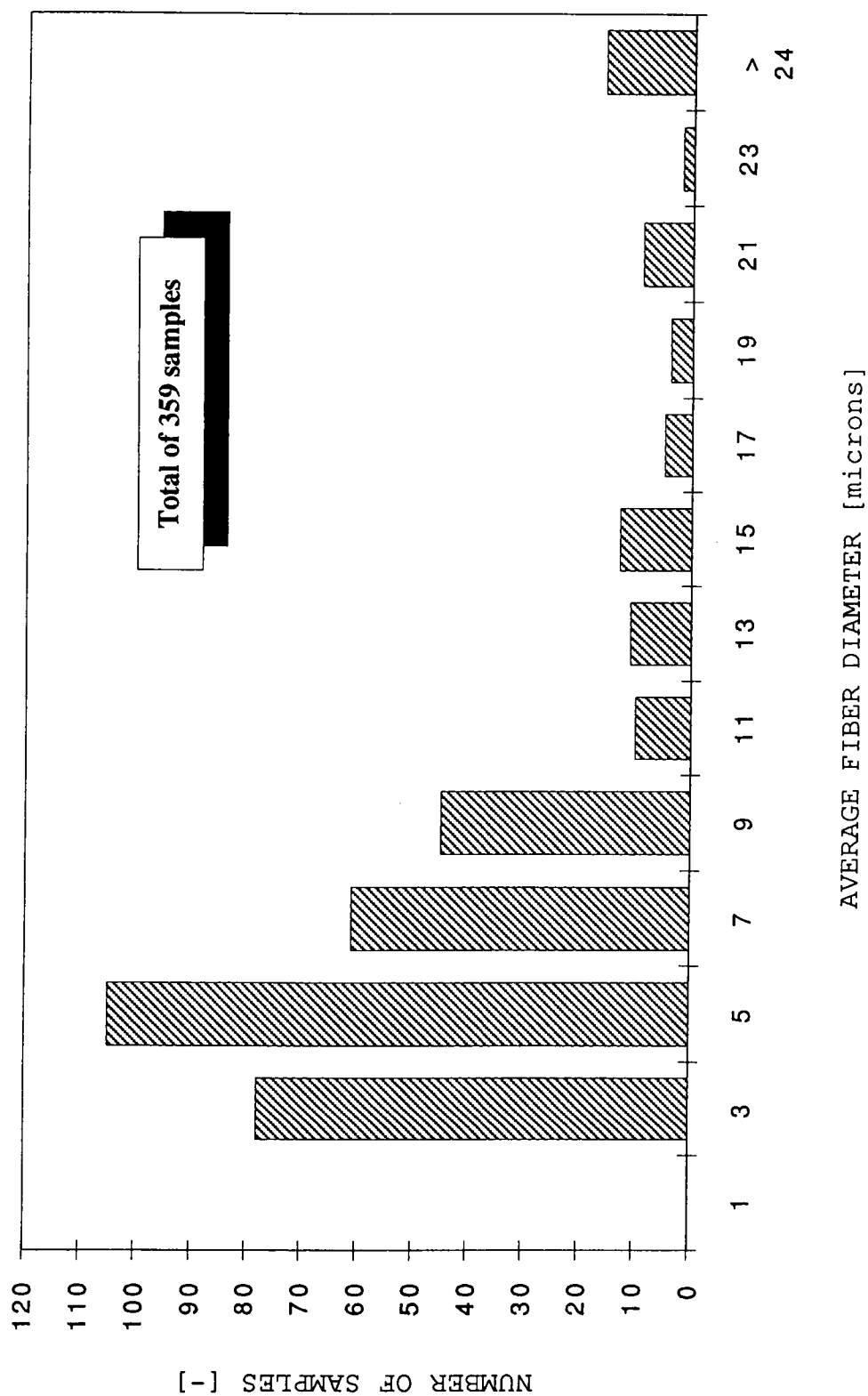


Figure 4.15: Distribution of measured average fiber diameter

Table 4.5: Distribution of the samples based on the absolute average diameter difference between measured and predicted values.

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MOMENTUM FLUX MODEL (Equation 4.47)		MASS FLUX MODEL (Equation 4.25)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	221	61.6	206	57.4
between 1 and 2	82	22.8	93	25.9
between 2 and 3	38	10.6	39	10.9
between 3 and 4	9	2.5	11	3.1
between 4 and 5	4	1.1	5	1.4
greater than 5	5	1.4	5	1.4
Total	359	Total	359	

Table 4.6: Distribution of the experimental data based on the measured average fiber diameter and absolute difference between measured and predicted values (MFR parameter not included in models).

Measured Average Fiber Diameter [microns]	Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MOMENTUM FLUX MODEL (Equation 4.47)		MASS FLUX MODEL (Equation 4.25)	
		Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 4	less than 2	77	21.4	77	21.4
	between 2 and 4	1	0.3	1	0.3
	greater than 4	0	0.0	0	0.0
from 4 to 6	less than 2	101	28.1	100	27.9
	between 2 and 4	4	1.1	5	1.4
	greater than 4	0	0.0	0	0.0
from 6 to 8	less than 2	51	14.2	49	13.6
	between 2 and 4	9	2.5	11	3.1
	greater than 4	1	0.3	1	0.3
from 8 to 10	less than 2	36	10.0	35	9.7
	between 2 and 4	7	1.9	8	2.2
	greater than 4	2	0.6	2	0.6
greater than 10	less than 2	38	10.6	38	10.6
	between 2 and 4	26	7.2	25	7.0
	greater than 4	6	1.7	7	1.9
Total		359	Total	359	

shows the number of samples that were predicted to be within 2, 4, and greater than 4 microns for groups of samples having measured average diameters within a specific range; from 0 to 4 microns, from 4 to 6 microns, etc. It can be seen that the majority of the samples having a measured average diameter smaller than 10 microns are predicted within 2 microns of the experimental value. This is true for both models. Also, a large percentage of the samples having a measured average diameter greater than 10 microns are predicted within 4 microns using either model. It should be remembered that 51% of the samples have a measured average diameter less than 6 microns and that the uncertainty in the measurement of the average diameter is 1.25 microns. It can be concluded then that the models can predict the average diameter of a melt blown fiber with an accuracy that is within two times the uncertainty of the measured values.

Expansion of Empirical Models to Other Polymer MFRs

The empirical models developed so far take into account all of the processing conditions that are believed to be the most important parameters that describe the melt blowing process: die geometry (air jet injection angle and air jet exit height), processing temperatures (air jet and polymer temperature), air flow conditions (air flow rate, air jet exit velocity), and polymer throughput. However,

polypropylene polymers of different viscosity (MFR) ranging from 35 to 1,500 MFR are used in industry, whereas these models were developed using data generated with a single polymer MFR, 650. Therefore, an attempt to expand these models to other polymer MFRs will be presented in this section.

Sherwood [16] produced 18 samples using 35 MFR polypropylene in the single hole melt blowing facility. These data points were combined with the 359 data points generated by the author and a new set of empirical models, which include the polymer MFR parameter (Ω) were developed. Equations 4.49 and 4.50 show the resulting empirical models generated with the momentum flux and the mass flux as the main parameters, respectively.

$$\delta_{33} = 0.002 + 3.5 \Psi^{-0.72} \Theta^{-6.26} \beta^{-0.73} \Phi^{-0.38} \xi^{-1.07} \Pi^{0.58} \Omega^{-0.44} \quad 4.49$$

$$(\gamma^2 = 0.9801)$$

$$\delta_{34} = 0.003 + 0.03 \Gamma^{-1.39} \Theta^{-6.1} \xi^{-1.8} \beta^{-0.66} \Phi^{-0.43} \Pi^{0.53} \Omega^{-0.44} \quad 4.50$$

$$(\gamma^2 = 0.9788)$$

Equations 4.51 and 4.52 show the associated modified average fiber diameter ratio terms for Equations 4.49 and 4.50, respectively.

$$\Delta_{33} = \Psi^{-0.72} \quad 4.51a$$

$$\Delta_{33} = \frac{\delta_{33} - 0.002}{3.5 \Theta^{-6.26} \beta^{-0.73} \Phi^{-0.38} \xi^{-1.07} \Pi^{0.58} \Omega^{-0.44}} \quad 4.51b$$

$$\Delta_{34} = \Gamma^{-1.39} \quad 4.52a$$

$$\Delta_{34} = \frac{\delta_{34} - 0.003}{0.03 \Theta^{-6.1} \xi^{-1.8} \beta^{-0.66} \Phi^{-0.43} \Pi^{0.53} \Omega^{-0.44}} \quad 4.52b$$

Figure 4.16 shows a comparison between the momentum flux empirical model developed without the MFR parameter (Equation 4.48a) and the 35 MFR experimental data. Figure 4.17 shows a comparison between the momentum flux model developed with the MFR parameter (Equation 4.51a) and the 35 MFR experimental data. It can be seen by comparing Figures 4.16 and 4.17 that the polymer viscosity is an important parameter in the melt blowing process. The model developed without the MFR parameter doesn't correlate the 35 MFR data very well. However, when the MFR parameter is included in the model, the results are significantly better. Table 4.7 lists the measured average diameter of the 35 MFR data, the predicted values from the models with and without the MFR parameter (Equations 4.51 and 4.48, respectively), and it also lists the corresponding absolute and percentile difference between predicted and measured values for the momentum flux models. It can be seen that 78% of the samples are predicted within 2 microns of the measured value using the model that includes the MFR parameter (Equation 4.49),

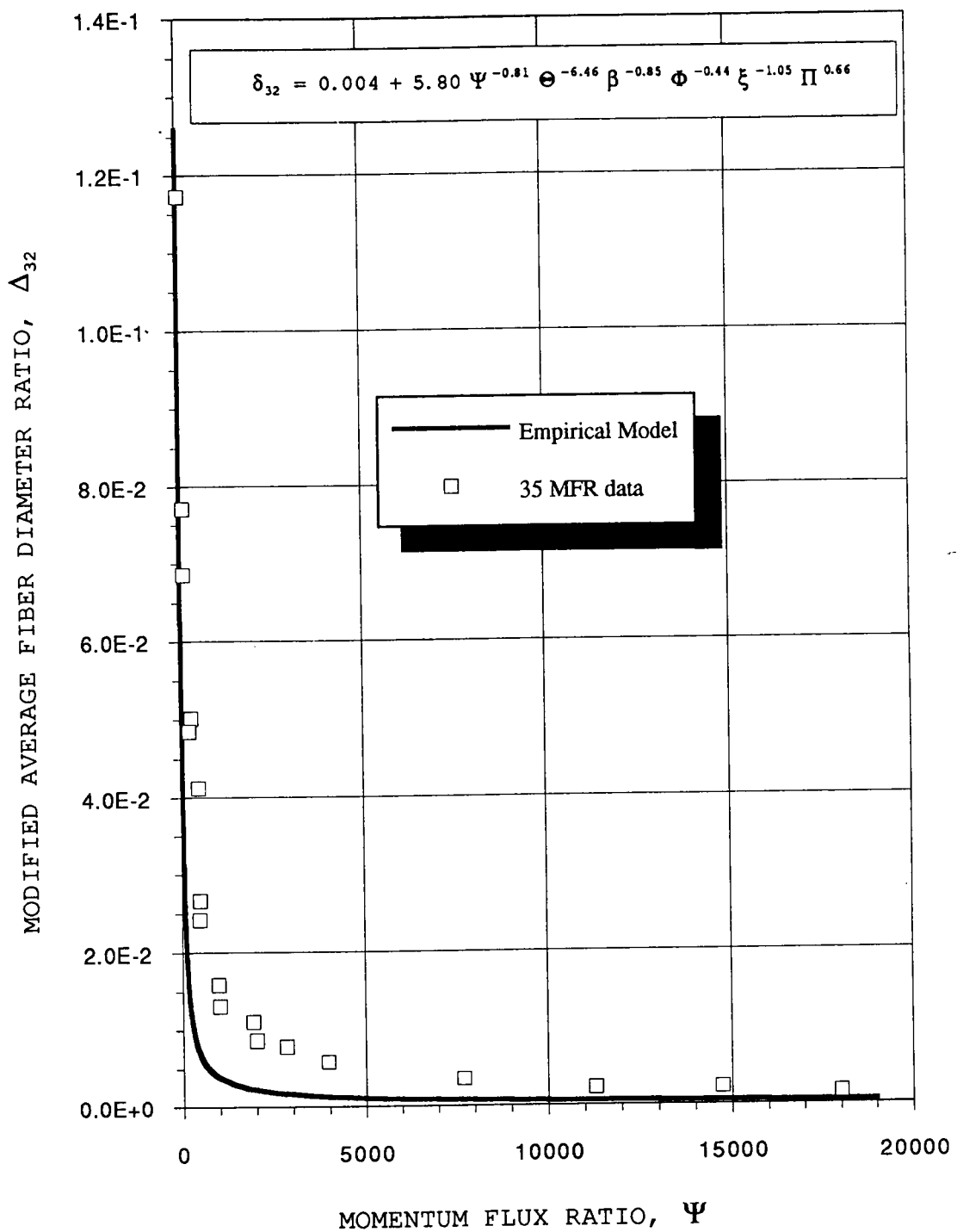


Figure 4.16: Comparison between momentum flux empirical model and 35 MFR experimental data (no MFR parameter included)

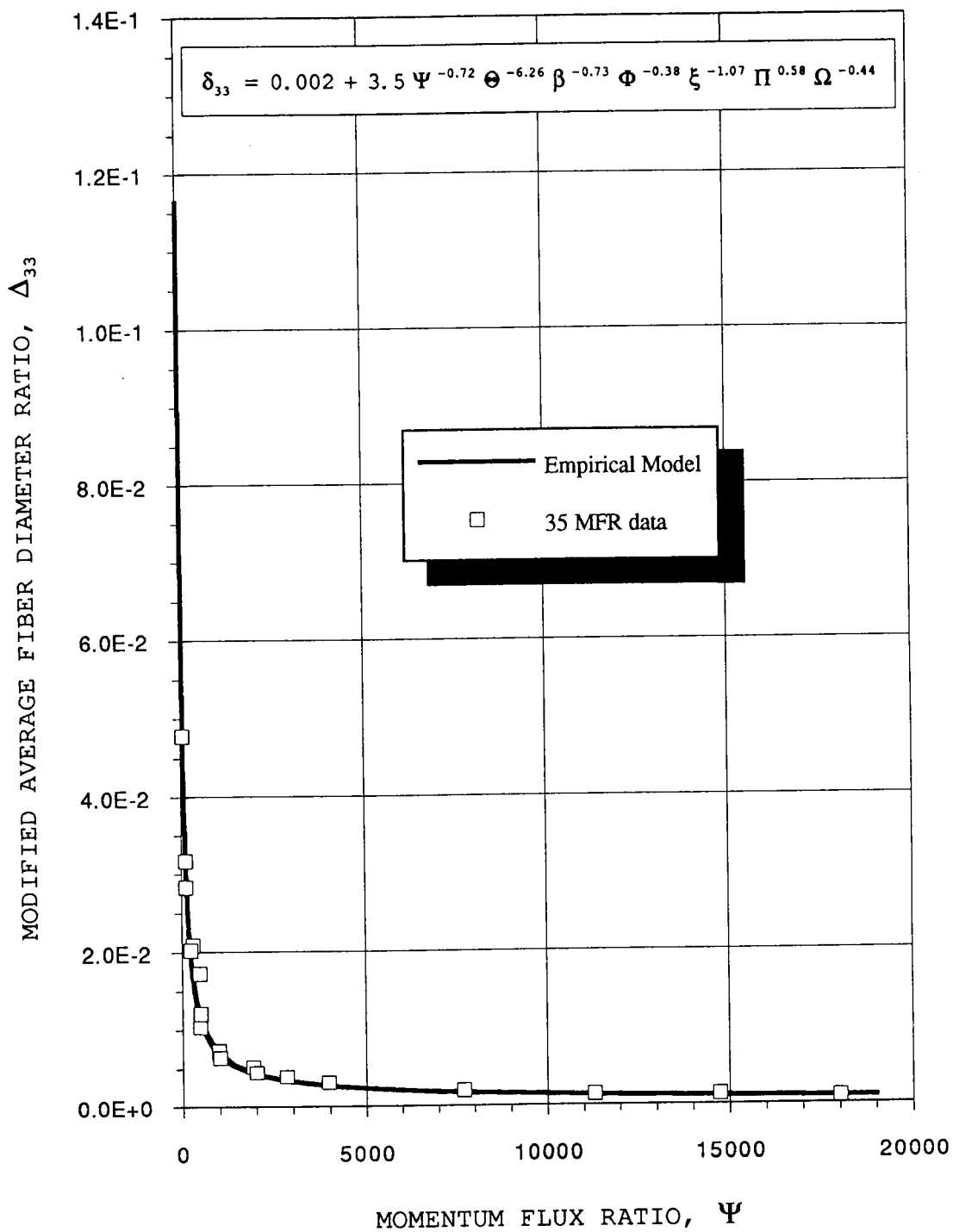


Figure 4.17: Comparison between momentum flux empirical model and 35 MFR experimental data (MFR parameter included)

Table 4.7: Distribution of the samples based on the absolute average diameter difference between measured and predicted values using the momentum flux models (35 MFR data).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MFR PARAMETER NOT INCLUDED (Equation 4.47)		MFR PARAMETER INCLUDED (Equation 4.49)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	0	0.0	6	33.3
between 1 and 2	1	5.6	8	44.4
between 2 and 3	2	11.1	0	0.0
between 3 and 4	0	0.0	2	11.1
between 4 and 5	1	5.6	0	0.0
greater than 5	14	77.8	2	11.1
Total	18	Total	18	

whereas only one data point (5%) is predicted within 2 microns using the model that does not include the MFR parameter (Equation 4.47).

Figures 4.18 and 4.19 show a similar comparison for the mass flux models developed with (Equation 4.50) and without (Equation 4.25) the MFR parameter, respectively. Table 4.8 summarizes the results for the comparison made between these two models. The same results that were found for the momentum flux models are seen for the mass flux models; 78% of the samples are predicted within 2 microns using the model that includes the MFR parameter and only one sample (5%) is predicted within 2 microns using the model that does not include the MFR parameter.

So far it has been shown that by adding the polymer MFR parameter to the empirical models, the 35 MFR data can be correlated with great success. However, nothing has been said about how well do these new models correlate the original data (650 MFR). Table 4.9 shows how well can these new models predict the average diameter of the original experimental data. Table 4.10 shows the distribution of the experimental data using the new models based on the absolute difference between the measured and predicted average diameter values. By comparing the results from Tables 4.10 and 4.6 (models with and without the MFR parameter included, respectively) it can be seen that there is no significant difference on how well both sets of models can predict the

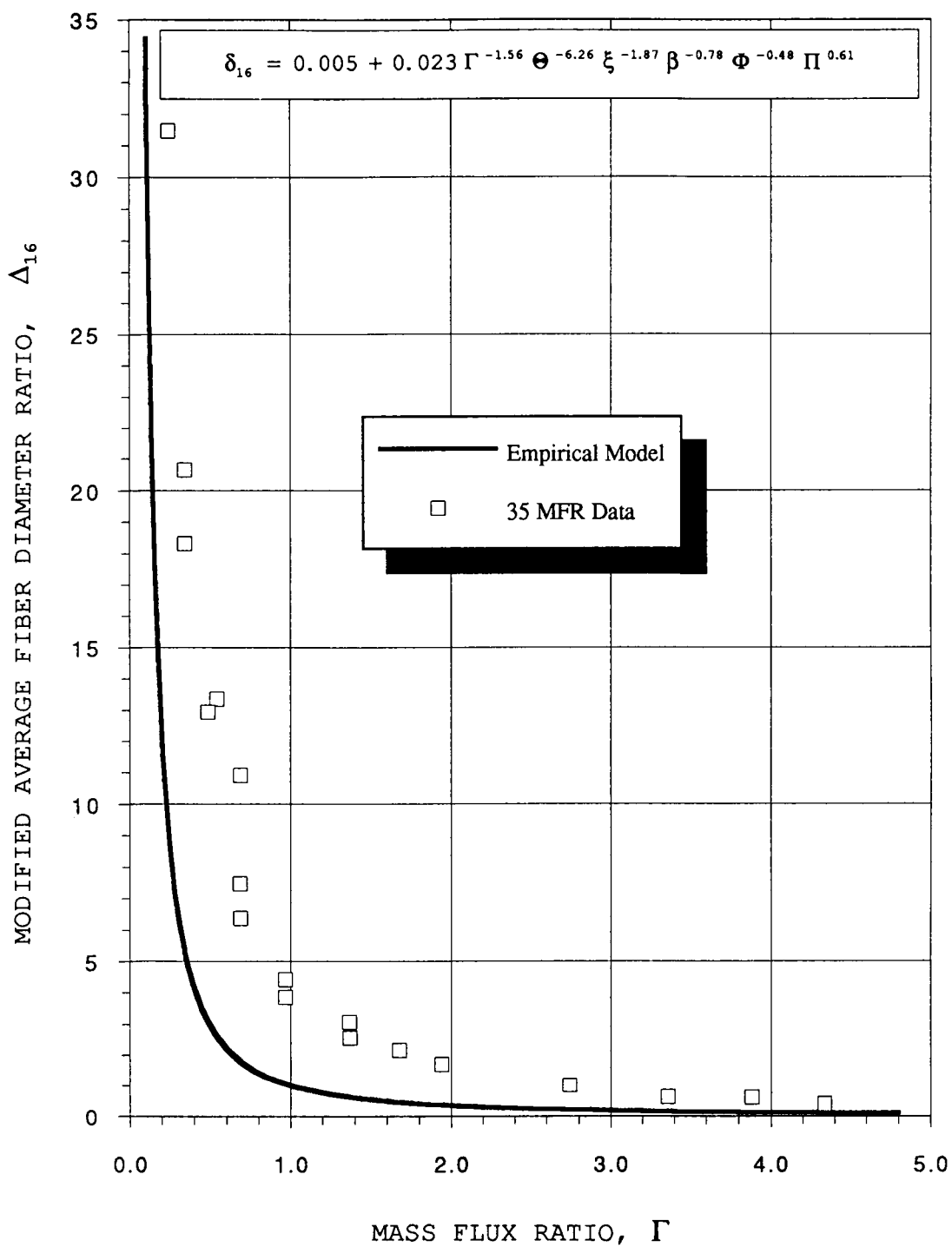


Figure 4.18: Comparison between mass flux empirical model and 35 MFR experimental data (no MFR parameter included)

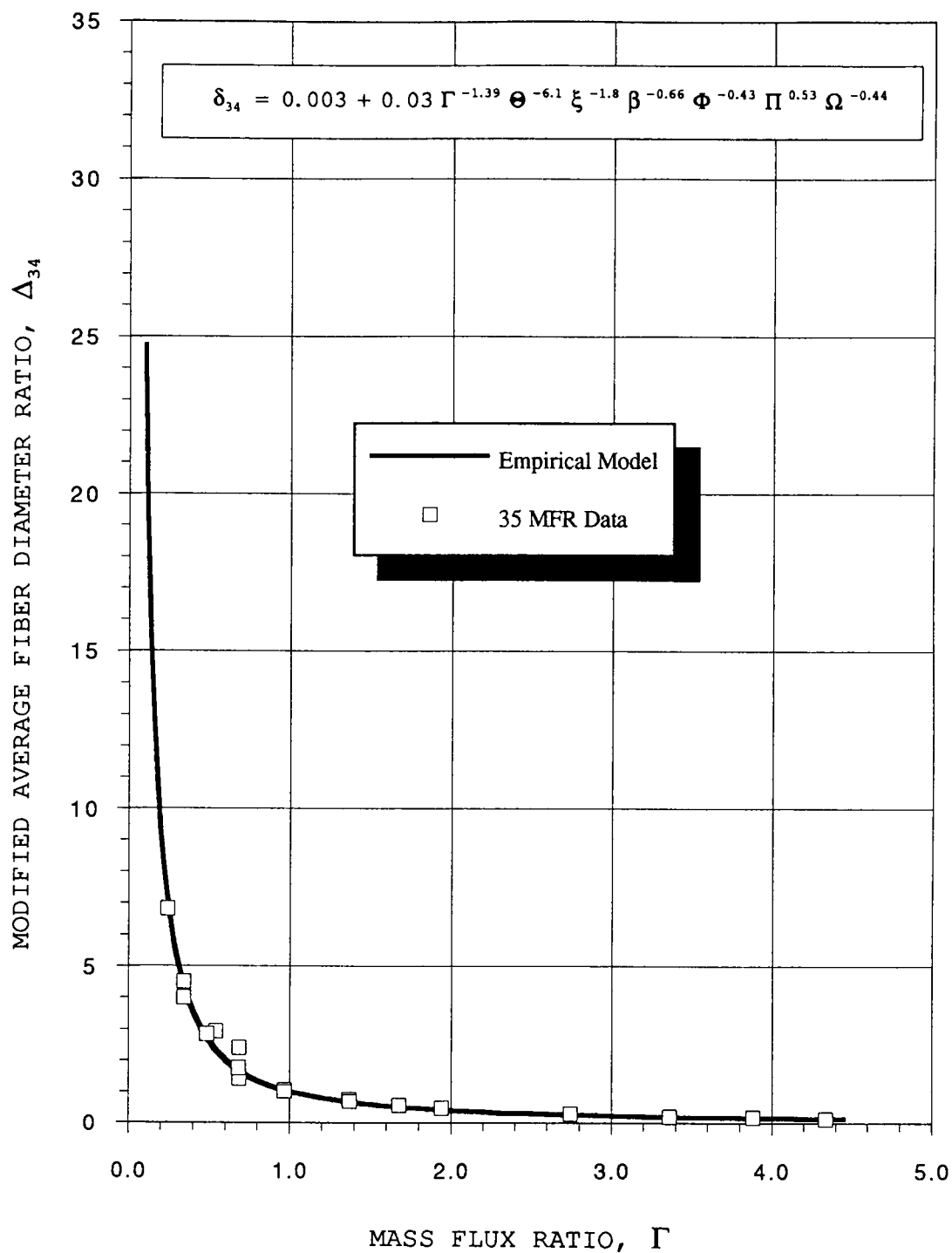


Figure 4.19: Comparison between mass flux empirical model and 35 MFR experimental data (MFR parameter included)

Table 4.8: Distribution of the samples based on the absolute average diameter difference between measured and predicted values using the mass flux models (35 MFR data).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MFR PARAMETER NOT INCLUDED (Equation 4.25)		MFR PARAMETER INCLUDED (Equation 4.50)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	0	0.0	10	55.6
between 1 and 2	1	5.6	4	22.2
between 2 and 3	2	11.1	1	5.6
between 3 and 4	0	0.0	0	0.0
between 4 and 5	1	5.6	1	5.6
greater than 5	14	77.8	2	11.1
Total	18	Total	18	

Table 4.9: Distribution of the samples based on the absolute average diameter difference between measured and predicted values (MFR parameter included in both models).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MOMENTUM FLUX MODEL (Equation 4.49)		MASS FLUX MODEL (Equation 4.50)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	208	57.9	199	55.4
between 1 and 2	98	27.3	95	26.5
between 2 and 3	33	9.2	43	12.0
between 3 and 4	11	3.1	11	3.1
between 4 and 5	3	0.8	4	1.1
greater than 5	6	1.7	7	1.9
Total	359	Total	359	

Table 4.10: Distribution of the experimental data based on the measured average fiber diameter and absolute difference between measured and predicted values (MFR parameter included in both models).

Measured Average Fiber Diameter [microns]	Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MOMENTUM FLUX MODEL (Equation 4.49)		MASS FLUX MODEL (Equation 4.50)	
		Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 4	less than 2	78	21.7	77	21.4
	between 2 and 4	0	0.0	1	0.3
	greater than 4	0	0.0	0	0.0
from 4 to 6	less than 2	101	28.1	98	27.3
	between 2 and 4	4	1.1	7	1.9
	greater than 4	0	0.0	0	0.0
from 6 to 8	less than 2	50	13.9	44	12.3
	between 2 and 4	11	3.1	16	4.5
	greater than 4	0	0.0	1	0.3
from 8 to 10	less than 2	36	10.0	35	9.7
	between 2 and 4	7	1.9	8	2.2
	greater than 4	2	0.6	2	0.6
greater than 10	less than 2	41	11.4	40	11.1
	between 2 and 4	22	6.1	22	6.1
	greater than 4	7	1.9	8	2.2
Total		359	Total	359	

average diameter of the original set of experimental data. Further evidence can be seen by comparing the results shown in Tables 4.9 and 4.5 (models with and without MFR parameter, respectively).

In conclusion, the addition of the MFR parameter, Ω , to the empirical models does not change their ability to predict the average diameter of the original experimental data (650 MFR). Furthermore, these models can also predict the average diameter of polymers of different viscosity within 2 microns.

Data from Independent Researcher

The experimental data (116 data points) collected by Haynes [13] using the single hole melt blowing facility are used in this section to validate the results obtained so far with the empirical models. All of these samples were produced with 800 MFR polypropylene.

Table 4.11 shows the distribution of the average fiber diameter as measured from the optical microscope. It can be seen that the measured average fiber diameters are equally distributed in three groups; smaller than 6 microns, between 6 and 12 microns, and greater than 12 microns. Figures 4.20 and 4.21 show a comparison between the momentum flux empirical model and the experimental data for the models developed with (Equation 4.49) and without (Equation 4.47)

Table 4.11: Distribution of average fiber diameter as measured from the optical microscope (Haynes' experimental data).

Measured Average Fiber Diameter [microns]	Number of Samples [-]	Percent of Total Population [%]	Partial Percentage [%]
less than 2	0	0.0	31.9
between 2 and 4	1	0.9	
between 4 and 6	36	31.0	
between 6 and 8	25	21.6	32.8
between 8 and 10	13	11.2	
between 10 and 12	8	6.9	
between 12 and 14	5	4.3	35.3
between 14 and 16	8	6.9	
between 16 and 18	2	1.7	
between 18 and 20	3	2.6	
between 20 and 22	6	5.2	
between 22 and 24	2	1.7	
greater than 24	7	6.0	
Total	116		

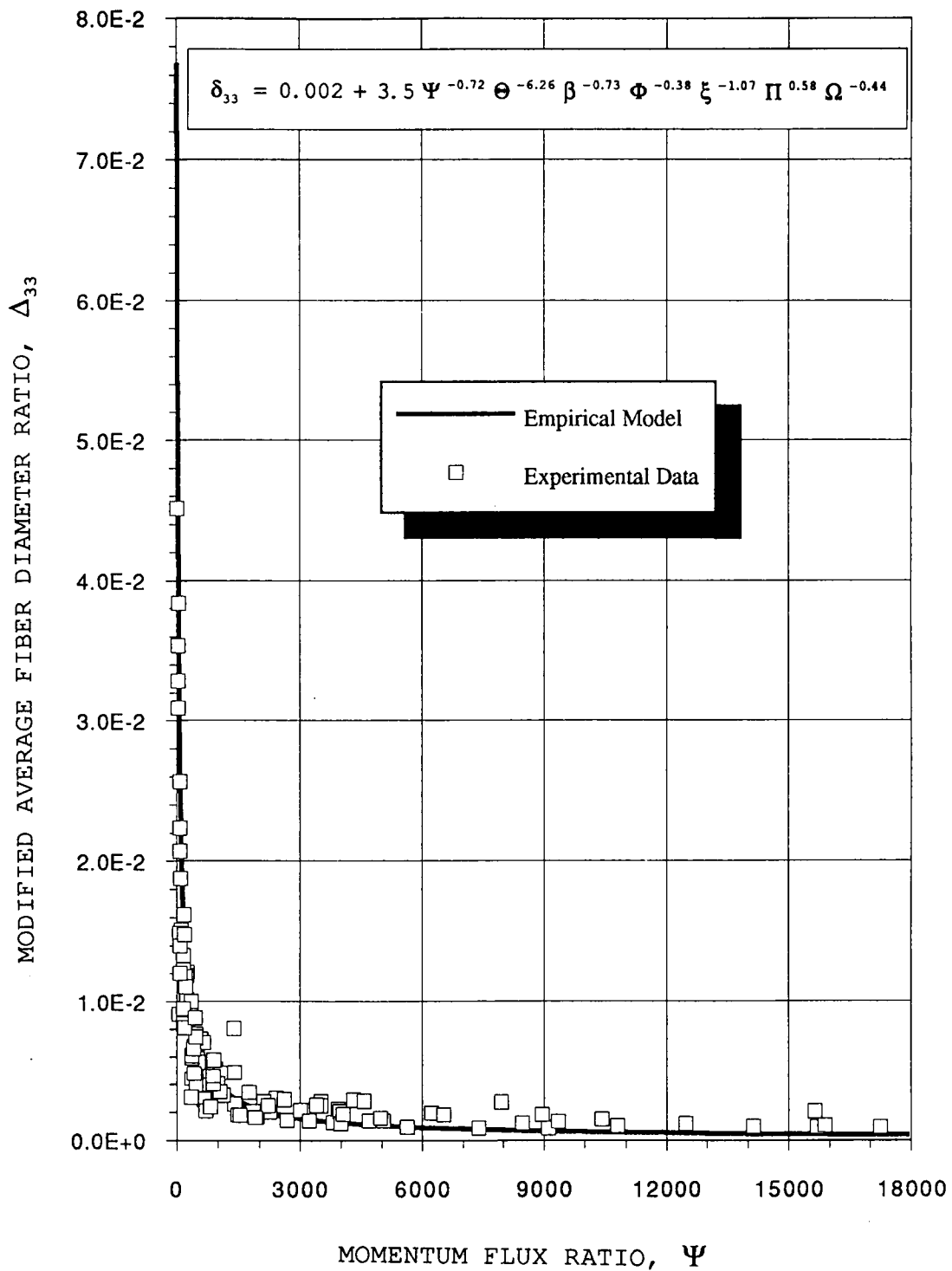


Figure 4.20: Comparison between momentum flux empirical model and other researcher's experimental data (MFR parameter included)

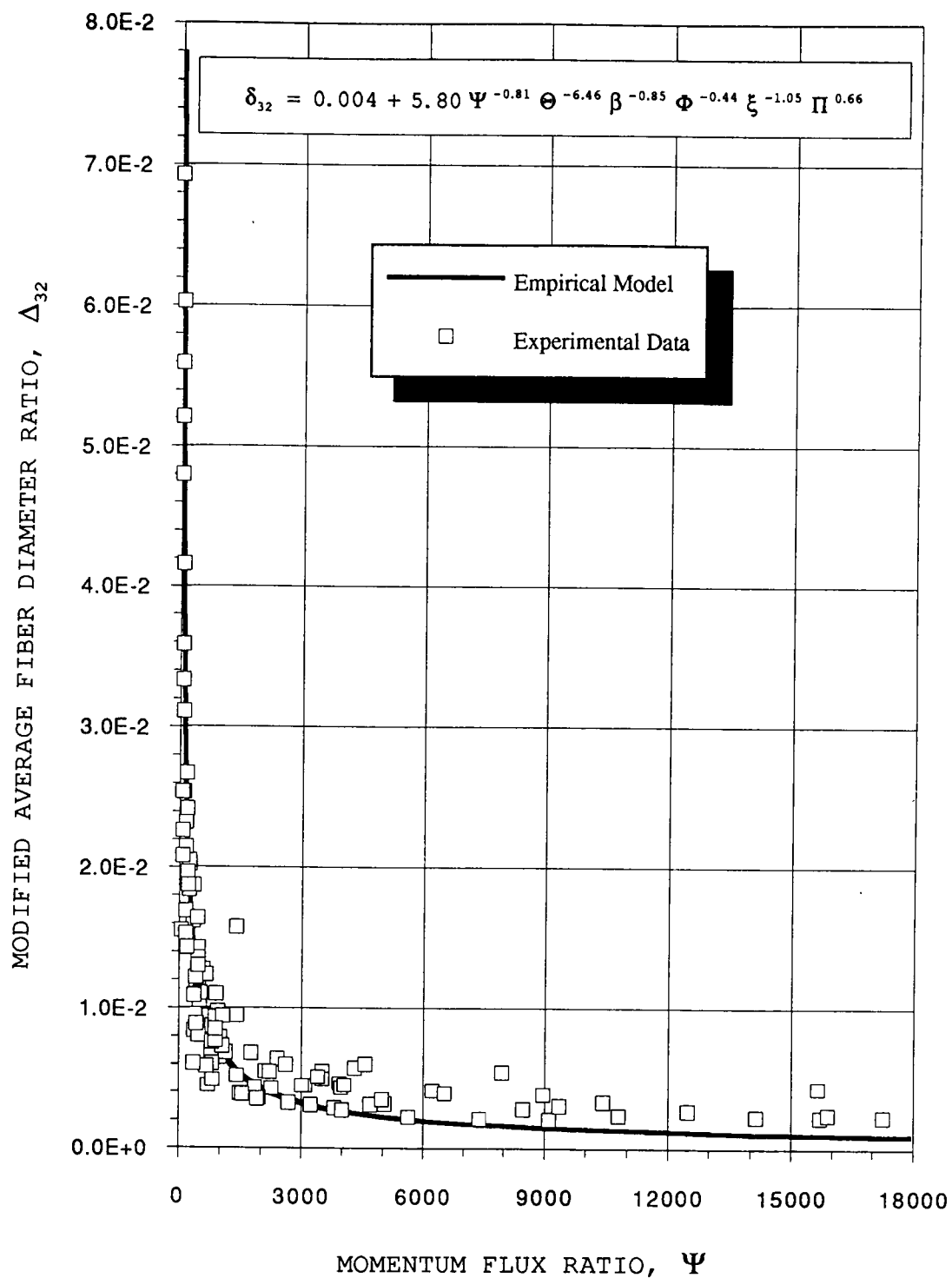


Figure 4.21: Comparison between momentum flux empirical model and other researcher's experimental data (no MFR parameter included)

the MFR parameter, respectively. The data on both plots fit the models very well. Table 4.12 shows the distribution of the samples based on the absolute average diameter difference between measured and experimental values using the momentum flux models. Both models predict 90% of the samples within 4 microns of the measured values. However, the model with the MFR parameter predicts 81.8% of the samples within 2 microns, whereas the models without the MFR parameter only predicts 77.3% of them being within 2 microns. Thus, the model that includes the MFR parameter fits the data a little better. This is to be expected since the model that does not include the MFR parameter was developed with data processed with 650 MFR.

Figures 4.22 and 4.23 show a comparison between the models and the experimental data for the mass flux models developed with (Equation 4.50) and without (Equation 4.25) the MFR parameter. Table 4.13 shows the distribution of the samples based on the absolute average diameter difference between measured and experimental values using the mass flux models. The results for the mass flux models, as expected, are very similar to the results obtained with the momentum flux models. Once again, the addition of the MFR parameter to fit experimental data generated with polymer MFRs other than 650 will show better results. This improvement however, is very small compared to the improvements obtained for the 35 MFR data.

Table 4.12: Distribution of the samples based on the absolute average diameter difference between measured and predicted values using the momentum flux models (Haynes' experimental data).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MFR PARAMETER NOT INCLUDED (Equation 4.47)		MFR PARAMETER INCLUDED (Equation 4.49)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	35	30.2	29	25.0
between 1 and 2	21	18.1	27	23.3
between 2 and 3	24	20.7	21	18.1
between 3 and 4	9	7.8	15	12.9
between 4 and 5	6	5.2	4	3.4
greater than 5	21	18.1	20	17.2
Total	116	Total	116	

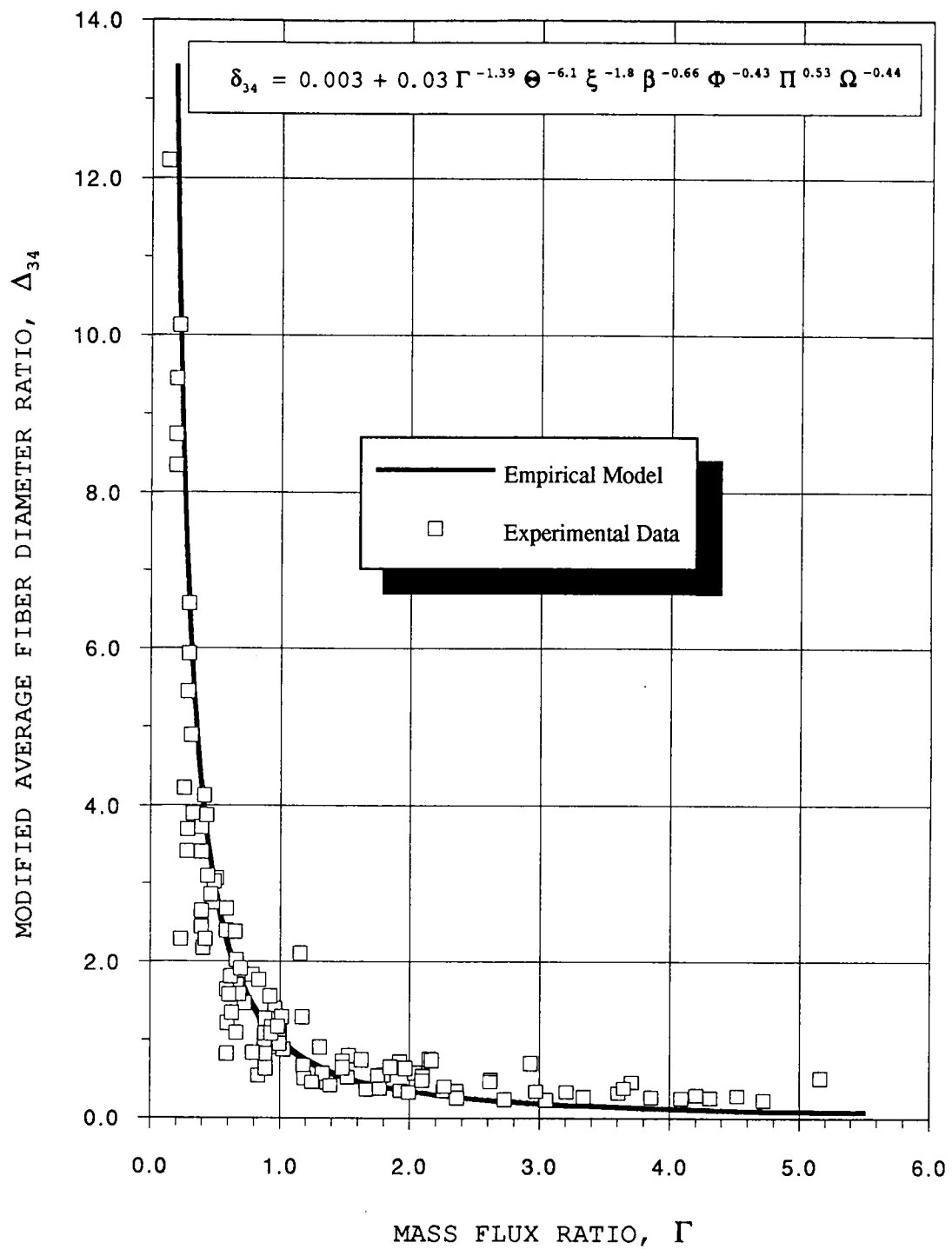


Figure 4.22: Comparison between mass flux empirical model and other researcher's experimental data (MFR parameter included)

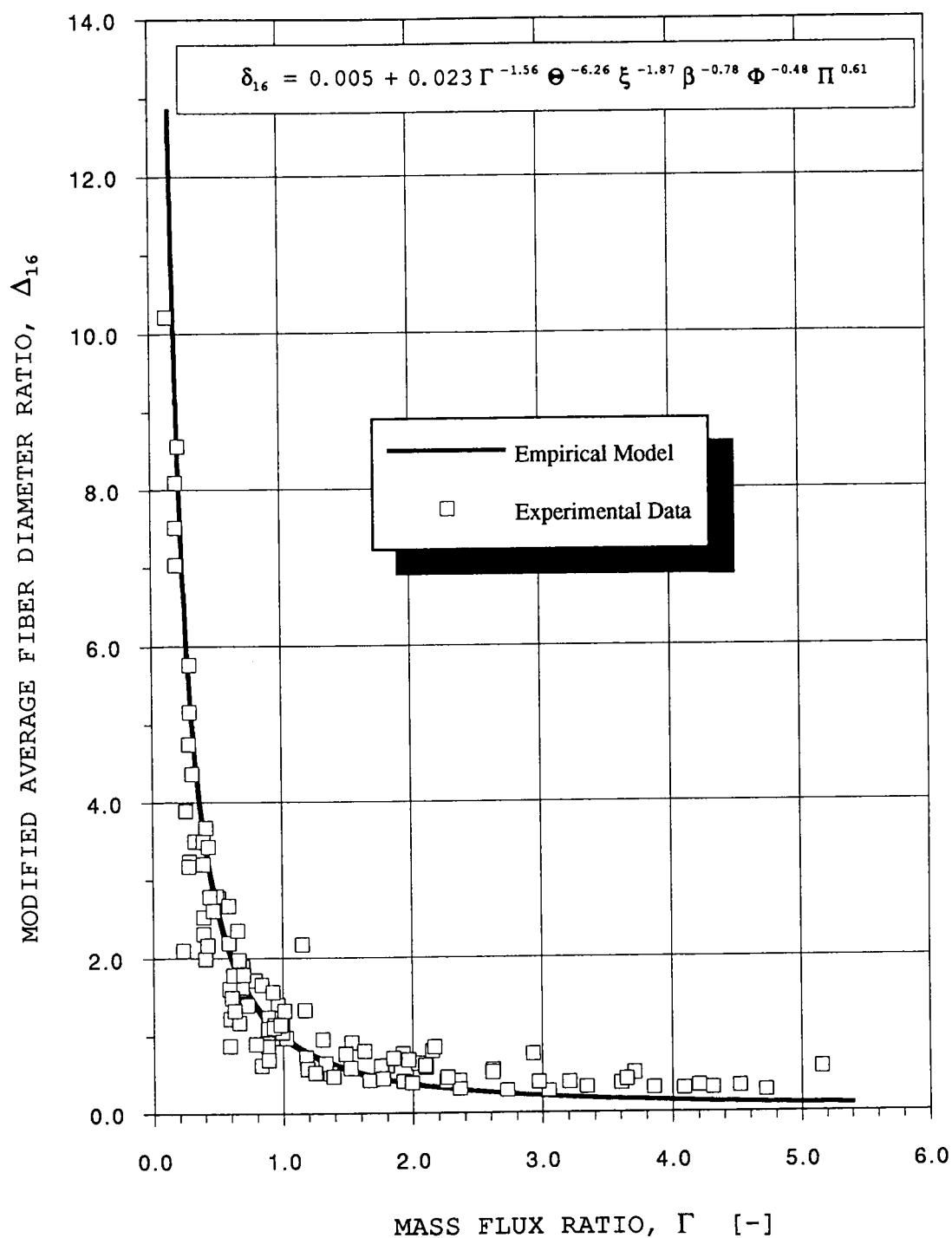


Figure 4.23: Comparison between mass flux empirical model and other researcher's experimental data (no MFR parameter included)

Table 4.13: Distribution of the samples based on the absolute average diameter difference between measured and predicted values using the mass flux models (Haynes' experimental data).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MFR PARAMETER NOT INCLUDED (Equation 4.25)		MFR PARAMETER INCLUDED (Equation 4.50)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	35	30.2	28	24.1
between 1 and 2	24	20.7	28	24.1
between 2 and 3	19	16.4	16	13.8
between 3 and 4	16	13.8	13	11.2
between 4 and 5	1	0.9	8	6.9
greater than 5	21	18.1	23	19.8
Total	116	Total	116	

In conclusion, both the momentum flux and the mass flux models (with or without the MFR parameter) models correlate the experimental data collected very well. Also, a small improvement in the correlation is accomplished by adding the MFR term to the models.

Data from UTK 20 Inch Multiple Hole Die

This section presents the efforts made to predict the average fiber diameter of experimental data collected at the UTK 20 inch multiple hole melt blowing facility using the models developed with the data collected at the single hole melt blowing facility.

A total of 22 data points were processed with 650 MFR polypropylene. All of the samples have a measured average diameter smaller than 10 microns. Table 4.14 shows the results obtained when the momentum flux models, both with and without the MFR parameter, are used to predict the average fiber diameter. The model that does not include the MFR parameter (Equation 4.47) predicts 77.3% of the samples within 2 microns of the measured average diameter and 90.9% within 4 microns. Similarly, the model that includes the MFR parameter (Equation 4.49) predicts 81.8% of the samples within 2 microns and 90.9% within 4 microns. Figures 4.24 and 4.25 show a comparison between the momentum flux empirical models (with and without the MFR parameter,

Table 4.14: Distribution of the samples based on the absolute average diameter difference between measured and predicted values using the momentum flux models (UTK 20" Die data).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MFR PARAMETER NOT INCLUDED (Equation 4.47)		MFR PARAMETER INCLUDED (Equation 4.49)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	11	50.0	13	59.1
between 1 and 2	6	27.3	5	22.7
between 2 and 3	2	9.1	2	9.1
between 3 and 4	1	4.5	0	0.0
between 4 and 5	0	0.0	1	4.5
greater than 5	2	9.1	1	4.5
Total	22	Total	22	

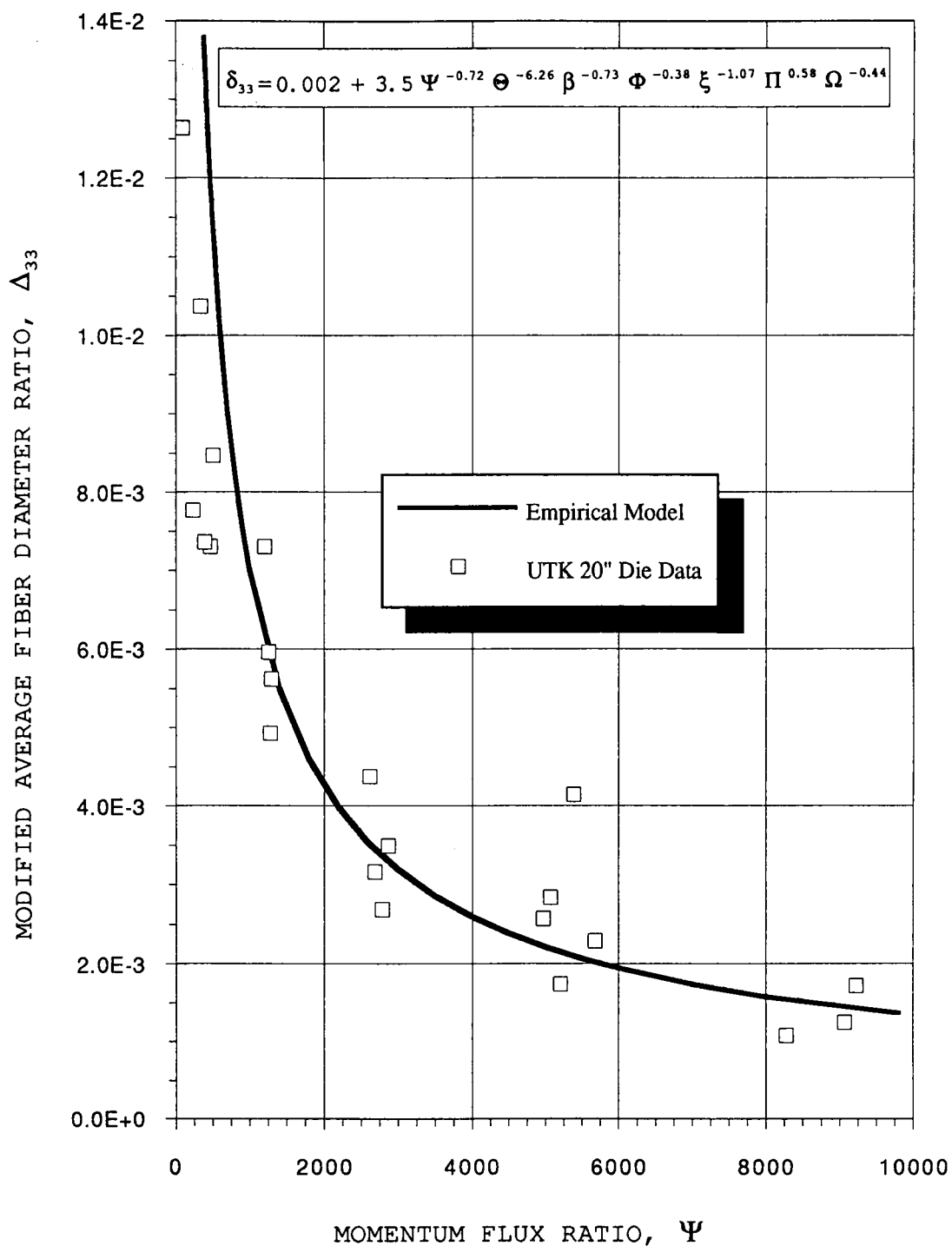


Figure 4.24: Comparison between momentum flux empirical model and UTK 20 inch die experimental data (MFR parameter included)

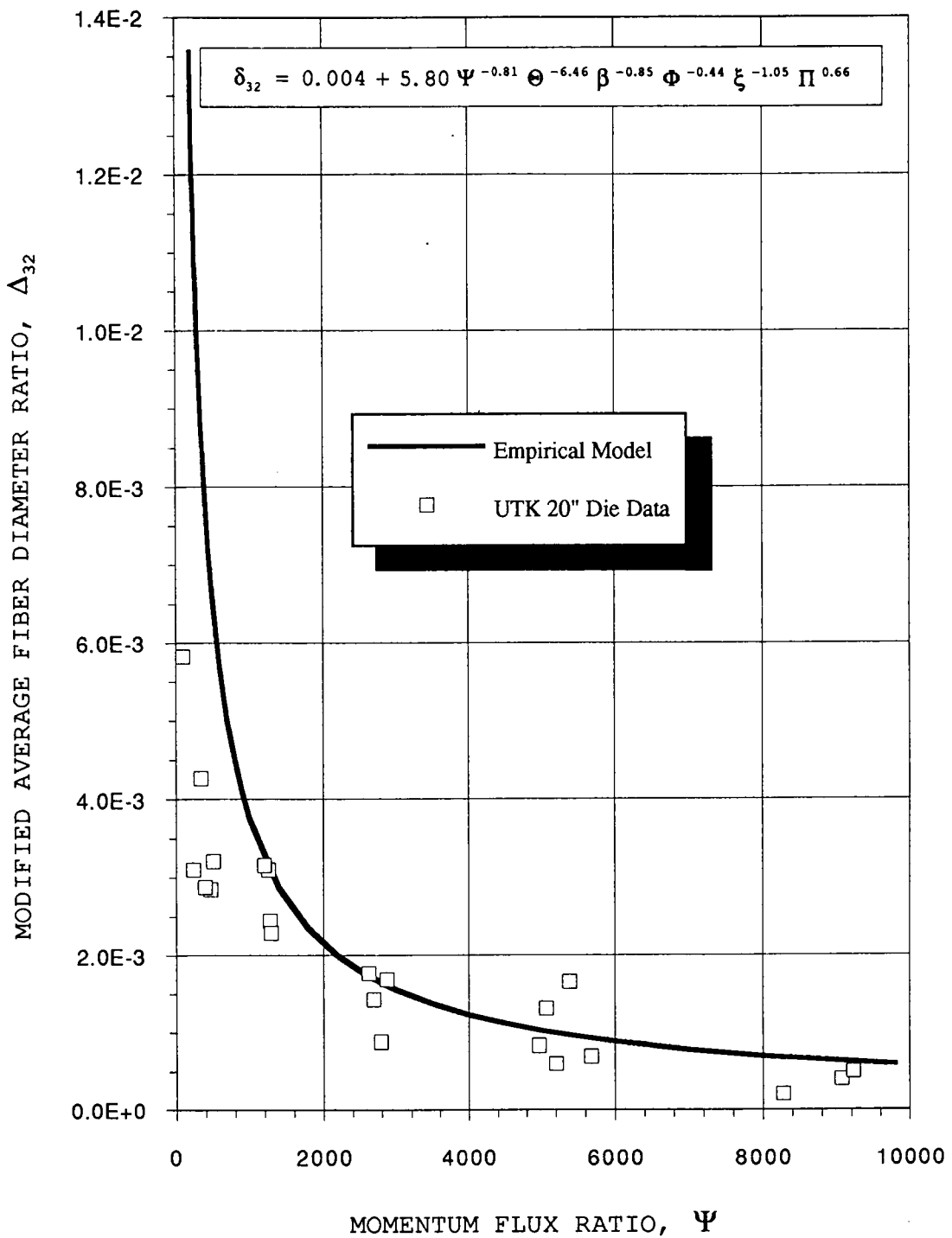


Figure 4.25: Comparison between momentum flux empirical model and UTK 20 inch die experiemntal data (no MFR parameter included)

respectively) and the experimental data. It is clear that these two models do an excellent job in correlating the experimental data obtained from a multi-hole die line rather than the single hole die.

Table 4.15 shows the results obtained when the mass flux models, both with and without the MFR parameter, are used to predict the average fiber diameter. The model that does not include the MFR parameter (Equation 4.25) predicts 77.3% of the samples within 2 microns of the measured average diameter and 90.9% within 4 microns. Similarly, the model that includes the MFR parameter (Equation 4.50) predicts 81.8% of the samples within 2 microns and 90.9% within 4 microns. Figures 4.26 and 4.27 show a comparison between the empirical models (with and without the MFR parameter, respectively) and the experimental data. It should be noted that not only these models also correlate the data well, but also, the results are the same as for the momentum flux models.

It can be concluded that the empirical models developed with the data collected at the single hole melt blowing facility can be effectively used to predict the average diameter of fibers processed at facilities other than just the single hole melt blowing facility. In particular, the data collected at the UTK 20 inch multiple hole die was successfully correlated with the models developed in this Chapter.

Table 4.15: Distribution of the samples based on the absolute average diameter difference between measured and predicted values using the mass flux models (UTK 20" Die data).

Absolute Average Diameter Difference Between Measured and Predicted Values [microns]	MFR PARAMETER NOT INCLUDED (Equation 4.25)		MFR PARAMETER INCLUDED (Equation 4.50)	
	Number of Samples [-]	Percent of Total Population [%]	Number of Samples [-]	Percent of Total Population [%]
less than 1	11	50.0	13	59.1
between 1 and 2	6	27.3	5	22.7
between 2 and 3	2	9.1	2	9.1
between 3 and 4	1	4.5	0	0.0
between 4 and 5	0	0.0	1	4.5
greater than 5	2	9.1	1	4.5
Total	22	Total	22	

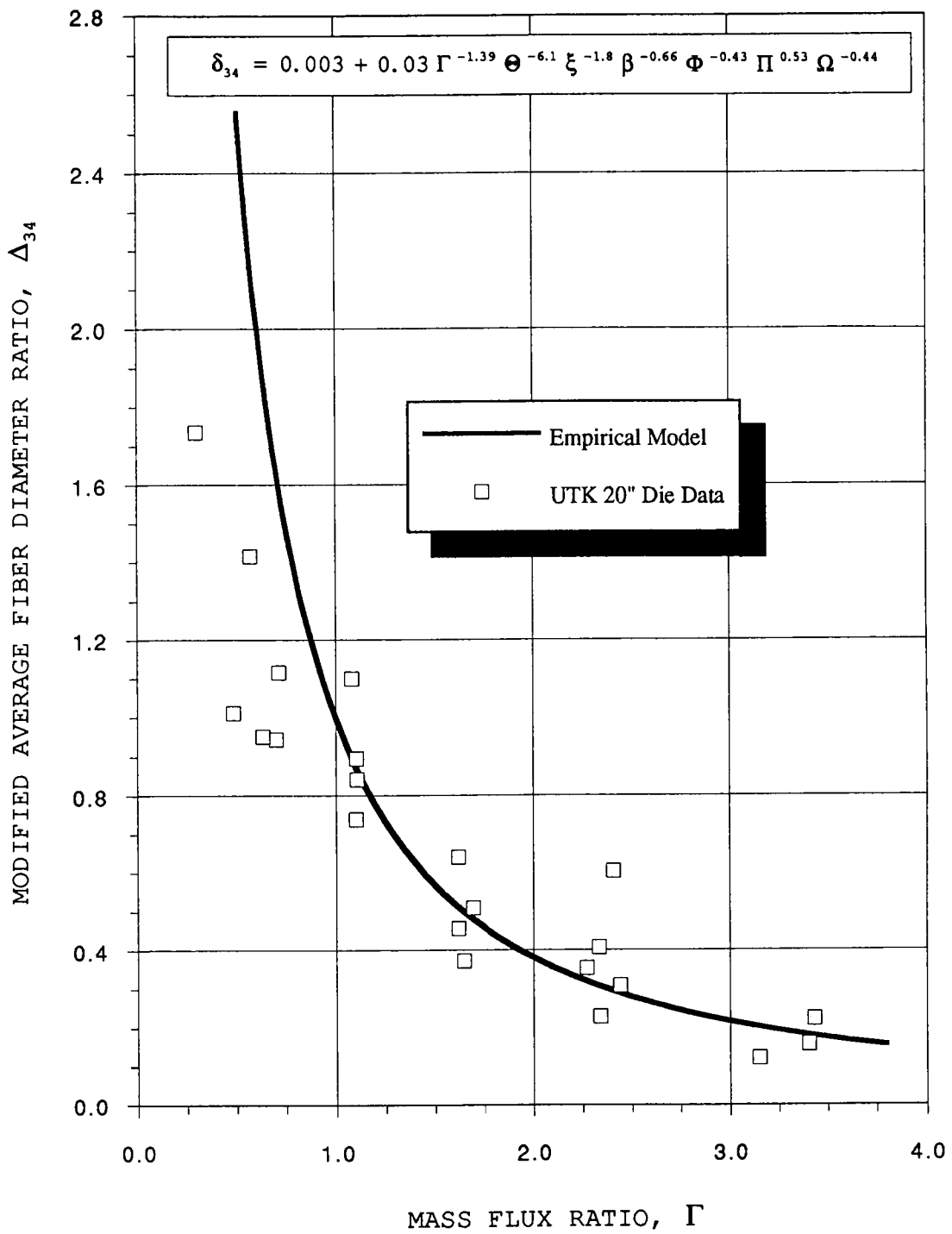


Figure 4.26: Comparison between mass flux empirical model and UTK 20 inch die experimental data (MFR parameter included)

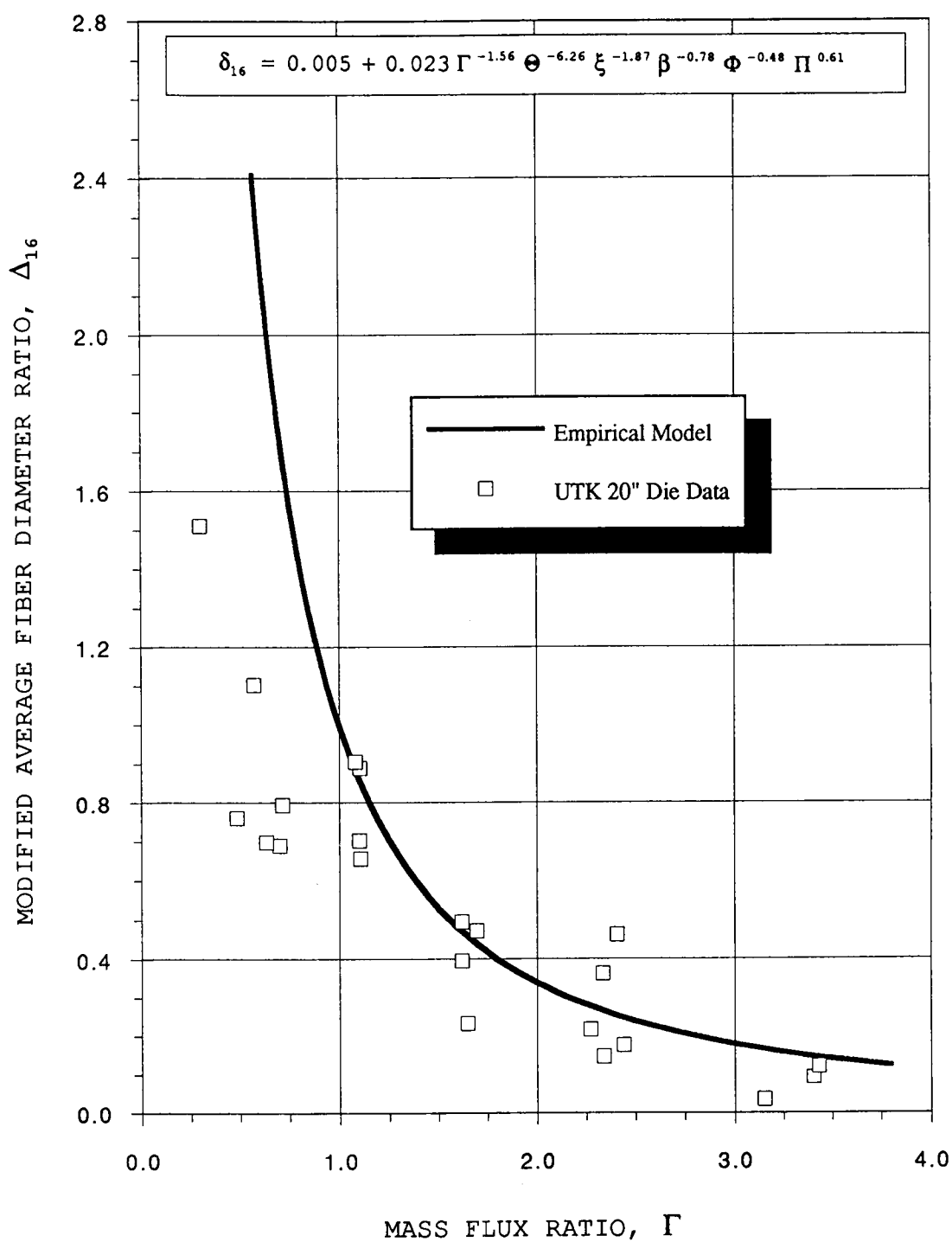


Figure 4.27: Comparison between mass flux empirical model and UTK 20 inch die experimental data (no MFR parameter included)

Absolute Temperature vs. Degrees Fahrenheit

The following section presents a study conducted to determine if deriving the dimensionless temperature ratio variables using degrees Fahrenheit or absolute temperatures has an effect in the predicted average diameter as determined by the empirical models.

The original dimensionless temperature ratio variables for the polymer and air jet, Θ and ξ respectively, were derived using absolute temperatures. The new parameters, Λ and τ respectively, were derived using degrees Fahrenheit. These parameters were combined with the other dimensionless variables and a two new models were developed. Equations 4.53 and 4.54 show the resulting momentum flux and the mass flux models developed with SAS:

$$\delta_{35} = 0.004 + 5.41 \Psi^{-0.80} \Lambda^{-3.29} \beta^{-0.84} \Phi^{-0.45} \tau^{-0.48} \Pi^{0.64} \quad 4.53$$
$$(\gamma^2 = 0.9788)$$

$$\delta_{36} = 0.005 + 0.022 \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta^{-0.77} \Phi^{-0.5} \Pi^{0.57} \quad 4.54$$
$$(\gamma^2 = 0.9771)$$

Table 4.16 shows a comparison between the two sets of models: the momentum flux models with absolute temperature (Equation 4.47) versus degrees Fahrenheit (Equation 4.53),

Table 4.16: Comparison between the empirical models developed with temperature dimensionless coefficients in degrees Fahrenheit and absolute.

Empirical Model	Coefficient of Multiple Correlation	Equation
$\delta_{32} = 0.004 + 5.80 \Psi^{-0.81} \Theta^{-6.46} \beta^{-0.85} \Phi^{-0.44} \xi^{-1.05} \Pi^{0.66}$	$\gamma^2 = 0.9791$	4.47
$\delta_{35} = 0.004 + 5.41 \Psi^{-0.80} \Lambda^{-3.29} \beta^{-0.84} \Phi^{-0.45} \tau^{-0.48} \Pi^{0.64}$	$\gamma^2 = 0.9788$	4.53
$\delta_{16} = 0.005 + 0.023 \Gamma^{-1.56} \Theta^{-6.26} \xi^{-1.87} \beta^{-0.78} \Phi^{-0.48} \Pi^{0.61}$	$\gamma^2 = 0.9771$	4.25
$\delta_{36} = 0.005 + 0.022 \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta^{-0.77} \Phi^{-0.5} \Pi^{0.57}$	$\gamma^2 = 0.9771$	4.54

and the mass flux models with absolute temperature (Equation 4.25) versus degrees Fahrenheit (Equation 4.54). It can be seen that the main difference between the models is in the exponents of the temperature dimensionless variables and in the multiplying constant of the momentum flux models. There is a small change in some of the other exponents which are due to numerical regression error propagation. The coefficient of multiple correlation for the corresponding mass flux and momentum flux also remain essentially unchanged whether degrees Fahrenheit or absolute temperatures are used in developing the models.

Therefore, it can be concluded that the empirical models will predict the average diameter of a melt blown fiber with the same degree of accuracy regardless of the units used to evaluate the dimensionless temperature variables. However, the exponents of these variables are sensitive to the units in which the dimensionless variables were evaluated, thus, care must be taken to ensure that the temperature dimensionless variables being used are consistent with the empirical model.

Reference Values for Dimensionless Variables

Since the accuracy of the empirical models to predict the average diameter is independent of the units used to evaluate the temperature dimensionless variables, then it is

natural to ask the following question; would the accuracy of the models change if a different reference value is used in evaluating other dimensionless variables? This section addresses this specific question.

As it is shown in Table 4.1, several of the dimensionless variables were evaluated using a specific reference value in the denominator. For instance, a polymer throughput reference value of 0.8 g/min was chosen to evaluate the polymer throughput ratio dimensionless variable in the model given by Equation 4.54. In order to answer the question raised earlier, two new empirical models were developed with different reference values for the polymer throughput term. Equations 4.55 and 4.56 show the empirical models developed using polymer reference values of 1.6 g/min and 0.4 g/min, respectively.

$$\delta_{37} = 0.005 + 0.013 \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta_{37}^{-0.77} \Phi^{-0.5} \Pi^{0.57} \quad 4.55$$

$$(\gamma^2 = 0.9771)$$

$$\delta_{38} = 0.005 + 0.038 \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta_{38}^{-0.77} \Phi^{-0.5} \Pi^{0.57} \quad 4.56$$

$$(\gamma^2 = 0.9771)$$

It can be seen by comparing Equations 4.54 through 4.56 that only the multiplying constant changes in all three models. All of the exponents and the constant remain

constant. Furthermore, the coefficient of multiple correlation also remains constant.

There is simple relationship between the expressions given by Equations 4.53 through 4.56 which allows the determination of the value of the multiplying constant given any reference value used for the polymer throughput. Equation 4.57 represents a generic model like the ones given by Equations 4.54 through 4.56.

$$\delta_j = A + B \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta_j^{-0.77} \Phi^{-0.5} \Pi^{0.57} \quad 4.57$$

$$\text{where } \beta_j = \frac{\dot{m}_p}{(\dot{m}_p)_{\text{ref}_j}} \quad \text{and } A = 0.005$$

Subtracting Equation 4.55 from Equation 4.57, the following expression results:

$$\begin{aligned} \delta_j - \delta_{37} = & B \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta_j^{-0.77} \Phi^{-0.5} \Pi^{0.57} \\ & - 0.013 \Gamma^{-1.55} \Lambda^{-3.2} \tau^{-0.86} \beta_{37}^{-0.77} \Phi^{-0.5} \Pi^{0.57} \end{aligned} \quad 4.58$$

Since $\delta_j = \delta_{37}$ and all of the exponents of the dimensionless variables are the same with the exception of the polymer throughput variables (β), then Equation 4.58 can be reduced to the following expression:

$$B \beta_j^{-0.77} = 0.013 \beta_{37}^{-0.77} \quad 4.59$$

Equation 4.59 can now be solved for the multiplying constant B.

$$B = 0.013 \left[\frac{\beta_{37}}{\beta_j} \right]^{-0.77} = 0.013 \left[\frac{(\dot{m}_p)_{ref_j}}{1.6} \right]^{-0.77} \quad 4.60$$

Equation 4.60 can be used to determine the multiplying constant that corresponds to the given polymer reference value used in the empirical model. For instance, for a polymer reference value of 0.4 g/min (Equation 4.56), the corresponding multiplying constant is:

$$B = 0.013 \left[\frac{0.4}{1.6} \right]^{-0.77} = 0.038 \quad 4.61$$

which corresponds to the value predicted by the regression analysis.

Therefore, a reference value other than the original 0.8 g/min value can be used for evaluating the polymer throughput dimensionless variable without altering the accuracy of the empirical models, and the corresponding multiplying constant can be calculated using Equation 4.60.

A similar analysis was performed for all the other dimensionless variables that require a reference value to be evaluated. All of models that were developed using reference values other than the ones listed in Table 4.1 showed the

same results found for the polymer throughput case; the exponents of all dimensionless variables remained constant, the coefficients of multiple correlation also remained constant, and only the multiplying constant changed. Table 4.17 summarizes the expressions derived for evaluating the multiplying constant when reference values other than the ones listed in Table 4.1 are used in the empirical models.

In conclusion, reference values for the dimensionless variables other than the ones listed in Table 4.1 can be used when using the empirical models developed in this Chapter. The accuracy of the model to predict the average diameter of fiber does not change, however, the multiplying constant must be reevaluated using the proper expression.

Table 4.17: Expressions for evaluating the multiplying constant when reference values other than the ones listed in Table 4.1 are used.

VARIABLE	MULTIPLYING CONSTANT WITH NEW REFERENCE VALUE
Polymer temperature ratio, Λ	$B = 0.022 \left[\frac{\text{new reference}}{500} \right]^{-3.20}$
Air jet temperature ratio, τ	$B = 0.022 \left[\frac{\text{new reference}}{375} \right]^{-0.86}$
Polymer throughput ratio, β	$B = 0.022 \left[\frac{\text{new reference}}{0.8} \right]^{-0.77}$
Air jet exit height ratio, Φ	$B = 0.022 \left[\frac{\text{new reference}}{2.00} \right]^{-0.50}$
Air jet injection angle ratio, Π	$B = 0.022 \left[\frac{\text{new reference}}{45} \right]^{0.57}$

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been developed based on the experimental results presented in this thesis.

Experimental Investigation

1. An increase in the air jet momentum decreases the average fiber diameter. An increase in air jet momentum can be achieved by increasing the air jet velocity or by increasing the air jet exit area. Furthermore, the air jet exit area can be increased by increasing the air gap, reducing the setback, or by reducing the air jet injection angle.
2. The uniformity of the fibers of a web is coupled to the final average fiber diameter. Webs with smaller average fiber diameter consistently have narrower fiber diameter distributions than webs with larger average fiber diameters.
3. The effect that the distance at which the fibers are collected (DCD) from the die tip have on the diameter of

the fibers is insignificant, at least for distances greater than 10 inches.

4. The polymer flow rate has a strong effect on the final average fiber diameter. Increasing the polymer throughput results in larger average fiber diameters.
5. Polymer processing temperature has a significant effect on the average fiber diameter. The higher the polymer temperature the smaller the average fiber diameter.
6. Air jet temperature does not appear to have a significant effect on the average fiber diameter. However, there is a trend of producing stronger fibers at lower air jet temperatures.

Empirical Correlation

1. The experimental data collected during this research was successfully correlated using several empirical models. All of the models that were developed predicted the average diameter of most of the samples within 2 microns.
2. There is no significant difference in the prediction of the average fiber diameter whether the mass flux ratio

term or the momentum flux ratio term is used in the empirical models. The momentum flux models predicted the average diameter of 84.4% of the samples within 2 microns, whereas the mass flux models predicted 83.3% of the samples within 2 microns. However, both of the models predicted the average diameter of 97.5% of the samples within 2 microns.

3. The empirical models were validated by successfully correlating experimental data collected by an independent researcher at the UTK single hole melt blowing facility.
4. The empirical models were expanded to account for the viscosity (MFR) of the polypropylene. These expanded models successfully correlated experimental data collected using 35 MFR polypropylene. The addition of the polymer MFR parameter did not change the ability of the models to predict the average diameter of the original data which was collected using 650 MFR polypropylene.
5. The empirical models successfully predicted the average diameter of samples collected at the UTK 20 inch multiple hole die facility. This result suggests that the empirical models could be used to predict the average diameter of samples collected on any melt blowing unit.

6. The dimensionless variables used to develop the empirical models take into account the most important parameters that describe the melt blowing process: die geometry (air jet exit area and air jet exit height), processing temperatures (air jet and polymer temperatures), air flow conditions (air flow rate and air jet exit velocity), and polymer throughput and MFR.
7. The ability of the models to predict the average diameter is independent of whether the temperature dimensionless variables (air jet and polymer temperature) are evaluated using degrees Fahrenheit or absolute temperatures. However, the exponents of these variables are different for both cases.
8. The degree of accuracy with which the models can predict the average diameter is also independent of the reference values that are used to evaluate the dimensionless variables. The multiplying constant is the only parameter that changes when the reference values are changed. The other constant and the exponents of the dimensionless variables remain unchanged.

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LIST OF REFERENCES

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APPENDICES

APPENDIX A

DERIVATION OF AIR FLOW RATE EXPRESSION

DERIVATION OF AIR FLOW RATE EXPRESSION

The following derivation is based on the ASME Flow Measurement Standard Code [15] and is also presented by Haynes [20]. The air flow rate passing through the air delivery system measuring orifice is given by Equation A.1 [20]:

$$\dot{m}_a = 359 C F d_{ori}^2 F_e \sqrt{h_m \rho_a} \quad A.1$$

where: C coefficient of discharge (dimensionless)
F velocity approach factor (dimensionless)
 F_e thermal expansion factor (dimensionless)
 h_m pressure drop (inches of water)
 d_{ori} measuring orifice diameter (inches)
 ρ_a density of air (lb_m / ft^3)

For the range of operating temperatures at which the air passes through the measuring orifice and consequently, the temperature range of the pipe itself at the measuring orifice, the thermal expansion factor for the orifice can be taken as unity [20]. The coefficient of discharge remains constant (0.616) for a wide range of Reynolds numbers [20]. The velocity approach factor is a function of the pipe

diameter (2.0 inches) and the measuring orifice diameter (1.0 inch). This relationship is given by Equation A.2:

$$F = \frac{1}{\sqrt{1 - (d_{\text{ori}}/d_{\text{pipe}})^4}} = \frac{1}{\sqrt{1 - 0.5^4}} = 1.03 \quad \text{A.2}$$

Substituting C, F, d_{ori} , and F_e , into Equation A.1:

$$\dot{m}_a = 245.7 \sqrt{h_m \rho_a} \quad \text{A.3}$$

Assuming air to behave as an ideal gas

$$\rho_a = \frac{p}{T_{\text{pipe}} R} \quad \text{A.4}$$

Where R is the universal gas constant and p is the absolute pressure in the pipe upstream from the measuring orifice. This absolute pressure is equal to the pressure set at the regulator (50 psig) plus the ambient pressure (14.7 psia), which is assumed to be constant for all practical purposes in this research. Substituting the values for the stagnation pressure and the universal gas constant, and expressing the pipe temperature in degrees Celsius, the density of air can be expressed in terms of only the air temperature at the measuring orifice:

$$\rho_a = \frac{174.1}{1.8T_{\text{pipe}} + 492} \quad \text{A.5}$$

Substituting Equation A.4 into A.3:

$$\dot{m}_a = 2.45 * 10^4 \sqrt{\frac{h_m}{1.8T_{\text{pipe}} + 492}} \quad \text{A.6}$$

where h_m is in inches of water, T_{pipe} is in degrees Celsius, and $\dot{m}_a$ is expressed in grams per minute

APPENDIX B

SINGLE HOLE MELT BLOWING FACILITY OPERATING PROCEDURES

SINGLE HOLE MELT BLOWING
FACILITY OPERATING PROCEDURES

Revised by: EDMUND G. SPENCER
May 1992

Notes of Caution

Most of the equipment (hardware) used in the process of making Melt-blown fibers is very sensitive and expensive. Therefore, it is very important to follow the procedures outlined in this handout to avoid any damage to the equipment. Also, the operator should monitor the different instruments and gages while collecting data in order to prevent any accidents that could cause harm to the operator or the equipment.

The following is a brief list of DO's and DO NOT's:

- DO NOT operate the air-heater without any air flowing through the air delivery system.
- DO NOT operate the extruder without the cooling water circulating.
- DO NOT operate the extruder without any polymer on the hopper.
- DO NOT let the air-heater cool by itself. When shutting-down, ALWAYS have air circulating through the air-heater until the temperature reads not less than 250 [F].
- ALWAYS make sure that the hopper valve is open and that the hopper has polymer in it.

By following these directions you will be contributing to the safety of the people in the room (and in the building!) and you will also be providing proper care to the equipment.

START-UP

- 1.- Open windows.
- 2.- Unlock air-heater and extruder locks.
- 3.- Turn main air valve on (black "T" handle)
- 4.- Turn test section air valve on (@ $\Delta P = 2.0$ [inches of water])
- 5.- Set temperature on air-heater and turn on (NOTE TIME on heater log sheet and on data sheet)
- 6.- Turn cooling water on (moderate flow rate to prevent overflow in sink). DO NOT operate extruder without cooling water circulating.
- 7.- Make sure hopper valve is open and that there is melt in the hopper.
- 8.- MAKE SURE SCREW MOTOR IS OFF. Press the stop button and make sure the screw-speed knob is all the way to the left.
- 9.- ALL heaters (except air-heater) should be OFF.
- 10.- Turn on the power to the extruder (red handle up).
- 11.- Set Zones temperatures (1 through 5) on the extruder.
- 12.- Once the AIR temperature is within 100 [°F] of the target temperature, turn on the extruder heaters on, Zones 1 through 5. NOTE THE TIME ON DATA SHEET
- 13.- Once the extruder heaters on zones 1 through 3 reach operating temperatures (green light comes on all three dials), set the cartridge heater (CH) temperature and turn them on (black box on top of extruder). CH temperature MUST BE SET ABOVE 400 [°F]
- 14.- After both, the CH's and the extruder heaters in zones 4 and 5 reach operating temperature, turn the screw motor on by pressing the start button on the extruder panel board. Gradually turn the screw-speed knob until the motor starts to turn. Once the motor is turning, reduce the rpm's to about 70 (on dial reading).

MONITOR THE MELT-PRESSURE GAGE

The melt pressure will rise abruptly until polymer starts to exit from the nose-piece. This is normal! If the pressure keeps increasing and there are no signs of polymer coming out of the nose-piece, TURN OFF the screw motor (first bring the dial to zero then press the stop button) and go back to the beginning of this step. If the same thing happens, then the orifice must be clogged. Refer to the note at the end of the Start-up procedure list.

- 15.- Allow the system to reach steady-state conditions. It usually takes 1 hour from the time the CH's were turned on.
- 16.- Once the system has reached steady-state conditions, adjust the screw speed to obtain the desired polymer throughput.

NOTE:

The die may periodically clog; check for a rise in melt pressure or chugging. To unclog the die, turn the screw and airflow off. Stick a small diameter wire into the orifice in order to remove any possible dirt in the orifice. Then restart the airflow and turn the screw on. TRY TO ACCOMPLISH THIS AS QUICKLY AS POSSIBLE. Repeat this procedure until polymer comes out of the orifice. If this procedure fails, it might be necessary to shut down and bake-out.

SHUT - DOWN

- 1.- With the screw still on, turn the air heater off (keep the airflow on)
- 2.- Set the following temperatures at the given Zones in the extruder:

<u>ZONE 1</u>	<u>ZONE 2</u>	<u>ZONE 3</u>	<u>ZONE 4</u>	<u>ZONE 5</u>
300 °F	350 °F	400 °F	400 °F	400 °F
- 3.- Set the CH temperature to 400 [F]
- 4.- When the lights on the extruder heaters turn green, turn the screw motor off by bringing the RPM dial to zero and pressing the STOP button on the extruder control panel.
- 5.- Turn off heaters of Zones 4 & 5 (dial to 'OFF'), and set heaters of Zones 1, 2 & 3 to the 'ON' position (blowers will come on)
- 6.- Turn the CH off.
- 7.- Leave the blowers on for about 20 more minutes.
- 8.- Shut down the extruder. Make sure screw motor is off and that all heaters are off.
Shut down power to extruder and lock.
- 9.- Lock main power switch for the air heater.
- 10.- Turn cooling water off.
- 11.- Shut airflow valve off. Turn main air valve off (black 'T' handle)
- 12.- Put lock keys back on the file cabinet.
- 13.- Close windows.
- 14.- Have a nice data reduction session !

BEFORE BRAKE-DOWN

- 1.- Proceed with SHUT-DOWN procedure up to Step 3.
- 2.- If a different MFR material is to be used after baking-out, follow all of the following steps. If the same MFR material is to be used, go to Step 7.
- 3.- Close the hopper valve. Remove hopper from extruder. Make sure hopper valve is closed before removing !
- 4.- Remove the bleed-screw located between Zones 3 & 4 on the extruder. Unscrew until a significant amount of material is flowing through it.
- 5.- Add some RED-MELT material on the screw inlet; it helps to see the transition between materials on the extruder. ALWAYS MAKE SURE THERE IS MELT ON THE SCREW
- 6.- Re-install the hopper with the new melt and let it bleed until no more red material is visible coming from the bleed hole.
- 7.- Turn the RPM dial on extruder to zero and press the STOP button to turn the screw off.
- 8.- Carefully remove the melt-pressure gage located between Zones 4 & 5. MAKE SURE MATERIAL IS MOLTEN TO PREVENT DAMAGE TO THE INSTRUMENT DURING REMOVAL. Wipe out excess of molten material at the tip of the gage and put the protecting cover at the tip.
- 9.- Proceed with the rest of the SHUT-DOWN procedure starting from Step 4
- 10.- Let the system reach ambient temperature before proceeding with break-down. It is recommended to continue with break-down the next day since parts will remain extremely hot for a long time. (trust me !)

BRAKE-DOWN & BAKING OUT

NOTE: Plan to be at the lab for at least 5 hours for each of the two baking out sessions:

1 hr heating up the oven

4 hr baking-out

- 1.- Open windows
- 2.- Turn oven on and set temperature to 350 [C]
- 3.- Disassembling the test section:
 - remove all insulation material from test section.
 - remove stagnation pressure gages.
 - remove left side-plate.
 - remove top & bottom face-plates.
 - remove cartridge heaters.
 - remove nose piece.
 - remove spacer block.
- 4.- Once the oven has reached setting temperature, bake-out the spacer block and the nose piece simultaneously for 4 hours.
- 5.- Disassembling Zones 4 to 5:
 - remove heaters and thermocouples in this area.
 - remove metal strap-piece (downstream from Zone 3).
 - remove metal part that goes from Zone 3 to test section.
 - remove all screws from this metal piece.
 - remove the screws from the band-heaters.

- take the metal piece to a vice and unscrew them apart.
 - remove band-heaters. the inner heater must be pulled hard to be removed, but carefully in order to prevent any damage.
- 6.- Bake all the metal parts along with the bleed-screw.
 - 7.- Once baking-out is completed, remove all possible carbon deposits on all of the parts that were baked, in particular the nose-piece orifice.

PUTTING IT BACK TOGETHER

- 1.- Make sure all of the parts that were baked-out are clean from any carbon deposits.
- 2.- Apply ANTI-SEIZE to the threads of the metal pieces. Also apply some to the threads of the Melt-pressure gage.
- 3.- In order to put things back together, follow the break-down procedure in reverse order. MAKE SURE ALL THREADS ARE FREE OF CARBON DEPOSITS.
- 4.- Install the Melt pressure-gage. DO NOT APPLY MORE THAN 144 [Lb./in²] of torque to the instrument. Get a torque wrench from the shop!
- 5.- Make sure to have the proper air gap and setback.

Before beginning Start-up , double check all instruments are well connected and that are in their corresponding places.

APPENDIX C

EXPERIMENTAL DATA

EXPERIMENTAL DATA

CASE ID (sample #)	d	Mp	Ta	Tp	Po	hm	Tpibe	De	Dg	α	MFR
	measured average diameter [μ m]	polymer throughput [g/min]	air jet temperature at test section [F]	polymer temperature at die tip [F]	stagnation pressure at test section [psig]	pressure drop across ADS orifice [" water]	air temperature at ADS orifice [C]	die setback [inch]	airgap [inch]	die node piece (total angle) [deg]	type of polymer [MFR]
2(09)	21.00	1.60	510	424	1.7	2.0	31.0	0.079	0.079	90	650
2(10)	12.69	1.60	510	424	3.6	4.0	31.0	0.079	0.079	90	650
2(11)	8.94	1.60	510	428	5.4	6.0	31.0	0.079	0.079	90	650
2(12)	7.86	1.60	511	432	6.7	8.0	31.0	0.079	0.079	90	650
2(13)	8.21	1.60	512	434	8.3	10.0	31.0	0.079	0.079	90	650
2(14)	5.99	1.60	508	434	9.4	12.0	31.0	0.079	0.079	90	650
2(15)	5.41	1.60	512	436	10.6	14.0	31.0	0.079	0.079	90	650
2(16)	5.16	1.60	507	437	11.8	16.0	31.0	0.079	0.079	90	650
3(17)	13.71	0.80	509	423	2.1	2.0	28.0	0.079	0.079	90	650
3(18)	8.25	0.80	509	425	3.8	4.0	28.0	0.079	0.079	90	650
3(19)	7.38	0.80	509	427	5.4	6.0	28.0	0.079	0.079	90	650
3(20)	5.48	0.80	508	429	7.0	8.0	28.0	0.079	0.079	90	650
3(21)	5.31	0.80	509	431	8.4	10.0	28.0	0.079	0.079	90	650
3(22)	4.09	0.80	505	436	9.5	12.0	28.0	0.079	0.079	90	650
3(23)	4.49	0.80	505	434	10.6	14.0	28.0	0.079	0.079	90	650
3(24)	3.78	0.80	505	436	11.5	16.0	28.0	0.079	0.079	90	650
4(25)	7.89	0.80	509	426	3.8	4.0	28.0	0.079	0.079	90	650
4(26)	9.20	0.80	509	429	3.8	4.0	28.0	0.079	0.079	90	650
4(28)	9.83	0.80	510	431	3.8	4.0	28.0	0.079	0.079	90	650
4(27)	4.35	0.80	507	431	8.2	10.0	28.0	0.079	0.079	90	650
4(29)	6.66	0.80	507	438	8.2	10.0	28.0	0.079	0.079	90	650
4(30)	7.57	0.80	508	439	8.2	10.0	28.0	0.079	0.079	90	650
5(01)	9.69	0.48	509	417	1.8	2.0	25.0	0.079	0.079	90	650
5(02)	6.89	0.48	509	418	3.9	4.0	25.0	0.079	0.079	90	650
5(03)	8.09	0.48	508	422	5.5	6.0	25.0	0.079	0.079	90	650
5(04)	8.68	0.48	509	424	7.1	8.0	25.0	0.079	0.079	90	650
5(05)	6.61	0.48	510	425	8.4	10.0	25.0	0.079	0.079	90	650
5(06)	5.26	0.48	510	428	9.6	12.0	25.0	0.079	0.079	90	650
5(07)	3.88	0.48	510	429	10.8	14.0	25.0	0.079	0.079	90	650
5(08)	3.49	0.48	509	428	11.8	16.0	25.0	0.079	0.079	90	650
6(01)	8.93	0.80	582	475	2.1	2.0	25.0	0.079	0.079	90	650
6(02)	5.96	0.80	582	481	4.2	4.0	25.0	0.079	0.079	90	650
6(03)	4.29	0.80	584	490	9.0	10.0	25.0	0.079	0.079	90	650
6(04)	2.86	0.80	583	486	11.6	14.0	25.0	0.079	0.079	90	650
7(05)	11.96	1.60	582	474	1.9	2.0	25.0	0.079	0.079	90	650
7(06)	6.41	1.60	582	479	5.8	6.0	25.0	0.079	0.079	90	650
7(07)	4.78	1.60	582	484	9.0	10.0	25.0	0.079	0.079	90	650
7(08)	3.19	1.60	579	487	11.6	14.0	25.0	0.079	0.079	90	650
8(09)	3.79	0.80	583	482	4.2	4.0	25.0	0.079	0.079	90	650
8(10)	5.80	0.80	583	482	4.2	4.0	25.0	0.079	0.079	90	650
8(11)	5.85	0.80	583	482	4.2	4.0	25.0	0.079	0.079	90	650

EXPERIMENTAL DATA

CASE ID (sample #)	d measured average diameter [μm]	Mp polymer throughput [g/min]	Ta air jet temperature at test section [F]	Tp polymer temperature at die tip [F]	Po stagnation pressure at test section [psig]	hm pressure drop across ADS orifice [" water]	Tlpe air temperature at ADS orifice [C]	De die setback [inch]	Dg airgap [inch]	α die node piece (total angle) [deg]	MFR type of polymer [MFR]
8(12)	3.89	0.80	583	483	9.0	10.0	25.0	0.079	0.079	90	650
8(13)	5.41	0.80	583	483	9.0	10.0	25.0	0.079	0.079	90	650
8(14)	3.78	0.80	583	483	9.0	10.0	25.0	0.079	0.079	90	650
9(01)	14.84	1.60	612	497	2.0	2.0	22.0	0.079	0.079	90	650
9(02)	5.96	1.60	614	500	6.1	6.0	22.0	0.079	0.079	90	650
9(03)	3.86	1.60	614	505	9.2	10.0	22.0	0.079	0.079	90	650
9(04)	3.51	1.60	610	502	12.0	14.0	22.0	0.079	0.079	90	650
10(05)	8.95	0.80	611	497	1.9	2.0	22.0	0.079	0.079	90	650
10(06)	5.01	0.80	613	501	5.9	6.0	22.0	0.079	0.079	90	650
10(07)	4.58	0.80	611	505	9.2	10.0	22.0	0.079	0.079	90	650
10(08)	2.79	0.80	611	508	11.8	14.0	22.0	0.079	0.079	90	650
11(09)	5.40	0.80	614	505	4.1	4.0	22.0	0.079	0.079	90	650
11(10)	4.79	0.80	614	505	4.1	4.0	22.0	0.079	0.079	90	650
11(11)	5.49	0.80	614	505	4.1	4.0	22.0	0.079	0.079	90	650
11(12)	3.79	0.80	614	505	9.2	10.0	22.0	0.079	0.079	90	650
11(13)	3.74	0.80	614	513	9.2	10.0	22.0	0.079	0.079	90	650
11(14)	4.70	0.80	614	517	9.2	10.0	22.0	0.079	0.079	90	650
12(01)	11.35	0.80	580	466	2.0	2.0	28.3	0.079	0.079	90	650
12(02)	9.39	0.80	580	466	2.0	2.0	28.3	0.079	0.079	90	650
12(03)	9.98	0.80	581	467	2.0	2.0	28.3	0.079	0.079	90	650
12(04)	7.66	0.80	581	467	2.0	2.0	28.3	0.079	0.079	90	650
13(05)	7.56	0.80	582	471	4.4	4.0	28.3	0.079	0.079	90	650
13(06)	6.79	0.80	582	473	4.4	4.0	28.3	0.079	0.079	90	650
13(07)	6.05	0.80	584	476	4.4	4.0	28.3	0.079	0.079	90	650
13(08)	5.15	0.80	584	477	4.5	4.0	28.3	0.079	0.079	90	650
14(09)	6.79	0.80	583	476	8.0	8.0	28.3	0.079	0.079	90	650
14(10)	4.90	0.80	583	480	8.1	8.0	28.3	0.079	0.079	90	650
14(11)	4.34	0.80	584	480	8.1	8.0	28.3	0.079	0.079	90	650
14(12)	3.39	0.80	582	479	8.1	8.0	28.3	0.079	0.079	90	650
15(01)	9.38	0.80	582	468	2.2	2.0	26.5	0.079	0.079	90	650
15(02)	8.02	0.80	582	468	2.2	2.0	26.5	0.079	0.079	90	650
15(03)	7.57	0.80	582	469	2.2	2.0	26.5	0.079	0.079	90	650
15(04)	8.19	0.80	582	469	2.2	2.0	26.5	0.079	0.079	90	650
15(05)	8.50	0.80	582	469	2.2	2.0	26.5	0.079	0.079	90	650
15(06)	7.71	0.80	583	470	2.2	2.0	26.5	0.079	0.079	90	650
16(07)	5.17	0.80	584	472	4.4	4.0	26.5	0.079	0.079	90	650
16(08)	4.47	0.80	584	474	4.4	4.0	26.5	0.079	0.079	90	650
16(09)	4.46	0.80	584	475	4.4	4.0	26.5	0.079	0.079	90	650
16(10)	4.29	0.80	584	476	4.4	4.0	26.5	0.079	0.079	90	650
16(11)	4.75	0.80	584	475	4.4	4.0	26.5	0.079	0.079	90	650
16(12)	5.50	0.80	585	476	4.4	4.0	26.5	0.079	0.079	90	650

EXPERIMENTAL DATA

CASE ID (sample #)	d	Mp	Ta	Tp	Po	hm	Tlpe	Ds	Dg	α	MFR
	measured average diameter [μ m]	polymer throughput [g/min]	air jet temperature at test section [F]	polymer temperature at die tip [F]	stagnation pressure at test section [psig]	pressure drop across ADS orifice [" water]	air temperature at ADS orifice [C]	die setback [inch]	airgap [inch]	die node piece (total angle) [deg]	type of polymer [MFR]
17(01)	4.97	0.80	585	479	8.2	8.0	29.0	0.079	0.079	90	650
17(02)	3.19	0.80	584	481	8.2	8.0	29.0	0.079	0.079	90	650
17(03)	3.77	0.80	585	481	8.2	8.0	29.0	0.079	0.079	90	650
17(04)	4.85	0.80	582	481	8.2	8.0	29.0	0.079	0.079	90	650
17(05)	3.53	0.80	585	482	8.2	8.0	29.0	0.079	0.079	90	650
17(06)	2.41	0.80	585	480	8.2	8.0	29.0	0.079	0.079	90	650
18(01)	7.56	0.80	581	470	2.2	2.0	29.5	0.079	0.079	90	650
18(02)	7.42	0.80	582	470	2.2	2.0	29.5	0.079	0.079	90	650
18(03)	7.88	0.80	582	470	2.2	2.0	29.5	0.079	0.079	90	650
18(04)	9.26	0.80	582	470	2.2	2.0	29.5	0.079	0.079	90	650
18(05)	4.49	0.80	583	476	6.5	6.0	29.5	0.079	0.079	90	650
18(06)	4.72	0.80	584	478	6.5	6.0	29.5	0.079	0.079	90	650
18(07)	5.72	0.80	584	479	6.5	6.0	29.5	0.079	0.079	90	650
18(08)	5.25	0.80	585	481	6.5	6.0	29.5	0.079	0.079	90	650
18(09)	4.55	0.80	584	485	9.9	10.0	29.5	0.079	0.079	90	650
18(10)	5.06	0.80	584	483	9.9	10.0	29.5	0.079	0.079	90	650
18(11)	3.71	0.80	584	485	9.8	10.0	29.5	0.079	0.079	90	650
18(12)	4.60	0.80	584	486	9.8	10.0	29.5	0.079	0.079	90	650
18(13)	4.32	0.80	582	483	16.7	20.0	29.5	0.079	0.079	90	650
18(14)	3.81	0.80	580	489	16.6	20.0	29.5	0.079	0.079	90	650
18(15)	3.96	0.80	579	490	16.5	20.0	29.5	0.079	0.079	90	650
18(16)	3.66	0.80	578	489	16.5	20.0	29.5	0.079	0.079	90	650
19(17)	12.80	1.60	582	470	2.0	2.0	29.5	0.079	0.079	90	650
19(18)	15.60	1.60	581	469	2.0	2.0	29.5	0.079	0.079	90	650
19(19)	16.10	1.60	581	469	2.0	2.0	29.5	0.079	0.079	90	650
19(20)	15.10	1.60	582	469	2.0	2.0	29.5	0.079	0.079	90	650
19(21)	6.10	1.60	583	478	6.2	6.0	29.5	0.079	0.079	90	650
19(22)	7.50	1.60	583	475	6.2	6.0	29.5	0.079	0.079	90	650
19(23)	6.70	1.60	584	474	6.2	6.0	29.5	0.079	0.079	90	650
19(24)	6.50	1.60	584	475	6.2	6.0	29.5	0.079	0.079	90	650
19(25)	4.90	1.60	584	480	9.6	10.0	29.5	0.079	0.079	90	650
19(26)	5.50	1.60	583	475	9.6	10.0	29.5	0.079	0.079	90	650
19(27)	5.30	1.60	583	476	9.6	10.0	29.5	0.079	0.079	90	650
19(28)	5.10	1.60	582	478	9.6	10.0	29.5	0.079	0.079	90	650
19(29)	3.90	1.60	577	480	16.4	20.0	29.5	0.079	0.079	90	650
19(30)	4.20	1.60	583	481	16.4	20.0	29.5	0.079	0.079	90	650
19(31)	3.90	1.60	581	482	16.4	20.0	29.5	0.079	0.079	90	650
19(32)	4.10	1.60	581	483	16.4	20.0	29.5	0.079	0.079	90	650
20(33)	26.46	3.00	582	467	2.0	2.0	29.5	0.079	0.079	90	650
20(34)	21.04	3.00	582	467	2.0	2.0	29.5	0.079	0.079	90	650
20(35)	21.67	3.00	582	467	2.0	2.0	29.5	0.079	0.079	90	650

EXPERIMENTAL DATA

CASE ID (sample #)	d measured average diameter [μm]	Mp polymer throughput [g/min]	Ta air jet temperature at test section [F]	Tp polymer temperature at die tip [F]	Ps stagnation pressure at test section [psig]	hm pressure drop across ADS orifice [" water]	Tpipe air temperature at ADS orifice [C]	Ds die setback [inch]	Dg airgap [inch]	α die node piece (total angle) [deg]	MFR type of polymer [MFR]
20(36)	21.55	3.00	582	467	2.0	2.0	29.5	0.079	0.079	90	650
20(37)	11.34	3.00	583	473	6.2	6.0	29.5	0.079	0.079	90	650
20(38)	9.43	3.00	583	473	6.2	6.0	29.5	0.079	0.079	90	650
20(39)	10.21	3.00	584	476	6.2	6.0	29.5	0.079	0.079	90	650
20(40)	8.11	3.00	584	477	6.2	6.0	29.5	0.079	0.079	90	650
20(41)	7.06	3.00	583	479	9.8	10.0	29.5	0.079	0.079	90	650
20(42)	7.03	3.00	584	479	9.8	10.0	29.5	0.079	0.079	90	650
20(43)	6.95	3.00	585	481	9.8	10.0	29.5	0.079	0.079	90	650
20(44)	7.21	3.00	584	482	9.8	10.0	29.5	0.079	0.079	90	650
20(45)	5.04	3.00	582	479	16.6	20.0	29.5	0.079	0.079	90	650
20(46)	5.80	3.00	580	486	16.6	20.0	29.5	0.079	0.079	90	650
20(47)	4.92	3.00	580	485	16.6	20.0	29.5	0.079	0.079	90	650
20(48)	5.17	3.00	580	488	16.6	20.0	29.5	0.079	0.079	90	650
21(01)	17.86	0.80	507	412	2.0	1.0	26.5	0.062	0.061	90	650
21(02)	11.19	0.80	508	413	4.3	2.0	26.5	0.062	0.061	90	650
21(03)	8.30	0.80	508	419	8.0	4.0	26.5	0.062	0.061	90	650
21(04)	8.01	0.80	509	424	14.2	8.0	26.5	0.062	0.061	90	650
21(05)	7.58	0.80	509	428	18.9	12.0	26.5	0.062	0.061	90	650
21(06)	8.88	0.80	510	428	23.0	16.0	26.5	0.062	0.061	90	650
22(07)	32.63	1.60	506	410	1.5	1.0	26.5	0.062	0.061	90	650
22(08)	21.80	1.60	507	414	4.1	2.0	26.5	0.062	0.061	90	650
22(09)	14.10	1.60	507	418	7.8	4.0	26.5	0.062	0.061	90	650
22(10)	9.36	1.60	508	421	14.0	8.0	26.5	0.062	0.061	90	650
22(11)	8.77	1.60	509	426	19.1	12.0	26.5	0.062	0.061	90	650
22(12)	7.16	1.60	508	430	23.1	16.0	26.5	0.062	0.061	90	650
23(13)	45.15	3.00	505	409	1.5	1.0	26.5	0.062	0.061	90	650
23(14)	27.90	3.00	507	413	4.1	2.0	26.5	0.062	0.061	90	650
23(15)	20.46	3.00	508	416	7.8	4.0	26.5	0.062	0.061	90	650
23(16)	13.60	3.00	507	423	14.1	8.0	26.5	0.062	0.061	90	650
23(17)	9.85	3.00	505	422	19.0	12.0	26.5	0.062	0.061	90	650
23(18)	8.35	3.00	510	427	23.0	16.0	26.5	0.062	0.061	90	650
24(01)	13.14	0.80	581	467	2.0	1.0	26.0	0.062	0.061	90	650
24(02)	9.03	0.80	581	471	4.7	2.0	26.0	0.062	0.061	90	650
24(03)	7.86	0.80	582	472	8.6	4.0	26.0	0.062	0.061	90	650
24(04)	6.00	0.80	579	475	15.4	8.0	26.0	0.062	0.061	90	650
24(05)	6.04	0.80	579	474	20.2	12.0	26.0	0.062	0.061	90	650
25(07)	24.92	1.60	580	465	1.6	1.0	26.0	0.062	0.061	90	650
25(08)	12.86	1.60	580	467	4.4	2.0	26.0	0.062	0.061	90	650
25(09)	7.27	1.60	580	470	8.4	4.0	26.0	0.062	0.061	90	650
25(10)	5.99	1.60	579	472	15.0	8.0	26.0	0.062	0.061	90	650
25(11)	5.99	1.60	577	475	20.2	12.0	26.0	0.062	0.061	90	650

EXPERIMENTAL DATA

CASE ID (sample #)	d	Mp	Ta	Tp	Po	hm	Tpibe	Ds	Dg	α	MFR
	measured average diameter [μm]	polymer throughput [g/min]	air jet temperature at test section [F]	polymer temperature at die tip [F]	stagnation pressure at test section [psig]	pressure drop across ADS orifice [" water]	air temperature at ADS orifice [C]	die setback [inch]	airgap [inch]	die node piece (total angle) [deg]	type of polymer [MFR]
25(12)	4.70	1.60	575	478	24.4	16.0	26.0	0.062	0.061	90	650
26(13)	36.02	3.00	579	465	2.8	1.0	26.0	0.062	0.061	90	650
26(14)	22.82	3.00	580	465	4.4	2.0	26.0	0.062	0.061	90	650
26(15)	12.05	3.00	580	467	8.3	4.0	26.0	0.062	0.061	90	650
26(16)	7.65	3.00	577	470	15.0	8.0	26.0	0.062	0.061	90	650
26(17)	6.55	3.00	575	474	20.1	12.0	26.0	0.062	0.061	90	650
26(18)	5.38	3.00	575	481	24.8	16.0	26.0	0.062	0.061	90	650
27(01)	9.53	0.80	613	496	2.6	1.0	27.3	0.062	0.061	90	650
27(02)	5.68	0.80	613	496	5.0	2.0	27.3	0.062	0.061	90	650
27(03)	5.21	0.80	614	500	9.0	4.0	27.3	0.062	0.061	90	650
27(04)	3.69	0.80	614	506	15.7	8.0	27.3	0.062	0.061	90	650
27(05)	3.67	0.80	612	512	21.0	12.0	27.3	0.062	0.061	90	650
28(07)	18.33	1.60	607	487	1.8	1.0	27.3	0.062	0.061	90	650
28(08)	9.47	1.60	611	490	4.6	2.0	27.3	0.062	0.061	90	650
28(09)	7.18	1.60	612	494	8.6	4.0	27.3	0.062	0.061	90	650
28(10)	5.23	1.60	610	499	15.4	8.0	27.3	0.062	0.061	90	650
28(11)	4.39	1.60	609	507	20.8	12.0	27.3	0.062	0.061	90	650
28(12)	3.75	1.60	608	506	24.8	16.0	27.3	0.062	0.061	90	650
29(13)	30.68	3.00	607	490	1.8	1.0	27.3	0.062	0.061	90	650
29(14)	19.11	3.00	610	491	4.6	2.0	27.3	0.062	0.061	90	650
29(15)	9.22	3.00	612	496	8.6	4.0	27.3	0.062	0.061	90	650
29(16)	6.25	3.00	612	498	15.4	8.0	27.3	0.062	0.061	90	650
29(17)	5.21	3.00	609	503	20.7	12.0	27.3	0.062	0.061	90	650
29(18)	5.02	3.00	610	509	25.3	16.0	27.3	0.062	0.061	90	650
30(01)	20.72	0.80	513	423	0.5	1.0	28.0	0.079	0.079	60	650
30(02)	13.75	0.80	514	425	1.1	2.0	28.0	0.079	0.079	60	650
30(03)	7.14	0.80	514	428	2.3	4.0	28.0	0.079	0.079	60	650
30(04)	6.36	0.80	514	429	4.3	8.0	28.0	0.079	0.079	60	650
30(05)	5.11	0.80	514	434	6.0	12.0	28.0	0.079	0.079	60	650
30(06)	4.32	0.80	512	434	7.7	16.0	28.0	0.079	0.079	60	650
30(07)	5.61	0.80	505	437	9.2	20.0	28.0	0.079	0.079	60	650
31(08)	40.30	1.60	510	419	0.4	1.0	28.0	0.079	0.079	60	650
31(09)	27.48	1.60	512	422	1.1	2.0	28.0	0.079	0.079	60	650
31(10)	14.52	1.60	513	424	2.4	4.0	28.0	0.079	0.079	60	650
31(11)	8.31	1.60	514	429	4.3	8.0	28.0	0.079	0.079	60	650
31(12)	7.52	1.60	515	432	6.1	12.0	28.0	0.079	0.079	60	650
31(13)	6.06	1.60	512	437	7.8	16.0	28.0	0.079	0.079	60	650
31(14)	5.34	1.60	508	435	4.4	20.0	28.0	0.079	0.079	60	650
32(15)	14.92	0.80	565	462	0.6	1.0	28.0	0.079	0.079	60	650
32(16)	8.73	0.80	566	464	1.2	2.0	28.0	0.079	0.079	60	650
32(17)	4.79	0.80	567	466	2.4	4.0	28.0	0.079	0.079	60	650

EXPERIMENTAL DATA

CASE ID (sample #)	d	Mp	Ta	Tp	Po	hm	Tlpe	Ds	Dg	α	MFR
	measured average diameter [μ m]	polymer throughput [g/min]	air jet temperature at test section [F]	polymer temperature at die tip [F]	stagnation pressure at test section [psig]	pressure drop across ADS orifice [" water]	air temperature at ADS orifice [C]	die setback [inch]	airgap [inch]	die node piece (total angle) [deg]	type of polymer [MFR]
32(18)	3.60	0.80	568	470	4.4	8.0	28.0	0.079	0.079	60	650
32(19)	3.35	0.80	567	476	6.3	12.0	28.0	0.079	0.079	60	650
32(20)	3.56	0.80	561	471	7.8	16.0	28.0	0.079	0.079	60	650
32(21)	4.28	0.80	558	473	9.8	20.0	28.0	0.079	0.079	60	650
33(22)	33.88	1.60	563	462	0.4	1.0	28.0	0.079	0.079	60	650
33(23)	17.44	1.60	565	462	1.1	2.0	28.0	0.079	0.079	60	650
33(24)	9.81	1.60	567	465	2.3	4.0	28.0	0.079	0.079	60	650
33(25)	5.21	1.60	568	469	4.5	8.0	28.0	0.079	0.079	60	650
33(26)	4.77	1.60	566	474	6.4	12.0	28.0	0.079	0.079	60	650
33(27)	4.28	1.60	567	477	8.0	16.0	28.0	0.079	0.079	60	650
33(28)	3.66	1.60	565	477	9.8	20.0	28.0	0.079	0.079	60	650
34(29)	11.42	0.80	608	500	0.7	1.0	27.0	0.079	0.079	60	650
34(30)	6.02	0.80	609	500	1.2	2.0	27.0	0.079	0.079	60	650
34(31)	4.02	0.80	610	504	2.5	4.0	27.0	0.079	0.079	60	650
34(32)	2.84	0.80	611	510	3.6	6.0	27.0	0.079	0.079	60	650
34(33)	3.39	0.80	610	506	4.8	8.0	27.0	0.079	0.079	60	650
34(34)	2.92	0.80	611	513	5.8	10.0	27.0	0.079	0.079	60	650
35(36)	27.63	1.60	607	496	0.6	1.0	27.0	0.079	0.079	60	650
35(37)	14.03	1.60	609	499	1.2	2.0	27.0	0.079	0.079	60	650
35(38)	6.95	1.60	610	502	2.5	4.0	27.0	0.079	0.079	60	650
35(39)	4.53	1.60	611	506	4.8	8.0	27.0	0.079	0.079	60	650
35(42)	3.94	1.60	609	512	5.7	10.0	27.0	0.079	0.079	60	650
35(40)	3.67	1.60	610	508	6.6	12.0	27.0	0.079	0.079	60	650
35(41)	2.99	1.60	608	513	8.5	16.0	27.0	0.079	0.079	60	650
36(01)	23.24	1.60	331	502	0.8	2.0	27.0	0.079	0.079	60	650
36(02)	13.24	1.60	329	502	1.8	4.0	27.0	0.079	0.079	60	650
36(03)	8.26	1.60	330	502	3.5	8.0	27.0	0.079	0.079	60	650
36(04)	7.63	1.60	331	500	5.0	12.0	27.0	0.079	0.079	60	650
36(05)	6.95	1.60	330	499	5.7	14.0	27.0	0.079	0.079	60	650
36(06)	6.53	1.60	330	500	6.4	16.0	27.0	0.079	0.079	60	650
36(07)	6.06	1.60	331	498	7.7	20.0	27.0	0.079	0.079	60	650
37(01)	19.05	1.60	402	497	0.8	2.0	28.0	0.079	0.079	60	650
37(02)	10.11	1.60	403	500	1.9	4.0	28.0	0.079	0.079	60	650
37(03)	6.93	1.60	402	508	3.8	8.0	28.0	0.079	0.079	60	650
37(04)	6.17	1.60	404	508	5.4	12.0	28.0	0.079	0.079	60	650
37(05)	5.15	1.60	404	511	6.1	14.0	28.0	0.079	0.079	60	650
37(06)	4.85	1.60	403	506	6.9	16.0	28.0	0.079	0.079	60	650
37(07)	4.72	1.60	404	507	8.4	20.0	28.0	0.079	0.079	60	650
38(08)	13.75	1.60	502	505	1.0	2.0	28.0	0.079	0.079	60	650
38(09)	7.41	1.60	504	505	2.1	4.0	28.0	0.079	0.079	60	650
38(10)	5.06	1.60	504	504	4.2	8.0	28.0	0.079	0.079	60	650

EXPERIMENTAL DATA

CASE ID (sample #)	d	Mp	Ta	Tp	Po	hm	Tp _{ie}	Ds	Dg	α	MFR
	measured average diameter [μm]	polymer throughput [g/min]	air jet temperature at test section [F]	polymer temperature at die tip [F]	stagnation pressure at test section [psig]	pressure drop across ADS orifice [" water]	air temperature at ADS orifice [C]	die setback [inch]	airgap [inch]	die piece node angle [deg]	type of polymer [MFR]
38(11)	4.30	1.60	503	502	5.9	12.0	28.0	0.079	0.079	60	650
38(12)	3.88	1.60	504	505	6.8	14.0	28.0	0.079	0.079	60	650
38(13)	3.98	1.60	507	501	7.8	16.0	28.0	0.079	0.079	60	650
38(14)	4.20	1.60	507	500	9.2	20.0	28.0	0.079	0.079	60	650
39(01)	25.44	1.60	402	553	0.4	1.0	24.5	0.079	0.079	60	650
39(02)	12.12	1.60	401	552	1.0	2.0	24.5	0.079	0.079	60	650
39(03)	7.35	1.60	400	550	2.0	4.0	24.5	0.079	0.079	60	650
39(04)	5.95	1.60	399	548	3.0	6.0	24.5	0.079	0.079	60	650
39(05)	5.21	1.60	398	549	3.8	8.0	24.5	0.079	0.079	60	650
39(06)	5.04	1.60	397	546	4.8	10.0	24.5	0.079	0.079	60	650
39(07)	4.96	1.60	395	545	5.5	12.0	24.5	0.079	0.079	60	650
39(08)	4.51	1.60	394	545	6.2	14.0	24.5	0.079	0.079	60	650
39(09)	4.17	1.60	394	549	7.0	16.0	24.5	0.079	0.079	60	650
40(01)	15.49	1.60	513	549	0.7	1.0	27.5	0.079	0.079	60	650
40(02)	7.24	1.60	513	549	1.2	2.0	27.5	0.079	0.079	60	650
40(03)	4.70	1.60	512	550	2.4	4.0	27.5	0.079	0.079	60	650
40(04)	4.36	1.60	511	550	3.3	6.0	27.5	0.079	0.079	60	650
40(05)	3.52	1.60	508	549	4.3	8.0	27.5	0.079	0.079	60	650
40(06)	4.17	1.60	507	549	5.2	10.0	27.5	0.079	0.079	60	650
40(07)	3.11	1.60	506	550	6.1	12.0	27.5	0.079	0.079	60	650
40(08)	3.26	1.60	505	549	6.9	14.0	27.5	0.079	0.079	60	650
40(09)	3.16	1.60	503	549	7.7	16.0	27.5	0.079	0.079	60	650
41(10)	10.27	1.60	513	600	0.5	1.0	27.5	0.079	0.079	60	650
41(11)	6.02	1.60	512	599	1.1	2.0	27.5	0.079	0.079	60	650
41(12)	3.96	1.60	512	599	2.2	4.0	27.5	0.079	0.079	60	650
41(13)	3.77	1.60	512	600	3.3	6.0	27.5	0.079	0.079	60	650
41(14)	3.41	1.60	511	599	4.3	8.0	27.5	0.079	0.079	60	650
41(15)	2.75	1.60	510	600	5.2	10.0	27.5	0.079	0.079	60	650
41(16)	2.77	1.60	509	606	6.1	12.0	27.5	0.079	0.079	60	650
41(17)	2.71	1.60	508	602	7.0	14.0	27.5	0.079	0.079	60	650
41(18)	2.88	1.60	507	605	7.8	16.0	27.5	0.079	0.079	60	650
42(10)	28.71	1.60	321	550	0.4	1.0	22.0	0.079	0.079	60	650
42(11)	15.36	1.60	320	548	1.0	2.0	22.0	0.079	0.079	60	650
42(12)	8.39	1.60	319	550	1.8	4.0	22.0	0.079	0.079	60	650
42(13)	6.76	1.60	319	547	2.8	6.0	22.0	0.079	0.079	60	650
42(14)	5.89	1.60	317	550	3.6	8.0	22.0	0.079	0.079	60	650
42(15)	5.30	1.60	316	547	4.4	10.0	22.0	0.079	0.079	60	650
42(16)	5.36	1.60	320	550	5.2	12.0	22.0	0.079	0.079	60	650
42(17)	4.41	1.60	321	550	5.8	14.0	22.0	0.079	0.079	60	650
42(18)	4.47	1.60	318	552	6.4	16.0	22.0	0.079	0.079	60	650
43(01)	40.42	1.60	243	509	0.4	1.0	25.5	0.079	0.079	60	650

EXPERIMENTAL DATA

CASE ID (sample #)	d measured average diameter [μm]	Mp polymer throughput [g/min]	Ta air jet temperature at test section [F]	Tp polymer temperature at die tip [F]	Po stagnation pressure at test section [psig]	hm pressure drop across ADS orifice [" water]	Tlpe air temperature at ADS orifice [C]	Ds die setback [inch]	Dg airgap [inch]	α die node piece (total angle) [deg]	MFR type of polymer [MFR]
43(02)	25.13	1.60	242	505	0.8	2.0	25.5	0.079	0.079	60	650
43(03)	16.48	1.60	241	507	1.6	4.0	25.5	0.079	0.079	60	650
43(04)	14.17	1.60	240	505	2.4	6.0	25.5	0.079	0.079	60	650
43(05)	11.19	1.60	240	504	3.2	8.0	25.5	0.079	0.079	60	650
43(06)	9.47	1.60	239	504	3.9	10.0	25.5	0.079	0.079	60	650
43(07)	8.66	1.60	238	502	4.6	12.0	25.5	0.079	0.079	60	650
43(08)	8.66	1.60	237	500	5.2	14.0	25.5	0.079	0.079	60	650
43(09)	7.29	1.60	235	498	5.8	16.0	25.5	0.079	0.079	60	650
44(10)	20.50	1.60	377	603	0.4	1.0	27.0	0.079	0.079	60	650
44(11)	8.40	1.60	377	602	1.0	2.0	27.0	0.079	0.079	60	650
44(12)	5.90	1.60	376	604	1.9	4.0	27.0	0.079	0.079	60	650
44(13)	3.90	1.60	376	600	2.9	6.0	27.0	0.079	0.079	60	650
44(14)	3.50	1.60	374	600	3.8	8.0	27.0	0.079	0.079	60	650
44(15)	3.70	1.60	373	602	4.6	10.0	27.0	0.079	0.079	60	650
44(16)	3.00	1.60	370	600	5.3	12.0	27.0	0.079	0.079	60	650
44(17)	3.30	1.60	370	599	6.0	14.0	27.0	0.079	0.079	60	650
44(18)	2.80	1.60	371	601	6.8	16.0	27.0	0.079	0.079	60	650
45(01)	15.95	1.60	404	601	0.5	1.0	27.5	0.079	0.079	60	650
45(02)	8.47	1.60	403	598	1.0	2.0	27.5	0.079	0.079	60	650
45(03)	4.91	1.60	402	601	2.0	4.0	27.5	0.079	0.079	60	650
45(04)	3.77	1.60	400	598	3.0	6.0	27.5	0.079	0.079	60	650
45(05)	3.50	1.60	400	601	3.9	8.0	27.5	0.079	0.079	60	650
45(06)	3.94	1.60	399	603	4.7	10.0	27.5	0.079	0.079	60	650
45(07)	3.03	1.60	399	601	5.5	12.0	27.5	0.079	0.079	60	650
45(08)	2.99	1.60	398	599	6.2	14.0	27.5	0.079	0.079	60	650
45(09)	2.96	1.60	400	605	6.9	16.0	27.5	0.079	0.079	60	650
46(10)	28.49	1.60	460	504	0.5	1.0	29.0	0.079	0.079	60	650
46(11)	17.24	1.60	460	503	1.0	2.0	29.0	0.079	0.079	60	650
46(12)	9.49	1.60	458	503	2.1	4.0	29.0	0.079	0.079	60	650
46(13)	6.98	1.60	457	503	3.1	6.0	29.0	0.079	0.079	60	650
46(14)	4.70	1.60	455	503	4.1	8.0	29.0	0.079	0.079	60	650
46(15)	4.60	1.60	454	503	5.0	10.0	29.0	0.079	0.079	60	650
46(16)	4.49	1.60	453	501	5.8	12.0	29.0	0.079	0.079	60	650
46(17)	4.47	1.60	452	498	6.2	14.0	29.0	0.079	0.079	60	650
46(18)	4.22	1.60	451	501	7.4	16.0	29.0	0.079	0.079	60	650
47(01)	21.55	1.60	463	550	0.4	1.0	29.0	0.079	0.079	60	650
47(02)	9.34	1.60	462	549	1.0	2.0	29.0	0.079	0.079	60	650
47(03)	6.06	1.60	461	549	2.1	4.0	29.0	0.079	0.079	60	650
47(04)	4.17	1.60	461	550	3.1	6.0	29.0	0.079	0.079	60	650
47(05)	3.79	1.60	461	552	4.2	8.0	29.0	0.079	0.079	60	650
47(06)	3.25	1.60	460	554	5.0	10.0	29.0	0.079	0.079	60	650

EXPERIMENTAL DATA

d	Mp	Ta	Tp	Po	hm	Tp _{pe}	Ds	Dg	α	MFR
measured average diameter [μm]	polymer throughput [g/min]	air jet temperature at test section [F]	polymer temperature at die tip [F]	stagnation pressure at test section [psig]	pressure drop across ADS orifice [" water]	air temperature at ADS orifice [C]	die setback [inch]	airgap [inch]	die node piece (total angle) [deg]	type of polymer [MFR]
4.05	1.60	458	552	5.8	12.0	29.0	0.079	0.079	60	650
3.35	1.60	458	554	6.6	14.0	29.0	0.079	0.079	60	650
3.01	1.60	457	557	7.4	16.0	29.0	0.079	0.079	60	650
15.21	1.60	464	599	0.5	1.0	26.0	0.079	0.079	60	650
5.46	1.60	464	601	1.1	2.0	26.0	0.079	0.079	60	650
4.15	1.60	463	598	2.2	4.0	26.0	0.079	0.079	60	650
3.20	1.60	462	600	3.2	6.0	26.0	0.079	0.079	60	650
3.18	1.60	461	599	4.2	8.0	26.0	0.079	0.079	60	650
2.88	1.60	460	603	5.2	10.0	26.0	0.079	0.079	60	650
2.37	1.60	460	599	6.0	12.0	26.0	0.079	0.079	60	650
2.69	1.60	457	601	6.8	14.0	26.0	0.079	0.079	60	650
2.57	1.60	459	597	7.6	16.0	26.0	0.079	0.079	60	650
19.19	3.20	407	500	5.2	0.5	25.3	0.005	0.010	60	650
15.28	3.20	406	497	8.8	1.0	25.3	0.005	0.010	60	650
10.27	3.20	407	498	11.8	1.5	25.3	0.005	0.010	60	650
8.92	3.20	406	492	14.6	2.0	25.3	0.005	0.010	60	650
8.44	3.20	406	494	19.4	3.0	25.3	0.005	0.010	60	650
7.73	3.20	406	497	23.8	4.0	25.3	0.005	0.010	60	650
7.96	3.20	403	489	25.9	5.0	25.3	0.005	0.010	60	650
6.56	3.20	404	484	30.6	6.0	25.3	0.005	0.010	60	650
6.02	3.20	404	496	33.8	7.0	25.3	0.005	0.010	60	650
6.27	3.20	402	490	37.0	8.0	25.3	0.005	0.010	60	650
8.71	1.60	498	604	4.3	0.5	26.5	0.005	0.010	60	650
6.27	1.60	499	603	9.7	1.0	26.5	0.005	0.010	60	650
5.25	1.60	500	601	13.1	1.5	26.5	0.005	0.010	60	650
3.98	1.60	501	595	16.4	2.0	26.5	0.005	0.010	60	650
3.88	1.60	503	593	21.8	3.0	26.5	0.005	0.010	60	650
3.31	1.60	504	593	26.8	4.0	26.5	0.005	0.010	60	650
3.13	1.60	502	590	30.6	5.0	26.5	0.005	0.010	60	650
3.11	1.60	503	582	33.9	6.0	26.5	0.005	0.010	60	650
3.40	1.60	502	588	37.2	7.0	26.5	0.005	0.010	60	650

CASE ID (sample #)
47(07)
47(08)
47(09)
48(01)
48(02)
48(03)
48(04)
48(05)
48(06)
48(07)
48(08)
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50(09)

APPENDIX D

DERIVATION OF AIR JET EXIT AREA EXPRESSION

DERIVATION OF AIR JET EXIT AREA EXPRESSION

Figure D.1 shows an exploded view of the die tip and face plates. The distance between the inclined surface of the die and the inner inclined surface of the face plates is called the air gap (d_g). The air gap reduces/increases the flow area available for the air to flow through the test section. Setback (d_s) is the distance between the tip of the nose piece and the exit plane of the test section. The included angle (α) of the die is also shown in Figure D.1. The angle θ represents the angle at which the top and bottom air jet streams converge at the tip of the die. This angle is one half of the die included angle ($\theta = \alpha/2$)

From the geometry of the die and the face plates shown in Figure 100, the following relationships can be written from fundamental geometry principles:

$$d_s = x_3 + x_1 \quad D.1$$

$$h = 2x_4 + d_{die} \quad D.2$$

$$x_3 = d_g \sin \theta \quad D.3$$

$$x_2 = x_1 \tan \theta \quad D.4$$

$$(d_g)^2 = (x_3)^2 + (x_4 + x_2)^2 \quad D.5$$

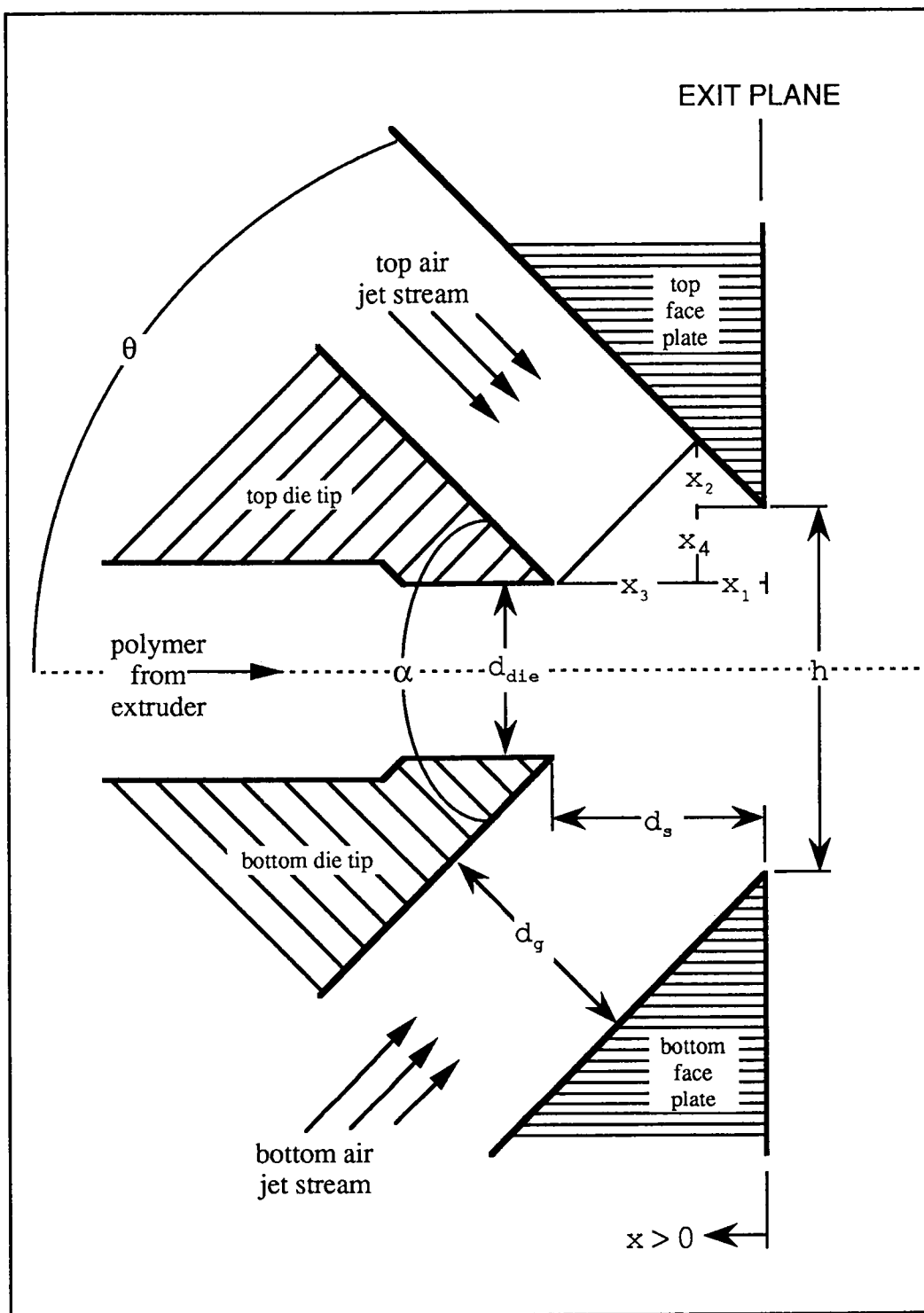


Figure D.1: Exploded view of the die tip and face plates

where

$$\theta = \alpha / 2$$

$$d_{\text{die}} = 356 \text{ microns}$$

Solving Equation D.5 for x_4 and substituting into Equation D.2:

$$h = 2 \left[\sqrt{(d_g)^2 - (x_3)^2} - x_2 \right] + d_{\text{die}} \quad \text{D.6}$$

Substituting x_3 from Equation D.3 into Equation D.6:

$$\begin{aligned} h &= 2 \left[\sqrt{(d_g)^2 - (d_g \sin \theta)^2} - x_2 \right] + d_{\text{die}} \\ &= 2 \left[d_g \cos \theta - x_2 \right] + d_{\text{die}} \end{aligned} \quad \text{D.7}$$

Substituting x_2 from Equation D.4 into Equation D.7:

$$h = 2 \left[d_g \cos \theta - x_1 \tan \theta \right] + d_{\text{die}} \quad \text{D.8}$$

Substituting x_1 from Equation D.1 into Equation D.8:

$$h = 2[d_g \cos \theta - (d_s - x_3) \tan \theta] + d_{die} \quad D.9$$

Substituting x_3 from Equation D.3 into Equation D.9:

$$h = 2[d_g \cos \theta - d_s \tan \theta + d_g \sin \theta \tan \theta] + d_{die} \quad D.10$$

Rearranging Equation D.10, the expression for the air jet exit height at the test section exit plane becomes:

$$h = 2[d_g(\cos \theta + \sin \theta \tan \theta) - d_s \tan \theta] + d_{die} \quad D.11$$

Equation D.11 expresses the air jet exit height in terms of variables that are easily measured; air gap, setback, and air jet injection angle. Both the 60 and 90 degrees included angle dies are 4 inches wide. Therefore, the air jet exit area is given by multiplying the air jet exit height by the width of the die:

$$A_e = 2.03 * 10^{-4} [d_g(\cos \theta + \sin \theta \tan \theta) - d_s \tan \theta] + d_{die} \quad D.12$$

where:

- A_e air jet exit area in m^2
- d_s setback in mm
- d_g air gap in mm
- θ air jet injection angle in degrees
- d_{die} die orifice diameter in mm

APPENDIX E

DERIVATION OF AIR JET EXIT VELOCITY EXPRESSION

DERIVATION OF AIR JET EXIT VELOCITY EXPRESSION

The velocity of the air jet at the exit plane of the test section will be derived in terms of experimental variables. Applying the principle of conservation of mass [21] to the air flowing through the air delivery system at the ADS measuring orifice and at the test section exit plane, results in the following expression:

$$\dot{m}_a|_{\text{ADS}} = \dot{m}_a|_{\text{ts}} \quad \text{E.1}$$

where: $\dot{m}_a|_{\text{ADS}}$ is the air flow rate as measured at the ADS measuring orifice (Appendix A, Equation A.6)

The mass flow rate of a gas through a channel is defined [22] by the following relationship:

$$\dot{m} = \rho A V \quad \text{E.2}$$

where: ρ is the density of the gas

A is the cross sectional flow area

V is the velocity of the gas

Substituting Equation E.2 into Equation E.1 and solving for the air velocity:

$$V_e = \frac{\dot{m}_a}{\rho_a|_{ts} A_e} \quad E.3$$

where: $\rho_a|_{ts}$ density of air at the exit plane

A_e air jet exit area (Appendix D)

The following relationship between temperature and pressure can be written for an isentropic process [22]:

$$\frac{T_1}{T_2} = \left[\frac{P_1}{P_2} \right]^{\left(\frac{\gamma-1}{\gamma} \right)} \quad E.4$$

where: γ is the specific heat ratio of the gas

For all practical purposes, an isentropic process can be assumed to occur from the inside of the test section to the exit of the test section. This assumption is valid since irreversibilities such as friction and heat losses are small. If state 1 is referenced to the stagnation properties

at the test section, and state 2 is referenced to the static properties at the exit plane of the test section, then Equation E.4 becomes:

$$T_a = T_{ao} \left[\frac{p}{p_o} \right]^{\left(\frac{\gamma-1}{\gamma} \right)} \quad \text{E.5}$$

where: T_a ... air jet static temperature
 T_{ao} ... air jet stagnation temperature
 p air jet static pressure
 p_o ... air jet stagnation pressure

Assuming air to behave as an ideal gas, the density at the exit plane can be expressed as [22]:

$$\rho_a = \frac{p}{RT_a} \quad \text{E.6}$$

where: R is the specific gas constant of air

Substituting Equation E.5 into E.6:

$$\rho_a = \frac{p}{RT_{ao} \left[\frac{p}{p_o} \right]^{\left(\frac{\gamma-1}{\gamma} \right)}} \quad \text{E.7}$$

and substituting Equation E.7 into E.3:

$$V_e = \frac{\dot{m}_a R T_{ao}}{A_e p} \left[\frac{p}{p_o} \right]^{\left(\frac{\gamma-1}{\gamma} \right)} \quad \text{E.8}$$

Equation E.8 represents the velocity of the air jet at the exit plane of the test section. The stagnation pressure (p_o), the stagnation temperature (T_{ao}), and the air flow rate ($\dot{m}_a$) are determined experimentally. The static pressure of the air jet at the exit plane is determined by applying the properties of a converging nozzle in an isentropic process.

The test section configuration resembles a converging nozzle. Therefore, the maximum Mach number that can be achieved at the exit plane of a converging nozzle is unity [21]. When the Mach number is unity, the properties of a fluid are referred to as critical properties and the flow is said to be choked. Furthermore, whenever the Mach number at the exit plane is less than unity, the static pressure at the exit plane is equal to the back (ambient) pressure.

The critical pressure ratio for air for an isentropic process ($\gamma = 1.4$) is given by [21]:

$$p^* = 0.5283 * p_o \quad \text{E.9}$$

where: p^* is the critical static pressure

The critical static pressure (p^*) in this case is 14.7 psia (ambient pressure). Solving Equation E.9 for the stagnation pressure, which is measured experimentally, the following value results:

$$p_o = \frac{14.7}{0.5283} = 27.8 \text{ psia} = 13.1 \text{ psig} \quad \text{E.10}$$

Whenever the pressure gauge located in the test section reads 13.1 psig or below, the static pressure at the exit plane is equal to the ambient pressure (14.7 psia) and Equation E.8 can be used to determine the air jet velocity. Whenever the pressure reads above 13.1 psig, the flow is choked and the exit pressure is no longer equal to the back pressure. Therefore, Equation E.9 can be used to calculate the static pressure (critical pressure) since the stagnation pressure is known and the flow is known to be choked. In this case, the exit air velocity would be given by substituting the expression for the critical pressure (Equation E.9):

$$V_e = \frac{\dot{m}_a R T_{ao}}{A_e (0.5283 * p_o)} [0.5283]^{\left(\frac{\gamma-1}{\gamma}\right)} \quad \text{E.11}$$

In conclusion, the air jet exit velocity is calculated using two different equations depending upon whether the flow is choked or not. If the flow is choked ($p_o > 13.1$ psig), Equation E.11 should be used, otherwise, Equation E.8 should be used ($p_o \leq 13.1$ psig).

VITA

The author was born in Athens, Texas, south of Dallas, on October 29, 1966. His parents and family moved to Santiago, Chile where he completed his High School studies and later attended college. Mr. Spencer studied Mechanical Engineering at The University of Chile from 1985 to 1987. He returned to the U.S. and attended The University of Tennessee in Knoxville where he obtained his Bachelor of Science degree in Aerospace Engineering graduating with honors on December, 1990.

Mr. Spencer continued post graduate studies at The University of Tennessee starting January, 1991. He joined The Boeing Company, Missiles and Space Division in Huntsville, Alabama on May, 1992 where he currently works as a Thermal Analyst in the International Space Station Alpha (ISSA) program.

This thesis was written to satisfy the requirement for the Master of Science degree in Aerospace Engineering.